Editorial

Fear feeds on ignorance, and a great niche was opened for fear when science became incomprehensible to those who were not its practitioners. For a long time it was assumed that anything as miraculously energetic as radioactivity must be beneficial.

One of the most famous quotations of Marie Curie is: “Nothing in life is to be feared. It is only to be understood.” Radiation has always been present in the environment and in our bodies. The human senses cannot detect radiation or discern whether or not a material is radioactive. Radioactivity is invisible, has no smell, makes no sound - in fact it cannot be detected by any of our senses. However, because radioactivity affects the atoms that it passes, we can easily monitor it using a variety of methods. There is a range of simple, sensitive instruments capable of detecting minute amounts of radiation from natural and man-made sources.

This bulletin on ‘Radiation Detection and Measurement’, Guest Edited by Dr. B.S. Tomar, a proficient specialist in the field, is expected to provide in-depth coverage of the basic principles of radiation detection as well as illustrating their myriad of applications in a full set of modern instruments. IANCAS thanks Dr. Tomar for adeptly choosing the experts in the field to author the articles. The authors have used their extensive research experience in radiation measurements, nuclear instrumentation, and radiation imaging to provide you with an invaluable resource. The writing style has maintained the readability that has attracted favorable response from readers and reviewers of the earlier bulletins.

G.A. Rama Rao
IANCAS Web Site Launched

www.iancas.org
Dear Members,

Since I last penned this column, a National Workshop at National Defence Academy (NDA), Pune and Advanced Workshop at BARC, Mumbai have been conducted. We were privileged to have Dr Anil Kakodkar, Chairman, AEC inaugurate the Workshop at NDA which was intended to help the institute revise its courses on nuclear sciences and update the teaching staff on the new developments. The Advance Workshop, spread over three weeks, has been an enriching experience both for the participants who were selected with great care, and, IANCAS itself. It provided an opportunity for IANCAS to get a systematic and objective feedback from a group of young researchers/teachers on the state of art of Radiochemistry discipline in universities and assess the impact of the National Workshops conducted so far all over the country. This information, needless to say, will guide the future policy planning and activities of IANCAS. I take this opportunity to thank all the resource persons/coordinators for their help in the smooth conduct of these Workshops.

IANCAS has launched its website (www.iancas.org). It is intended to work as a platform for dissemination of information on IANCAS activities, future programs, Workshops, awards, publications, and, being interactive members can send their suggestions online to secretary/president/feedback@iancas.org. The thematic bulletins as well as the book “Fundamentals of Radiochemistry” can be downloaded in addition to application forms for awards, life-membership etc. It also carries a list of all the thematic bulletins, National Workshops conducted so far and provides necessary information to potential host institutions. The most important thing for a web site to sustain interest is the content. We have a section called “Radiochemistry Resources” which, at present, carries some selected & interesting links. It needs to be updated on a regular interval and I look forward to your contribution and cooperation in identifying important portals dealing with Radiochemistry and nuclear sciences. I urge all the members to visit the website and send their comments/feedback on the web page.

The current issue is on radiation detection & measurement. This topic is important and integral to any research/teaching in nuclear sciences at all levels. The articles cover entire gamut of radiation interaction and detection methods. I am sure you will enjoy reading this issue. I take this opportunity to thank the authors and the guest editor, Dr B.S. Tomar. You can send your feedback/suggestions (very important to beat complacency) on this issue to feedback@iancas.org.

On behalf of IANCAS, I thank the Board of Research in Nuclear Sciences (BRNS) for financial support for our activities.

P.K. Pujari
NUCAR-2005
Seventh Biennial Symposium on Nuclear and Radiochemistry (NUCAR 2005)
March 15-18, 2005
Guru Nanak Dev University, Amritsar 143 005, India

Board of Research in Nuclear Sciences (BRNS), Department of Atomic Energy, in collaboration with Guru Nanak Dev University, Amritsar is organizing a four-day symposium on Nuclear and Radiochemistry to provide a forum for effective interaction among the scientists in the areas of Nuclear and Radiochemistry and Applications of Radioisotopes for the advancement of these disciplines. The scientists engaged in research in these areas are invited to participate in the above symposium and make it a memorable event.

The scope of the Symposium is
1. Nuclear chemistry
2. Chemistry of actinides and reactor materials
3. Spectroscopy of actinides
4. Chemistry of fission and activation products
5. Radioanalytical chemistry
6. Radioisotope applications
7. Radioactivity in environment
8. Nuclear instrumentation

The scientific programme of the symposium will include invited talks by eminent scientists as well as contributed papers. The contributed papers will be divided into oral and poster presentations. Invited talks and contributed papers will be published as preprint volume to be distributed to the delegates during the symposium.

Those who wish to participate in the symposium may please send the registration details to the Convener / Secretary by FAX or E-mail at the address given below.

Important Dates
Intimation of Participation October 31, 2004
Receipt of Paper November 30, 2004
Request for accommodation January 31, 2005

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Registration fee may be paid by D.D. in favour of NUCAR 2005 payable at Mumbai or in Cash at the time of Registration.

For further details, please contact:
Dr. Keshav Chander
Convener, Symposium Organising Committee NUCAR 2005
Fuel Chemistry Division, BARC
Trombay, Mumbai 400 085, INDIA
Telephone : 25595012 / 25592013
FAX : 91-22-25505151/25519613
E-mail: nucar05@apsara.barc.ernet.in
    nucar05@rediffmail.com
    keshav@magnum.barc.ernet.in

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www.barc.ernet.in/webpages/symposium/nucar05
www.iancas.org
Indian Association of Nuclear Chemists and Allied Scientists (IANCAS) invites nominations for the annual Tarun Datta Memorial Young Scientist Award from eligible scientists for their outstanding contributions in the field of Nuclear and Radiochemistry. The award, carrying an amount of Rs. 5000/- in cash, a citation and a medal, will be presented during the Annual General Body Meeting (AGM) of IANCAS to be held during 2005, the date and venue will be intimated later.

Eligibility

Citizens of Indian nationality below 35 years of age as on December 31, 2004 and working at least for the last five years with significant contributions in the field of Nuclear and Radiochemistry or Applications of Radioisotopes for the basic research in any branch of science, are eligible to apply.

It may be noted that the award would be given for research work carried out in India.

How to apply?

The application should be as per the proforma given on the reverse side of this announcement. Photocopies of the proforma may also be used. Applicants should submit the proforma along with a summary (not exceeding 500 words) highlighting the significant research contributions, during the last five years. In addition, they should enclose two passport size photographs, proof of age, and reprints of best five published papers in support of the application and a declaration by the applicant ratified by the Head of the Department, Research Guide or Head of the Institution. The declaration should also bring out clearly the contributions of the co-workers.

The application, complete in all respects should reach the General Secretary, IANCAS on or before November 15, 2004.

Selection

An expert panel will scrutinise the applications and judge the best research contribution for the award. The awardee has to present her/his work by giving a lecture during the AGM of IANCAS the date and venue of which will be intimated later. The awardee will be provided with DA and to and fro first class train fare, if the awardee cannot get the same from any other source.

It may please be noted that the decision of the expert panel is FINAL and canvassing in any form is a disqualification.

Completed application may please be forwarded to

Dr. P.K. Pujari
General Secretary, IANCAS
C/o Radiochemistry Division
BARC, Trombay, Mumbai 400 085
E-mail : secretary@iancas.org

(Application proforma can be downloaded from www.iancas.org)
IANCAS - Prof. H.J. Arnikar - Best Thesis Award

The Indian Association of Nuclear Chemists and Allied Scientists is happy to announce the institution of an Annual Award for the best thesis in the field of radiochemistry and Allied Sciences. The award carries a medal, a citation and Rs. 5,000/- in cash. The awardee will be provided return I class/AC III tier fare to attend the award function, which will be held during the Annual General Body meeting of IANCAS during 2005, the date and venue will be intimated later.

Eligibility

2. The work reported in the thesis should be in any one of the following fields
   - Radiochemistry
   - Nuclear Chemistry
   - Nuclear Materials
   - Radioanalytical Chemistry
   - Isotope Production
   - Radiotracer Studies
   - Radioactivity Measurement or
   - Any Allied Fields wherein Radioisotopes are Used
3. Age limit: There is no age limit for this award

How to Apply?

The nomination should be sent by the Ph.D. Guide along with 3 copies of the synopsis as submitted to the University and a write up not exceeding 500 words highlighting the aim of the work and the most recently reported work from the thesis should also be submitted, along with reprints or manuscripts. It is essential that a copy of the Ph.D. Degree certificate/provisional certificate from the University is also submitted.

Last Date: on or before November 15, 2004

The application, complete in all respects, should reach the General Secretary, IANCAS, C/o Radiochemistry Division, Bhabha Atomic Research Centre, Mumbai - 400 085.

Selection

A panel of experts nominated by the Executive Committee of IANCAS comprising of members from Department of Atomic Energy and the Universities will select the best thesis. It may please be noted that the decision of the panel is FINAL and canvassing in any form will be a disqualification. The awardee will be given an opportunity to present his/her work during the Annual General Body Meeting of IANCAS.

(Application proforma can be downloaded from www.iancas.org)
Radiation Detection and Measurement

Guest Editor

Dr. B.S. Tomar
Radiochemistry Division
Bhabha Atomic Research Centre
Mumbai 400 085
Just like the tiny nucleus (size \( \sim 10^{-15} \) m) located at the center of the atom cannot be seen through human eyes, the nuclear radiation emanating from the nucleus or from the nucleus-nucleus interaction is not discernible by us. The nuclear radiation consists of not only gamma rays but also charged particles like protons, alphas etc and neutral particles like neutrons etc. The detectors are in some sense our eyes through whom the different types of nuclear radiation can be seen and quantified. As the nuclear radiation encompasses a range of particle types (and gamma rays), and no single detector can handle the arduous task of measuring the different types of nuclear radiations, it is but natural, detectors of varying types have been developed over the years. Radiation detectors make use of gas, liquid and solid medium to sense the radiation. They also make use of different properties of these sensors and accordingly we have gas filled detectors, scintillation detectors, semiconductor detectors and their hybrids. Depending upon the application—be it detection of radiation with high efficiency, discrimination of different type of radiation, measurement of energies with high energy resolution, sensing the arrival time of the radiation—the appropriate type of the detector is employed. As it happened in many other areas, nuclear radiation detectors primarily developed for basic research are now widely used in many areas of societal interest. With the increasing availability of newer sensing materials and modern pulse processing techniques and counting setups, one has witnessed a rapid growth in the field of radiation detectors and techniques.

In the present monograph, an attempt has been made to capture this exciting field of modern invention, covering various aspects of nuclear radiation detector and measurement. Understanding the basic interaction mechanism of radiation with matter is crucial for appreciating the functioning of radiation detectors. An introduction is given to this aspect followed by extensive coverage of conventional and advanced detectors of different types based on gas, scintillators and semiconductors. Radiation measurement is finally accomplished by complex pulse processing techniques. Often, the user is not clear about the appropriate detector which is most efficient for the desired application. The monograph ends with a discussion on this aspect as well.

Who could have expected a simple looking scintillation detector will finally end up in the medical marvel of Positron Emission Tomography! Recognising the importance of radiation detectors not only for basic research but also their impact in other applied areas of the medicine, the highest honour in science, the Nobel Prize was awarded to Prof. Charpak for his innovative & pioneering contributions to the broad field of radiation detectors. Even though a number of comprehensive text books and treatises have been written by experts (usually a couple of authors) on Radiation Detector & Measurement, the present monograph is an attempt to capture this exciting & fast developing field through the voice of a number of working scientists. Both the experts and the freshers in particular, the student community will find this monograph very informative and upto date in content.

Over the years, the IANCAS and its members have been bringing out excellent monographs on various types of science and technology of great relevance to society at large. The present one on Radiation Detection and measurement belongs to this series. I am sure the scientific community will find the series of articles contained in this monograph very comprehensive and useful. The monograph may also be used as a text book for a graduate level course on Radiation Detectors.
Guest Editorial

Dr. B.S. Tomar

Detection and measurement of ionising radiation is one of the most important aspect of any field related to nuclear science. From the photographic plates, which were used by Henry Becquerel for the discovery of radioactivity, through the robust Geiger Muller and sodium iodide counters, to the latest state of the art HPGe based high resolution gamma ray spectrometers, there has been tremendous advancement in the field of radiation detectors. Compared to the earlier systems of NIM bins, high voltage, amplifier timer scalar, etc., modern counting systems come in the form a simple PC based card, which has all the components of the counting system except the detector. Furthermore, depending upon the application, detectors come in different sizes and shapes. Thus, while one can now simultaneously count alpha and beta radiations using the same detector using pulse shape discrimination technique, it is now possible to count samples with dead time close to 100%, using loss free counting systems. Today gamma ray detectors having both the characteristics of high photo-fraction of NaI(Tl) and high energy resolution of HPGe detector have been developed, e.g., CdZnTe detectors, though they are still available in small sizes.

One of the past bulletins (Vol. 15, No. 4, October 1999) was devoted to ionising radiation sources, which was also, incidently, edited by me. The present bulletin contains articles on detection and measurement of almost all types of ionising radiations. For the development of radiation detector it is essential to understand the mechanism of interaction of the ionising radiation with matter, which is the subject matter of the first chapter. This is followed by introduction to the electronics involved in radiation detection and measurement. Gas filled detectors, scintillator detectors, both organic and inorganic, and subsequently semiconductor detectors have been described in separate chapters considering the important role of these detectors in any nuclear science laboratory. Neutron detectors have been discussed in a separate chapter owing to the special class of radiations they belong to. The last chapter has been written with a view to provide information on how to chose a detector for a particular application.

I thank all the contributors for their timely submission of articles. I hope the readers will find the information useful and stimulating. I look forward to receiving their comments and suggestions.
Interaction of Radiation with Matter

Dr. K.L. Ramakumar is currently the Head, Trace Elements Analysis Section of Fuel Chemistry Division in Bhabha Atomic Research Centre, Mumbai. He is a specialist in the fields of trace elemental analysis by Mass Spectrometry and Ion Chromatography, thermal analysis by Differential Scanning Calorimetry as well as in analytical chemistry. Dr. Ramakumar has been a Peer Reviewer for International Science Foundation (USA) Program for providing research grants to Russian Scientists. He was also on an Expert assignment to IAEA’s Safeguards Analytical Laboratory (SAL) at Seibersdorf, Austria to check and establish calibration procedures for precise and accurate mass spectrometric analysis. He is a recognized Research Guide of Mumbai University. He has more than 180 publications to his credit.

Introduction

The term “radiation” in nuclear science refers to all those particles/ electromagnetic radiations emitted as a result of nuclear reactions including radioactive decay. These include charged, neutral, and electromagnetic radiations. Table 1 classifies these radiations.

The radiation propagates out from the originating nucleus and interacts with other matter along its path. This matter can be solid, liquid or gaseous medium. The nature of interactions and the consequence of these interactions is the subject of interaction of radiation with matter. Understanding the interaction of radiation with matter helps in identifying the radiation, and measuring its energy. This in turn helps in deciding the shielding materials for proper protection. Effectiveness of the medium and its response to the incident radiation and its ability to absorb the energy from radiation can also be understood. Whatever may be the medium, the nature of interaction of any radiation in matter will be same. However, the mode of interaction of charged particles is different from that of neutral particles and electromagnetic radiation even though the ultimate consequence of interaction remains the same. For simplicity sake, we will understand the nature of interactions in terms on heavy charged particles (e.g. alpha particles), light charged particles e.g. electrons), gamma rays, and neutrons.

Interaction of Charged Particles

All the interaction processes of charged particles with matter are due primarily to Coulomb forces. The net outcome of such interaction is the reduction in the kinetic energy of the particle/radiation during interaction ultimately resulting in either complete absorption of radiation or stopping of the particle and its charge neutralization. These interaction processes include excitation, ionization, scattering and various types of

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<td>Electromagnetic</td>
<td>Gamma rays, x-rays</td>
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TABLE 1. Classification of nuclear radiations

Dr. K.L. Ramakumar, Fuel Chemistry Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400 085; E-mail: kram@magnum.barc.ernet.in
radiative losses of energy. On an average, approximately 34 electron volts of energy is lost for each primary ion pair formed in air. This is more or less independent of nature of charged particle. Only about half to two-thirds of this energy is actually required to remove the orbital electron, the balance being lost in electronic excitation processes. The mechanisms by which a charged particle loses its kinetic energy, or deflected from its original path, involve four principal types of interaction.

**Inelastic Collision with Atomic Electrons**

Inelastic collisions with bound atomic electrons are usually the predominant mechanism by which a charged particle loses its kinetic energy in an absorber. As a result of each collision, one or more atomic electrons experience a transition to an excited state (excitation) or to an unbound state (ionization).

**Inelastic Collision with a Nucleus**

In a close encounter with a nucleus, the incident charged particle experiences a deflection. In some such deflections, if the energy of the particle is near the relativistic range, a quantum of radiation (bremsstrahlung) is emitted, and a corresponding amount of kinetic energy is lost by the incident particle.

**Elastic Collision with a Nucleus**

In elastic nuclear scattering the incident particle is deflected but does not radiate, nor does it excite the nucleus. The incident particle loses only the kinetic energy required for conservation of momentum between the two particles. Incident electrons have a high probability of experiencing nuclear elastic scattering.

**Elastic Collision with Atomic Electrons**

An incident charged particle may be elastically deflected in the field of atomic electrons of an atom. Energy and momentum are conserved, and the energy transfer is less than the lowest excitation potential of the electrons, so that the interaction is really with the atom as a whole. Such interactions are significant only for the case of very low energy (<100 eV) incident electron.

It should be clearly understood that in an absorbing material, a moving charged particle is slowed down and finally brought to rest by the combined action of all four of these elastic and inelastic processes. In general, each incident particle may experience a number of collisions of each type. Which type of interaction, if any, will occur when a charged particle passes a particular atom is described only by the laws of chance/probability. Even though the theory of individual encounters is of great importance for a clear understanding of the behaviour of charged particle in matter, the statistical average of the effect of all the collisions is what is obtained by direct experiment and is more convenience to interpret the gross results. In this chapter, we will try to understand only the gross effects of interaction. It is also convenient and desirable to distinguish between the behaviour of heavy particles and light particles. As mentioned earlier, the “heavy particle” group includes all those whose rest mass is large compared to that of an atomic electron. The “light particle” group consists only of electrons and positrons.

**Interaction of Heavy Charged Particles (e.g. Alpha Particles) with Matter**

The interaction of alpha particles with matter is less complicated than the interaction of light charged particles e.g. electrons. Heavy particles lose most of their energy through ionization and excitation of the atoms in the absorber. Elastic nuclear scattering and bremsstrahlung are generally negligible. Alpha collisions may result in energy transfer by (1) ionization and/or (2) excitation. Since a finite amount of energy is required to ionize or excite an atom, the kinetic energy of the alpha particle is gradually dissipated by such interactions until it captures two electrons and settles down to a quiet existence as a helium atom. Since the average amount of energy to ionize most materials is much less than the initial energy of most alpha particles, many ionizations will occur before the alpha particle is stopped. For example if the initial kinetic energy of alpha particle is 5 MeV, the number of ion pairs formed is 5 MeV x 10⁶/34 eV/ion pair = 1.5 x 10⁵ ion pairs.

**Specific Ionization or Stopping Power**

As a charged particle passes through an absorber, the energy loss can be measured several ways. One method used is specific ionization (SI).
Specific ionization is the number of ion pairs formed by the particle per unit path length and is often used when the energy loss is continuous and constant such as with beta particles (electrons) or alpha particles. When this is expressed as the energy loss per unit distance traveled this quantity is called stopping power (S). The number of ion pairs produced is dependent on the type of ionizing particle and the material being ionized.

According to Bohr’s classical theory of rate of energy loss, it is assumed that all the electrons in the absorber are free electrons. This assumption is justified for those collisions, in which the electron receives so much kinetic energy that its binding energy can be neglected. Based on this assumption, which is valid under some special circumstances of collision time and impact parameter, Bohr derived an expression for the stopping power or specific ionization:

\[
S = -\frac{dE}{dx} = \frac{4\pi z^2e^4}{m_e V^2} \frac{N\ln 2m_e V^2}{2\pi\sqrt{2\alpha}^2 (M + m_e)}
\]

where \(M, V, E,\) and \(ze\) are, respectively, the mass, velocity, kinetic energy, and the charge of the incident particle. \(N\) and \(Z\) are the number density and charge of the absorber, \(m_e\) is the mass of the electron and \(\sqrt{2}\alpha\) is a quantity related to natural frequency of vibration of bound electron in the absorber atom. Unfortunately, this classical theory fails to account for energy loss suffered by the incident particle even when colliding with a bound electron. Quantum mechanical theories as enunciated by Mott, Bethe, and Bloch overcame this limitation. Bethe’s expression for energy loss (stopping power) is given by

\[
S = -\frac{dE}{dx} = \frac{4\pi z^2e^4}{m_e V^2} \frac{N\ln 2m_e V^2}{I}
\]

where \(I\) is geometric mean of all ionization and excitation potentials of the absorbing atom. When the velocity of the incident particles is in the relativistic range \((V = \beta c, c\) is the velocity of light), Bethe’s formula becomes

\[
S = -\frac{dE}{dx} = \frac{4\pi z^2e^4}{m_e V^2} N\left[ \frac{2m_e V^2}{I} - \ln(1-\beta^2) - \beta^2 \right]
\]

It can be seen from the above expression that the stopping power is greatest for high-density, high-Z materials, and for ions in higher charge states. Figure 1 is a sketch of Bragg Curve for the rate of energy loss. As the charged particle loses its energy, the stopping power increases. At the end of its path, the stopping power is the highest. Thus, along the path, the ion-pair density is the highest at the path end.

**Usefulness of Stopping Power Equation**

1. It may be noted that \(S \propto z^2\) and also proportional to \(1/V^2\) or \(1/E\) of the incident particle. Thus if charge and velocity of incident charged particle remaining same, \(S\) becomes independent of its mass.

2. Consider an alpha particle \((^{4}\text{He}^+\text{ z = 2})\) and a proton \((^{1}\text{H}^+\text{ z = 1})\). If the velocity of both the particles is same, then \(-dE/dx \propto z^2\). For \(\alpha\) particle, specific ionization will be four times that of proton.

3. \[
-\frac{dE}{dx} = \frac{z^2}{V^2} = \frac{dE}{dx}\frac{1}{\sqrt{2m_v}^2} \alpha \frac{1}{2} \text{mz}^2
\]

Thus the product of initial energy of the charged particle and its specific ionization in a medium is proportional to its mass. Based on this principle, particle identifier detectors are made.
Range

Inversely related to the stopping power of the absorber is the range (R) of the charged particle. The concept of range only has meaning for charged particles whose energy is kinetic energy which is lost continuously along their path. The range of a charged particle in an absorber is the average depth of penetration of the charged particle into the absorber before it loses all its kinetic energy and stops. If a particle has a high range, the absorber has a low stopping power. If the particle has a short range, the absorber has a high stopping power.

Alpha particles from a given radionuclide are all emitted with the same energy, consequently those emitted from a given source will have approximately the same range in material. A typical range of monoenergetic alpha particles is given in Fig. 2.

Even though of same energy, as collisions in the medium and rate of energy transfer are purely statistical in nature, distribution of ranges known as straggling is observed. For a given energy E of the charged particle, range can be expressed as

$$R = a \frac{E^2}{mz^2}$$

where a is a constant depends on the medium, m and z are mass and charge of the charged particle.

Range is usually expressed in centimeters or cm x density = g.cm⁻². In air, for example, the range is empirically given as

$$R_a = 0.318 E^{3/2}$$

where $R_a$ = Range in cm of air at 1 atmosphere and 15°C and $E$ = Energy in MeV.

### Calculations involving Range of different radiations in different media

1. **Range of same charged particle in different medium**: If range in air ($R_a$) is known, then range $R_z$ in another medium of atomic number $z$ is given by

$$R_z = R_a \left[ 0.90 + 0.0275z + (0.06 - 0.0086z) \log \frac{E}{m} \right]$$

Range is expressed in mg.cm⁻² and $E$ is in MeV.

2. **Range of two different particles with same velocity in the same medium**: $R_z = R_i \left[ \frac{m_z z_i^2}{m_i z_i^2} \right]$.

3. **Range in a compound medium**: Range ($R_c$) in a compound medium = $\sum w_i R_i$ where $w_i$ is weight fractions of individual components in the medium and $R_i$ is the corresponding range in that component medium.

4. **Stopping power in a compound medium**: Stopping power of a molecule or a mixture of atoms or molecules is the sum of the stopping powers of all the component atoms (Bragg-Kleeman rule)

$$\frac{1}{N_c} \left( \frac{dE}{dx} \right)_c = \sum a_i \frac{1}{N_i} \left( \frac{dE}{dx} \right)_i$$

where $N$ is atom density and $a$ = atom fraction of the component.
An approximate expression for the alpha-range in solids is given by
\[ R_\alpha = 3.2 \times 10^{-4} \frac{R_\alpha}{\rho}, \]
where \( \rho \) is density of solid in g cm\(^{-3}\).

**Interaction of Light Charged Particles (e.g., Electrons) with Matter**

The mass of an electron or beta particle is about 1/1800 that of a proton. Particles with mass comparable to those of electrons are light charged particles. Newtonian physics applied to estimate the velocity of high-energy electrons gives velocities larger than that of light, the limiting speed. Thus, Einstein’s theory of relativity must be applied. A simple method in agreement with the theory of relativity is to consider the relative mass as the sum of rest mass and kinetic energy, \((0.51 + E_k)\) MeV, \(m = (0.51 + E_k)\) MeV. The velocity of the electron is then \(v = (1 - 0.51/m)^{1/2}c\).

For a given kinetic energy, the velocity of an electron will be almost 2000 times that of a proton and about 8000 times that of an alpha particle. For non-relativistic velocities of electrons, Bethe’s formula for energy loss for electrons is given by

\[ \frac{dE}{dx} = 4\pi^2 e^4 \frac{N Z \ln \frac{m_e v^2}{\sqrt{2} I}}{m_v v^2} \]

Rate of energy loss or specific ionization caused by the passage of electrons in a medium is therefore substantially less. The number of ion pairs produced per unit distance traveled is also less. There is another important consideration. The mass of the electron is same as that of the atomic electrons in the medium. Further unlike the mono-energetic nature of alpha particles being emitted from a source, the energy spectrum of beta particles is continuous with a maximum limiting value. Hence, the interaction of electrons in a medium is characterised by (1) non-linear or tortuous paths (see Fig. 3) unlike in the case of alpha particles, (2) larger deviations from the path, (3) larger fraction of energy transfer per interaction, (4) severe straggling, (5) enormous scattering, and (6) even back scattering from the incident surface of the medium. Because of these larger deviations and larger scattering, the actual path length of an electron in a medium is always greater than its range in the medium. There are many electrons in a material, and fast-moving electrons go through a medium with considerable deflection as depicted in the diagram shown. Thus, the ranges for beta particles are poorly defined due to enormous range straggling, low intensities for a spread of thickness as shown in the diagram.

**Fig. 3** Range and path length of electrons.

- Path length = S (Entry to end of Path)
- Range = R Linear distance
- Path length > Range

The relation between the path length and the range is shown in Fig. 4.

**Mechanisms of Interaction Between Electrons and Matter**

Ionization, bremsstrahlung radiation, and annihilation with positrons are the three
mechanisms by which electrons lose energy in a medium. Coulomb interactions between fast moving electrons and molecular electrons excite and ionize the molecule, producing ion pairs like in the case of heavy charged particles. In the case of positrons, the annihilation with electrons is another mechanism of interaction which results in conversion of the total mass of the electron-positron pair into energy in the form of photons.

When a fast-moving electron is accelerated or decelerated when passing through the field of atomic nuclei, a photon is emitted, and such photons are called bremsstrahlung radiation.

Acceleration produced by a nucleus of charge $Ze$ and mass $M$ on a particle of charge $ze$ and mass $m$ is proportional to $MZe^2/m$.

Intensity is proportional to $(acceleration)^2 \times (ze)^2 = (MZe^2/m)^2 \times (ze)^2 = M^2Z^2ze^6/m^2$

Bremsstrahlung intensity $\alpha \frac{M^2Z^2ze^6}{m^2}$

Thus the energy emitted by an accelerated particle is proportional to $1/m^2$, with $m$ the rest mass of the particle; bremsstrahlung therefore plays a particularly important role for light particles such as electrons. At the critical energy ($E_c$) of approximately 500 MeV/Z for electrons, the average energy loss by radiation and by ionization is the same.

Annihilation of electron and positron can also be a mode of interaction particularly with positrons. The resulting gamma rays will then interact with the matter as explained below.

Total energy loss in the case of electron interaction in the medium mainly consists of two components coulombic and radiative due to bremsstrahlung:

$$\left(\frac{dE}{dx}\right)_r = \left(\frac{dE}{dx}\right)_c + \left(\frac{dE}{dx}\right)_r$$

In any medium, it can be assumed

$$\frac{(dE/dx)_r}{(dE/dx)_c} = \frac{EZ}{800}$$

where $E$ is in MeV and $Z$ is the atomic number of the medium. It is seen that radiative losses are more for a given energy of an electron in high $Z$ elements (e.g. lead) than in low $Z$ elements (e.g. Al). For attenuation of electrons therefore lead is not suitable.

Bremsstrahlung radiation

Bremsstrahlung radiation is a German word for breaking radiation. In the vicinity of an electric field being generated by the atomic nuclei, the acceleration of passing electrons changes substantially, which results in change in the kinetic energy of the electrons. This change (break) in kinetic energy is manifested as electromagnetic radiation called Bremsstrahlung radiation.

Synchrotron radiation

If the change in the acceleration of electrons is due to the presence of magnetic field, then also electromagnetic radiation is emitted. This is called synchrotron radiation.

Bremsstrahlung radiation and discovery of $\mu$ meson

$\mu$ meson owes its discovery due to clear understanding of Bremsstrahlung radiation observed in cosmic ray interactions. As mentioned, total Bremsstrahlung intensity varies inversely as the square of the mass of the incident particle. Heavier particles therefore show almost negligible Bremsstrahlung. The $\mu$ meson was at first thought to be an electron in cosmic rays. But the radiative losses of its energy were far too small for an electron. Subsequently $\mu$ meson was found to have a rest mass about $207m_e$. This would mean its radiative losses are about 40,000 times smaller than the losses of an electron of the same velocity. This was indeed the case.
Range-Energy Relations for Mono-energetic Electrons

Exact calculation of the range of electrons is not possible due to multiple scattering. Straggling is predominant in the case of electrons due to very low mass as shown in Fig. 5. Important observations are:

1. Final portion of the curve is because of straggling
2. Transmission dose not become zero due to $\gamma$ rays
3. Shape of the curve depends on the experimental arrangement

Concave shape toward the origin results if (1) detection is by electron counting, (2) low-Z elements are used as absorbers, and (3) collimating slit system allows electrons which have been deflected by 30° or less to be counted

Convex shape toward the origin results if (1) detection is by an ionization chamber, (2) high-Z elements are used as absorbers, and (3) narrow collimation is employed.

Empirical Range-Energy relationships were proposed by many investigators for different energy ranges. Important among them are the ones proposed by Katz and Penford.

For Energies from 0.01 MeV to 3 MeV: $R_0$ (mg/cm$^2$) = 412E$^n$ (n = 1.265 - 0.0954 ln E)

For energies from 1 MeV to 20 MeV: $R_0$ (mg/cm$^2$) = 530E – 106

Absorption of Continuous $\beta$ ray Spectra

Despite having continuous energies up to $\beta_{\text{max}}$, $\beta$ particle absorption spectrum shows a very close exponential behaviour (Fig. 6). This is attributed to accidental consequence of the shape of $\beta$ ray spectra and the differences between the scattering and absorption of electrons which have various initial energies. $R_m$ gives the maximum range of $\beta$ particle in the medium. Note the $\gamma$ tail invariably present along with $\beta$'s. Unlike in the case of heavy charged particles, the determination of $R_m$ for $\beta$ particles is not easy. Feather’s method of evaluating the maximum range for $\beta$ particles is widely used. This can easily be adopted for laboratory experiments.

Mass Absorption Coefficient for Continuous $\beta$-ray Spectra

For continuous $\beta$-ray spectra, a plot of logarithm of transmission against absorber thickness is generally as shown above for mono-energetic $\beta$-rays and can be expressed as $I/I_0 = e^{-\mu x}$ where $I/I_0$ is the fraction of the $\beta$'s transmitted after passing through x cm of absorber and $\mu$ cm$^{-1}$ is the apparent absorption coefficient of the medium. The mass absorption coefficient $\mu/\rho$ where $\rho$ is the density of the absorber, is nearly independent of the atomic weight of the absorber. The value of $\mu/\rho$ can be empirically related to energy of $\beta$-rays ($\beta_{\text{max}}$) as $\mu/\rho = 17/E_m^{1.14}$ where $E_m$ is in MeV and $\mu/\rho$ is expressed in cm$^2$/g of Al. The absorber thickness required to
reduce the β-ray intensity to half of its original value is given by $D_{1/2} = 0.04E^{1.14}$ g Al/\(\text{cm}^2\).

Interaction of Electromagnetic radiations with Matter

Gamma or X-rays do not carry an electric charge and therefore may pass through a large number of atoms without any interaction taking place. However, occasionally they will interact with an atomic electron or an atomic nucleus in one of a number of ways. Possible processes by which the electromagnetic field of the γ-ray interact with matter are given below:

<table>
<thead>
<tr>
<th>Kinds of interaction</th>
<th>Effects of interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Interaction with atomic electrons</td>
<td>(a) Complete absorption</td>
</tr>
<tr>
<td>2. Interaction with nucleons</td>
<td>(b) Elastic scattering (coherent)</td>
</tr>
<tr>
<td>3. Interaction with the electric field surrounding the nuclei or electrons</td>
<td>(c) Inelastic scattering (incoherent)</td>
</tr>
<tr>
<td>4. Interaction with the meson field surrounding nucleons</td>
<td></td>
</tr>
</tbody>
</table>

Thus there are 12 different processes by which γ rays can interact with matter. But there are only three major processes on interaction. These are the Compton effect (1c), the photoelectric effect (1a), and pair production (3a).

**Photoelectric Effect**

In this interaction the energy of the x-ray or gamma-ray is completely transferred to an atomic electron which is ejected from its atom. The x-ray or gamma-ray no longer exists after the collision.

**Compton Effect**

The x-ray or gamma-ray loses only part of its energy in its interaction with an atomic electron. The
The electron is ejected from its atom. The x-ray or gamma-ray of reduced energy and the electron fly off in different directions.

**Pair Production**

Gamma-rays with an energy greater than about 1.2 MeV may interact with an atomic nucleus to form an electron positron pair. The gamma-ray energy is completely converted into the mass and kinetic energy of the electron and positron with only a very small amount going to the nucleus in order to conserve momentum.

**Photoelectric Absorption**

The process of photoelectric absorption is shown in Fig. 7. An incident photon is completely absorbed by an atom in the absorber material, and one of the atomic electrons is ejected. This ejected electron is known as a photoelectron. The electron must be bound to the atom, to conserve energy and momentum. The kinetic energy of the photoelectron is given by

\[ T_e = E_{\gamma} - B_e \]

where \( B_e \) is the binding energy of the atomic electron. The vacancy left in the atomic structure by the ejected electron is filled by one of the electrons from a higher shell. This transition is accompanied by an emission of an X-ray. These X-rays are also absorbed by the detector. Photoelectric absorption is the most favourable process for the \( \gamma \)-ray spectroscopist, since the incident photon deposits all of its energy into the detector, but it is only dominant for low energy photons (\( \lesssim 200 \text{ keV} \)). The interaction is again dependent upon Z, and an approximate expression for the absorption probability (\( \tau \)) is

\[ \tau \propto \frac{Z^n}{E_{\gamma}^{3.5}} \]

Here \( n \) is normally between 4 and 5 depending on the absorber material. This dependence on Z explains the choice of high-Z materials such as lead for shielding purposes.

**Compton Scattering**

Figure 8 schematically shows the process of Compton scattering. In this case, an incident \( \gamma \) ray scatters from an outer shell electron in the absorber material at an angle \( \theta \), and some of the \( \gamma \)-ray energy is imparted to the electron. Conservation of energy and momentum leads us to the following expression for the energy of the scattered photon:

\[ E'_{\gamma} = \frac{E_{\gamma}}{1 + \left( \frac{E_{\gamma}}{m_e c^2} \right)(1 - \cos \theta)} \]

where \( E_{\gamma} \) is the incident photon energy, \( E'_{\gamma} \) is the energy of the scattered photon, \( \theta \) is the scattering angle and \( m_e c^2 \) is the electron rest mass energy. The kinetic energy of the electron after the collision is given by

\[ T_e = E_{\gamma} - E'_{\gamma} = \frac{E_{\gamma}' (1 - \cos \theta)}{m_e c^2 + E_{\gamma}' (1 - \cos \theta)} \]

It can be seen that, since all scattering angles are possible, the electron energy ranges from zero for \( \theta = 0^\circ \) to \( 2E_{\gamma}'/(m_e c^2 + 2E_{\gamma}') \) for \( \theta = 180^\circ \), and that the photon never loses the whole of its energy in any one collision. The scattered photon can then continue through the absorber and interact again or scatter out of the absorber material completely. This process, where the scattered photon escapes, is very important for the \( \gamma \)-ray spectroscopist. If the full energy of the incident photon is not absorbed in the detector, then there is a continuous background in the energy spectrum, known as the Compton continuum. This continuum extends up to an energy corresponding to the maximum energy transfer, where there is a sharp cut-off point, known as the Compton edge. Compton scattering is the most
probable process for photons in the intermediate energy range and the probability decreases rapidly with increasing energy. The probability is also dependent on the number of electrons available for the photon to scatter from, and hence increases with increasing Z. An approximate expression for the Compton scattering probability is given by $\sigma \propto \frac{Z}{E}$.

Pair Production

The third important $\gamma$-ray interaction is the process of pair production, shown in Fig. 9. If the incident photon energy is greater than 1.022 MeV (twice the electron rest mass) in the presence of an atomic nucleus an electron/positron pair can be produced. The presence of atomic nucleus is necessary for momentum conservation.

Pair production is also possible in the field of an atomic electron. In this case, for the conservation of momentum, however, the minimum photon energy should be $4m_0c^2 = 2.04$ MeV. Usually this is referred to as triplet production (one positron and two electrons). Kinetic energy of one of the electrons is usually lower than the other two particles. The ratio of triplets to pairs strongly depends on the energy of incident photon. Higher the energy, larger is the ratio. For a given energy of the photon, this ratio decreases as the atomic number of the absorbing medium increases. Thus triple production is rare in natural circumstances but becomes significant at very high energies of photons ($> 100$ MeV) in low Z absorbers.

Any residual energy beyond 1.02 MeV is distributed evenly between the electron and positron as kinetic energy. As the positron slows to thermal energies through interaction with the absorbing medium, it can annihilate with one the atomic electrons producing two $\gamma$ rays of energy 511 keV.

These $\gamma$ rays can then either be absorbed or escape the detector. This is evidenced by the so-called escape peaks observed in $\gamma$-ray spectra. If one of the 511 keV photons escapes the detector, then a peak is observed at $E_\gamma - m_0c^2$ (single escape peak). If both escape, then a peak is observed at $E_\gamma - 2m_0c^2$ (double escape peak). The process of pair production only becomes important for high energy $\gamma$ rays ($5 - 10$ MeV). An approximate expression for the pair production probability $\kappa$ given by $\kappa \propto \frac{Z^2}{\gamma} \log E_\gamma$.

Total absorption probability for gamma ray interaction from all these three processes $(\sigma + \kappa)$ passes through a minimum because of the functional dependence on energy.

Unlike charged particles, a well-collimated beam of $\gamma$ rays shows a truly exponential absorption in matter. This is because photons are absorbed or scattered in a single event. That is, those collimated photons which pass through the absorber have no interaction, while the ones absorbed have been eliminated from the beam in a single event. This leads to exponential attenuation. $I = I_0e^{-\mu x}$ where $\mu$ is mass absorption coefficient and $x$ is the absorber depth.

**Pair production and Bremsstrahlung**

The pair production process is intimately related to the bremsstrahlung process. In Bremsstrahlung, an electron undergoes a transition between two states, both of positive energy, and a photon is emitted instead of being absorbed. The electron, when it enters the nuclear field, is acted on by the electromagnetic field of the emitted photon, as well as by the coulomb field of the nucleus. The intermediate states of the entire system involve the negative energy states which characterize the Dirac electronic theory. The pair production process also takes recourse to the Dirac electron theory of positive and negative electron states and the processes involves lifting of an electron from negative state to a positive state, there by creating a hole and electron pair. The nuclear cross section is of the order of $(Z^2/137)(e^2/m_0c^2)$ for both the processes. In both the processes, coupling between charged particles and electromagnetic field is necessary for the process to occur.

![Fig. 9 The process of pair production / annihilation](image-url)
thickness. \( I_o \) is the initial intensity and \( I \) is the transmitted intensity of gamma rays.

**Interaction of Neutrons with Matter**

Neutrons do not carry any electric charge and as a result they do not have any coulombic interactions with atomic electrons in passing through matter. In other words, they do not directly produce ionization and are not continuously slowed down. They interact with atomic nuclei, but only through the nuclear force which has an extremely short range. Therefore they must score an almost direct hit on a nucleus before an interaction occurs. Since atomic nuclei are so much smaller than the atoms, the probability of an energetic neutron hitting a nucleus is very low and neutrons can traverse great thicknesses of material before being stopped. The way in which neutrons interact with matter depends to a large extent on their energies, which can range from hundreds of MeV down to fractions of an eV. Neutrons are uncharged particles and do not interact with atomic electrons in the matter through which they are passing, but they do interact with the nuclei of these atoms. The nuclear force, which leads to these interactions, is very short ranged which means the neutrons have to pass close to a nucleus for an interaction to take place. Because of the small size of the nucleus in relation to the atom as a whole, the neutrons will have a low probability of interaction, and could thus travel considerable distances in matter. The most common neutron reactions are (1) Spallation reactions, (2) Elastic scattering, (3) Inelastic scattering, (4) Transmutation, (5) Radiative capture.

**Spallation Reactions**

At very high energies (over 150 MeV) neutrons may strike a nucleus producing a shower of secondary particles including secondary neutrons and gamma rays. These high energy secondary particles would in turn interact within the medium and get detected.

**Elastic Scattering**

In addition to the nuclear reactions there are also elastic interactions where the neutrons simply bounce off atomic nuclei. The elastic interaction of neutrons with atomic nuclei is most important at neutron energies below the threshold for nuclear reactions at a few MeV. The amount of energy which a neutron loses in a collision with a nucleus will be large only if the nucleus is relatively light. The most violently recoiling atomic nuclei are the lightest, namely those of hydrogen atoms. These recoiling atoms in turn cause ionization in the matter. In collisions with heavy nuclides, neutrons lose little energy. In collisions with light nuclides such as H, D, He, and C, neutrons lose a major portion of their energies. A neutron can lose all its kinetic energy in a single collision with a proton. Thus, light nuclides are effective moderators, but not heavy nuclides.

**Inelastic Scattering**

A neutron may strike a nucleus and form a compound nucleus instead of bouncing off as in elastic scattering. This nucleus is unstable and emits a neutron of lower energy together with a gamma photon which takes up the remaining energy. This process, called inelastic scattering, is most effective at high neutron energies in heavy materials, but at lower energies (a few MeV) elastic scattering becomes a more important reaction for energy loss provided there are light nuclei present.

**Transmutation**

When neutrons, protons, or other secondary particles produced by spallation strike a nucleus and form a compound nucleus which then ejects a different particle, a transmutation is said to have occurred. This is because the target nucleus is changed from one element to another. These nuclear reactions are most likely to occur when the energy of the incident particle is between a few MeV and several tens of MeV. An example is the neutron-proton (n,p) reaction with oxygen described below.

\[ ^{16}\text{O}(n,p)^{16}\text{N} \]

\[ ^{16}\text{O} \quad ^{16}\text{N} \]

\[ ^{16}\text{O}(n,p)^{16}\text{N} \] captures a high energy neutron and emits a proton to form \(^{16}\text{N}\). \(^{16}\text{O}(n,p)^{16}\text{N} \) is radioactive with a half-life of 7.2 seconds; it is a beta emitter and also emits very hard gamma rays which have energies of 6 or 7 MeV.

In addition to (n,p) reactions, many other reactions such as (n,2n), (n,\alpha) are possible. Most of these reactions result in nuclei which are deficient in neutrons and therefore decay by positron emission or electron capture.
Neutrons are detected indirectly by observing the protons knocked loose by them or by nuclear reactions induced by them. For example, the alpha particles are easily detected in the nuclear reactions.

\[
{^{14}\text{N} + n} \rightarrow {^{11}\text{B} + \alpha}, {^{10}\text{B} + n} \rightarrow {^{7}\text{Li} + \alpha \text{ or Li} + n} \rightarrow {^{7}\text{Li} + \alpha}.
\]

Slow neutrons are thus indirectly measured by a proportional counter, which is filled with BF₃ gas. The products, \(^7\text{Li}\) and \(\alpha\) ionize the gas in the proportional counter and the signals are detected. Fission reactions induced by neutrons can also serve for neutron detection.

**Radiative Capture**

This is one of the most common neutron reactions. The neutron is again captured by a nucleus which emits only a gamma photon. This reaction, which occurs in most materials, is the most important one for neutrons with very low energy. The product nuclei of \((n,\gamma)\) reactions are usually radioactive and are beta and gamma emitters.

Two of the typical neutron capture reactions are the \((n,\gamma)\) reaction in \(^{59}\text{Co}\), which is normal stable cobalt metal and quite commonly occurs in steel, to produce \(^{60}\text{Co}\), which is radioactive. The cobalt readily captures neutrons, and \(^{60}\text{Co}\) has a half-life of about 5 years. The other is the neutron capture in \(^{23}\text{Na}\), which is normal, stable sodium. In this case the product is the radioisotope \(^{24}\text{Na}\).

Neutrons therefore produce ionization indirectly through the protons, recoiling nuclei, and other massive particles which are products of various reactions of neutrons with atomic nuclei. These particles are all much heavier than the electrons which generate the ionization in gamma-ray interactions. The heavier particles generate ionization more densely along their path, and therefore have a higher linear energy transfer (LET). This is very important to be considered, as energetic neutrons are more effective at producing damage than x or gamma rays for the same amount of ionization per unit mass of biological matter such as tissues.

Once neutrons have been slowed down so that they have on the average no more energy than the atoms in the surrounding material, they are called thermal neutrons. Such neutrons behave much like a gas and their propagation through matter is analogous to diffusion. Thermal neutrons are readily captured by the nuclei of a variety of atoms, and this capture usually is accompanied by the emission of fairly energetic gamma rays. Thermal neutrons therefore pose the same sort of hazard as energetic gamma rays.

Neutron interactions are used in the production of radioisotopes.

**Behaviour of Fission Fragments**

Range-energy relationships for particles which are much heavier than protons and \(\alpha\) particles (e.g. fission fragments) are largely empirical. The fission fragments, for example have the properties as shown in Table 2.

As the fragment moves through the absorber, capture and loss of electrons will be important. The This continuous reduction in charge compounded by reduction in velocity results in steady reduction in the energy loses \((dE/dx)\) along the path (Fig. 10). Towards the end of the path, the final portion of the range is characterized by elastic nuclear collisions,

### TABLE 2.

<table>
<thead>
<tr>
<th></th>
<th>Light fragments</th>
<th>Heavy fragments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass number A</td>
<td>97</td>
<td>138</td>
</tr>
<tr>
<td>Nuclear charge z</td>
<td>38 (Sr)</td>
<td>54 (Xe)</td>
</tr>
<tr>
<td>Kinetic energy E</td>
<td>95 MeV</td>
<td>67 MeV</td>
</tr>
<tr>
<td>Initial velocity (v_0)</td>
<td>(1.4 \times 10^9) cm/sec</td>
<td>(0.93 \times 10^9) cm/sec</td>
</tr>
<tr>
<td>Initial ionic charge (e)</td>
<td>20e</td>
<td>22e</td>
</tr>
<tr>
<td>Mean range in air R</td>
<td>2.5 air-cm</td>
<td>1.9 air-cm</td>
</tr>
</tbody>
</table>
in which relatively large energy transfers take place. Figure 10 shows the behaviour of fission fragments in a medium.

Fig. 10  Energy loss per unit path length for heavy and light fission fragments from $^{235}\text{U}(n,f)$
Interaction of all types of ionising radiations, namely, alpha, beta, gamma or x-rays and neutrons with the material of the detector results in formation of ion pairs or electrons-hole pairs. Collection of these charge carriers across the electrodes of the detector yields a signal, which is often too small to be directly processed and counted. Therefore this signal is amplified, usually with shaping, to a convenient level for processing and counting. However noise too gets amplified along with the detector output signal. Hence improvement of the signal to noise ratio is an important aspect of amplification and shaping. In this article a brief description of the various electronic components of a radiation detection system including amplification, shaping and subsequent processing are given followed by some of the developments in the field.

The block diagram of a typical energy spectroscopy system is shown in Fig. 1. The charge output of the detector is converted to a voltage pulse in the preamplifier, which is further amplified and shaped in the shaping amplifier. The analog to digital converter (ADC) gives a digital address output corresponding to the pulse height to be used by the data acquisition system to build a count vs. energy histogram, which is then processed by software to extract the necessary information. When distribution of time intervals between specific types of events is of interest, discriminators are used to extract timing information from the fast detector pulses and a pulse height spectrum corresponding to the time interval spectrum is derived with a time to amplitude converter (Fig. 2). A multi-parameter system has several detectors followed by dedicated energy and timing spectroscopy channels operated in synchronism for measurement of time correlated events.

**Energy Spectroscopy**

*Factors affecting resolution*

The statistical variation of number of charge carriers liberated per event imposes a fundamental limitation on resolution for a given type of detector. Other degrading mechanisms present in the detector or preamplifier (Fig. 3) may be listed as follows:

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**Fig. 1** Block diagram of typical pulse height spectroscopy system

**Fig. 2** Block diagram of typical timing spectroscopy system
1. Shape variation of the detector pulse.
2. Shot noise associated with total leakage current of the detector and the input element of the preamplifier, typically a FET.
3. Channel noise of the FET.
4. Flicker noise of the FET.
5. Johnson noise of the feedback resistor.

**Charge Sensitive Preamplifiers**

The charge sensitive configuration is most often used in preamplifier design since the output is insensitive to detector capacitance variation. The output is also insensitive to active component variation because of overall feedback.

The channel noise of a JFET is reduced by increase of the transconductance $g_m$. However the total capacitance $C$ at the gate, including detector capacitance, increases amplification of series noise relative to the signal. The FET is selected for optimum $g_m/C^2$. The FET is also selected for low input current and flicker noise.

The detector leakage and FET input current as well as Johnson noise are temperature dependent and reduce with cooling. Hence the detector, FET and the feedback resistor are cooled with liquid nitrogen in the case of HPGe or Si(Li) detectors. For less critical applications thermo-electric cooling is used. No cooling is used if detector signal is strong and resolution requirement is not critical, as in the case of surface barrier silicon detectors for alpha spectrometry.

The noise current from the feedback resistor is minimised if the resistance is made as large as possible consistent with the feedback current requirement for the energy deposition rate in the detector. The resistor is absent altogether in pulse feedback type of preamplifiers. In the case of pulsed optical feedback (Fig. 4) the charge across the feedback capacitor is allowed to build up until a threshold is reached. At this time the FET junction is illuminated by a pulse of light to generate photocurrent in the drain-gate junction of the FET which restores the capacitor. A transistor provides the restoration charge in a similar manner in transistor-reset preamplifiers which are capable of operation at very high count rate. The output waveform in both cases has a staircase appearance frequented by very large restoration steps. The pulse-shaping amplifier should be capable of handling the corresponding overload pulse. It should also have pile up rejection facility to discard events during the overload recovery interval.

**Pulse Shaping Amplifiers**

These amplifiers amplify the relatively weak signal available from detector-preamplifier combination to levels suitable for pulse height analysers or timing applications. They also provide the pulse shaping function for optimum combination of low noise and good count rate capability. The principal conclusions regarding noise performance of linear time-invariant pulse shaping amplifiers are as follows:

1. The equivalent noise charge (ENC) of symmetric triangle and Gaussian output shapes are close to the optimum.
2. When the time scale $\tau$ of the shaping is changed, contributions of series and shunt noise change as $1/\tau$ and $\tau$ respectively. For any combination of series and shunt noise there is an optimum time scale.

Among the shapes discussed above, an approximately Gaussian shape is easiest to realise and suitable for ADC. So shaping amplifiers of old
vintage used semi-Gaussian shaping realised with active filters. Modern amplifiers additionally provide quasi-triangular shaping which is realised by weighted sum of intermediate stage outputs of the Gaussian shaper.

The block diagram of a nuclear pulse-shaping amplifier is shown in Fig. 5. All shaping amplifiers have a pole-zero cancellation arrangement at an early stage in the amplification chain. Proper adjustment of this gives a vast improvement in high count-rate behaviour by ensuring fast return of pulses to baseline. When resolution is degraded by pulse pile up, improvement is possible by reducing the time scale of the shaping taking advantage of the slow variation of ENC with time scale. Hence many shaping amplifiers have easily accessible means of changing shaping time. The effect of pile up can be greatly reduced if the pile up reject (PUR) output signal available from the amplifier is connected to the delayed anticoincidence (or PUR) input of the nuclear ADC. This signal spans the time interval of the pile up and prevents conversion of the piled up output pulse in the ADC. Modern amplifiers also include a baseline restorer (BLR) which improves resolution by reducing slow variations of baseline such as thermal drift, microphonics and pulse rate induced variations by operating a feedback loop which restores the output to ground potential in pulse free intervals.

When detector rise time variation is significant the resulting variation in output is small if the curvature at output pulse top is low. Hence Gaussian shaping would give better performance if shaping time is increased. This would however result in poor high count-rate performance. The gated integrator method of shaping integrates a Gaussian shaped pulse to get a flat-topped output and eliminates its variation with detector rise time. It is possible to maintain good high count-rate behaviour in gated integrator amplifiers by keeping the underlying Gaussian shaping time low.

**Nuclear Pulse Height analysers**

Nuclear ADCs are usually based on the Wilkinson or successive approximation conversion schemes.

**Wilkinson ADC**

The block diagram of a Wilkinson ADC is shown in Fig. 6. The input analog pulse is applied to a stretcher circuit that detects the peak of the input pulse. At this point, the stretcher capacitor is disconnected from the input and discharged by a constant current source. The count of a fast clock in the discharge interval is proportional to the input pulse height. This count is used as address by the histogram memory updating circuit to increment the count of the addressed location. The output has inherently good differential nonlinearity. The conversion process at peak detection is started only if the input amplitude is within LLD and ULD levels. In some designs there is provision of anticoincidence with pile up reject (PUR) input to prevent conversion if pile up occurs.

**Successive Approximation ADC**

The block diagram of a successive approximation nuclear ADC is shown in Fig. 7. The peak pulse output is detected in a stretcher and applied to a conventional fast successive
approximation ADC. The direct digital output of these ADCs is not suitable for nuclear spectroscopy because of large differential nonlinearity. So the output is smoothed using the sliding technique of Gatti in which a random pedestal is added to the analog input and an equivalent digital code is subtracted from the output in each conversion cycle. As in the case of Wilkinson ADCs, LLD, ULD and PUR qualifiers may be used for conversion.

Wilkinson ADCs have large conversion time when the output channel number is large. Hence they are used at low counting rate experiments or when small conversion gain is needed. In all other applications successive approximation ADCs are preferred.

**Ratio to Digital Converter**

This is a type of successive approximation ADC in which the reference voltage of the internal ADC is not fixed as in the case of ADCs for pulse height analysis. Instead it is derived as the sum of the peak value of two inputs. When one of the input pulses is converted with this sum reference the output is proportional to the converted input expressed as a fraction of the sum of inputs. This type of converter, known as RDC, is used in experiments with position sensitive detectors.

**Computer Based Data Acquisition Systems and Data Processing**

When personal computers became available, the mechanical frame, power supply, computing power and display capability of the PC were utilised to the fullest extent by building the pulse height analyser in the form of a PC card which contained the ADC and histogram memory. Sometimes the PC-card also contains programmable detector bias supply and pulse shaping amplifier. The computational powers of the PC are exploited by providing peak fitting and nuclide identification software. In a multi-parameter system time correlated data from multi-detector experiments processed with multiple ADCs, TDCs, etc., are acquired. Multi-input ADCs in CAMAC crate may be used in such experiments to conserve space and for ease of configuration. Relevant aspects of data correlation may then be extracted and presented by suitable software.

**Timing Techniques**

In many experiments it is necessary to obtain timing information about two or more nuclear events. The arrangement for a timing experiment involving two particles emitted in coincidence is shown in Fig. 2. In each chain the detector generates a signal because of interaction with the incident particle. The signal is amplified and fed to a time pickoff unit which gives a timing signal which is called machine time. This signal should ideally be in a fixed time relation with the event time. In practice the delay shows variation about a mean. This happens due to the following mechanisms:

1. The input variation \( \sigma_v \) due to random variations such as fluctuations in the number of

![Fig. 7 Block diagram of successive approximation ADC.](image-url)
charge carriers liberated in the detector and amplifier noise causes a corresponding time variation $\sigma_t$, in the time obtained from the pickoff element (Fig. 8). This is known as timing jitter.

2. Slope variation due to amplitude and shape variation of the pulse causes a corresponding variation in the time to cross threshold in the time pickoff element (Fig. 8). This is known as timing walk. The effect is minimised when the threshold crossing is always at the same phase point of the input waveform such as at zero crossing.

Modern time pickoffs are built with fast bipolar integrated comparators. Two of the most widely used types will be discussed.

**Time Pickoffs**

**Leading Edge Discriminators**

These are based on threshold crossing comparators. The timing signal is generated at the instant of threshold crossing and is therefore subject to amplitude dependent timing walk. If the experiment also records amplitude information it may be possible to correct for timing walk in computer based experiments. Since the output is often used for coincidence purposes, its width is standardised to a preset width.

**Constant Fraction Discriminators**

In this the input to a fast comparator is effectively applied as a bipolar signal. The arrangement behaves as a zero-crossing comparator and the timing output is nearly free from amplitude dependent walk. The formation of bipolar pulse from unipolar input is shown in Fig. 9. The generation of output is dependent on amplitude qualifier from an arming comparator. The output time width is standardized for use in coincidence experiments.

**Time Interval Measurement**

**Time to Amplitude Converters**

In time to amplitude converters (TAC) a constant current is switched into an integrating capacitor at the arrival of the timing signal of an initiating event and stopped with the timing signal of another event. The integrated charge is proportional to the time interval. The voltage on the capacitor can be digitised for the purpose of timing spectroscopy. The time resolution may be ~10ps in the lowest range. Resolution gets worse when the full-scale time increases.

![Fig. 8 Jitter and walk in timing circuits](image)

![Fig. 9 Bipolar pulse formation in CFD](image)
**Time to Digital Converters**

When time intervals are large, relatively good resolution can be maintained with direct counting time to digital converters (TDC). The resolution is limited by the maximum operating frequency of input counters. Better resolution is obtained by interpolation between counts of the high frequency clock by a built-in conventional TAC (e.g., TDC100, ORTEC).

**Coincidence Measurement**

Often the purpose of timing experiments is to find coincidence between various detector events within a given time window of a starting event. Modules providing n-fold coincidence from a limited number of inputs are available commercially. However when it is necessary to provide output for any arbitrary sum or product of the inputs these modules are unsuitable. In such cases memory based coincidence may be used. In this approach the standardised timing signals derived from the detectors are imposed on the address lines of a fast static RAM. The memory is pre-programmed to provide output in a desired state for all address combinations of interest. If the devices have multiple output bits then each of them may be programmed differently. The memory can be reprogrammed to provide a different set of coincidence conditions. This method works well till the number of inputs does not exceed the number of address lines of the memory device. Use of multiple devices may introduce additional delay and timing skew. Latest field programmable gate arrays (FPGA) have large number of I/O pins and are fast enough. So they may be used in such cases if the necessary logic function for coincidence can be accommodated in the FPGA keeping timing skew at acceptable levels.

**Fast pulse Amplifiers for Timing**

These are high bandwidth (>100MHz) amplifiers capable of amplification with minimal degradation of input pulse rise-time. The amplifiers can drive only cables with matched termination and often have only unidirectional drive capability to take advantage of the unipolar nature of detector pulses. Timing filter amplifiers may provide an optional low time constant integration in the signal path for optimum performance in some experiments.

**Charge to Digital Converter**

In certain timing experiments amplitude analysis is also of interest. When the detector pulses occur at a very high rate or when no improvement is expected by pulse shaping, the pulse from the detector is directly integrated on a capacitor in a given time gate and the stretched voltage is converted and acquired in a data acquisition system in the usual manner.

**Indigenous Development of Nuclear Instrumentation**

Electronics Division, BARC has been engaged in development of the entire range of nuclear electronics from front-end electronics to computer based counting systems. Nuclear Instrumentation Modules (NIM) and systems developed in this Division have been supplied to many users in BARC and other units of DAE. Technologies for many of these products have been transferred to ECIL and other private parties. At present work is going on for miniaturisation of circuits for high-density instrumentation. Many hybrid microcircuits have been developed for this purpose. A program for development of application specific integrated circuits (ASIC) is under way.

**High Voltage Supplies**

A 2.5KV/1mA supply suitable for photo-multipliers was developed and is now marketed by ECIL as model HV4827N. The basic HV design was later incorporated into a computer controlled multiple HV system providing 80 independent channels per crate [1]. These crates (MHS4015) have been fabricated by ECIL and supplied for use in the TACTIC gamma ray telescope under the GRACE project of NRL at Mount Abu. Recently several types of hybrid microcircuits have been developed for use in high multiplicity HV systems [2]. A 5KV supply suitable for HPGe and Si(Li) has been marketed by ECIL as model HV4828N.

**Preamplifiers**

A type of charge sensitive preamplifier with low dynamic input impedance has been supplied in
large numbers for use with linear position sensitive detectors in neutron diffraction spectrometers at DHRUVA. A recently developed preamplifier [3] suitable for proportional counter, surface barrier and PIN detectors uses a BEL hybrid BMC-1521 for which technology was developed in Electronics Division, BARC.

**Pulse Shaping Amplifiers**

A shaping amplifier marketed by ECIL as model PA4901N [4] has been used in large numbers in the neutron diffraction spectrometers at DHRUVA. For applications, where shaping is changed frequently, a Spectroscopy Amplifier [5] is marketed by ECIL as model PA4903N and also by NUCLEONIX Ltd. A PC based shaping amplifier with programmable gain and PZ adjustment suitable for dedicated counting systems has been developed [6]. Recently a multiple preamplifier ASIC and a multiple preamplifier cum shaping amplifier ASIC [7] have been successfully fabricated at SCL, Chandigarh.

**Data Acquisition Systems for Nuclear Spectroscopy**

The PCA-95 and later the MCA-2000 [8] type of PC-MCA with ISA bus, marketed by ECIL, have been widely used for nuclear energy spectroscopy. The PHAST PC-MCA [9], with spectrum stabilisation facility, has been marketed by ECIL and Nucleonix, Hyderabad. Recently a PCI bus PC-MCA [10] has been developed. The ratio to digital converter [11] and its data acquisition system [12,13] has been used in the neutron diffraction spectrometers at DHRUVA. A multi-parameter system [14] has been used in many experimental groups. Development of a CAMAC 8K Octal Nuclear ADC [15] suitable for such systems has been reported. The operating and data analysis software of all these systems have also been developed in-house.

**Instrumentation for Timing Experiments**

Fast amplifiers, leading edge discriminators and charge to digital converters developed in Electronics Division and manufactured in ECIL have been used in large numbers for instrumentation of the TACTIC gamma-ray telescope at Mount Abu of the GRACE project. Improvements of these designs with better integrated circuits and hybrid microcircuits have been reported. Development of constant fraction discriminator unit and FPGA based programmable coincidence unit has also been reported. Hybrid microcircuits BMC-1522 for time to amplitude conversion and BMC1560 for constant fraction discrimination have been developed for high-density instrumentation. Work is in progress for the design of an ASIC for constant fraction discriminators. This will be used in instrumentation for new gamma-ray telescopes of the GRACE project.

**Acknowledgement**

The author wishes to acknowledge the staff of Electronics Division for the indigenous development carried out over the years in the field of nuclear instrumentation and Dr. S.K.Kataria, Associate Director, Electronics and Instrumentation Group, Head, Electronics Division for providing motivation towards self-sufficiency in this important area of development.

**References**

Scintillators as Nuclear Radiation Detectors

**Introduction**

Scintillation detectors have been used to detect nuclear radiations for more than half a century. These detectors work on the principle that when a charged particle interacts with the detector material, the energy lost to the electrons of this medium via ionization and excitation processes is partly converted to characteristic scintillation photons. These photons are detected in devices such as photomultiplier tubes or photodiodes to produce electronic pulses. When neutral particles such as photons interact with the scintillator fast electrons are produced which cause scintillation as mentioned above. The advantages of these detectors are that they are robust, fast, efficient and can be configured in various shapes and large sizes. The energy resolution is poorer than that of semiconductor detectors but adequate for many purposes. In the following a brief review of the different kinds of scintillators is presented along with their strengths and examples of their use in experimental setups. More complete reviews can be found in the references listed in [1].

**Scintillators**

Scintillators can be broadly classified as inorganic and organic. Some examples in the former category are NaI(Tl), BaF2 and BGO (Bi4Ge3O12). Whereas inorganic scintillators are mostly solids, organic scintillators in the liquid state are also used. Examples of solid organic scintillators are stilbene, anthracene and POPOP loaded polystyrene plastics. Organic liquid scintillators are based on activator doped xylene or other such solvents and discussed in detail in the following article of this bulletin.

How is the energy of a particle converted to scintillations? If the particle to be detected is charged, the primary mode of loss of energy is electronic. The secondary electrons transfer some of this energy to excitations in the scintillator, which deexcite through scintillation photons with a characteristic emission spectrum. For this scintillation to propagate unhindered the self-absorption has to be small. This is achieved in different ways. For example in NaI the scintillation arises from deexcitation of thallium, which is added in small concentrations (~100 ppm). A significant fraction of the energy loss couples to excitation of
the Tl activator states. Since the concentration of thallium in NaI is small, self-absorption of the scintillation photons is small, and scintillation attenuation lengths are large. This is important in the fabrication of large size detectors. In organic scintillators the singlet states excited by the interacting charged particle decay to excited vibrational states based on the ground state. This leads to an emission spectrum, which is peaked at a longer wavelength than the absorption spectrum. The desirable consequence is that the scintillation light is not absorbed by itself. The singlet states can also decay to triplet states, which decay to the vibrational states built on the ground state on a much longer time scale. However a fraction of the triplet states can couple to the fast decaying singlet state leading to a delayed scintillation. The excitation of the long-lived triplet states depends on the ionization density and the transition to the fast decaying singlet proceeds via triplet-triplet interactions. Since this goes as the square of the triplet density, the slower component is more for particles with a higher stopping power. This property is often known as pulse shape discrimination (PSD) and can be used to identify particles.

Some of the desired characteristics of scintillator detector are large light output for a given energy deposited by a radiation, emission spectrum matched to photosensitive devices, fast scintillation decay time, little or no afterglow, linearity of response, large radiation damage threshold, physical and chemical stability in normal environmental conditions, ease of manufacture and cost. Scintillators are available in a variety of chemical forms ranging from materials with low atomic numbers (such as plastics, LiF etc) to high Z materials (BGO, PbWO₄ etc) with a range of densities. Some of these properties for a sample of inorganic and organic scintillators are listed in Table 1.

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Density (g.cm⁻³)</th>
<th>Refractive index</th>
<th>Scintillation characteristics</th>
<th>Hygroscopic</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Decay time (ns)</td>
<td>λ_max (nm)</td>
<td>photons/MeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inorganic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaI(Tl)</td>
<td>3.67</td>
<td>1.85</td>
<td>230</td>
<td>415</td>
<td>38000</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>4.51</td>
<td>1.80</td>
<td>1000</td>
<td>540</td>
<td>52000</td>
</tr>
<tr>
<td>CsI (pure)</td>
<td>4.51</td>
<td>1.80</td>
<td>10,36/1000</td>
<td>305/480</td>
<td>17000</td>
</tr>
<tr>
<td>BGO</td>
<td>7.13</td>
<td>2.15</td>
<td>300</td>
<td>460</td>
<td>8200</td>
</tr>
<tr>
<td>BaF₄</td>
<td>4.88</td>
<td>1.58/1.50</td>
<td>0.6/600</td>
<td>220/325</td>
<td>2000/6500</td>
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<td>CaF₂(Eu)</td>
<td>3.19</td>
<td>1.44</td>
<td>940</td>
<td>435</td>
<td>24000</td>
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<tr>
<td>LiI(Eu)</td>
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<td>1.96</td>
<td>1400</td>
<td>470</td>
<td>11000</td>
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<tr>
<td>PbWO₄</td>
<td>8.28</td>
<td>2.6</td>
<td>5-15</td>
<td>440/500</td>
<td>4000</td>
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<tr>
<td>LaBr₃(Ce)</td>
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<td>30</td>
<td>358</td>
<td>61000</td>
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<tr>
<td>Lu₂SiO₅(Ce) (LSO)</td>
<td>7.35</td>
<td>1.82</td>
<td>11/36</td>
<td>420</td>
<td>20000/9000</td>
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<td>Organic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anthracene</td>
<td>1.25</td>
<td>1.62</td>
<td>30</td>
<td>447</td>
<td>16300</td>
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<tr>
<td>BC400</td>
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<td>1.58</td>
<td>2.4</td>
<td>423</td>
<td>10000</td>
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<tr>
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<td>1.58</td>
<td>0.7</td>
<td>370</td>
<td>16000</td>
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<tr>
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<td>1.58</td>
<td>264</td>
<td>428</td>
<td>6700</td>
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<tr>
<td>BC501A</td>
<td>0.874</td>
<td>1.58</td>
<td>3/32/270</td>
<td>425</td>
<td>12700</td>
</tr>
</tbody>
</table>

Table 1. Comparison of properties of some inorganic and organic scintillators
Light Detection and Pulse Processing

First of all the scintillator in the required size and shape is chosen keeping in view the particular application. If the scintillator is hygroscopic it is hermetically sealed in a can, usually made of aluminum. The can is lined with a diffuse light scattering material such as a mixture of MgO and Al₂O₃. Non-hygroscopic scintillators are made light tight using a combination of an inner lining of a suitable white paper, Teflon tape (for BaF₂) or a thin layer of MgO/Al₂O₃ with an outer layer of black tape. For large size scintillators the relector/ diffuse scatterer is wrapped loosely to allow total internal reflection which helps in transmitting the scintillation light to the ends where the light sensitive devices are usually located. It is also sometimes necessary to use light guides to channel the light onto the light detection device. For example in geometries where there is a space constraint or where there is a large magnetic field the light sensor might have to be placed elsewhere. These light guides are usually made of transparent acrylic of suitable length and shape to match the requirements. The presence of an intermediate light guide results in a loss of light at each interface (scintillator-light guide and attenuation in the light guide itself).

The scintillation photons are detected by devices such as the photomultipliers, photodiodes and recently, avalanche photodiodes. Various kinds of photomultipliers (PMTs) are available commercially. They are chosen on the basis of their suitability for the particular scintillator and application. The most important specifications are the photocathode diameter (few mm to 50 cm), spectral sensitivity (quantum efficiency as a function of incident photon wavelength typically with a maximum in the range of 25%), gain (typically up to 10⁷), transit time (ranging from 100 to 35 nsec) and its spread (ranging from 10 to 1.5 nsec), linearity of response over a certain dynamic range and dark counts (relevant in low count rate applications such as in ¹⁴C dating or measurements involving long halflives). Photodiodes come in modest sizes with active areas up to about 20 x 20 mm² but can be configured in arrays to cover larger areas. They have much higher peak quantum efficiencies ~ 80-90%, require low bias voltages for their operation, have much higher immunity to high magnetic fields and are compact. The absence of gain in the device makes it vulnerable to electronic noise. However in cases where the signal to noise ratio is adequate the advantages of compactness, efficiency of light detection and ease of operation make this an attractive photon detector. Avalanche photodiodes have recently become available with gains of up to ~10³. Presently, however, these are available in relatively small sizes of about a few mm².

How is the light signal converted to a voltage pulse, which can be subsequently processed? In the case of the PMT the largest signal is obtained across the load at the anode. The signal shape depends on the product of the load resistance (R_L) and stray capacitance (C) to (signal) ground. If RC < (scintillation decay time) then the voltage pulse has a rise time of RC and a decay time ≈ τ. This is suited for high count rate applications or for deriving fast timing information. If, on the other hand, RC > τ the pulse has a rise time of τ and fall time of RC. Such pulses are suited for pulse height or energy measurements. In applications where both energy as well as timing information is required from the scintillation detector the conflicting requirements on pulse shape are met by using the anode signal for timing and a pulse from a load across an earlier dynode for energy. The timing information is obtained in relation to a timing reference. This may be another detector or the RF reference in case of pulsed beam induced reactions.

The energy deposited in the scintillator detector can be measured by two different techniques. In the first the long tail pulses from the dynode are sent to a preamplifier and then to a shaping amplifier. The pulse height of the resulting pulse is then digitized by an analog to digital converter (ADC). Alternatively the anode signal is split and one of them used to generate the timing (or fast logic) pulse. The other is sent through an appropriate delay, with or without amplification, to a charge to digital converter (QDC or CDC). The QDC also requires a gating signal whose width is chosen to be 2-3 times the scintillation decay time. The pulsed current, proportional to the scintillation output, integrated over an appropriate time is a measure of the total scintillation light and hence the energy deposited by the detected particle. The latter method is relatively simple and can also be used with higher
count rates. However, the former is more suitable in noisy environments because of the filtering involved during the pulse shaping.

Some Examples of Scintillator Detectors and Arrays

In this section, some examples of scintillation detectors used in various experiments are described briefly.

NaI(Tl) Detectors for Gamma Rays and Charged Particles

The NaI(Tl) scintillator is most widely used for gamma ray detection and measurements. It is reasonably cheap and can be made in large sizes (up to 50 cm in diameter and 50 cm depth) needed to contain the electromagnetic shower triggered by a high energy gamma ray. The scintillation photon yield is one of the highest leading to an energy resolution of about 6.5% at 662 keV if a low dark current PMT is used. One example of a high energy gamma detector array consists of seven closely packed detectors of regular hexagon cross section (depth 15 cm and 13 cm face to opposite face) [2]. A typical spectrum of the 4.43 MeV gamma rays from a $^{241}$Am-Be source is shown in Fig. 1. Here the linear signals from all seven detectors have been summed in a summing amplifier. The full energy peak at 4.43 MeV and the single escape peak (due to the escape of one of the 511 keV positron annihilation photons) are seen clearly.

Like many other scintillators NaI(Tl) also has the useful property of PSD which helps identify the incident particle. For example, gamma ray, proton and alpha interactions with NaI(Tl) lead to scintillations with decay times of about 230, 210 and 190 nsec, respectively. By measuring the time difference between the start of the pulse (derived from a constant fraction timing discriminator, for example) and the zero cross over of the bipolar pulse after doubly differentiating and amplifying the dynode pulse, the light particles such as electrons, protons, deuterons, $^3$He and $^4$He can be identified. An example of a zero crossover time vs. energy deposited two dimensional spectrum from a 5 cm $\phi$ x 3.8 cm thick NaI(Tl) detector with a thin (6 mg/cm$^2$) Havar window is shown in Fig. 2 [3].

BaF$_2$ detector Array for High Energy Gamma Rays

BaF$_2$ as a scintillator material has several advantages over other materials. The main
advantage is the fast response arising from one of the scintillation components which has a decay time of only 0.6 nsec. It is also only mildly hygroscopic. The interaction cross section with slow neutrons is significantly smaller than that of NaI(Tl) making it an excellent choice for high energy gamma ray measurements. An example of a large BaF$_2$ array is the two arm photon spectrometer TAPS detector consisting of 512 scintillators of regular hexagon cross section (6 cm face to face, 25 cm depth). This has been used extensively for studies of giant resonances in nuclei, $\pi^0$ and $\eta$ production in nuclear collisions, nucleon-nucleon bremsstrahlung etc. A compact BaF$_2$ array [3] based on seven close packed hexagonal cross section detectors (6 cm face to face, 20 cm depth) has been used at the 14 MV BARC-TIFR Pelletron accelerator at Mumbai to make measurements of the giant dipole resonance built on excited states. Typical energy and time spectra are shown in Fig. 3.

**BGO Gamma Ray Multiplicity Array**

BGO is a dense scintillator with a high Z ingredient making it the ideal choice for anti Compton shields for high purity germanium detectors, compact $\gamma$-multiplicity arrays, PET arrays, and in electromagnetic calorimeters in high energy...
physics experiments. It is not hygroscopic and is very rugged unlike NaI(Tl) and BaF₂. It also has a very small afterglow. The first two properties of high density and Z ensure that the cross talk between detectors in a γ-multiplicity array is small. An example of a BGO γ-multiplicity array is shown in Fig. 4. Such an array can be used to broadly tag the angular momentum of the evaporation residue and the initial compound nucleus on an event by event basis. It can also be used to provide the reference timing signal from a nuclear reaction event which can be used for time of flight measurements.

**Plastic Wall for Neutron Measurements**

Energy measurements of neutrons are typically done using the time of flight (TOF) technique since the neutron does not deposit all its energy in a scintillator in a typical interaction. In order to minimize the background from gamma rays the material of choice is the organic scintillator. For high detection efficiency the thickness of the detectors needs to be as large as possible. On the other hand thicker detectors lead to a larger spread in the measured TOF. Hence the required energy resolution dictates the choice of thickness. For typical spectral measurements the intrinsic detection efficiency is much smaller than that of a gamma ray detector. Since good energy resolution demands good TOF resolution (implying large source-detector separation), the neutron detector has to be large in size. One such array, shown in Fig. 5, consists of fifteen bars of plastic scintillator (6 cm x 6 cm x 100 cm) viewed at either end by fast photomultipliers. The timing information from both these PMTs can be used to deduce the TOF, and hence the energy of the neutron, as well as the position where the interaction took place. The array will be used to make measurements of neutron energy spectra in heavy ion reactions at the 14 MV Pelletron at Mumbai.

Typical TOF spectra with 6.3 and 8 MeV protons incident on a natLiF target are shown in Fig. 6. The TOF was measured with respect to 429 keV γ-rays detected in a BaF₂ array placed close to the target.
An example of a much bigger array is the Large Area Neutron Detector (LAND) at GSI. The array (size 2 x 2 x 2 m³) consists of plastic scintillator interspersed with iron sheets and has an efficiency of about 80% for neutrons of energy greater than about 400 MeV.

Acknowledgements

The author wishes to thank D.R. Chakrabarty for useful discussions.

References


**Liquid Scintillation Detectors and their Applications**

**Introduction**

A scintillation detector may be defined as a material which emits light sparks when ionizing radiation passes through it. Scintillation materials may be solids, liquids or gases. The intensity of light flashes mainly depend on the energy of radiation deposited in the scintillator. Solid scintillation detectors specifically NaI based scintillators were the oldest and widely used materials for gamma ray detection. Gaseous scintillators, say a few inert gases, have had limited applications in the detection of X-ray. Liquid scintillators fall in the category of organic scintillators, where plastic scintillators in polycrystalline form could be used for $\beta$-particle or X-rays detection and the liquid scintillator which is a mixture of two to three components dissolved uniformly in a suitable solvent is traditionally used for the detection of alpha and low energy $\beta$-particles. Organic scintillators including liquid scintillators are mostly aromatic hydrocarbons whose molecules contain benzene ring structures with non-aromatic substitutes. The luminescence (scintillation) process consists of transition of single molecule from one level to another in the energy level structure. The molecule in the electronic excited state, when sufficiently stable against other process of energy release, returns to ground state by the emission light sparks. The mean life for this process is of the order of $10^{-8}$ sec.

**Scintillation Mechanism**

A liquid scintillator primarily consists of one or two solvents and one or two solutes along with other optional materials like solubilisers and chemiluminiscent inhibitors which all put together are commonly called as cocktail. Multiple solvents and solutes are used to enhance the energy transfer process and increase the photo cathode efficiency. The $\beta$-particle dissipates its energy by collisions with the solvent molecules of the cocktail. In a liquid, which is relatively dense, the $^3\text{H}$ beta particle will travel only short distances before all of its kinetic energy is dissipated. The net result of the interaction is the ionization and excitation of molecules of the solution, the latter being of interest in liquid scintillation technique. The excited solvent...
molecules can transfer energy to one another and to the solute molecule, whose orbital electron cloud gets disturbed and rise to a state of excitation. The excited orbital electron of the solute molecule returns to the ground state and a light photon is emitted. Thus, a single $\beta$ particle will cause excitation of many solvent and solute molecules resulting in a number of light sparks. The process of photon emission is illustrated in Fig. 1. In a simple approximation and when interferences are excluded, the intensity of light is proportional to the initial energy of the $\beta$ particle. The light photons are then passed on to the cathode of PMT and depending on its efficiency, a number of primary electrons are produced which are multiplied to form an electrical pulse for further spectral analysis.

The amount of energy required to produce one photo electron for a liquid scintillator is about 100 eV and is 3 times less than that required for a NaI(Tl) detector. On considering a photo electric efficiency for a PMT cathode as about 30%, Quantum efficiency of ~ 12% and optical efficiency of about 90% a 18.0 keV $\beta$- particle produces about 180 photo electrons.

$\beta$- particle energy = 18.0 keV, Total photon energy = 0.12 x 18000 = 2160 eV

No. of photons of 3eV each = 2160/3 = 720 photons

No. of photons striking cathode = 720 x 0.9 = 648 photons

No. of photo electrons = 0.30 x 648 = 194 $\hat{e}$

The energy required to produce a photo electron= 18000/194 = 93 eV $\sim$ 100 eV

**Fig. 1 Schematics of Scintillation Mechanism**

**Liquid Scintillation Counting Instrumentation**

The basic design of instrumentation for liquid scintillation counting (LSC) had its beginning in the early 1950 featuring coincidence pulse detection using two diametrically opposed photomultiplier tubes (PMT). The basic detection concept still remains the same except for the digital technological advancements and signal processing. With the advances in digital signal processing, newer technologies were utilized to reduce the background in addition to those achieved by coincidence pulse detection. The conceptual design of the LSC system is shown in Fig. 2. The most early models would have counted the pulses when coincidence criterion has been satisfied. Later versions have used three or four independent discriminators (LLD & ULD) for the purpose of using interference correction mechanisms and also to understand the pulse levels. The latest versions use the spectral analyzers in conjunction with personal computer based spectral analysis customized softwares.

The energy of $\beta$ particle is normally dissipated in a period of time of the order of 5 nano second. The dual PMTs produce signals corresponding to the same event and are fed to a circuit which produces an output only if the two signals occur together within a resolving time of approximately 20 nano second. The basic counting system employing methods of coincidence detection and summation counting result in approximately 30 counts per minute (cpm) background and an efficiency of 30 to 40% for tritium energy window. A decrease in background (from 30 cpm to 1 cpm) and increase in efficiency (from 40% to 50%) has been achieved in most modern commercial systems using burst counting.

**Fig. 2 Conceptual Instrumentation of LSC system**
techniques, cooling of PMT and also making use of Bismuth Germanium Oxide (BGO) guards etc.

The summed signals are amplified and digitized using a fixed gain Analog to Digital Converter (ADC) with calibration of 0.5 keV/channel and stored in 0-4096 channels to cover an energy range of 0 – 2000 keV. The spectra can be handled in variety ways by the investigator to produce configuration of his choice using different criterion parameters like spectrum end points, figure of merit (FOM) etc.

Liquid Scintillation Mixtures

One of the most important consideration in LSC is the choice of scintillation cocktail. An aqueous medium accepting scintillator solution is composed of several components such as solvent, solute (primary & secondary) and surfactants described as given below.

Solvent

A chemical substance which converts the kinetic energy of β radiation into excitation energy and transfers this energy to scintillator molecule. In some cocktails, a primary solvent and secondary solvent also exist to increase the energy transfer process.

Primary Scintillator (Solute)

A chemical substance which converts excitation energy into photons.

Secondary Scintillator (Solute)

A chemical substance which shifts the wavelength of emitted photons into an optimal wavelength response range of PMT.

Surfactant

A chemical substance which forms a stable, homogenous emulsion through the formation of micelles with aqueous samples and organic solvents.

A few important characteristics of some widely used solvents are as follows:

(i) It must dissolve the radioactive sample and the solute materials.
(ii) It must have low content of natural ¹⁴C.

(iii) It must have high transparency to the photons of light emitted by the scintillator molecule.

Primary Solvents

<table>
<thead>
<tr>
<th>Solvent</th>
<th>RPH</th>
<th>FP (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 1,2,4 Trimethylbenzene</td>
<td>112</td>
<td>50</td>
</tr>
<tr>
<td>(b) Xylene</td>
<td>110</td>
<td>30</td>
</tr>
<tr>
<td>(c) Toluene</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>(d) Benzene</td>
<td>85</td>
<td>-11</td>
</tr>
<tr>
<td>(e) 1,4 Dioxane</td>
<td>65</td>
<td>12</td>
</tr>
<tr>
<td>(f) Alkylbenzene</td>
<td>91</td>
<td>150</td>
</tr>
<tr>
<td>(g) Di-isopropyl Naphthalene</td>
<td>105</td>
<td>152</td>
</tr>
</tbody>
</table>

The relative pulse height (RPH) for each solvent is given with reference to toluene as 100. If RPH falls below 100, the energy transfer and resultant output of photons is reduced, and it is clear that higher the value of RPH better is the solvent for scintillation counting. Thus, the solvent 1,4 Dioxane, which is one of the widely used solvents in liquid scintillation applications in Indian Nuclear Power Stations has poorest RPH and therefore will result in giving low efficiency. If the flash point (the lowest temperature at which the vapour of liquid catches fire) is very low, the sample can easily be ignited and can be considered as a potential fire hazard.

A few important solutes (primary and secondary) are listed below. The scintillator molecules accept energy from the excited solvent molecules and get excited to higher energy state. The excited solute molecules return to ground rate with release of energy in the form of light photons. The peak fluorescence of these light sparks is in the range of wavelength 300 – 450 nm with varying quantum yields. One needs to strike a balance between the peak fluorescence and quantum yield before choosing a solute. If the solute chosen has lower peak fluorescence (375 nm), where the PMT cathode has poor sensitivity, a secondary solute must be added. Secondary solute molecules mainly act as wavelength shifters to change the photon wavelength to about 400 – 420 nm where PMTs sensitivity is high. Modern LSC systems use PMTs having wide range spectral sensitivity and the use of
Secondary solutes is not absolutely necessary. However, in colour quenched samples, the secondary solute helps in effectively transferring energy to produce light flashes in the sensitive region of PMT.

**Primary Solutes**

(a) PPO : 2,5 Diphenyl Oxazole, 5 - 7 g/l conc., 375 nm max. Fluorescence, 0.83 quantum yield, 1.4 nano second decay time.

(b) BBOT: 2,5- bis- 2-(tert- Butylbenzoxazolyl)-Thiophene), 7 g/l conc., 446 nm max. Fluorescence, 0.61 quantum yield, 1.6 nano second decay time.

**Secondary Solutes**

(a) POPOP:[1,4-bis-[2-(5-phenyloxazolyl)-Benzene], 0.05 – 0.2 g/l conc., 425 nm max. Fluorescence.

(b) bis-MSB: [p-bis(o-Methylstyryl)-Benzene], 1.5 g/l conc., 425 nm max. Fluorescence, 0.61 quantum yield, 1.6 nano second decay time.

(c) M2-POPOP:[1,4-bis-[2-(4-Methyl-5-Phenylxazolyl)-Benzene], 0.1 – 0.5 g/l conc., 427 nm max. Fluorescence.

The fourth component of the cocktail is an emulsifier which accepts aqueous samples. This is the most important component of the aqueous accepting scintillation solution because it provides a method for making a homogenous solution between the aqueous sample and scintillation solution. The most common surfactants are: TRITON N57 (Nonionic), Dodecyl benzene sodium sulphonate (Anionic) and Hyamin 166 (Cationic). The advantage and disadvantages of few widely used cocktails are described in the following paragraphs.

**Dioxane Based Cocktail: [1 L dioxane, 120 g Naphthalene, 4 g PPO, 0.05 g POPOP]**

The dioxane based scintillator is one of the low cost cocktail prepared in the laboratory which can take up, a maximum of 20% aqueous load in (4 ml sample +15 ml scintillator), but one needs to be careful at this load as some times phase separation could occur. The dioxane purity will also have an effect on the sample load capacity. The absolute efficiency for a 4ml water + 15ml scintillator and for other combinations, the efficiencies are 1 + 5 : 35%, 2 + 15 : 30 %, 3 + 15 : 25% respectively.

Although dioxane based scintillator is simple to prepare and of low cost, it has a few disadvantages namely low sample load, auto oxidation leading to the formation of peroxides which are strong quenching substances and chemiluminescence producers. Further, it has relatively low counting efficiency, low flash point, high toxicity, suspicious of being carcinogenic and also non-biodegradable. The chemiluminescence can exist from a few minutes to two or three days after the formation of peroxides.

**Instagel**

It is a commercial cocktail from M/s-Packard and consists of toluene, a secondary solute and an emulsifier. The sample load is 50% i.e. it can take equal quantity of aqueous sample as that of scintillator solution. This cocktail has low flash point indicating a fire hazard if not handled properly is highly carcinogenic and also non-biodegradable. At 25°C, the cocktail produces different phases at different sample loads.

Single phase : for samples loads of < 17%

Two phase : for samples loads of 17 to 27%.

Gel phase : for samples loads of > 27%

Thus, one must be careful in using samples load of 17 – 27% as the sample is not homogenously distributed. The absolute efficiency for 3H aqueous samples for different sample loads are - 1+10 : 38%, 5+10 : 27%, 1+15 : 40%, 5+15 : 30% and 10+10 : 18% respectively. The efficiency for sealed and non-quenched 3H standard in a toluene based scintillator for standard LSC system is in the range of 50 – 60%.

However, the cocktails based on the solvents mentioned above under primary solvents (except DIN) have problems such as non-biodegradability, carcinogenic and also have low flash point. Due to the above mentioned environmental, health and disposable problems, a new cocktail based on Di-isopropyl Naphthalene was introduced. It has the following characteristics:
(a) DIN has not been identified as hazardous and is widely used in manufacturing of carbonless copy paper.

(b) DIN has high flash point (152°C).

(c) DIN is considered as bio-degradable.

It has same sample load and efficiency as compared to Instagel commercial cocktail. The DIN based cocktails are available under the commercial name Ultima Gold-XR from M/s. Packard.

**Quenching And Correction Mechanisms**

In liquid scintillation counting, quenching is the most important interference. The main quenching material is generally the sample itself as the sample molecules do not help in excitation mechanism. The β particles kinetic energy may be dissipated in the collisions with sample molecules which are incapable of transferring energy to the solute. The same is true if the solvent and solute substances have chemical impurities. The loss or reduction of energy of β particle due to the presence of sample and impurity molecules is known as quenching. The sample molecules and impurity substances absorb the energy and dissipate in the form of heat. This kind of quenching is known as chemical quenching. Another form of quenching is generally known as color quenching and this occurs during passage of light photons. The light photons may be absorbed partially or completely, the wavelength may be changed to low sensitive region due to the presence of color in the sample. In both forms of quenching, the number of photons reaching the PMT per keV of β-energy are reduced and thus the efficiency. The end point energy of the β-spectrum gets skewed towards lower energy side. For the radionuclides with high energy β-particles, there may be shift in the spectrum towards lower energy side, but the counting efficiency does not change significantly. Due to quenching, the counting of tritium whose E<sub>max</sub> is 18.6 keV is affected in terms of efficiency to a far greater extent as compared to 14C whose E<sub>max</sub> is 156 keV. However, for each sample, there must be a mechanism to correct for the quenching as the degree of quenching in each sample is different.

Manufacturers of LSCs commonly equip their systems with one or more quench indicating parameters (QIPs) for automatic correction of efficiency for each sample. Various QIPs currently available are: SCR (sample Channel Ratio), SIS (Spectral Index of Sample), ESR (External Standard Ratio), ESC (External Standard Counts), SIE (Spectral Index of External Standard), TSIE (Transformed Spectral Index of External Standard), Internal standardization etc. A detailed explanation of all the above QIPs is beyond the scope of this article, the limitations of a few widely used QIPs are discussed below.

**SCR**

Sample Channel Ratio is based on the ratio of counts accumulated in two independent counting channels of appropriately divided energy i.e for ³H generally the two energy windows are 0 - 18.6 keV and 2 – 18.6 keV and for ¹⁴C they are 0 – 156 keV and 4 to 156 keV. SCR accuracy changes as the degree of quenching increases and for heavily quenched samples SCR is not applicable. It does not depend on the number of counts accumulated in each window.

**SIS**

Spectrum Index of Sample is derived from the average energy of β-spectrum formulae and utilizes counts in each channel of the energy spectrum of interest (e.g. 0–18.6 keV for ³H). SIS indicates the movement of end point energy as the degree of quenching in sample varies, moving lower energy side for highly quenched samples and moving towards E<sub>max</sub> for less quenched samples.

The formulae for SIS is given by:

\[
SIS = K \times \frac{\sum_{x=0}^{6} E \times n(E)}{\sum_{E} n(E)}
\]

K : Normalisation factor obtained from an un-quenched spectrum representing the standard spectrum.

U : upper level energy (18.6 keV for tritium)

E : β – particle energy in steps of 0.5 keV.

n(E): Number of counts in the energy region of E + 0.5 keV (one channel)

SIS utilizes the entire spectral data and does not need any additional counting as with the case of...
external standard QIP. It was found that SIS for an unquenched $^3$H standard (sealed standard) was approximately around 19 and for different levels of quenched standards SIS was found to be in the range of 8 to 18. Experiments have indicated that, for proper estimation of degree of quench, it requires significant number of counts to be accumulated in each channel, resulting in a very long counting time for environmental level tritium measurements. It was found that for concentration of approximately $\leq 1$ Bq in the sample, SIS does not truly indicate the degree of quenching.

Thus while using QIPs and developing quench curves (correlation between QIP and efficiency) it is essential to determine the applicability of them at various levels of concentrations The dynamic range of QIP is indicated on the curves.

### Background in LSC Systems

One of the most important parameter for low level measurements for radiation counting system is the background. Background in LSC systems comes from various sources as listed below:

(a) PMT and glass vial (37%) : Background from glass vial mainly comes from the cosmic rays interaction with the glass to produce Cerenkov radiations, secondary electrons. Natural radiation in PMT construction materials also adds to background.

(b) Scintillator (31%) : Cosmic ray interactions and natural radioactive contamination of solvent and solute chemicals along with small contribution from chemiluminescene.

(c) Cross talk (22%) : A spontaneous scintillation event within the photo cathode which release a photo $\bar{\epsilon}$ from the cathode. This scintillation may be simultaneously viewed by the other PMT producing a coincident event within resolving time.

(d) Instrument background (10%) : Noise contribution from PMTs may be due to dark noise or after pulse noise.

The methods of reducing the background include:

(a) Use of moderate and excessive passive shielding around the PMTs.

(b) Masking PMTs and vials to minimize cross talk.

(c) Use of guard detectors such as BGO (Bi$_4$Ge$_3$O$_{12}$) or plastic scintillator for anti-coincidence measurement.

(d) Application of time resolved burst counting techniques (high sensitive mode or low level counting mode).

In the last method, a technique of differentiating the background pulse from that of $\beta$ decay, namely the pulse index (PI) is used to reject the background pulse. Usually a background event

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No PI</th>
<th>Normal PI</th>
<th>Low level PI</th>
<th>Ultra Low Level PI</th>
<th>Super Low Level PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>System/model</td>
<td>2100 TR</td>
<td>2900 TR</td>
<td>3100 TR</td>
<td>3100 TR</td>
<td>3170 TR/SL</td>
</tr>
<tr>
<td>Bkg(glass) cpm</td>
<td>22</td>
<td>19</td>
<td>13</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Eff%(glass)</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>29.5</td>
<td>26.5</td>
</tr>
<tr>
<td>FOM(E$^2$/B)</td>
<td>52</td>
<td>60</td>
<td>89</td>
<td>145</td>
<td>234</td>
</tr>
<tr>
<td>Bkg(plastic) cpm</td>
<td>11</td>
<td>11</td>
<td>10</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Eff%(glass)</td>
<td>34</td>
<td>34</td>
<td>33.5</td>
<td>29</td>
<td>28</td>
</tr>
<tr>
<td>FOM(E$^2$/B)</td>
<td>105</td>
<td>105</td>
<td>112</td>
<td>168</td>
<td>392</td>
</tr>
</tbody>
</table>

For $^3$H window of 18.6 keV and 8 ml water, 12 ml Ultima gold scintillator
produces a sharp pulse of higher amplitude and few nanosecond width followed by a few (may be 5) after pulses in duration of about 5 µsec. Broadly the pulse index technique counts the after pulses and rejects the background events after comparing with the pre-determined index. The background for several types of standard systems of M/s. Packard for 3H window along with efficiency and FOM are given in Table 1.

Applications

LSC systems can be used to measure and estimate radioactivity due to various radionuclides emitting β or β – γ and α radiation. However, it is widely used for the measurement of low energy β – emitters and pure β – emitters as other β – γ and α – emitters are determined commonly by γ – spectrometry using HPGe and α – spectrometry using Si-Surface barrier detectors. A few applications of LSC are:

(i) Measurement of 3H in environmental samples like air, ground water, ocean water and biological samples for free 3H and organically bound 3H. Different sample preparation techniques like distillation, condensation, bubbler, electrolytic enrichment, oxidation of biological samples etc. are used for obtaining an aqueous tritiated solution readily soluble in the scintillation mixture. The natural occurrence of 3H precipitation (produced from cosmic rays interaction with nitrogen and oxygen) varies from 0.5 Bq/l at equator to 3 Bq/l at high altitudes. For low level measurements DIN (Di-isopropyl Naphthalene) based cocktails which accept 50% sample load and ultra low level LSC systems are employed. Detection limit of about 2 to 4 Bq/l (100 min, counting time, 2 cpm Bkg, 20% efficiency 10 ml sample load for 3170 TR/SL and 100 min. 1 cpm, 20%, 10 ml for Quantulus 1220). Further lower levels can be achieved by the use of electrolytic enrichment techniques. 3H has been used as tracer for hydrological studies to model the ground water movement.

(ii) Measurement of 14C in plant material for radio carbon dating, environmental samples around facilities which produce radio labeled compounds for biomedical, and agricultural tracer studies and in the environment of nuclear fuel cycle facilities. The sample preparation technique involves mainly absorption of CO2 in organic or inorganic bases and this forms the major part of the determination than that of 14C measurement in LSC.

(iii) Cerenkov Radiation Counting: The electromagnetic radiation emitted by β-particles when they travel with a speed greater than that of light in a denser medium is known as Cerenkov radiation. Generally, hard β-emitters have the capability of moving at a velocity greater than that of light in medium (may be water) and emit Cerenkov light photon. Cerenkov light photons have similar energy as that of photons emitted during 3H β-decay in a scintillation solution. Thus, the set up designed and standardized in a LSC for 3H measurement can be used for Cerenkov radiation detection. The threshold β-particle energy has been determined as 263 keV for water medium (Knoll, 1989) and it basically depends on the refractive index of the medium. Potential Cerenkov radiation emitting radionuclides along with their Emax and approximate efficiency (%) in water medium are as follows.

\[ ^{90}\text{Y} \quad (E_{\text{max}} \approx 2284 \text{ keV}) \quad 50\% \]  
\[ ^{89}\text{Sr} \quad (E_{\text{max}} \approx 1492 \text{ keV}) \quad 27\% \]  
\[ ^{40}\text{K} \quad (E_{\text{max}} \approx 1310 \text{ keV}) \quad 33\% \]  
\[ ^{134}\text{Cs} \quad (E_{\text{max}} \approx 662 \text{ keV}) \quad 3.4\% \]  
\[ ^{137}\text{Cs} \quad (E_{\text{max}} \approx 514 \text{ keV}) \quad 3.5\% \]  
\[ ^{90}\text{Sr} \quad (E_{\text{max}} \approx 546 \text{ keV}) \quad 2.5\% \]  
\[ ^{60}\text{Co} \quad (E_{\text{max}} \approx 318 \text{ keV}) \quad 5.2\% \]  
\[ ^{106}\text{Ru} - ^{106}\text{Rh} \quad (E_{\text{max}} \approx 3530 \text{ keV}) \quad 60\% \]  
\[ ^{144}\text{Ce} - ^{90}\text{Pr} \quad (E_{\text{max}} \approx 2980 \text{ keV}) \quad 60\% \]  
\[ ^{32}\text{P} \quad (E_{\text{max}} \approx 1710 \text{ keV}) \quad 30\% \]

Extensive study was conducted for measuring 90Sr-90Y in equilibrium and 89Sr in various environmental matrices like fresh water, bore well water, soil, reactor radwaste samples, biological samples utilizing methods like non destructive assay (No chemical separation), simplified chemical analysis and also by conventional radio-chemical analysis methods. For instance, a 2.0 Bq of 89Sr/90Y (in equilibrium) standard diluted with water to make up a volume of 20 ml in a LSC vial and counted in an LSC of 0.1 cps background gives approximately a count rate of 1 cps. Detailed investigations can be found in several publications like Ross (1961), Regan (1976), Carmon (1979, 1986), Rao (1998).

(iv) Measurement of 90Sr in environmental samples.

(v) Measurement of 32P in agricultural, radio pharmaceutical industry.
(vi) Measurement of $\alpha$ – emitters with or without using pulse shape discrimination technology.

References

Semiconductor Detectors

Introduction

One of the marvels of detectors developed in the last 50 years for nuclear radiation detection, has been the semiconductor detectors (SCD) based on silicon and germanium. They have revolutionised radiation detection in terms of energy resolution, rapid response, particle identification capability and compact size. They have more or less replaced the gas and scintillation detectors in most applications. The SCD have the virtues of both the gas and the scintillation detectors. One of the striking properties of a semiconductor is the small size of the band gap between the valence band and the conduction band, which is of the order of one eV. Hence the energy required to create one charge pair of electron and hole in a semiconductor is approximately 3 eV and is significantly smaller than that for a gas detector where the energy required for electron - ion pair is between 20 and 30 eV. The corresponding value for a scintillation detector is nearly 100 eV. This single feature of semiconductor is the most attractive and results in the superior energy resolution of the detector. Being a solid, the stopping length of nuclear radiation in a semiconductor detector is also relatively small and hence the corresponding stopping time. The semiconductors being compact in size, the electron - hole pairs created from the ionising radiation are collected in a very fast time scale (order of ns) under the applied electric field. The fast response of the detector, coupled with superior energy resolution, has enabled identification of a variety of nuclear particles produced in a nuclear reaction and over a wide range of energies and mass/charge values. The development of the semiconductors has a significant role in the growth of nuclear physics research over the years. Despite the fact that the detectors are sensitive to radiation damage, light and temperature, delicate to handle, they are the most popular ones in nuclear radiation detection and other applications.

Working Principle

One of the parameters for a semi conducting material to be suitable for detector is the value of the band gap. In this respect, silicon and germanium that belong to the IVth group of periodic table are the
ideal candidates having the band gap values of 1.1 and 0.7 eV respectively. At room temperature, while the valance band (VB) is filled with electrons, the conduction band (CB) is nearly empty but for the small number of electrons which have been excited due to thermal excitation and which have crossed the band gap. At room temperature, the typical conduction electron densities in silicon and germanium are about $10^{16}$ and $10^{19}$ per cubic meter respectively. Loss of electrons from the valence band will constitute a hole density in the valence band. The electron - hole pair so produced will constitute a dark current in the detector when being used for detection of nuclear radiation. The electrons and holes that are produced due to interaction of radiation with the detector have to be significantly more than the ones, which are present due to thermal excitations. Reduction of the leakage current due to thermal excitation is the challenge in using semiconductors as detectors.

The electrical conduction of semiconductors is usually tailored by controlled addition of impurities, broadly called dopants. The trivalent (B) and the pentavalent (P, As) elements are generally used as dopants. In the case of the pentavalent atoms, four of the electrons form covalent bonds with the four electrons of Si or Ge and the fifth electron of the donor moves easily through the lattice of Si or Ge and forms a set of donor states close to but below the conduction band. This will facilitate easy transfer of electrons from donor state to the conduction band. The semiconductors doped with pentavalent materials are called n-type. Similarly, the semiconductor doped with group III atoms are called p-type as in this case the extra hole (only three covalent bonds are formed) is created and the new energy levels are formed near the valence band but above it. These aspects are depicted in Fig. 1a. It can be easily shown that even for 2 parts per million donor impurity atoms in silicon, the impurity concentration can be as high as $10^{23}$ per cubic meter much higher than the value of $10^{16}$ from a undoped semiconductor. This in turn will lead to more recombination of electrons with the holes and the resultant reduction in hole density in n-type material.

**Fig. 1a** Energy band structure of pure, n-type and p-type semiconductors

**Fig. 1b** Schematic diagram of a pn-junction, before and after applying the reverse bias.
By choosing the right dopant concentration, the resistivity of silicon (germanium) can be altered. As a result of doping, one ends up with a material having a much greater number of conduction electrons and the number of holes much lower than the pure material. In this case, the electrons are the majority carriers and the holes are the minority carriers. This is the way to get n-type semiconductor. In a similar way by doping with a trivalent impurity, a p-type semiconductor is obtained with holes being the majority carriers and the electrons playing the role of minority carriers. It is clear that doping with type III or type V impurities changes the character and the resistivity of the semiconductor. Ideally one would like to have as pure a semiconductor as possible, which would have resulted in a large value of resistivity. However, to obtain hyper pure Si or Ge free from impurities and other trapping centers is not trivial. That is why the doping route has been followed to change the resistivity in a controlled manner.

In general the leakage current in a semiconductor is much higher than the current that will be flowing due to the ionising particle produced charge carriers. Hence an n-type or p-type semiconductor itself cannot function well as a detector. How to overcome this problem and use the semiconductor as a detector is the challenge. The creation of a rectifying junction drastically reduces the leakage current and this will be discussed now. When a p-type and a n-type materials are brought into contact, the electrons from the n-type material can diffuse into the p-type zone (where electrons are less in number) across the junction and combine with the holes. In the vicinity of the boundary between two materials, the charge carriers are neutralised, creating a region called the depletion region free from mobile charge carriers. As a result of electron diffusion into the p-type from n-type, positively charged fixed donor sites are left behind on the -n type material close to the boundary. Similarly, the diffusion of holes to n-type leaves behind a negatively charged fixed acceptor sites close to the junction on the p-type material. The Fermi energies of the p and the n regions are the same as must be in the case for equilibrium. The space charge from the fixed sites creates an electric field, which prevents further migration of the majority charge carriers across the junction. No current flows when no radiation is present. However, now the minority carriers will flow but this current should be very small resulting in low leakage current. This situation is ideal for detection of external radiation and the current generated due to its interaction with the detector material. If radiation enters the depletion region and creates electrons - holes (the result is very similar to that of ionising radiation entering an ionisation chamber), electrons flow in one direction and the holes towards the other side. In practice the detectors are operated with large reverse bias voltage and this has two effects: it increases the depletion region making the sensitive volume (depletion region) for charge collection larger and also increases the electric field in the depletion region making collection of charges faster. These aspects are also shown in Fig.1b.

Generally a thin layer of high concentration p-type material is formed on top of n-type silicon to form a pn-junction. The n-type silicon is oxidised on one side and coated with a thin gold layer to form thin p-type material and a rectifying electrical contact. The other side of n-type material is coated with aluminium for electrical contact. Reverse bias is applied with positive voltage on the n-type side. The depletion depth is related to the resistivity of the crystal and to the applied voltage. It is given as \( d = 5.5 \left( \frac{p}{\rho_n} \right)^{1/2} \) for n-type material and \( = 3.3 \left( \frac{p}{\rho_p} \right)^{1/2} \) for p-type material. (\( d \) in microns, \( \rho \) in ohm - m and \( V \) in volts). It is clear that high resistive material is required to increase the depletion depth. One-way to achieve this is by diffusing highly mobile light atoms like Li to compensate the opposite charge carrier. By starting with a p-type material and doping with lithium, we achieve a thin n-type region similar to that discussed above. By heating the crystal lithium is drifted into the p region and this leads to larger depletion region. By employing this technique it has been possible to achieve depletion depths of the order of several mms easily. However, this method also requires cooling the detector as otherwise the drifted Li will drift back to the surface. One thing to note is in the case of semiconductor materials, the electron and the hole velocities are not very different in contrast to the large differences observed between electrons and ions. Combined with small size and fast travel of charge carriers, the time scale for charge collection are a few ns in the case of semiconductor detector.
The Fano factor (F), a non-statistical factor that ultimately decides the energy resolution is of the order of 0.1 in the case of SCD. The energy resolution in the case of 3.3 MeV alpha particles stopped in the detector leads to production of roughly one million charge pairs. The statistical fluctuation on this number is one thousand. Hence resolution is given as $2.35 \frac{F}{N}^{1/2}$ where N is the statistical uncertainty on the number of charge carriers. For 3.3 MeV alphas this theoretical limit works out to be 0.074 % (2.5 keV). However the observed resolution is around 10 keV, arising mainly due to the electronic noise and the dead layer on the detector.

Cooling the detectors leads to better energy resolution (due to reduction in thermally generated noise contribution) and also in time resolution (due to increased mobility of electrons). This point will be discussed again while we take up the applications of SCD.

**Semiconductor Detector Applications**

The semiconductor based detectors have been employed for the detection of charged particles, γ/X-rays and neutrons. High-resolution γ/X-ray spectroscopy has been possible, thanks to the development of SCD. The detectors have been used in stand alone mode or in conjunction with other detectors for charged particle identification in terms of mass (M), charge (Z) and energy (E). We discuss below some of the applications of the SCD as engaged in nuclear physics research.

**Spectroscopy**

The early work with semiconductor detectors focused mainly on detection of α-particles, electrons and heavy ions. Nowadays, superior varieties for example, ion implanted silicon detectors and Si-pin diodes have been developed that are more rugged against damage and some of them have even larger active area. They are in great demand for high-resolution measurements with accelerator based nuclear physics experiments. One of the recent growths in SCD technology has been the development of high purity Si or Ge. In view of their high resistivity, thicker SCD have become available. The cooled high purity Germanium (HPGe) detectors owing to their excellent energy resolution are being used in the analysis of complex γ-ray spectra in basic nuclear physics research and several other applied areas. These detectors need to be cooled only when in use unlike Lithium drifted Ge detectors that are also being used for X-ray and γ-ray spectroscopy and have to be stored/used in liquid nitrogen temperature. At present HPGe detectors offer highest resolution available for γ-ray energy from a few keV up to 10 MeV. When compared with NaI detector the difference is striking. At 1.33 MeV ($^{60}$Co), HPGe resolution is about 0.15% (2 keV) while for NaI this value is around 8% (100keV). Recently Compton suppressed clover detector, segmented into four parts with the shape of clover is being used worldwide for γ-ray spectroscopy as they offer much larger photo peak efficiency. These detectors consist of HPGe crystal surrounded by BGO crystals that act as Compton suppression shield. The GAMMASPHERE array based on more than 100 HPGe detectors and EXOGAM array of clover detectors are some of the large efficiency devices in operation in the world.

**Particle Identification**

Nuclear reactions with heavy ion collisions result in final products with a wide range of isotopic species and kinetic energies in the exit channel. The variety of the final products increases both as the energy and mass of the colliding nuclei increases. Detection of the reaction products in terms of their mass, charge and energy is an important part of such studies. Identification methods utilize the ionization signals produced when the ions pass through one or more detectors. The signal contains both the amplitude and time information and the particle identification methods exploit one or both types of information.

**Detector Telescope**

The pattern of ionization produced by an energetic ion along its track through a detector medium is an important parameter for the particle identification. Absorption of the ion energy in a stack of two or more detectors permits a measurement of the pattern of energy loss and the sum of the signals from the detectors is a measure of the total incident energy of the ion. Combining the total energy and energy loss pattern allows...
identification of the ion. Such an arrangement is known as a detector telescope. The well-known Bethe–Bloch equation for non-relativistic particles, used for energy loss per unit length can be simplified as

$$\frac{dE}{dx} \propto \frac{MZ^2}{E}$$

where $M$ is mass of the ion of energy $E$ and charge $Z$. This expression suggests the simplest form of particle identification, consisting of a very thin ($\Delta E$) detector followed by a second $E$ detector in which the particle stops (Fig. 2). The product $E \times \frac{dE}{dx}$ provides a measure of $MZ^2$ (Table 1). The usefulness of this method in identifying an ion uniquely is best for elements of $Z<6$. This method is less suitable for larger $Z$, as overlap exists between the range of the $MZ^2$ values for the element and the elements of higher $Z$. In many applications stack of thin detectors is used to get a detailed picture of ionization track leading to better identification. Typical thickness of $\Delta E$ – Si-detectors ranges from 10 to 100 microns for heavy ions in the energy range of a few tens of MeV. These detectors are placed in a special transmission type of mount. For detection of low energy heavy ions, in some cases gas-Si hybrid telescope is useful. The gas detector can have a very flexible thickness for $\Delta E$, depending on the gas pressure. The gas ionization chambers are useful as $\Delta E$ detectors because very thin Si – transmission detectors with uniform thickness cannot be made easily. Usually the $\Delta E$ signal is plotted against the $E$ detector signal or the total energy obtained by summing the two signals as shown in Fig. 3. It can be seen in the figure that the different particle groups can be identified as different hyperbola as per their unique $MZ^2$ values.

### Table 1

<table>
<thead>
<tr>
<th>$M$</th>
<th>$Z$</th>
<th>$MZ^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
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<td>112</td>
</tr>
<tr>
<td>9</td>
<td>4</td>
<td>144</td>
</tr>
</tbody>
</table>

**Time of Flight Measurement**

The time of flight measurement for heavy ions has become very popular to determine the mass of the ion. A system with two detectors separated by a distance $l$ gives the time, $(\Delta t)$, taken by an ion moving away from the target with a velocity $v$ to pass between them (Fig. 4). The velocity $v$ is determined according to $v = l/t$ and if the energy $E$ of the ion is also measured, then assuming that the energy loss in the start detector is negligible, the mass $M$ can be determined as
The Si detectors due to their fast timing properties and good energy resolution are being used in many applications for deriving both the time and the energy (E) information. Even though faster detectors like micro channel plates and parallel plate avalanche counters are becoming popular as start detectors, Si detectors are still used to derive the stop time and measure of E of the energetic particle. They are popular as E – detectors in a TOF assembly owing to their excellent energy resolution which in turn improves the mass resolution. For 28 MeV $^{28}$Si ion, to travel a distance of 28 cm, the time taken will be 20 nsec.

**Position – Sensitive Detectors**

Semiconductor detectors are widely being used as position sensing devices, mostly at the focal plane of mass dispersive devices like spectrographs. Also, when they are placed inside a scattering chamber, angle of the scattered particle can be obtained by converting the position information into the related angle. These detectors provide both one-dimensional and two-dimensional information. The common design consists of a series of individual electrodes as strips placed on the same semiconductor base. Each electrode then acts as a separate detector giving position information along one dimension. They are known as strip detectors and can provide both X and Y position information by suitable arrangement of the detectors. In addition they can also be used as AE detector in a telescope assembly thus providing both position and energy loss information. Typical width of the strips is of the order of 0.2 to 2mm.

Figure 5 shows the state of the art, strip detector assembly, being used for modern radioactive ion beam experiments. Each element of the array consists of a 32- strip Si- DE detector, a double-sided 32- strip Si-E detector, and four CsI crystals. These telescopes can be assembled in different configurations in a flexible way to study different reactions like transfer reactions, elastic/inelastic scattering etc.

**Neutron Detection**

Usually neutron detection is done through nuclear reactions involving $^6$Li as a target. A thin layer of (LiF) on a suitable backing is prepared. This in turn is placed between two Si-detectors. When low energy neutron interacts with $^6$Li, the reaction products are triton and alpha. The reaction involved is $^1n + ^6Li → ^3He + ^3H + Q$ (4.78 MeV)

$$M = 2 \frac{E}{v^2} = 2E \frac{t^2}{l^2}$$
They enter the two detectors placed opposite to each other. A coincidence between the two is a valid neutron detection event. By measuring the energy of the two detected particles, the energy of the incoming neutron can be estimated. In Fig. 6, the scheme adopted for detection of neutrons using Si detectors is shown.

**New Developments in Semiconductor Detectors**

Various semiconductor materials that have high Z and can be operated at room temperature for high-resolution photon spectrometry are being investigated for their usage as detectors. Although many compounds have been tried, only detectors made of GaAs, CdTe and HgI₂ have achieved good energy resolution for low energy photons. GaAs has almost same effective Z as Ge and a sufficiently large band gap (1.42 eV). But it is not widely used. Cadmium Telluride has a band gap of 1.45 eV and atomic number 48 and 52. This makes it highly efficient for γ-ray detection. This was the first material, other than Si, to have been developed as a room temperature detector. HgI₂ has even higher Z (80 and 53) with an energy gap of 2.14 eV but higher electron hole creation energy (~ 4.4 eV). Though these new detector types present many favorable properties for γ-ray detection, they are still facing many problems like incomplete charge collection. It is difficult to build large volume detectors because of non-uniformities. They are expensive as it is difficult to grow good quality crystals. Research in this direction is very active. However portable detectors employing CdTe, have been developed and are in use for on field activity, away from the laboratory.

**Conclusion**

In this article, a brief account of SCD and their use in nuclear science investigations has been given. The SCD having superior energy resolution have been instrumental in unravelling new features of nuclear structure in particular. Si and Ge are the two widely used semiconductor materials intended for SCD. There are interesting developments for other compound semiconductors. SCD in stand alone mode or in conjunction with other detector have been regularly employed in particle identification in terms of mass, charge and energy in many nuclear physics investigations. Currently large efficiency and highly granular, 4p charged particle and gamma arrays consisting of a large number of detectors, primarily SCD are the main workhorses in many nuclear physics experiments and this trend is expected to continue in the years to come.

The authors thank Indian Association of Nuclear Chemists and Allied Scientists (IANCAS) for this opportunity to write this article.

**References**

Principles and Applications of Gas-filled Radiation Detectors

**Introduction**

The development and use of radiation detectors began with the development of nuclear science itself. Gas-ionisation devices were some of the earliest to be developed and have been in use for many years. Gas-filled detectors include ionisation chambers, proportional counters, GM counters etc., and in all these devices the ionisation produced by the incident radiation generates a signal proportional to the intensity of the radiation falling on the sensitive volume. Most of these detectors can be indigenously developed according to the required specification, using locally available materials and technology.
Detectors that are tailor-made to suit the exact specifications can be better integrated into the monitoring system. Most of them provide stable and reliable operation over a long period of time.

Gas-filled detectors can be constructed with metal and ceramic components and are usually filled with an inert gas. Therefore, these devices can be made relatively robust and tolerant to high radiation and temperature levels. They can be installed in inaccessible areas in reactors and other nuclear facilities and their signals can be monitored to obtain information about the radiation. This is one of the reasons why these devices continue to be in demand in nuclear research and industry. Several text books describe the basic principles of gas-filled detectors [1,2].

**Principle of Operation**

In general, ionisation detectors consist of a gas-filled chamber with a central electrode well insulated from the chamber walls (Fig. 1). A voltage V is applied between the wall and the central electrode. The gas molecules are ionised by radiation. Here, the liberated electron and the positively charged atom constitute the ion pair. Under the influence of the electric field, the positive and negative ions tend to migrate towards the negative and positive electrodes respectively. Electrons are collected more rapidly since the electric collecting force is inversely proportional to the mass of the particle. The collection of the charge constitutes an ionisation signal.

At lower voltages, the ion pairs may recombine. Electrons created by ionisation may be taken up by positively charged atoms to form a neutral atom by recombination. They may sometimes attach themselves to neutral atoms to form negative ions with mass comparable to that of the positive ions formed in the ionisation process. In pure nitrogen and noble gases like argon, negative ions are not formed generally. In these gases, the negative charge carriers are predominantly electrons. Recombination of ions reduces this current, which is then no longer proportional to the incident radiation. As the applied voltage is increased, recombination losses reduce and saturation current is obtained. Ion chambers operate in this voltage region. The voltage required to obtain saturation current is called saturation voltage and its value depends mainly on the type of gas used and its pressure.

At higher voltages, charge multiplication takes place and the pulse height is proportional to the energy of the radiation. The collected charge is multiplied by an amplification factor since the electrons released in the primary ionising events are accelerated sufficiently to produce additional ionisation. Proportional counters operate in this region. At still higher voltages, the pulse height is independent of the energy and this is called the Geiger-Müller region. Here, the charge is amplified to a value that is limited by the characteristics of the chamber and the external circuit (Fig. 2).

**Ionisation Chambers**

Ionisation chambers are gas-filled devices that collect and measure the electric charge of ions and electrons produced as a result of exposure to radiation. The ionisation is caused by the interaction...
of incident radiation and secondary radiation from
the chamber structure with the fixed, known volume
of gas in the chamber. The quantity of collected
charge is a measure of the incident radiation. The
free electrons make many collisions with the gas
molecules as they move about. The average distance
travelled between collisions is called the mean free
path and it is inversely proportional to the gas
pressure p. The direction of electron motion is
random, but there is a drift towards the positive
electrode under the influence of the applied electric
field (E). The average drift velocity w is given by
\[ w = \frac{\mu E}{p} \]
where \( \mu \) is the mobility, which is about \( 10^6 \)
\((\text{cm/sec}) \ (\text{volts/cm})^{-1}\) for electrons.

There is a tendency for the electrons to attach
themselves to the neutral atoms with which they
collide, thus forming negative ions. The electron
attachment coefficient is defined as the probability
of attachment per collision of an electron with
neutral atoms. The values of attachment coefficient
vary widely with gas type, electron energy and the
applied voltage. While halogen gases, oxygen and
water vapour have large electron attachment
coefficients of the order of \( 10^{-4} \), argon, nitrogen,
carbon dioxide etc have coefficients of the order of
\( 10^{-6} \). The presence of oxygen and water vapour in air
increases the probability of negative ion formation.
Compared to gases like argon, loss of ionisation due
to recombination in air is greater at a given voltage.

Under ideal cavity conditions described in the
Bragg-Gray theory, ionisation is caused entirely by
electrons originating in the wall material due to
absorption of photons and their direct absorption in
the gas is negligible. At high gas pressures, however,
nearly all the ionisation is due to the direct
absorption of photons in the gas. Although the
absorption process is exponential, the fraction
absorbed in the gas is so small that it increases
virtually linearly with pressure. All the ionisation
produced in this gas by the incident gamma rays is
collected if sufficiently high potential is applied
between the electrodes. The resulting saturation
current is proportional to the gamma exposure rate.

The current-voltage characteristics of the
chamber indicate that when the specific ionisation is
high, the fractional loss in saturation current is larger
and the characteristic curve has a larger slope. As the
potential across the electrodes increases, more and
more ions are collected before they recombine.
When the voltage is sufficiently high, all the ions
caused by the radiation within the sensitive volume
are collected. At this stage, any increase in the
applied voltage does not result in an increase in the
signal current. Ion chambers are operated in
saturation condition, by applying voltage that does
not allow recombination losses. In practice, a
voltage twice that of \( V_{0.9} \) (i.e. the voltage required for
90% saturation current) is chosen as the operating
voltage.

It is possible to analyse the performance of ion
chambers by theoretical methods on the basis of
design parameters and preliminary performance data
[3-5]. These techniques have helped to extend the
dynamic range of gamma-sensitive ion chambers.

 Ion chamber output can be processed either in
pulse mode (used when the number of events are
small in number) or current mode (used when the
number of events is too high for the pulse mode). In
the pulse mode, the relative values of the time
constant \( RC (\tau) \) of the external circuit and the charge
collection time are important. For \( \tau < t_c \) (charge
collection time) the current flowing through the load
resistance, \( R_l \) is the instantaneous value of the
detector current. The voltage nearly follows the time
dependence of the current and detectors are used in
this mode when the event rates are very high (current
sensitive mode of pulse operation). Detectors are
usually operated where \( \tau > t_c \). Here very little current
flows in the external circuit during the charge
collection and the detector current in integrated
momentarily on the capacitance. If the timing

![Fig. 3 Saturation characteristic of an ion chamber](image-url)
between the events is large the capacitance discharges though R returning the voltage to zero (Fig. 4).

Ion chambers operating in current mode are used for measuring exposure dose from gamma rays or X-rays. This is done over a wide range, from environmental cosmic and terrestrial levels of the order of a few µR/h to very high intensity levels (tens or hundreds of MR/h) within the core of a reactor. For absolute measurements of exposure, free-air standard chambers are employed. As the energy of the X- or gamma-ray photon increases, so does the size of the standard ionisation chamber. This condition arises since the air wall surrounding the sensitive volume of the chamber must have a thickness greater than the range of the secondary electrons. This difficulty is circumvented through the use of a wall of solid material with the same chemical composition as of the air. Such a wall is referred to as an air-equivalent wall.

In dosimetric studies measurements are carried out on the effects of radiation on matter. Bragg-Gray principle states that the amount of radiation produced in a gas cavity serves as a measure of the energy dissipated in the surrounding material. It is assumed that the small gas cavity is traversed by the same flow of corpuscular radiation as exists in the material under consideration. Tissue-equivalent ion chambers are used in dosimetric studies where the wall and the gas contain elements equivalent to the tissue. Ion chambers with well-type re-entrant cavity are used in nuclear medicine for the assay of radiopharmaceuticals. Flow-type ion chambers are used to monitor air-borne radioactivity due to the presence of beta active isotopes like tritium.

Ion chambers are made neutron sensitive by coating the electrodes with materials capable of absorbing thermal neutrons and emitting prompt charged particles that ionise the gas. Typical examples are boron-10 (3840 b) and uranium-235 (550 b). Normally isotopes enriched to 90% or more are used. However, detectors have been developed with lower levels of enrichment [6]. In personnel monitoring applications, they are used as integrating type pocket dosimeters. Here the charge released in the chamber over a time is determined yielding a quantity related to the total radiation incident on the chamber during the period of measurement.

Neutron detection is a vital aspect of reactor instrumentation. Neutron flux is continuously monitored at designated locations either within, or outside the reactor vessel from start up to full power operation. The signals from these devices ensure that the reactor power does not vary too rapidly and that the power level does not exceed the safe limit. Ion chambers with all-welded construction, improved electrode design and additional electrode structures have resulted in better performance characteristics.

**Proportional Counters**

A proportional counter is a gas filled detector in which higher field strength than isonization chamber is used and internal pulse amplification takes place. It is designed to operate using charge multiplication, caused when the drift velocity of electrons and ions is sufficiently energetic to increase the total ionisation. This requires a strong voltage gradient, which can be created when one electrode is a surface and the other is a thin wire. The original charge deposited is multiplied by a factor that can be as large as $10^5$, resulting in a signal pulse of the order of 100mV. The pulse height is proportional to the number of ion pairs generated and, therefore, to the energy deposited. They can be used as energy spectrometers for X-rays and other types of radiation.

The most common applications of these devices employ pulse-mode operation in which they handle up to $10^6$ counts/sec. Use is made of the fact that a gain in pulse size is achieved while the
dependence of the pulse size on the primary ionisation is preserved (Fig. 5&6).

The gas multiplication makes it possible for the counting of a given type of nuclear particle with less amplification in the associated electronic equipment than is needed with pulse-type ionisation chambers. For example, alpha particles can be counted easily in the presence of beta particles making use of the large difference in the specific ionisation of the two particle types. Similarly gamma-induced pulses in reactor instrumentation can be neglected while monitoring low neutron flux levels in the start up range. Integral bias curves (Fig. 7) are plotted to set the amplitude discriminator level so that noise pulses can be eliminated. For a given discriminator bias, the operating voltage is selected on the basis of the voltage plateau (Fig. 8).

Gases such as hydrogen, methane, helium-3 and boron trifluoride are used for neutron detection. Boron-lined counters have comparatively lower neutron sensitivity and better tolerance to gamma background. However some design changes in the electrode configuration have resulted in enhancing the neutron sensitivity [8]. Other neutron-sensitive materials such as Ag have also been used in applications involving pulsed neutron monitoring [9]. For general applications, argon with a 10% admixture of methane, ethanol, carbon dioxide or isobutane is used for higher amplification factor. Organic vapours act as quenching agents to limit the extent of the gas discharge.

In proportional counters the gas discharge remains confined to a small area and this fact is made use of in one- and two-dimensional position sensitive detectors. Multiwire proportional counters play a major role in particle physics where, for example, a beam of scattered particles is monitored for energy resolution and other parameters. These detectors can be made neutron-sensitive by suitable choice of gas. Flow and sealed proportional counters are also used in contamination monitoring applications in health physics.
Fission Detectors

Fission detectors with their electrodes coated with U-235 are used in either pulse-mode or current-mode [10]. In mean-level operation, the neutron-induced current is measured and the signal is proportional to the neutron flux. Other fissile elements like U-233 have also been employed. Here attempts have been made to overcome the higher specific alpha activity [11]. Fission detectors are used for reactor in-core neutron monitoring also [12]. Fission detectors can be used for neutron detection in gamma background levels up to 1MR/h.

Geiger-Müller Counters

These devices consist of an outer cylindrical cathode with a thick anode wire stretched along the axis. Compared to proportional counters, the applied potential is higher and larger discharges are produced by the incident radiation. The avalanches triggered by primary ionisation fill the entire axial volume near the wire, generating a saturation discharge that is independent of the size of the original event. Therefore GM counters can not be used as energy spectrometers but they have a high sensitivity to weakly ionising events. The output signal can be of the order of 1V even for a single ion pair and can be processed without further amplifications.

GM counters can be used for detecting any type of nuclear radiation, which will produce ionisation within the tube, no matter how small the amount of ionisation. They are widely used for counting electrons, beta particles, gamma rays and X-rays, which have small specific ionisation that is hard to detect. Since the pulse size is independent of particle energy, GM counters can not distinguish between different particles.

Quenching gases are used in GM counters to prevent multiple pulsing. Electronic quenching is carried out sometimes, with the use of a large 100MΩ load resistor. However, this increases the time constant of the system, resulting in a dead time of about 10ms. Internal quenching is done either by using a halogen mixture or an organic vapour in the fill gas. Organic quenching agents are gradually used up and limit the operating life of the tube to about $10^8-10^9$ counts. Halogen mixtures tend to react chemically with detector components and limit the life to about $10^{10}-10^{13}$ counts. GM counters are good at detecting low level radioactivity. At high exposure rates, their life is limited.

GM counters are widely used in nuclear research and industry in health physics as portable survey meters, area monitors and contamination monitors.

Spark Chambers

The spark chamber is a direct extension of the GM counter in which the applied potential is increased to the point where it is almost sufficient to cause a spark between the electrodes. Ionising radiation passing through the detector initiates a spark discharge, which records the event. Spark chambers are similar to scintillation detectors except that a gas like helium, neon or argon is used instead of a phosphor. By pulsing a high voltage on spaced plates in a gas chamber, a visible spark is obtained from the local ion multiplication. Like GM counters it does not measure the energy deposited but records the position of the event. The spark chamber is an imaging gas counter and it is used primarily as a research tool in subatomic physics.

References


Neutron Detectors

Measurement of neutron flux forms one of the most important parameters during the operation of a nuclear reactor. Design and fabrication of neutron detectors, which can withstand the hostile environment of a nuclear reactor is therefore a challenge to the nuclear scientists. Apart from this, neutron counting is also used in the assay of heavier elements, which undergo spontaneous fission, e.g., $^{252}$Cf, $^{240}$Pu, etc., or after active neutron interrogation of fissile materials. The different types of neutron detectors are described in the present article.

Introduction

Neutrons are indirectly detected through nuclear reactions, which result in energetic charged particles such as protons, alpha particles, fast recoils as well as fission fragments. The neutron interaction cross section depends on energy of neutrons as well as the target nuclide characteristics. The energy spectrum of the neutrons depends on the source of neutrons [1]. Conventionally the slow neutron region is below the cadmium cut off of about 0.5 eV. The neutrons above the cadmium cut off and up to hundreds of keV are called epithermal and intermediate energy neutrons respectively. The neutrons above 1 MeV region are fast neutrons. The neutron detectors are based on nuclear reactions using a range of nuclides in ingenious configurations. The detectors are used for measurement of neutron source intensities, neutron flux and energy spectrum. The detectors for on line detection of neutrons make use of nuclear reactions, which emit prompt reaction products. In some cases reaction products having half-lives in the region of seconds to years also find useful applications in the design of detectors. The nuclear data of the most popular materials used mostly for prompt neutron detection and neutron detector based nuclear instrumentation is given in Table 1. The charged particles can directly deposit energy in the gaseous medium by ionisation or produce scintillations in suitable solid or liquid scintillation materials. The fast response detectors can be classified as gas based detectors, scintillator detectors or self-powered neutron detectors. The offline detectors are based on neutron activation materials.

Theory of Gas Based Detectors

Gas filled detector is used to detect either thermal neutrons (E=0.025eV) by $^{10}$Be(n, a)$^{7}$Li or $^{3}$He (n, p) $^{3}$T reactions or fast neutrons via recoil interactions in light gases like hydrogen or helium. The configuration of the detectors is similar and a typical set up for a gas filled detector is shown in Fig. 1. The metal cylinder is made up of either stainless steel (SS) or aluminium and the wall thickness is about 0.5 mm. Performance wise both SS or aluminum are quite satisfactory but have slight difference in neutron transmission or structural strength. SS walls absorb about 3% of neutrons; while aluminium walls absorb about 0.5%. Thus use of aluminum improves the detection efficiency. SS tubes are advantageous from the point of view of low background. Brass tubes are also used in certain applications where it is desired to detect gross gamma activity with change in gas composition.

Dr. G.K. Gubbi obtained M.Sc. (Nuclear Physics) from Karnatak University and joined 11th Batch of BARC Training School in 1967. Initially he worked on the experimental determination of reactor physics parameters for heavy water moderated multi-rod UO$_2$ clusters using ZERLINA reactor. He was deputed to Australian Atomic Energy Commission for a year under Indo Australian Exchange Program. He was actively associated with the development of gamma scanners for the quality control of FBTR as well as plutonium based fuel elements for Tarapur Reactors. His current interests are heavy ion induced nuclear fission and the development of non-destructive assay techniques at various stages of nuclear fuel cycle. He obtained Ph.D. from University of Mumbai in heavy ion induced nuclear reactions. He has more than 60 publications to his credit in international journals, symposia and technical reports.
central anode wire is typically 0.03-mm diameter gold plated tungsten wire and held by ceramic insulators. Tungsten provides tensile strength for the thin wire, and the gold plating offers improved electrical conductivity. For improving the performance of the detector the interior of the detector walls are coated with activated charcoal. The activated charcoal absorbs electronegative products that build up during neutron interaction. The charged particles deposit their full kinetic energy in the medium by ionisation and excitation of atoms and molecules. About 30 eV is required to create an electron ion pair and in case of $^3$He(n, p) reaction, a total positive and negative charge of $8 \times 10^{-15}$ coulombs is produced. The application of high voltage to the anode wire prevents recombination and charge collection at appropriate electrode leads to the development of electrical signal. The magnitude of the output pulse depends upon the applied voltage; detector geometry and type of fill gas. The detector operates in either ionisation or proportional region. In the ionisation region, the applied voltage is sufficient to collect all the

Fig. 1 Schematic of gas-filled neutron detector

TABLE 1. Nuclear reactions for detection of neutrons

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Nuclide of interest and Natural Abundance (%)</th>
<th>Nuclear Reaction</th>
<th>Q value (MeV)</th>
<th>Reaction Products (Energy)</th>
<th>Thermal neutron cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$^9$B(n, α)$^7$Li (19.8)</td>
<td>$^{10}$B(n, α)$^7$Li (94%)</td>
<td>2.792</td>
<td>$E_α$ (1.47)</td>
<td>3840 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{10}$B(n, α)$^7$Li* (6%)</td>
<td>2.310</td>
<td>$E_α$ (0.84)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$E_β$ (0.478)</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>$^3$He (0.000138)</td>
<td>$^3$He (n, p) $^3$T</td>
<td>0.764</td>
<td>$E_p$ (0.573)</td>
<td>5330 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$E_β$ (0.191)</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>$^6$Li (7.4)</td>
<td>$^6$Li (n, α)$^3$T</td>
<td>4.78</td>
<td>$E_α$ (2.73)</td>
<td>940 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$E_α$ (2.05)</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>$^{233,235}$U, $^{239}$Pu</td>
<td>$^{233,235}$U, $^{239}$Pu (n, fission)</td>
<td>200</td>
<td>Light fragment peak (100), Heavy fragment (70 MeV)</td>
<td>1000b</td>
</tr>
<tr>
<td>5.</td>
<td>$^3$He</td>
<td>Elastic scattering</td>
<td></td>
<td>Recoil protons and alpha particles</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>$^{155}$Gd (14.8), $^{157}$Gd (15.65)</td>
<td>$^{155}$Gd + n $→ ^{156}$Gd$^*$</td>
<td>1.54</td>
<td>Capture gamma rays and conversion electrons</td>
<td>61000 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{157}$Gd + n $→ ^{158}$Gd$^*$</td>
<td></td>
<td></td>
<td>254000 b</td>
</tr>
<tr>
<td>7.</td>
<td>$^{51}$V (99.75)</td>
<td>$^{51}$V(n, γ)$^{52}$V</td>
<td>4.95</td>
<td>$^{52}$V $→ ^{52}$V$^*$</td>
<td>6.9 b</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>End Point =2.47, $T_{1/2}$= 225 s</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>$^{103}$Rh (100)</td>
<td>$^{103}$Rh(n, γ)$^{104}$Rh</td>
<td>11 b (m)</td>
<td>$^{104}$Rh $→ ^{104}$Rh$^*$</td>
<td>1.1 b (m) + 139 (g)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>End Point =2.44</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>$T_{1/2}$= 265 s + 44 s</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>$^{59}$Co (100)</td>
<td>$^{59}$Co + n $→ ^{59}$Co$^*$</td>
<td>Capture gamma rays</td>
<td>$^{59}$Co $→ ^{59}$Co$^*$</td>
<td>37 b</td>
</tr>
</tbody>
</table>
electrons before they can recombine. This extends over a plateau region where small changes in the applied voltage do not increase the pulse height and the charge collected is proportional to the energy deposited and is independent of applied voltage. Detectors operated in this region are called ion chambers.

As the applied voltage is increased further, the primary electrons gain sufficient energy to create secondary ionisation. The process is confined to a very narrow region around the anode wire and is called avalanche ionisation or gas multiplication. The total charge produced is linearly proportional to initial energy deposited in the gas up to a certain region of applied voltage and is called proportional region. The secondary gas amplification factor can be as high as $10^3$ to $10^5$ in well-designed proportional counters. The advantage of cylindrical detector is the high electrical field in the vicinity of the anode wire required for avalanche ionisation. Gas filled neutron counters typically employ $^3$He, $^4$He or BF$_3$, CH$_4$ as primary constituent at pressure of less than 1 to about 20 atmospheres depending upon the application. A heavy gas such as krypton is also added for reducing the range of the reaction products to improve the performance. A polyatomic gas may be added to proportional counters to serve as a quench gas. The rotational degrees of freedom available to polyatomic gas molecules serve to limit the energy gained by electrons by electric potential thus helping to dampen and shorten the avalanche process and improve the pulse height resolution. Tubes filled with $^3$He and $^4$He often have a small quantity of CH$_4$ or CO$_2$ as quench gas. BF$_3$ being a polyatomic gas, does not need a quench gas but needs higher operating voltage compared to monoatomic gas filled detectors. Also polyatomic gas restricts inter collision energy gain so that fill pressures are less than one atmosphere as in case of BF$_3$ counters. A typical pulse height spectrum of a gas-based detector-using thermal is shown in Fig. 2.

**The Wall Effect**

If the neutron reaction takes place away from the wall of the detector, both the reaction products may be able to deposit the full energy. For reaction products formed near the wall, one of the reaction product deposits full energy, the rest is only partial energy. This gives rise to a peculiar pulse height distribution with shoulders as shown in Fig. 2. By setting the discriminator and gradually increasing the high voltage, a counting plateau appears. The flattest portion of the plateau should occur when the effective discrimination is just below the pulse height distribution. Under this condition only neutron pulses are counted and electronic noise and other low amplitude events will be rejected. Setting the operating voltage at the center of the plateau gives a stable operating bias voltage and small drifts of the high voltage do not affect the neutron sensitivity.

**Gamma Ray Sensitivity of Neutron Counters**

Most nuclear material emits 10 or more times as many gamma rays as neutrons and hence the gamma-ray sensitivity of a detector is an important criterion in its selection. Gamma rays interact primarily with the wall of the counter and create secondary electrons (photoelectric, compton or pair production) that may escape into the counter gas. The electron range in gas is very large and only a small fraction of its energy is deposited in the gas. Thus gamma ray interactions result in much lower amplitude pulses and simple amplitude discrimination can eliminate this effect. However at high gamma radiation fields, pulse pileup of gamma-induced pulses becomes nearly equal to the neutron induced pulses and discrimination may be difficult. Pulse shape discrimination is employed to

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overcome this effect. At very high gamma doses, the chemical changes may occur in BF$_3$ gas due to molecular dissociation leading to degraded pulse height spectra but employing activated charcoal within the tube acts as an absorbing agent for contaminants and exhibits good operating characteristics in gamma ray fluxes up to 1000 R/hr.

**BF$_3$ Proportional Counters**

In this detector, boron trifluoride (BF$_3$) serves as a target material for formation of charged particles from slow neutrons as well as a suitable fill gas. Commercially, BF$_3$ gas enriched in $^{10}$B is also available for higher detection efficiency. Because the performance of BF$_3$ as a proportional gas is poor at higher pressures, it is operated at pressures in the range of 0.5-1.0 atm. With typical anode diameters of 0.1 mm or less, operating voltages tend to be about 2000 – 3000 V. Typical gas multiplication at these operating voltages is of the order of 100-500. Because of high operating voltages, the BF$_3$ counters are more prone to spurious pulses under high humidity or mechanical vibrations. However, it has been reported that BF$_3$ tubes can successfully operate in gamma exposures of the order of 10 R/h. Operating temperatures for a typical detector is in the range of 100-150° C. For BF$_3$, the resolution (Full Width at Half Maximum [FWHM] divided by the peak value) of the total energy peak of the charge particle can vary from 5% to 40%, depending on the design of the counter. These detectors are cheaper in cost than $^3$He detectors, but polyatomic nature of the gas in the tube reduces their shelf-life.

**Boron Lined Proportional Counters**

Boron can be introduced in the detector in the form of a solid coating on the interior wall of the gas filled detector to obviate the limitations associated with using BF$_3$ as a fill gas. The fill gas like argon can then be filled at much higher pressures resulting in faster timing characteristics and increased neutron sensitivity. The coating thickness is in the region of 1mg/cm$^2$ (range of alpha particles in boron) for achieving maximum efficiency. If the thickness is increased further efficiency will decrease because of attenuation of neutrons in the coating. In this case only one of the reaction products escapes into the gas. The maximum energy that can be deposited by an alpha particle is its initial kinetic energy of 1.47 MeV. The pulse height distribution is rectangular. Similar arguments hold for deposition of energy by the $^7$Li in the detector medium. A schematic of the composite pulse height distribution is shown in Fig. 3. This distribution does not lead to a well-defined counting plateau. Because of this the performance of boron-lined counters is less satisfactory than BF$_3$ tubes for long term counting stability.

However the fill gas such as argon can be chosen at 0.25atm with an admixture of CO$_2$ for fast timing and lower operating voltage (600 – 850 V). These detectors can be used to detect neutrons in very high gamma ray fields. With proper electronics, the detector can be operated at gamma fields in the region of 1000 R/h with a 50% loss in neutron detection efficiency resulting from higher discriminator setting required to reject pile up of gamma ray induced pulses.

**$^3$He Proportional Counters**

Helium-3 gas has more thermal neutron cross-section than BF$_3$ [Table 1]. $^3$He (n, p) reaction is an attractive alternative for slow neutron detection. However no solid compounds of helium.
can be formed and the material must be used in gaseous form only. $^3$He of sufficient purity is an acceptable proportional gas. Because the ranges of the reaction products are unusually large, wall effect is more pronounced than for a BF$_3$ tube of similar size and fill pressure. One method of reducing the range of charged particles is to add a small amount of heavier gas like Krypton to enhance the stopping power. The counters can be filled with much higher pressures than BF$_3$ counters. So high efficiency $^3$He detectors are commercially available for a wide range of applications. The lower Q value of the $^3$He reaction makes gamma ray discrimination more difficult than that for an equivalent BF$_3$ tube. Operating temperature for a typical detector is in the range of 100 - 150°C. As in the case of BF$_3$ counters, activated charcoal coating enhances the lifetime of a tube by absorbing the electronegative poisons that build up during long-term usage. $^3$He detectors have energy resolution around 4% - 10% and are costlier than BF$_3$ counters. They have long shelf-life, but are useful for neutron fluxes of the order of $10^6$ to $10^8$.

**Fission Counters**

The outstanding characteristic of the fission reaction is the large Q value (≈200 MeV) of which about 160 MeV appears as kinetic energy of fission fragments. Therefore very low background counters can be designed to monitor neutrons in the presence of high gamma ray fields. Nonlinearities are particularly important for densely ionising fission fragments and the size of the pulse may not be as large as calculated by assuming simple linearity with energy. But still the pulse height will be much higher than pulses formed by other competing neutron reactions. The most popular form of fission detector is an ionisation chamber that has its inner surface coated with a fissile material. These fission chambers can function in both pulse and current mode and are used as on line neutron flux monitors in nuclear reactors. The pulse height distribution for thin deposit (thickness smaller than the range of fission products) detector shows familiar double humped fission fragment energy spectrum. The light and heavy fragments peak around 100 and 70 MeV respectively. If the deposit is made thicker for increasing the detection efficiency, energy loss of fragments within the deposit will distort the shape of the pulse height distribution. For a layer of highly enriched $^{235}$U of 2-3mg/cm$^2$ thickness, the corresponding detection efficiency in $2\pi$ geometry is about 0.5% at thermal neutron energy and about 0.1% at 0.5 eV. Fission chambers with higher detection efficiency can be designed by providing multiple layers of fissile deposits and detecting the fragments in each segment of the chamber between the layers.

The fissile isotopes used in fission counters, are alpha active (specific activity of $^{239}$Pu > $^{233}$U > $^{235}$U etc.) resulting in undesirable alpha induced background. The average energy of alpha particles is about 5 MeV, which is much smaller than the average energy of the fission fragments. The average range of fission fragments is approximately half the range of 5 MeV alpha particles. Further more, for fission fragments the energy loss is much higher at the beginning of the track and the reverse is true for alpha particles. So by proper design of the fission chambers, the alpha induced background can be minimised and alpha pulses can be easily discriminated on the basis of their amplitudes. Extensive review of various fission chamber designs can be found in [5].

**Gas Based Recoil Proportional Counters**

The fill gas is usually hydrogen, methane (CH$_4$) or helium. For a nucleus of atomic weight A the maximum energy ($E_{\text{max}}$) that can be transferred to the nucleus by a neutron of energy $E_n$ in a collision is given by eqn (1)

$$E_{\text{max}} = 4AE_n/(A+1)^2$$

The actual energy transferred to the recoiling nucleus lies in the range of 0- $E_{\text{max}}$, depending on the scattering angle with all scattering angles being equally probable. Equation (1) shows that the fractional energy transfer to the recoiling nucleus is maximum for hydrogen and decreases for heavier nuclei. Usually methane, which has high hydrogen content, is employed as a fill gas. $^4$He ($E_{\text{max}} = 0.64 E_n$) is also popularly used as a fill gas. The scattering cross sections are much lower than absorption cross sections of $^4$He and $^{10}$B. The efficiency of detecting a fast neutron by an elastic scattering interaction is about two orders of magnitude less than thermal neutron detection efficiency of $^3$He proportional counters of similar size and fill gas pressure. These
Gas proportional counters are operated with voltages in the range of 1200 to 2400 V. Gas fill pressures are typically 10-20 atm. for 4He proportional counters. Relative to 4He, CH4 or H2 based detectors require higher operating voltage and are limited to lower fill pressures and lower efficiencies but faster signal rise times. The gamma ray sensitivity of the both types of detectors is comparable and detectors can be used in gamma ray fields of roughly 1R/h if appropriate threshold is used. A typical neutron and gamma ray response of a 4He detector is shown in Fig. 4. As the neutron detection process takes place without thermalisation, neutron is detected rapidly and some information on its initial energy is preserved. They are useful for counting neutrons in the energy range of 20 keV to 20 MeV. Also fast neutron coincidence counting with resolving times of 10-100 ns is also feasible.

**Solid State Neutron Detectors**

Due to the non-availability of a fill gas containing lithium, neutron detection is based on detection of reaction products using surface barrier detectors or scintillators. Q value of the lithium reaction (4.78 MeV) offers a great advantage for discrimination against gamma ray pileup. Silicon surface barrier detectors are used to study 6Li (n, α) 3T reaction based neutron detection. A schematic of the detection process is shown in Fig. 5. A thin layer of (50-100 μg/cm²) thick coating of lithium fluoride or lithium containing material is prepared on a very thin backing and placed between two Silicon Surface Barrier detectors. When the neutron energy is low, the two reaction products are oppositely directed and coincidence counting of the reaction products can be performed. Neglecting the energy loss of the charged particles before they reach the active volume, the sum of the energy deposited in the two detectors should be equal to the incoming neutron energy plus the Q value of the reaction. This is the principle of silicon sandwich spectrometer for determination of neutron energy spectrum.

For neutron flux measurement in the presence of high gamma ray background, a solid-state neutron detector was developed in BARC [3]. Lithium fluoride enriched in 6Li (95%) was directly evaporated on the sensitive area of a miniature surface barrier detector. The detector was tested in APSARA reactor for thermal neutron flux measurement in the range of 10¹²-10¹⁰ n/cm²/s. The
sensitivity of the detector was $1.3 \times 10^{-3}$ counts per second per unit thermal neutron flux.

**Solid State Nuclear Track Detector (SSNTD)**

Solid state nuclear track detectors (SSNTDs) are insulating solids both naturally occurring and man-made. There are several types of these detectors including inorganic crystals, glasses and plastics. Some examples are given in Table 1. When a heavily ionizing charged particle passes through such insulating solids, it leaves a narrow trail of damage about 50Å in diameter along its path. This is called "Latent track" as it cannot be seen with the naked eye. It is possible to view this latent track with an electron microscope. The exact nature of the physical and chemical changes occurring at the damage site depends on the charge $[Z]$ and speed $[\beta = v/c]$ of the particle, on the chemical structure of the detector material and also on the environmental conditions like temperature and pressure. These latent tracks can be enlarged / developed so that they can be viewed under an optical microscope by etching with some chemicals such as sodium hydroxide and hydrochloric acid.

Neutron dosimetry with SSNTD has been rapidly progressing since the development of CR-39 plastic. Its attractive features of proton registration, insensitivity to photons and small size allows its application to personal neutron dose monitoring in mixed radiation field. In 1966 Becker reported that recoil and $[n,\alpha]$ reactions can be used for neutron dosimetry using CR-39 [allyl diglycolcarbonate, C$_{12}$H$_{18}$O$_7$]. Cr-39 plastic has excellent feature in charged particle registration and has been applied to fruitful research subjects. From the view point of neutron measurement, still a minor role is assigned to track detectors compared to other active counters such as organic scintillators and proportional counters, but CR-39 is considered to serve as one of the promising elements in neutron field appearing in laser induced fusion research, where fission neutrons would be emitted as a single pulse of few hundred Pico seconds. A large variety of SSNTD have been developed for neutron dosimetry. The neutron dose equivalent is measured by counting the number of tracks per unit area on the detector surface caused by the heavy charged particle produced by neutron through fission, scattering, $[n,\alpha]$ and other reactions. Proton recoil measurement using CR-39 is being routinely used for neutron dosimetry. This has also found use in low neutron flux measurements. This is a emerging field and is finding application for neutron measurements in various fields.

**Scintillation Detectors**

Lithium containing scintillators are quite common as slow neutron detectors [Fig. 7] Lithium iodide with europium as activator (~0.1 atom %), gives light outputs of about 35% of equivalent NaI (TI). The scintillation decay time is approximately 0.3 μs. Scintillation efficiency of lithium iodide is nearly the same for both electrons and heavy charged particles. A 4.1 MeV electron will yield about the same light as the 4.78 MeV reaction products. The gamma ray discrimination is rather poor. Because of the high density (4.08 g/cc), the thickness of the crystal need not be large for efficient neutron detection. A 10 mm thick crystal prepared from highly enriched $^6$Li has nearly 100% efficiency for neutrons of energy up to 0.5 eV.
Other types of scintillators include a lithium compound dispersed in a matrix of ZnS(Ag) having thickness about 0.6 mm. The charged particles following neutron interaction produce scintillations in ZnS (Ag). As the thickness of detector is very small, gamma rays do not deposit much energy and hence offer excellent discrimination against gamma rays. These detectors are commercially available (NE 421 of Nuclear Enterprises).

One useful configuration for thermal neutron counting consists of lithium loaded glass scintillators. ZnS (Ag) crystals in a glass medium or cerium activated silicate glasses are commercially available with thickness of about 1 mm. For thermal neutrons, efficiencies in the range of 25-99%, are possible in gamma ray fields of the order of 1 R/h.

Fast neutron detectors that consist of ZnS(Ag) crystals dispersed in Lucite are called Hornyak buttons. The recoiling proton in the Lucite deposits its energy in the scintillator. Their detection efficiency is low (1%) because of poor light transmission properties of the scintillator.

Plastic and Liquid Scintillators

Plastic and liquid (organic) scintillators are often used for fast neutron detection because of their fast response and moderate cost. The proton recoils produced in the hydrogenous scintillator are used for neutron detection. The organic scintillators are also loaded with lithium, boron or gadolinium. The charged particles/capture gamma rays/conversion electrons following the interaction, deposit energy in the medium and give neutron induced pulse. Their detection efficiency is low (1%) because of poor light transmission properties of the scintillator.

Self Powered Neutron Detectors

A unique type of neutron detector that is widely used for in core neutron flux mapping of operating nuclear reactors is the self-powered detector. J.W. Hillborn did pioneering work on these detectors [4]. These detectors incorporate a material of high neutron capture cross-section leading to emission of β particles or capture gamma rays. Rhodium and vanadium (Table 1) are chosen as neutron sensitive materials. A schematic of the detector is shown in Fig 6. The activation product $^{104}$Rh is produced by neutron capture in the central electrode also called as emitter. The β particles emitted by $^{104}$Rh penetrate through the insulator by the virtue of their kinetic energy and are collected by inconel outer shell called as collector. The current is proportional to the rate at which the neutrons are captured in the detector. The detectors are called self-powered as no external bias is applied for the collection of the electrons from the central electrode. The other construction materials are made up of low neutron capture cross sections. Cobalt based self-powered detector makes use of the gamma rays emitted following neutron capture. The gamma rays interact in the electrode to produce secondary electrons. The current due to the secondary electrons is used as the basic detector signal. Vanadium has a lower sensitivity and somewhat slower response than rhodium. Vanadium emitters have become more common in reactor applications because of lower burn up, permitting use over a period of several years in nuclear reactors.

Neutron Activation Detectors

The neutron detectors discussed above produce prompt output pulse for each detected neutron. Neutron interactions also induce radioactivity in certain materials. The nuclear data of these activation materials are given in Table 2 and 3 respectively. If a sample containing N atoms having a neutron activation cross section ($\sigma$) is irradiated for time (T) in a neutron flux (\(\phi\)), the activity (A) of the activation product (decay constant = \(\lambda\)) at the end of the irradiation is given by eqn (2)

$$A = N \sigma \phi \exp (-\lambda T) \quad (2)$$

The measured β or γ activity of the sample is used to measure the neutron flux. For threshold detectors, the activity is proportional to the flux of
### TABLE 2. Materials Useful as Slow Neutron Activation Detectors [1]

<table>
<thead>
<tr>
<th>Element</th>
<th>Isotopic abundance (%)</th>
<th>Thermal neutron Activation Cross Section (b)</th>
<th>Activation product</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manganese</td>
<td>55Mn (100)</td>
<td>13.2 ± 0.1</td>
<td>56Mn</td>
<td>2.58 h</td>
</tr>
<tr>
<td></td>
<td>59Co (100)</td>
<td>16.9 ± 1.5</td>
<td>60mCo 60Co</td>
<td>10.4 m 5.28 y</td>
</tr>
<tr>
<td>Cobalt</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>63Cu (69.1)</td>
<td>4.41 ± 0.20</td>
<td>64Cu 66Cu</td>
<td>12.87 h 5.14 m</td>
</tr>
<tr>
<td></td>
<td>65Cu (30.9)</td>
<td>4.18 ± 1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>107Ag (51.35)</td>
<td>45 ± 4</td>
<td>108Ag 110mAg</td>
<td>2.3 m 253 d</td>
</tr>
<tr>
<td>Indium</td>
<td>111In (4.23)</td>
<td>56 ± 12 2.0 ± 0.6 160 ± 2 42 ± 1</td>
<td>114mIn 114In 116mIn 116In</td>
<td>49 d 72 s 54.12 m 14.1 s</td>
</tr>
<tr>
<td>Dysprosium</td>
<td>164Dy (28.18)</td>
<td>2000 ± 200 800 ± 100</td>
<td>165mDy 165Dy</td>
<td>1.3 m 140 m</td>
</tr>
<tr>
<td>Gold</td>
<td>197Au (100)</td>
<td>98.5 ± 0.4</td>
<td>198Au</td>
<td>2.695 d</td>
</tr>
</tbody>
</table>

### TABLE 3. Materials useful as Threshold Activation Detectors [1]

<table>
<thead>
<tr>
<th>Material</th>
<th>Reactions of interest</th>
<th>Isotopic abundance (%)</th>
<th>Half-life</th>
<th>Threshold energy of neutron (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>^19F(n,2n)^18F</td>
<td>100.0</td>
<td>109.7m</td>
<td>11.6</td>
</tr>
<tr>
<td>Mg</td>
<td>^22Mn(n, p)^24Na</td>
<td>78.7</td>
<td>15.0 h</td>
<td>6.0</td>
</tr>
<tr>
<td>Al</td>
<td>^27Al(n, o)^24Na</td>
<td>100.0</td>
<td>15.0 h</td>
<td>4.9</td>
</tr>
<tr>
<td>Al</td>
<td>^27Al(n, p)^24Mg</td>
<td>100.0</td>
<td>9.46 m</td>
<td>3.8</td>
</tr>
<tr>
<td>Fe</td>
<td>^56Fe(n, p)^56Mn</td>
<td>91.7</td>
<td>2.56 h</td>
<td>4.9</td>
</tr>
<tr>
<td>Co</td>
<td>^59Co(n, a)^56Mn</td>
<td>100.0</td>
<td>2.56 h</td>
<td>5.2</td>
</tr>
<tr>
<td>Ni</td>
<td>^58Ni(n,2n)^57Ni</td>
<td>67.9</td>
<td>36.0 h</td>
<td>13.0</td>
</tr>
<tr>
<td>Ni</td>
<td>^58Ni(n, p)^59Co</td>
<td>67.9</td>
<td>71.6 d</td>
<td>1.9</td>
</tr>
<tr>
<td>Cu</td>
<td>^63Cu(n,2n)^62Cu</td>
<td>69.1</td>
<td>9.8 m</td>
<td>11.9</td>
</tr>
<tr>
<td>Cu</td>
<td>^65Cu(n,2n)^64Cu</td>
<td>30.9</td>
<td>12.7 h</td>
<td>11.9</td>
</tr>
<tr>
<td>Zn</td>
<td>^64Zn(n, p)^64Cu</td>
<td>48.8</td>
<td>12.7 h</td>
<td>2.0</td>
</tr>
<tr>
<td>In</td>
<td>^113In(n, n')^115In</td>
<td>95.7</td>
<td>4.50 h</td>
<td>0.5</td>
</tr>
<tr>
<td>I</td>
<td>^125I(n,2n)^126I</td>
<td>100.0</td>
<td>13.0 d</td>
<td>9.3</td>
</tr>
<tr>
<td>Au</td>
<td>^197Au(n,2n)^196Au</td>
<td>100.0</td>
<td>6.18 d</td>
<td>8.6</td>
</tr>
<tr>
<td>Li</td>
<td>^6Li(n, αn)^7Li</td>
<td>92.58</td>
<td>12.3 y</td>
<td>3.8</td>
</tr>
</tbody>
</table>
neutrons above the threshold energy of the detector. Neutron spectrum can be deduced by using a series of threshold detectors (Table 3), followed by unfolding techniques [6].

**Neutron Bubble Detectors**

Recently new emerging trend in neutron detector technology has come out with neutron bubble detectors. These detectors are reusable, integrating, passive dosimeters that allow instant visible detection of neutron radiation.

Here, minute droplets of superheated liquid are dispersed throughout an elastic polymer. When neutrons strike these droplets they form small gas bubbles that remain fixed in the polymer, providing a real time, immediate visual record of the dose. Dose is directly proportional to the number of bubbles. Detector response is independent of dose rate and is tissue equivalent. Bubble detectors are compact in size and lightweight. They can be clipped to a coat or pocket, located in areas where access is limited or placed in close proximity to neutron source environment for quick measurement. Bubble detectors have virtually isotropic angular response. This helps in accurate measurement of neutron direction irrespective of the placement of the detector. These detectors have zero gamma ray sensitivity.

These detectors are commercially available in different types. They have flat energy response in the range 200keV to 15MeV and are available in the different sensitive ranges such as 0.56, 2.2,6.8 & 22 bubbles/mrem.

The simplest and low cast models are also available commercially to record thermal neutron dose measurements. These are very useful in particular for Health Physicists who want to monitor the neutron dose on routine basis. They have thermal neutron sensitivity of approximately 20-40 bubbles/mrem. More details can be seen in ref.7.

Bubble neutron detectors can be also used in neutron spectroscopy. Here the detectors are arranged in an array geometry to sense the different energy thresholds. Each spectral measurement can be made with respect to sensing particular location of the energy threshold.

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Advanced Techniques and Instrumentation in Radiation Detection

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The phenomenon of radioactivity has been very useful for the investigation of various physical and chemical processes. In order to use radioactivity as a tool for the scientific research, expertise in techniques of radiation detection and measurement becomes very important. There are mainly three types of nuclear radiations, namely, heavy charged particles (α-particles), fast electrons and positrons (β-particles) and electromagnetic radiations (γ-rays). In the context of radiation detection, neutrons and fission fragments and heavy charged particles also add to the list of nuclear radiations. Radiation detection involves the interaction of nuclear radiation with a detection medium resulting in excitation and ionization. The ionization produced in the detection medium is converted to an electrical signal and measured. At present, a variety of radiation detectors are available and their usage depends on the requirement. Detailed information about various types of radiation detectors can be obtained in the book written by G. F. Knoll [1]. At present solid-state semiconductor detectors and scintillation detectors are most commonly used for radiation detection and measurement. There are three important performance characteristics for radiation detectors, namely, (1) detection efficiency (2) energy resolution and (3) timing characteristics. When energy resolution is the priority, semiconductor detectors e.g. high purity germanium (HPGe) detectors [1] for the detection of gamma-rays are preferred over scintillation detectors. However, when high detection efficiency or fast timing characteristics are required, scintillation detectors are preferred over semiconductor detectors. At present, detectors based on both inorganic as well as organic scintillating materials are available. The organic scintillation detectors, in general, provide better timing characteristics but poorer energy resolution compared to inorganic scintillation detectors.
The primary information obtained by the radiation detectors is the energy and intensity of the radiation. This information can be used for identification and quantification of the source radionuclide. This information is very important for tracer studies of various physical and chemical processes. By using the radiation detectors with suitable electronic support, a large number of nuclear techniques have been developed, which have tremendously increased the applications of nuclear probes in various areas of research. A few important nuclear techniques based on the gamma-ray spectrometry are discussed in this article. A gamma photon, while passing through a medium, can transfer its full energy to an electron in the medium (Photo electric effect), or it can partially transfer its energy to an electron (Compton scattering) and get scattered or it can generate an electron-positron pair by depositing its full energy (Pair production). In a given medium, the probability of these effects depends upon the energy of the gamma rays. A typical gamma-ray spectrum of a soil standard acquired using HPGe detector is shown in Fig. 1. The peaks in the gamma-ray spectrum correspond to the full energy deposition of the gamma-rays in the detection medium.

**Compton Suppression in Gamma-Ray Spectrometry**

Out of the three types of interactions of gamma-rays with the detection medium, the Compton effect is undesired as it contributes to a continuum in the gamma-ray spectrum, making the detection of low intensity gamma rays uncertain. By making proper changes in the detection system, Compton events can be rejected to a large extent. A Compton suppressed detection system is shown in Fig. 2. In this system, the HPGe detector is surrounded by the shield of BGO (Bismuth germanate oxide) detectors to detect the gamma rays undergoing Compton scattering and escaping from the HPGe detectors. The basic principle of the Compton suppression is that if a gamma-ray escapes from the HPGe detector after partially depositing its energy, it may be registered in one of the BGO detectors surrounding the HPGe detector. The electronic circuit can be designed in such a way that if there is a simultaneous registration of gamma rays in HPGe detector and one of the BGO detectors (i.e. the signals of the two detectors are in coincidence), the corresponding event in the HPGe detector will be rejected. Thus the principle of anti-coincidence between the two gamma-rays is used for the Compton suppression. The Compton suppressed and unsuppressed gamma-ray spectra are shown in Fig. 1 as solid and dashed lines respectively. For Compton suppression, in place of BGO shield, a shield of NaI(Tl) detectors can also be used.

**Life-time Measurement of Excited Nuclear States by Gamma-Gamma Coincidence**

The coincidence measurement of the two gamma-rays, which are in cascade, can provide information about the life-time of the intermediate level involved in the gamma-ray transition. A block diagram for the measurement of the life-time of an excited state is shown in Fig. 3. For life-time measurements usually scintillation detectors are used due to the requirement of the fast timing. The life-time measurement circuit consists of two parts, namely, slow and fast. In the fast part, the energy
information about the incident radiation is not important. The detector signal is fed to a constant fraction discriminator (CFD), which generates a logic signal representing the time of arrival of the incident radiation. The CFD output of one detector is fed to start input of the TAC (Time to amplitude converter) and that of the other detector is fed to stop input of the TAC. TAC generates voltage pulse whose amplitude is proportional to the time difference between the start and stop signal. The TAC output is supplied to a PC based multi-channel analyzer. The stop signal from the CFD is supplied through a delay to shift the TAC signal away from the zero channel in the multi-channel analyzer. The fast part of the circuit generates output for any two gamma rays, which are in cascade and are registered in detectors D1 and D2 in coincidence. However, to choose the desired gamma rays depending upon the energy level of interest, slow part of the coincidence circuit is used. In this part the detector signal is fed to the amplifier (AMP) for proper shaping and amplification of the detector output. The output of the amplifier is fed to the timing single channel analyzer (TSCA). TSCA provides the facility for choosing the pulses having pulse height in a given range of voltage. Thus TSCA provides the energy selectivity. The output signals of TSCA are fed to a fast coincidence unit (FCU), which is set in coincidence mode. The FCU generates an output if the two input signals are in coincidence i.e. the two signals are registered within the resolving time of the FCU. The FCU output is fed to the STROBE input of the TAC. Thus TAC will generate output only when the start and stop signals are followed by STROBE. Thus the TAC spectrum shows the life-time of the desired energy level. In order for life-time to be measured, it should be larger than the resolution time of the setup.

**Gamma-Gamma Coincidence in Decay Scheme Studies**

The coincidence measurements are very useful for establishing the decay scheme of a radionuclide. A simple 2-detector setup for the coincidence measurement of the gamma-rays is shown in Fig. 4. The timing part of the circuit is same as in Fig. 3. However, as the gamma-spectrum encountered in the decay scheme studies is usually very complex, HPGe detectors are used in conjunction with a multi-parameter data acquisition system. The use of multi-parameter data acquisition system removes the requirement of many multi channel analyzers (MCA). This becomes very important when many detectors are used for the measurement. In decay scheme studies, the quality of the data depends very much on the number of the detectors. Further, multi-parameter data acquisition system provides the facility of software gating of the energies, which is otherwise done using TSCA as discussed in the previous section. The use of TSCA in decay scheme
studies is impractical as two TSCAs will be required for the coincidence measurement of a pair of gamma-rays. There is a master gate in a multi-parameter system, which is opened by a strobe signal and remains open depending upon the width of the strobe pulse. The energy outputs and the TAC output signals coming within the gate are registered. To generate the strobe pulse, the SCA output of the TAC, which is a logic signal, is supplied to the input of GDG (Gate and Delay generator). The GDG output is a logic pulse, whose width can be varied. With this setup, information about the coincidence between the two gamma-rays as well as the life-time of the nuclear states are simultaneously obtained. K. Sudarshan et al [2] have studied the decay scheme of the $^{194}\text{Tl}$ and identified new levels in the decay scheme of this nucleus. In the decay scheme studies, the quality of data depends upon the number of detectors used. At present facilities such as gamma-spheres have been developed for nuclear spectroscopic studies. Gamma-spheres consists of large number of HPGe detectors, surrounding the radiation source. Thus, good count rates are obtained even for higher fold coincidence measurements.

**Gamma-Gamma Coincidence Measurement in Positron Annihilation Spectroscopy**

Positron annihilation spectroscopy (PAS) is a powerful tool for research in many areas of science, particularly in material science. When positron travels through a medium, it gets thermalised and annihilates with one of the electrons in the medium. In the annihilation process, the electron and positron disappear and gamma-radiations with total energy of 1022 keV are emitted as the sum of the rest mass of the positron and electron is 1022 keV. The probability of observing two 511 keV gamma rays is maximum at nearly 180°. In PAS studies usually $^{22}\text{Na}$ is used as positron source, which emits a gamma-ray of 1274 keV following the positron emission. Thus the time difference between the 1274 keV gamma ray and 511 keV annihilation gamma ray gives information about the life-time of the positron in the medium. This, in turn, gives information about the electron density in the medium, as positron life-time in the medium depends upon the electron density in the medium. For, life-time measurement the same set-up as shown in Fig. 3 can be used. The positron life-time measurement in silica supported porous materials by Babu et al. [3] provides information about the pore size distribution, which is an important factor in deciding its catalytic properties. Similarly, life-time measurements in the low temperature superconductor MgB$_2$ by Pujari et al. [4], revealed a sudden change in the electron density at the annihilation sites in the medium below Tc.

Since positrons annihilate with the moving electron, there is a broadening of 511 keV peak due to Doppler effect. Thus, information about the electron momentum can be obtained by measuring the width of the 511 keV peak in the gamma-ray spectrum. The electrons near the valence shell
possess lower momentum compared to the core electrons. Therefore, the Doppler shift in 511 keV gamma ray resulting from the annihilation with core electrons is higher compared to the Doppler shift in the 511 keV gamma rays resulting from the annihilation with the valence electrons. Thus, the central region (low momentum region) in the peak contains information about momentum of valence electrons, and the region near the peak edges (high momentum region) contains information about the momentum of core electrons. Thus, high momentum region of 511 keV peak is a signature of the element.

In the case of $^{22}\text{Na}$, the 511 keV peak sits over the Compton continuum of 1274 keV gamma-ray. Thus, accessibility to high momentum region is limited by the Compton continuum. This problem is solved by coincidence measurement of the two 511 keV gamma rays resulting from the annihilation and the technique is known as Coincidence Doppler Broadening (CDB) technique. A block diagram of the CDB setup is shown in Fig. 5. This setup is similar to that of life-time setup shown in Fig. 3. However, here multi-parameter data acquisition system is used. In the multi-parameter data acquisition system, the signals of the two 511 keV gamma-rays registered in two detectors are added and recorded. Thus signal height becomes proportional to 1022 keV, and is shifted to an energy region where the Compton due to the 1274 keV peak is low. Thus, in CDB technique, there is a significant improvement in the quality of information about the high momentum region. The CDB studies on MgB$_2$ by Pujari et al. [4] have revealed that there is an increase in the electron density in the boron sub-lattice below Tc.

**Gamma-Gamma Coincidence in Time Differential Perturbed Angular Correlation (TDPAC) Studies**

The TDPAC studies provide information about the electric field gradients and/or magnetic fields around the probe nucleus. There is an angular correlation between the directions of emission of the two gamma rays, which are in cascade. This is because of the constraint of angular momentum conservation. If the life-time of the intermediate level is sufficiently long e.g. in the range of nanosecond or more, the population of the m-states of the intermediate level may change due the interaction between the nuclear electric quadrupole moment/magnetic dipole moments of the probe with the surrounding external electric field gradient/magnetic field leading to the perturbation in the angular correlation. Thus the intermediate level in
the gamma-gamma cascade should have suitable life-time.

In TDPAC measurements, one detector is fixed and the coincidence measurements of the cascade gamma-rays at 90° and 180° are carried out. Thus if only two detectors are used, the circuit setup will be same as shown in Fig. 3. However, use of three detectors can significantly reduce the experimental time. In this case, multi-parameter data acquisition system becomes very useful. The coincidence output of the D1-D2 and D1-D3 are put in OR-gate and the output of the OR-gate is fed to GDG (gate and delay generator). The output of the GDG which is a logic signal, is used to open the gate of the multi-parameter system (Fig. 6.) Along with the TAC signals, the energy signals of the detectors can also be fed to the multi-parameter system and the data can be acquired in the list mode. S. K. Das et al. have studied the degree of polymerization of hafnium, in various acids using this technique [5].

The applications of nuclear techniques discussed in this article are only few of the large number of applications of nuclear techniques in various areas of science. The, evolution of the detector technology and electronics has significantly improved the probing capacity and versatility of nuclear techniques.

References
How to chose a Detector for a particular Application?

Dr. B.S. Tomar obtained his M.Sc. Degree in chemistry from Garhwal University, Srinagar in 1979. After a brief stint at the Indian Institute of technology, Kanpur as a Junior research Fellow, he joined the 25th batch of the BARC Training School in 1981. He won the Homi Bhabha Prize for securing the first rank among the chemistry trainees and subsequently joined the Radiochemistry Division in 1982. He obtained his Ph.D. Degree in Chemistry from Bombay University in 1990. His areas of research include Nuclear Chemistry in general and Nuclear Fission, Nuclear reactions and Perturbed Angular Correlation in particular. In September 2003, he took over as Head, Actinide Chemistry Section and initiated studies on Speciation of Actinides and Fission Products in environment. He is a Ph.D. guide of University of Mumbai and has a large number of publications in the international journals. He is a member of the IAEA expert panel on Detection and Measurement of Radiation.

Nuclear science has evolved into one of the most advance subjects in the world today. The field of radiochemistry has overlap with almost all branches of experimental sciences owing to the numerous applications of radioisotopes. Today radioisotopes are being widely used in research in a variety of fields such as, chemistry, biology, geochemistry, archaeology, environmental science and most importantly in the field of industry, medicine and agriculture in solving day to day problems.

Any application of radioisotopes, whether it is sealed source application or radiotracer application involving wet radiochemical operation, requires detection and measurement of radiations emitted by the radioisotopes. Owing to the invisible nature of the ionizing radiations, it is important that a radiation worker, before entering the radioactive area knows the level of radiation. Thus, radiation detection and measurement forms an important part of any nuclear science application [1]. Though nuclear physicists and chemists are well aware of the details of the interaction of radiations with matter and the mechanism of radiation detection as well as nuclear instrumentation, a large number of researchers working in other allied fields might not have complete access to the detailed literature on radiation detectors. During the past more than two decades I have been observing that a large number of researchers working with radioisotopes are in need of a practical handbook on radiation detectors, particularly with regard to choosing a detector for a particular application. With this intent this chapter is aimed as giving the readers brief information about how chose a detector for their application. The basic principles of different types of detector have been described in detail in other chapters of this bulletin.

An agricultural scientist may be using mainly radioisotopes like $^{14}$C, $^{32}$P, $^{65}$Zn etc., that is, mainly β, γ emitting radioisotopes. The samples may be of solid soil, aqueous solution or even the parts of plants as dried/ashed samples. A biologist may have the aqueous or non aqueous solution containing $^{14}$C, $^{3}$H, $^{35}$S, $^{32}$P labeled radiochemicals for counting. A geochemist may have soil samples or minerals for measurement of natural radioactivity or induced by irradiation in a nuclear reactor. These samples may have wide range of radioisotopes spanning the entire range of Z and A. An environmental scientist may have samples of air, dust, water, soil etc for monitoring radioactivity. An archaeologist may have $^{14}$C bearing fossil samples or lead/uranium bearing minerals for age determination. Though the majority of the radiochemists could be handling all types of radiations, e.g., α, β, γ emitting radioisotopes, an analytical chemist may be using X-ray Fluorescence (XRF) for trace element detection while actinide chemists may be handling alpha emitting actinides. The present chapter is

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IANCAS Bulletin 255 July 2004
Gross Radiation Measurements

A Geiger Muller (GM) counter is the most suitable detector for measurement of gross activity of a sample owing to its low cost, ruggedness and ease of operation. The GM counter cannot distinguish between different types of radiations. However in the case of a pure radioisotope and where relative measurements are being carried out, it can be safely used even for quantitative measurements. The sample has to be in the form of a planchette or a filter paper. For pure beta emitters like, $^{35}$S, $^{32}$P, etc., it can be used for absolute activity measurement following efficiency calibration with standard activity.

Alpha Counting

Most radiochemists working in the field of separation science and handling alpha emitting radioisotopes use liquid scintillation counters for quantitative measurement of alpha activity. Of course the poor energy resolution of this detector precludes assay of different alpha emitters in the same sample. The nearly 100% detection efficiency of this counter is of great advantage and even as low as few Bq of alpha emitters can be assayed with good precision. The sample in the form of a 50 μl aqueous or non-aqueous solution is dissolved in suitable scintillator cocktail which then acts as a detector coupled to photo-multiplier (PM) tube. The counter is limited to single isotope as it cannot distinguish between different alpha groups.

Flow proportional counter: A gas flow proportional counter is also widely used for gross alpha activity of thin solid samples in the form of stainless steel (SS) planchette. The sample is introduced inside the chamber and the gas (P10) flows over the sample. The efficiency of detector is close to 50% though the poor energy resolution limits the use of this counter to pure alpha emitters only. Prior to introduction in the detector chamber the gas is bubbled through an oil trap so as to remove any traces of oxygen or moisture, which impair the performance of the counter.

In the case of samples having multiple alpha emitting radioisotopes, one has to use surface barrier silicon detector which has the best energy resolution, of the order of 15 keV at 5 MeV alpha energy. The sample has to be very thin (almost weightless) so as to minimize the alpha energy loss in the sample. The efficiency of the detector is governed by the solid angle subtended by the detector at the sample. Typical efficiency values are around 5-10%. It requires a vacuum chamber with thermocouple gauge for measurement of vacuum which should be less than $10^{-2}$ torr. A typical alpha spectrometer consists of a vacuum chamber fitted with a microdot to BNC vacuum feed through connector to couple the detector with the preamplifier, which is outside the chamber, an spectroscopy amplifier, detector bias (HV) unit and multi-channel analyzer (MCA).

Fission Fragments

Owing to their high kinetic energy (60-100 MeV), fission fragments can be counted easily in an ionization chamber or flow proportional counter. The background of the counter is nearly zero due to the inherently large height of the fission fragment pulse. For energy spectroscopy of fission fragments, surface barrier silicon detectors are used.

Heavy Charged Particles

In a nuclear reaction, several heavy charged particles (HCP) like proton, alpha particles and heavier ions may be formed. Measurement of all these HCP’s requires a ΔE-E telescope, which consists of a thin ΔE silicon detector or gas ionization detector and a thick (E) silicon detector. The ion loses a small part of its energy in the ΔE detector and is finally stopped completely in the E detector. A two dimensional plot of the pulse heights of the two detectors gives rectangular hyperbolae due to different ions, represented by the following equation,

$$-dE/dX \propto m z^2 / E$$

(1)

where, $-dE/dX$ is the stopping power of the ion, m and z are the mass and charge respectively of the ion and E is its energy. The ions are separated due to their different m and z. Even, isotopes of an element e.g.
$^{12,13,14}$C can be separated by proper choice of the thickness of the $\Delta E$ detector. For light ions having $Z$ up to 10 (Ne), silicon based $\Delta E$ detectors of thickness around 15-25$\mu$m are suitable, while for heavier ions gas based ionization detectors are required, wherein the effective thickness of the detector can be varied by altering the pressure of the chamber.

**Beta Counting**

Beta counting in general requires the sample to be in the form of a pure radioisotope owing to the continuous nature of beta spectrum, though in the case of the mixture of radioisotopes having different half-lives, the beta counting data as a function of time can be resolved into the activity due to individual radioisotopes. Low energy beta emitters, like $^3$H (0.02 MeV) and $^{14}$C (0.2MeV) are best counted in liquid scintillation counter. The detection efficiency is close to 100%. Modern commercially available scintillation counters have provision for automatic counting of a large number of samples. For counting of high energy beta emitters, like $^{32}$P, $^{35}$S, etc., proportional counters are used. The samples are in the form of SS planchette or precipitate on a filter paper. In the case of beta counting the self absorption in the samples as well as backscattering from the backing sample holder become important and have to be corrected for. Low background beta counters are based on proportional counters in anticoincidence with a NaI(Tl) detector to reduce the cosmic ray background to as low as 0.1 counts per minute (CPM). For the measurement of absolute activity of the beta gamma emitting radioisotopes, a 4$\times$ $\beta$-$\gamma$ counter is used. Following set of equations are used to calculate the absolute activity ($N_0$).

$$\begin{align*}
N_\beta &= N_0 \varepsilon_\beta; \\
N_\gamma &= N_0 \varepsilon_\gamma; \\
N_{\beta\gamma} &= N_0 \varepsilon_\beta \varepsilon_\gamma; \\
N_0 &= N_\beta \cdot N_\gamma / N_{\beta\gamma}
\end{align*}$$

(2)

Where, $N_\beta$, $N_\gamma$ and $N_{\beta\gamma}$ are the count rate for beta, gamma and $\beta$-$\gamma$ coincidences respectively. $\varepsilon_\beta$ and $\varepsilon_\gamma$ are the detection efficiency for beta and gamma counting which get cancelled. In nuclear spectroscopic studies one often needs to measure conversion coefficients, which are obtained by measurement of conversion electrons. Window less Si(Li) detectors, having extremely high energy resolution, (150 eV at 5.9 keV) are used for measurement of conversion electrons. The sample is introduced in the small vacuum chamber coupled to the Si(Li) detector.

**Simultaneous Alpha Beta Counting**

In many situations, it is required to measure the alpha as well as beta activity in the same sample. Modern detector systems based on pulse height discriminations are being widely used to discriminate the beta and alpha pulses from the same detector. The methodology is based on the difference in the rise time of the pulses from alpha and beta particles generated in a liquid scintillation detector. Due to the high LET of the alpha particles, their energy is deposited in a smaller detector volume leading to a large concentration of ion pairs, which facilitates the formation of triplet states. Thus the fluorescence decay time for alpha particle induced fluorescence is more than that due to beta particles, resulting in high rise-time of the alpha pulses than that of beta pulses. By properly selecting the time pickoff signals, it is possible to segregate the alpha and beta signals into different bins in the MCA.

**Gamma/X-ray Counting**

The most widely used detector for gamma rays is the NaI(Tl) detector, which can be called as the workhorse of the gamma counting. The low cost, ease of operation and ruggedness of this detector has made it as the most popular gamma detector amongst the nuclear scientists. The nearly 100% detection efficiency in a well type NaI(Tl) detector offers great advantage for counting of low activity samples. Of course the poor energy resolution (~7%) of the detector makes it unsuitable for measurements in the case of multi-gamma samples. However, for mono-isotopic samples this is the best detector to be used. The detector is available in various sizes, but a size of 3” diameter by 3” long cylindrical form is most commonly used. The sample can be in solid or liquid form. In the case of thick solid samples attenuation of the gamma rays in the samples has to be taken into account.

For samples containing multiple radioisotopes, a high purity germanium (HPGe) based high-resolution gamma spectrometry system is required. The semiconductor detector is the workhorse of the gamma ray spectrometry. The high energy resolution, typically, 1.9 keV at 1332 keV, is
available in a standard HPGe detector. Since the active volume of the HPGe detector is difficult to measure, it is often quoted in terms of the percentage efficiency with respect for a 3”x3” NaI(Tl) detector for 1332 keV at 25cm. Thus when we say a 40% HPGe, it essentially means the efficiency of this detector is 40% when measured with respect to a 3”x3” NaI(Tl) for 1332 keV gamma ray of 60Co, at a distance of 25 cm from the source. Most of the radionuclides have gamma rays in the energy range of 50 keV to 2000 keV. For routine gamma ray spectrometry, therefore, a HPGe detector having efficiency in the range of 20-40% is suitable. The HPGe detectors are of two types, namely n-type and p-type. In the case of p-type HPGe detectors the outer surface of the germanium crystal is heavily doped with a n-type impurity. As a result the detection efficiency falls drastically below 100 keV. Hence for high efficiency for low energy gamma rays, it is preferred to use a n-type HPGe detector. n-type HPGe detector has added advantages in that it is more resistant to radiation damage in a neutron field, compared to a p-type HPGe.

In many applications, it is desirable to count low energy gamma rays in the range of 40-400 keV as in the case of determination of isotopic composition of plutonium samples [2]. In such cases, low energy photon spectrometers (LEPS) having lower volume are used. These detectors have better energy resolution (typically 500 eV at 121.8 keV) than the conventional 20-40% HPGe detectors (~1keV) due to faster collection of electrons and holes at the respective electrodes. For low energy gamma rays ($E_\gamma < 40$ keV) the detector should have a window made of a low Z material, to minimize the attenuation of the gamma ray intensity in the window. Most LEPS detectors use a thin beryllium window. The efficiency of HPGe detector decreases with increasing gamma ray energy, which cannot be compensated by just using higher volume detectors. The reason being that the energy resolution of the detector increases with increasing volume. Further the technology has not been developed to manufacture bigger crystals of germanium of sufficient purity, though of late 100% HPGe detectors have been claimed to be available in the market. As the gamma ray energy increases, the photo-fraction decreases. Therefore, most of the interaction takes place through Compton scattering and pair production, resulting in high Compton background and annihilation gamma ray escape peaks. Compton suppressed HPGe detectors are therefore used for measurement of gamma rays in the high background of high-energy gamma rays. In this system, the HPGe detector is surrounded by an annular scintillator detector, either NaI(Tl) or BGO, which is in anticoincidence with the former. The reduction in Compton background is quantified in terms of peak to total ratio, which is typically, about 3.0 for the best Compton suppressed HPGe detectors.

Search is on for a detector which will have the high efficiency similar to that of the NaI(Tl) detector and high energy resolution, like that of HPGe detector. The requirement of cooling the HPGe detector to liquid nitrogen (LN2) temperature during operation is an impediment in many applications requiring remote operations. In this direction a new semiconductor detector, namely, CdZnTe, has been developed, which has much better energy resolution (12 keV at 661 keV) than NaI(Tl) and high photofraction, though they are still available in small volumes of about 1 cm$^3$ [3]. These detectors need not be kept at LN2 temperature during operation due to their higher band gap and hence are ideal for operation under hostile conditions, e.g. monitoring of the spent fuel stored in underground water, monitoring of strategic materials for safeguard purposes, measurement of radionuclides in high active areas of a operating nuclear reactor, like primary heat transfer system, etc.

For measurement of X-rays Si(Li) detectors are most commonly used, though in wave length dispersive XRD machines, xenon filled proportional counters are also used. In the case of energy dispersive mode, one has to necessarily use Si(Li) detector owing to the requirement of high energy resolution. Typical energy resolution of Si(Li) detectors is around 150 eV at 5.9 keV X-ray energy of $^{55}$Fe.

Neutron Counting

Neutron counting is encountered during nuclear reactor operation, quantitative assay of plutonium bearing materials or any other spontaneously fissioning radioisotope, like, $^{252}$Cf. Proportional counters having $^3$He or BF$_3$ as fill gas
are most commonly used for neutron counting. In nuclear physics experiments, requiring large volume detectors, a solution of gadolinium nitrate in a liquid scintillator is also used for neutron counting. In nuclear reactors, on line neutron flux monitoring is carried out using self-powered neutron detectors.

**Timing Spectroscopy**

In many applications, instead of measurement of energy or quantity of radiation, one is interested in the time difference between two radiations emitted in coincidence. In such cases, the timing characteristics of the detector pulse are more important than the energy. The timing signal for any radiation is generated from the voltage pulse by suitable electronic modules called time pickoff units. The most commonly used unit is the constant fraction discriminator (CFD), which generates a logic signal at a time when there is zero cross over in the summed signal of the original signal and another delayed and attenuated signal generated from the first signal. Other method is leading edge wherein the timing signal is generated when the voltage pulse has achieved a certain fraction of its peak value. It is therefore imperative that the voltage signal from the detector is not shaped further in the amplifier, before the timing signal is generated. Of course in certain type of detectors, like HPGe, the detector signal is first shaped in a timing filter amplifier, due to the varying rise time of pulses. For best timing signals, it is essential that the detector pulse output has low rise time. In the case of scintillation detectors, the rise time of the pulse generated at the anode of the PM tube is governed by the fluorescence decay time of the scintillator material. Plastic scintillators have the shortest fluorescence decay time and hence are used when best time resolution are required, e.g. in the case of positron annihilation spectroscopy [4]. Plastic scintillators owing to their low Z, have poor photo peak efficiency and hence are not suitable for energy measurement. Therefore in case both energy and timing information are important, inorganic scintillators, like, NaI(Tl), BaF₂, or bismuth germanium oxide (BGO) are used. The volume of the detector is taken smaller than that used in energy measurement, as the resolving time increases with increasing volume of the detector, which also depends upon the gamma ray energy. Typical resolving time achieved in the case of 1”x1” NaI(Tl) detectors is about one nanosecond for two 511 keV gamma rays. In the case of BaF₂ detectors of same volume, the resolving time is about 400 pico seconds. Perturbed angular correlation studies [5], requiring a time resolution of 0.5 to one nanosecond, are carried out using either NaI(Tl) or BaF₂ detectors, while positron annihilation studies, requiring a time resolution of 200 pico-second, are carried out with BaF₂ or plastic scintillators. In the case of HPGe detectors, the typical values of time resolution achieved are about 10-20 nanoseconds.

**Conclusion**

The quest for understanding the subatomic phenomena, like, structure of atom and the nucleus, radioactive decay, etc., and using the available knowledge for understanding other non-nuclear phenomena, led to the development of various radiation detectors, whose benefits we are reaping today. From the measurement of cosmic rays in the cloud chambers in the early forties and fifties, to the study of sub-nucleonic particles, like quarks and gluons, nuclear scientists have taken a giant leap forward in the field of radiation detection and measurement. Depending upon the requirement, radiation detectors are being adopted to maximize the benefit of the technological development. For example, nondestructive assay of nuclear fuel materials uses the knowledge of radiation detectors, to design and fabricate different types of NDA equipments, like neutron well coincidence counters (NWCC) for assay of Pu in sealed samples (6), fuel pin scanners for quality control of fuel pins, use of delayed neutrons in differentiating the fissile isotopes (²³⁵U, ²³⁹Pu, etc.) and so on. Thus it is up to the experimenter to define the problem and then chose the right detector depending upon the application.

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### TABLE 1. Choice of Detector

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Detector</th>
<th>Sample</th>
<th>Eff.</th>
<th>Res.</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross α,β,γ</td>
<td>GM counter</td>
<td>Planchette</td>
<td>~30%</td>
<td>——</td>
<td>Pure beta emitters</td>
</tr>
<tr>
<td>Gross α Counting</td>
<td>Zn(S)</td>
<td>Filter Paper Swipe</td>
<td>~50%</td>
<td>Poor</td>
<td>Contamin. monitoring</td>
</tr>
<tr>
<td>α Counting (Mono isotopic)</td>
<td>Liquid Scintillator</td>
<td>Sample dissolved in detector</td>
<td>~100%</td>
<td>Poor</td>
<td>Routine α Counting</td>
</tr>
<tr>
<td>α Counting (Mono isotopic)</td>
<td>Proportional Counter</td>
<td>SS Planchette</td>
<td>~50%</td>
<td>~1%</td>
<td>Routine α Counting</td>
</tr>
<tr>
<td>Multiple α source</td>
<td>Surf. barrier Si Detector</td>
<td>SS Planchette</td>
<td>&lt;50%</td>
<td>~0.3%</td>
<td>Routine α Spectrometry</td>
</tr>
<tr>
<td>Fission Fragments</td>
<td>Ionisation Chamber</td>
<td>SS Panchette</td>
<td>~100%</td>
<td>~1%</td>
<td>Routine FF counting</td>
</tr>
<tr>
<td>P, α, HCP</td>
<td>ΔE-E tel. (Si – Si) (Gas-Si)</td>
<td>Target</td>
<td>&lt;1%</td>
<td>~0.3%</td>
<td>Nuclear reactions</td>
</tr>
<tr>
<td>Low energy β</td>
<td>Liquid Scintillator</td>
<td>Sample dissolved in detector</td>
<td>~100%</td>
<td>——</td>
<td>Routine 3H, 14C samples</td>
</tr>
<tr>
<td>High energy β</td>
<td>Proportional Counter</td>
<td>SS Planchette</td>
<td>~50%</td>
<td>——</td>
<td>32P, 33S, other beta emitters</td>
</tr>
<tr>
<td>Low bkgd. β</td>
<td>Prop. Counter - anti coin. with NaI(Tl)</td>
<td>SS Planchette</td>
<td>~50%</td>
<td>——</td>
<td>Bkgd ~0.1cpm</td>
</tr>
<tr>
<td>4π β-γ</td>
<td>Prop. Counter in Coinc. with NaI(Tl)</td>
<td>SS Planchette</td>
<td>~50%</td>
<td>——</td>
<td>Measurement of absolute activity</td>
</tr>
<tr>
<td>Conversion electrons</td>
<td>Window less Si(Li)</td>
<td>SS Planchette</td>
<td>~50%</td>
<td>~0.3%</td>
<td>Nuclear spectroscopy</td>
</tr>
<tr>
<td>Mixed α, β counting</td>
<td>Pulse shape descriminator (LSC)</td>
<td>Sample dissolved in scintillator</td>
<td>~100%</td>
<td>Poor</td>
<td>Counting of α, β in a mixed source</td>
</tr>
<tr>
<td>Gross γ Counting</td>
<td>NaI(Tl) counter</td>
<td>Solid/Liq.</td>
<td>~100%</td>
<td>~7%</td>
<td>Routine γ Counting</td>
</tr>
<tr>
<td>Mono isotopic</td>
<td>NaI(Tl) counter</td>
<td>-do-</td>
<td>~100%</td>
<td>~7%</td>
<td>Routine γ Counting</td>
</tr>
<tr>
<td>Multi γ source</td>
<td>~40% HPGe</td>
<td>-do-</td>
<td>&lt;10%</td>
<td>1.8 keV at 1332 keV</td>
<td>Routine γ spectrometry</td>
</tr>
<tr>
<td>40 –2000 keV</td>
<td>~10% HPGe</td>
<td>-do-</td>
<td>&lt;10%</td>
<td>500 eV at 121 keV</td>
<td>Isotopic Composition of Pu</td>
</tr>
<tr>
<td>5-60keV</td>
<td>5cc HPGe Be window</td>
<td>-do-</td>
<td>&lt;10%</td>
<td>Low energy γ-ray / X-ray</td>
<td></td>
</tr>
<tr>
<td>5-60keV</td>
<td>2cc Si(Li) Be window</td>
<td>-do-</td>
<td>&lt;10%</td>
<td>150 eV at 5.9 keV</td>
<td>XRF</td>
</tr>
<tr>
<td>100keV-6MeV</td>
<td>Compton Suppressed HPGe</td>
<td>-do-</td>
<td>&lt;10%</td>
<td>Prompt gamma measurements</td>
<td></td>
</tr>
</tbody>
</table>

July 2004 260 IANCAS Bulletin
A Report on 52nd National Workshop by Dr. G.A. Rama Rao, Coordinator, Fuel Chemistry Division, BARC

The 52nd BRNS-IANCAS National Workshop on ‘Radiochemistry and Applications of Radioisotopes’ was held at Centre for Biotechnology, Nagarjuna University, Guntur during February 2-10, 2004. 54 delegates from various departments of the university, colleges in Guntur, Tenali, Bapatla, Vijayawada, Ongole, Narasaraopet, Visakhapatnam and Nandigama participated in this workshop.

The Workshop was inaugurated by Dr. V. Venugopal, Associate Director, Radiochemistry & Isotope Group, Head, Fuel Chemistry Division, BARC and President, IANCAS in a function that was presided over by Prof. L. Venugopala Reddy, Vice-Chancellor, Nagarjuna University. Prof. Reddy complimented IANCAS for conducting workshops at universities and colleges, which would enable people to appreciate the beneficial aspects of radioisotopes in general and nuclear power in particular. He mentioned that nuclear power is bound to play an effective role in the power-starved country like India. Dr. Venugopal underlined the objectives of IANCAS in popularizing the subject of radiochemistry and application of radioisotopes in the academic institutions through lectures and experiments. Dr. G.A. Rama Rao, the coordinator of the workshop, on behalf of IANCAS, briefed the course content of the workshop.

A Half-Day seminar was arranged on ‘Relevance of Nuclear Power’ after the inauguration function. The seminar assumed importance in the wake of opposition to Uranium mining in Nalgonda, the neighbouring District to Guntur, with apprehensions about nuclear radiation.

The seminar was conducted by Dr. K. L. Ramakumar, FCD, BARC. Speaking on the occasion, Dr. Venugopal described the abundance of resources in the country and pointed the need to adopt nuclear power as an alternate option for the sustenance of the development. Dr. Arun K. Sharma, Head, FTD, BARC highlighted the valuable role of nuclear radiation in the development of seeds of several varieties and irradiation of food products to improve the shelf-life. Sri T. Vijayakumar, Director, Vijayawada Thermal Power Station (VTPS), explained the contribution of thermal power in feeding the grid and also stressed the need to look for other sources of power to meet the ever-increasing demand. Sri A. Anjaneyulu President, Chamber of Commerce, Guntur Chapter, enquired about the cost effectiveness in processing Mirchi and other food products. Sri Gadde Mangaiah, President, Tobacco Growers Association, Guntur and merchants of cold storage plants for spices in Guntur participated in the seminar.

The demonstration experiment on the use of radioactive isotope (Iodine-131) in studying the uptake of the nutrients by the Green gram plant drew wide appreciation from the participants.

Many schools and colleges in and around Guntur have sent invitations evincing interest in the one-day workshop. The IANCAS resource persons comprising Dr. A. V. R. Reddy, Dr. (Mrs.) Veena Sagar, Sri T. V. Vittal Rao and Dr. G. A. Rama Rao visited fifteen institutions in and around Guntur and gave lectures and conducted experiments for the benefit of more than 2000 students.

Dr. P. R. Vasudeva Rao, Associate Director, Chemical Group, IGCAR, Kalpakkam was the Chief Guest. Dr. Rao donated a set of GM Counter and Gamma Spectrometer and the sealed radioisotope sources to Dr. K. Sambasiva Rao, Director of the Workshop, through the Registrar and wished that the instruments would find better use in the Centre as well as in educating the younger students from schools and colleges. Dr. (Mrs.) Veena Sagar, Practical coordinator, proposed a formal vote of thanks to the local organizers and various agencies in DAE responsible for the success of the workshop.
A report on Advanced Workshop by Dr. V.K. Manchanda, Convener, Head, Radiochemistry Division, BARC and Vice-President, IANCAS

In the Golden Jubilee Year of DAE, BRNS-IANCAS conducted the Advanced Workshop of three weeks duration for university/college teachers at BARC during May 3-23, 2004. The objectives of the Advanced Workshop were

(a) To acquaint the participants with the present and future programmes of the Department of Atomic Energy, related to Nuclear Fuel Cycle and Applications of Radioisotopes in agriculture, medicine, industry and research.

(b) To highlight the potential of Radiochemistry discipline in the implementation of different programmes of the Department.

(c) To discuss the present status of radiochemical work being pursued at different academic institutions in the country and devise plans to strengthen it.

IANCAS has chosen 30 participants from (1) those institutions which have excellent performance index in the written test conducted by HRDD, BARC for the OCES programme, (2) Academic institutions around the DAE installations and (3) Institutions where IANCAS conducted Workshops in the past and who have at least a decade to contribute to their academic pursuits.

About 40 resource persons delivered lectures and about 25 were involved in demonstration/experimental work. The inauguration function was presided over by Shri H.S. Kamath, Director, NFG and RC&I Group, BARC and the inaugural address was delivered by Shri R.K. Sinha, Director, RD & D Group, BARC. Special features of the advanced workshop were:

(i) The core syllabus of IANCAS National Workshop was covered in depth. Special lectures on current topics such as Thorium Utilization, Heavy Water Production, Advanced Nuclear Fuels, Fast Breeder Reactors, Nuclear Power, Nuclear Fuel Reprocessing, Waste Management, Accelerators etc. were delivered by the experts in the chosen field.

(ii) The specially designed experiments for the advanced workshop gave an exposure to the participants in handling of HPGe detector, Silicon surface barrier detector, Liquid scintillation counting, Solid State Nuclear Track Detector (SSNTD), Neutron Activation analysis (NAA) and demonstration experiments like Pneumatic Control Facility (PCF) (CIRUS), sedimentation rate (Hydrology), plant uptake of nutrients (Agriculture Science).

(iii) Visits were arranged to Pelletron-TIFR, RMC, BRIT, ISOMED, WIP, CIRUS and DHRUVA.

(iv) Each participant made a presentation (of about 10 minutes) on his/her present and proposed academic/research activities with particular emphasis on the use of radioisotopes.

(v) Poster Exhibition on “IANCAS brings to you Facts and Figures” was arranged.

Valedictory programme was presided over by Dr. R.B. Grover, Director, Knowledge Management Group, BARC and Secretary, BRNS. Valedictory address was delivered by Dr. Baldev Raj, Director, IGCAR.

Areas of particular interest mentioned by the participants are:

(a) Use of SSNTD for environmental studies and

(b) Use of radiotracers in physico-chemical sciences

IANCAS acknowledges the support of Chairman, AEC, Secretary, DAE, Government of India, Director, BARC and Chairman, Basic Sciences Committee, BRNS and other DAE-BRNS dignitaries for their support. IANCAS acknowledges whole-heartedly the excellent work done by Dr.V.K. Manchanda, Head, Radiochemistry Division, Convener, Advanced Workshop, Vice-President, IANCAS, all the resource persons...
and members of the local organizing committee led by Dr. A.V.R. Reddy, Chairman, Technical Committee and Dr. V.N. Vaidya, Chairman, Local Organizing Committee.

**College/School workshops since 2004**

1. Katrap Vidyalaya, Kulgaon, Badlapur (Dr.U.M.Kasar)
2. A two-day workshop at V.S.R. & N.V.R. College at Tenali, Guntur Dt for the students of B.Sc (Chemistry & Physics) and M.Sc (Physics) (Dr.V.Venugopal, Dr.K.L. Ramakumar, Dr.G.A.Rama Rao, Dr.(Mrs.) Veena Sagar and Sri Amit Sachdeva).
3. A one-day workshop for the faculty of Bapatla Engg college, College of Agriculture and College of Pharmacy at Bapatla, Guntur District: (Dr.V.Venugopal, Dr.K.L. Ramakumar, Dr.G.A.Rama Rao, Dr.(Mrs.) Veena Sagar and Sri Amit Sachdeva).
4. A one day workshop at Pragati Educational Centre at Guntur: Students of 11th and 12th std (Dr.(Mrs.) Veena Sagar and Sri T.V.Vittal Rao).
5. A one day workshop at Bhashyam institute, Guntur Students of 10th, 11th, and 12th std. (Dr.A.V.R.Reddy, Dr.(Mrs.) Veena Sagar and Sri T.V.Vittal Rao).
6. A one day workshop at Vikas Educational Institute, Guntur Students of 11th and 12th std. (Dr.A.V.R.Reddy, Dr.(Mrs.) Veena Sagar and Sri T.V.Vittal Rao).
7. Lecture at TJPS College, Guntur for Post Graduate courses on Indian Power situation and Nuclear reactions (Dr.A.V.R.Reddy).
8. Vijan residential college, Guntur, Postgraduate students (Dr.A.V.R.Reddy, Dr.(Mrs.) Veena Sagar and Sri T.V.Vittal Rao).
9. A lecture at RVR Engg College, Guntur, for the staff and Postgraduate Students of Chemistry and Physics (Dr.G.A.Rama Rao).
10. Post Graduate students from KVR college, Nandigama (80 Km from Guntur) and SSN College from Narasaraopet (40 Km). (Sri Amit Sachdeva, Dr.P.N.Pathak and Sri S.Venkiteswaran and Sri Krishna Mohan).
11. JKC College, Guntur for Post Graduate students of chemistry, physics and biochemistry. (Dr.G.A.Rama Rao, Sri Krishna Mohan, Dr.(Mrs.) Veena Sagar and Sri T.V.Vittal Rao)
12. M.Sc (Physics) students from Layola College, Vijayawada (Sri Amit Sachdeva, Sri S.Venkiteswaran and Dr.P.N.Pathak, Sri Rakshit Swarup and Sri Krishna Mohan).
13. Students of Nagarjuna university from biochemistry, microbiology and environmental chemistry (Sri Amit Sachdeva, Sri S.Venkiteswaran, Sri R.N.Pandey, Sri Rakshit Swarup and Sri R.Krishna Mohan)
15. Students of 9th and 10th std from Sri Venkateswara Bala Kutir. (Dr.(Mrs.) Veena Sagar and Sri T.V.Vittal Rao).
16. Physics, chemistry and biochemistry Students of TJPS College (Dr.G.A.Rama Rao, Dr.(Mrs.) Veena Sagar and Sri T.V.Vittal Rao).
17. Lokgram High School, Kalyan (Dr.U.M.Kasar)
18. Students of 10th std at Training School Hostel, Anushakti Nagar (Dr.A.V.R Reddy, Dr.(Mrs.) Veena Sagar and Mrs. Thanamani)
19. Andhra Education Society, Wadala, Mumbai (Dr.G.A.Rama Rao, Dr.Y.P.Naik, Smt. Thanamani, Sri D.B.Paranjape and Sri D.Chandrasekhar)
20. A two-day Workshop at National College, Bandra, Mumbai (Dr.V.K.Manchanda, Dr.(Mrs.) Meera Venkatesh, Dr. Raghunath Acharya, Dr.S.K.Mukerjee, Dr.P.K.Pujari, Dr.(Mrs.) Veena Sagar, Dr.(Mrs.) Aruna Korde, Mrs.Drishti Satpathy, Sri Amit Sachdeva and Sri Nilesh Satpathy).
NUCLEUS

Element 110 named

On November 9, 1994 at 4:39 pm, the first atom with atomic number 110 was detected at the Gesellschaft für Schwerionenforschung (GSI) in Darmstadt, in Germany. For the last ten years, this element has been the subject of an intense search by many laboratories world-wide.

Element 110 was produced by fusing a nickel and lead atom together. This was achieved by accelerating the nickel atoms to a high energy in the heavy ion accelerator. This rare reaction occurs only at a very specific velocity of the nickel projectile. Over a period of many days, many billion billion nickel atoms must be shot at a lead target in order to produce and identify a single atom of element 110. The atoms produced in the nickel-lead collisions are selected by a velocity filter and then captured in a detector system which measures their decay. The energy of the emitted helium nuclei serves to identify the atom. This element was only found to have a lifetime of less than 1/1000th of a second.

In 2001, a joint IUPAC-IUPAP Working Party (JWP) confirmed the discovery of element number 110 and this by the collaboration of Hofmann et al. from the Gesellschaft für Schwerionenforschung mbH (GSI) in Darmstadt, Germany (Pure Appl. Chem. 73, 959-967 (2001)). The most relevant experiment resulted from the fusion-evaporation using a $^{62}$Ni beam on an isotopically enriched $^{208}$Pb target, which produced four chains of alpha-emitting nuclides following the presumed formation of $^{268}$110 + n. (S. Hofman et al., Z. Phys. A350, 277-280 (1995)).

In accordance with IUPAC procedures, the discoverers at the GSI were invited to propose a name and symbol for element 110 to the Inorganic Chemistry Division. Hofmann’s team proposed the name darmstadtium, with the symbol Ds. This name continues the long-established tradition of naming an element after the place of its discovery.

At the 42nd General Assembly (9-17 August 2003) in Ottawa, Canada, the IUPAC Council officially approved the name for element of atomic number 110, to be known as darmstadtium, with symbol Ds.
STATEMENT ABOUT OWNERSHIP AND OTHER PARTICULARS ABOUT
IANCAS REQUIRED TO BE PUBLISHED UNDER RULE 8 OF THE
REGISTRAR OF NEWSPAPERS FOR INDIA RULE 1958

FORM IV

Place of Publication : BARC, Mumbai
Periodicity of Publication : Quarterly
Publisher’s Name (Nationality) and address : Dr. P.K. Pujari (Indian)
                                          C/o Radiochemistry Division
                                          BARC, Mumbai – 400 085.
Printer’s Name (Nationality) and address : Dr. P.K. Pujari (Indian)
                                          C/o Radiochemistry Division
                                          BARC, Mumbai – 400 085
Publication Printed at : Perfect Prints,
                        22/23 Jyoti Industrial Estate,
                        Nooribaba Darga Road,
                        Thane – 400 601
Editor’s Name (Nationality) and address : Dr. G.A. Rama Rao (Indian)
                                          Fuel chemistry Division, BARC
                                          Mumbai – 400 085
Name and address of Owner of the Publication : Indian Association of Nuclear Chemists
                                               and Allied Scientists
                                               C/o Radiochemistry Division, BARC
                                               Mumbai – 400 085.

I, Dr. G.A. Rama Rao, hereby declare that the particulars given above are true to the best of my knowledge and belief.

Mumbai 400 085
28.6.2004
Sd/-
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Editor