Indian Journal of Pure & Applied Physics
Vol. 62, October 2024, pp. 940-950
DOI: 10.56042/ijpap.v62i10.4639

Gamma Ray Spectrometry – An indispensable tool for Uranium Exploration

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Received 29 May 2024; accepted 4 September 2024

Gamma ray spectrometry is a well-established non-invasive and highly effective geophysical technique utilized for uranium exploration and resource assessment. This paper aims to provide a comprehensive overview of the principles, methodologies, and applications of gamma ray spectrometry for uranium exploration. Description of the underlying physics, instrumentation, data processing techniques and recent advancements in the field are also presented. It is followed with a case study highlighting successful application in uranium prospecting, emphasizing the technique's significance in modern exploration practices. The article concludes with prospects and potential research directions to further enhance the efficiency and accuracy of gamma ray spectrometry in uranium exploration.

Keywords: Gamma ray spectrometry; Scintillation; NaI(Tl); HPGe

1 Introduction

Uranium is a naturally occurring radioactive element with atomic number 92 and symbol U[1]. It plays an important role in nuclear energy production and has strategic importance for many industries. Following are some of the key points that emphasize the significance of uranium element:

Nuclear Energy Production: Uranium is used as primary fuel in nuclear reactors for electricity generation. Uranium nuclei undergo nuclear fission and split into lighter nuclei with release of tremendous amount of energy. Heat from this energy then produces steam, which drives turbines connected to electricity generators. Nuclear power plants generate a significant proportion of the world's electricity and offer a reliable and low-carbon energy source[2]. Nuclear power plants have the capability to provide base load power, which means they can operate continuously at a stable output, independent of fluctuations in demand. This makes nuclear power a reliable and consistent electricity source, complementing intermittent renewable energy sources like solar and wind, which are dependent on weather conditions[3].

Low Carbon Emissions: Nuclear power also presents a low-carbon energy alternative as the greenhouse gas emissions are almost negligible during electricity generation. When compared with fossil fuels (coal, oil, and natural gas), nuclear power does not contribute directly to climate change or air pollution, which makes it an attractive option to combat climate change and reduces the dependence on fossil fuels[4-8].

Energy Security and Diversification: Countries that have indigenous uranium resources have an advantage in terms of energy security and diverseness of energy sources. This reduces dependency on imported fossil fuels which in turn increases countries energy reliability and decreases vulnerability to geopolitical tensions[9-11].

Strategic Importance: Uranium's importance lies far beyond energy production. It is a critical component of nuclear armament, where some isotopes of uranium that are fissile are used in nuclear explosives[12]. International safeguards, rules and regulations are enacted and implemented that ensure peaceful use of nuclear technology and prevent the proliferation of nuclear weapons[13,14].

Medical and Industrial Applications: Uranium has varied applications in several industries apart from energy and weapons. In the field of medicine, certain isotopes are used for radiation therapy in cancer treatment and for diagnostic purposes[15,16]. Moreover, different compounds of uranium are used in diverse industrial applications, like production of glass and ceramics, dyes, and pigments to name a few[17,18].

Research and Scientific Advancements: Crucial role is played by uranium in advancing scientific knowledge and understanding. Unique properties and behavior of Uranium under extreme conditions

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provide research areas in fields of nuclear physics, astrophysics and geochemistry[19,20].

With an overview of the varied and important applications of uranium listed above it becomes inevitable to explore and identify the resources of uranium. However, the task of identification and quantification of uranium resources presents several challenges. The next section provides an insight into this.

2 Challenges in Uranium Exploration

Identifying and assessing uranium resources present many challenges because of unique characters and complex geology of uranium deposits[21]. Uranium deposits can occur in a variety of geological settings with significant complexity in terms of physical and chemical characteristics[22]. For example, geological setting may have volcanic, sedimentary or intrusive environment which makes the identification and characterization a difficult task[23]. Further, uranium mineralization normally occurs at varied depths, this necessitates the requirement of modern and advanced exploration methodologies and techniques for exploration and assessment of these resources precisely[24]. Another challenge associated with uranium exploration is related with the grade of uranium deposits. Uranium deposits often have a low concentration of uranium in the ore. Such deposits are referred to as low-grade deposit[25]. Hence, to extract and concentrate the uranium economically it becomes necessary to ensure large- scale exploration efforts and advanced processing techniques.

Another feature of Uranium deposits is their occurrence in remote and difficult-to-access locations, like tough terrains, deserts or areas where infrastructure is very limited[26,27]. Exploration and development in such sites can be challenging from logistics point of view and may require appreciable investment in transportation and logistics. Further, Uranium is a radioactive element and its exploration and assessment involve handling of radioactive materials. So, it is crucial throughout the exploration and mining process to ensure the safety of workers and inhabitants by implementing required radiation protection protocols[28]. The mining and processing of uranium raise environmental concerns, particularly related to the management and disposal of radioactive waste and the potential for water contamination[29]. Adherence to stringent environmental regulations and the implementation of responsible mining practices are essential to mitigate these risks[30].

Apart from these challenges exploration and development of uranium resources is a time-consuming process. It takes several years to conclude exploration activities, obtain necessary approvals and develop mining facilities before commercial production can be started. These challenges can be overcome by adopting a multidisciplinary approach, involving geologists, physicists, chemists, engineers, environmentalists and policymakers.

3 Uranium Exploration & Gamma ray Spectrometry

In uranium exploration Gamma ray spectrometry is a powerful and promising geophysical tool[31-33]. It is based on the detection and analysis of gamma rays emitted by naturally occurring radioactive isotopes of uranium and its daughters (decay products)[34,35].

Uranium is a radioactive element and its isotopes, such as uranium-238, uranium- 235 and uranium-234 or their radioactive daughters emit gamma rays as they undergo radioactive decay. These gamma rays carry characteristic information about the presence and distribution of uranium in the subsurface. Gamma ray spectrometry is a non-invasive method which means that it does not require physical contact with the area of interest[36]. Airborne gamma ray surveys are also conducted over large regions to map the distribution of radioactive elements and assess the geological favorability for uranium exploration. It is possible to cover large survey areas efficiently without interfering with or disturbing the environment. It also reduces the requirement of extensive ground access[37]. Geoscientists can identify favorable areas with anomalous radioactivity signatures by conducting regional-scale surveys based on gamma ray spectrometry[38]. These regions of anomaly can be taken up as potential targets for a detailed exploration work. In addition to regional surveys, gamma ray spectrometry can be used for prospect-scale investigations to assess the extent and intensity of uranium mineralization within a specific target area[39]. This method helps narrow down exploration efforts to areas of higher interest.

Gamma ray spectrometry provides radiometric measurements, which involve quantifying the energy and intensity of gamma rays emitted from the subsurface. These measurements can be correlated with the presence of uranium and other radioactive elements to estimate the concentration and distribution of uranium minerals. Its ability to detect and quantify gamma rays emitted by radioactive isotopes, including uranium and its decay products, makes it indispensable for exploring and assessing uranium resources.

Ground-based gamma ray spectrometry is employed to identify and delineate uranium anomalies and help prioritize exploration targets. For sub-surface investigation Gamma ray spectrometry is a critical tool for borehole logging in boreholes[40]. It provides real-time information about the geological formations encountered during drilling, including uranium-bearing rock units. During drilling, gamma ray measurements help geologists assess the lithology, stratigraphy, and radioactivity of the rocks penetrated by the borehole. Gamma ray spectrometry aids in the identification of specific uranium-bearing minerals to certain extent based on their characteristic gamma ray emissions. For example, Al-Jafar *et al*. have demonstrated the determination of clay minerals using gamma ray spectroscopy[41].

Gamma ray spectrometry data assists in characterizing uranium deposits, including their size, shape, and radioactivity distribution. Zonation studies (demarcating zones based on K, U and Th concentration) using gamma ray data help understand the geological evolution of uranium deposits and their potential for resource estimation. Gamma ray spectrometry data is integrated with other geochemical data to identify pathfinder elements associated with uranium mineralization[42]. Geochemical anomalies detected by gamma ray spectrometry can guide further exploration efforts. Gamma ray spectrometry is used in environmental monitoring to assess natural radioactivity and detect anomalies that may indicate uranium or other mineral occurrences[43].

Gamma ray spectrometry can not only detect uranium but also provide information about other radioactive elements like thorium and potassium that may be present in the subsurface. Interpretation of geological features is aided by this multi-elemental data and can be helpful in differentiating between different types of mineral deposits[44]. Modern gamma ray spectrometers offer high resolution and accuracy, allowing precise measurement of gamma ray energies and intensities. This improved resolution helps in identifying and characterizing minute variations in radioactivity, which may prove critical in locating concealed uranium deposits. Gamma ray spectrometry can also be integrated with other geophysical and geological techniques like magnetic surveys, electromagnetic surveys, and geological mapping[45]. This integration improves and enhances the effectiveness of exploration program by providing a more comprehensive understanding about the subsurface geology[46]. Since, it is a cost-effective exploration tool, it enables early-stage target identification and helps in optimizing the allocation of exploration resources. Gamma ray spectrometry is an invaluable tool for uranium exploration, enabling geoscientists and exploration teams to efficiently target and evaluate potential uranium resources with reduced exploration risk and improved accuracy.

4 Interaction of Gamma rays with matter

The interaction of gamma rays with a material follows a course that depends on the energy of the gamma ray[47]. However, interactions can be broadly categorized into three main processes: photoelectric effect, Compton scattering, and pair production. Each process is dominant over different energy ranges of the incident gamma rays. At low energies (less than 100 keV), it is more probable that gamma rays get absorbed through the photoelectric effect. In this process, a gamma ray interacts with an inner- shell electron in an atom, ejecting the electron from the atom and creating a photoelectron. The energy of the photoelectron is equal to the energy of the incident gamma ray minus the binding energy of the electron shell. For very low-energy gammarays, coherent scattering or Rayleigh scattering is pre-dominant. In Rayleigh scattering the gamma ray interacts with the entire atom, causing it to vibrate slightly and the gamma ray scatters with no loss of energy. At intermediate energies (100 keV to 2 MeV), Compton scattering is the predominant interaction mechanism. In this process gamma ray interacts inelastically with loosely bound outer-shell electrons thereby transferring some of its energy to the electron and undergoes a change in direction. The scattered gamma ray has lower energy and longer wavelength in comparison to the incident gamma ray. At very high energies (above 2 MeV), gamma rays can interact with the matter via pair production. In pair production, the energy of the gamma ray gets converted into an electron-positron pair in the presence of electric field of the nucleus. The threshold energy for pair production process is approximately 1.02 MeV and the excess energy over this threshold is distributed between the positron and the electron. All these processes result in partial or complete transfer of the gamma-ray photon energy to electron energy. The photon either disappears entirely or is scattered through a significant angle[48].

It becomes important here to emphasize on the fact that that the probability of each interaction process mentioned above depends on the energy of the incident gamma ray and atomic number (Z) of the material. In gamma ray spectrometry a thorough understanding of these interaction processes is essential for accurate interpretation of gamma ray data for determining emitting source characteristics or the composition of material being examined[49,50]. Different gamma energies are important for detecting and characterizing uranium isotopes and their decay products. The main types of gamma rays associated with uranium exploration include.

Gamma Rays from Uranium and its daughters[51]: Uranium isotopes (such as ^{235}U) and their radioactive daughters (such as daughters of ^{238}U) emit gamma rays during their radioactive decay processes. These gamma rays have characteristic energy signatures that are used to identify and quantify the presence of uranium in the subsurface. The most prominent gamma ray emissions from ^{238}U series are at energies of 1001 keV, 934 keV and 609 keV. Uranium isotopes undergo a series of radioactive decay steps, forming a decay chain that includes various other radioactive elements, each with its characteristic gamma rays. The decay chain of ^{238}U includes isotopes such as ^{234}Th, ^{226}Ra,^{214}Pb and ^{214}Bi, each emitting gamma rays at specific energies The gamma rays emitted during the decay of these elements can also provide valuable information about the presence and type of uranium mineralization. Radium isotopes emit gamma rays at various energies, with the most common being ^{226}Ra at 186 keV, 295 keV, and 352 keV. ^{214}Bi emits an important gamma at 1.76 MeV that is used extensively in gamma ray spectrometry. ^{235}U, the fissile isotope used for nuclear reactions, emits gamma rays at energies of approximately 186 keV and 143 keV. By using Hyper Purity Germanium detector a direct estimate of ^{238}U can be obtained by counting the 1001 KeV gamma energy emitted by daughter ^{234m}Pa of ^{238}U.

Thorium Gamma Rays[52]: Thorium is another radioactive element which is often associated with uranium deposits. Some of the gamma energies from ^{232}Th decay series are approximately 238 keV, 583 keV, 911 keV and 2.615 MeV. Thorium decay product ^{208}Tl, emits gamma rays at 2.615 MeV which is used extensively in spectrometry and is relevant to uranium exploration.

Potassium Gamma Rays[53]: Potassium-40 (K-40) is another naturally occurring radioactive element relevant to uranium exploration. It emits gamma rays that can be detected during gamma ray spectrometry surveys. K-40 emits gamma rays at energy of approximately 1.46 MeV.

In gamma ray spectrometry, the energy characteristics of different gamma rays are measured and analyzed to identify the presence and concentrations of uranium and associated radioactive elements in the subsurface. This data is important for assessment of the potential of uranium resources and guiding the exploration program.

5 Instrumentation for gamma ray spectrometry

To carry out exploration of uranium, different types of gamma ray spectrometers are used to detect and measure the gamma rays emitted by naturally occurring radioactive isotopes, including uranium and its decay products[54,55]. Each spectrometer has its own advantages and is suited for a particular exploration pathway.

Scintillation Detectors: Scintillation detectors are widely used in gamma ray spectrometry due to their practicality, portability, and relatively lower cost. Scintillation detectors consist of scintillation crystal, which emit flashes of light (scintillations) when gamma rays or other high-energy particles interact with them. Common scintillation materials include sodium iodide (NaI) doped with thallium (NaI(Tl)) and cesium iodide (CsI) doped with thallium (CsI(Tl)). The emitted scintillation light is then detected by a photomultiplier tube (PMT) or a photodiode, which converts the light pulses into electrical signals[56]. The electrical signals are then processed and analyzed to determine the energy of the incident gamma rays. Scintillation detectors cover a broad energy range, making them suitable for detecting gamma rays emitted by various radioactive isotopes, including uranium and/or its decay products. Scintillation detectors have high detection efficiency for gamma rays, meaning they can detect a significant percentage of incident gamma rays, making them suitable for use in various applications, including environmental surveys and field exploration[57]. Scintillation detectors are relatively compact and lightweight, enabling their use in field applications and borehole logging in drilled holes for uranium exploration. Scintillation detectors provide real-time measurements, allowing for rapid data collection and on-site analysis during field surveys. Scintillation detectors are generally cost-effective, making them accessible to a broader range of users and exploration projects.

Although scintillation detectors have several advantages, however, the energy resolution of scintillation detectors is typically lower compared to high-purity germanium detectors. This reduced resolution can result in less precise gamma ray energy measurements. Scintillation detectors may suffer from spectral interferences, where gamma rays of different energies produce overlapping peaks in the gamma ray spectrum, making it challenging to distinguish between different isotopes accurately. They are susceptible to background noise from ambient radiation, which can affect data accuracy, especially in areas with high natural radioactive background or near othergamma ray sources. They may also exhibit non-linearity at high gamma ray energies, which can complicate data analysis and calibration.

High-Purity Germanium Detectors (HPGe): High-purity germanium detectors are renowned for their exceptional energy resolution, making them highly suitable for precise gamma ray energy measurements in uranium exploration and other fields[58]. These detectors utilize high-purity germanium crystals, which have excellent energy resolution due to their high atomic number and low electronic noise characteristics[59]. The germanium crystal is cooled to cryogenic temperatures (usually with liquid nitrogen) to reduce thermal noise and improve sensitivity. The electrical signals generated by gamma ray interactions in the germanium crystal are processed using advanced signal processing electronics to obtain precise gamma ray energy measurements. High-purity germanium detectors offer outstanding energy resolution; therefore, identification and quantification of gamma ray energies is precise and accurate. Resolution is crucial for resolving closely spaced gamma ray peaks and distinguishing different isotopes. Nowadays, HPGe detectors having high detection efficiency for gamma rays are also available making them suitable for detecting low- intensity gamma ray emissions, such as those from low-grade uranium deposits or other samples[60]. The high energy resolution also allows for specific identification of isotopes, even in complex environments with overlapping gamma ray spectra. HPGe detectors have well-established calibration methods, ensuring reliable energy calibration.

With all these advantages, HPGe detectors still present different limitations like they are more expensive and complex to operate than scintillation detectors, hindering their widespread use in some applications[61]. The need for cryogenic cooling can be a logistical challenge, especially in remote or field-based exploration site. Germanium crystals are relatively fragile when compared with scintillation crystals and can be easily damaged. Hence, careful handling and transportation is a must when using these detectors.

To summarize, scintillation detectors are favored for their portability and cost- effectiveness, making them suitable for rapid field surveys. On the other hand, high- purity germanium detectors are valued for their exceptional energy resolution, enabling precise and reliable gamma ray energy measurements in complex geological settings and uranium exploration projects where accurate isotopic identification is critical. The choice between these detectors depends on the specific requirements, budget, and objectives of the exploration project.

Hyper-Spectral Gamma Ray Spectrometer (HSGRS): HSGRS is a more advanced gamma ray spectrometer that combines multiple scintillation crystals with different sensitivities to gamma rays of varying energies, allowing for a broader energy range of detection[62]. The main components include multiple scintillation crystals with different materials or thicknesses, photomultiplier tubes (PMTs) or photodiodes for light detection, and advanced signal processing electronics. Gamma rays interact with the different scintillation crystals, producing scintillation light with varying intensities. The light from each crystal is detected separately, and the resulting signals are combined to create a detailed spectrum covering a wide range of gamma ray energies. These gamma ray spectrometers play a crucial role in uranium exploration, helping geologists and exploration teams detect and analyze gamma ray emissions from uranium and associated radioactive elements in the subsurface[63]. The data collected from these spectrometers aid in identifying potential uranium mineralization and optimizing exploration efforts.

6 Data Acquisition and Processing

The data acquisition process in gamma ray spectrometry involves several important steps including data collection, calibration, and quality control measures. These steps ensure the accuracy, reliability, and validity of the collected gamma ray data. The first step in data acquisition is to collect gamma ray data using the selected gamma ray spectrometer. The spectrometer is positioned at the measurement location, such as on the ground surface for a field survey or down hole in a borehole for subsurface exploration or in a pre-defined geometry in laboratory-based setup. The spectrometer records the number of gamma ray interactions with the detector at different energy levels over a specific time interval. This data is generally collected in the form of a gamma ray spectrum, which plots the intensity of gamma rays as a function of energy.

Calibration of the spectrometer is important to relate the recorded energy levels in the gamma ray spectrum to actual gamma ray energies. The spectrometer needs to be calibrated using standard gamma ray sources with known energies. The calibration process involves exposing the spectrometer to gamma rays from standard sources like cobalt-60, cesium-137, *etc*. The recorded gamma ray spectrum is then compared to the expected energies of the standard sources in order to carry out energy calibration of the spectrometer[64,65].

Gamma ray spectrometers also detect the background gamma rays from natural radioactivity and other sources apart from the gamma rays of interest from a target material. Background gamma rays can interfere with the accurate detection of the target gamma rays. Therefore, background subtraction is carried out in which the gamma ray spectrum in an area is measured without the target materials to obtain the background spectrum. The background spectrum is then subtracted from the measured spectrum to isolate the gamma rays of interest.

Gamma ray spectrometers also have a dead time, which is the time during which the detector is unable to record gamma ray interactions immediately after a previous interaction. This dead time can lead to underestimation of the actual gamma ray count rate. Dead time correction is applied to compensate for this effect and obtain accurate count rates. The correction is based on the known dead time of the detector and the measured gamma ray count rates[66,67].

7 Quality Control Measures

To ensure the quality and reliability of the data, regular quality control measures are essential. This includes regular instrument checks, verifying the calibration and assessment of data consistency and repeatability[68]. Quality control also involves conducting field checks in which measurements are taken in areas known to have no radioactivity to identify and quantify any potential contamination or instrumental effects[69,70]. By following these steps and implementing proper quality control measures, the data acquisition process in gamma ray spectrometry yields accurate and reliable gamma ray spectrum which provides valuable information for geological interpretations and facilitates the identification and assessment of uranium and other radioactive minerals in the subsurface.

8 Data processing techniques

Faithful processing (extracting the correct gamma energy from the spectrum) of information from raw gamma ray spectrum collected during gamma ray spectrometry is important to identify the radioactive isotopes present in the measured spectra, quantify their concentrations and interpret the geological implications. Energy calibration is a vital data processing step involving relating the recorded energy levels in the gamma ray spectrum to actual gamma ray energies[71]. This calibration is achieved using standard gamma ray sources with well-known energies. The fitting equation obtained from the calibration curve is then used to convert channel numbers (energy bins) in the spectrum to corresponding gamma ray energies. This enables accurate identification of isotopes based on their characteristic gamma ray energies.

In a gamma ray spectrum, energy peaks correspond to characteristic gamma ray energies emitted by different radioactive isotopes Peak fitting is carried out for identification and characterization of these peaks for determination of the isotopes that are present in the measured spectrum. Various mathematical methodologies, such as Gaussian or Lorentzian curve fitting, are used to fit the peaks accurately. The identification of isotopes is based on known characteristic gamma ray energies from standard sources and published gamma ray emission data. Gamma ray detectors have varying efficiencies at different energies, leading to distortions in peak intensities. Photopeak efficiency correction involves applying correction factors to account for these variations and obtain accurate activity measurements for each isotope.

Another important aspect is Background subtraction. It is a data processing step for removing the contribution of background gamma rays from natural radioactivity and other sources. Background subtraction ensures that the spectrum represents the gamma rays originating from the target material. In some cases, there is a possibility that the gamma ray spectra acquired in underground environments or near the Earth's surface may be affected by radon gas. This leads to additional background gamma rays. Radon correction is carried out to account for the radoninduced background so that more accurate gamma ray data can be obtained[72-74].

An alternative technique known as Full spectrum analysis (FSA) involves analyzing the entire gamma ray spectrum to assess the presence of multiple isotopes and their relative contributions. This technique finds utility when the spectrum contains overlapping peaks or multiple isotopes with similar gamma ray energies. More accurate quantification of different isotopes and their concentrations can be achieved by analyzing the full spectrum. After identification of the isotopes, analysis is carried out for determining their concentrations in the sample. This analysis depends on the peak areas or counts corresponding to each isotope, calibrated against known standard sources of known activity[75,76].

In the entire process of data processing, quality assurance and quality control measures are mandatory to ensure the accuracy and reliability of the results obtained. This involves checks for consistency, repeatability and data validation to validate the integrity of the processed data. By using data processing techniques, gamma ray spectrometry data can be transformed into valuable information for geological mapping, uranium prospecting and environmental monitoring among other applications.

9 Case study of uranium prospecting using gamma ray spectrometry

Gamma ray spectrometry has played vital role in identification and quantification of uranium provenances such as Singhbhum Shear Zone, Jharkhand[77-79], Bhima Basin, Karnataka[80,81], Cuddapah Basin, Andhra Pradesh[82,83], Meghalaya, Northeast India[84,85], McArthur River Uranium Mine, Canada[86], Ranger Uranium Mine, Australia[87], *etc*. These are some examples to demonstrate how gamma ray spectrometry has played an important role in identification and demarcation of uranium mineralization in various geological settings. Its ability to cover large areas efficiently and its sensitivity to detect radioactive elements makes it an indispensable tool for the exploration and assessment of uranium resources.

Atomic Minerals Directorate for Exploration and Research (AMD), Department of Atomic Energy, India is the prime agency that is actively involved in exploration of atomic minerals, particularly, Uranium, in India. The focused efforts made by AMD have resulted in identification of several uranium provenances in the country. Here we present a case study from Singhbhum Shear Zone, Jharkhand, India to demonstrate how gamma ray spectrometry has aided the Uranium exploration program.

The Singhbhum Shear Zone in Jharkhand, India, is known for its significant uranium deposits. Gamma ray spectrometry has been extensively used in this region to identify and map areas of elevated radioactivity. The data obtained from gamma ray spectrometry have guided further exploration and helped in targeting drillholes, leading to the discovery of uranium deposits in the region.

10 Methodology

Samples are analyzed for estimation of eU_3O_8, $Ra(eU_3O_8)$, ThO_2 and K by High energy gamma ray spectrometry (HEGS). eU_3O_8 is concentration of radioactive materials present in the sample compared with U_3O_8 standard in equilibrium with its daughter products. eU_3O_8 is estimated by counting of all gamma photons of energy 400 keV to 3 MeV. Uranium and thorium themselves are alpha emitters but form respective series, elements of which emit their own characteristic gamma radiations; intensities of these characteristic gamma radiations are proportional to the concentrations of the respective radioisotopes in the sample. Assuming secular equilibrium of the radioactive series, the counting the gamma-rays from any of the daughter gives the concentration of the parent. Gamma-rays which have least interference and high relative abundance are selected. Accordingly, 1.76 MeV gammas from ^{214}Bi ($t_{½}$=19.7 min) of the Radium group (Ra-group) of the U-Series is selected for the estimation of $Ra(eU_3O_8)$ and 2.62 MeV gamma-rays emitted by ^{208}Tl ($t_{½}$=3.08 min) of the Th-Series is counted for estimation of ThO_2. Gamma-rays of energy 1.46 MeV emitted by ^{40}K(t½=1.33×109 y) are counted for estimating concentration of K.

11 Instrumentation

HEGS system comprises of a 5″×4″ NaI(Tl) crystal optically coupled to PMT. Signals from PMT is fed directly to the dMCA-pro Digital Signal Processing (DSP) based Multi-Channel Analyzer (MCA) (Target, Germany). This digitizes the signals and stores them in the desired format (counts vs channel number) by the inbuilt software (winTMCA32). The complete assembly is enclosed in a 4″ thick lead chamber to reduce background. Energy calibration of the system is carried out using ^{137}Cs (662 keV) and ^{60}Co (1173 keV and 1332 keV). Standard Reference Materials

(SRMs) RGU-1 (U-400 ppm; U_3O_8-472 ppm), RGTh-1(Th-800 ppm; ThO_2-910 ppm), and RGK-1 (K-44.8%) procured from International Atomic Energy Agency (IAEA), Vienna are used to calculated stripping factors (α, β, γ and a). The SRMs are also used to find out sensitivities of the respective channels. Being a comparative method, standards and samples crushed to same mesh size (-200) are taken in plastic containers of same shape and size in order to maintain the geometry of the measurement. Airtight containers are used to avoid escape of gaseous member of U-series, radon (^{222}Rn) ($t_{1/2}$=3.825 d) and are kept for a month for attainment of equilibrium of ^{222}Rn and its daughter products with its parent Radium (^{226}Ra), as estimation of Ra(eU_3O_8) is based on the counting of 1.76 MeV gamma-rays from ^{214}Bi which comes after ^{222}Rn in the U-series. Considering the stripping factors, sensitivities of the respective channels and the background observed in each channel, the minimum reportable grades are found to be 2 ppm of eU_3O_8, 10 ppm of ThO_2, 5 ppm of Ra(eU_3O_8) and 0.5% of K at 1σ error level of 10%.

12 Results

Tables 1 and 2 list the gamma ray spectrometry results of samples collected from Singhbhum shear zone. Samples in table 1 are taken from the drilled borehole core samples. Boreholes are drilled in different phases of Uranium exploration and it is important to discriminate between the Uraniferous and Thoriferous values in the borehole for planning of exploration program. Gamma ray spectrometry plays vital role in this phase as it can provide fast results in a non-destructive way.

Similarly, Table 2 lists the gamma ray spectrometry of surface grab samples collected during the Reconnoitary survey phase of exploration. The importance of the result lies in the fact that these values can be used to look for any radiometric anomaly in the study area that may be helpful in carrying out detailed survey assisted with borehole drilling.

Uranium exploration program of AMD assisted with gamma ray spectrometry has resulted in establishing various uranium deposits in Singhbhum Shear Zone, like Jaduguda, Bagjata, Bhatin, Banduhurang, Kudada, *etc*. to name a few.

13 Recent Developments and Future Prospects

This section presents a brief overview of the recent developments and future prospects of gamma ray spectrometry for uranium exploration.

Advanced Detector Materials: Researchers have been investigating and developing new detector materials with improved properties, such as higher energy resolution and reduced background noise. For example, advancements in high-purity germanium (HPGe) detector technology have led to improved energy resolution, enhancing the ability to resolve closely spaced gamma ray peaks and identify isotopes more accurately[88-90].

Compton Imaging: Compton imaging is a technique that allows for the reconstruction of the

Table 1 — Gamma Spectrometry results of samplesfrom SSZ (values in %)

Sample Name.	eU3O8	ThO2	RaeU3O8
SSZ-01	0.027	<0.005	0.027
SSZ-02	0.045	<0.005	0.043
SSZ-03	0.011	<0.005	0.010
SSZ-04	0.010	<0.005	0.010
SSZ-05	0.012	<0.005	0.012
SSZ-06	0.013	<0.005	0.013
SSZ-07	0.013	<0.005	0.013
SSZ-08	0.010	<0.005	0.010
SSZ-09	0.089	<0.005	0.087
SSZ-10	0.011	<0.005	0.010
SSZ-11	0.021	<0.005	0.020
SSZ-12	0.010	<0.005	0.010
SSZ-13	0.050	<0.005	0.050
SSZ-14	0.014	<0.005	0.013
SSZ-15	0.012	<0.005	0.012
SSZ-16	0.037	<0.005	0.037
SSZ-17	0.090	0.005	0.087
SSZ-18	0.010	<0.005	0.009
SSZ-19	0.017	<0.005	0.017
SSZ-20	0.019	<0.005	0.019
SSZ-21	0.057	<0.005	0.055
SSZ-22	0.018	<0.005	0.017
SSZ-23	0.096	<0.005	0.095
SSZ-24	0.081	<0.005	0.080
SSZ-25	0.030	<0.005	0.030

Table 2 — Gamma Spectrometry results of samplesfrom SSZ (values in ppm)

S. No	Sample Name	eU3O8	ThO2	RaeU3O8	K
			ppm		%
1	SSZ-26	26	29	<5	3.8
2	SSZ-27	38	31	15	3.0
3	SSZ-28	84	50	48	5.6
4	SSZ-29	13	22	<5	<0.5
5	SSZ-30	25	26	13	<0.5
6	SSZ-31	90	35	64	4.5
7	SSZ-32	85	21	67	3.7
8	SSZ-33	2	<10	<5	<0.5
9	SSZ-34	32	64	<5	<0.5
10	SSZ-35	45	40	13	5.4

direction and energy of gamma rays emitted from radioactive sources. It provides a three-dimensional visualization of gamma ray sources and has the potential to improve spatial resolution in gamma ray spectrometry applications[91].

Spectral Deconvolution and Overlapping Peaks: Improving data analysis methods for spectral deconvolution is crucial to resolving overlapping peaks from different radioactive isotopes. Research can focus on developing advanced algorithms and statistical techniques for robustly identifying individual gamma ray peaks and quantifying their contributions[92,93,94].

Gamma Ray Spectrometer Calibration and Uncertainty: Research can be directed towards improving gamma ray spectrometer calibration methods and quantifying uncertainty in measurements. Accurate calibration is essential for reliable data interpretation, and understanding measurement uncertainties will provide better confidence in exploration results[95].

Integrating gamma ray spectrometry with Artificial Intelligence and Machine Learning: Data analysis techniques based on artificial intelligence (AI) and machine learning have been explored to automate and enhance the analysis of gamma ray spectra. AI algorithms can assist in peak fitting, isotope identification, and background subtraction making data processing more efficient and accurate[96,97].

Integration with Other Geophysical Techniques: Investigating ways to integrate gamma ray spectrometry data with other geophysical methods, such as magnetic and electromagnetic surveys, can lead to more comprehensive exploration strategies. Combining data from multiple techniques can improve target identification and reduce ambiguity in complex geological settings[98].

Portable and UAV-Based Systems: Advancements in sensor miniaturization and integration have led to the development of portable gamma ray spectrometers and unmanned aerial vehicle (UAV) or drone-based systems. These advancements enable more flexible and efficient data acquisition in remote or challenging terrains[99].

By focusing on these research areas, the application of gamma ray spectrometry in uranium exploration can be further enhanced, leading to more efficient and effective exploration strategies and improved resource assessment. It becomes important to note that the field of gamma ray spectrometry continues to evolve and ongoing R & D efforts are likely to bring further advancements and improvements in technology and data analysis techniques. Researchers and practitioners in the field are continuously exploring innovative ways to enhance the capabilities and applications of gamma ray spectrometry for use in uranium exploration.

14 Conclusion

Gamma ray spectrometry is a powerful and essential tool in uranium exploration, offering significant contributions to uranium resource assessment and sustainable energy production. Its significance lies in its ability to detect and quantify gamma rays emitted by radioactive isotopes, including uranium and its decay products. Gamma ray spectrometry provides precise identification of uranium isotopes based on their characteristic gamma ray energies. The technique also helps in exploration by rapidly covering large areas and identifying anomalous radioactivity that may indicate uranium mineralization. This helps geologists to prioritize exploration targets which in turn reduces exploration time and costs. It also becomes possible to distinguish uranium mineralization from other radioactive elements and assess the potential of uranium resources more accurately. This allows for reliable resource estimation. Spectrometric data assists in determining the size, grade, and distribution of uranium deposits which is important for assessing the economic viability.

Ongoing advancements in gamma ray spectrometry technology and data analysis techniques are continuously improving the accuracy and efficiency of uranium exploration. New developments, such as AI-assisted data analysis and UAV-based surveys, contribute to sustainable exploration practices. As the world transitions towards cleaner and sustainable energy sources, gamma ray spectrometry's role in identifying and assessing uranium resources becomes even more crucial.

In conclusion, gamma ray spectrometry plays a central role in uranium exploration by precisely identifying uranium and associated radionuclides, estimating resources and contributing to sustainable energy production. Its efficient data acquisition and environmental monitoring capabilities make it an invaluable tool for responsible and sustainable uranium resource management, supporting the global transition to cleaner energy solutions.

Acknowledgement

Authors are thankful to Director, Atomic Minerals Directorate for Exploration and Research, DAE for necessary support and encouragement.

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