

Editorial Office:

Dr. Sabrina Turba

Wiley-VCH Verlag GmbH & Co. KGaA

Boschstr. 12, 69469 Weinheim, Germany

phone: +49-(0)6201-606-574

fax: +49-(0)6201-606-331

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Analysis of Ores and its Purified Constituents by γ -Spectrometry with Calculation of Uranium Isotopic Atom, Mass, and Activity Ratios

Mohamed A. E. Abdel-Rahman,^{*,[a]} Hoda Abu Shady,^[b] and Sayed A. El-Mongy^[c]

Abstract. The physical verifications, that the national and international inspectors carry out in order to perform a credibility control, often consist in the measurement of physical quantities, related to the declared nuclear material properties, by Non-destructive Assay (NDA). Analysis of ores and its purified constituent's samples has been carried out in this work using non-destructive gamma assay technique. The spectrometer based on HpGe detector and its electronics was calibrated using standard IAEA multi-lines gamma sources. The efficiency calibration curve was plotted for broad gamma energies; 50–2600 keV. The gamma transition of ^{235}U (143.7, 163.3, 185.7, and 205.3 keV) and ^{238}U (63, 766.3, and 1001.03 keV) were used for qualitative and quantitative assay of the samples. The specific activities of the samples

were calculated based on the determined efficiency, branching ratio (emission probability per disintegration), mass of sample and count rate of the characteristics gamma transitions of uranium isotopes at fixed geometrical conditions. A simplified equation was derived for calculation of ^{235}U atom ratios. The results of calculation show natural origin of the analyzed samples; around 0.72%. Where, the anthropogenic ^{236}U was not detected at all in the spectra. The uranium activity ratios ($^{235}\text{U}/^{238}\text{U}$) were calculated based on the measured activity. The uranium isotopic mass and total uranium content of the investigated samples were also calculated. The results obtained are depicted, tabulated and discussed in comparison with recent published national and international works.

1 Introduction

Assay of ores, treated products, nuclear materials, and environmental samples are of vital objective for qualitative and quantitative analysis. Signature radionuclides are currently used to track origin of samples. Quality of the analytical techniques is a crucial parameter for quality of results. Generally, the quality assurance (QA) require various quality control (QC) measurements to be performed for analytical method such as; calibration, validation, quality control, and proficiency testing.^[1] The advantage of NDA measurements is the possibility to perform the necessary verification, without excessive interference with the operator's industrial process and without alteration of the nuclear material under assay.^[2–4]

The concentrations of uranium vary according to the substances it is mixed with and according to the places, where it is found. For example, when uranium is mixed with granite that covers 60% of the Earth's crust, there are approximately four parts of uranium per million, i.e. 999,996 parts of granite and four parts of uranium.^[5] High-grade ore body ca. 20%U (200,000 ppm U), Low-grade ore body ca. 0.1%U (1,000 ppm U), Granite 4 ppm U, sedimentary rock 2 ppm U, average in Earth's continental crust 2.8 ppm U, seawater

0.003 ppm U. Concentrations of uranium that are economic to mine are considered ore. Uranium is present in low concentrations in many rocks and bodies of water, but extraction is only economically viable from richer deposits. The decision to mine is a function of many factors including extraction method, market prices, and social and environmental considerations. Uranium deposits are found all over the world. The largest deposits of uranium are found in Australia, Kazakhstan and Canada. High-grade deposits are only found in Canada.

This study is mainly focus on assay and calculation of uranium natural enrichment percentage, isotopic activity ratio, mass and total uranium content of ores and its treated constituents samples (starting point of the nuclear fuel cycle) using NDA approach for verification and quantification purposes.

2 Experimental Section

2.1 Leaching Process of Ore Samples

Different ores samples from Gattar mountain were collected and prepared for leaching of yellow cake. Details of the leaching process stages are given in recent work with EDX analysis of the samples.^[6]

2.2 Preparation for γ -Spectrometry Assay

The collected ores and purified constituents samples were dried in a drying oven at 90 °C overnight. The samples were crushed and sieved using a 2 mm mesh for homogenization of grain size. Each sample was then weighed for moister determination and transferred to small plastic Marinilli and sealed. The samples were measured for 24 h. The dead time correction was also considered.

* Dr. M. A. E. Abdel-Rahman
E-Mail: mabdelrahman@mtc.edu.eg

[a] Nuclear Engineering Department
Military Technical College
Kobry El-Kobbah, Cairo, Egypt

[b] Physics Department
Faculty of Science
Cairo University
Cairo, Egypt

[c] Nuclear and Radiological Regularity Authority (ENRRA)
Nasr city, Cairo, Egypt

2.3 γ -Spectrometer Set-up

The system used consists of a coaxial hyper pure germanium (HpGe) detector of CANBERRA with relative efficiency of about 50%. Its energy resolution is 1.95 keV at 1332 keV of ^{60}Co source. The detector high voltage (H.V.) is 3.3 kV. It is connected to a Canberra DSA-1000 digital signal analyzer (MCA). The HpGe crystal was fully immersed in liquid nitrogen (LN) through its cryostat for cooling ($-200\text{ }^{\circ}\text{C}$) to reduce noises/leakage current. The HpGe detector was shielded to avoid the surrounding background effect (such as natural radioactivity in building materials, cosmic rays and uranium decay series) by 10 cm thick lead shield lined with Cu and Cd for X-ray. General layout of γ -spectrometer with its electronics can be shown in Figure 1.

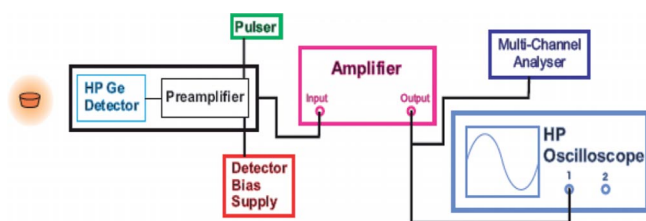


Figure 1. Lay-out of γ -spectrometer with its electronics.

Finally, the obtained spectra due to the samples were automatically analyzed using γ -spectroscopy Genie-2000 software of Canberra products.

2.4 γ -Spectrometer Energy and Efficiency Calibration

Before the spectra analysis, both the energy and efficiency calibration of the measuring system were performed by using a standard IAEA sources (Eckert & Ziegler Analytics (EZA) isotopes product model; S-14 (^{234}U , ^{235}U and ^{238}U), S-16 (^{241}Am , ^{109}Cd , ^{57}Co , ^{139}Ce , ^{203}Hg , ^{113}Sn , ^{137}Cs , ^{88}Y , and ^{60}Co) and S-27 (^{154}Eu , ^{155}Eu , and ^{125}Sb). They have well-known activities that used for verification and validation of calibration results (Table 1). The spectra of all the samples and standard sources were measured in the same conditions and at the same geometry as the background counting.

In this study, both energy and efficiency calibration of the HpGe system were performed firstly to ensure the accuracy of the detector and

consequently for spectrum analysis. By using abovementioned standard sources with known γ -ray transitions and their corresponding counts, a linear relationship between channel number and energy was plotted. This relationship was deduced by the following linear Equation (1):

$$\text{Energy (keV)} = 0.439 + 0.385 \times (\text{ch.}) + 3.653 \times 10^{-8} \times (\text{ch.})^2 \quad (1)$$

The absolute photo-peak efficiency of the HpGe detector, which depends on the source-detector geometry and gamma energy, was performed according to the following Equation (2):

$$\varepsilon_{\text{abs}} = (C_i/N_\gamma) \times 100\% \quad (2)$$

where C_i is the total number of count recorded per unit time and N_γ is the number of gamma quanta emitted by the source per unit time and can be calculated by Equation (3):

$$N_\gamma = D_s I_\gamma(E_\gamma) \quad (3)$$

where D_s is the certified activity or the disintegration rate of the source. $I_\gamma(E_\gamma)$ is the branching ratio or the emission probability per disintegration. The absolute efficiency at different energies was investigated and estimated at 7 cm source-to-detector distance along the detector axis by using standard IAEA sources. The efficiency curve of the detector vs. different photo-peak energies was plotted in this work and similar one has been published in a recent work.^[7] In general, the efficiency curve shows two regions of different behavior according to attenuation and absorption of energy within the matrix of the container. The first region at low energies, from 50 to 186 keV, where the efficiency increases rapidly with increasing the energy until reach the maximum value at the terminal of this range (ca. 186 keV). In contrast, the second region, beyond this range the efficiency value decreases exponentially with increasing the energy as is shown in Figure 2.

2.5 Spectra Analysis and Specific Activity Calculations

The characteristics uranium photo-peaks of each spectrum were identified by matching their centroid energies with the energy transitions of the built in reference nuclides library. The γ -transitions emitted from the samples lie in a wide range of energies; about 50 keV to 2.6 MeV, covering the naturally occurring radioactive materials (^{238}U , ^{235}U , ^{232}Th decay series and ^{40}K). The specific activity of ^{238}U in the samples was quantified using the γ -lines of its daughters: $^{234\text{m}}\text{Pa}$ (1001.03 and 766.36 keV) and ^{234}Th (63.29 keV). While, the γ -energies of the

Table 1. Standard IAEA radionuclide sources used for calibrations.

Standard source	Isotope	Half-life /d	Activity /KBq	Reference date
S-14	^{234}U	8.967×10^7	12.52	9/6/2010
	^{235}U	2.571×10^{11}	0.588	
	^{238}U	1.632×10^{12}	12.78	
S-16	^{241}Am	1.58×10^5	1.981	1/4/2011
	^{109}Cd	4.626×10^2	2.734	
	^{57}Co	2.718×10^2	1.475	
	^{139}Ce	1.376×10^2	2.055	
	^{203}Hg	4.661×10^1	4.778	
	^{113}Sn	1.151×10^2	2.866	
	^{137}Cs	1.098×10^4	1.824	
	^{88}Y	1.066×10^2	6.997	
	^{60}Co	1.925×10^3	3.490	
S-27	^{154}Eu	3.139×10^3	42.30	19/9/2012
	^{155}Eu	1.736×10^3	20.50	
	^{125}Sb	1.008×10^3	39.88	

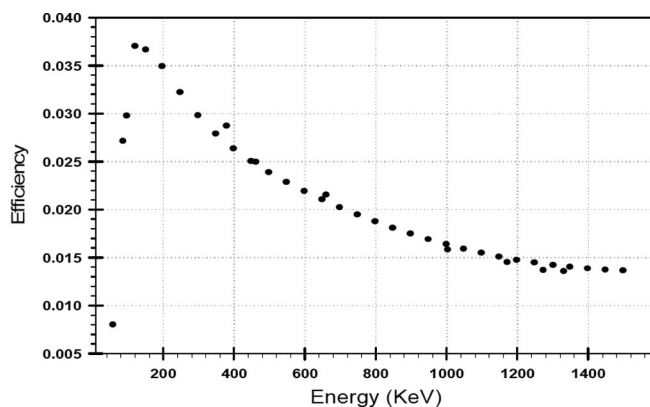


Figure 2. Polynomial fitted efficiency calibration curve of the γ -spectrometer.

^{235}U (143.7, 163.3, 185.7 and 205.3 keV) were identified and used for activity calculations. Both ^{40}K (1460.83 keV) and ^{232}Th series (583, 911, 968 keV) were observed in the analyzed samples spectra before treatment. Nevertheless, their activities were not considered in this study.

The samples specific activity (A) analysis given in $\text{Bq}\cdot\text{kg}^{-1}$ of ^{238}U and ^{235}U (A_{238} and A_{235}) are estimated using the corresponding count rate of the γ -lines by substituting in Equation (4):

$$A = \frac{C_{\text{net}}}{\varepsilon_{\text{abs}} \cdot I_{\gamma}(E_{\gamma}) \cdot T \cdot M} \quad (4)$$

where C_{net} is the net number of counts in a given photo-peak region (ROI) subtracting the background peak counts. M is the mass of the measured sample (in kg). ε_{abs} is the absolute detector efficiency at specific energy (E_{γ}). T is the counting time at the same fixed geometrical conditions.

The anthropogenic ^{236}U , $^{235}\text{U}(\text{n}, \gamma)^{236}\text{U}$, of 2.35×10^7 years half-life time was searched for in the spectra of the analyzed samples. As a matter of fact, the ^{236}U has also $<10^{-11}$ natural abundance.

3 Results and Discussion

3.1 Results of Uranium Specific Activity Assay of the Samples

The measured specific activity in $\text{Bq}\cdot\text{kg}^{-1}$ of ^{235}U and ^{238}U before (ores) and after treatment are summarized in Table 2. The activity values for the ores samples; before purification, are in the range from 0.35×10^3 to $2.84 \times 10^3 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{235}U and from 0.798×10^4 to $6.12 \times 10^4 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{238}U . After purification, the values are in the range from 0.67×10^3 to $3.58 \times 10^3 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{235}U and from 1.36×10^4 to $7.1 \times 10^4 \text{ Bq}\cdot\text{kg}^{-1}$ for ^{238}U , respectively. The analyzed purified yellow cake ore samples show higher specific activity after treatment in comparison to before purification. This is mainly attributed to the removing of impurities, which led to concentration of uranium in the treated samples.^[6]

3.2 $^{235}\text{U}/^{238}\text{U}$ Activity Ratios Calculations

The activity ratios of uranium were found by dividing the average specific activity of the gamma lines from ^{235}U (143.7, 163.3, 185.7, and 205.3 keV) to the activity of ^{238}U (1001.3 keV from $^{234\text{m}}\text{Pa}$, the daughter of ^{238}U). It was found that the average activity ratio values of the ores samples before purification are 0.045, 0.043, and 0.046, respectively. After treatment, these values are 0.050, 0.049, and 0.050, respectively.^[6] These values are in the limit of the natural reference $^{235}\text{U}/^{238}\text{U}$ activity ratio value 0.046.

3.3 ^{235}U Atom Ratio Calculations by Derivation an Equation

The activity ratio of $^{235}\text{U}/^{238}\text{U}$ as measured by γ -spectrometer and calculated by Equation (4). This equation can be rewritten as follow [Equation (5)]:

$$A_{235} = \frac{C_{235}}{\varepsilon_{235} \cdot I_{\gamma}(E_{\gamma})_{235}}, \quad A_{238} = \frac{C_{238}}{\varepsilon_{238} \cdot I_{\gamma}(E_{\gamma})_{238}} \quad (5)$$

The number of atoms in both ^{235}U (N_{235}) and ^{238}U (N_{238}) can also be expressed as Equation (6):

$$N_{235} = \frac{A_{235}}{\lambda_{235}} \Rightarrow N_{235} = \frac{C_{235}}{\varepsilon_{235} \cdot I_{\gamma}(E_{\gamma})_{235}} \cdot \frac{1}{\lambda_{235}} = \frac{C_{235}}{\varepsilon_{235} \cdot I_{\gamma}(E_{\gamma})_{235}} \cdot \frac{(\tau_{1/2})_{235}}{\ln 2}$$

$$N_{238} = \frac{A_{238}}{\lambda_{238}} \Rightarrow N_{238} = \frac{C_{238}}{\varepsilon_{238} \cdot I_{\gamma}(E_{\gamma})_{238}} \cdot \frac{1}{\lambda_{238}} = \frac{C_{238}}{\varepsilon_{238} \cdot I_{\gamma}(E_{\gamma})_{238}} \cdot \frac{(\tau_{1/2})_{238}}{\ln 2} \quad (6)$$

where λ_{235} and λ_{238} are the decay constant (s^{-1}) of ^{235}U and ^{238}U , respectively. $(\tau_{1/2})_{235}$ and $(\tau_{1/2})_{238}$ are the half-life times of ^{235}U and ^{238}U in seconds, respectively. The difference in intensity of ^{235}U and ^{238}U gamma emission energies is based on the difference in the corresponding number of atoms of ^{235}U and ^{238}U in the samples. The natural enrichment; atom ratio percentage ($\%E$), can be estimated in samples according to the following Equation (7)^[3]:

$$\%E = \left(\frac{N_{235}}{N_{235} + N_{238}} \right) \times 100 \quad (7)$$

By substituting Equation (6) in Equation (7), one can find:

$$E \% = \left(\frac{\frac{C_{235}}{\varepsilon_{235} \cdot I_{\gamma}(E_{\gamma})_{235} \cdot \lambda_{235}}}{\frac{C_{235}}{\varepsilon_{235} \cdot I_{\gamma}(E_{\gamma})_{235} \cdot \lambda_{235}} + \frac{C_{238}}{\varepsilon_{238} \cdot I_{\gamma}(E_{\gamma})_{238} \cdot \lambda_{238}}} \right) \times 100$$

Finally, it can be written as Equation (8):

$$E \% = \left(\frac{1}{1 + \left(\frac{C_{238}}{C_{235}} \right) \cdot \left(\frac{\varepsilon_{235}}{\varepsilon_{238}} \right) \cdot \left(\frac{I_{\gamma}(E_{\gamma})_{235}}{I_{\gamma}(E_{\gamma})_{238}} \right) \cdot \left(\frac{\lambda_{235}}{\lambda_{238}} \right)} \right) \times 100 \quad (8)$$

Table 3 shows the results of both the calculated atom density; for ^{235}U and ^{238}U , and also the natural uranium enrichment percentage with its uncertainties for the analyzed samples before and after purification. The natural enrichment percentages of the samples were calculated based on the

Table 2. The specific activity of the analyzed samples before and after treatment.

Radio-isotopes	En-ergy / keV	Activity concentration /Bq·kg ⁻¹											
		Sample-1 before purification		Sample-2 after purification		Sample-3 before purification		Sample-4 after purification		Sample-5 before purification		Sample-6 after purification	
		Ac.	Av. ±SD	Ac.	Av. ±SD	Ac.	Av. ±SD	Ac.	Av. ±SD	Ac.	Av. ±SD	Ac.	Av. ±SD
U-235	143.76	330.4	0.351E+3 ±4.9%	647.0	0.67E+3 ±3.4%	2.20E+3	2.17E+3 ±5.2%	3.41E+3	3.54E+3 ±3.3%	2.78E+3	2.84E+3 ±2.3%	3.47E+3	3.58E+3 ±3.1%
	163.33	359.2		678.8		2.31E+3		3.63E+3		2.85E+3		3.59E+3	
	185.71	346.0		687.5		2.23E+3		3.57E+3		2.86E+3		3.62E+3	
	205.31	370.6		701.2		2.08E+3		3.59E+3		2.91E+3		3.70E+3	
U-238	1001.03	7886.0	0.798E+4 ±1.8%	13675.	1.36E+4 ±1.8%	5.14E+4	5.01E+4 ±3.6%	7.24E+4	7.08E+4 ±3%	6.24E+4	6.12E+4 ±2.9%	7.22E+4	7.1E+4 ±2.4%
(Pa-234m)	766.36	8086.6		13648.		4.89E+4		6.94E+4		6.00E+4		6.98E+4	

Table 3. The atom density and natural enrichment percentage of the analyzed samples.

Radio-isotopes	Energy / keV	Half life time $\tau_{1/2}$	Ores before purification									
			Sample-1		Sample-3		Sample-5					
			Atom density N = A / λ	Natural enrichment, E %	Atom density N = A / λ	Natural enrichment, E %	Atom density N = A / λ	Natural enrichment, E %				
U-235	143.76	7×10^8	1.05E+19	0.647	0.688 ±0.033	7.011E+19	0.661	0.661 ± 0.034	8.84E+19	0.686	0.703 ± 0.016	
	163.33	7×10^8	1.14E+19	0.703		7.365E+19	0.694		9.07E+19	0.704		
	185.71	7×10^8	1.1E+19	0.677		7.107E+19	0.671		9.11E+19	0.707		
	205.31	7×10^8	1.18E+19	0.725		6.638E+19	0.626		9.26E+19	0.718		
Pa-234m	1001.03	4.5×10^9	1.61E+21	1.61E+21	–	1.053E+22	1.05E+22	–	1.28E+22	1.28E+22	–	
	766.36	4.5×10^9	1.66E+21			8.573E+21			1.23E+22			
Radio-isotopes	Energy / keV	Half life time, $\tau_{1/2}$	Product after purification									
			Sample-2		Sample-4		Sample-6					
			Atom density N = A / λ	Natural enrichment, E %	Atom density N = A / λ	Natural enrichment, E %	Atom density N = A / λ	Natural enrichment, E %				
U-235	143.76	7×10^8	2.06E+19	0.730	0.766 ± 0.025	1.08E+20	0.726	0.755 ± 0.024	1.10E+20	0.742	0.766 ± 0.023	
	163.33	7×10^8	2.16E+19	0.766		1.16E+20	0.773		1.14E+20	0.767		
	185.71	7×10^8	2.19E+19	0.775		1.14E+20	0.761		1.15E+20	0.774		
	205.31	7×10^8	2.23E+19	0.791		1.14E+20	0.765		1.17E+20	0.789		
Pa-234m	1001.03	4.5×10^9	2.8E+21	2.8E+21	–	1.48E+22	1.48E+22	–	1.47E+22	1.47E+22	–	
	766.36	4.5×10^9	2.79E+21			1.42E+22			1.42E+22			

above-mentioned four gamma lines of ²³⁵U and the two lines representing ²³⁸U.

The result shows that the natural uranium enrichment values as calculated by Equation (8), before purification, are 0.688 ± 0.033 , 0.661 ± 0.034 and 0.703 ± 0.016 , respectively. After treatment, the values were 0.766 ± 0.025 , 0.755 ± 0.024 and 0.766 ± 0.023 , respectively. These values show a variation in the natural enrichment percentage of the analyzed samples with the average value within the normal signature value 0.72%.^[8,9] This slight variation could be attributed to the change in efficiency of the detector at different gamma transitions of ²³⁵U (143.7, 163.3, 185.7, and 205.3 keV) and ²³⁸U (766 and 1001 keV). The highest difference between the calculated natural %E after purification and the reference value was ca. 6% at the γ -line 205.3 keV. This could be due to the low emission probability at this γ -line, 4.7%. For the other γ -lines,

the variation was found to be in the range from 1 to 4%. Additionally, there was almost no difference between the calculated natural %E even using the gamma lines at 766.3 keV or 1001 keV of ²³⁸U. It was also observed that the calculated values of the analyzed samples are of the same level as in other publication.^[9] These approach allows the natural enrichment calculation without use of standards or without determination of geometry-dependent calibration parameters.^[10]

The artificial ²³⁶U was not identified in the analyzed samples. Generally, and due to the high abundance of uranium in the Earth's crust; ca. 3 ppm, natural U in the environment dilutes anthropogenic uranium (²³⁶U), which can be detected by small variation in the ²³⁵U/²³⁸U ratio (natural value is 0.00725) and the presence of ²³⁶U. To distinguish natural from anthropogenic uranium, ²³⁶U or the isotopic ratio ²³⁶U/²³⁸U is more effective as an indicator than the ²³⁵U/²³⁸U ratio. The deviation

Table 4. The uranium isotope masses and the total uranium content percentage.

Radio-isotopes	Energy / keV	Ores before purification								
		Sample-1		Total U content	Sample-3		Total U content	Sample-5		
		Calculated uranium isotopic mass /g			Calculated uranium isotopic mass /g			Calculated uranium isotopic mass /g		Total U content
U-235	143.76	4.11E-03	4.37E-3 ±0.00022	59.25 %	2.74E-02	2.73E-2 ±0.00141	53.91 %	3.45E-02	3.53E-2 ±0.00081	61.55 %
	163.33	4.47E-03			2.87E-02			3.54E-02		
	185.71	4.30E-03			2.77E-02			3.56E-02		
	205.31	4.61E-03			2.59E-02			3.61E-02		
Pa-234m	1001.03	6.28E-01	6.35E-1 ±0.01129	–	4.09E+00	3.71E+0 ±0.536	–	4.97E+00	4.87E+0 ±0.1394	–
	766.36	6.43E-01			3.33E+00			4.77E+00		
Radio-isotopes	Energy / keV	Product after purification								
		Sample-2		Total U content	Sample-4		Total U content	Sample-6		
		Calculated uranium isotopic mass /g			Calculated uranium isotopic mass /g			Calculated uranium isotopic mass /g		Total U content
U-235	143.76	8.04E-03	8.447E-3 ±0.00029	90.54 %	4.23E-02	4.40E-2 ±0.00146	86.11 %	4.31E-02	4.46E-2 ±0.0014	88.69 %
	163.33	8.44E-03			4.51E-02			4.47E-02		
	185.71	8.55E-03			4.43E-02			4.50E-02		
	205.31	8.72E-03			4.46E-02			4.59E-02		
Pa-234m	1001.03	1.09E+00	1.09E+0 ±0.0015	–	5.76E+00	5.64E+0 ±0.1675	–	5.75E+00	5.65E+0 ±0.135	–
	766.36	1.09E+00			5.52E+00			5.55E+00		

of the $^{235}\text{U}/^{238}\text{U}$ ratio from the natural value cannot always give conclusive information because the ^{235}U enrichment and therefore the $^{235}\text{U}/^{238}\text{U}$ ratio in spent fuel can vary significantly. The advantage of ^{236}U is the large dynamic range between the natural and anthropogenic $^{236}\text{U}/^{238}\text{U}$ isotopic ratio.^[11]

3.4 Results of Uranium Isotopic Mass and Total Uranium Content Calculations

The specific uranium mass of the samples based on the measured prominent gamma signature were employed for the mass estimation of ^{235}U and ^{238}U . The following equation was used for uranium mass calculation [Equation (9)]:

$$m_{235} = \frac{A_{235}}{\lambda_{235}} \cdot \frac{M_{235}}{N_a} \quad \& \quad m_{238} = \frac{A_{238}}{\lambda_{238}} \cdot \frac{M_{238}}{N_a} \quad (9)$$

where m_{235} and m_{238} are the masses of ^{235}U and ^{238}U respectively. M_{235} and M_{238} are the atomic weight of ^{235}U and ^{238}U , respectively. N_a is the Avogadro's number. The total natural uranium content (C_{content}) was estimated by using the ratio between the total uranium mass ($m_{235} + m_{238}$) and the sample mass as given in the following Equation (10):

$$U_{\text{content}} \% = \frac{(m_{235} + m_{238})}{m_{\text{sample}}} \times 100 \quad (10)$$

The uranium isotopic mass, m_{235} and m_{238} , and the total uranium content of the analyzed samples after purification based on the four γ -lines of ^{235}U and representing ^{238}U lines are shown in Table 4.

It was observed as given in Table 4 that the uranium isotopic mass values of the samples after purification are 8.04×10^{-3} ,

8.44×10^{-3} , 8.55×10^{-3} , and 8.72×10^{-3} g, respectively, with average value of $8.44 \times 10^{-3} \pm 0.00029$ g. It was also found as shown in Table 4 that the total uranium content percentages, before purification, are 59.25 %, 53.91 %, and 61.55 % respectively. After purification, these values were calculated and found to be 90.54 %, 86.11 %, and 88.69 %, respectively. Also, it was observed that the total uranium content (in %) based on the γ -line 1001.03 keV representing ^{238}U gave a better result than that obtained from the 766 keV. This could be attributed to the difference of branching ratio and efficiency of these γ -transitions.

4 Conclusions

In this study, an advanced well calibrated non-destructive γ -assay technique based on HpGe detector was precisely used for analysis and verification of ores and the produced constituent samples. The determined specific activities of the analyzed ores samples are of very high levels of uranium. The $^{235}\text{U}/^{238}\text{U}$ activity ratios were calculated and found to be around the natural value 0.046. The atom ratios of ^{235}U (natural uranium enrichment, %E) was estimated by a derived equation and quantified to be within the natural origin and signature, 0.72 %. The artificial ^{236}U was not identified at all in the spectra of the analyzed samples. The total uranium content of 59.2, 53.9, and 61.5 % and 90.5, 86.1, and 88.6 % of the samples were found before and after treatment, respectively. The uranium isotopic mass of the samples was also estimated and found to be of natural origin and limit.

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Keywords: HpGe spectrometer; Ore and purified product activity; ^{235}U / ^{238}U atom ratio; Uranium; U mass ratios

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M. A. E. Abdel-Rahman,* H. Abu Shady,

S. A. El-Mongy 1-7

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