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DETERMINATION OF THE HOMOGENEITY OF THE $^{235}U/^{238}U$ RATIO DISTRIBUTION TO VERIFY SURFACE HOMOGENEITY OF SAMPLES USING ICP-MS

S.N. Afanasiev*, I.O. Afanasieva, S.O. Vanzha, D.V. Kutnii
National Science Center "Kharkiv Institute of Physics and Technology", Kharkiv, Ukraine
****E-mail: afanserg@kipt.kharkov.ua***

The degree of inhomogeneity in the distribution of the $^{235}U/^{238}U$ ratio in a uranium-bearing material can serve as a direct "signature" of the technological process, enabling the identification of its manufacturing method. In this work, the spatial homogeneity of the $^{235}U/^{238}U$ isotope ratio on the surface of uranium-bearing samples – obtained by mechanical and chemical mixing of the starting components – was studied using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). To conduct the study, a series of samples fabricated using different technological processes (mechanical and chemical mixing of identical starting materials) was analyzed. It was established that samples obtained by chemical mixing are characterized by a high degree of homogeneity in the $^{235}U/^{238}U$ distribution, whereas mechanically mixed samples exhibit pronounced spatial heterogeneity, with local deviations reaching the values of the starting materials**.**

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INTRODUCTION

One of the pressing tasks during the investigation of nuclear incidents in the field of nuclear security is the analysis of isotopic, elemental, nuclear-physical, and chemical "signatures" of nuclear or radioactive materials to establish their origin, enrichment or processing history, intended purpose, and distribution pathways [1, 2]. To address these tasks, a separate scientific discipline – nuclear forensics – emerged in the 1990s at the intersection of nuclear physics, analytical chemistry, and forensic science. Specialized laboratories around the world continue to improve both their theoretical and methodological frameworks, as well as the practical application of the acquired knowledge in the investigation of specific incidents [3–5]. To obtain the most comprehensive information about the object of study, a wide range of analytical methods is applied, encompassing both destructive and non-destructive analyses (e.g., HRGS, XRF, XRD [6, 7] and ICP-MS, alpha-spectrometry, analytical chemistry [8]). Even within a single spectrometric method, various measurement procedures are implemented, enabling the acquisition of characteristic parameters that significantly increase the reliability and confidence of nuclear forensic conclusions.

Technological mixtures of uranium-bearing materials represent some of the most complex yet critically important objects of study in the field of nuclear forensics. The relevance of researching these materials is driven by several factors:

- ✓ role in future nuclear energy technologies – they enable the reuse of depleted or reprocessed uranium, reduce the volume of high-level radioactive waste, and increase the efficiency of uranium resource utilization;
- ✓ complexity of identification – the presence of multiple starting components with distinct enrichments, isotopic compositions, and origins creates a complex spectrum of secondary nuclides and fission products, thereby complicating analytical characterization;
- ✓ metrological value – such materials serve as the basis for developing analytical samples (e.g., calibration or reference materials) with specified enrichments for applications in nuclear technologies, analytical chemistry, and export safeguards.

At the same time, the specificity and widespread deployment of such materials in nuclear energy create risks of unauthorized trafficking – such as smuggling attempts, undeclared utilization, or the illicit diversion of both the bulk mixture and its individual components. Therefore, establishing a methodology to identify the "signatures" of mixed samples for origin determination holds high practical value for nuclear forensics, physical protection, and safeguards systems. One such "signature" is the heterogeneity of the $^{235}U/^{238}U$ isotope ratio distribution within a sample, which arises from blending components with distinct enrichments. Characterizing this heterogeneity is impossible using conventional ICP-MS, as this technique requires total sample dissolution, which inherently eradicates any initial spatial heterogeneities in the isotopic distribution. To overcome this limitation, laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) is utilized, enabling direct, localized surface analysis without destructive sample dissolution. By employing the line-scanning technique – involving the continuous translation of the laser beam along a predetermined trajectory – this method allows for the real-time recording of the spatial distribution of $^{235}U^+$ and $^{238}U^+$ ion intensities. In the case of mixed materials exhibiting surface heterogeneity, the laser beam successively ablates individual microparticles or agglomerates of the precursor phases. Consequently, the mass spectrometer registers characteristic fluctuations in the $^{235}U/^{238}U$ isotope ratio between the boundary values inherent to the initial constituents, thereby facilitating the identification of the starting components even within a blended matrix.

This work presents the results of measuring the $^{235}U/^{238}U$ isotope ratio and evaluating its surface homogeneity for mixed uranium-bearing materials produced via mechanical and chemical mixing, using LA-ICP-MS.

EXPERIMENTAL

INSTRUMENTATION

The measurements were performed using a high-resolution inductively coupled plasma mass spectrometer (ELEMENT2 ICP-MS), and an NWR213 laser ablation system was used for sampling and introducing the sample material into the mass spectrometer. The main parameters of the mass spectrometer and the laser system used during the measurements are given in Table and in [9, 10]. The high resolution and high sensitivity, which enable the analysis of elements at extremely low concentrations, are a significant advantage of this mass spectrometer. In this work, a medium-resolution mode was used ($R \approx 4000$, defined at 10% peak height), and the signal instability did not exceed 1% over a 10-min measurement period.

Main parameters of the mass spectrometer and laser system

ICP-MS parameters	
Generator power	1100 W
Reflected power	10 W
ICP working gas	Ar
Coolant gas flow rate	16 ml/min
Auxiliary gas flow rate	0.9 ml/min
Resolution (M/ΔM)	4000
Detection regime	Dual (Analog/Counting)
Laser system parameters	
Laser type	Nd:YAG
Laser wavelength	213 nm
Carrier gas flow rate (He)	450 ml/min
Laser power density	$7 \cdot 10^7$ W/cm^2
Pulse frequency	5 Hz
Pulse duration	3…5 ns
Laser spot size (∅)	3 μm

The analytical signals were the ion current intensities of the $^{235}U^+$ and $^{238}U^+$ isotopes (determined by the area of the corresponding mass peaks) minus the average value of the background signal (blank) measured immediately before the sample analysis. In this work, the uranium isotope intensity ratio $R = I(^{235}U)/I(^{238}U)$ was investigated. To account for the mass discrimination effect (mass bias) caused by the different efficiencies of ion transport and focusing in the extraction zone and mass analyzer, the instrument was pre-calibrated using certified solutions of isotopic reference materials CRM U100 and CRM U200 (in the liquid sample introduction mode). Since the relative mass difference between ^{235}U and ^{238}U is small (≈1.27%), the mass discrimination factor obtained in the liquid mode is metrologically adequate for correcting measurements in the laser ablation mode. The mass discrimination correction factor (β) was calculated as:

$$\beta = \frac{\ln(R_{cert} / R_{cert}^{meas})}{\ln(m(^{235}U) / m(^{238}U))}, \quad (1)$$

where R_{cert} is the certified uranium isotope ratio in CRM U100 and CRM U200, and R_{cert}^{meas} is the measured value during calibration.

The experimentally obtained R value for the studied sample was corrected taking into account β:

$$R_{corr} = R_{meas} \left\{ m(^{235}U) / m(^{238}U) \right\}^{\beta}. \quad (2)$$

In our case, β was taken as the arithmetic mean of the coefficients obtained from the CRM U100 and CRM U200 standards.

MATERIALS

To test the proposed hypothesis regarding the feasibility of identifying the technological process and starting components based on the spatial heterogeneity of the isotopic composition, two uranium-bearing samples with nominal ^{235}U enrichments of 2% ($R_2 = 0.0204$) and 4% ($R_4 = 0.0417$) were synthesized in this work. The samples were formulated according to two distinct technological routes - mechanical and chemical mixing of identical uranium dioxide-based starting materials: depleted uranium with a ^{235}U mass fraction of 0.47% ($R_{DU} = 0.0047$) and low-enriched uranium with a ^{235}U content of 19.78% ($R_{LEU} = 0.2465$). The calculation of the mass ratios of the starting components required to obtain mixtures with a specified final concentration was carried out using the Pearson square method (diagonal mixing scheme):

$$w = \frac{m_1 w_1 + m_2 w_2}{m_1 + m_2}, \quad (3)$$

where w represents the target mass fraction of ^{235}U in the final mixture, while w_1 and w_2 denote the ^{235}U mass fractions of the first and second starting materials, with m_1 and m_2 being their respective masses. The required mass proportions of the starting materials needed to achieve the specified target enrichments were calculated based on the certified specification data of the precursor substances. To obtain the mixture with a nominal enrichment of 2% (R_2), the calculated mass fractions of depleted and low-enriched uranium were 92.07 and 7.93%, respectively; for the 4% enriched sample (R_4), the proportions were 81.71 and 18.29% respectively.

Mechanical mixing was performed using a rotating gravity mixer of the "tumble mixer" type. Before mixing the uranium dioxide powders, preliminary studies were conducted to determine the optimal processing time using model materials BC and Al_2O_3). The blending duration was incrementally increased from 1 to 20 h in 1-hour steps. After each stage, representative samples were collected and examined via optical microscopy to evaluate the homogeneity of the blend. The results demonstrated that satisfactory homogeneity is achieved after 5 h of mixing. Further extending the mixing time up to 20 h yielded negligible improvement in the distribution of the components. Consequently, the actual mixing of the uranium dioxide powders was carried out for 6 h. The enrichment values of the prepared mixtures were monitored using a high-purity germanium (HPGe) semiconductor gamma spectrometer (model GL 0515R)

by measuring the ^{235}U isotope content at five distinct spatial orientations. Four measurements were conducted with the detector positioned opposite the side surface of the container holding the uranium dioxide powder mixture; each subsequent measurement involved rotating the container by 90° relative to the detector-to-sample axis. The fifth measurement of the ^{235}U content was performed with the detector facing the end face surface of the container. Spectral processing and the calculation of ^{235}U abundance were carried out using the MGAU software. The results showed good agreement within the uncertainty limits across all five measurement positions. The average enrichment values determined from these configurations were (2.162 ± 0.092) and (4.064 ± 0.131) % for the first and second mixtures, respectively.

For chemical mixing, the same starting materials were used as for the mechanical process. Accurately weighed portions of the precursor powders, combined in the calculated ratio to achieve the target ^{235}U enrichment, were transferred into a pre-prepared flask. The mixture was dissolved in a calculated volume of concentrated nitric acid to ensure the complete dissolution of uranium as uranyl nitrate. Co-precipitation was then induced using an aqueous ammonia solution as the precipitant until a neutral pH of 7 was reached, which was monitored with pH indicator strips. The resulting precipitate was collected via filtration on ashless filter paper, transferred into a crucible, and dried in an oven at 40…60 °C to a constant mass**.** Next, the crucible containing the dry precipitate and filter was placed in a muffle furnace for gradual heating and calcination within a temperature range of 950…1000 °C for 10…15 min until complete ashing of the filter was achieved. Completion of the thermal decomposition reaction was similarly verified by ensuring a constant residual mass. The isotopic composition of these samples was verified using a gamma spectrometer equipped with a planar BEGe 3830 HPGe detector, with enrichment calculated via the MGAU software. The resulting enrichment values were determined to be (2.032 ± 0.012) and (4.045 ± 0.021) %, respectively.

It should be noted that the enrichment values determined by high-resolution gamma spectrometry (HRGS) are averaged (integrated) over the entire surface and volume of the measured sample.

To confirm the completeness of chemical transformations during chemical mixing and to precisely identify the phase composition of the obtained materials, X-ray diffraction (XRD) phase analysis was performed. The measurements were carried out on a DRON-2.0 X-ray diffractometer using monochromated Cu-K_α radiation with a selective Ni filter. The diffracted radiation was recorded using a scintillation detector. Qualitative phase analysis was performed by comparing the obtained diffraction patterns with the ICDD PDF-2 international crystallographic database. The diffraction patterns of the studied samples are shown in Fig. 1.

The powders obtained by mechanical mixing are single-phase and consist of uranium oxide UO_2 (fluorite structure type, cubic crystal system, space group № 225). The crystal lattice parameter of the uranium oxide UO_2 in both samples is identical within the measurement error and is $a = (5.459 \pm 1 \cdot 10^{-3})$Å and $a = (5.458 \pm 1 \cdot 10^{-3})$Å, respectively.

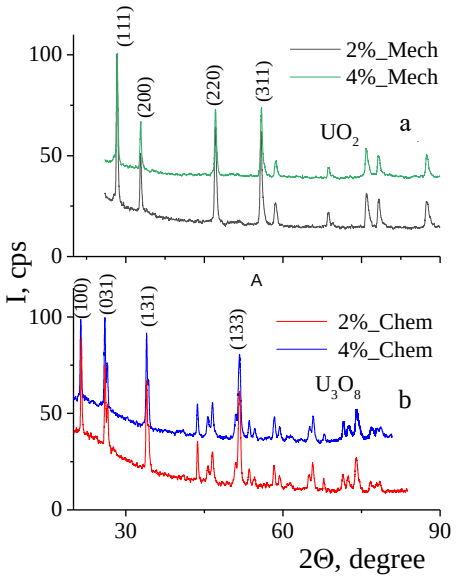


Fig. 1. Diffractograms of mixed samples: a – mechanical mixing (Mech), b – chemical mixing (Chem). Explanation in the text

The samples obtained by chemical mixing followed by annealing are also single-phase, but consist of triuranium octoxide α-U_3O_8 (orthorhombic crystal system, space group № 38). The calculated lattice parameters for α-U_3O_8 are: a = 4.145Å, b = 11.916Å, c = 6.716Å. The absence of reflections from extraneous compounds indicates the complete occurrence of phase transformations during chemical mixing and confirms the high-purity single-phase state of all manufactured materials.

PROCEDURE

The samples were prepared for analysis by compacting the powders into pellets using a hydraulic press with a maximum load capacity of 200 kN. Binder-free pressing was performed at a compaction pressure of 35 kN/cm², yielding mechanically stable cylindrical pellets with a height of 3 mm and a diameter of 8 mm.

The LA-ICP-MS analytical procedure was implemented as follows: three scanning zones were selected on the surface of each pellet, arranged symmetrically at a distance of 3 mm from the center (forming vertices of an equilateral triangle). The laser ablation parameters were configured as follows: a spot diameter of 3 mm, a pulse repetition rate of 5 Hz, and a pulse energy of 0.13 mJ. The length of each analyzed track was approximately 125 μm. Since the laser spot diameter exceeded the translation step size, measurements were conducted in an ablation zone overlap mode (spatial oversampling) to ensure continuous recording of isotopic ratio variations along the profile, thereby enabling clear resolution of the boundaries between micro-volumes of distinct isotopic compositions.

Fig. 2 shows micrographs of the analyzed sample surfaces: on the left is the result of mechanical mixing, and on the right is that of chemical mixing, with an

identical enrichment of 2%. A solid yellow line, 125 μm in length (corresponding to 250 scan steps), indicates the scan trajectory for one of the three analytical positions (1, 2, 3).

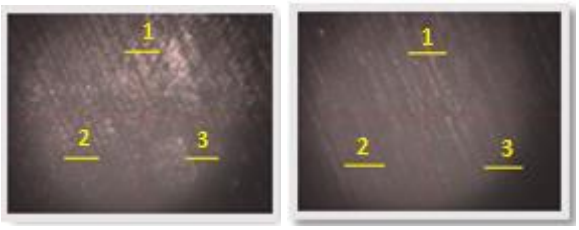


Fig. 2. Surface morphology and laser scan trajectory (yellow line) for 2 %-enriched samples obtained by mechanical (left) and chemical (right) mixing

Scanning at all three selected positions was carried out sequentially under identical measurement conditions – first for the mechanically mixed samples and then for the chemically prepared samples.

RESULTS AND DISCUSSION

Fig. 3 shows the ^{235}U content distribution in three positions for samples with nominal enrichments of 2 and 4% obtained by mechanical (Mech) and chemical (Chem) methods.

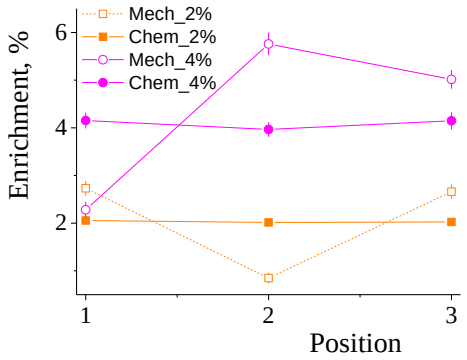


Fig. 3. Dependence of enrichment on measurement position for mechanical (Mech) and chemical (Chem) mixing

As can be seen from the figure, a high spatial homogeneity of the isotopic composition is observed for the samples of the chemical series. The enrichment values in all three positions practically coincide within the measurement error and correspond to the calculated values. The average values across the three positions are (2.031 ± 0.041) and (4.063 ± 0.062)%, which agree within the error limits with the obtained integral gamma-spectrometry values (2.032 and 4.045%).

In contrast, for the samples of the mechanical series, a spatial heterogeneity of the ^{235}U content between different positions is clearly observed for both the 2 and 4% samples. In addition, the spread of values is significantly larger than that for the chemical precipitation samples. Averaging the results across the three positions yields values of (2.082 ± 0.621) and (4.253 ± 1.152)%, which in terms of their mean values are close to the gamma spectrometry data (2.16 and 4.06 %).

Based on the obtained results, it can be concluded that localized isotopic analysis across various surface regions using LA-ICP-MS enables the differentiation of material manufacturing technologies – specifically, mechanical versus chemical mixing. For the chemically homogenized samples, the enrichment values across all analyzed positions remain identical within the experimental uncertainty margins. Conversely, the mechanically mixed samples exhibit significant local fluctuations, which can be defined as a distinctive "signature" of mechanical blending.

It should be emphasized that the data presented in Fig. 3 are also to some extent integral, since each point on the graph is the result of statistical averaging along a solid line 125 μm in length over all 250 scan steps.

The results presented in Fig. 3 prompt a detailed analysis of the enrichment distribution across each of the 250 data points for all three positions of every sample.

Fig. 4 shows the distributions of the $^{235}U/^{238}U$ isotopic ratio as a function of scan time (250 measurement points with a dwell time of 0.6 s per point) for the 2 %-enriched samples. The plots for the mechanical mixture (Mech) are presented on the left, and those for the chemical mixture (Chem) on the right. The line numbering corresponds to the analytical positions (1, 2, 3) shown in Figs. 2 and 3.

The horizontal solid line indicates the calculated theoretical value of the isotopic ratio $R_2 = 0.0204$, which corresponds to an enrichment of 2%.

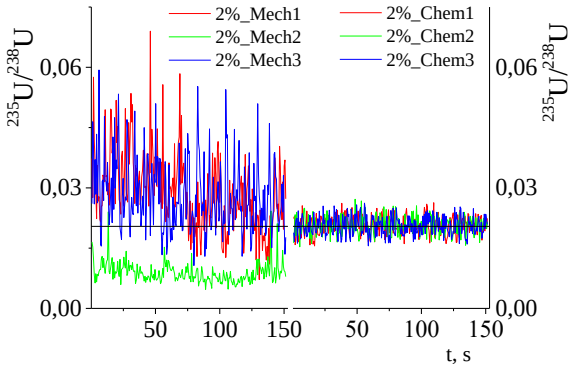


Fig. 4. Time dependence of the $^{235}U/^{238}U$ isotopic ratio along the scan line for samples with a nominal enrichment of 2% obtained by mechanical (left) and chemical (right) mixing at three analytical positions

As can be seen from Fig. 4, for the chemical mixing samples, a high homogeneity of the $^{235}U/^{238}U$ isotopic ratio is observed at each scan step. The degree of heterogeneity, calculated as the average relative standard deviation across three positions (RSD_2%_chem) relative to the theoretical line is only 3.74%, which confirms the high spatial homogeneity of the enrichment distribution along the surface.

For the sample obtained by mechanical mixing, a fundamentally different behavior of the time dependence of the $^{235}U/^{238}U$ isotopic ratio is observed. For all three positions, both deviations of the average levels relative to the theoretical value and significant fluctuations of the $^{235}U/^{238}U$ ratio in both positive and negative directions are recorded. The degree of heterogeneity, calculated as the relative standard deviation (RSD_2%_mech1 = 35.94%, RSD_2%_mech2 = 28.55% and RSD_2%_mech3 = 37.72%), indicates a substantial heterogeneity of the local isotopic composition. Also, for the mechanical

series sample, the minimum and maximum values of the $^{235}U/^{238}U$ ratio across all iterations were found to be 0.0047 and 0.0690, respectively. It is important to note that the minimum value coincides with the isotopic ratio of the starting depleted uranium (R_{DU} = 0.0047) used to prepare the mixture.

Fig. 5 shows the distributions of the $^{235}U/^{238}U$ isotopic ratio as a function of scan time for 4%-enriched samples. The arrangement and numbering are the same as in Fig. 4. As can be seen from the figure, for chemical mixing, the uniformity of all three distributions is preserved with respect to the theoretically calculated value of the $^{235}U/^{238}U$ ratio: R_4 = 0.0417 (RSD_4%_chem = 4.58 %).

In contrast, for the mechanical mixture, a pattern similar to the 2%-enriched sample is observed: a significant deviation from the calculated value and high-amplitude fluctuations of the $^{235}U/^{238}U$ ratio. The degree of heterogeneity, calculated as the values RSD_4%_mech1 = 33.53%, RSD_4%_mech2 = 38.26%, and RSD_4%_mech3 = 39.41%, confirms the substantial isotopic heterogeneity of the sample.

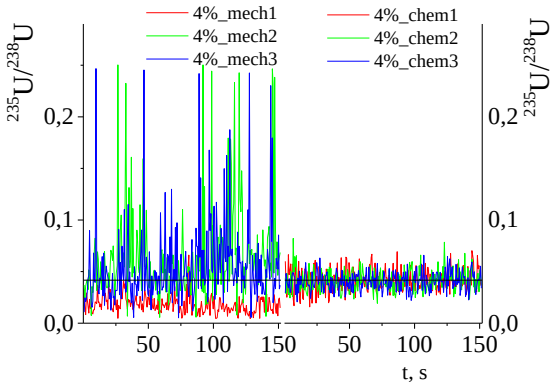


Fig. 5. Time dependence of the $^{235}U/^{238}U$ isotopic ratio along the scan line for the 4%-enriched samples: mechanically mixed (left) and chemically mixed (right), evaluated at three analytical positions

Analysis of the results of all iterations for the mechanical series sample made it possible to establish the extreme values of the $^{235}U/^{238}U$ ratio: R_{min} = 0.0046 and R_{max} = 0.2504. The minimum value precisely coincides with the isotopic composition of depleted uranium (R_{DU} = 0.0047), while the maximum coincides with the isotopic composition of the second starting component (R_{LEU} = 0.2455).

Notably, a distinct difference was observed in the maximum $^{235}U/^{238}U$ ratio values recorded for the mechanically mixed samples with 2% (0.069) and 4% (0.2504) enrichments. The lack of direct detection of the pure, highly enriched starting phase (R_{LEU} = 0.2455) in the 2% sample is likely due to the small mass fraction of this component within the matrix. According to mass balance calculations, to achieve a nominal enrichment of 2%, the LEU phase accounts for only about 8% of the mixture, whereas for the 4% sample, it increases to ≈18%. Given the discrete nature of laser scanning and the spot size, the probability of direct laser beam impingement onto an isolated LEU micro-grain in the 2% sample is statistically low. In this scenario, the laser predominantly ablates the depleted uranium matrix (R_{DU}) or interphase contact zones, yielding intermediate values (R ≈ 0.02…0.07). The higher content of the low-enriched phase in the 4 % sample substantially enhances the probability of its detection, enabling the recording of the extreme value R_{max} = 0.2504, which corresponds precisely to the initial LEU component.

The obtained results demonstrate that the local LA-ICP-MS method is an effective tool for studying mixed uranium-bearing samples. Unlike integral methods (HRGS or ICP-MS with prior sample dissolution), which determine only the averaged isotopic composition or nominal enrichment, the analysis of the $^{235}U/^{238}U$ isotopic ratio heterogeneity makes it possible to:

- clearly distinguish mechanical mixing from chemical precipitation by the presence of high signal variability (degree of heterogeneity RSD > 30% versus RSD < 5%),
- directly identify the “isotopic passport” of the starting components used to prepare the mixture.

This is of exceptional importance for nuclear forensic investigations in establishing the origin of unlawfully seized uranium-bearing materials and reconstructing their manufacturing process.

CONCLUSIONS

A key objective of nuclear forensics is determining the manufacturing processes of uranium-bearing materials to establish the sources of illicit trafficking. Regarding the characterization of mixed uranium samples, bulk analytical methods – such as HRGS and ICP-MS requiring sample dissolution – yield only the average isotopic content. Consequently, these methods fail to detect origin concealment via the blending of materials from diverse sources. To address this limitation, developing techniques capable of resolving micro-scale material heterogeneity is critically important. One such approach is laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), which enables direct, localized surface analysis without prior sample dissolution.

To evaluate the proposed hypothesis that the processing history and precursor materials can be identified based on spatial isotopic heterogeneity via LA-ICP-MS, uranium-bearing samples with 2 and 4% enrichments were prepared. The samples were produced by blending two starting materials – depleted uranium (0.47 weight% ^{235}U) and low-enriched uranium (19.78 weight % ^{235}U) – in the calculated mass proportions using two fundamentally distinct technological routes: dry mechanical mixing and chemical co-precipitation.

The spatial distribution of ^{235}U and ^{238}U ion intensities was obtained using LA-ICP-MS. Surface scanning was performed along a 125 μm line at three analytical positions evenly spaced from the sample center.

Analysis of the $^{235}U/^{238}U$ isotopic ratio revealed that chemical co-precipitation yields spatial distribution homogeneity across both enrichment levels. The mean spatial values closely agree within the experimental uncertainty with the bulk values obtained by high-

resolution gamma spectrometry (HRGS). In contrast, mechanically mixed samples exhibit pronounced heterogeneity, which was clearly evident in both the bulk $^{235}U/^{238}U$ ratios across all three analytical positions and the spatial profiles along individual scan tracks for both the 2 and 4% enriched samples. These findings demonstrate that spatial heterogeneity in the $^{235}U/^{238}U$ isotopic ratio serves as an unambiguous signature of a mechanical mixture preparation route.

The evaluation of transient signal spikes and plateau regions along the spatial profile enabled the experimental recording of $^{235}U/^{238}U$ ratios that closely match those of the unblended starting materials. Consequently, LA-ICP-MS represents a highly effective tool for the nuclear forensic identification of precursor components within mechanically prepared mixtures.

Thus, the LA-ICP-MS method demonstrates unique analytical value for nuclear forensics. Due to high spatial resolution, minimal destructiveness, and the absence of complex chemical sample preparation, this method makes it possible to investigate complex heterogeneous materials.

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ВИЗНАЧЕННЯ ОДНОРІДНОСТІ РОЗПОДІЛУ СПІВВІДНОШЕННЯ $^{235}U/^{238}U$ ДЛЯ ПЕРЕВІРКИ ОДНОРІДНОСТІ ПОВЕРХНІ ЗРАЗКІВ ІЗ ВИКОРИСТАННЯМ МЕТОДУ ICP-MS

С.М. Афанасьев, І.О. Афанасьєва, С.О. Ванжа, Д.В. Кутній

Представлено аналіз ізотопного співвідношення $^{235}U/^{238}U$ та оцінку його однорідності на поверхні зразка за допомогою мас-спектрометрії з індуктивно-зв'язаною плазмою і системою лазерної абляції (LA-ICP-MS). Для дослідження створено змішані уранвмісні зразки за різними виробничими процедурами – механічним і хімічним змішуванням однакових вихідних матеріалів. Однорідність співвідношення $^{235}U/^{238}U$ може бути прямою «сигнатурою» технологічного процесу, яка дозволить визначити процес виготовлення або переробки ядерного матеріалу. Використання лазерної абляції дозволило провести локальний ізотопний аналіз без повного розчинення зразка при фіксації просторового розподілу співвідношення інтенсивностей іонів ^{235}U та ^{238}U безпосередньо на поверхні створених зразків. Для оцінки однорідності ізотопного співвідношення $^{235}U/^{238}U$ було використано методику лінійного сканування – безперервний рух лазерного променя вздовж вибраної лінії. Визначено, що в хімічних зразках однорідність розподілу $^{235}U/^{238}U$ зберігається, у той час як механічні зразки мають суттєву неоднорідність і прояв значень вихідного матеріалу.