JOINT INSTITUTE FOR NUCLEAR RESEARCH
Flerov Laboratory of Nuclear Reactions

FINAL REPORT ON THE INTEREST PROGRAMME

Production and Spectroscopic Investigation of New Neutron-Rich Isotopes Near the Neutron N=126 Shell Closure Using the Multinucleon Transfer Reactions

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Abstract

The Mass Analyzer of Super Heavy Atoms *(MASHA)*, located at the Flerov Laboratory of Nuclear Reactions *(FLNR)* in the Joint Institute for Nuclear Research *(JINR)* in Dubna, Russia, is a powerful mass spectrometer capable of studying superheavy elements. By utilizing the Isotope Separation On-Line *(ISOL)* technique and the beamline of the Cyclotron $U-400M$, MASHA achieves a resolving power of approximately 1700, allowing for the separation and analysis of reaction products from multi-nucleon transfer and complete fusion reactions. In this study, data collected by the MASHA setup at FLNR for the reactions $^{40}Ar + {}^{148}Sm,\ ^{40}Ar + {}^{166}Er, and\ ^{48}Ca + {}^{242}Pu$ near the neutron $N = 126$ shell closure were analyzed using Origin Software. The resulting *α-decay* energy profile was investigated, providing valuable insights into the properties of these isotopes.

Introduction

The study of isotopes belonging to the superheavy elements, specifically those situated within the island of stability in the nuclear stability map, holds significant importance due to their anticipated longer lifetimes compared to other isotopes of these elements. The MASHA setup at the FLNR in JINR, Dubna, Russia, serves as a mass spectrometer capable of investigating a wide range of masses up to $450\ atomic\ mass\ units$, focusing on the physical properties of superheavy elements. Employing the Isotope Separator Online (ISOL) technique, reaction products are separated and detected using a multi-channel silicon detector situated at the focal plane of the MASHA apparatus.

This paper aims to explore the production and spectroscopic investigation of Mercury and Radon isotopes through complete fusion reactions involving neutron evaporation residues and multi-nucleon transfer reactions. The reactions studied include $^{40}Ar + {}^{148}Sm \rightarrow {}^{188-xn}Hg + xn$, $^{40}Ar + {}^{166}Er \rightarrow {}^{206-x}Hg + xn$, and $^{48}Ca + {}^{242}Pu$. These isotopes were passed through the magnetooptical system of the MASHA setup with a charge state of $Q = +1$, allowing their separation based on the mass-to-charge ratio. Detection of the isotopes was achieved using a position-sensitive silicon detector. The experimental data obtained were thoroughly analyzed, and spectroscopic investigations were carried out to gain a comprehensive understanding of the isotopes' properties.

The MASHA setup, operating at a resolving power of approximately 1700, provides a valuable tool for mass identification of superheavy nuclides. Leveraging the solid ISOL method, the setup enables the analysis of real data collected from experiments involving complete fusion reactions and multi-nucleon transfer reactions. The α-decay chains obtained from position-sensitive silicon detectors were used to calculate the masses of identified isotopes, their half-lives, Alpha Branching Ratios (ABR), α-decay energies (E_a), and their probability of decaying with specific energy values. Furthermore, one-dimensional α-decay energy spectra were plotted, and peak analysis was performed. Gaussian fitting functions were employed to obtain fits for both the parent nuclei and their α-decay products. Heatmaps, depicting a two-dimensional

energy-position graph, were generated based on the 1D histograms of α-decay energy spectra for the isotopes.

The synthesis of superheavy nuclei often relies on radiochemistry, where decay chains ending with known nuclei play a crucial role in identifying nuclides. However, due to the relatively short half-lives of superheavy nuclei, kinematic separators are frequently employed to ensure reliable and efficient separation, albeit without measuring the core mass.

Masha setup

The MASHA spectrometer is a complex setup designed for nuclear research. It comprises several crucial components that work together to achieve accurate measurements. The overall layout of the MASHA spectrometer includes an ion-optical layout, an ECR ion source, a hot catcher, a target box, detectors, and a control system (Vedeneev et al., 2017).

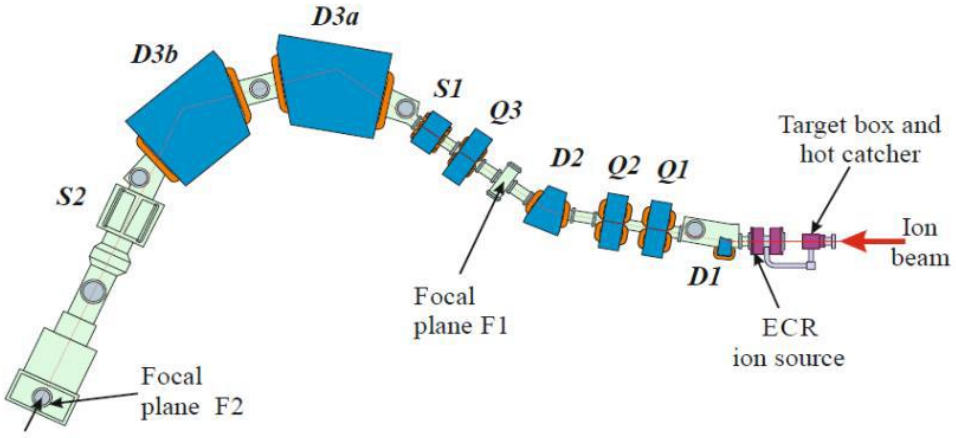


Figure 1: MASHA Setup

Figure 1 shows MASHA setup: there are four dipole magnets - D1, D2, D3a, and D3b , 3 quadrupole lenses – Q1, Q2, and Q3, sextupole lenses – S1 and S2, and the detection system in focal planes of the separator.

Target box

The Target box is a significant part of the setup, consisting of a rotating disc divided into six sectors sputtered with target material. The disc rotates at a frequency of approximately $25\ Hz$. When a high-energy ion beam collides with the target material, nuclear reactions are induced, resulting in reaction products. The hot catcher, situated after the target box, captures, and stops these reaction products as well as any unreacted beam.

Figure 2: Rotating Target Disc

Hot catcher

The Hot catcher comprises two main components: a poly-graphene heater and an absorber material. The absorber material, typically a thin film of graphite or carbon nanotubes, is heated by the poly-graphene heater to temperatures ranging from $1800\ to\ 2000\ K$. The nuclear reaction products are vaporized by the absorber material and converted into a gaseous form, subsequently passing into the ECR ion source (Mamatova et al., 2019).

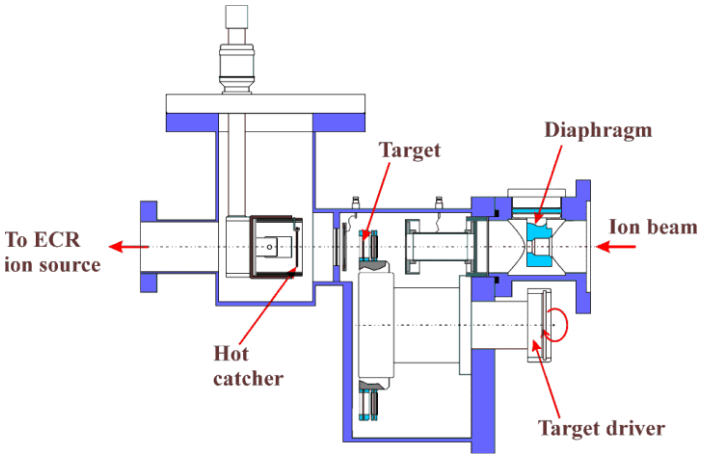


Figure 3: Complete Schematic

ECR ion source

The ECR ion source plays a crucial role in the MASHA spectrometer. Operating at a frequency of $2.45\ GHz$, it ionizes the gaseous isotopic products of the nuclear reaction to a charge state of $Q = +1$. The ionized atoms are then accelerated to an energy of $38\ keV$ using a three-electrode electrostatic lens. The ion source achieves a high ionization efficiency of approximately 90%, even for noble gases.

MAGNETO-OPTICAL SYSTEM

After ionization, the ion beams are separated based on their mass-to-charge ratio by a magneto-optical system. This system consists of four dipole magnets $(D1, D2, D3a, D3b)$, three quadrupole lenses $(Q1, Q2, Q3)$, and two sextupole lenses $(S1, S2)$. The magnetic fields generated by these components enable the separation of heavy nuclei, ensuring precise mass separation (Rodin, Belozerov, Chernysheva, et al., 2014).

POSITION SENSITIVE Si DETECTOR

Finally, the separated ions of interest are focused on the focal plane using the magneto-optical system, and their detection is facilitated by a position-sensitive Si detector. The Si detector consists of multiple detector panels, including a frontal detector with 192 $strips$, upper and lower detectors with 64 $strips\ each$, and lateral detectors with 16 $strips\ each$. These detectors have an energy resolution of approximately 30 keV and enable the determination of the energies of alpha-emission and spontaneous fission. Additionally, four additional detector panels are installed to increase the geometrical efficiency of alpha-decay product detection (Rodin, Belozerov, Chernysheva, et al., 2014).

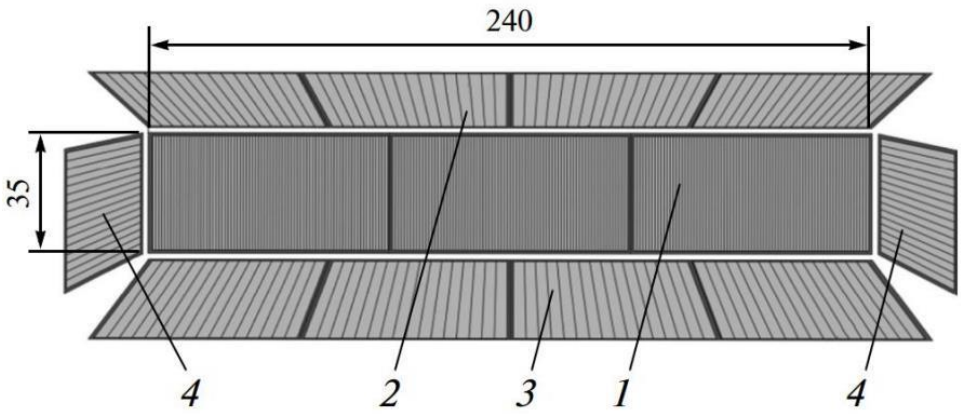


Figure 4: Position sensitive Si detector.

All MASHA spectrometer's main components work harmoniously to enable precise nuclear research and detection of nuclear reaction products.

Project Goals and Measurement Methods

The MASHA spectrometer is a sophisticated setup used for nuclear research, specifically focusing on the analysis of various nuclear reactions. It comprises several integral components that work in tandem to ensure precise measurements and accurate data acquisition.

To begin the experimental process, data obtained from the reactions of $^{40}Ar + {}^{148}Sm, {}^{40}Ar + {}^{166}Er, and {}^{48}Ca + {}^{242}Pu$ are plotted using OriginPro software. These plots are then fitted using peak analyzer tools to determine the product isotopes based on their decay energy and alpha branching ratio. Furthermore, a heatmap is constructed, showcasing the

reaction profiles of the three reactions. The y-axis of the heatmap is calibrated using the $E(alpha\ decay) = a * x + b$ formula, allowing for the extraction of alpha decay energy values for different isotopes.

The experiments involve complete fusion reactions with neutron evaporation residues and multi-nucleon transfer reactions. In complete fusion reactions, the product nucleus is formed when the total number of protons in the projectile particle and the target nucleus are combined. On the other hand, multi-nucleon transfer reactions can lead to the formation of various nuclides with atomic numbers ranging from that of the projectile particle to the sum of the atomic numbers of the projectile particle and target nucleus. These reactions may result in proton-rich or neutron-rich product nuclei.

The FLNR's $U - 400M$ cyclotron is utilized to accelerate the projectile particles ($40Ar\ and\ 48Ca$) to high velocities, reaching energies of approximately $198\ MeV$ and 240MeV, respectively. These high-energy particles enter the MASHA setup and induce nuclear reactions by colliding with target material sputtered in a rotating disc within the target box. The products of these nuclear reactions, which include isotopes of Hg (in the case $^{40}Ar + {}^{148}Sm$) and Rn (in the case of $^{40}Ar + {}^{166}Er, and {}^{48}Ca + {}^{242}Pu$), are captured and stopped by the absorber material within the hot catcher. Typically, the absorber material consists of a thin film of graphite or carbon nanotubes that is heated to temperatures of around $1800\ to\ 2000°C$ using IR radiation and direct current.

The isotopic products, now in a gaseous form, diffuse through the absorber material and proceed to the ECR ion source through a vacuum pipe. Within the ECR ion source, the gaseous isotopes are ionized to a charge state of $Q = +1$. Subsequently, a three-electrode system accelerates the ionized atoms to an energy of interest. The magnetooptical system within the MASHA setup separates the ions based on their mass-to-charge ratio, ensuring precise mass separation.

At the focal plane, a position-sensitive Si detector is employed to detect the separated ions. This detector consists of multiple panels, each equipped with a specific number of strips. The strips allow for the determination of the energies of alpha emissions and spontaneous fission, providing valuable insights into the detected isotopes. In particular, the Si detector's high resolution and sensitivity enables the detection of even a single alpha or beta particle. Additionally, a hybrid pixel detector of the TIMEPIX type is utilized in conjunction with the MASHA setup to collect data on neutron-rich Rn isotopes.

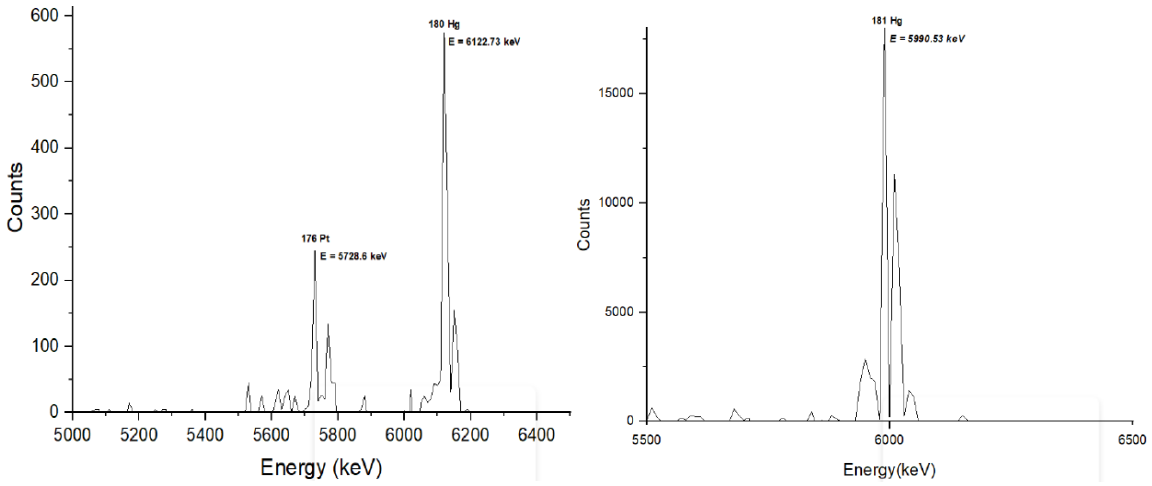
The collected data is subjected to thorough analysis using Origin software, enabling the creation of histograms depicting counts versus energy for the isotopes of Hg and Rn resulting from the nuclear reactions. These histograms are then utilized to identify prominent peaks and calculate their respective alpha decay energy (E_a) values. By cross-referencing the obtained energy values with the table of nuclides, the specific isotopes detected at unique strip numbers can be identified. Moreover, the mass, alpha branching ratio, and daughter nuclei of the detected isotopes can be investigated using the same table of nuclides.

Additionally, a two-dimensional energy-position graph, commonly referred to as a heatmap, is generated for all three test experiments. The heatmap provides a comprehensive visual representation of the isotopes detected at different strip numbers, along with the corresponding counts of alpha particles with a common energy. This common energy corresponds to the alpha decay energy of each respective isotope.

Results

1. $^{40}\mathrm{Ar} + {}^{148}\mathrm{Sm} \rightarrow {}^{188-\mathrm{xn}}\mathrm{Hg} + xn$

The complete fusion reaction was performed at the MASHA setup, using ^{148}Sm as the target material sputtered in a rotating disc. The resulting nuclear reaction yielded isotopes of Hg; however, only long-lived Hg isotopes with a half-life greater than the average separation time $(1.8 \pm 0.3\ s)$ employed by the ISOL method for this reaction were detected. This reaction specifically led to the production of six isotopes of mercury - ^{180}Hg, ^{181}Hg, ^{182}Hg, ^{183}Hg, ^{184}Hg, ^{185}Hg - indicating that the x in the reaction formula represents the range of 3 to 8 neutrons evaporating during the reaction. These Hg isotopes were identified through their spectra and the energy releases observed. Figure 5 displays the spectra of the different isotopes, showcasing their respective energy peaks and alpha branching ratios for each nucleus. Additionally, the lower-energy peaks observed, originating from the energy released during the alpha decay of the Hg nucleus and the subsequent production of a daughter nucleus, were identified as platinum isotope.



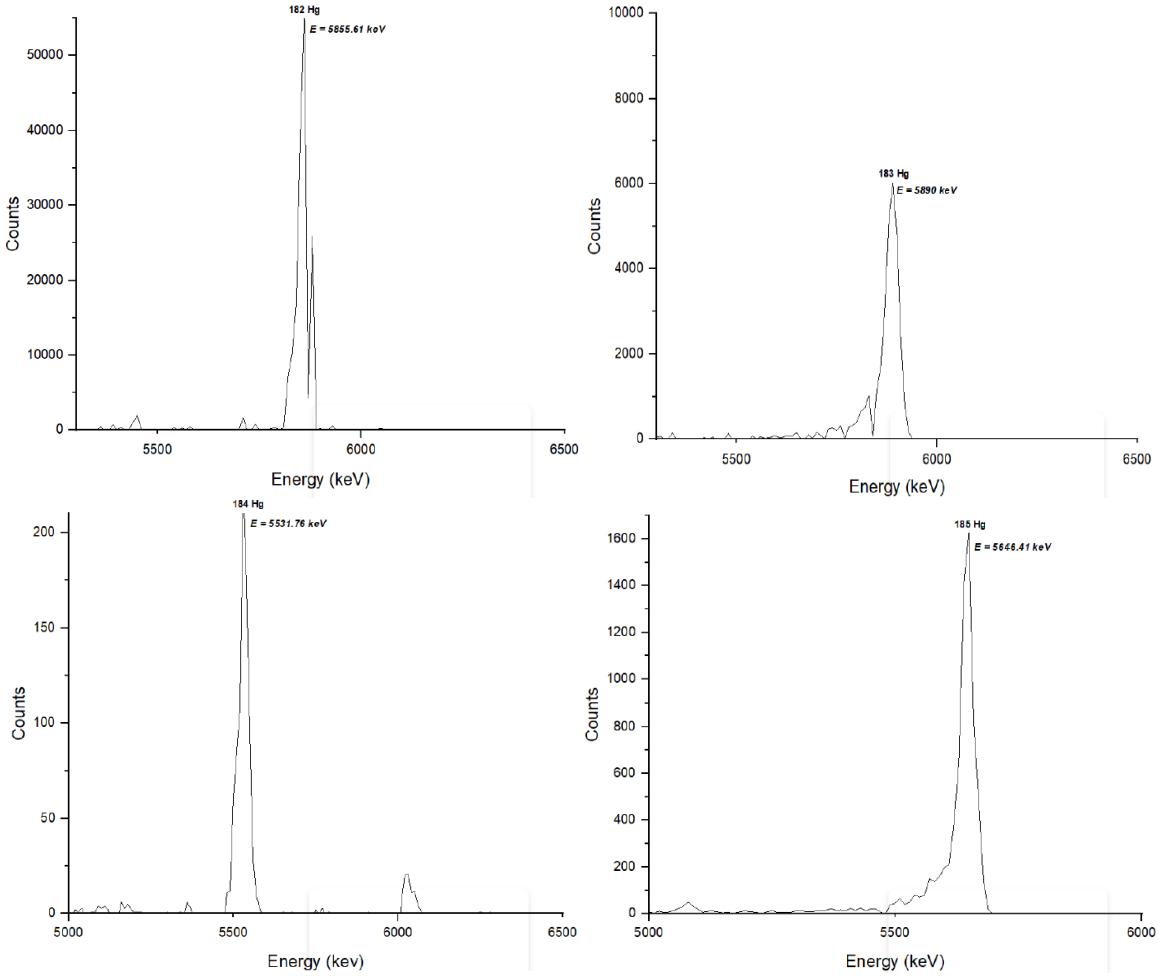


Figure 5

Figure 5 shows the energy spectra of mercury isotopes: (1) ^{180}Hg, (2) ^{181}Hg, (3) ^{182}Hg, (4) ^{183}Hg, (5) ^{184}Hg, and (6) ^{185}Hg. The energy values at the peaks of each isotope can be determined from the graphs. A comparison between these observed values and their corresponding theoretical values in the provided table will serve as a reliable indicator of the progress and accuracy achieved in the experimental work.

Isotope	Experimental Energy (KeV)	Theoretical Energy (KeV)	|Error percentage %|
^{180}Hg	6122.73	6119	0.061%
^{176}Pt	5728.6	5753	0.424%
^{181}Hg	5990.53	6006	0.258%
^{182}Hg	5855.61	5867	0.194%
^{183}Hg	5890	5904	0.237%
^{184}Hg	5531.76	5535	0.059%
^{185}Hg	5646.41	5653	0.117%

Table 1

Heatmap

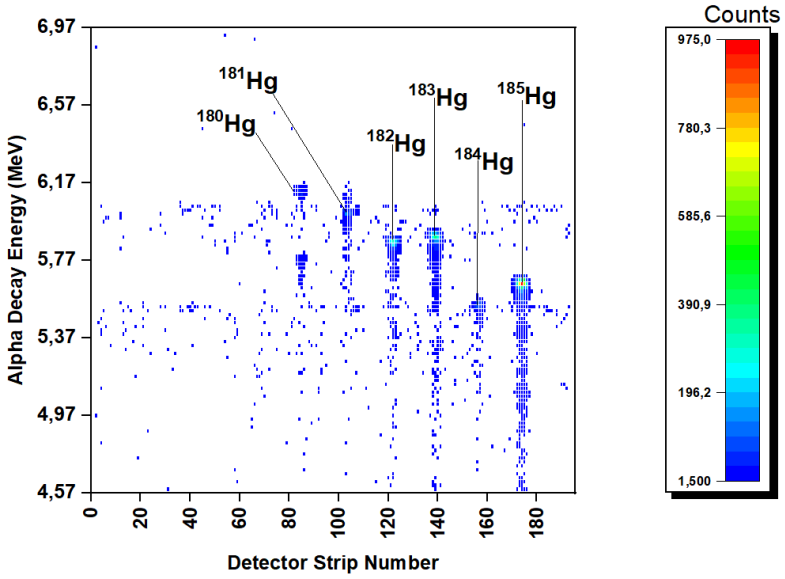


Figure 6: Heatmap of isotopes

2. $^{40}\mathrm{Ar} + {}^{166}\mathrm{Er} \rightarrow {}^{206-\mathrm{xn}}\mathrm{Rn} + xn$

A powerful fusion reaction was conducted by colliding a high-energy projectile particle $(^{40}\mathrm{Ar})$ with an energy of approximately 198 MeV, emitted from the window of the $U-400M$ cyclotron, with a target material of $^{166}\mathrm{Er}$ in the form of a rotating disc within the MASHA facility's target box. This reaction resulted in the production of five distinct isotopes of Radon: $^{201}\mathrm{Rn}$, $^{202}\mathrm{Rn}$, $^{203}\mathrm{Rn}$, $^{204}\mathrm{Rn}$, and $^{205}\mathrm{Rn}$. Figure 7 exhibits the spectra of these various radon isotopes, showcasing their unique energy peaks. Additionally, an additional peak was identified, corresponding to the energy released by Polonium (Po), which is itself a product of the alpha decay of Radon. In Spectrum 3, alongside the $^{205}\mathrm{Rn}$ peak, a representative peak attributed to the Astatine-205 isotope, produced through the beta decay of Radon, is also visible. Table 2 presents a comparison between the radioisotope data obtained from experiments and the theoretical data. This data was acquired using the experimental data from the MASHA detector and control system, enabling the plotting of α-decay energy spectra and energy-position graphs.

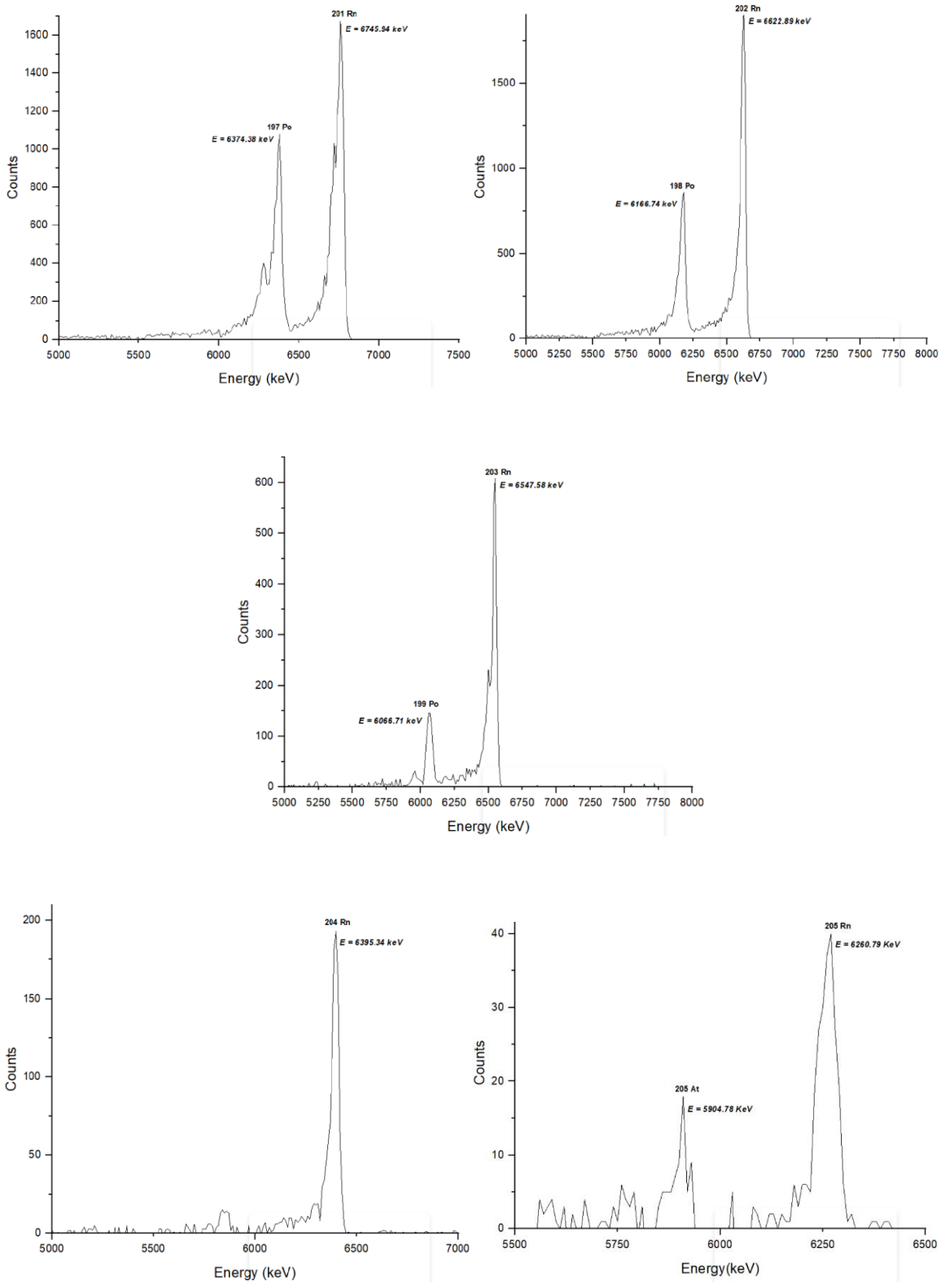


Figure 7

Figure 7 shows the energy spectra of radon and polonium isotopes. The energy values at the peaks of each isotope can be determined from the graphs.

Isotope	Experimental Energy (KeV)	Theoretical Energy (KeV)	|Error percentage %|
^{201}Rn	6745.94	6725	0.311%
^{197}Po	6374.38	6383	0.135%
^{202}Rn	6622.89	6639.5	0.25%
^{198}Po	6166.74	6182	0.247%
^{203}Rn	6547.58	6549	0.022%
^{199}Po	6066.71	6059	0.127%
^{204}Rn	6395.34	6418.9	0.367%
^{205}Rn	6260.79	6262	0.019%
^{205}At	5904.78	5902	0.047%

Table 2

Heatmap

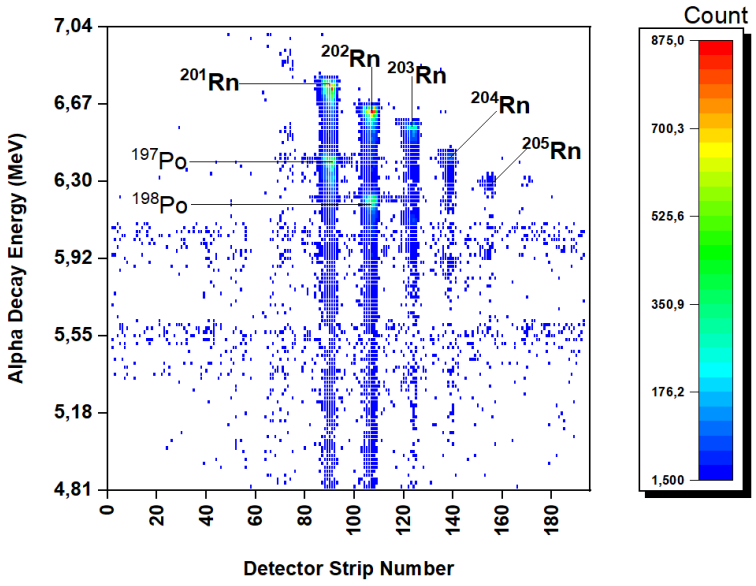


Figure 8

3. $^{48}Ca + {}^{242}Pu$

In contrast to the complete fusion reactions described earlier, the reaction of $^{48}Ca + {}^{242}Pu$, under specific conditions, utilized the Multi-Nucleon Transfer Reactions (MNTR) technique to produce neutron-rich Rn isotopes in the vicinity of the neutron $N = 126$ shell closure configuration. This unique reaction allowed for the identification and subsequent spectroscopic investigation of the produced isotopes. However, it was observed that only those Rn isotopes that had a minimum lifetime of 35 ms were able to reach and be detected by the detector, while others underwent decay along their path.

The complete energy spectrum resulting from the $^{48}\mathrm{Ca} + {}^{242}\mathrm{Pu}$ reaction is depicted in Figure 9. Specifically, this reaction yielded three isotopes of radon: ^{212}Rn, ^{218}Rn, and ^{219}Rn. One of the spectra revealed the identification of alpha decay products originating from ^{218}Rn, namely ^{214}Po and ^{210}Po. Additionally, another figure displays the energy spectra of the ^{215}Po isotope, which arises from the alpha decay of ^{219}Rn.

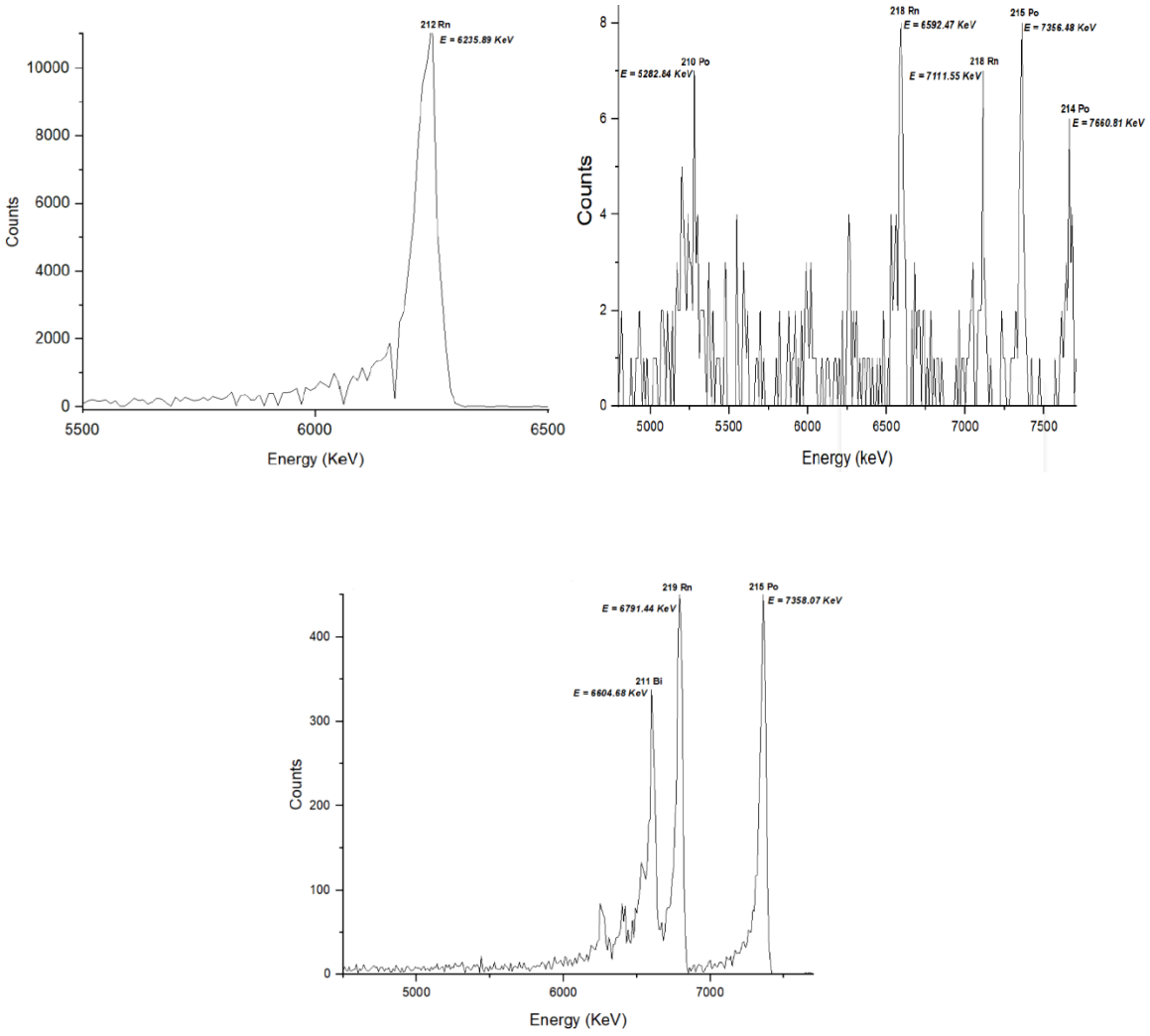


Figure 9

Figure 9 shows the energy spectra of radon and polonium isotopes. The energy values at the peaks of each isotope can be determined from the graphs.

Isotope	Experimental Energy (KeV)	Theoretical Energy (KeV)	|Error percentage %|
^{212}Rn	6235.89	6264	0.449%
^{214}Po	7660.81	7686.82	0.338%
^{218}Rn	7111.55	7129.2	0.248%
^{218}Rn	6592.47	6609.8	0.262%
^{210}Po	5282.84	5304.33	0.405%
^{219}Rn	5791.44	6552.6	11.616%
^{215}Po	7358.07	7386.1	0.379%
^{211}Bi	6604.68	6802	2.901%

Table 3

Heatmap

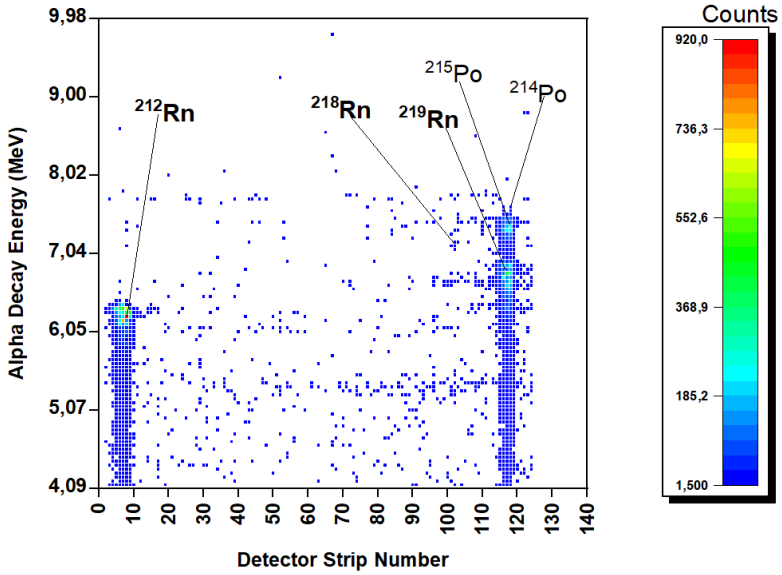


Figure 10

Discussion

In this experiment, the production and spectroscopic investigation of Hg and Rn isotopes using different nuclear reactions were conducted. The reactions examined were $^{40}Ar + {}^{148}Sm, {}^{40}Ar + {}^{166}Er, and {}^{48}Ca + {}^{242}Pu$, which resulted in the formation of Hg and Rn isotopes. The experimental data collected from the MASHA setup were analyzed, and a 1D α-decay energy spectrum graph was plotted for the strips of the detector that detected isotopic products.

To further analyze the data, 1D histograms were generated, and a 2D energy-position graph was plotted separately for Hg and Rn isotopes. By studying these graphs and cross-referencing with a nuclide chart, the masses of the super-heavy nuclei detected at different strips of the Si-based Position Sensitive Detector (PSD) were identified. Additionally, using the 1D histograms and the nuclide chart, the alpha decay energy (E_a), alpha branching ratio (ABR), counts, and the probability of decay with a specific amount of energy were calculated for the identified isotopes. The results showed that mercury isotopes (^{180}Hg, ^{181}Hg, ^{182}Hg, ^{183}Hg, ^{184}Hg, ^{185}Hg) were produced in the complete fusion reaction of $^{40}Ar + {}^{148}Sm$. The fusion reactions of $^{40}Ar + {}^{166}Er, and {}^{48}Ca + {}^{242}Pu$ produced radon isotopes (^{201}Rn, ^{202}Rn, ^{203}Rn, ^{204}Rn, ^{205}Rn, ^{212}Rn, ^{218}Rn, ^{219}Rn).The experimentally determined alpha decay energy values of the isotopes and their daughter nuclei agreed with the theoretically predicted energies, with small deviations observed. These findings demonstrate the effectiveness of the MASHA setup in investigating super-heavy isotopes with limited stability and short lifetimes.

Acknowledgement

I would like to express my gratitude to Mr. Viacheslav Vedeneev, my scientific supervisor, for his invaluable guidance and unwavering support throughout the duration of this research project. I am also grateful to the INTEREST team for their consistent assistance and support. Additionally, I extend my appreciation to the Joint Institute of Nuclear Research for granting me the opportunity to work on this project and acquire valuable knowledge and experience.

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