JOINT INSTITUTE FOR NUCLEAR RESEARCH
Flerov Laboratory of Nuclear Reactions

FINAL REPORT ON THE INTEREST PROGRAMME

Determination of masses of the super heavy elements in the experiments on synthesis of Cn and Fl using the reactions 48Ca + 242Pu and 48Ca + 244Pu

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Abstract

The last few decades nuclear scientists have made a huge impact in the area of Super Heavy Elements (SHE), which more specific are elements with atomic number Z=113-118. In order to identify these elements, we use the Isotope Separator On-Line (ISOL) method in the Mass Analyzer of Super Heavy Atoms (MASHA) installation at Flerov Laboratory of Nuclear Reactions (FLNR) at JINR. With this method we aspire to measure accurately on-line the mass-to-charge ratio of the SHE isotopes and their respective energies of α-decay. Furthermore, the main parts of MASHA are described. In the last and most principal section of this project, we process the experimental data of the reactions $^{40}Ar+^{148}Sm$, $^{40}Ar+^{166}Er$ and $^{48}Ca+^{242}Pu$ by constructing histograms and heatmaps, with the purpose of detecting the energy peaks, that lead us to Hg and Rn isotopes. These isotopes are produced from the aforementioned heavy ion fusion and multinucleon reactions.

Project goals

This project aims to perform a mass measurement of short-lived isotopes of Hg (as the homologue to SHE), Rn and its daughter nuclei by α-decay chains at position sensitive Si detector. Simultaneous yield measurements of Cn, Fl and Hg.

Contents

1. Introduction

After the first synthesis of the transuranium element Neptunium in 1940, we observe a massive flourishing in the field of Super Heavy Elements (SHE). More specific, SHEs are those chemical elements, that have atomic number greater than 103. Recent discoveries of the syntheses of the elements with Z=113-118 have revealed that their decay time is relatively long, more than 1 second, so we are able to perform a chemical identification of these nuclei. For the elements 112 and 114 it has been proved very difficult to measure, due to the low production rate of about 1 atom per week of bombardment, which is caused by the very low cross section for the reaction.

For this reason have been developed many mass-spectrometric techniques and in MASHA setup the ISOL method is being used. The advantage of this apparatus is that we can measure mass-to-charge ratios of SHE isotopes with the simultaneous detection of their α-decays. In this project, we get involved with the following reactions: $^{40}Ar+^{148}Sm$, $^{40}Ar+^{166}Er$ and $^{48}Ca+^{242}Pu$. In the first experiment, $^{40}Ar+^{148}Sm$, radioactive isotopes of Hg were synthesized as a product of the fusion reaction. Isotopes of Rn have been produced in the second fusion, $^{40}Ar+^{166}Er$, as well as in the third multinuclear reaction, $^{48}Ca+^{242}Pu$. The use of Hg as a result of the aforementioned reactions can be justified for multiple reasons, but mainly because it is volatile and share the same chemical and physical properties with elements 112 (Copernicium) and 114 (Flerovium).

2. Experimental Setup

The experimental setup is called MASHA, which stands for Mass Analyzer of Super Heavy Atoms. This separator was designed and manufactured to carry out precise measurements of atomic masses of superheavy atoms, using mass spectrometry technology. The installation includes a target assembly with a hot catcher, an ion source based on the electron cyclotron resonance (ECR), a magneto-optical analyzer with four dipole magnets (D_1, D_2, D_{3a}, D_{3b}), three quadruple lenses (Q_1, Q_2, Q_3), two sextuple lenses (S_1, S_2) and a detection system located in the focal plane of the spectrometer. All these parts are shown in Figure 1.

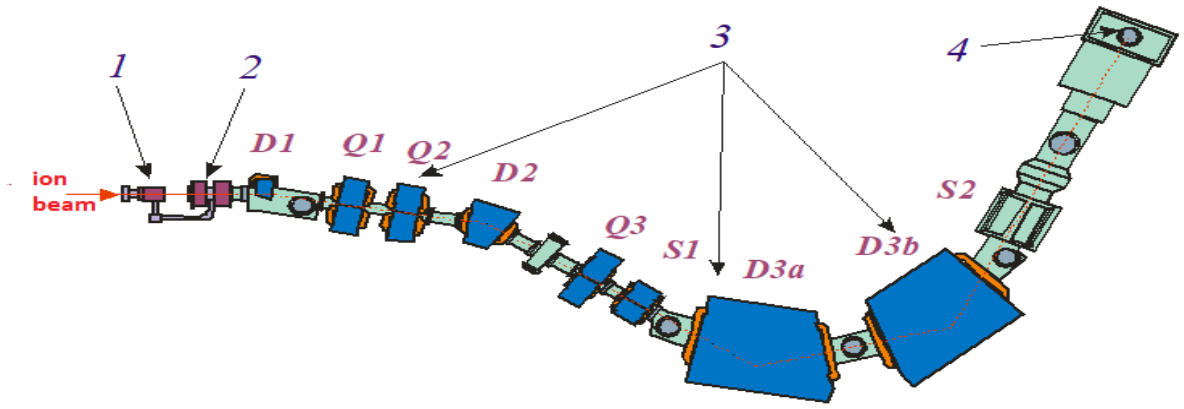

***Figure 1**: Schematic depiction of the MASHA setup. (1) Target box with hot catcher, (2) ion source, (3) mass separator, (4) DAQ in the focal plane.*

2.1 A Target Assembly and a Hot Catcher

The target box is consisted of a block of 12 rotating targets, assembled into cassettes and the disc rotates at a frequency of 25 Hz. The hot catcher is made of flexible graphite and is shaped as a 30 mm diameter disk, with density of 1 g/cm^3, a thickness of 0.6 mm and an operating temperature of 1800-2000^o C. Prior to the heating target, the primary heavy ion beam is injected through the diagnostic system, which is consisted of a pick-up detector and a Faraday cup, in order to measure the position, the intensity and the energy of the beam. Behind the diagnostic system, a stationary target is located in place between two grids, which are cooled down with water. Nuclear reaction products escape from the target, pass through the separating foil and are stopped in the graphite absorber. In the meantime of the cooling process, ions fill their electron orbitals and diffuse through the vacuum of the hot catcher in the form of atoms and, moving over the pipeline, reach the ECR source.

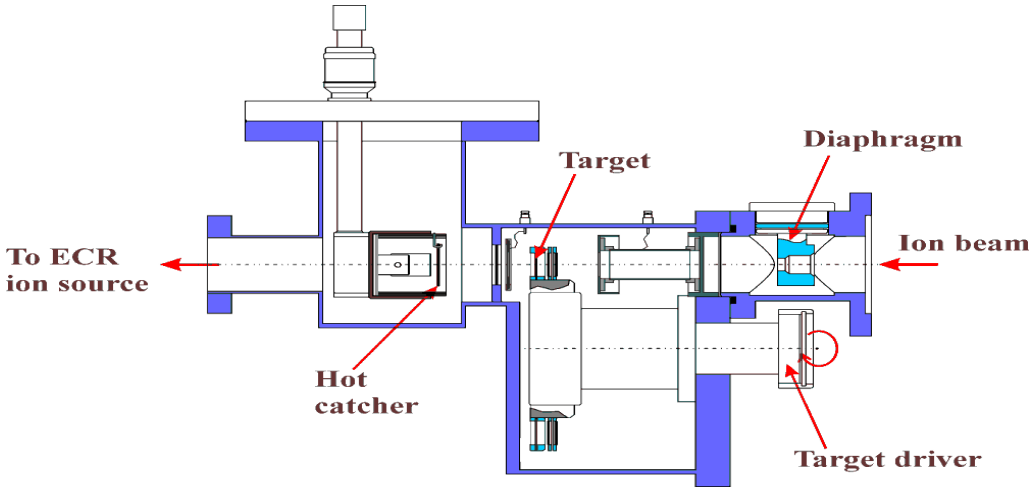

***Figure 2**: Representation of the ECR ion source and the hot target.*

2.2 ECR Ion Source

The Electron Cyclotron Resonance (ECR) ion source has been selected for ionizing atoms of the nuclear reaction products to a charge state of Q=+1 and it contains an ultra-high frequency microwave oscillator of 2.45 GHz. The ionization efficiency is as high as 90% for noble gases and therefore the ions that are in the current are almost 100% singly ionized. These ions are accelerated at energies up to 38 keV by a three-electrode electrostatic lens and gathered into a beam, which is then separated with a magneto-optical system of the mass spectrometer. Helium was used as a buffer gas and its pressure was regulated with the use of a controlled piezoelectric valve at a value of about (1-2) $\cdot 10^{-3}$ Pa. The walls of the source and all other pipes and detectors are covered with a layer of titanium nitride TiN, in order to prevent any interactions.

2.3 Detector

The detection system consists of two different types of detectors. The one is a focal plane silicon multi strip detector that detects the nuclear reaction products. In order to cover as much area as possible, this detector is a well-type, which contains front, side and lateral detectors. The front detector consists of 192 focal strips with a 1.25 nm step, while the side and latter planes are divided into 64 (5 nm step) and 16 strips respectively. Thereby, it is achieved a total efficiency of detection of more than 90%.

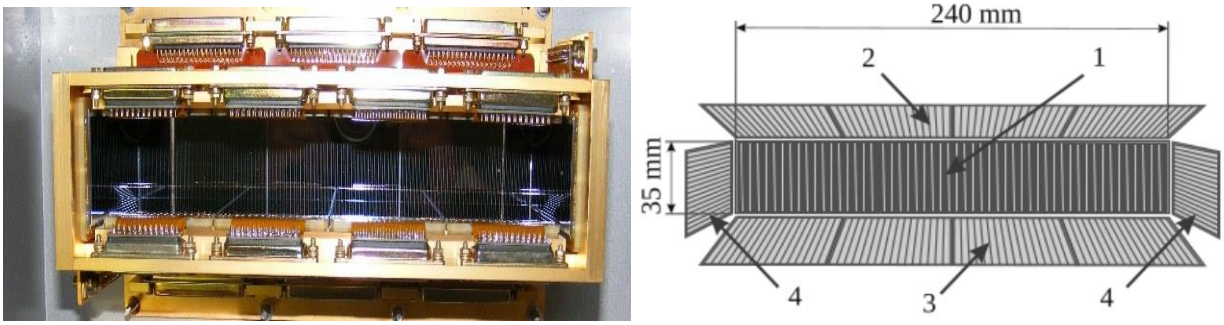

***Figure 3**: Focal plane silicon multi strip detector: (1) front detector, (2)-(3) side detectors and (4) lateral detectors.*

The other type of detector that is used, is TIMEPIX. It consists of an array of 256x256 square pixels of 55 μm pitch size for full sensitive area 14x14 mm^2. It is a silicon sensor of 300 μm width and it is able to detect any type of radiation such as α and β particles, fission fragments and electromagnetic radiation (γ and X-rays).

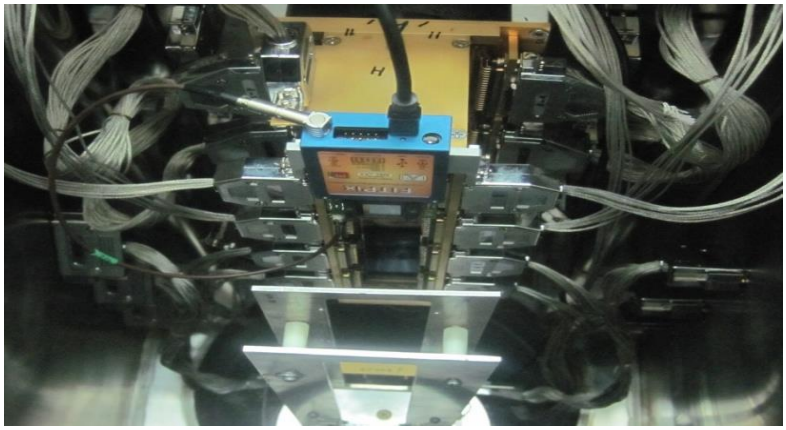

***Figure 4**: TIMEPIX detector*

2.4 Data Acquisition System

The detectors produce signals, all of which are collected with independent spectrometric channels. In order to analyze these signals, a data acquisition system is being used and it consists of 22 charge-sensitive preamplifiers, with 16 channels that stand outside the vacuum chamber. Then, from the preamplifiers the signals are routed to the 8-channel driver amplifiers with a built-in multiplexer. Moreover, it has 5 digitizers from XIA (PXI standard) with 16 channels, the frequency is 250 MHz, the energy resolution is approximately 25 keV and the computing system is a 12-bit system. After the amplification and the multiplexing, three outputs from the multiplexer are used: alpha, fragment and digital channels. The last one includes the information on the source of the input signal. These outputs are connected to the XIA multichannel high-speed digitizers.

3. Methods

First of all, it is needed to measure the initial ion beam energy. For this particular reason, there are 3 independent energy measurement units in the installation, 2 pick-up detectors with 2 pre-amplifiers located before the entrance of the installation, on a heavy ion beamline and working as a Time-of-Flight (TOF) and 1 latter Silicon detector working as a Total Kinetic Energy calorimeter (TKE).

In the beginning, the beam is accelerated with the U400M cyclotron and then passes through the target box, reacting with the rotating target. After that, the unaffected beam and the reaction products are stopped by the hot catcher. The reaction products diffuse to the ECR, while the

recoil nuclei that escape from the target layer, stop at a depth of a micrometers scale in the graphite catcher.

The proposed setup is a combination of the so-called ISOL method of synthesis and separation of radioactive nuclei with the classical method of mass analysis, allowing precise mass measurements of the synthesized nuclides in a wide mass range (A = 1-450 u). The mass of an atom can be determined with mass resolution of about M/dM=1600. The α-energies are detected as the count of α-particles and then we form a matrix of α-energies with the number of strips. The strip number corresponds to the mass number.

4. Results and Discussion

The reactions that will be discussed are the following:

i) Fusion reaction: $^{40}Ar + {}^{148}Sm \rightarrow {}^{188\text{-}xn}Hg + xn$

ii) Fusion reaction: $^{40}Ar + {}^{166}Er \rightarrow {}^{206\text{-}xn}Rn + xn$

iii) Multineutron reaction: $^{48}Ca + {}^{242}Pu \rightarrow {}^{21x}Rn$

Below, many α-decays of the isotopes are presented in the diagrams and in most cases we can distinguish the peaks-decay energies of the daughter nuclei. In every reaction we study, the last graph depicts a heatmap, after a calibration procedure.

The data were processed with the OriginPro software. The histograms are one-dimensional energy spectra from each strip and the heatmaps represent two-dimensional spectra of the energy dependence on the strip number.

The main source of background is the background from the detector, the cosmic rays and the active electronic gadgets.

4.1 Production of mercury isotopes in the reactions $^{40}Ar+^{148}Sm$

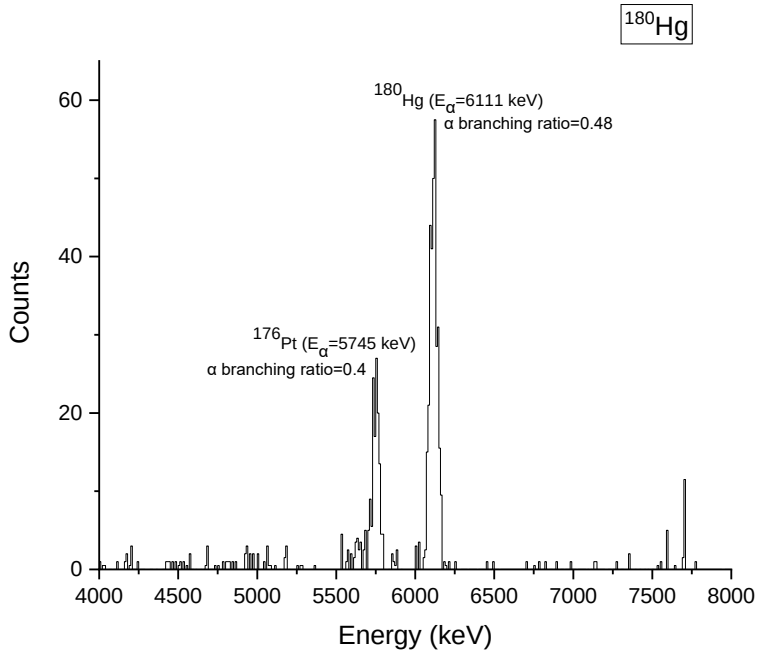

***Figure 5**: Energy spectrum of α-particles from decays of ^{180}Hg.*

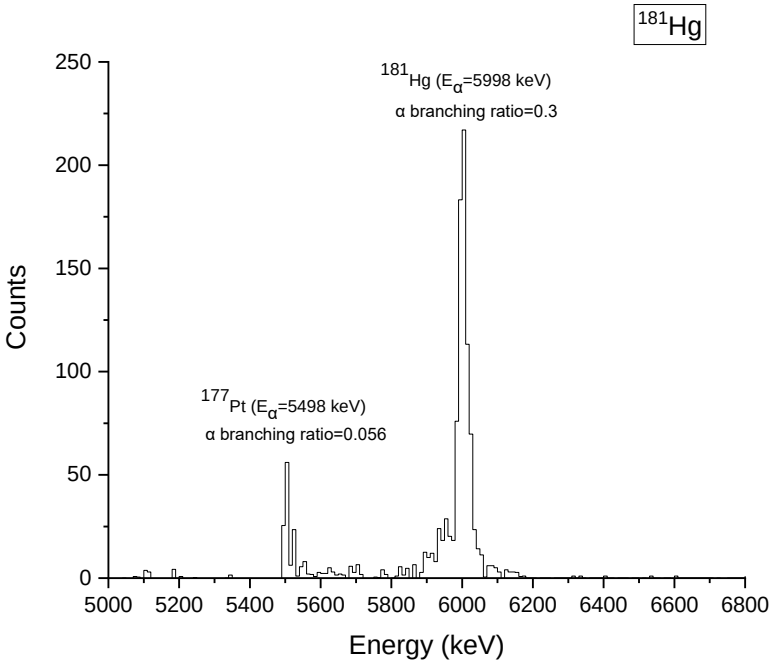

***Figure 6**: Energy spectrum of α-particles from decays of ^{181}Hg.*

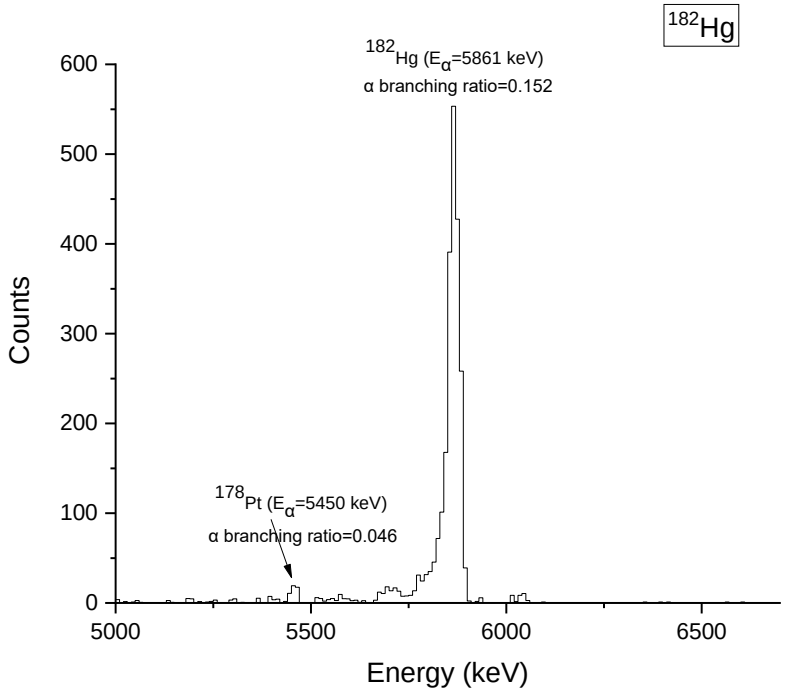

***Figure 7**: Energy spectrum of α-particles from decays of ^{182}Hg.*

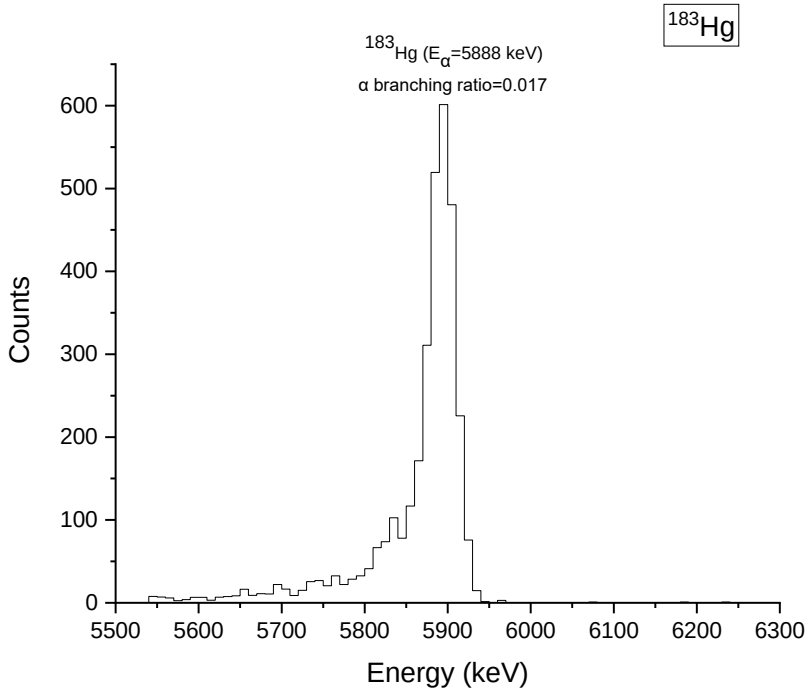

***Figure 8**: Energy spectrum of α-particles from decays of ^{183}Hg.*

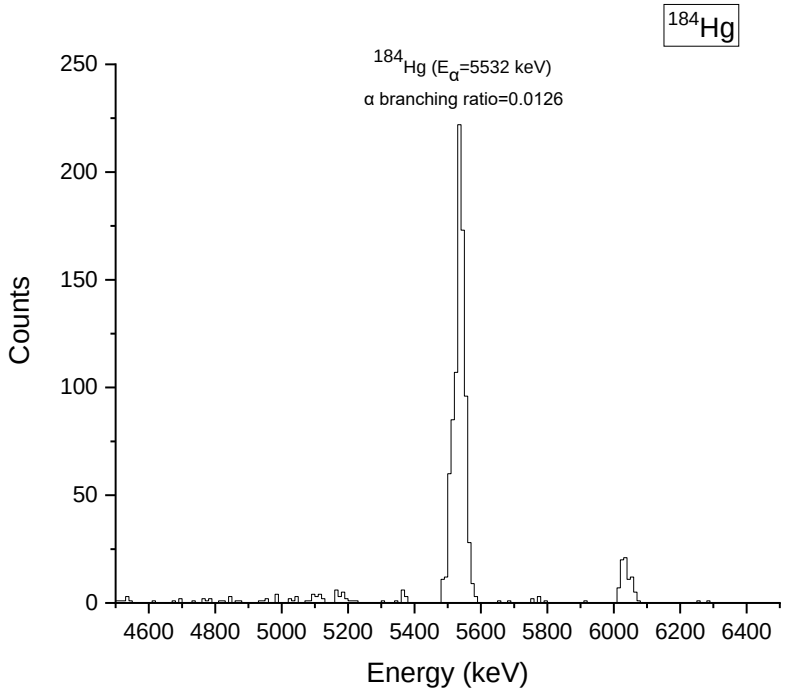

***Figure 9**: Energy spectrum of α-particles from decays of ^{184}Hg.*

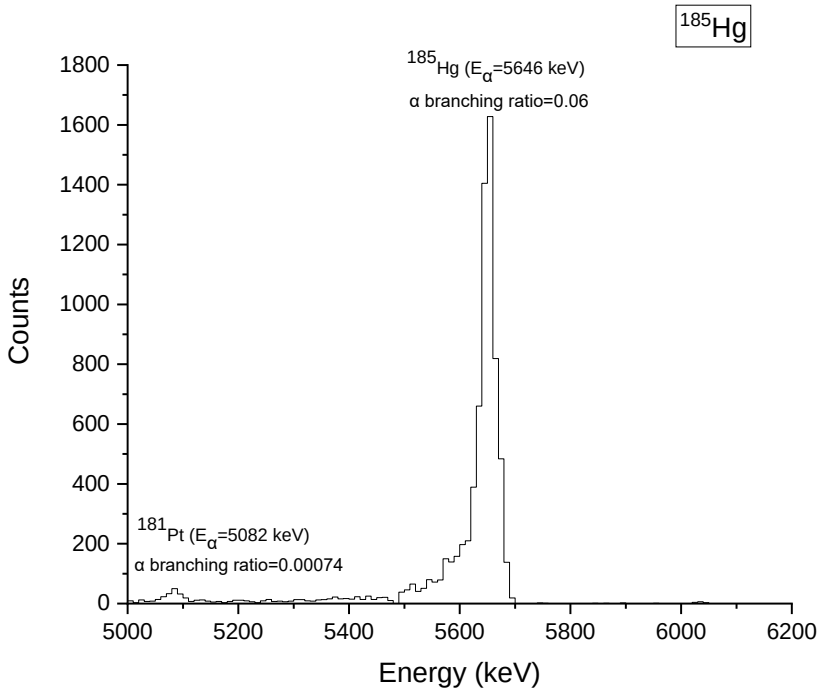

***Figure 10**: Energy spectrum of α-particles from decays of ^{185}Hg.*

***Table 1**: Hg isotopes.*

Isotope	E_α (keV)	Theoretical E_α (keV)	Half-life (sec)
^{180}Hg	6111	6119	2.58
^{181}Hg	5998	6006	3.54
^{182}Hg	5861	5867	10.83
^{183}Hg	5888	5904	9.4
^{184}Hg	5532	5535	30.9
^{185}Hg	5646	5653	49.1

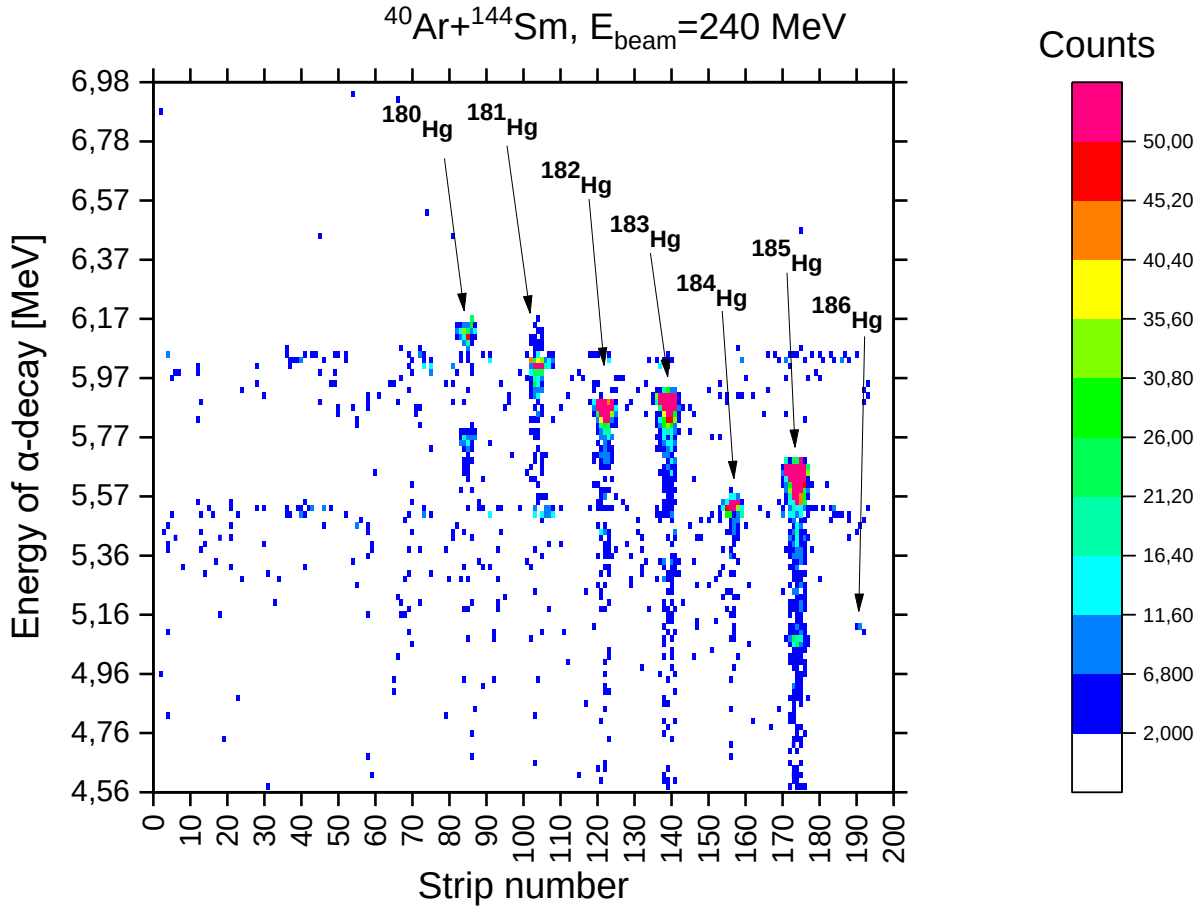

***Figure 11**: Heatmap for Hg isotopes (Energy of α-decay vs strip number).*

4.2 Production of radon isotopes in the reactions $^{40}Ar+^{166}Er$

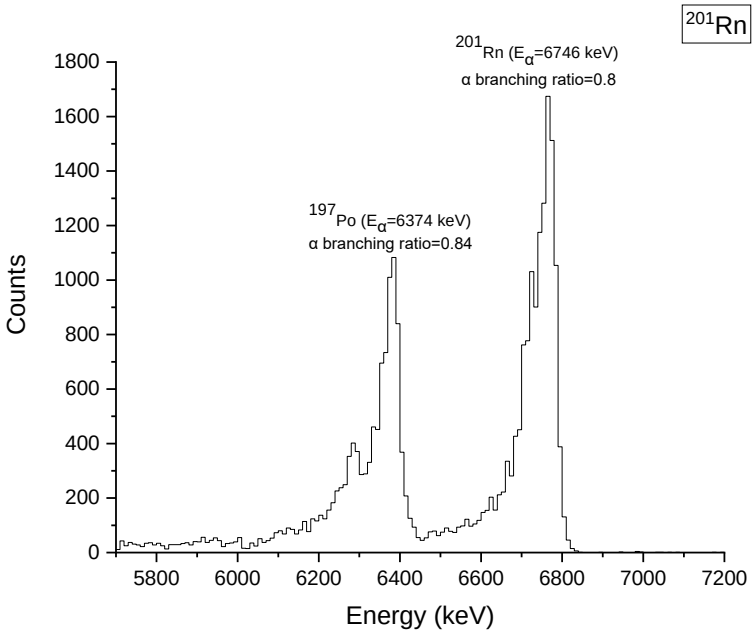

***Figure 12**: Energy spectrum of α-particles from decays of ^{201}Rn.*

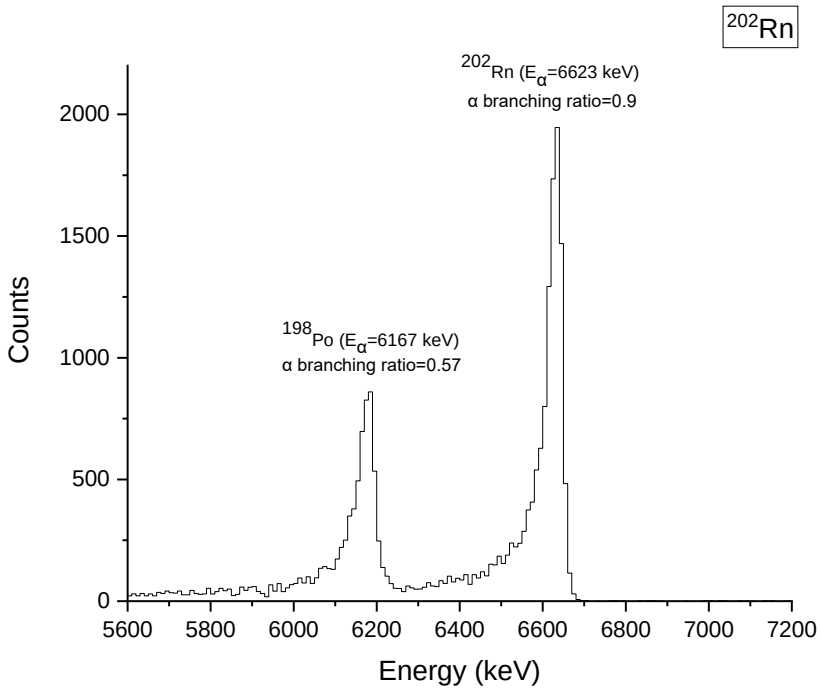

***Figure 13**: Energy spectrum of α-particles from decays of ^{202}Rn.*

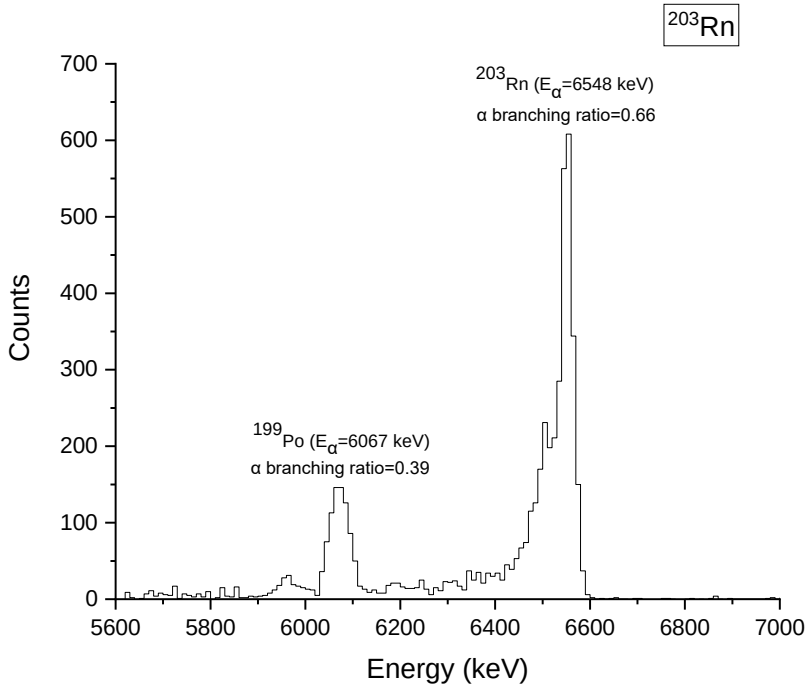

***Figure 14**: Energy spectrum of α-particles from decays of ^{203}Rn.*

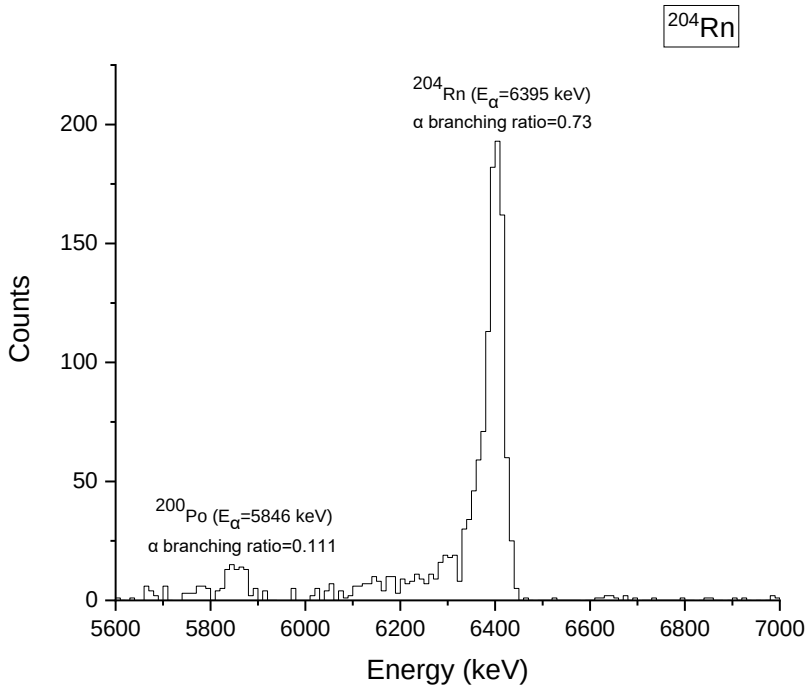

***Figure 15**: Energy spectrum of α-particles from decays of ^{204}Rn.*

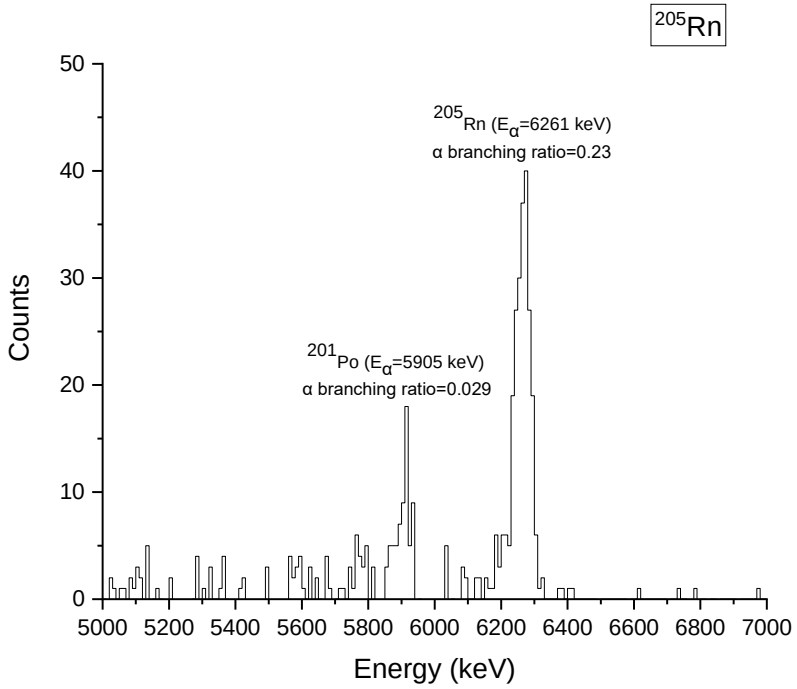

***Figure 16**: Energy spectrum of α-particles from decays of ^{205}Rn.*

***Table 2**: Rn isotopes*

Isotope	E_α (keV)	Theoretical E_α (keV)	Half-life (sec)
^{201}Rn	6746	6725	7.1
^{202}Rn	6623	6639	10
^{203}Rn	6548	6549	45
^{204}Rn	6395	6419	74.4
^{205}Rn	6261	6262	170

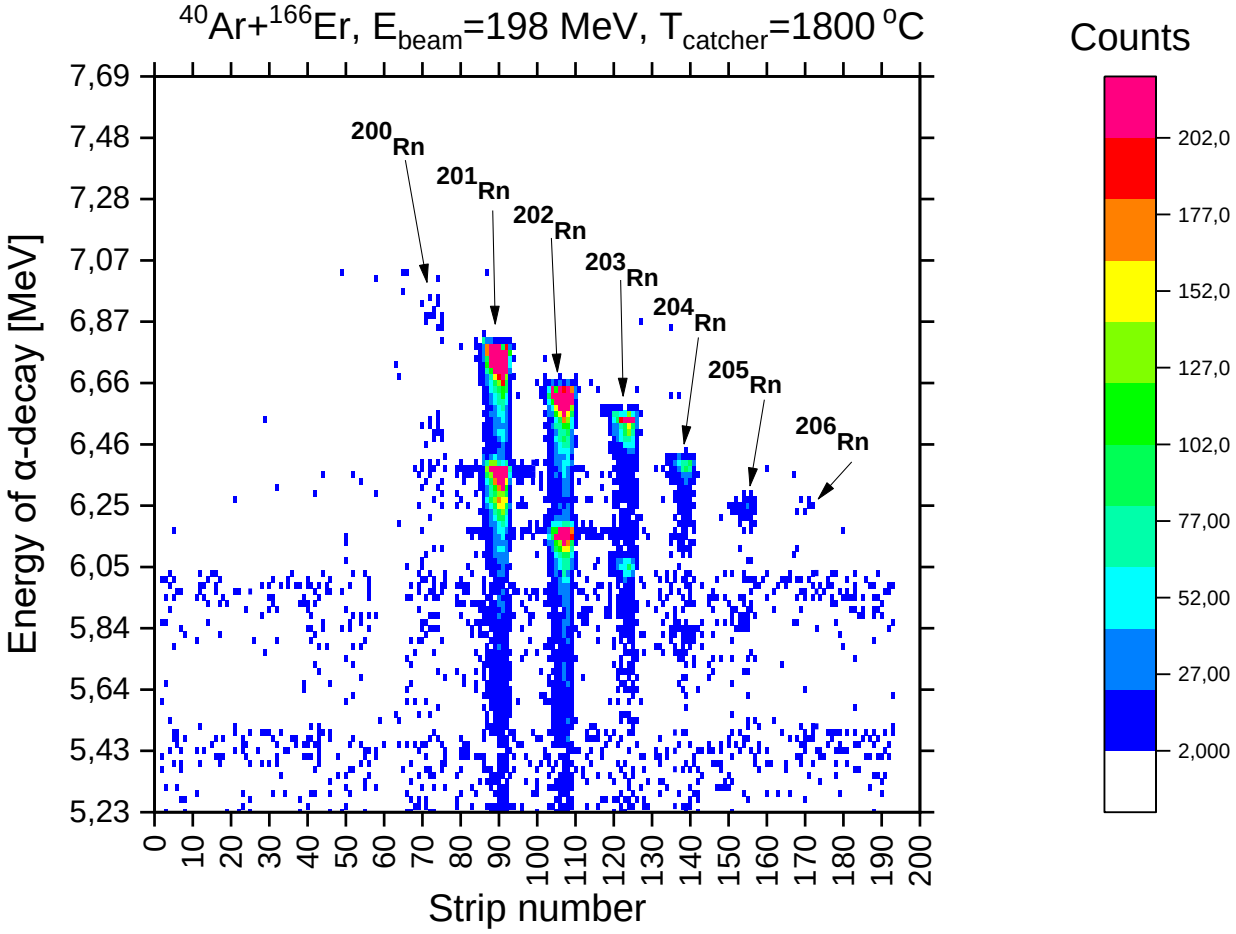

***Figure 17**: Heatmap for Rn isotopes (Energy of α-decay vs strip number).*

4.3 Production of radon isotopes in the reactions $^{48}Ca+^{242}Pu$

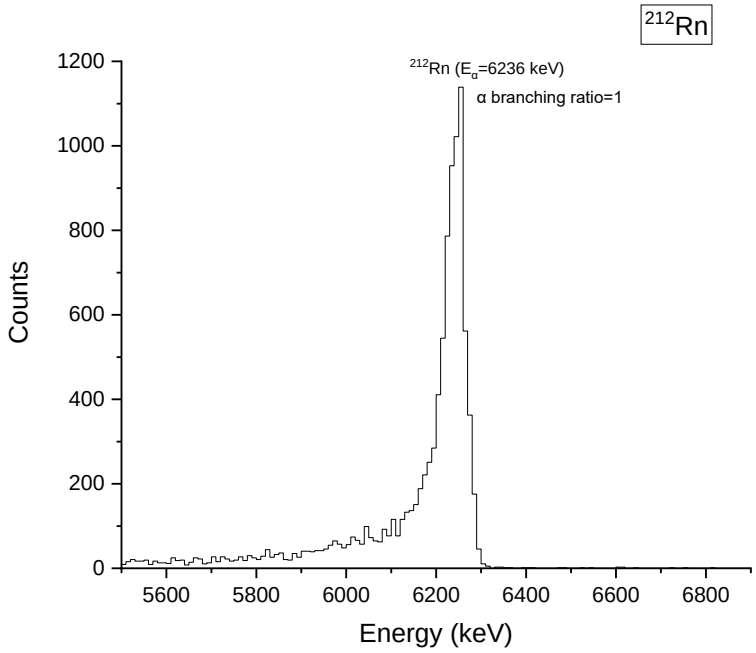

***Figure 18**: Energy spectrum of α-particles from decays of ^{212}Rn.*

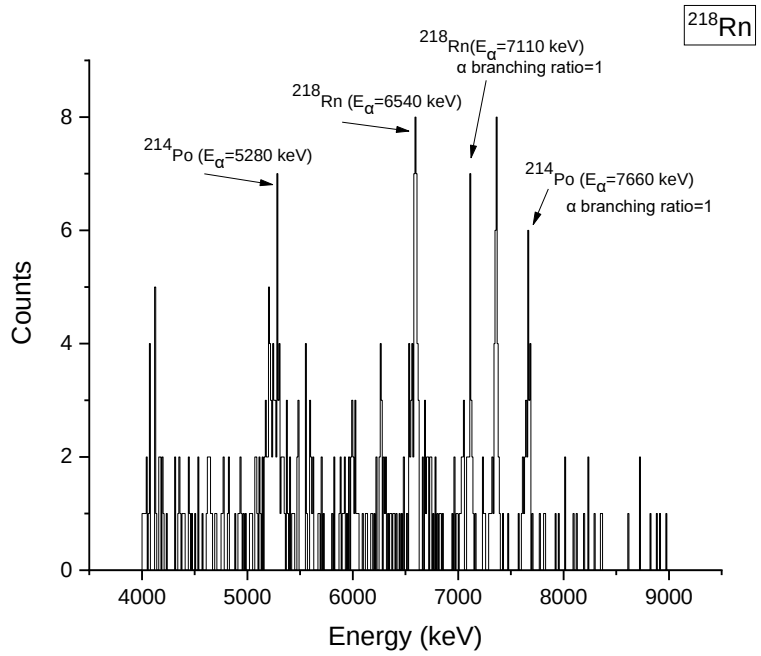

***Figure 19**: Energy spectrum of α-particles from decays of ^{218}Rn.*

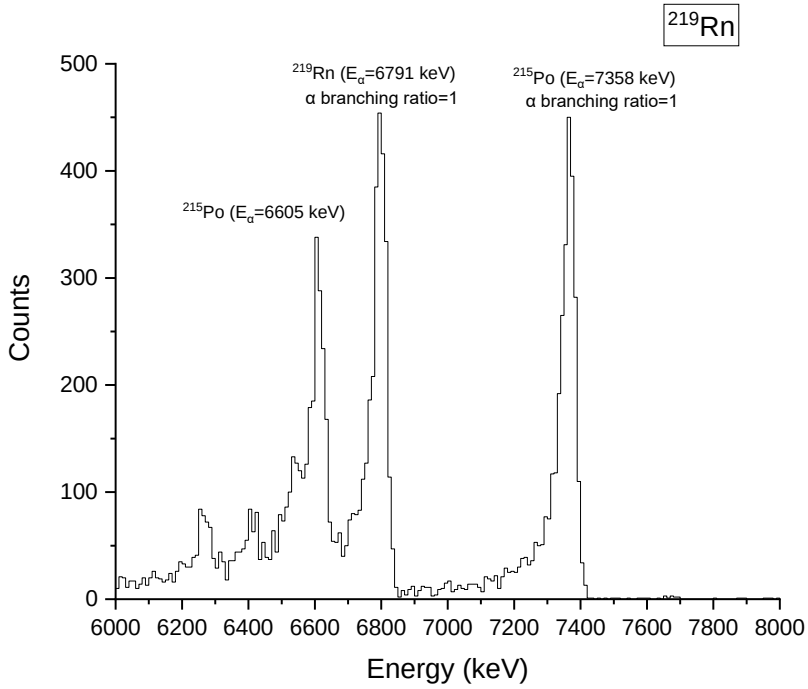

***Figure 20**: Energy spectrum of α-particles from decays of ^{219}Rn.*

***Table 3**: Rn isotopes*

Isotope	E_α (keV)	Theoretical E_α (keV)	Half-life (sec)
^{212}Rn	6236	6264	1434
^{218}Rn	7110	7129	$35 \cdot 10^{-3}$
^{219}Rn	6791	6819	3.96

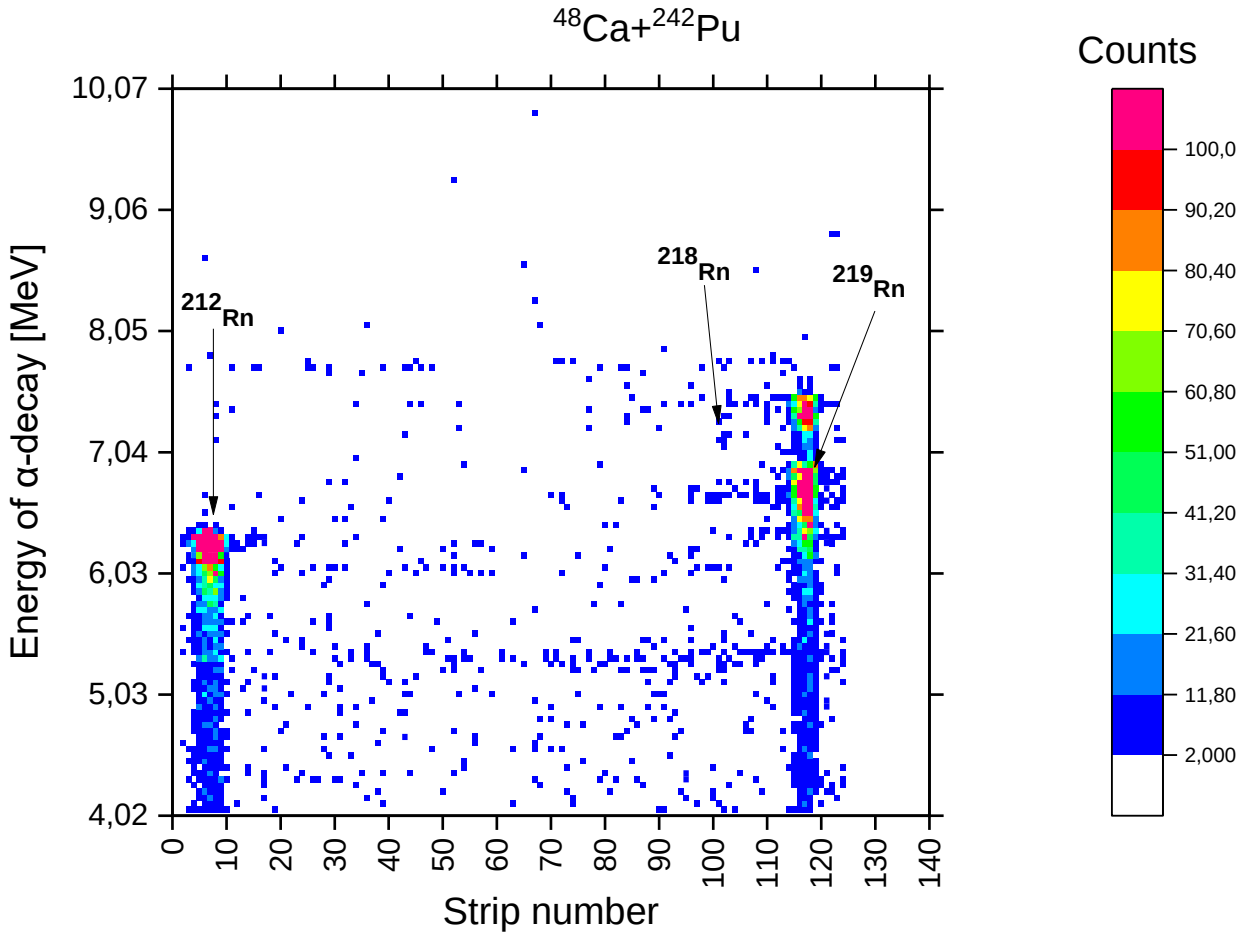

***Figure 21**: Heatmap of the isotopes ^{212}Rn, ^{218}Rn, ^{219}Rn (Energy of α-decay vs strip number). The isotopes of $^{213\text{-}217}$Rn do not exist, due to their short half-lives (less than 0.5 ms).*

5. Conclusion

In this project we described the MASHA setup and studied the Super Heavy Elements. The experimental results proved the functionality of the apparatus and moreover the energies of α-decays of isotopes from the reactions ^{40}Ar+^{148}Sm, ^{40}Ar+^{166}Er and ^{48}Ca+^{242}Pu were determined. These results were analyzed in graphs while the experimental values were compared with the literature.

6. Acknowledgements

I want to thank the INTEREST program for providing us such a great opportunity to extend our knowledge and be involved in real experimental methods in nuclear research. I also want to express my deep gratitude to my supervisor Mr Viacheslav Vedeneev for giving me the privilege to participate in this project and for his valuable guidance and support.

7. References

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