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

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Abstract

Mass Analyser of Heavy Atoms (MASHA) was built for identification of superheavy elements (SHE) by their mass-to-charge ratios. The yields of SHE in full fusion reactions ^{48}Ca + ^{242}Pu, ^{48}Ca + ^{244}Pu is very low due to its low cross-sections of several nanobarns. That is why the reactions of Hg formations as the possible homologue of 112 and 114 were used for the test experiments. The separation efficiency of mercury could predict the separation efficiency of superheavy elements and therefore predict its expected yields.

Introduction

The synthesis of superheavy elements that make up the so-called "island of stability" is an one of the main task of modern physics. Researchers are interested in investigation of heavy elements due to their shell effects, which cause them to be remarkably stable [4]. For synthesis of stable heavy nucleus, it is necessary to introduce as many neutrons as possible into it. Inasmuch neutrons have no electric charge, it allow them go inside the nucleus without impediments of electromagnetic forces, thus, making neutrons a great construction nucleons of an atomic cores. To create the nucleus of a new element, the interacting cores of the projectile and target must merge with each other, become a one. To do this, it is needed to get close enough to each other that short-range nuclear forces became to act, in other words, there is a strong interaction. Now scientists collide two heavy nuclei, expecting outcome of impact will be a core of total

mass. To conduct experiment, one of nuclei should be accelerated to a speed of about 0.1 of the speed of light using a heavy ion accelerator. All superheavy elements were obtained such way. Recent syntheses of super heavy elements (SHE) upwards with $Z = 113$ revealed nuclei with relatively long lifetimes (> 1 s) that can be chemically identified and characterized. The considerable increase in the stability of SHE points toward an initial confirmation of the existence of the island of stability [2]. It behooves to emphasize the island of stability is located in the region of neutron-excess superheavy nuclei, therefore, the target and beam nuclei must also contain excess of neutrons. Having received a beam of calcium of the required intensity, experimentalists irradiate plutonium target. If, as result of the fusion of two nuclei, atoms of new elements are formed, it should escape from target and continue moving forward together with the beam. However, it must be separated from the initial beam and other reaction products. This function is performed by the separator. Basic problem of this research is low reaction cross-section of SHE with the complex of low total efficiency, which leads to a production rate of about one atom per week of bombardment [3]. So, more powerful accelerators are being created at the moment to increase the yields of SHEs. The choice of α radioactive Hg is justified by the predicted shared chemical and physical properties of the two with elements Z = 112 and Z = 114 [1]. While the extrapolation of those properties to SHE is vulnerable to inaccuracies due to pronounced relativistic effects, it can nevertheless provide a good enough approximation for the behaviour of Cn and Fl inside the mass separator.

Brief description of setup

Mass Analyzer of Super Heavy Atoms (MASHA) [5] is designed and manufactured for the purpose of identifying the mass of superheavy nuclei using mass spectrometry technology. The unique features of the mass separator are related to its ability to measure masses synthesized isotopes of superheavy elements and simultaneously record their α-decays and spontaneous fission. The MASHA installation consists of a target assembly with a hot catcher, an ion source based on the electron cyclotron resonance (ECR), a magneto-optical analyzer (mass spectrometer) comprising four dipole magnets (D_1, D_2, D_{3a} and D_{3b}), three quadrupole lenses ($Q_{1,2,3}$) and two sextupole lenses (S_1, S_2). The detection system is located in the focal plane of the spectrometer.

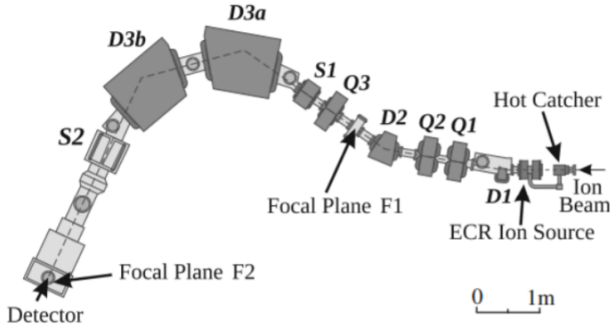

Figure 1: Mass-separator MASHA

Main parts of setup

1. Ion-Optical Layout: the mass analyzer includes four dipole magnets (D_1, D_2, D_{3a} and D_{3b}), three quadrupole lenses ($Q_{1,2,3}$), two sextupole lenses (S_1, S_2) and a focal plane detector system.
2. Electron Cyclotron Resonance (ECR) Ion Source: the ECR ion source operates at a microwave generator frequency of 2.45 GHz. The ion beam is separated by the magneto-optical mass-to-charge ratio analyzer. After the atoms of nuclear reaction products are ionized to the charge state Q=+1, they are accelerated by a three-electrode electrostatic lense. A high ionization efficiency up to 80 % measured for noble gases is obtained with this source.
3. Target box (Rotating targets + hot catcher): the hot catcher is part of the target assembly. There is the block of rotating targets, assembled into cassettes, for proliferation of efficiency and better heat distribution. The disc rotates at the frequency of 25 Hz via Siemens electric engine. The hot catcher represents the foil from thermally expanded graphite heated directly by current for absence heating losses and provides regularity of heating. Foil has a polygraphene structure with a density of 1 g/cm^3 and a thickness of 0.6 mm. It uses thin graphite foil because of connection to its thermal reliability instead titanium

foil [5]. The reaction products separate from ion beam. Needed products cool down and stop inside solid carbon catcher. During stop ions fulfill their electron orbitals, thus recombinate, and diffuse from the catcher, because it's heated up to quite high temperature and transport to the ECR ion source, where it is ionizes to +1 charge state and get enough energy to go further as a secondary beam through magnetic mass separator. Here the loose of atoms is very high, measured efficiency of the solid ISOL-method is about 7 % and transportation time reaches 2 seconds, which can be inappropriate for the measurements the properties of short-lived isotopes. At this stage the main losses in time and efficiency occur, especially, reaction product yields from aggregate phase of graphite.
4. Detectors and Control Systems: In order to detect the reaction products, a silicon strip detector system is used in the MASHA. Each strip is an electrically isolated silicon detector of step 1.25 mm in a focal plane. When the nuclei sit on a detector surface it starts to decay in all 4π sphere. To cover as much as possible space, detector configuration is well-type with focal and side crystals. This type of detector can detect alpha particles and fragments, which is suitable for neutron-deficient alpha active nuclei and has an energy resolution of about 25 keV. For the neutron-rich nuclei, which decays mainly by beta minus mode the TIMEPIX pixel detector is used and could be located inside chamber except one of the strip detector crystal. It represents an all-in one box with sensitive area of 14×14 mm area consisting the 256×256 pixel and could be used as a tracking two-dimensional detector.

Initial ion beam energy measurement

It is one of the most important thing to be aware of an incoming beam energy. Due to low reaction cross-section of SHE (about units of picobarns) even at a normal radiation intensity of 0.5 pmkA, it takes weeks to produce a single atom SHE. In addition, the peak definitions of it lays in a very narrow energy interval. Hence, if the energy is determined imprecisely the yields of nuclei drops drastically. For these reasons, there are 3 independent energy measurement units at MASHA installation: 2 pick-up detectors, located before entrance to the installation on a heavy ion beamline and working as the time-of-flight, 2 microchannel plate detectors and one silicon pin diode on a latter works as the total kinetic energy calorimeter.

Method

The beam is accelerated with the U400M cyclotron then goes through the target box then the not interacted beam and the reaction products are stopped by the hot catcher. The recoil nuclei that escape from the target layer stop in the graphite catcher at a depth of several micrometers. Due to the high temperature

of the catcher, they diffuse into the ion source chamber, are extracted from the plasma with the help of three-electrode electrostatic lenses, accelerated by an electric field, and analyzed by mass by magnetic fields as they move towards the detector. In this design, the mass of the atom can be determined with mass resolution of about $\frac{M}{\mathrm{d}M} = 1600$. Since the reaction products tend to decay. Then the matrix of α-energies is formed by the number of strips. The strip number corresponds to the mass number.

Data analysis

Applied data collection programs allow to observe one-dimensional energy spectra from each strip and two-dimensional spectra of the energy dependence on the strip number. The decay energies were measured for the Hg and Rn isotopes. Comparison of the results with the tabular energy of α-decays allows us to determine each isotope. The main source of background is background of detector, active electronic gadgets, cosmic rays and others.

Task

The challenge includes plotting and analyzing data from the detectors, which were obtained from three different reactions. Then, based on the results, it is determined the decay energy, alpha branching ratio and the isotopes, implementing a calibration of the strip detector. Results are showed on the heat map.

Outcomes

The synthesis of Hg and Rn was investigated using the reactions
1. $^{40}\mathrm{Ar} + {}^{144}\mathrm{Sm} \rightarrow \mathrm{Hg}$, $E_{\mathrm{beam}} = 5 - 7$ MeV/n
2. $^{40}\mathrm{Ar} + {}^{166}\mathrm{Er} \rightarrow \mathrm{Rn}$, $E_{\mathrm{beam}} = 5 - 7$ MeV/n
3. $^{48}\mathrm{Ca} + {}^{242}\mathrm{Pu} \rightarrow \mathrm{Rn}$ (multi-nucleon transfer reactions)

The data were processed by OriginPro software environment, where data of the energy spectra of the α-decays were entered in the form of ASCII-tables. In this case, α-spectrum obtained isotopes were illustrated taking into account the evaporation of a certain number of neutrons from the excited compound nucleus.

Due to the short lifetime of radon isotopes $^{212}\mathrm{Rn}$, $^{218}\mathrm{Rn}$, $^{219}\mathrm{Rn}$, MASHA was unable to identify these isotopes. These isotopes decay on the way to the detector, without getting to it: their half-life is shorter than counted installation separation time.

Table 1: α-decay energies of the produced isotopes with the values from literature

№	изотоп	$T_{1/2}$ s	E_α keV	$E_{\alpha_t ab}$ keV
1	^{180}Hg	2.58	6120	6119
2	^{176}Pt	6.3	5750	5753
3	^{181}Hg	10.83	6000	6006
4	^{177}Pt	11	5500	5517
5	^{182}Hg	9.4	5860	5867
6	^{183}Hg	30.9	5890	5904
7	^{179}Pt	21.2	5830	5834
8	^{184}Hg	49.1	5530	5535
9	^{185}Hg	82.8	5650	5653

Table 2: α-decay energies of the produced isotopes with the values from literature

№	изотоп	$T_{1/2}$	E_α keV	$E_{\alpha_t ab}$ keV
1	^{201}Rn	7	6760	6725
2	^{197}Po	25.8	6380	6383
3	^{202}Rn	10	6630	6639
4	^{198}Po	106.2	6180	6182
5	^{203}Rn	28	6550	6549
6	^{199}Po	250.2	6060	6059
7	^{204}Rn	74.4	6400	6418.9
8	^{200}Po	690	5840	5861.9
9	^{205}Rn	170	6270	6262
10	^{201}Po	534	5760	5786

Table 3: α-decay energies of the produced isotopes with the values from literature

№	изотоп	$T_{1/2}$	E_α keV	$E_{\alpha_{tab}}$ keV
1	^{212}Rn	1434	6250	6264
2	^{218}Rn	2100	6590	6590
3	^{218}Rn	2100	7360	7129
4	^{219}Rn	3.96	6790	6819
5	^{219}Rn	3.96	6600	6552
6	^{215}Po	$1.78 \cdot 10^{-3}$	7360	7386

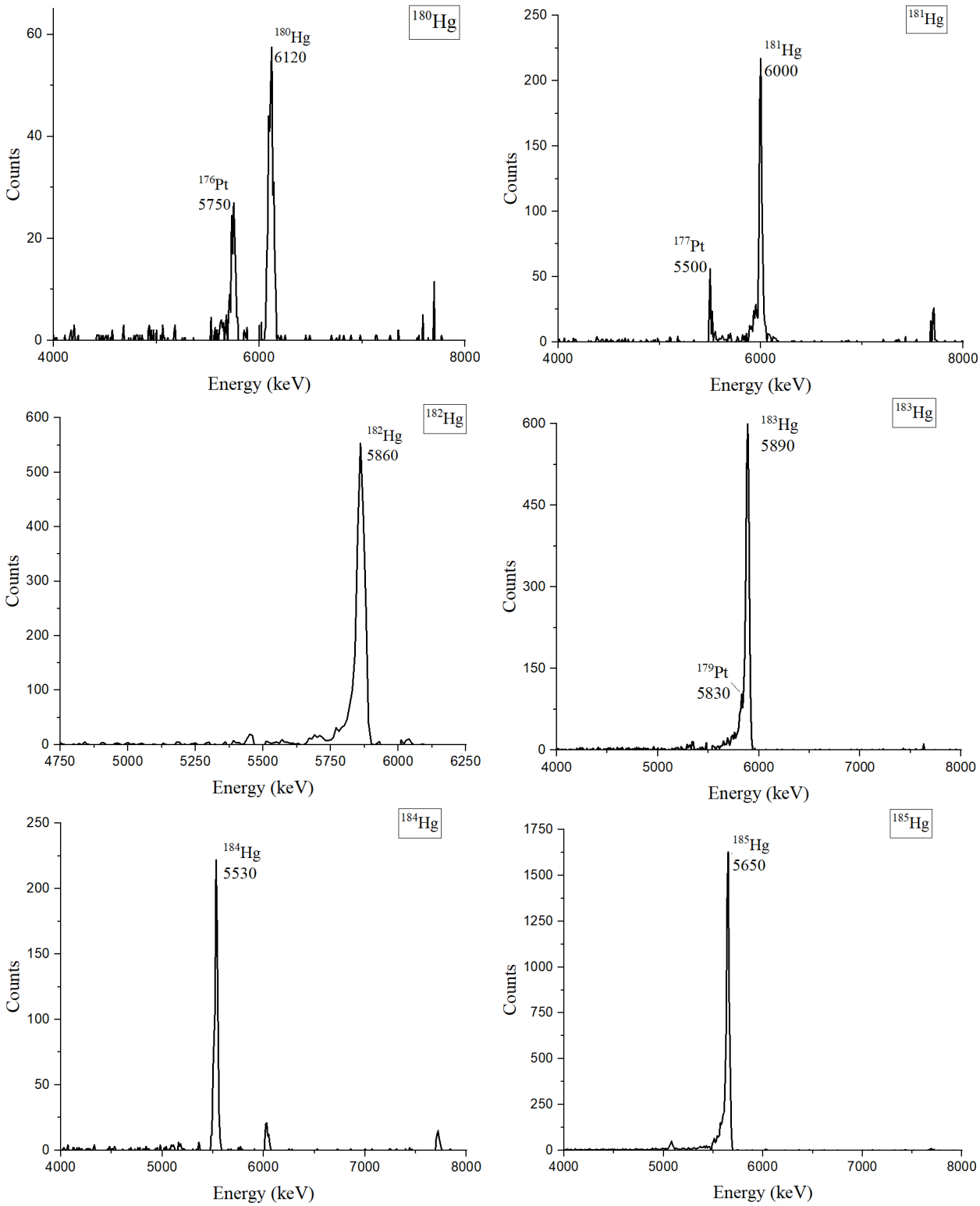

Figure 2: Energy spectrum of the α-particles from decays of Hg

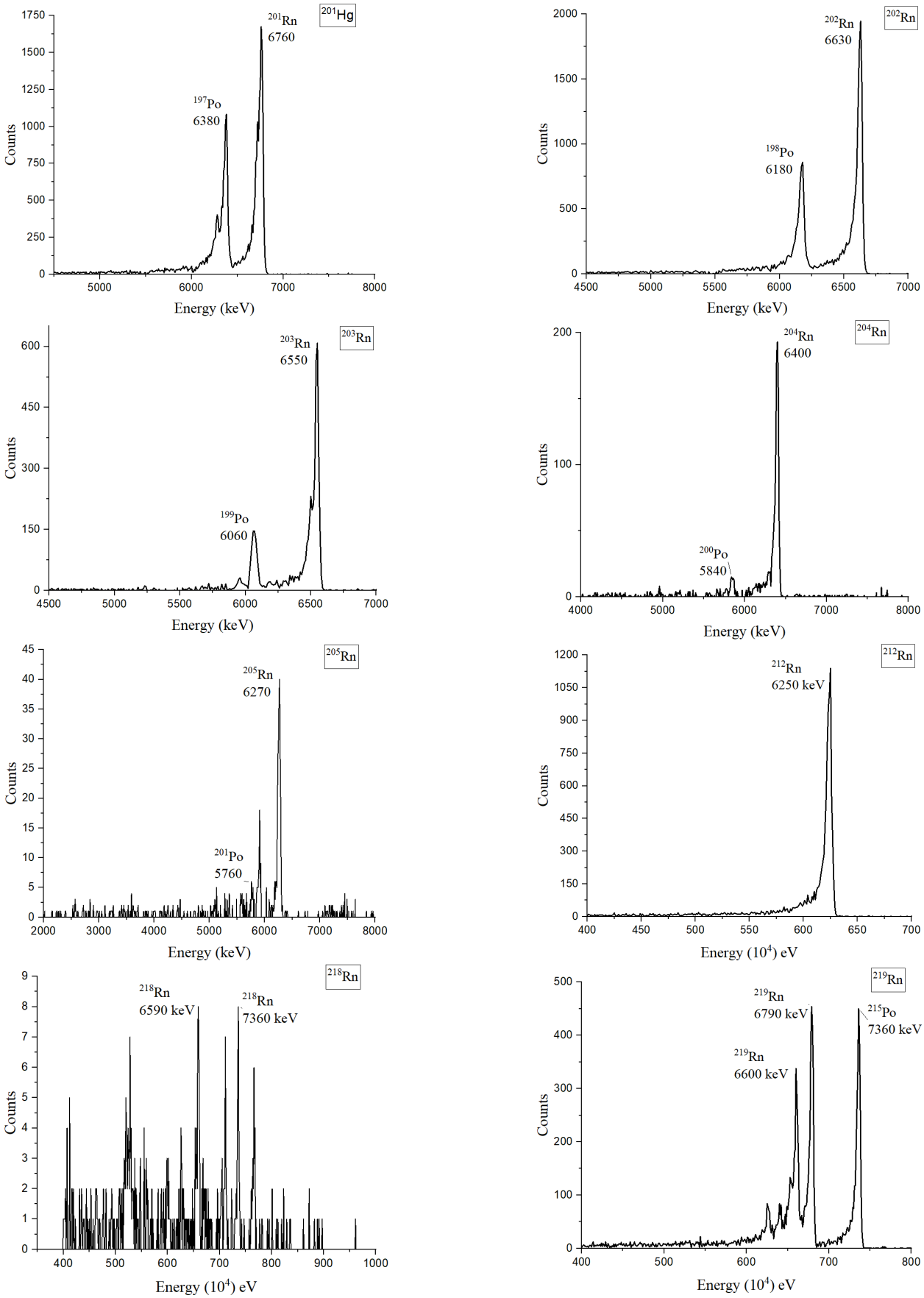

Figure 3: Energy spectrum of the α-particles from decays of Rn

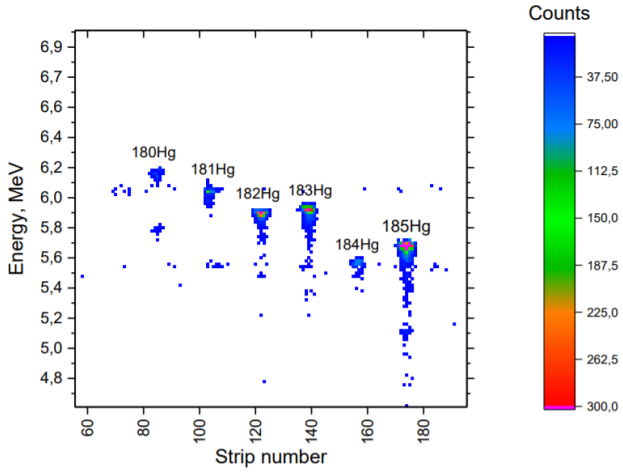

Figure 4: Energy and strip number plot of the α-particles from decays of mercury isotopes

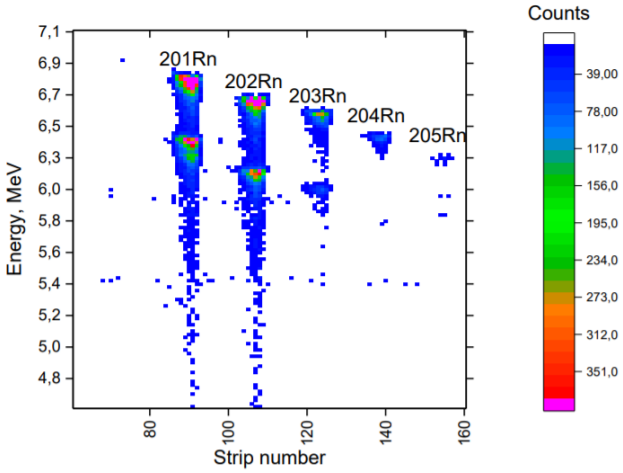

Figure 5: Energy and strip number plot of the α-particles from decays of radon isotopes

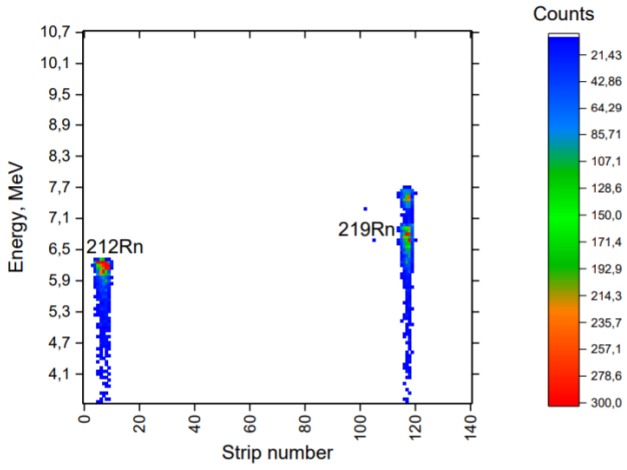

Figure 6: Energy and strip number plot of the α-particles from decays of radon isotopes

Conclusion

The mass-separator MASHA was constructed to identify the superheavy elements by their mass-to-charge ratio and getting additional details by using the detector system. In the focal plane of the silicon detector, products of the above given complete fusion reactions and multi-nucleon transfer reactions were detected. α-spectra of the evaporative residues of the complete fusion reactions were analyzed. Defined energies are well-matched with the values from the literature.

Acknowledgments

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