JOINT INSTITUTE FOR NUCLEAR RESEARCH
Flerov Laboratory of Nuclear Reactions

FINAL REPORT ON THE INTEREST PROGRAMME

Optimization of the solid ISOL method for volatile reaction products of heavy ion beam reactions

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Abstract:

Physicists were able to create new and unstable heavy elements in the 1940's. With the discovery and development of new superheavy materials, researchers' interest has not stopped, leading to concepts such as "Island of Stability" and "Sea of Instability." The MASHA (Mass Analyzer of Super Heavy Atoms) mass spectrometer was designed for the identification and measurement of physical properties of superheavy elements, such as decay energy and modes, mass and half-lives. A strong ISOL (Isotope Separation On-Line) system is used for the MASHA setup. These experiments are being carried out at the MASHA facility of the Flerov Laboratory of Nuclear Reactions (FLNR) of the Joint Institute of Nuclear Research (JINR).

Introduction:

The On-line Method of Isotope Separation (ISOL) is an efficient separation method that is used to isolate the reaction products, where the super heavy isotopes are isolated from the reaction products. The ISOL system is carried out through many steps: production, thermalization, ionization, extraction, mass separation, cooling, charge-state breeding, and acceleration. The ISOL techniques depend on the availability of the radioactive species produced in a target and thermalized in a catcher consisting of solid, liquid or gas material. The target and catcher are often one and the same system. The isotopes are subsequently extracted from the catcher material and ionized in an ion source. The species will be mass analyzed using a dipole magnet after extraction from the ion source and then accelerated to the required energy. The ultimate aim for ISOL systems is the production of beams of exotic nuclei that are abundant, pure, of good ion optical quality and variable in energy basically from rest to intermediate energy. The whole production sequence must possess the following properties:

Efficient:

The production rate of the very exotic nuclei will always be marginal. Therefore, any manipulation of the reaction products – e.g., ionization, purification, acceleration, and transport to the detection system has to be very efficient; otherwise the precious nuclei will be lost.

Selective:

The unwanted, usually more stable, nuclei are produced much more abundantly in the nuclear reaction process. Furthermore, ISOL systems often produce beams of isotopes from the target material itself or from other components of the target-ion source system. Therefore, in an efficient way, the separation mechanism could differentiate between the desired and unwanted species.

High Production Rate:

The production cross-section of a particular reaction is energy dependent. Accelerators that can produce the highest beam intensities have to be used and target systems have to be produced that can cope with the primary beam and secondary reaction products' power deposition.

Fast:

As we are dealing with short-lived exotic nuclei, the losses due to radioactive decay between the moment of production and the arrival at the experimental set-up should be kept to a minimum.

MASHA:

The Mass Analyzer for Heavy Atoms Mass Analyzer (MASHA) is a setup that uses a combination of the ISOL method and the classic magnetic mass analysis method to separate the super heavy elements. It is designed for the determination of the masses of super heavy elements as reaction products. This separator allows to measure on-line the mass-to-charge ratios of super heavy element isotopes with simultaneous detection of their alpha-decays and spontaneous fission. Both a fast-on-line separation of the nuclides with half-lives from 0.6 to 30s and a high separation efficiency needed for reactions with low cross sections (< 5 pb) are of importance in these measurements. The MASHA was constructed at one of the beam outs of U-400M cyclotron in the Flerov Laboratory of Nuclear Reactions, JINR at Dubna, Russia.

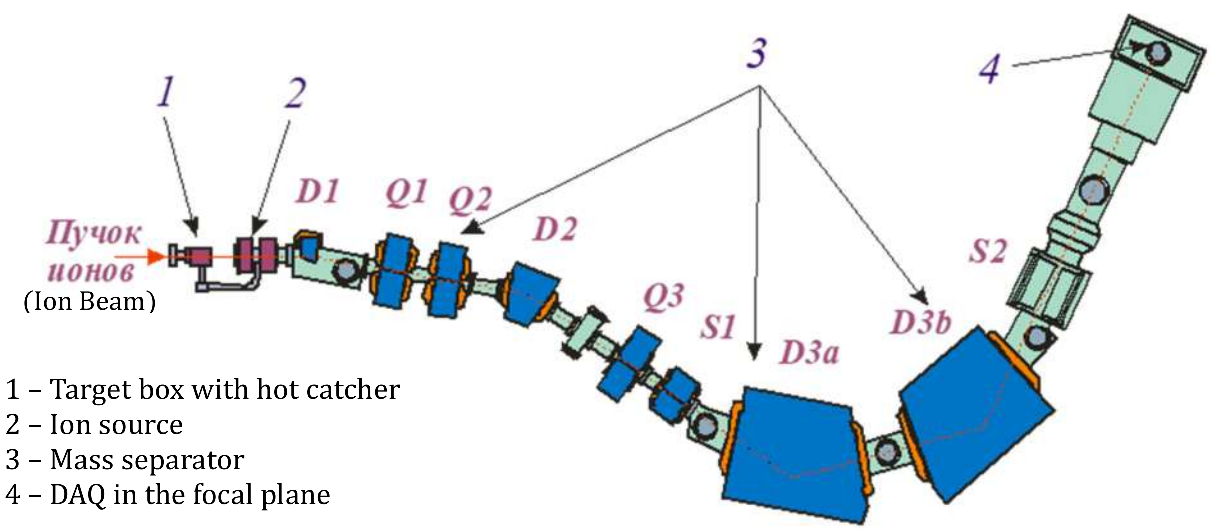


Figure: Mass Analyzer for Heavy Atoms Mass Analyzer (MASHA)

Target box & hot catcher:

The recoil nuclei, flying out of the target, are implanted into a catcher heated to a temperature T_{heat} ~1800-2000K. The target is a rotating one represents the wheel with sectors, assembled into 6 cassettes, with 2 sectors each. The thickness of the target is determined by the range of the recoil nuclei in the working layer, it depends on the kinetic energy of the heavy atom produced from the fusion reaction. The idea to use a rotating target instead of stationary target is better efficiency and heat distribution.

The material of hot catcher is flexible thermally expanded graphite which have the porous polygraphene structure with porosity of 75%, that has density of 1 g/cm3, thickness of 0.6 mm, and it is shaped as a 30 mm diameter disk. Also, its operating temperature is 1800~2000 K and its delivery time of nuclides to the ion source (ECR) (the separation time determined with the beam interruption method [3]) is 1.8±0.3 s.

Ion source:
Atoms diffused from the heated catcher are injected into the ion source. We use ion source of the ECR type that operates at high frequency of 2.45 GHz. When the atoms reach the ECR they ionized to the charge Q=+1, then there is three electrode electrostatic lens that accelerate the ions accelerate the ions up to 38 keV and the ion beam formed is then separated by the magneto-optical mass-to-charge ratio analyser[4]. The ion beam formed is separated by the magneto-optical mass-to-charge ratio analyser. The ionization efficiency obtained for noble gases is about 90%.

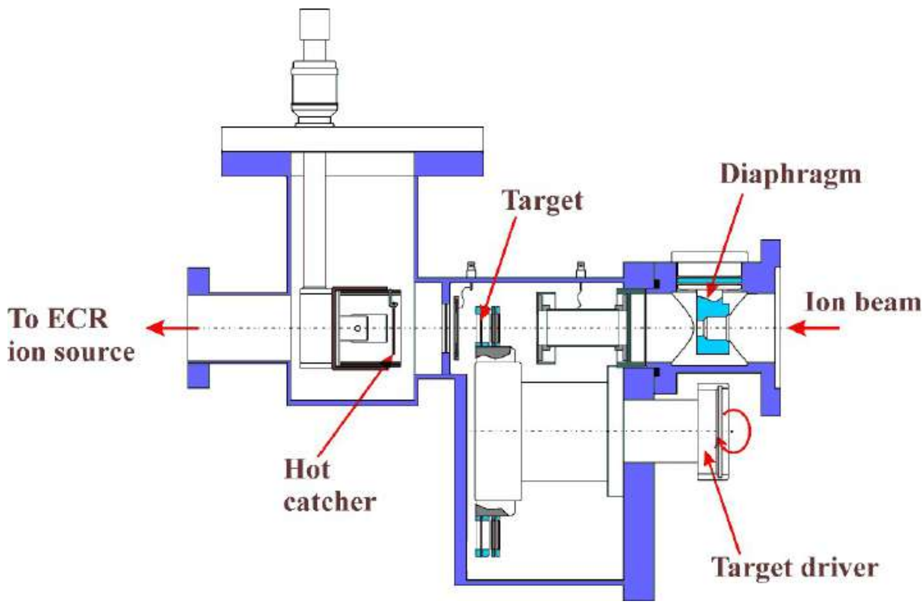


Figure: Hot Catcher Scheme

The mass separator:
The mass separator in this set up is a magnetic-optical analyser. The separation of ions depends on their magnetic rigidity in a permanent magnetic field. The determination of the mass of super heavy atoms is done with accuracy of Δm=0.25-0.30 e.m.u.

DAQ in the focal plane:
In the focal plane of the magnetic analyser detectors are placed, which register the position and decay of the separated atom. The well-type position sensitive strip construction of detector with a focal, side and lateral crystals make it possible to register and determine the masses and decay energies both of evaporation residues and of their daughter decay products with a bigger geometric efficiency. The registration of the atoms in the focal plane of the separator requires exclusion of the alpha-particle background from the decay of target-like nuclei, especially from the decay products of light isotopes of actinide elements (Th and U), produced in deep inelastic collisions or quasi-fission. These nuclei are some 40-60 e.m.u. away from the mass of the superheavy atom and can be separated already at the intermediate focal plane.

Task Results:

The task given was to take data from of products of three different reactions (complete fusion neutron evaporation residues and multinucleon transfer)

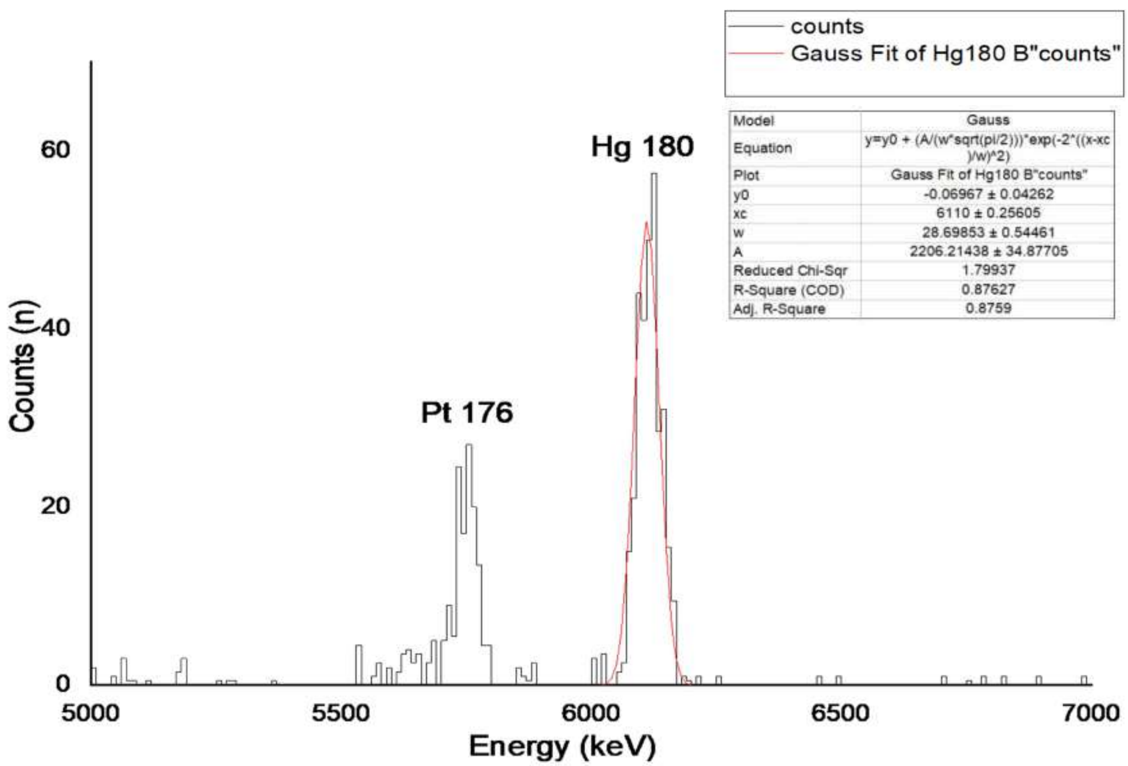
($^{40}Ar+^{148}Sm \longrightarrow ^{188-xn}Hg+xn$),
($^{40}Ar+^{166}Er \longrightarrow ^{206-xn}Rn+xn$) and
($^{48}Ca+^{242}Pu \longrightarrow ^{21x}Rn$).

Draw their histograms and analyse the peaks of their alpha energy radiation and their daughter nuclei, then draw their heat maps.

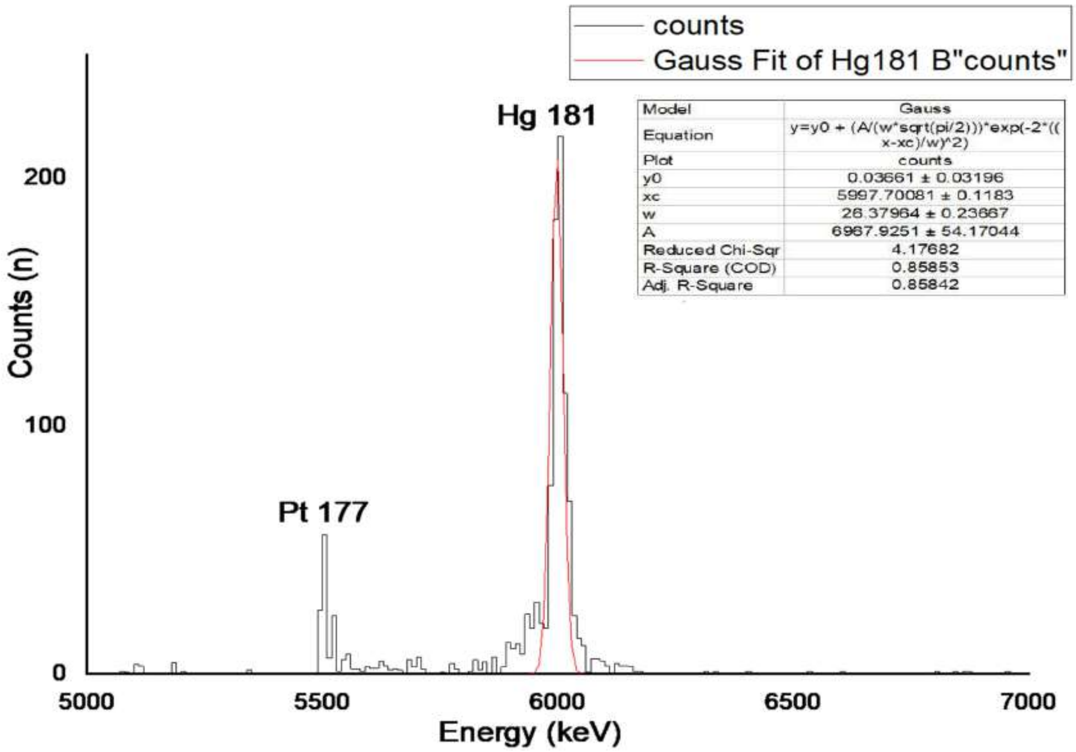
1. $^{40}Ar+^{148}Sm \longrightarrow ^{188-xn}Hg+xn$

This fusion reaction gives mercury isotopes with different mass numbers (180,181,182,183,184,185)

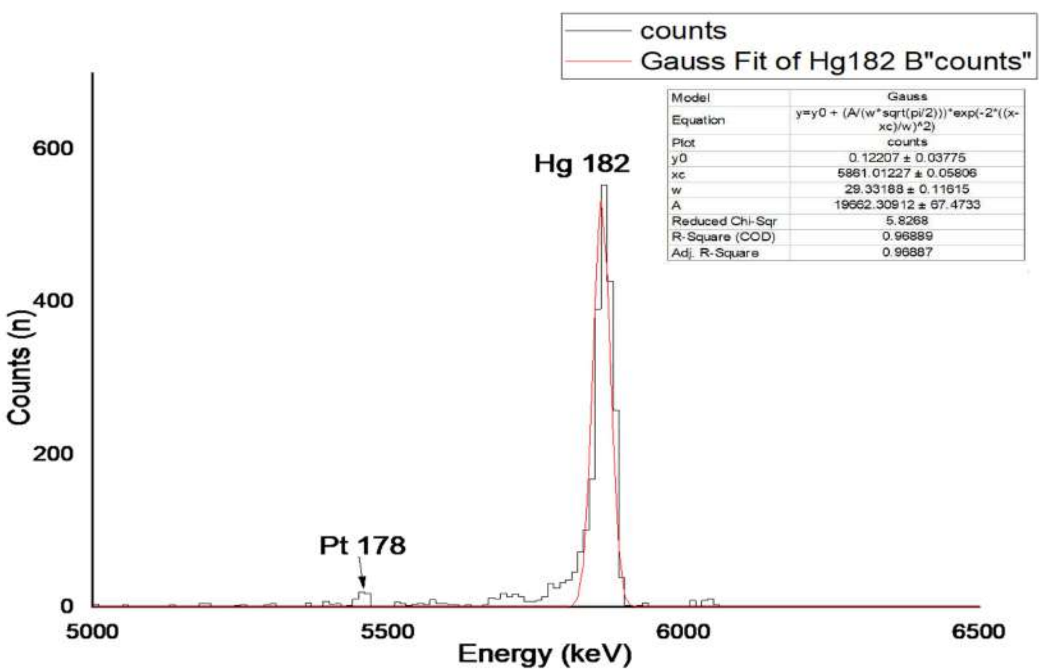
a) Hg 180:
   This mercury isotope has half-life time of 2.58 seconds, it 48% decays by alpha of energy 6118 keV, giving a daughter Pt 176 that has half-life of 6.35 s and it 40% decays by alpha of energy 5753 keV.



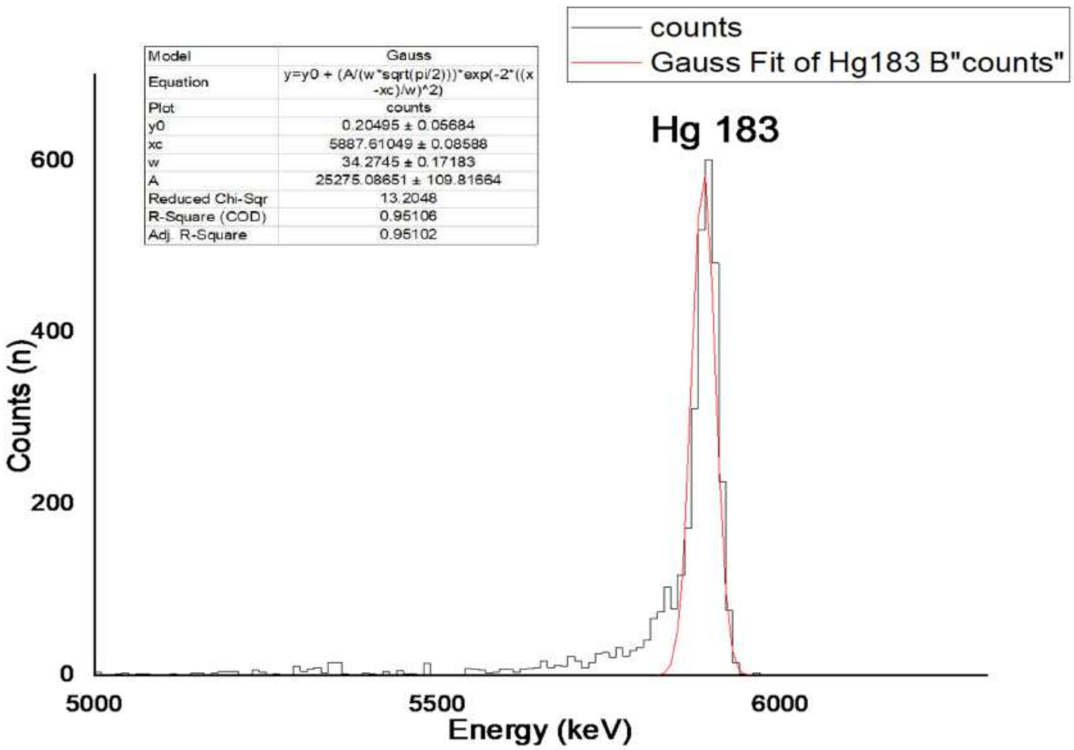
b) Hg 181:
It has half-life of 3.5 s, and it 30% decays by alpha of energy 6006 keV, giving a daughter Pt 177 that has half-life time 11 s, and it 5.6% decays by alpha of 5517 keV.



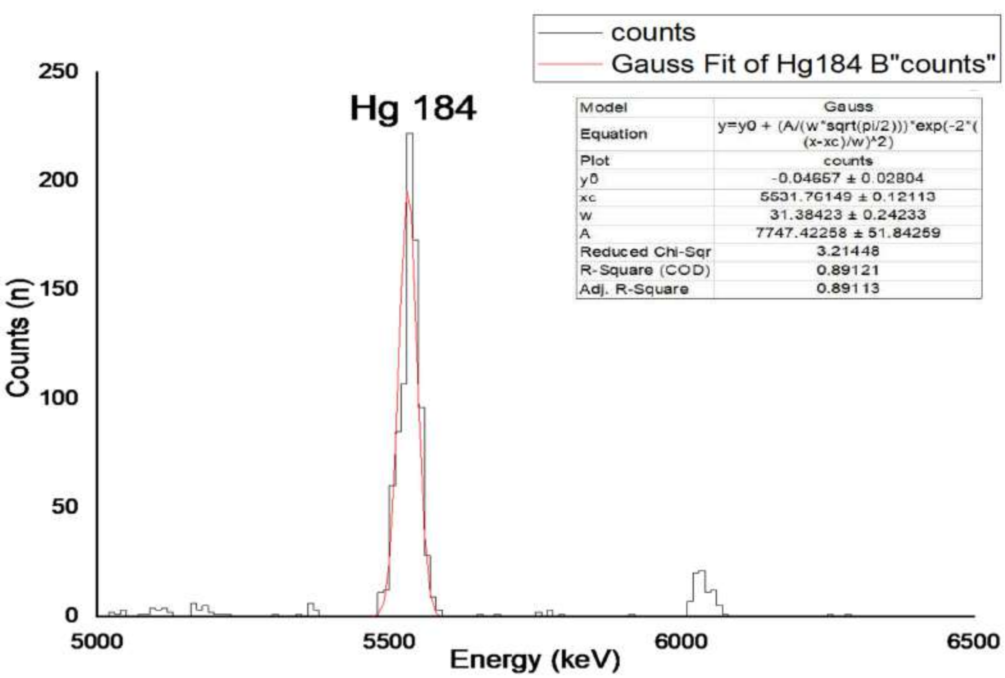
c) Hg 182:
It has half-life time of 10.835 s, and it 15.2% decays by alpha of energy 5867 keV, giving a daughter Pt 178 that has half-life of 21.1 s and it 4.6% decays by alpha of energy 5446 keV.



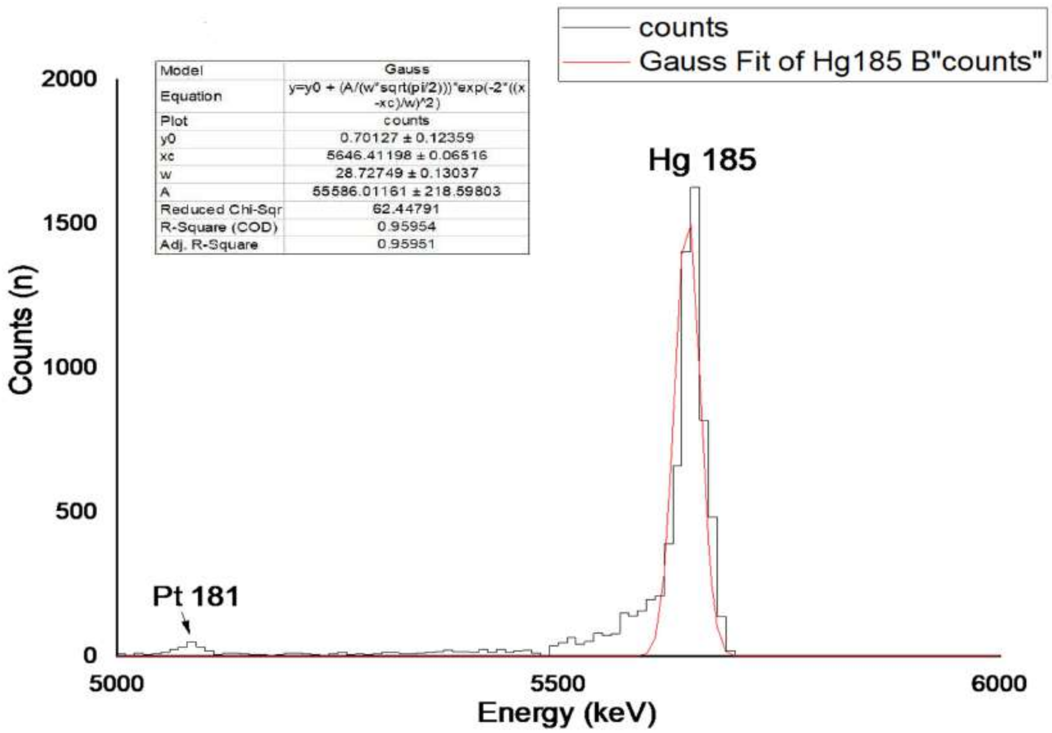
d) Hg 183:
It has half-life of 9.4 s, and it 11.7% decays by alpha of energy 5904 keV, giving a daughter Pt 179 that has half-life of 21.1 s, and it 0.24% decays by alpha of energy 5195 keV.



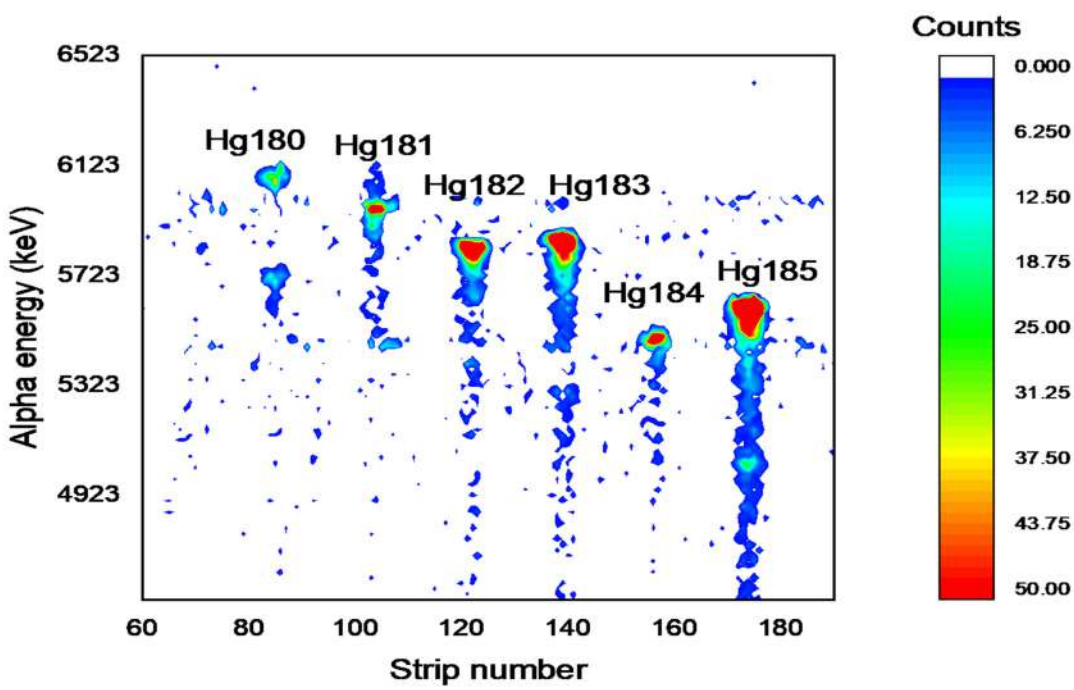
e) Hg 184:
It has half-life of 30.9 s, and it 1.26% decays by alpha of energy 5535 keV, giving a daughter Pt 180 that has half-life of 56 s, and it 0.3% decays by alpha of energy 5140 keV.



f) Hg 185:
It has half-life of 49.1 s, and it 6% decays by alpha of energy 5653 keV, giving a daughter Pt 181 that has half-life of 52 s, and it 0.074% decays by alpha of energy 5036 keV



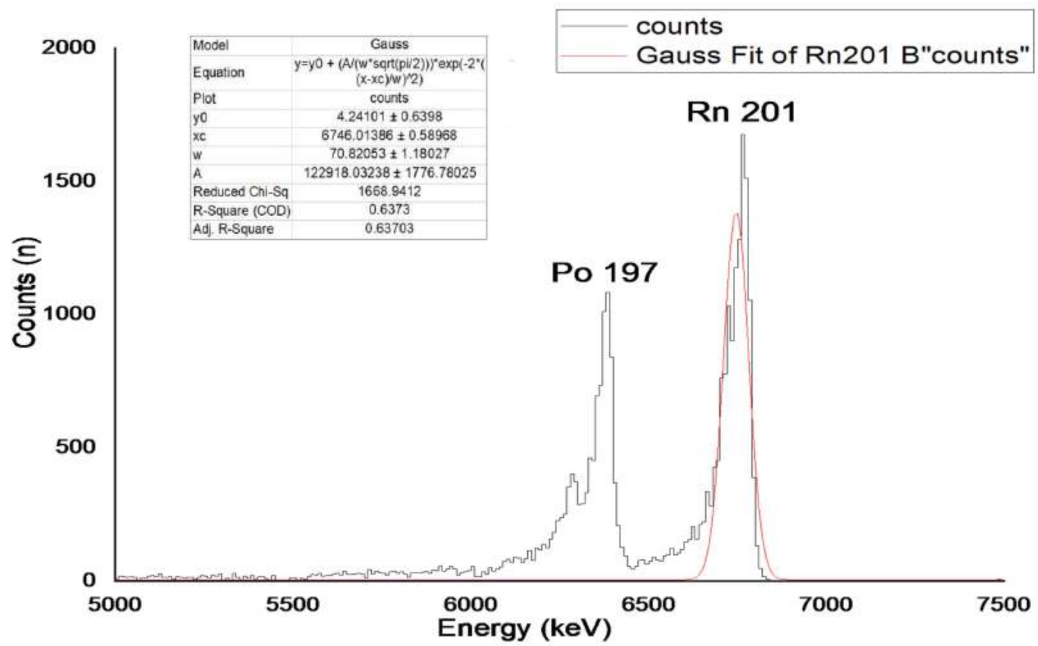
The heat map for mercury isotopes:



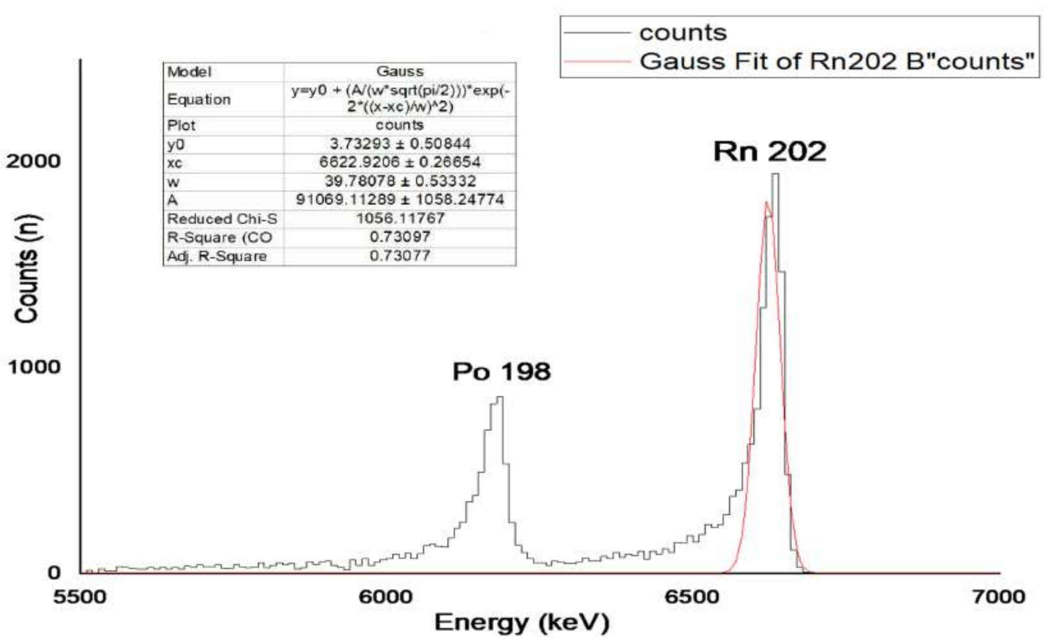
2. $^{40}Ar + ^{166}Er \longrightarrow ^{206-xn}Rn + xn$

This reaction yields Radon isotopes with different mass numbers (201,202,203,204,205)

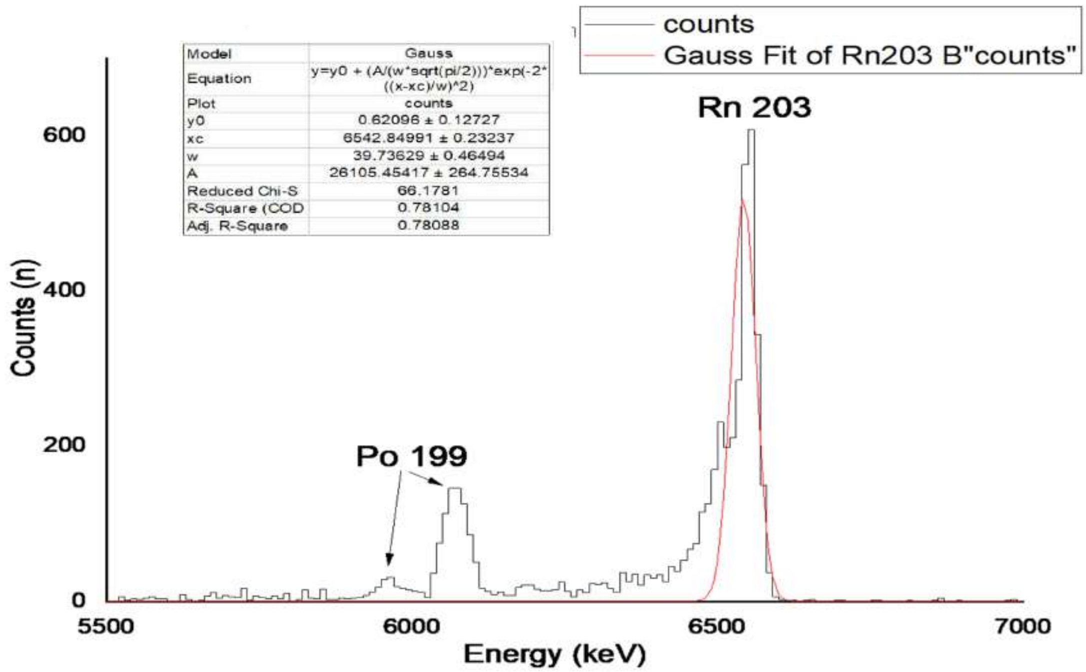
a) Rn 201:
This isotope has half-life time of 7.1 s, it 80% decays by alpha of energy 6725 keV, it gives daughter Po 197 that has two different decay modes. 44% has half-life of 53.6 s, and decays by alpha of 6281 keV. 84% has half-life of 25.8 s, and also decays by alpha but of energy of 6383.4 keV.



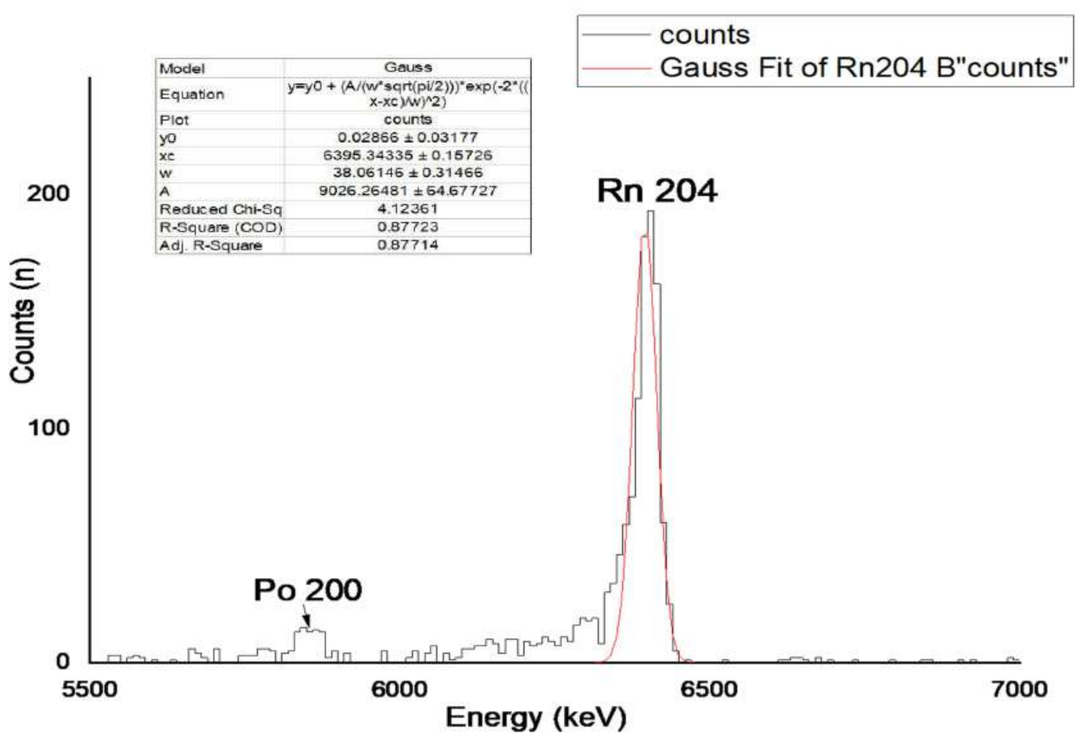
b) Rn 202:
It has half-life of 10 s, and 90% it decays by alpha of energy 6639 keV, giving a daughter Po 198 of half-life 1.77 minutes and 57% it decays by alpha of energy 6182 keV.



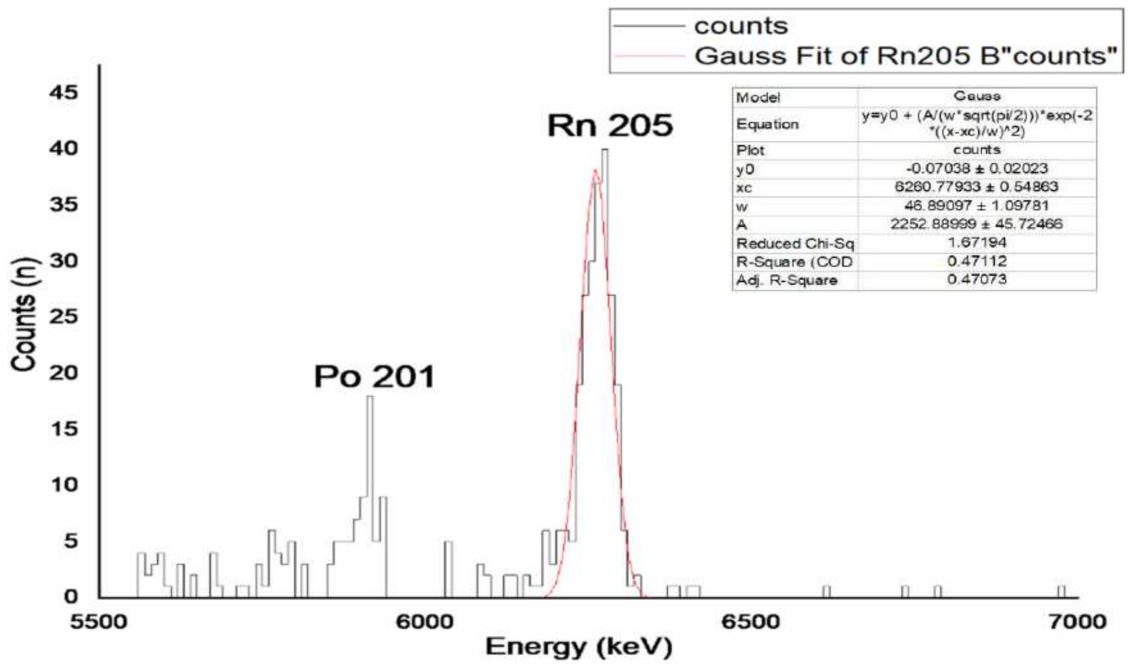
c) Rn 203:
It has half-life of 45 s, and 66% it decays by alpha of energy 6499 keV, giving a daughter Po 199 of half-life 5.48 m, and 12% it decays by alpha of energy 5952 keV.



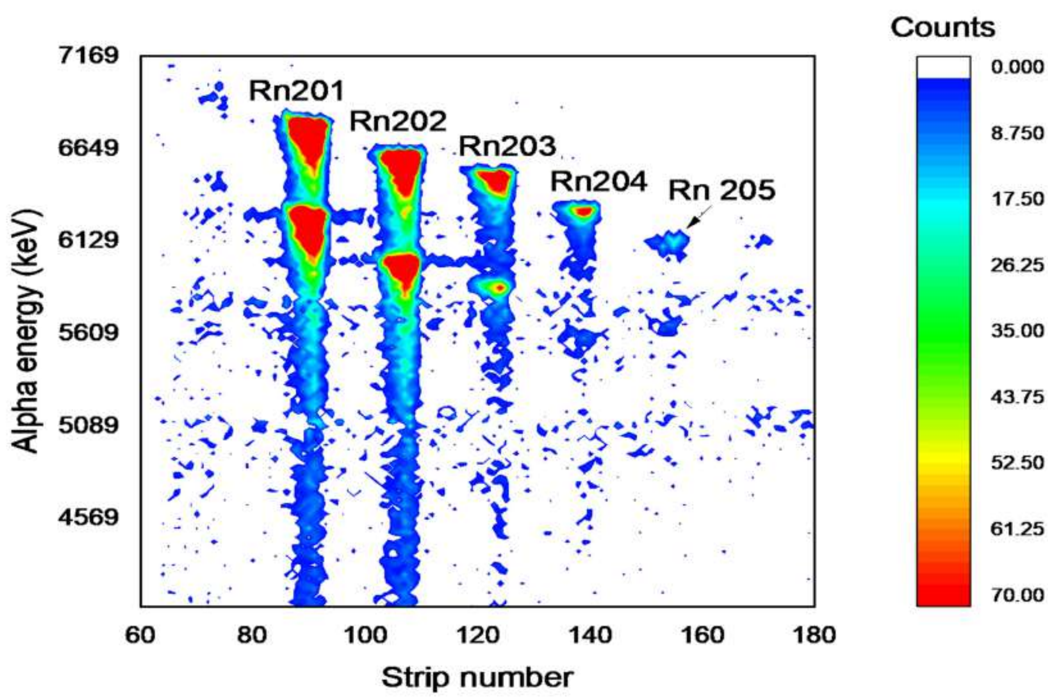
d) Rn 204:
It has half-life of 1.24 m, and 73% it decays by alpha of energy 6418.9 keV, giving a daughter Po 200 of half-life 11.5 m, and 11% it decays by alpha of energy 5861 keV.



e) Rn 205:
It has half-life of 170 s, and 23% it decays by alpha of energy 6262 keV, giving a daughter Po 201 of half-life 15.3 m, and 1.6% it decays by alpha of energy 5683 keV.



The heat map for Radon isotopes:

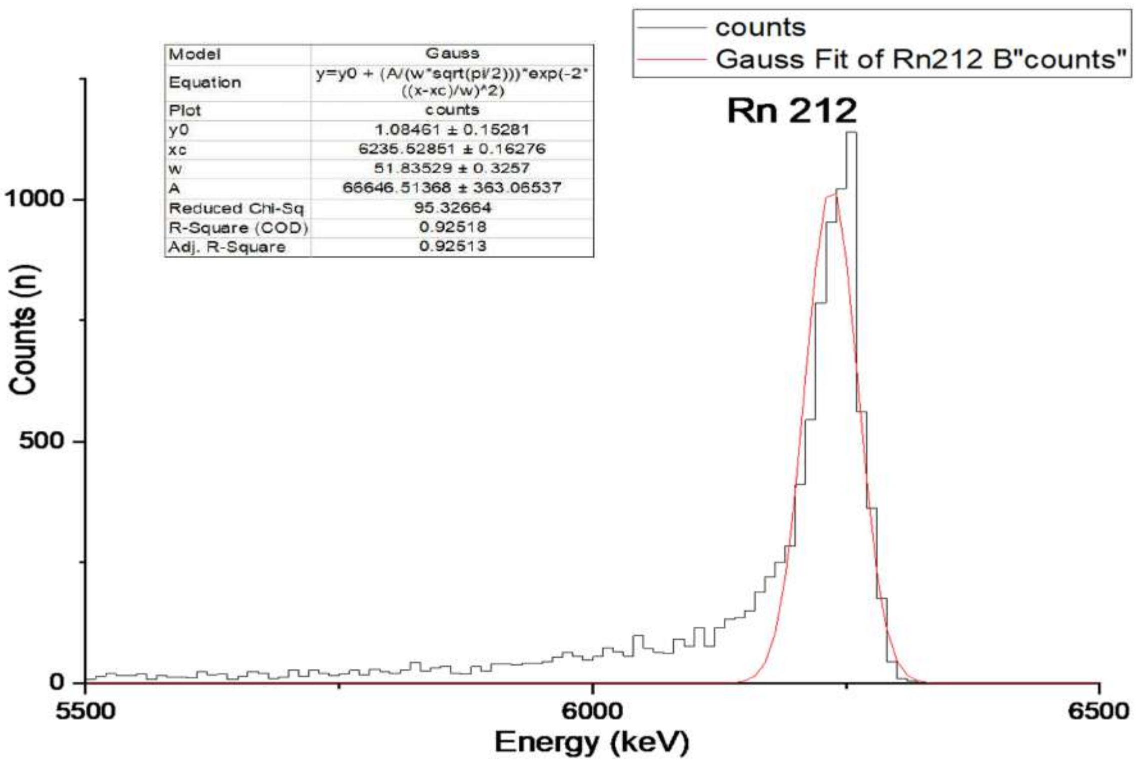


3. $^{48}Ca + ^{242}Pu \longrightarrow ^{21x}Rn$

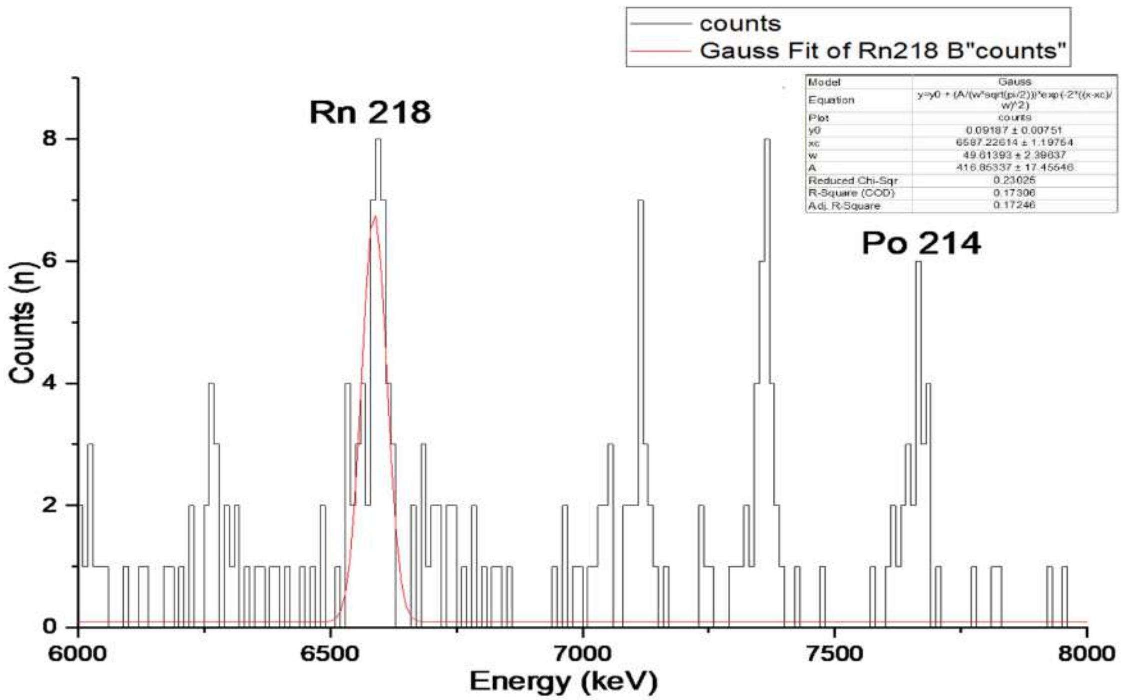
This reaction gives different radon isotopes with mass number that varies from 211, 212, 213, 214, 215, 216, 217, 218, and 219 which fit to the strip detector area.

The graphical data of the 212, 218, and 219 radon isotopes only are provided, because of the very small half-life time of the 211, 213, 214, 215, 216, and 217 radon isotopes (smaller than 35 ms) and the average separation time of the isotopes of this reaction was 1.8±0.3 s [3]. Hence, the long lived isotopes were the only ones to reach the focal plane.

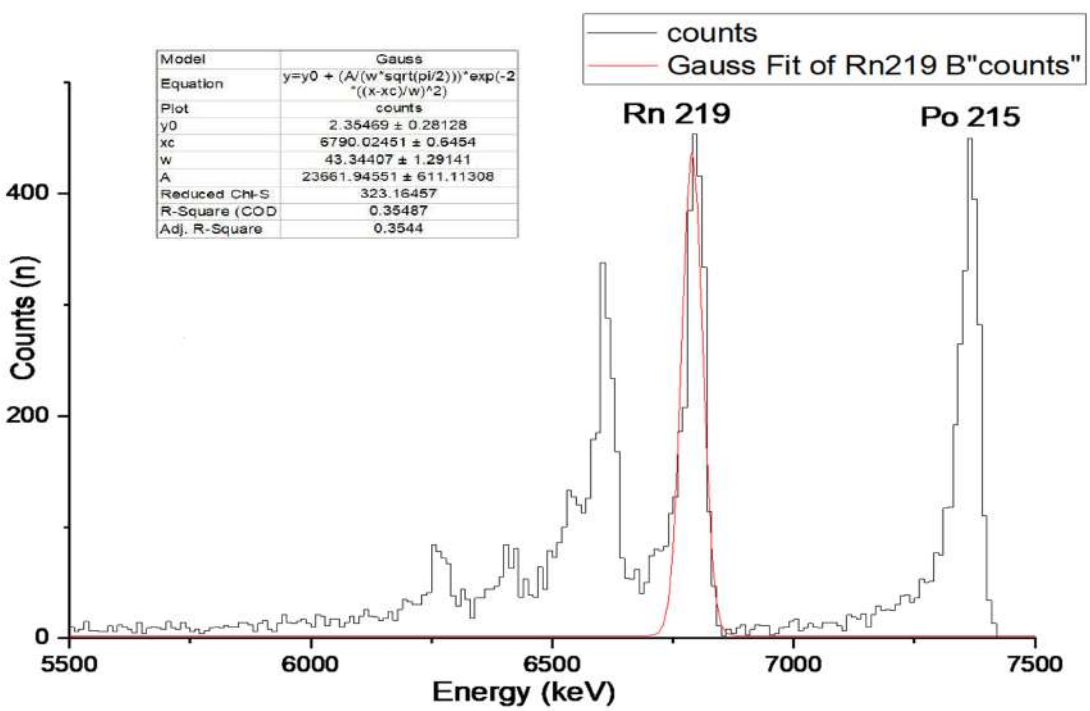
a) Rn 212:
   This radon isotope has half-life time of 23.9 m, it 100% decays by alpha of energy 6264 keV, giving a daughter Po 208 that has half-life of 2.898 years, and it 99.99% decays by alpha of energy 5114.9 keV.



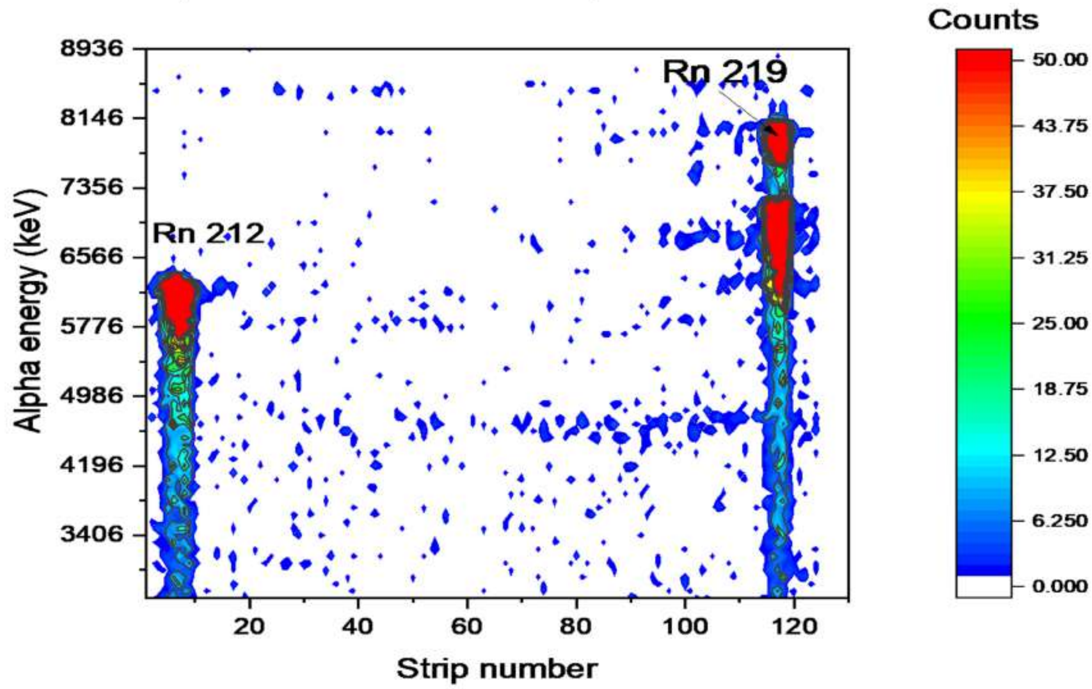
b) Rn 218:
It has half-life of 35 ms, it 100% deacys by alpha of energy 7129.2 keV, giving a daughter Po 214 that has half-life of 164.5 µs, it 100% decays by alpha of 7686.82 keV.



c) Rn 219:
It has half-life of 3.96 s, it 100% decays by alpha of energy 6819 keV, giving a daughter Po 215 that has half-life of 1.781 ms, it 100% decays by alpha of energy 7386 keV.



The heat map of this reaction for radon isotopes:



Conclusion:

The comprehensive study and analysis of superheavy elements allows us to learn more about the mechanism of nuclear reactions and the nature of the "Island of Stability," a predicted set of isotopes of superheavy elements that may have considerably longer half-lives than the isotopes of these elements that are known to exist.

The Isotope On-Line (ISOL) separation method is used to produce quality beam of nuclei and can be followed by post acceleration, these methods transport the nuclei of interest away from their place of production, where a large background from nuclear reactions is present, to a well-shielded experimental set-up, where the nuclear properties can be explored. Moreover, it makes possible the mass-analysis of new born nuclei by cooling them. Apart from creating low- background conditions for the experiment, the transport serves at the same time to purify the beam and to prepare it in the necessary conditions with respect to energy, time and ion optical properties for the experiments. The MASHA set up uses these methods in separating the atoms and it is continuously improved to get a better efficiency and to measure more data about the atoms.

Experiments with improving ISOL method, construction and materials are still also continuing at the MASHA facility. It was previously performed in a divided in space solid catcher. This construction eliminates the heat load on the catcher material thus, performing the separation efficiency stability.

Furthermore, it seems to be a rational idea to use modern carbon-based nanomaterials. In a test experiment, graphene foil and carbon nanotube paper sheet performs good results, showing great stability of separation efficiency and decreasing separation time, which opens a wider perspective to the study of short-lived isotopes.

Acknowledgements:

I would like to thank my supervisor Mr. Viacheslav Vedeneev for letting me work under his guidance and I would like to thank him for the time he spent for us with this project. Finally this report cannot be complete without thanking the JINR team for their efforts to organize this programme irrespective of the difficulties caused due the COVID-19 pandemic situation.

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