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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1. Abstract:

After physicists in 1940s were able to produce new unstable heavy elements, it became an interest for researchers to produce more super heavy elements and study them. By getting to know these elements better we can explore more concepts like “island of stability”. The method used in this is the isotope separation on-line method which is used in mass analysis of short-lived isotopes and separate them from the primary ion beam in an online mode. This is done using MASHA set up which is a mass separator with great resolving power. Experiments are done at Masha facility, FLNR, JINR. [1]

2. Introduction:

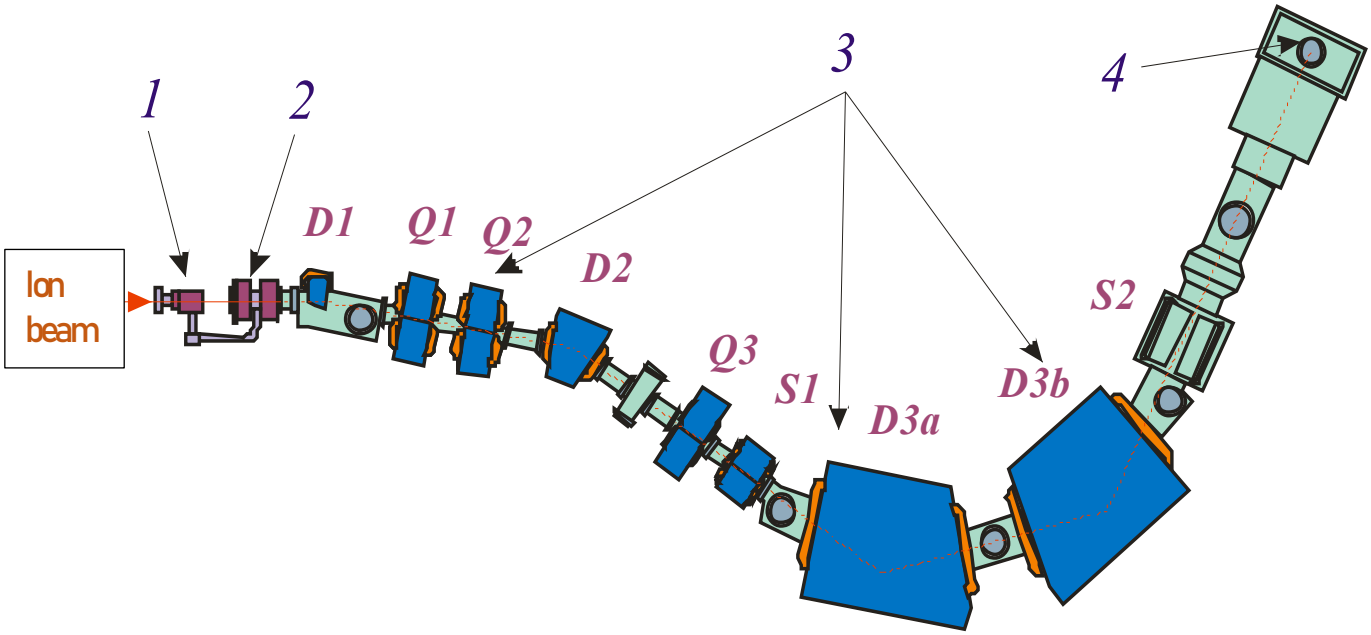
The isotope separation on-line method (ISOL) is an effective method of separation that is used to separate the reaction products, where it separates the super heavy isotopes from the original beam so we can study them and determine their masses. ISOL system is done through many steps: production, thermalization, ionization, extraction, mass separation, cooling, charge-state breeding, and acceleration. Also, in this method we should check:

1. The efficiency of separation as the production rate of the very exotic nuclei will always be marginal. Therefore, any manipulation with the reaction products – e.g., ionization, purification, acceleration, transport to the detection system has to be very efficient, otherwise one loses the “precious” nuclei.
2. The selectivity of the separation as in the nuclear reaction process the unwanted in general more stable nuclei are being produced much more abundantly. Furthermore, ISOL systems often produce beams of isotopes from the target material itself or from other components of the target-ion source system. Thus, the separation process should distinguish between the wanted and unwanted species in an effective way.
3. Most importantly, the time of separation has to be short as 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. Another thing to take care of is choosing the material of the catcher used, in ISOL we can have a solid, liquid, or a gas catcher, each type has a certain application. In our application of carbon nanomaterial, the best choice of a catcher was the solid one as it provide the efficiency and the speed we need. This method is done by MASHA set up. [2]

3. MASHA:

Mass Analyzer for Super Heavy Atoms (MASHA) is a set up that used for the separation of the super heavy elements using a combination of the ISOL method and the classic magnetic mass analysis method. It is designed for the determination of the masses of super heavy elements as reaction products. It was constructed at one of the beams out of U-400M cyclotron at FLNR, JINR, Dubna, Russia.

The main parts of MASHA are:



1) Target box + hot catcher:

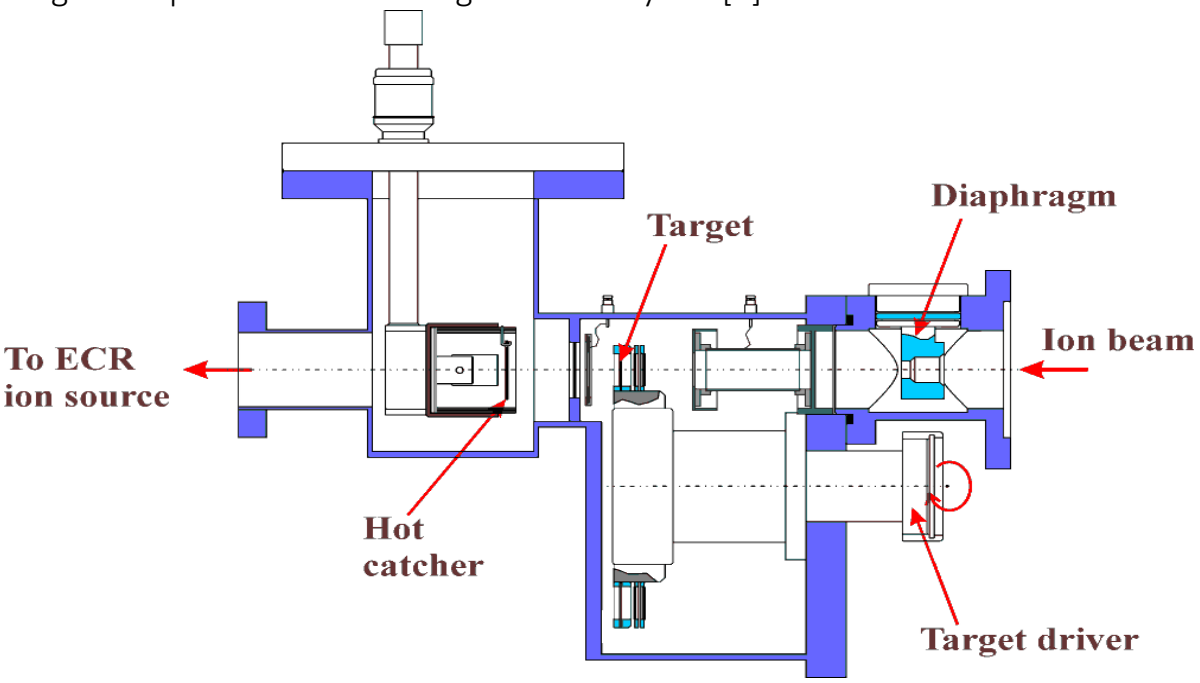
The recoil nuclei, flying out of the target, are implanted into a catcher heated to a temperature T_{heat} ~1800-2000k. The target is a rotating one represents the wheel with sectors, assembled into 6 cassettes, with 2 sectors each, as it has better efficiency and heat distribution than the stationary target. 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 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/cm^3, 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.

2) 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 up to 38 keV. And the ion beam formed is then separated by the magneto-optical mass-to-charge ratio analyzer. [4]



3) The mass separator:

Mass separator in this set up is a magnetic-optical analyzer. 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.

4) DAQ in the focal plane:

In the focal plane of the magnetic analyzer 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. [5]

➔Task Results:

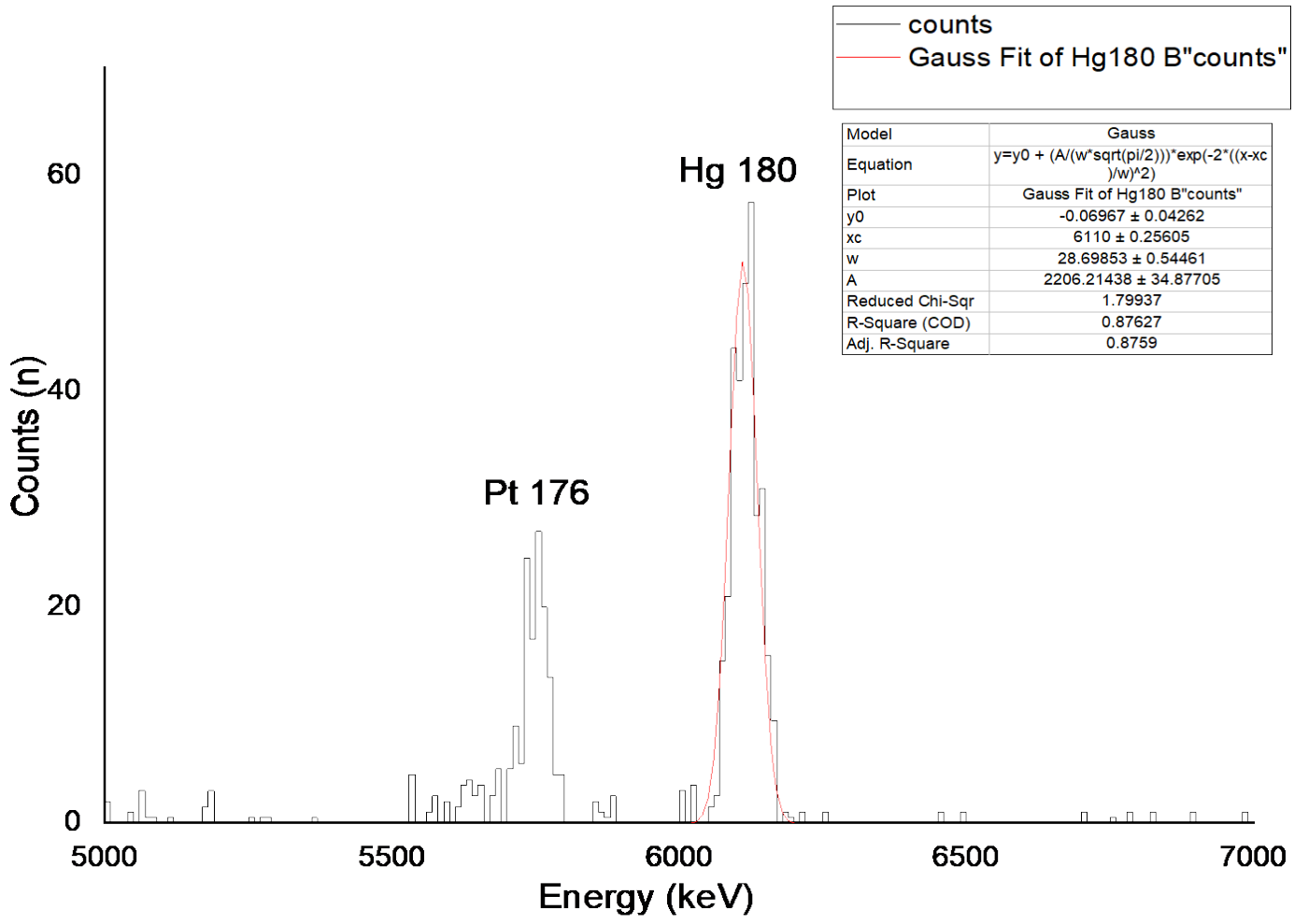
Our task was to take the data of products of three different reactions: complete fusion neutron evaporation residues ($^{40}Ar+^{148}Sm \rightarrow ^{188-xn}Hg+xn$), ($^{40}Ar+^{166}Er \rightarrow ^{206-xn}Rn+xn$) and multinucleon transfer ($^{48}Ca+^{242}Pu \rightarrow ^{21x}Rn$). Draw their histograms and analyze the peaks of their alpha energy radiation and their daughter nuclei, then draw their heat maps.

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

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

i. Hg 180:

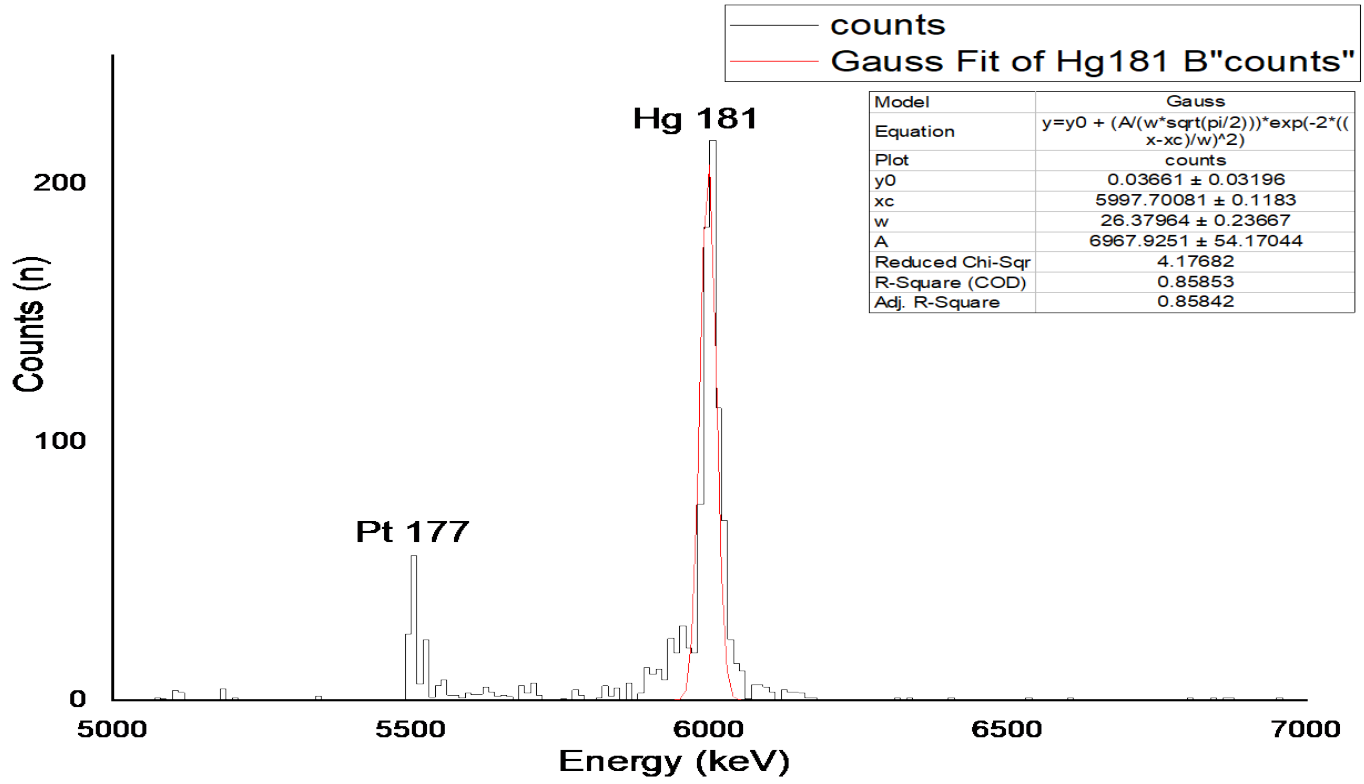
This mercury isotope has half-life time of 2.58 seconds, it 48% decays by alpha of energy 6118 keV, giving a daughter Pt 176 that has half-life of 6.35 s and it 40% decays by alpha of energy 5753 keV



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	Gauss Fit of Hg180 B"counts"
y0	-0.06967 ± 0.04262
xc	6110 ± 0.25605
w	28.69853 ± 0.54461
A	2206.21438 ± 34.87705
Reduced Chi-Sqr	1.79937
R-Square (COD)	0.87627
Adj. R-Square	0.8759

ii.Hg 181:

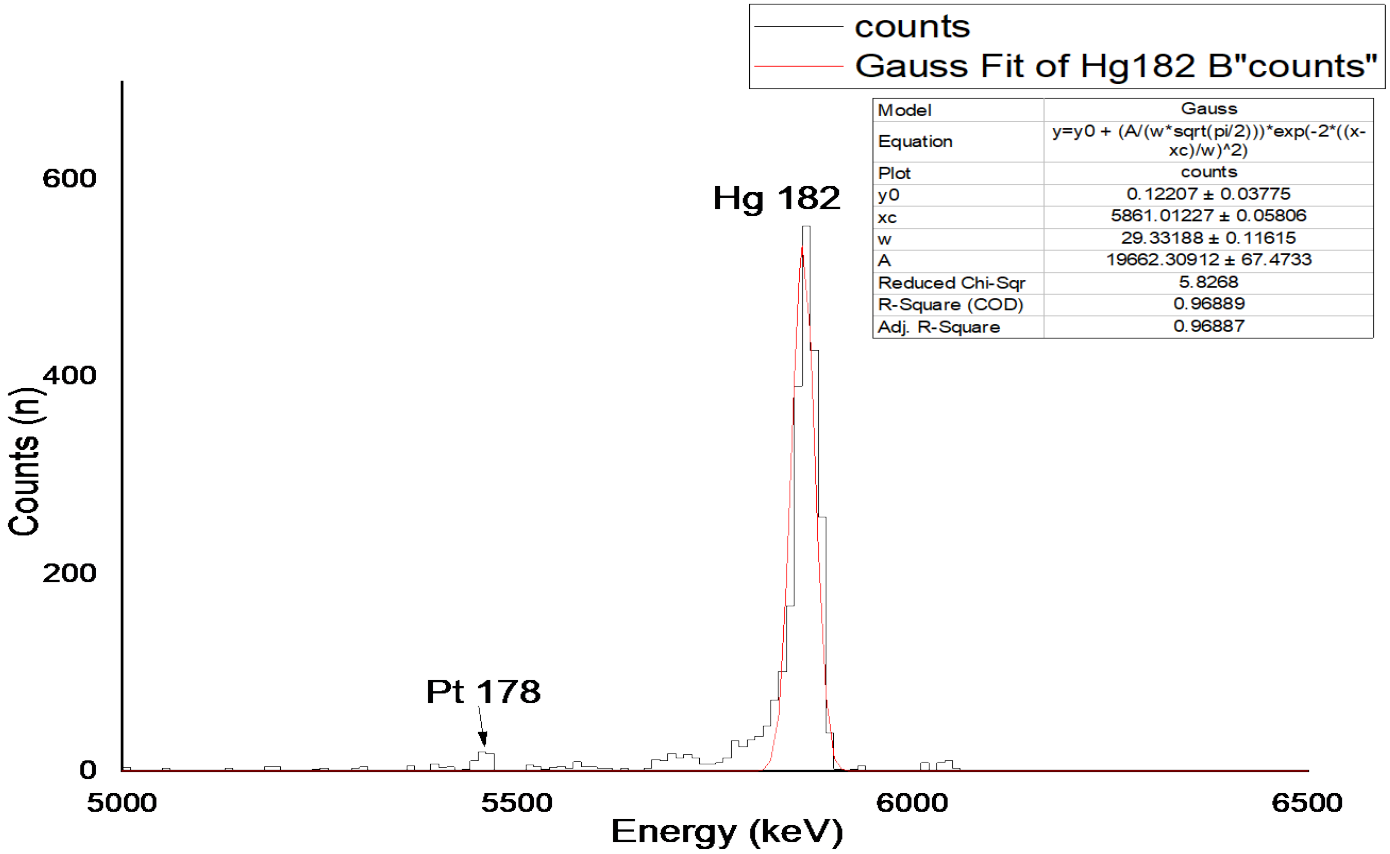
It has half-life of 3.5 s, and it 30% decays by alpha of energy 6006 keV, giving a daughter Pt 177 that has half-life time 11 s, and it 5.6% decays by alpha of 5517 keV



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	counts
y0	0.03661 ± 0.03196
xc	5997.70081 ± 0.1183
w	26.37964 ± 0.23667
A	6967.9251 ± 54.17044
Reduced Chi-Sqr	4.17682
R-Square (COD)	0.85853
Adj. R-Square	0.85842

iii.Hg 182:

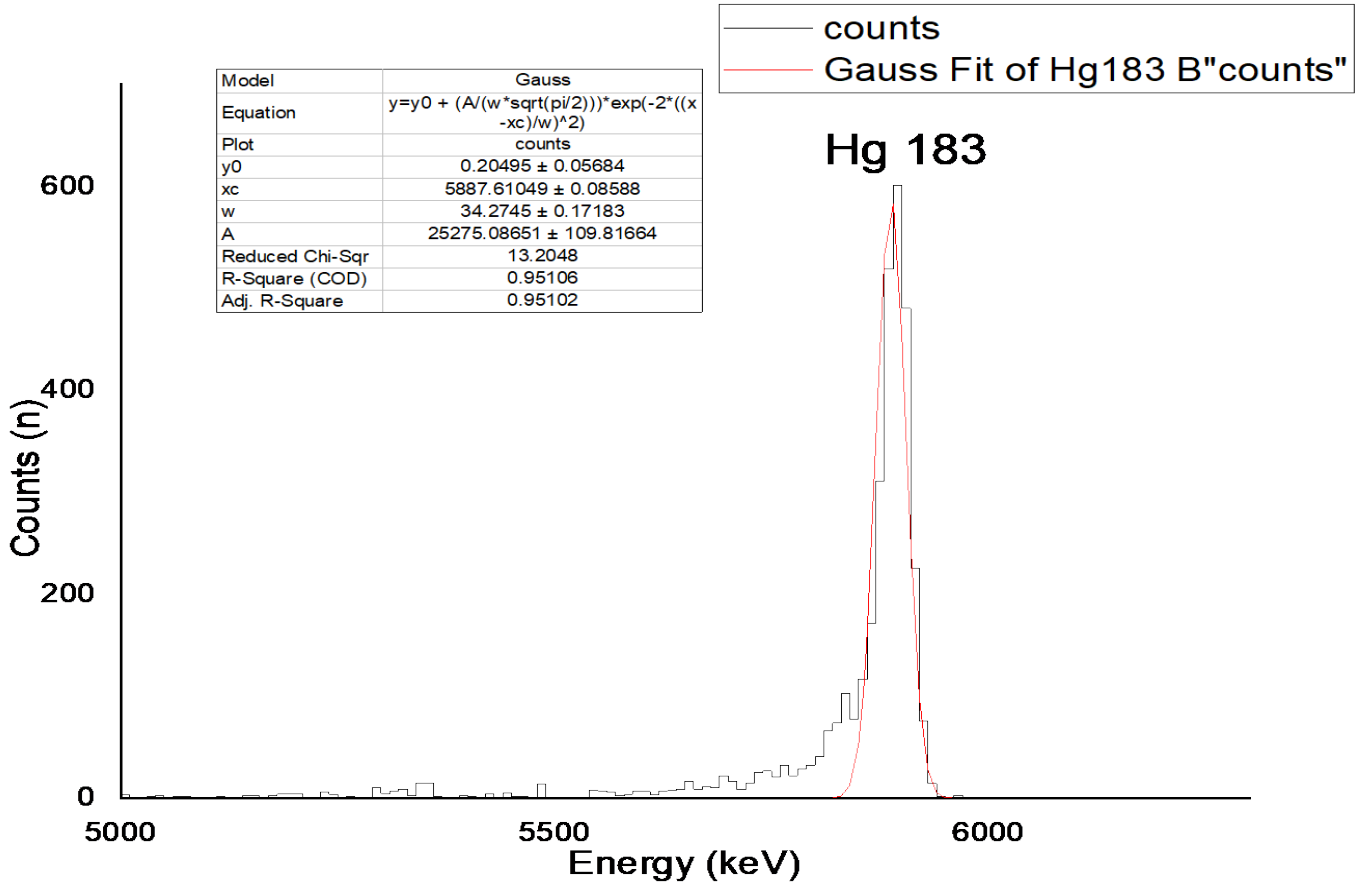
It has half-life time of 10.835 s, and it 15.2% decays by alpha of energy 5867 keV, giving a daughter Pt 178 that has half-life of 21.1 s and it 4.6% decays by alpha of energy 5446 keV



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	counts
y0	0.12207 ± 0.03775
xc	5861.01227 ± 0.05806
w	29.33188 ± 0.11615
A	19662.30912 ± 67.4733
Reduced Chi-Sqr	5.8268
R-Square (COD)	0.96889
Adj. R-Square	0.96887

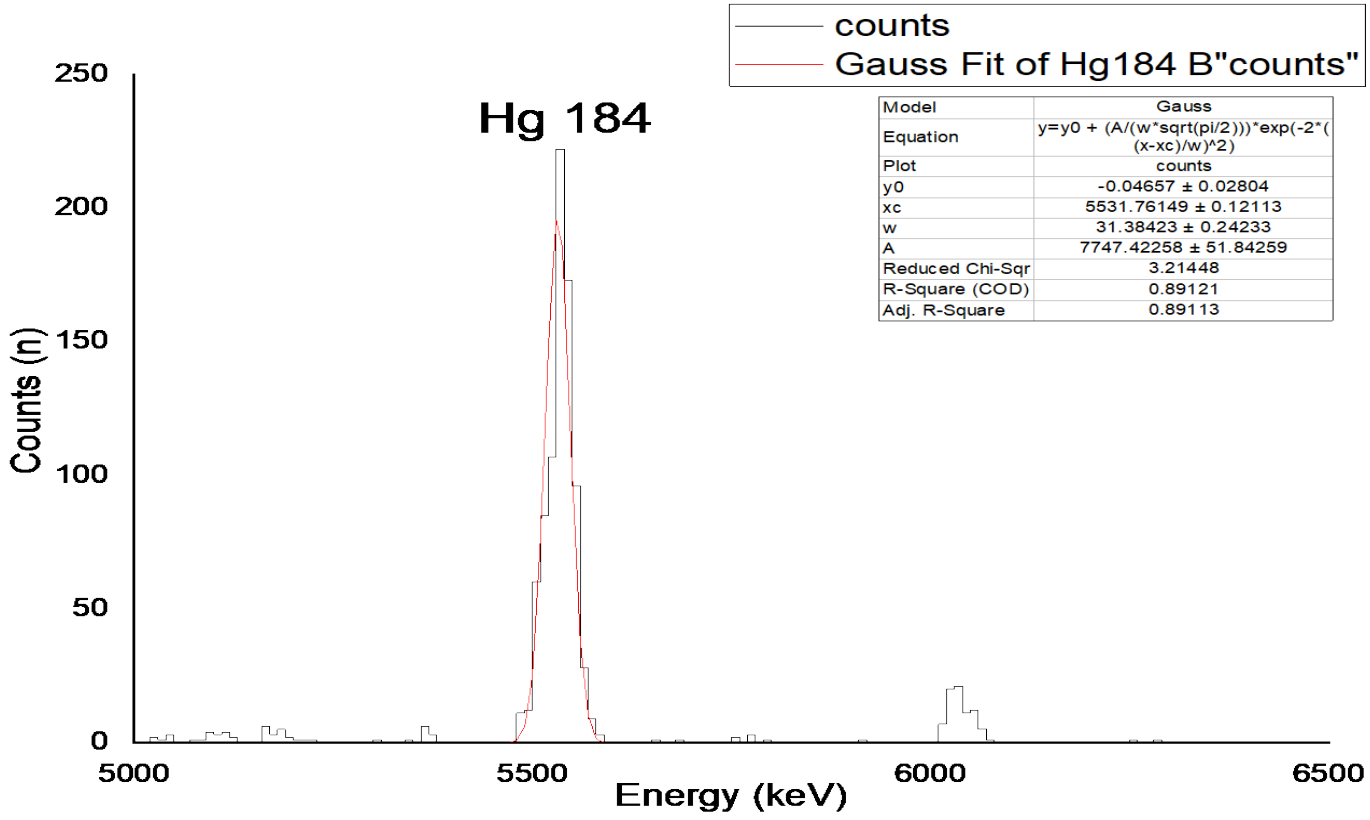
iv.Hg 183:

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.



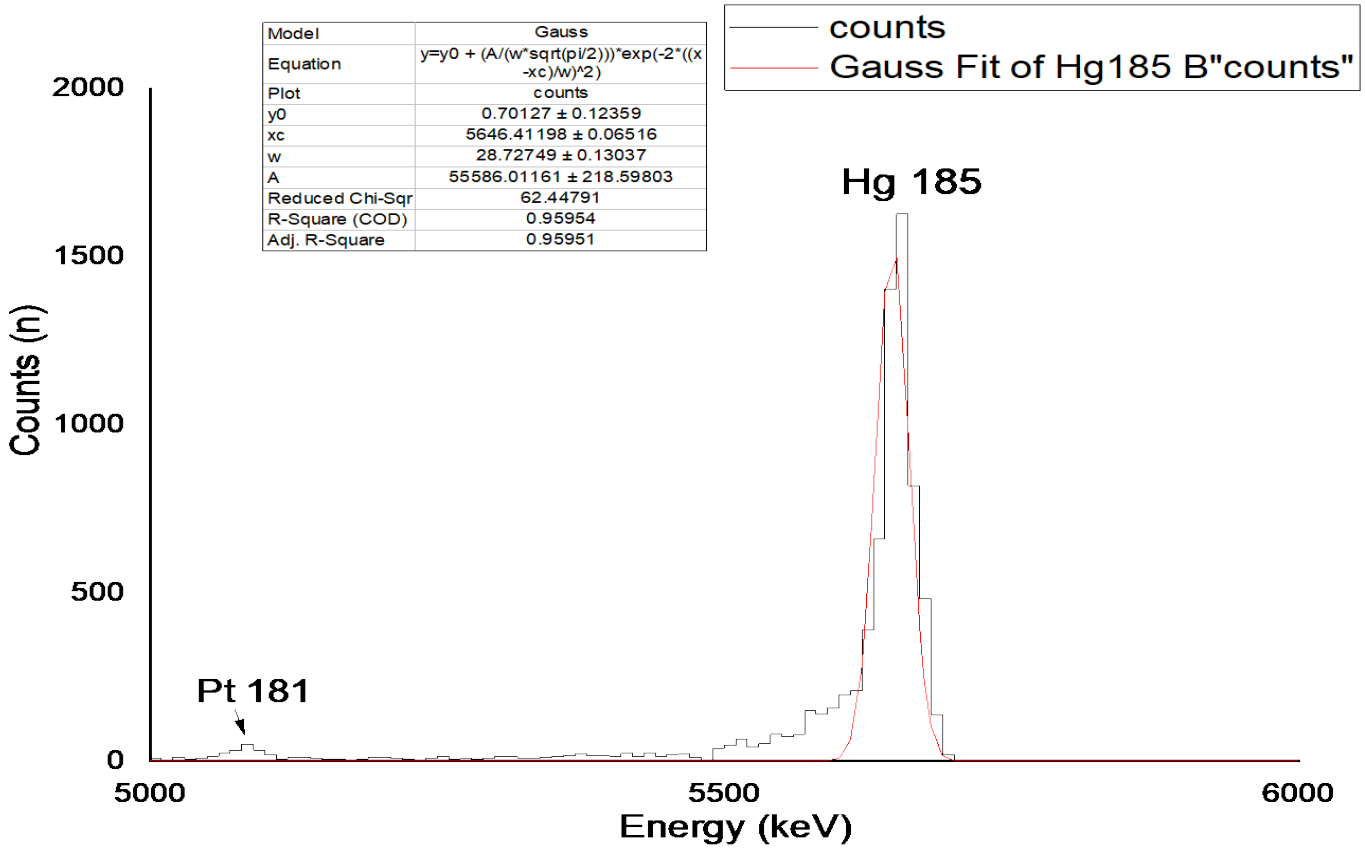
v.Hg 184:

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.

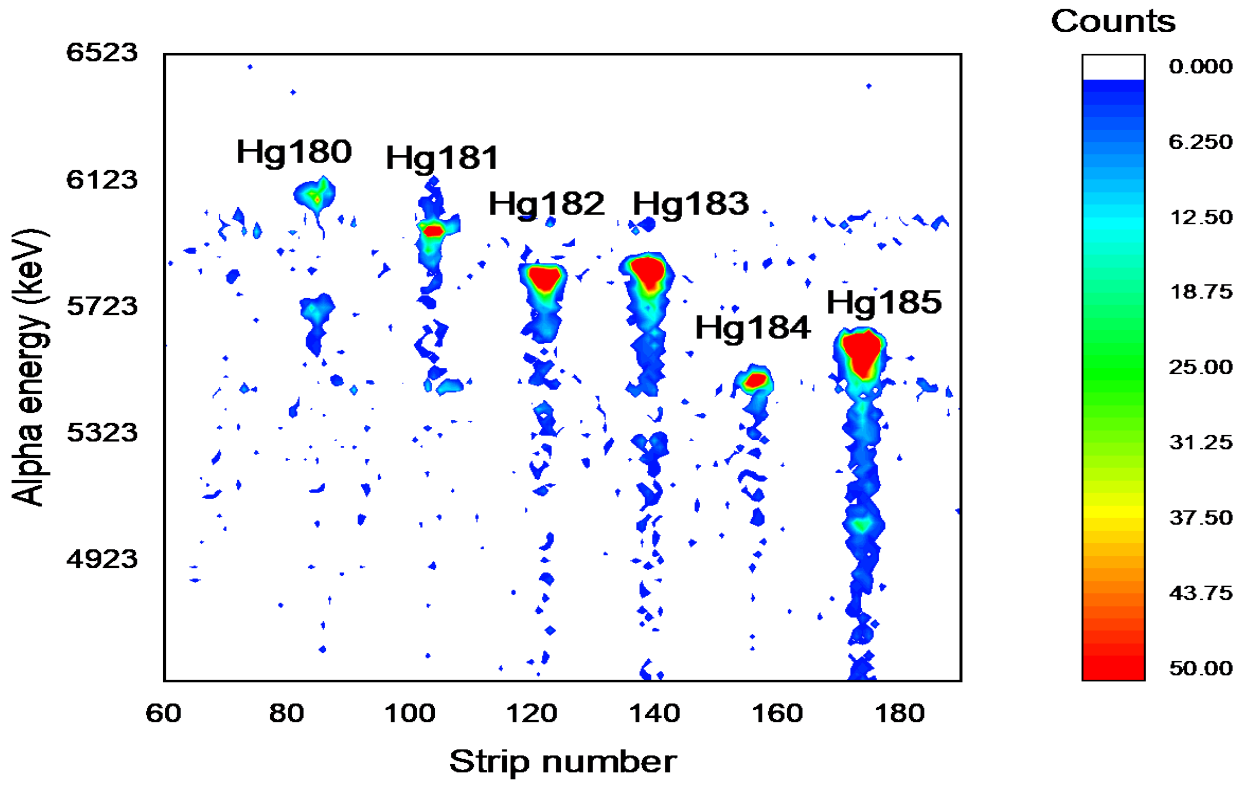


vi.Hg 185:

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 this mercury isotopes:

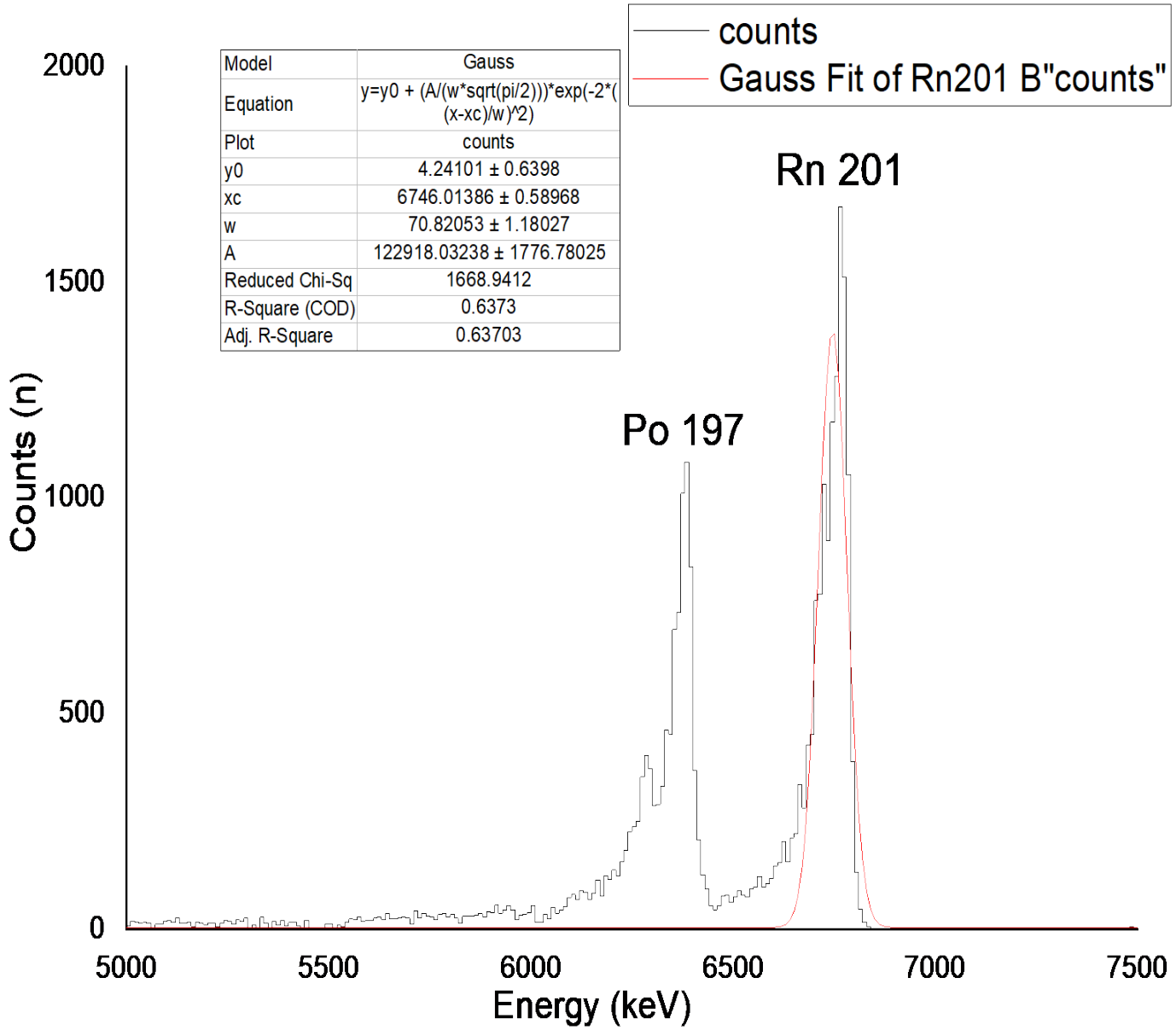


2) $^{40}Ar+^{166}Er \rightarrow ^{206-xn}Rn+xn$

This reaction gives radon isotopes with mass numbers of (201,202,203,204,205)

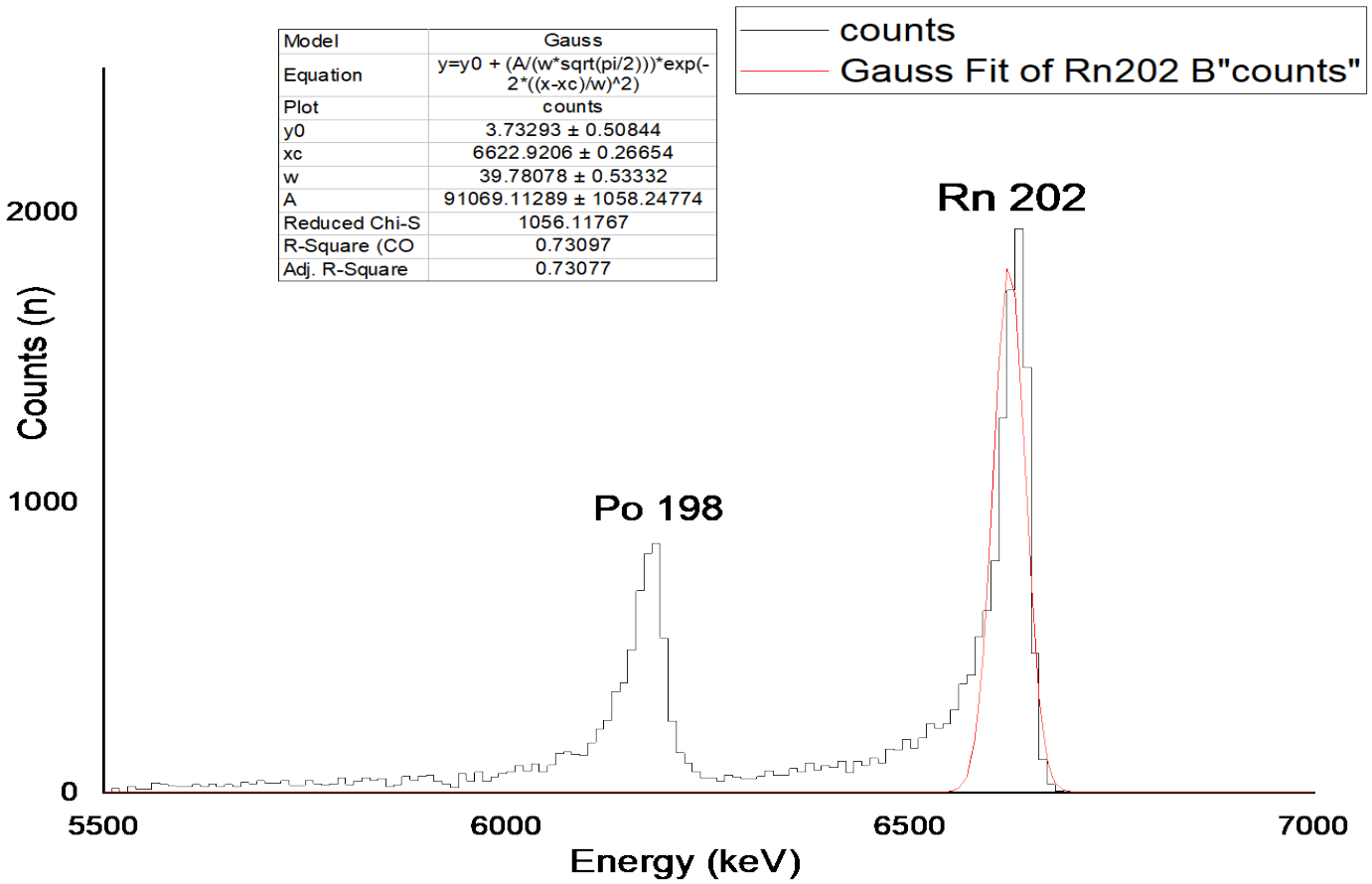
i.Rn 201:

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.



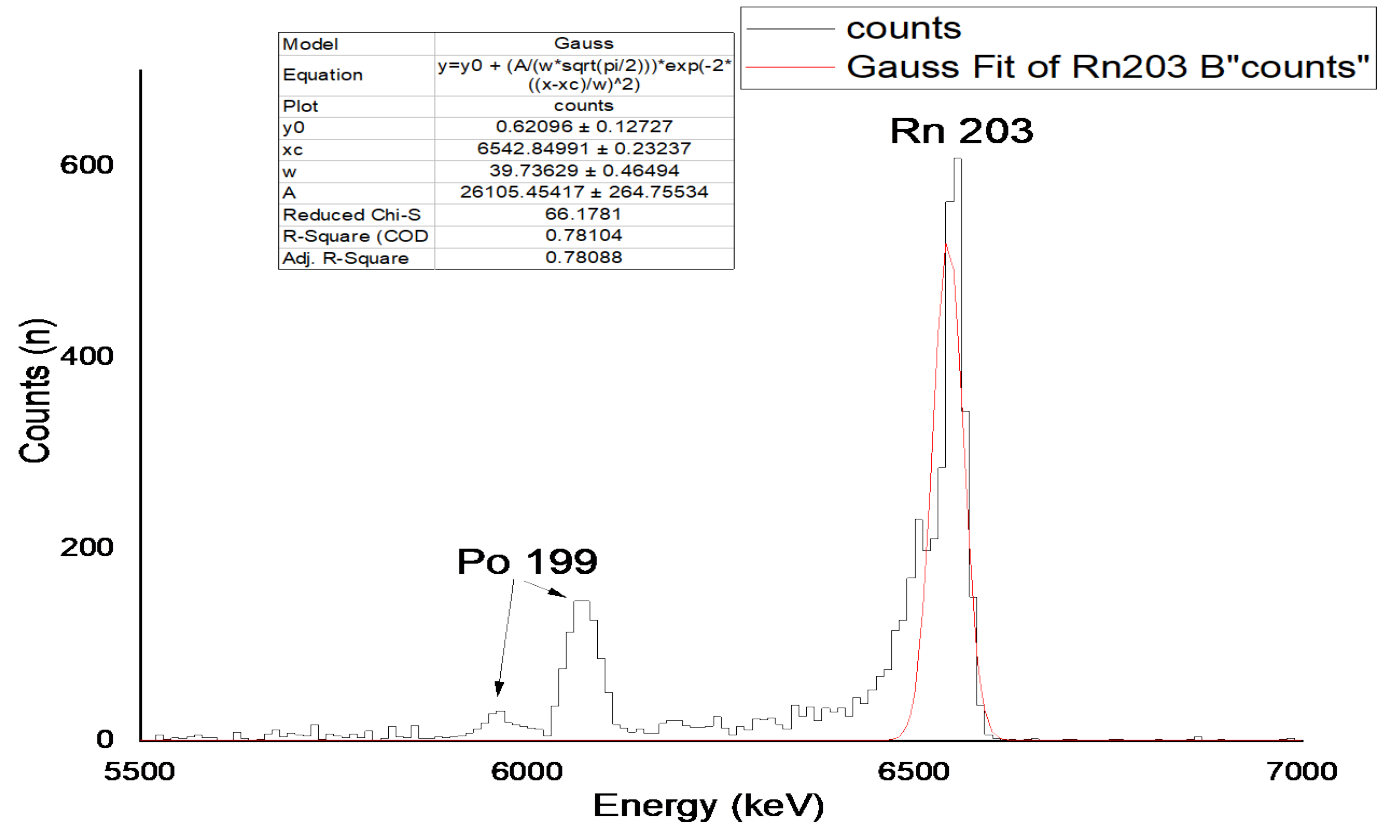
ii.Rn 202:

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.



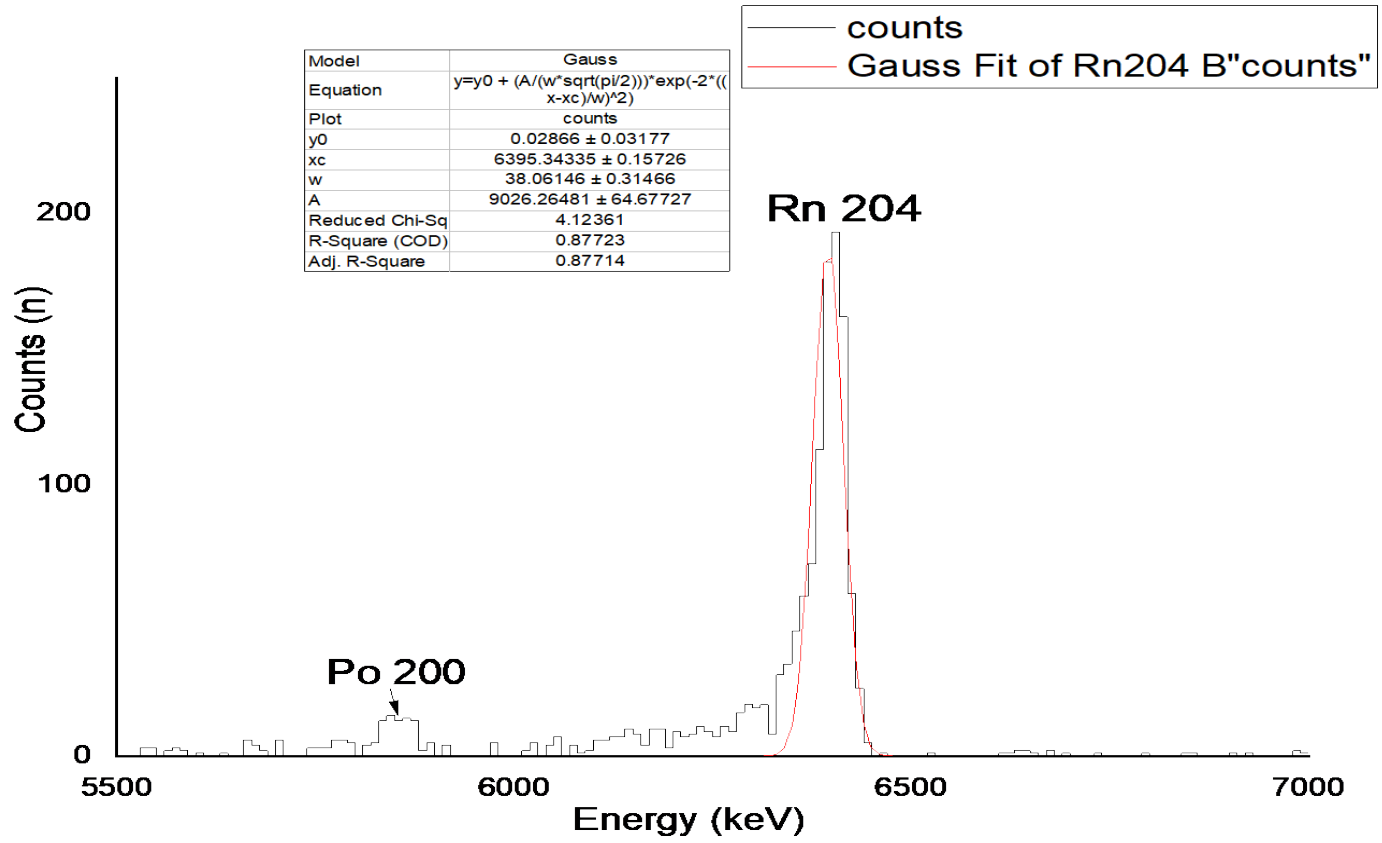
iii.Rn 203:

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.



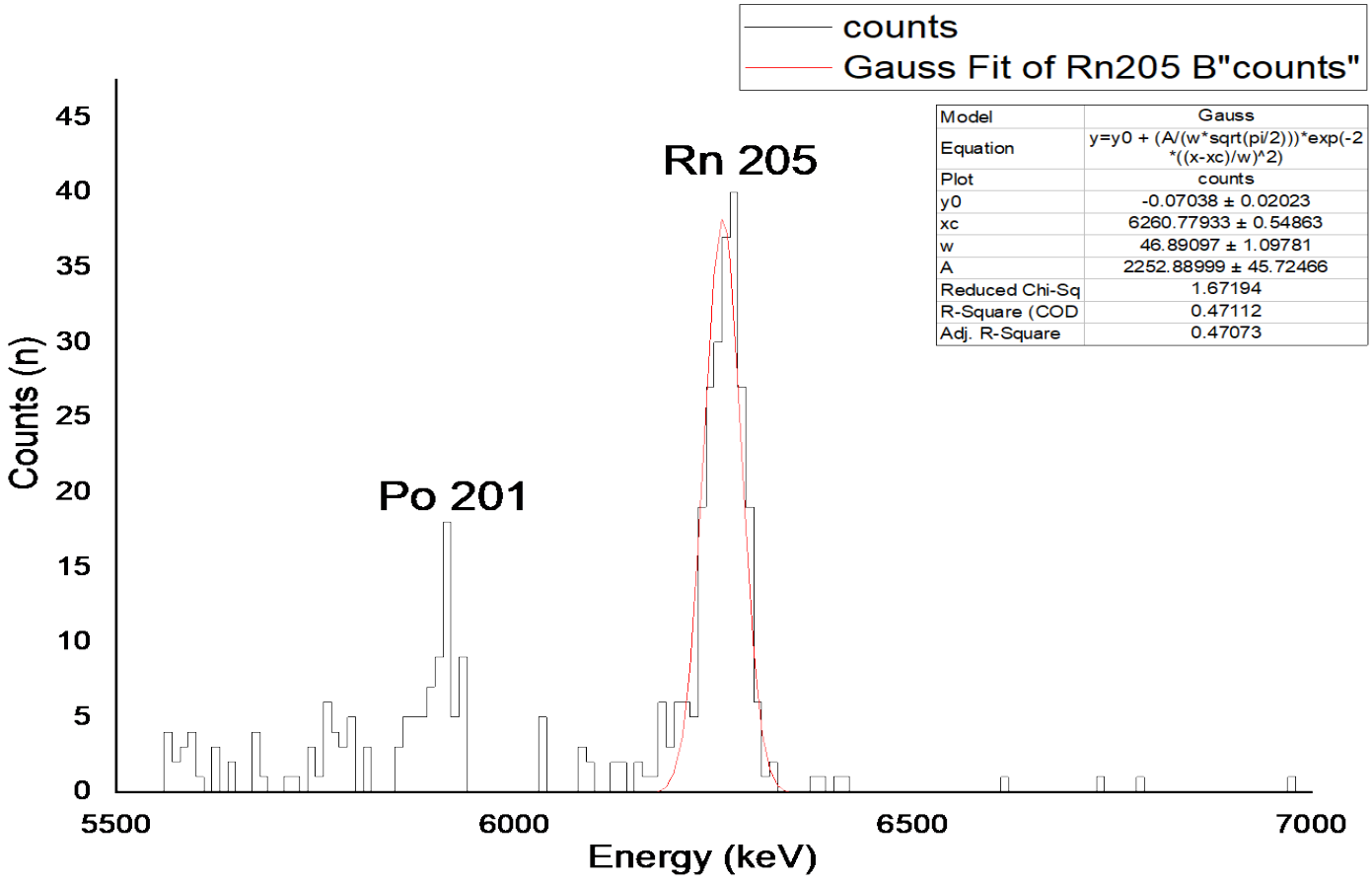
iv.Rn 204:

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.

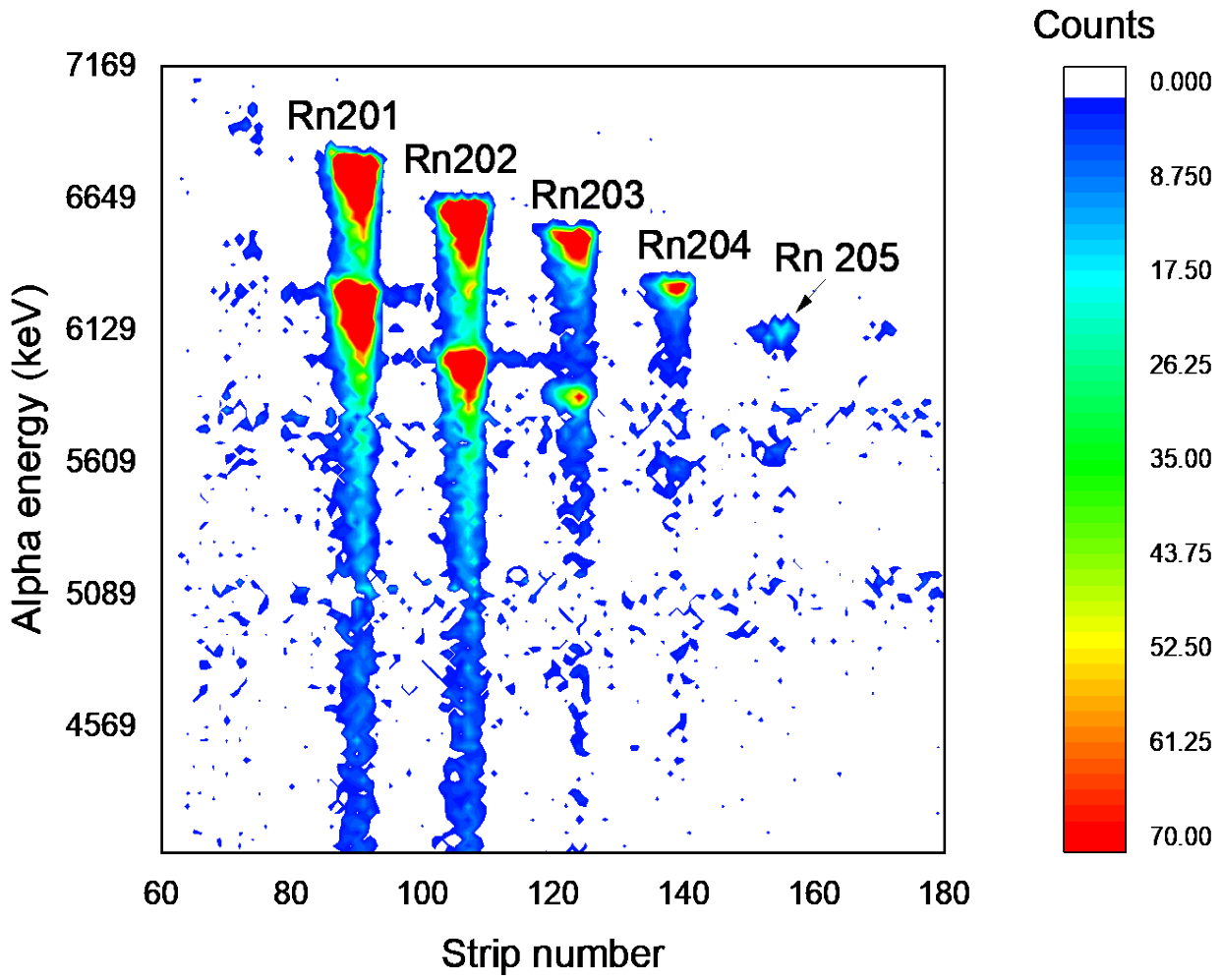


v.Rn 205:

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 of radon isotopes:



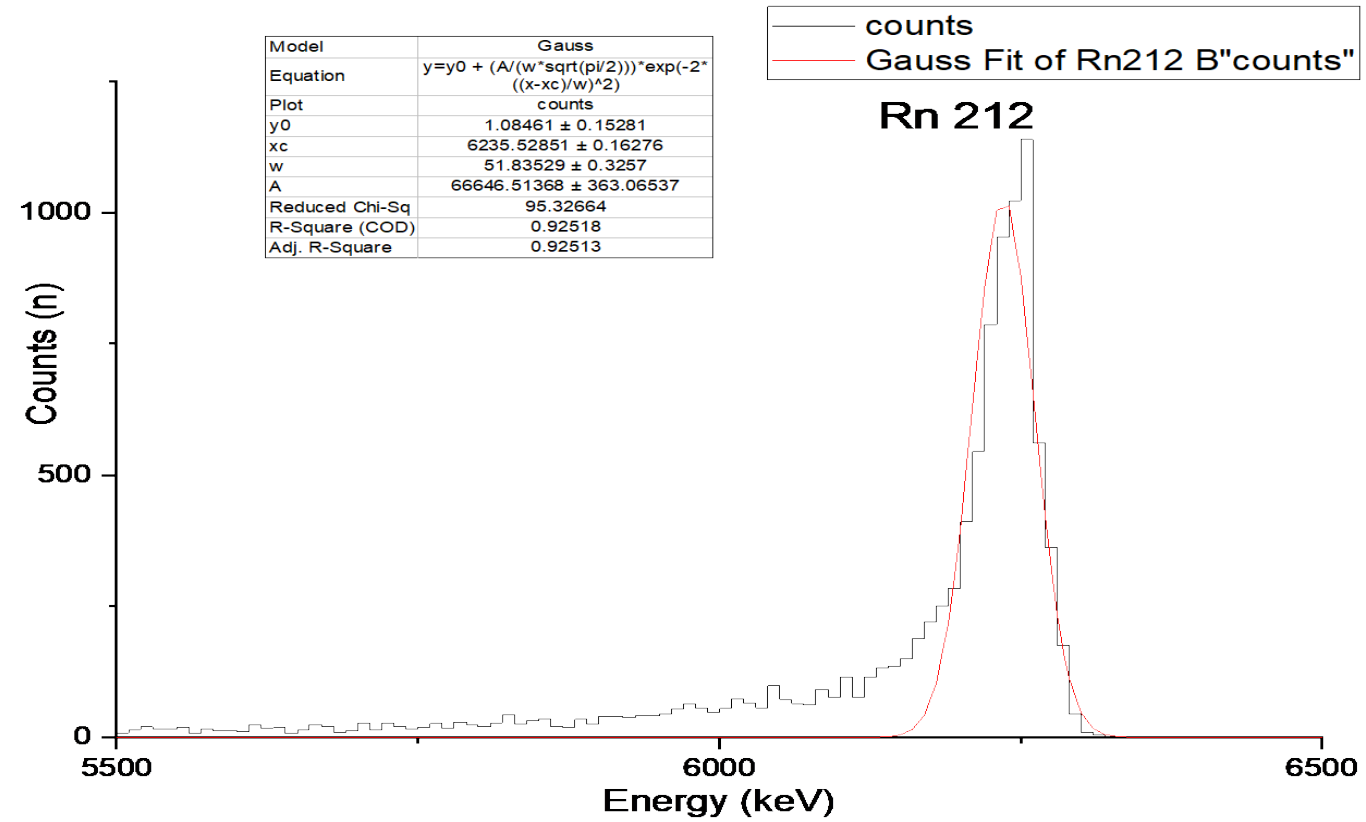
3) $^{48}Ca+^{242}Pu \rightarrow ^{21x}Rn$

This reaction gives different radon isotopes with mass number that varies from (211, 212, ……,218,219) which fit to the strip detector area.

In our graphs we have the data of the 212, 218, and 219 radon isotopes only, that is 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], so the long lived isotopes were the only ones to reach the focal plane.

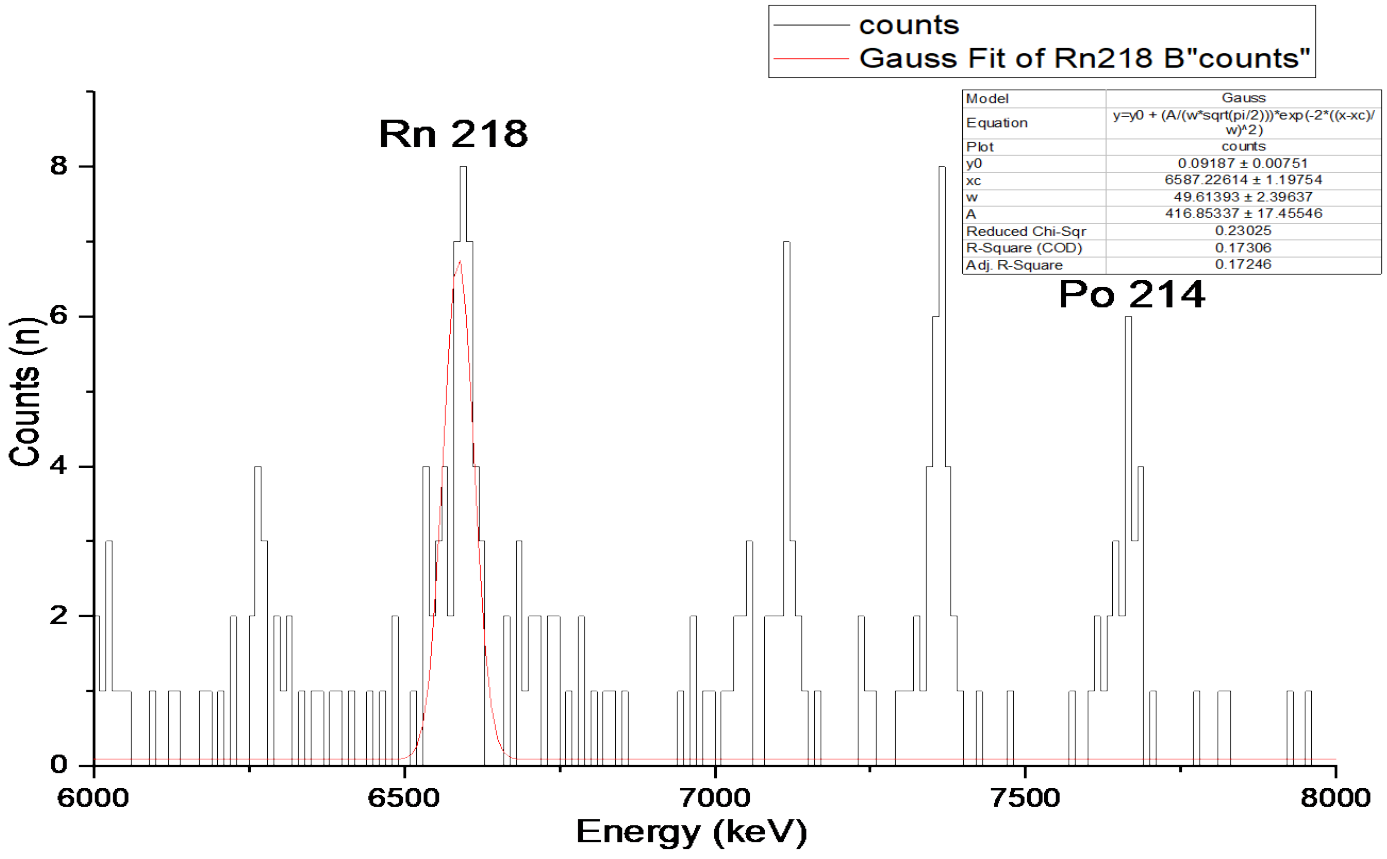
i.Rn 212:

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 be alpha of energy 5114.9 keV.



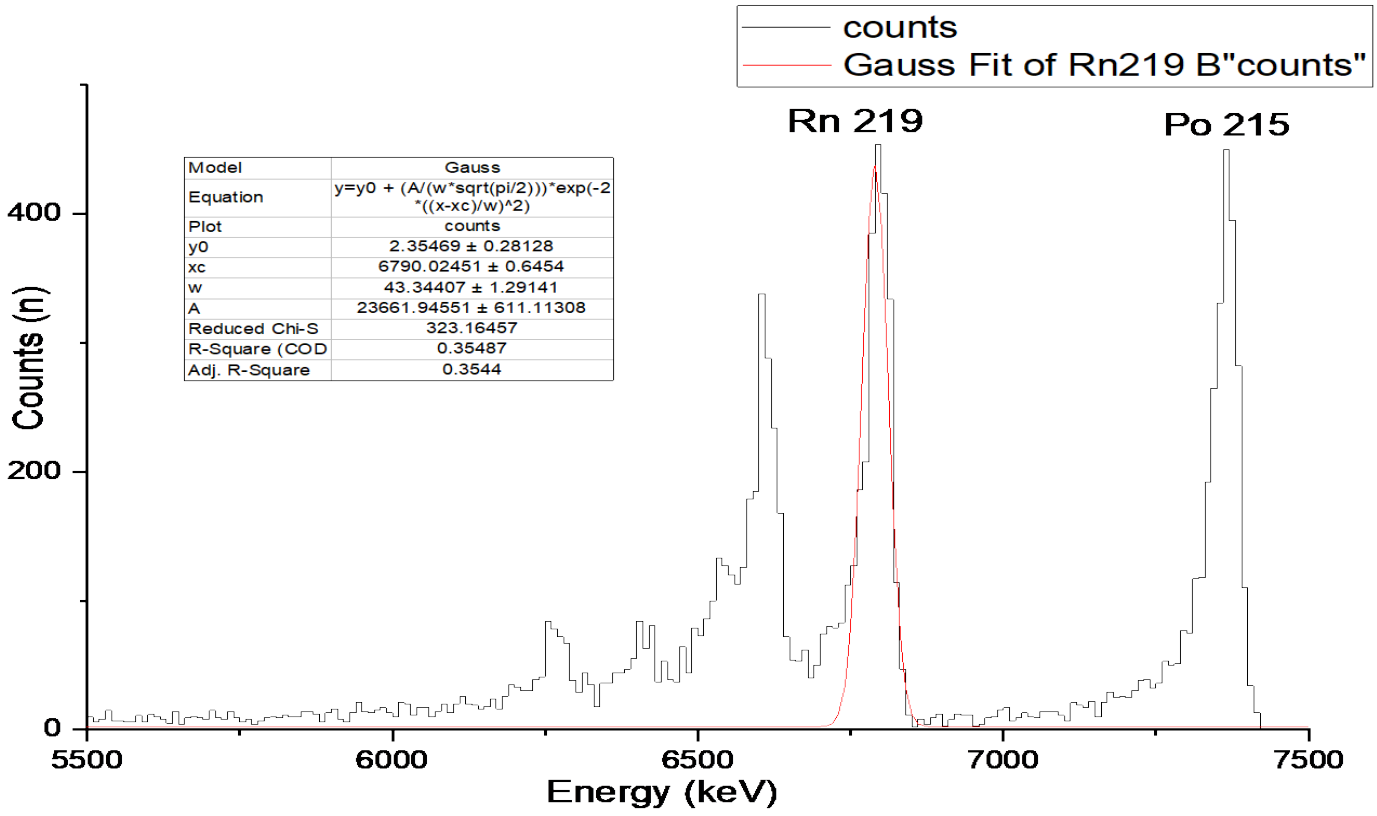
ii.Rn 218:

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% deacys by alpha of 7686.82 keV

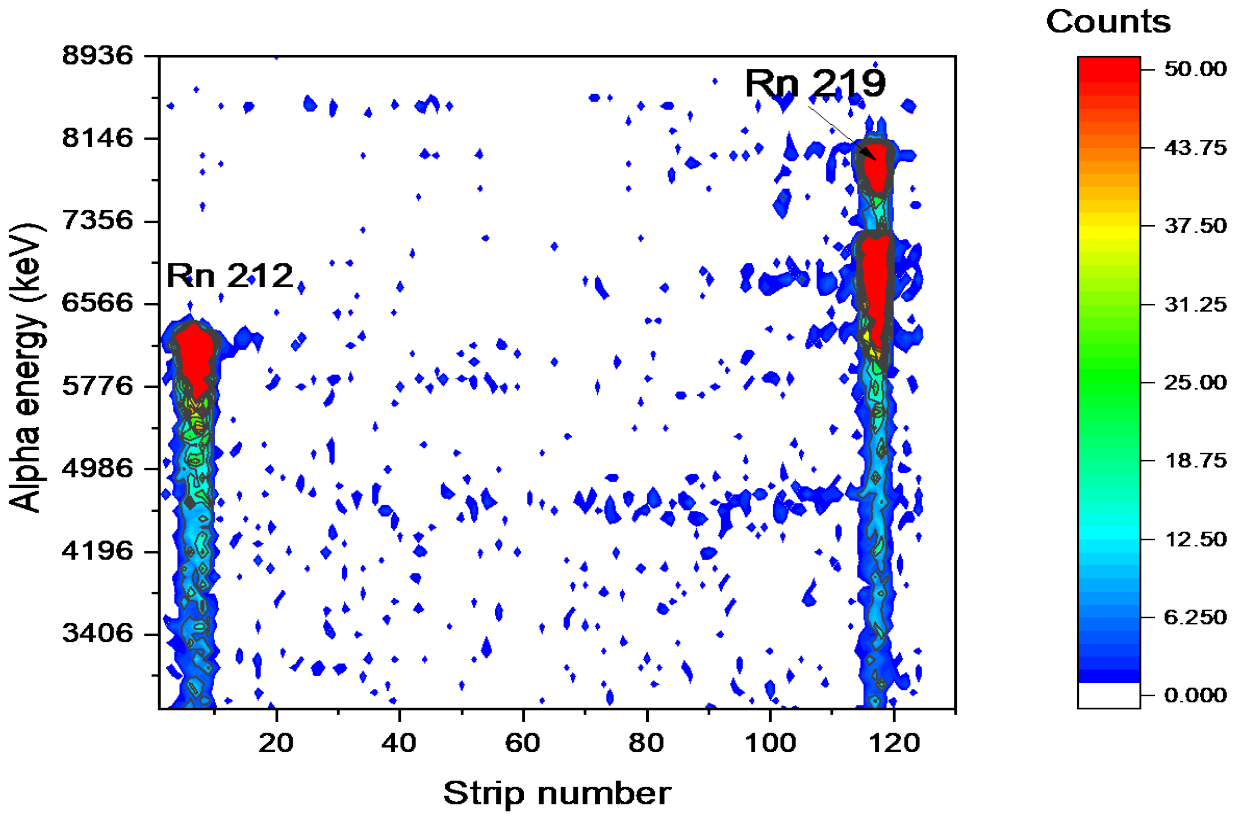


iii.Rn 219:

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 for radon isotopes of this reaction:



➔conclusion:

Studying of the superheavy elements helps in telling us more about the structure and mechanism of the nuclear reactions and the possibility of existence of the "island of stability" which is a predicted set of isotopes of superheavy elements that may have considerably longer half-lives than known isotopes of these elements. ISOL method is a very good technique to get a good quality beams of nuclei and it 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 newborn 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. MASHA set up uses these methods in separating the atoms, it is continuously improved to get better efficiency and to measure more data about the atoms. Experiments with improving ISOL method, construction and materials are continuing at Masha facility. Already it was performed a divided in space solid catcher. This construction eliminates the heat load on the catcher material thus performing the separation efficiency stability. In addition, using new nanomaterials based on carbon seems to be perspective idea. Graphene foil and carbon nanotube paper sheet performs good results in a test experiments showed great separation efficiency stability and decreasing of separation time, which opens a big perspective to the short-lived isotopes analysis.

➔acknowledgments:

I would like to thank Mr. Viacheslav Vedeneev our supervisor, for his time, help, his work with us and his really great projects. I am also very grateful for INTEREST team for their effort and for organization of this training. And JINR institute for making the INTEREST training happen this year although of all these difficulties we are going through this year.

References

[1] C. Moskowitz, "Superheavy Element 117 Points to Fabled "Island of Stability" on Periodic Table," *Scientific American,* 2014.

[2] P. V. Duppen, "Isotope Separation On line and Post Acceleration," *Springer-Verlag Berlin Heidelberg,* pp. 37-77, 2006.

[3] A.M. Rodin, A.V. Belozerov, E.V. Chernysheva et al., "Separation efficiency of MASHA facility for short-lived mercury isotopes," *Hyperfine interact,* vol. 227, pp. 209-221, 2014.

[4] V. Yu. Vedeneev1 · A. M. Rodin1 · L. Krupa1,3 · A. V. Belozerov1 ·..., "The current status of the MASHA setup," *Springer International Publishing Switzerland ,* 2017.

[5] Y. T. Oganessian, "On-Line Mass Separator of SuperHeavy Atoms," *Nuclear Instrument and Methods A,* pp. 33-46, 2002.