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

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.

The discovery of Super Heavy Elements (SHEs) with the atomic numbers of Z=113- 118 was one of the outstanding scientific achievements of the last decade. The synthesis of new nuclides stimulated efforts to develop methods of their identification via the Isotope Separator On- Line (ISOL) technique. At FLNR, the mass-separator MASHA (Mass Analyzer of Super Heavy Atoms) was built and put into operation this separator allows to measure on-line the mass-to-charge ratios of SHE isotopes with simultaneous detection of their α-decays and spontaneous fission. By getting to know these elements better concepts like "island of stability" can be explored. The method used in this is the isotope separation on-line method which is used in mass analysis of short-lived isotopes and separates 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.

Introduction to ISOL method

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
- Acceleration
- Mass separation
- Charge state breeding

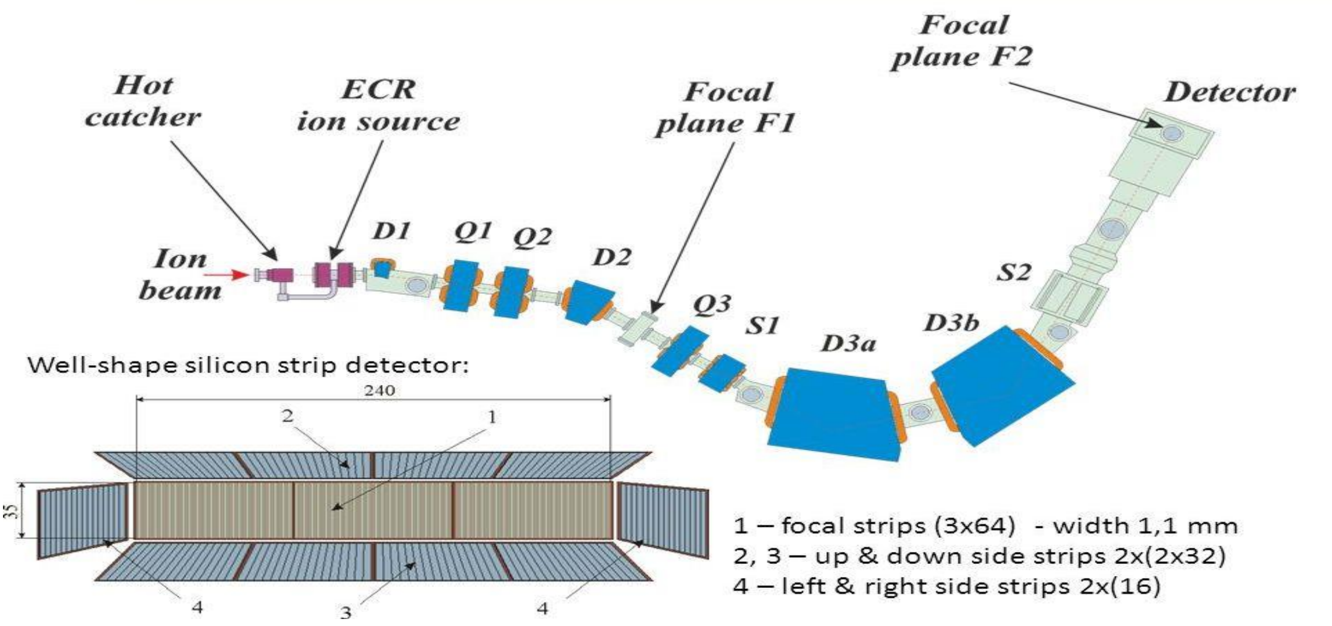
POINTS TO BE TAKEN CARE OF:

1. The ISOL method has been associated with thick targets in which the terminalization goes inside the graphite catcher unit and diffuses out to an ion source for further acceleration and separation.
2. The great advantage of the thick targets is the large total cross-section available for production of ions.
3. The disadvantage of ISOL method in general is the difficulty to achieve high beam purity due to the many isobars of different elements produced simultaneously in the target.
4. An active target and ion source development programme is crucial for the success of any ISOL facility

3.MASHA(Mass Analyser for Super Heavy Atoms)

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 design needed 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:



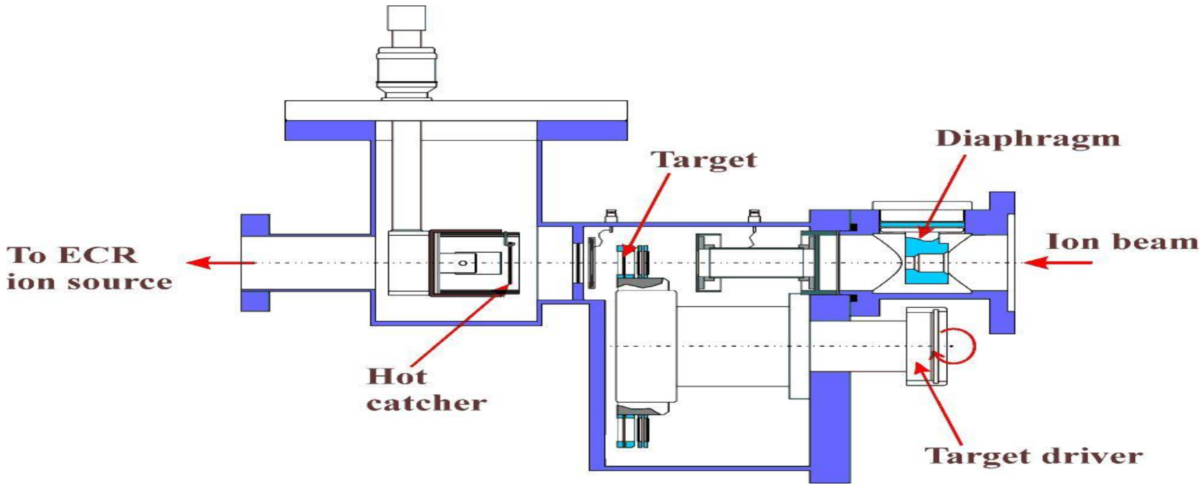
❖ A Target Assembly and a Hot Catcher

Prior to hitting the target, the primary beam of heavy ions passes through the diagnostic system composed of a split type aperture of the electrostatic induction sensor and a Faraday cup. The split aperture is divided into four sectors each of which measures the fraction of the beam current that does not fall into the hole of the aperture. This system allows control of the beam position relative to the ion guide. Nuclear reaction products escape from the target, pass through the separating foil, and are stopped in the graphite absorber, which is heated to a temperature of 1800–2000 K. In the form of atoms, the products diffuse from the graphite absorber to the vacuum volume of the hot catcher and, moving over the pipeline, reach the ECR source.

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.

❖ Ion Source

An ion source based on the ECR (the ECR source) with a 2.45 GHz frequency of its microwave oscillator is used for ionizing atoms of nuclear reaction products. In the ECR, atoms are ionized to charge state Q = +1, accelerated with the aid of the three electrode system, and gathered into a beam, which is thereafter separated by the magneto-optical system of the mass spectrometer. The ECR source helps to obtain ion currents consisting of almost 100% of singly ionized atoms, and the ionization efficiency of noble gases is as high as 90%. When the atoms reach the ECR they are ionized to the charge Q=+1, then there is three electrode electrostatic lens that accelerates the ions up to 38 keV and the ion beam formed is then separated by the magneto-optical mass-to-charge ratio analyzer.



❖ 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 in a region of Z=112-114 is done with accuracy of Δm=0.25-0.30 e.m.u. where mass resolution M/dM reaches 1700.

❖ 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.

✓ Task Results:

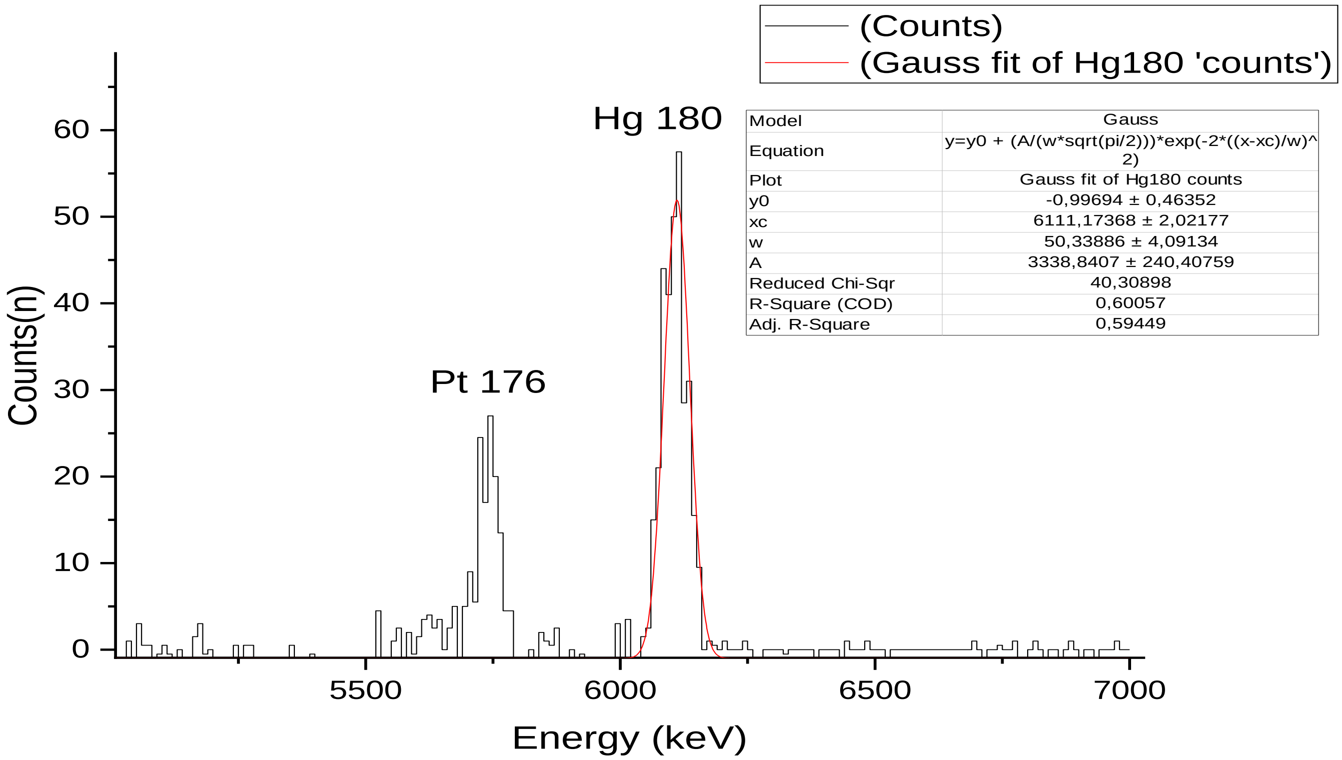
The task was to take the data of products of three different reactions: complete fusion neutron evaporation residues (^{40}Ar+^{148}Sm → $^{188\text{-}xn}$Hg+xn), (^{40}Ar+^{166}Er → $^{206\text{-}xn}$Rn+xn) and multinucleon transfer (^{48}Ca+^{242}Pu → ^{21x}Rn). Draw their histograms and analyze the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

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

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

Hg 180

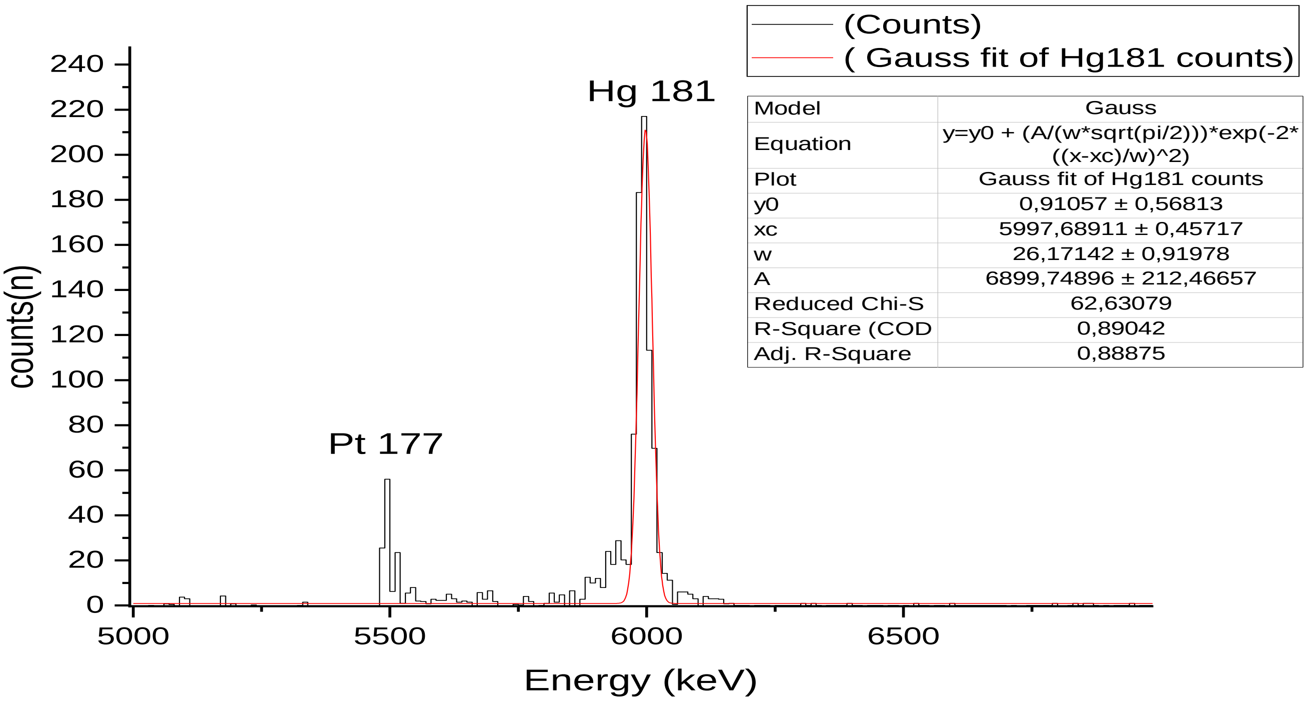
- This mercury isotope has half-life time of 2.58 seconds.
- It decays 48% by alpha of energy 6118 keV, giving a daughter Pt 176 that has half-life of 6.35 s and it 40% decays by alpha of energy 5753 keV.



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	Gauss fit of Hg180 counts
y0	-0,99694 ± 0,46352
xc	6111,17368 ± 2,02177
w	50,33886 ± 4,09134
A	3338,8407 ± 240,40759
Reduced Chi-Sqr	40,30898
R-Square (COD)	0,60057
Adj. R-Square	0,59449

Hg 181

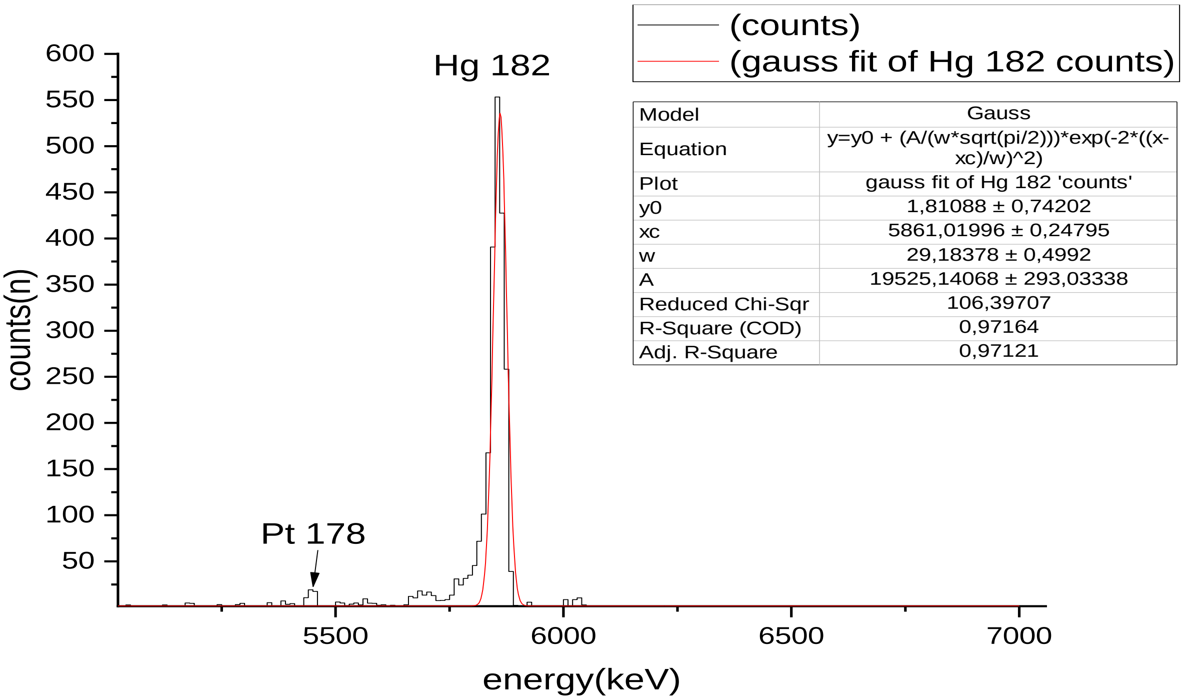
- It has half-life of 3.5 s.
- It 30% decays by alpha of energy 6006 keV, giving a daughter Pt 177 that has half-life time 11 s, and it 5.6% decays by alpha of 5517 keV.



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	Gauss fit of Hg181 counts
y0	0,91057 ± 0,56813
xc	5997,68911 ± 0,45717
w	26,17142 ± 0,91978
A	6899,74896 ± 212,46657
Reduced Chi-S	62,63079
R-Square (COD	0,89042
Adj. R-Square	0,88875

Hg 182

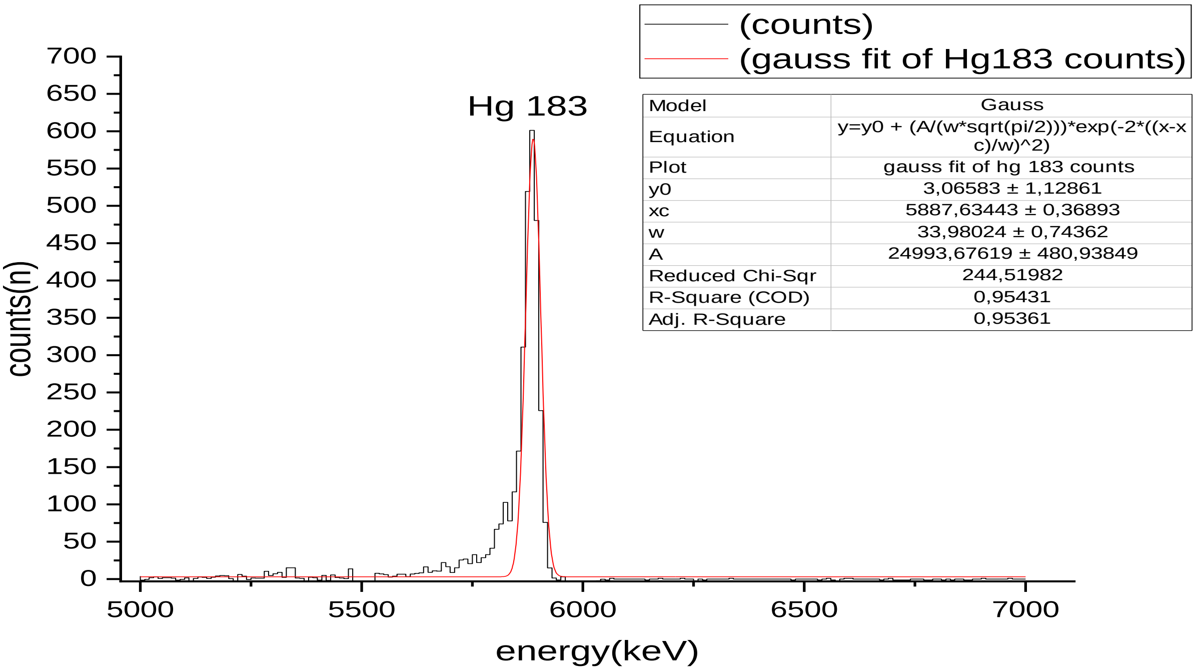
- It has half-life time of 10.835 s.
- It 15.2% decays by alpha of energy 5867 keV, giving a daughter Pt 178 that has half-life of 21.1 s and it 4.6% decays by alpha of energy 5446 keV.



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	gauss fit of Hg 182 'counts'
y0	1,81088 ± 0,74202
xc	5861,01996 ± 0,24795
w	29,18378 ± 0,4992
A	19525,14068 ± 293,03338
Reduced Chi-Sqr	106,39707
R-Square (COD)	0,97164
Adj. R-Square	0,97121

Hg 183

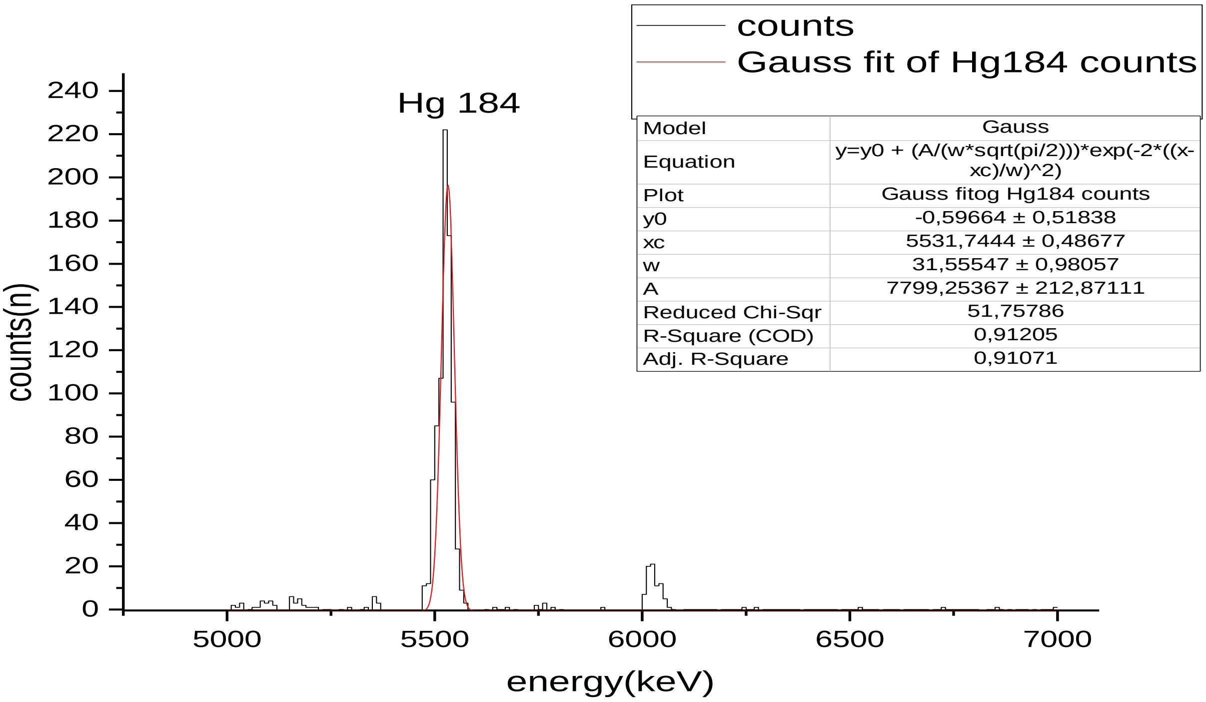
- It has half-life of 9.4 s.
- It 11.7% decays by alpha of energy 5904 keV, giving a daughter Pt 179 that has half-life of 21.1 s, and it 0.24% decays by alpha of energy 5195 keV.



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	gauss fit of hg 183 counts
y0	3,06583 ± 1,12861
xc	5887,63443 ± 0,36893
w	33,98024 ± 0,74362
A	24993,67619 ± 480,93849
Reduced Chi-Sqr	244,51982
R-Square (COD)	0,95431
Adj. R-Square	0,95361

Hg 184

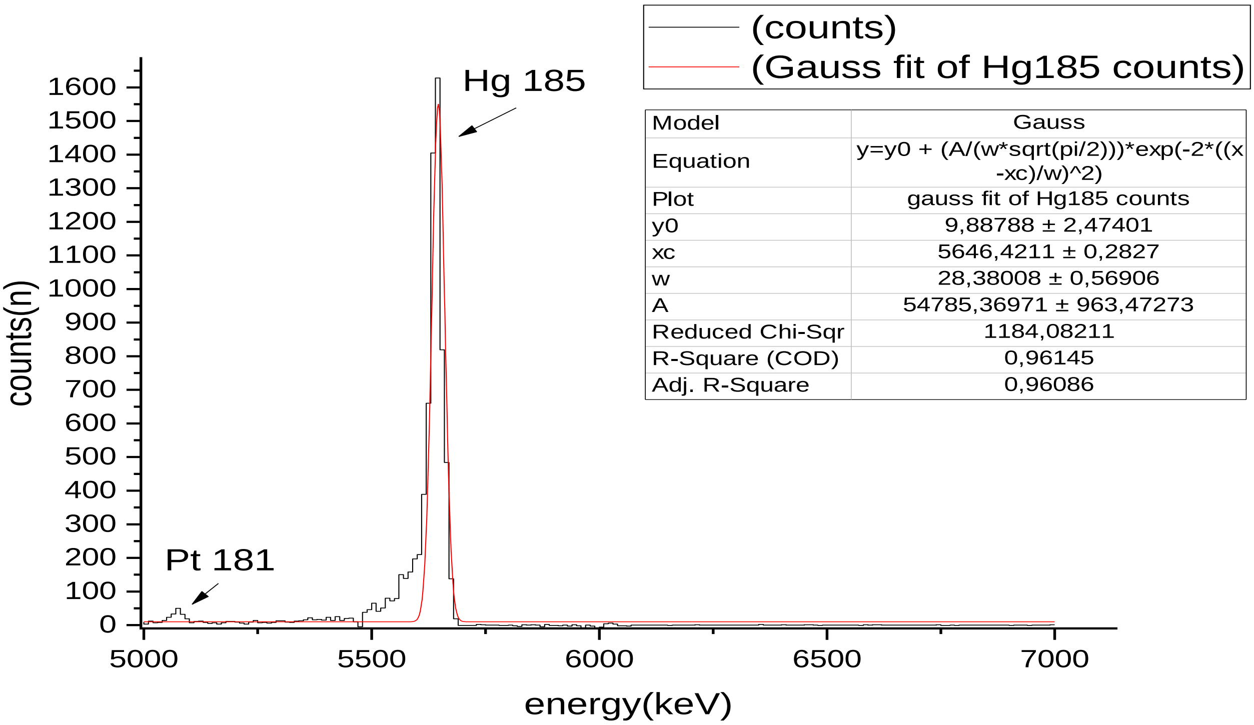
- It has half-life of 30.9 s.
- It 1.26% decays by alpha of energy 5535 keV, giving a daughter Pt 180 that has half-life of 56 s, and it 0.3% decays by alpha of energy 5140 keV.



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	Gauss fitog Hg184 counts
y0	-0,59664 ± 0,51838
xc	5531,7444 ± 0,48677
w	31,55547 ± 0,98057
A	7799,25367 ± 212,87111
Reduced Chi-Sqr	51,75786
R-Square (COD)	0,91205
Adj. R-Square	0,91071

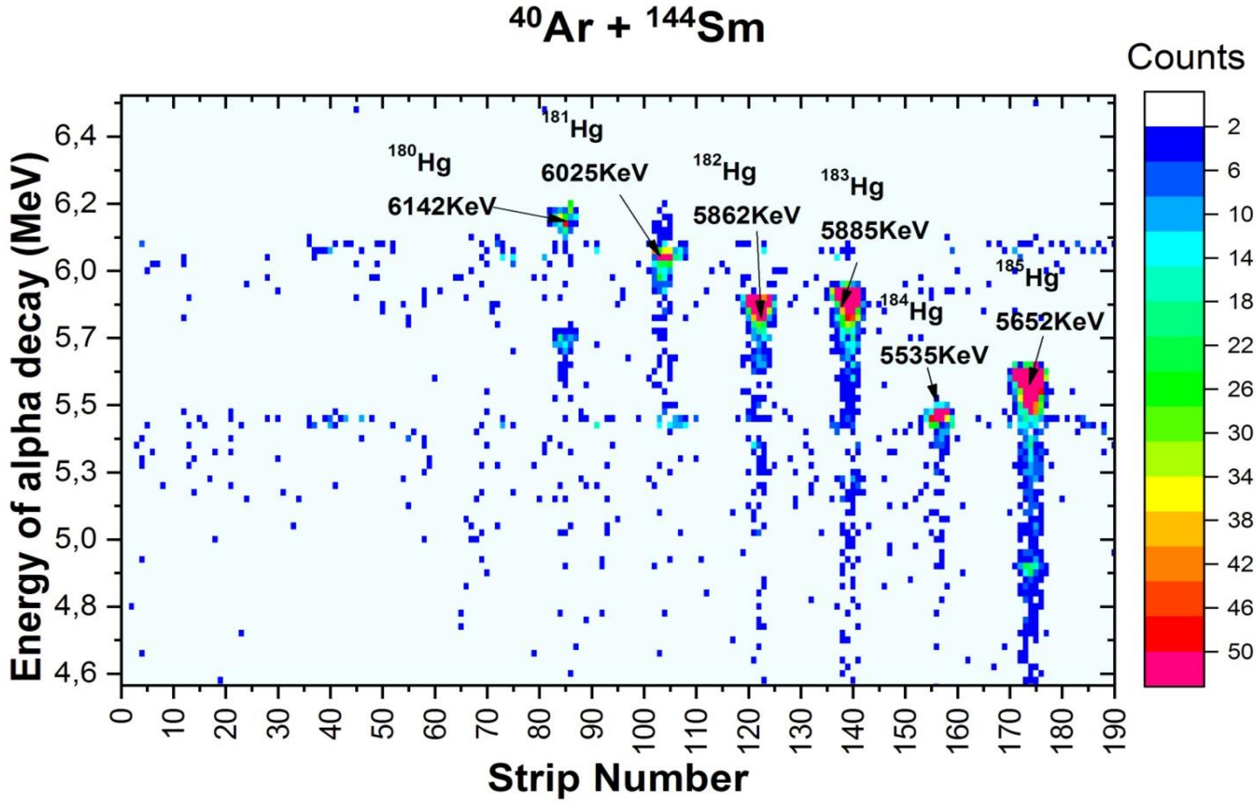
Hg 185

- It has half-life of 49.1 s.
- 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.



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	gauss fit of Hg185 counts
y0	9,88788 ± 2,47401
xc	5646,4211 ± 0,2827
w	28,38008 ± 0,56906
A	54785,36971 ± 963,47273
Reduced Chi-Sqr	1184,08211
R-Square (COD)	0,96145
Adj. R-Square	0,96086

HEAT MAP FOR THIS MERCURY ISOTOPE:



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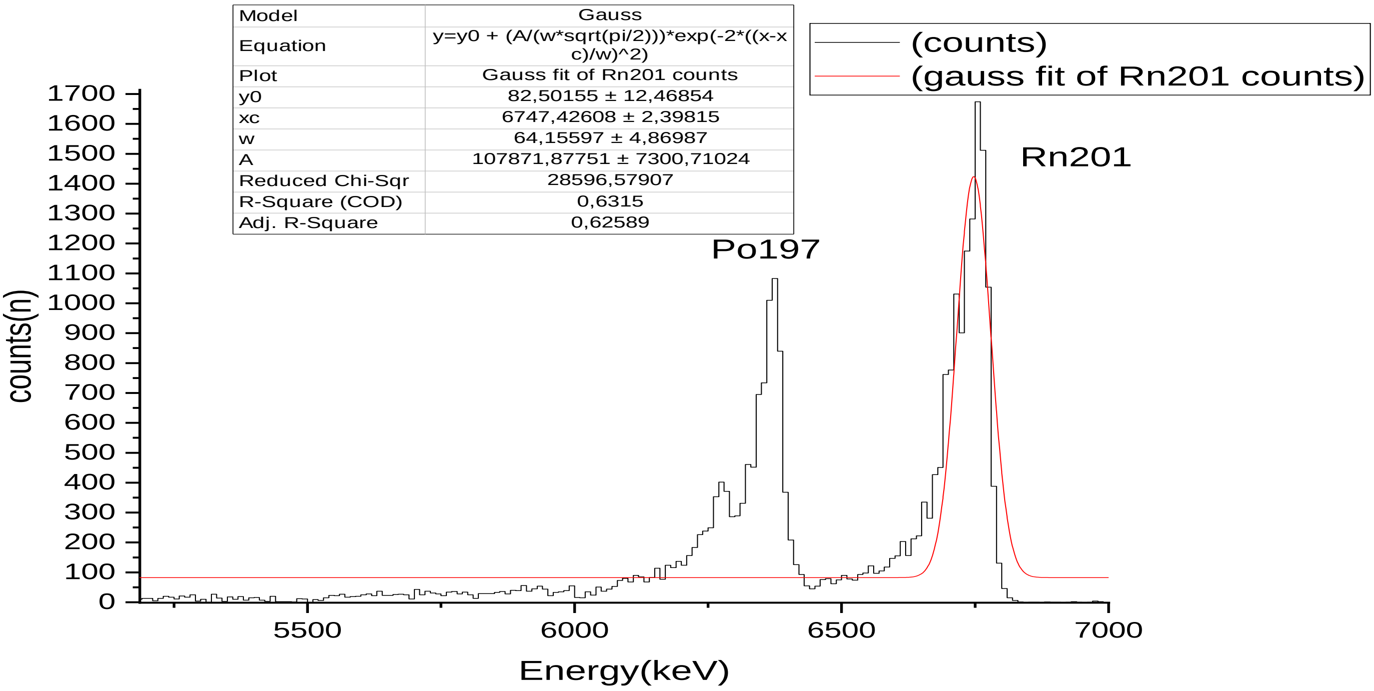
2) $^{40}Ar+^{166}Er\rightarrow^{206-xn}Rn+xn$

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

Rn 201:

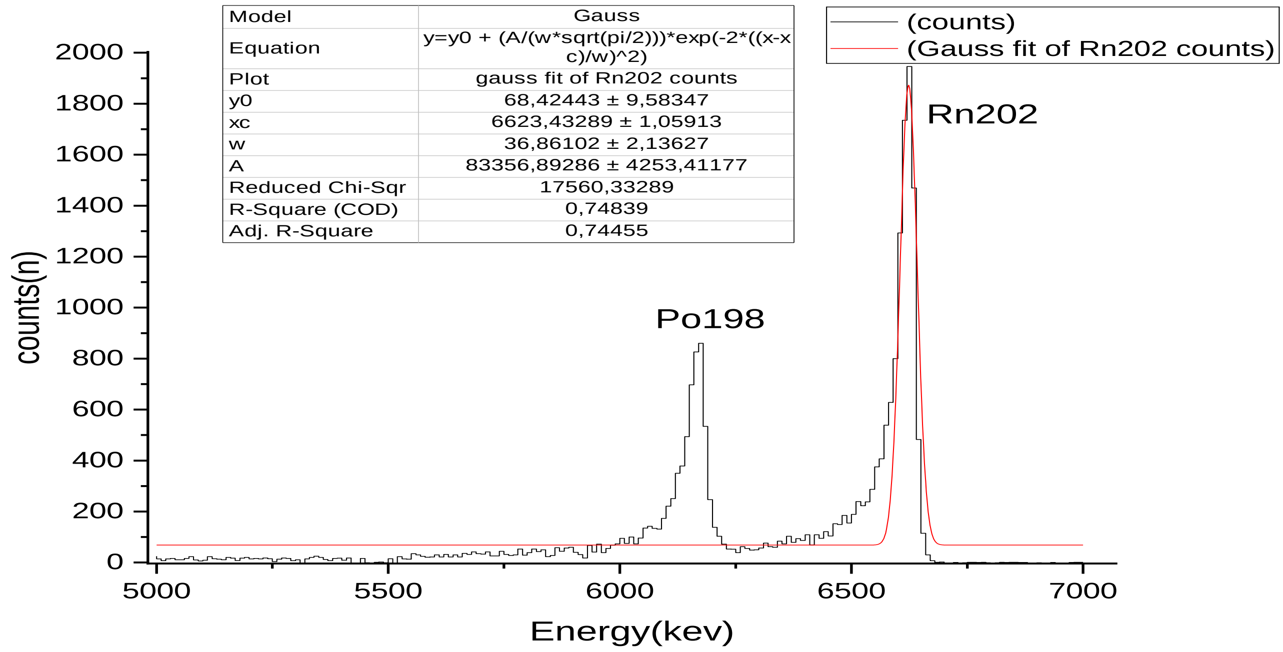
- This isotope has half-life time of 7.1 s.
- It 80% decays by alpha of energy 6725 keV, it gives daughter Po 197 that has two different decay modes. 44% has half-life of 53.6 s, and decays by alpha of 6281 keV. 84% has half-life of 25.8 s, and also decays by alpha but of energy of 6383.4 keV.



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	Gauss fit of Rn201 counts
y0	82,50155 ± 12,46854
xc	6747,42608 ± 2,39815
w	64,15597 ± 4,86987
A	107871,87751 ± 7300,71024
Reduced Chi-Sqr	28596,57907
R-Square (COD)	0,6315
Adj. R-Square	0,62589

Rn 202:

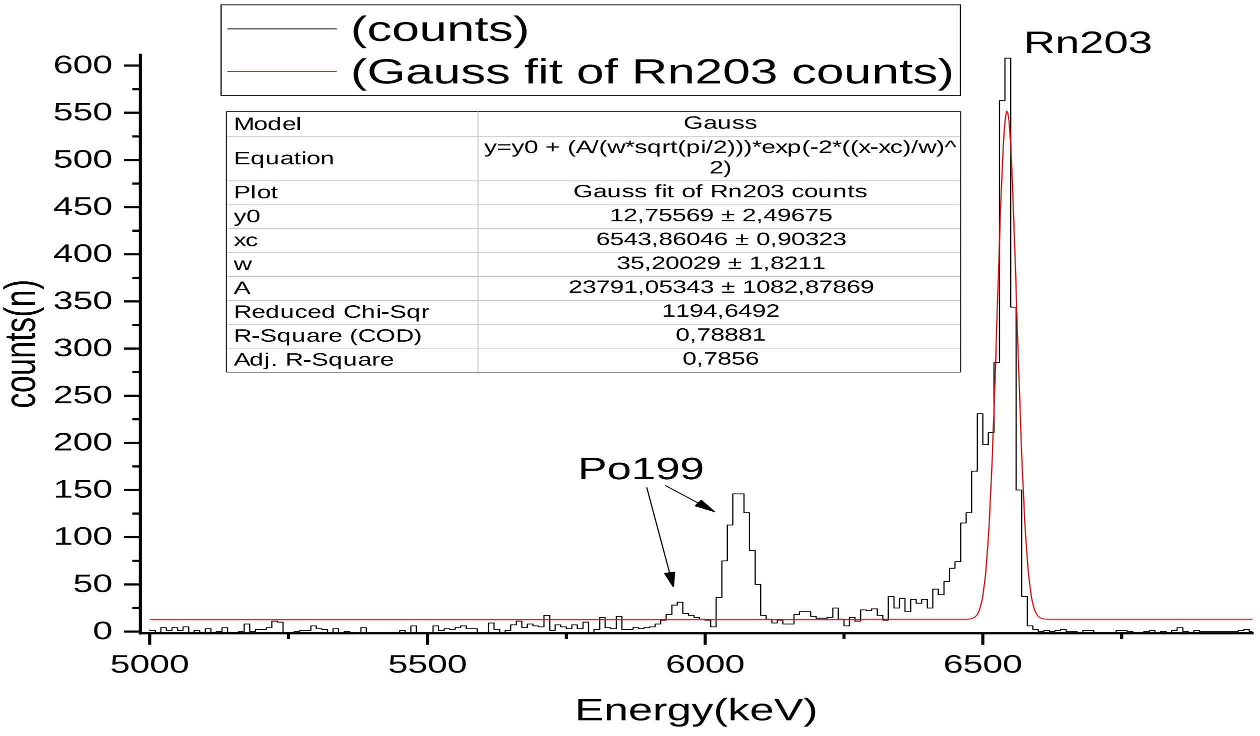
- It has half-life of 10 s.
- 90% of it decays by alpha of energy 6639 keV, giving a daughter Po 198 of half-life 1.77 minutes and 57% it decays by alpha of energy 6182 keV.



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	gauss fit of Rn202 counts
y0	68,42443 ± 9,58347
xc	6623,43289 ± 1,05913
w	36,86102 ± 2,13627
A	83356,89286 ± 4253,41177
Reduced Chi-Sqr	17560,33289
R-Square (COD)	0,74839
Adj. R-Square	0,74455

Rn 203:

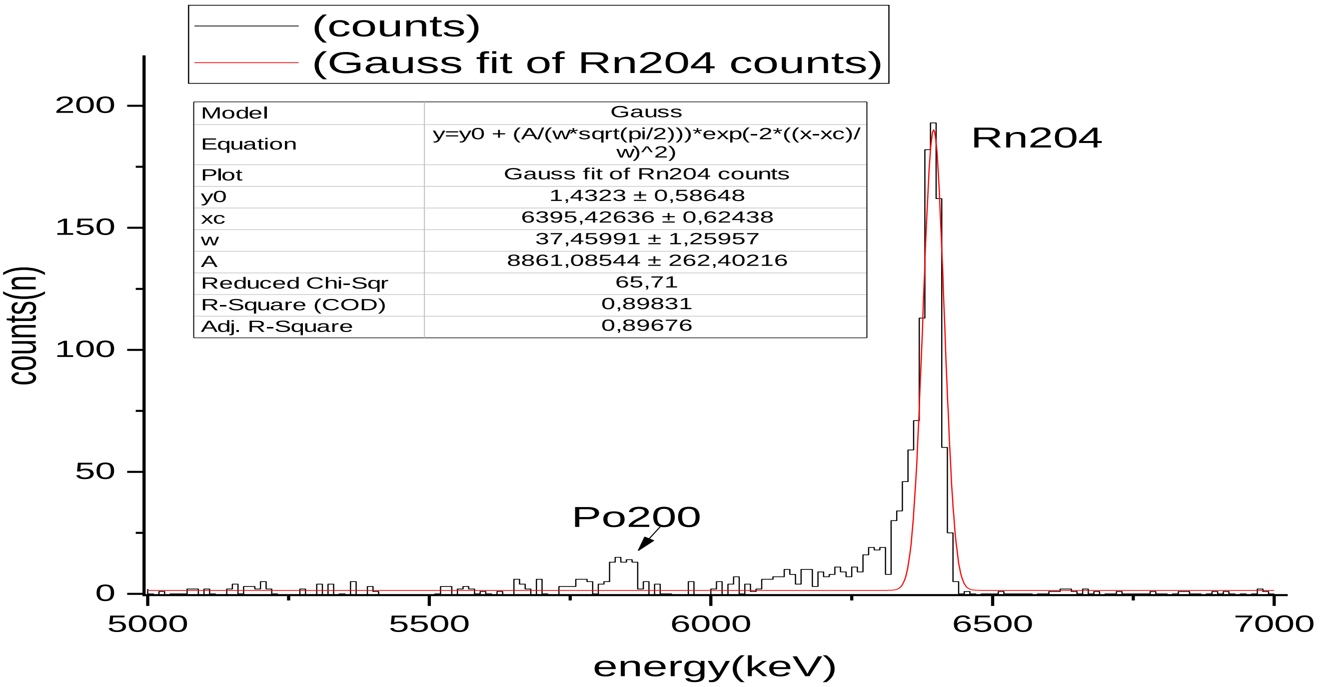
- It has half-life of 45 s.
- 66% of it decays by alpha of energy 6499 keV, giving a daughter Po 199 of half-life 5.48 m, and 12% it decays by alpha of energy 5952 keV.



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	Gauss fit of Rn203 counts
y0	12,75569 ± 2,49675
xc	6543,86046 ± 0,90323
w	35,20029 ± 1,8211
A	23791,05343 ± 1082,87869
Reduced Chi-Sqr	1194,6492
R-Square (COD)	0,78881
Adj. R-Square	0,7856

Rn 204:

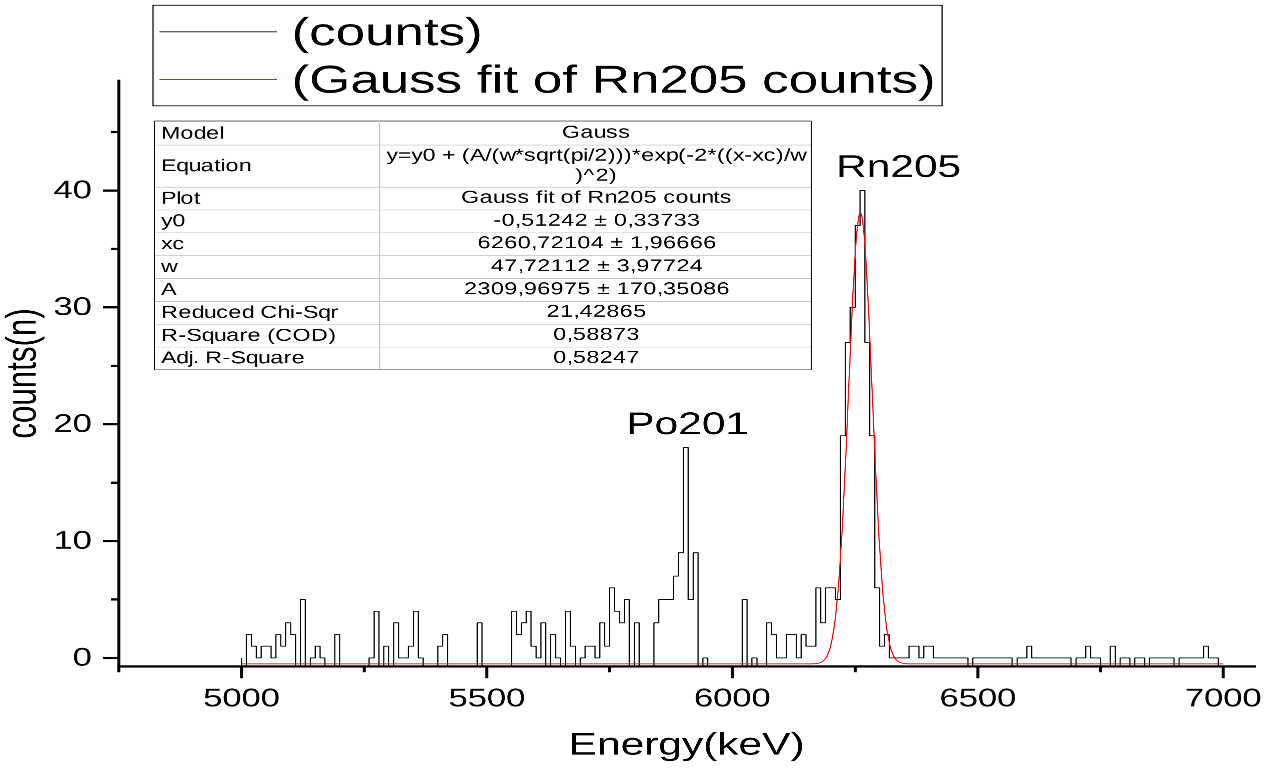
- It has half-life of 1.24 m
- 73% of it decays by alpha of energy 6418.9 keV, giving a daughter Po 200 of half-life 11.5 m, and 11% it decays by alpha of energy 5861 keV.



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	Gauss fit of Rn204 counts
y0	1,4323 ± 0,58648
xc	6395,42636 ± 0,62438
w	37,45991 ± 1,25957
A	8861,08544 ± 262,40216
Reduced Chi-Sqr	65,71
R-Square (COD)	0,89831
Adj. R-Square	0,89676

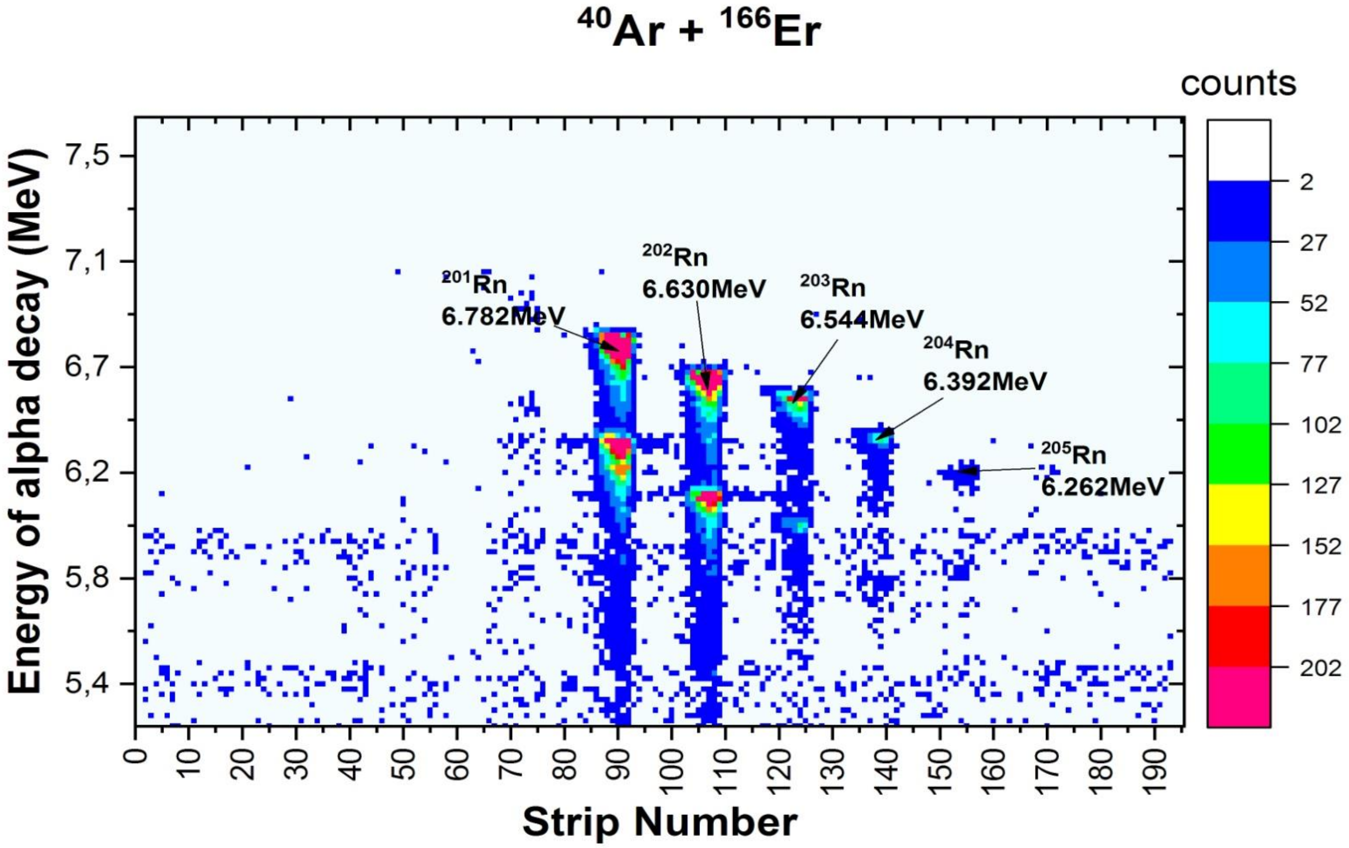
Rn 205:

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.



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	Gauss fit of Rn205 counts
y0	-0,51242 ± 0,33733
xc	6260,72104 ± 1,96666
w	47,72112 ± 3,97724
A	2309,96975 ± 170,35086
Reduced Chi-Sqr	21,42865
R-Square (COD)	0,58873
Adj. R-Square	0,58247

HEAT MAP OF RADON ISOTOPES.



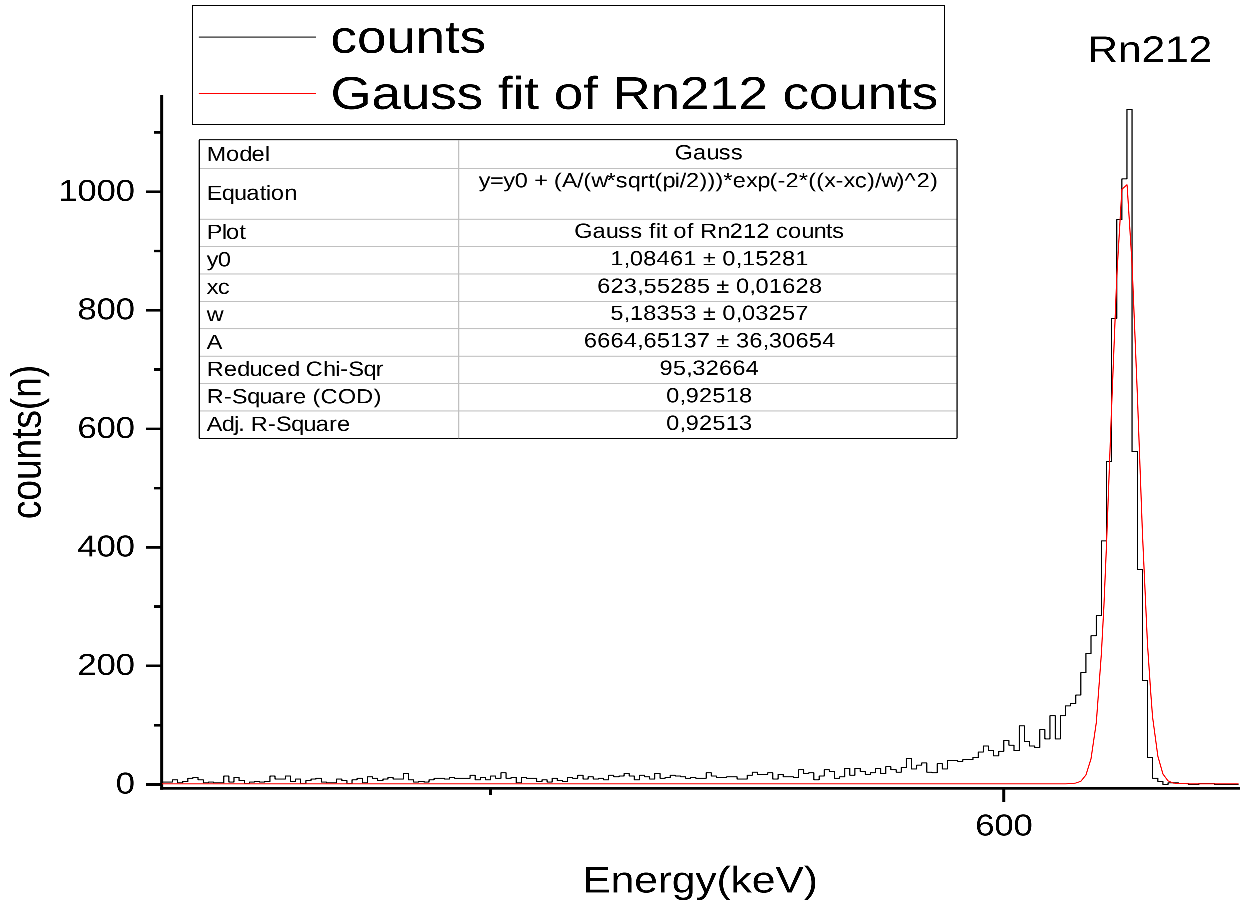
3) $^{48}Ca+^{242}Pu \rightarrow ^{21x}Rn$

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.

Rn 212:

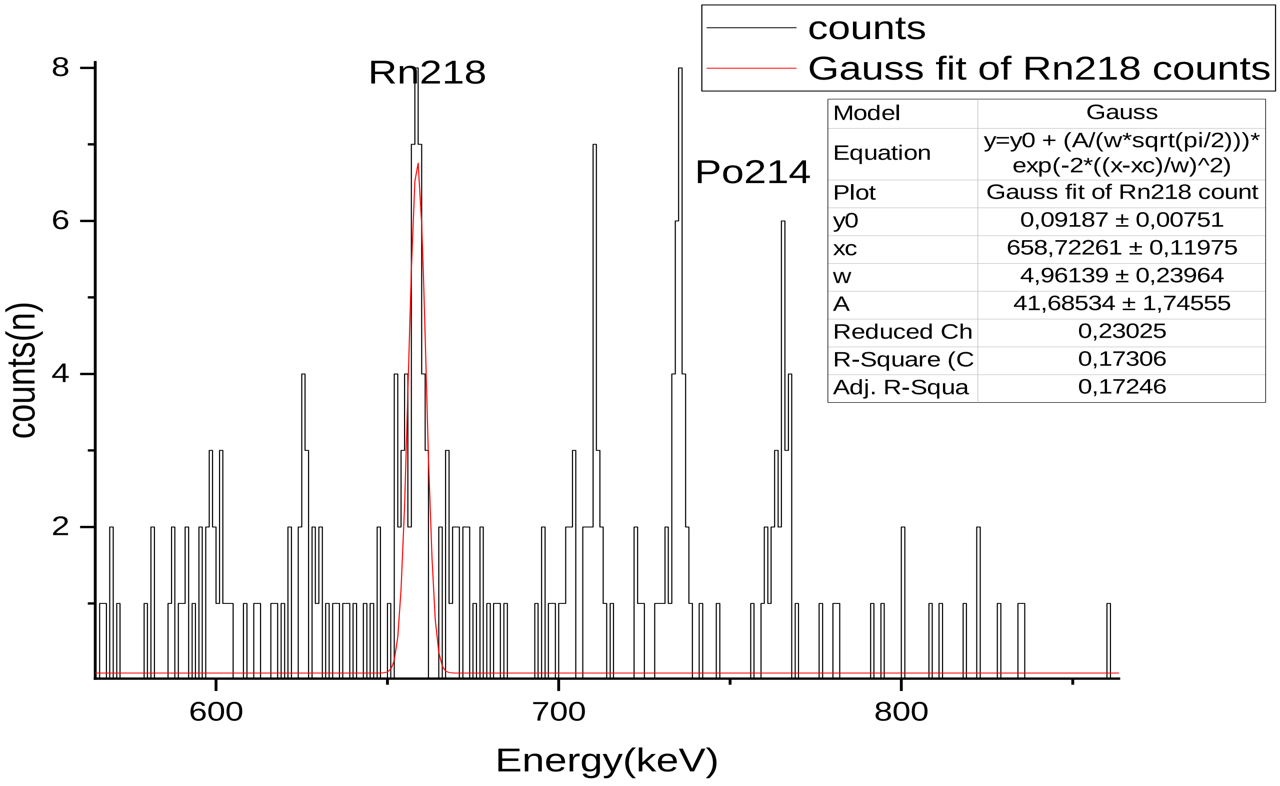
This radon isotope has half-life time of 23.9 m, it 100% decays by alpha of energy 6264 keV, giving a daughter Po 208 that has half-life of 2.898 years, and it 99.99% decays be alpha of energy 5114.9 keV.



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	Gauss fit of Rn212 counts
y0	1,08461 ± 0,15281
xc	623,55285 ± 0,01628
w	5,18353 ± 0,03257
A	6664,65137 ± 36,30654
Reduced Chi-Sqr	95,32664
R-Square (COD)	0,92518
Adj. R-Square	0,92513

Rn 218:

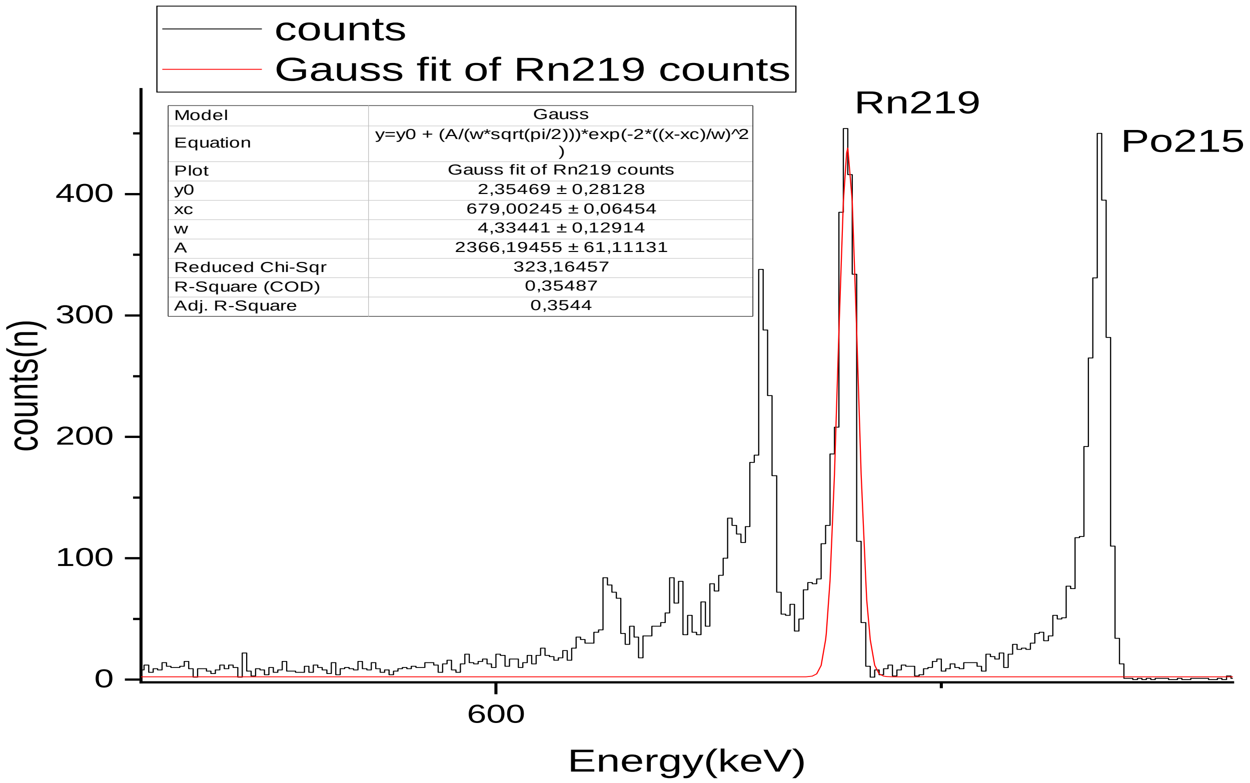
It has half-life of 35 ms, it 100% deacys by alpha of energy 7129.2 keV, giving a daughter Po 214 that has half-life of 164.5 µs, it 100% deacys by alpha of 7686.82 keV.



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))* exp(-2*((x-xc)/w)^2)
Plot	Gauss fit of Rn218 count
y0	0,09187 ± 0,00751
xc	658,72261 ± 0,11975
w	4,96139 ± 0,23964
A	41,68534 ± 1,74555
Reduced Ch	0,23025
R-Square (C	0,17306
Adj. R-Squa	0,17246

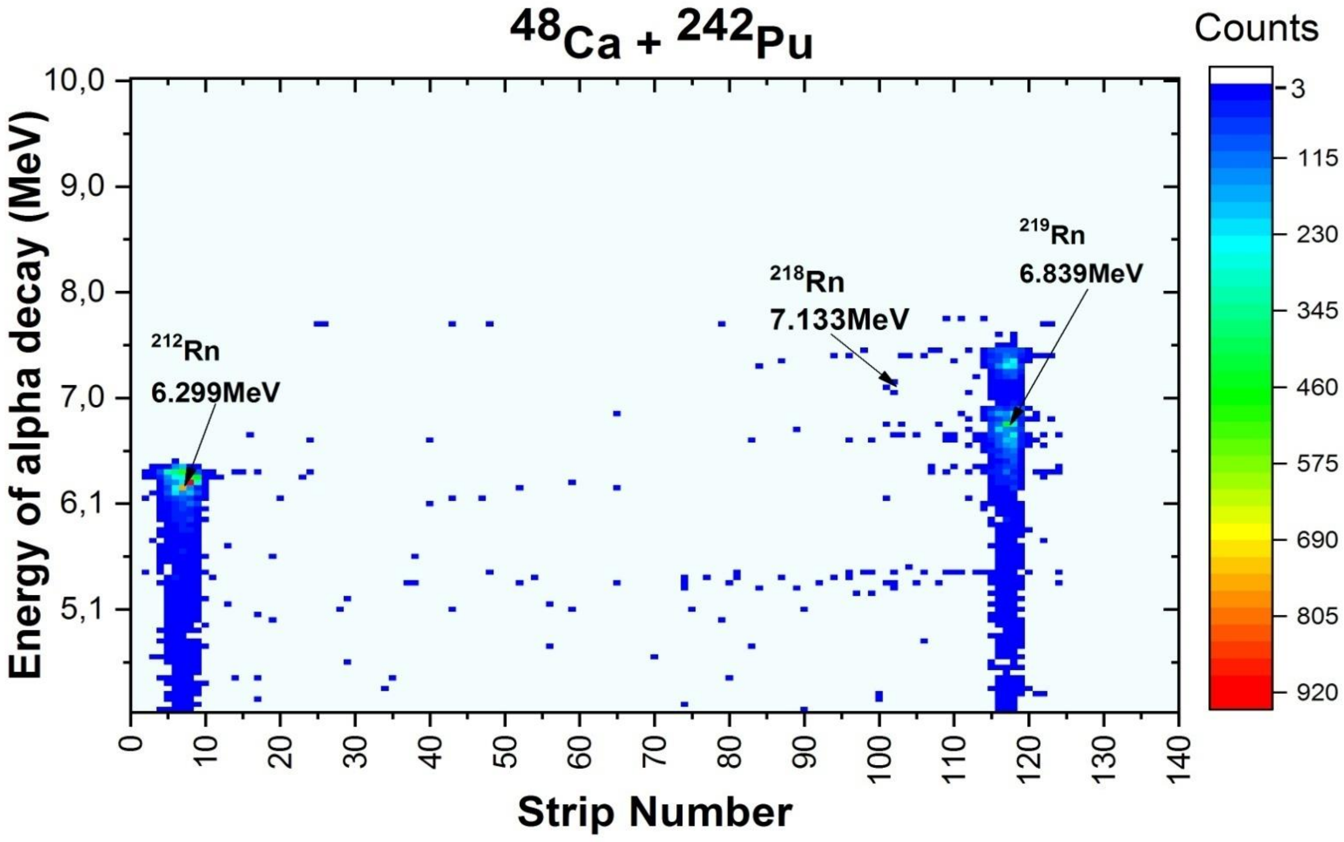
Rn 219:

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



Model	Gauss
Equation	y=y0 + (A/(w*sqrt(pi/2)))*exp(-2*((x-xc)/w)^2)
Plot	Gauss fit of Rn219 counts
y0	2,35469 ± 0,28128
xc	679,00245 ± 0,06454
w	4,33441 ± 0,12914
A	2366,19455 ± 61,11131
Reduced Chi-Sqr	323,16457
R-Square (COD)	0,35487
Adj. R-Square	0,3544

Heat map for radon isotope



➔Conclusion:

The main parts of MASHA setup were described, which are continuously improved. Studying of the super heavy elements helps in telling us more about the structure and the possibility of existence of the “island of stability” which is a predicted set of isotopes of super heavy elements that might have considerably longer half-lives than known isotopes of these elements. ISOL method is a very well known technique to get good quality beams 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. It is also 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 ions, 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.
The construction eliminates the heat load on the catcher material thus performing the separation efficiency stability using new nanomaterials based on carbon seems appealing. 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:

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References:

1. Chemical identification of Dubnium as a decay product of element 115 produced in the reaction 48Ca + 243Am. S.N. Dmitriev, Yu.Ts. Oganessyan, V.K. Utyonkov et al. Dubnium as a decay product.

2. Chemical characterization of element 112. R. Eichler, N. V. Aksenov, A. V. Belozerov et al. Nature. Letters. Vol. 447, May 2007.

3. The current status of MASHA setup. V. Yu. Vedeneev, A.M. Rodin, L.Krupa. Hyperfine Interactions 238:19 (2017).

4. Separation efficiency of the MASHA facility for short-lived mercury isotopes. A.M. Rodin,

A.V. Belozerov, E.V. Chernysheva. Hyperfine Interactions. 227:209-221 (2014).
5. MASHA Separator on the Heavy Ion Beam for Determining Masses and Nuclear Physical Properties of Isotopes of Heavy and Super heavy Elements. A.M. Rodin, A.V. Belozerov, D.V. Vanin. Instruments and Experimental Techniques, 2014, Vol. 57, No. 4, pp. 386–393. © Pleiades Publishing, Ltd., 2014.