JOINT INSTITUTE FOR NUCLEAR RESEARCH

FLEROV LABORATORY of NUCLEAR REACTIONS

FINAL REPORT ON THE

INTEREST PROGRAMME

Production and spectroscopic investigation of new neutron-rich isotopes near the neutron N=126 shell closure using the multinucleon transfer reactions

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Participation period:

05 October – 13 November, Wave 1,

Dubna, 2020

Abstract

To study about the Super Heavy Elements(SHE),their properties like their half-lives, decay modes, etc we have to use particle accelerators or cyclotrons in which they have some physical installations for different purposes at the beam opening. These installations helps to determine the various elements and their properties, that are produces with the help of accelerators. Mass Analyzer of Super Heavy Atoms(MASHA) located at one of the beamlines of U-400M cyclotron is described. It has resolving power about M/ΔM= 1700, which is enough for the identification of mass of super heavy nuclides. The MASHA setup uses ISOL(Isotope Separation On- Line) method. In the present report production of new neutron rich isotopes at N(neutron no.)=126,which is a shell closure are being described, using complete fusion and multi-nucleon transfer reactions and their spectroscopic investigation. Moreover study about MASHA and its construction and working is also described.

Introduction

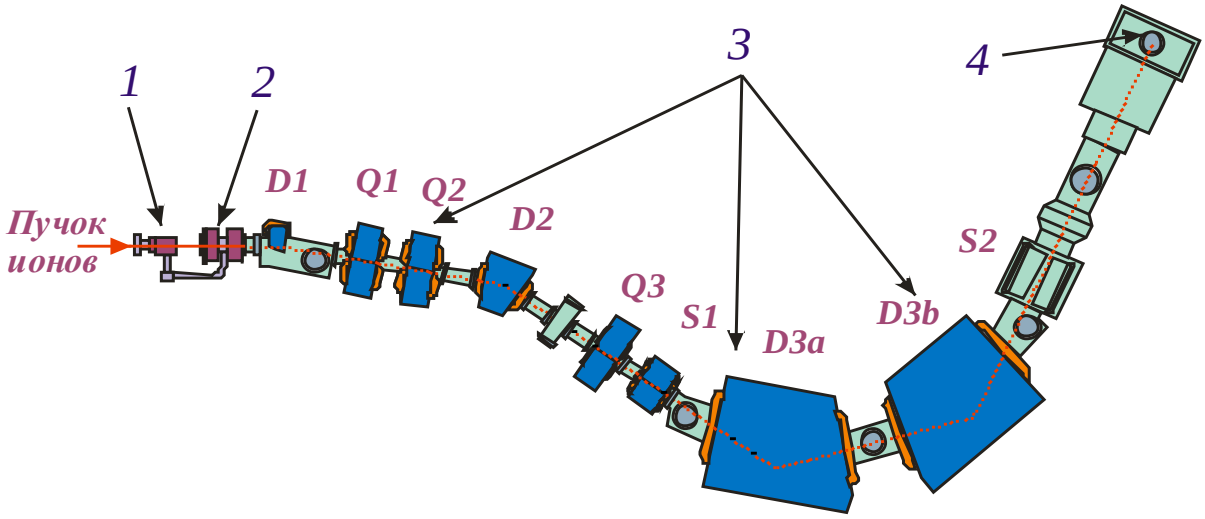
The discovery of super heavy elements(SHE) with the proton number(Z) between 113-118 also with the neutron rich isotopes of elements between Z=104-112 has been discovered at the end of twentieth century and beginning of twenty first century. The first type of experiments to produce these elements was performed at JINR, Dubna, Russia. First for it cyclotron U-120 was used, which is no anymore. For the SHE production and investigation their chemical and physical properties, two main FLNR installations are used-cyclotrons U400 and U400M. Nowadays, a new SHE factory with the head of DC-280 high-intensity cyclotron started their test beams irradiations. In FLNR the SHE are produced or synthesised via complete fusion reaction with neutron-excess actinoid nuclei.

MASHA facility, located at the beamline of U400M cyclotron, consist of various parts, which gives the desired results and identification of elements produce. The products of reaction are being produced using the complete fusion reactions, in which the isotopes of mercury(Hg) and Radon(Rn) are produced. As it was said MASHA's method of online analysis is based on the ISOL Method for determining the newly formed isotopes. Cyclotron ejects the projectile ion (e.g. $^{40,48}Ca^{5+}$ or $^{36,40}Ar^{5+}$) at beam energy of 5-7 MeV/nucleon.

The setup consist of target assembly with a hot catcher, an ion source based on electron cyclotron resonance(ECR); a magneto-optical analyser(mass spectrometer). The target is located before the hot catcher unit. The reaction products get deposited on the graphite absorber. Thermally expanded graphite which represents a porous poly-graphene structure with a porosity of 75%absorber, which is placed behind the target. After that, due to diffusion these products get injected in the ECR ion source and from there after ionizing they get transferred to the mass separator(MASHA) which consist of Dipole magnets, quadruple lenses and sextuple lenses. Short-lived isotopes decays are being detected in the focal plane of the separator.

Another application of MASHA is related to study the neutron rich nuclei near the N=126 shell closure, which produced in the multi-nucleon transfer reactions and complete fusion reactions with the mass-to-charge ratio separation of target-like fragments.

Mass Analyzer of Super Heavy Atoms

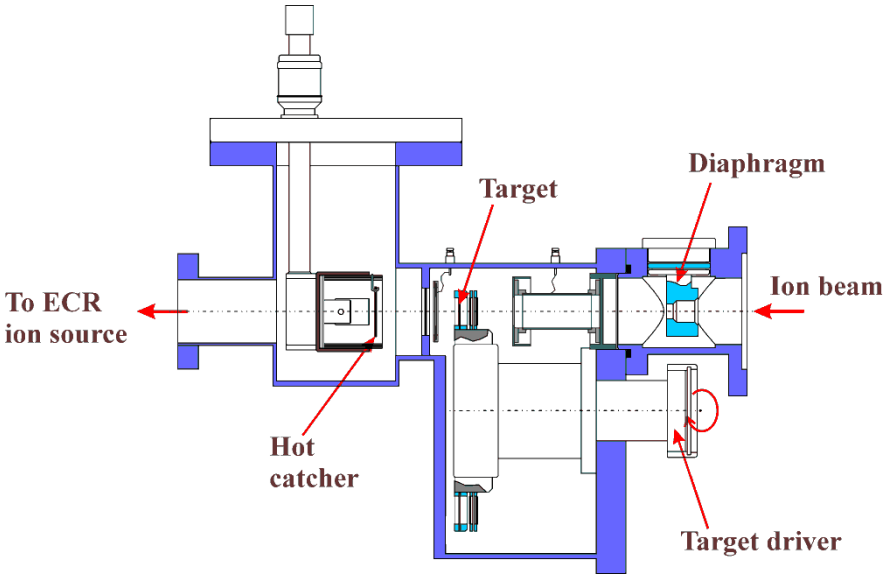


1 – Target box with hot catcher;
2 – Ion source;
3 – Mass separator;
4 – DAQ in the focal plane.

General ion-optical parameters:

- Range of energy variation, keV 15-40
- Range of *Br* variation, Tm 0.08-0.5
- Mass acceptance, % +/-2.8
- Angular acceptance, mrad +/-14
- Diameter the ion source exit hole, mm 5.0
- Horizontal magnification at F1/F2 0.39/0.68
- Mass dispersion at F1/F2, mm/% 1.5/39.0
- Linear mass resolution at F1 75
- Mass resolution at F2 1300

Rotating target and Hot catcher scheme



While performing the multinucleon reactions and complete fusion reactions, a hot catcher is used to thermalize and stop the products of fusion reactions and transport it into the ECR ion source.
The first part is composed of diagnostic and collimation system, which controls the beam energy, intensity and position relative to the ion guide. After it there is a rotating target, which consists of 6 sectors assembled in cassettes having 2 sectors each. It rotates via electric engine with the frequency of 25Hz.

After that nuclear products escape from the target, passes the division foil which serves as a gate for low energy reaction products and represents the thin(tens of $\mu g/cm^2$) carbon foil confined in a honeycomb structure with the 85% transparency and then stopped by a graphite absorber(heated up to 1800-2000K).

In the hot catcher the foil made of polygraphene of density $1 g/cm^3$ and thickness 0.6mm is used as an absorber material. It is shaped in the form of disc of diameter 30mmand placed behind the target at the distance of 30mm. The absorber is heated directly by dint of a constant electric current($I \leq 200$ A).

Then the products diffuses from the graphite in the forms of atoms and moving to ECR ion source. In ECR the products are ionized to a charge state Q=+1 and

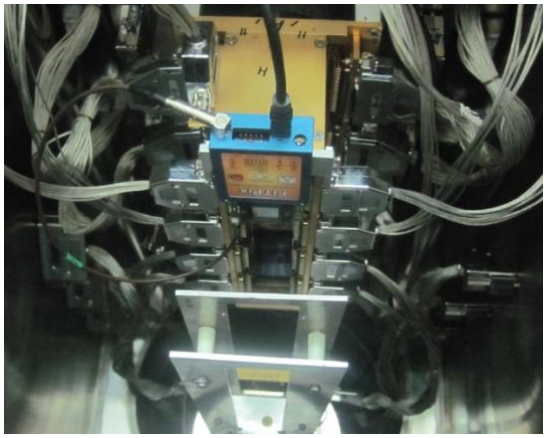
accelerated with the aid of three electrode system. ECR stands for Electron Cyclotron Resonance phenomenon.

Detectors

Focal plane silicon multi strip detector

- Configuration – well type
- Number of the focal strips – 192 (step – 1.25 mm)
- Number of the back side strips – 160 (step – 5 mm)
- Total efficiency – more than 90%

TIMEPIX detector



- An array of 256x256 square pixels of pitch size 55mm for full sensitive area 14x14 mm^2.
- Silicon sensor of 300 µm thickness.

My Task

Our main aim is to analyse the alpha decay of the nuclei at the N=126, which is a shell closure.

We have to perform the analysis the alpha of alpha decaying nuclei near the N=126 shell closure.

Find peaks and tracks using the histograms and identify the isotope of mercury(Hg) and radon(Rn)

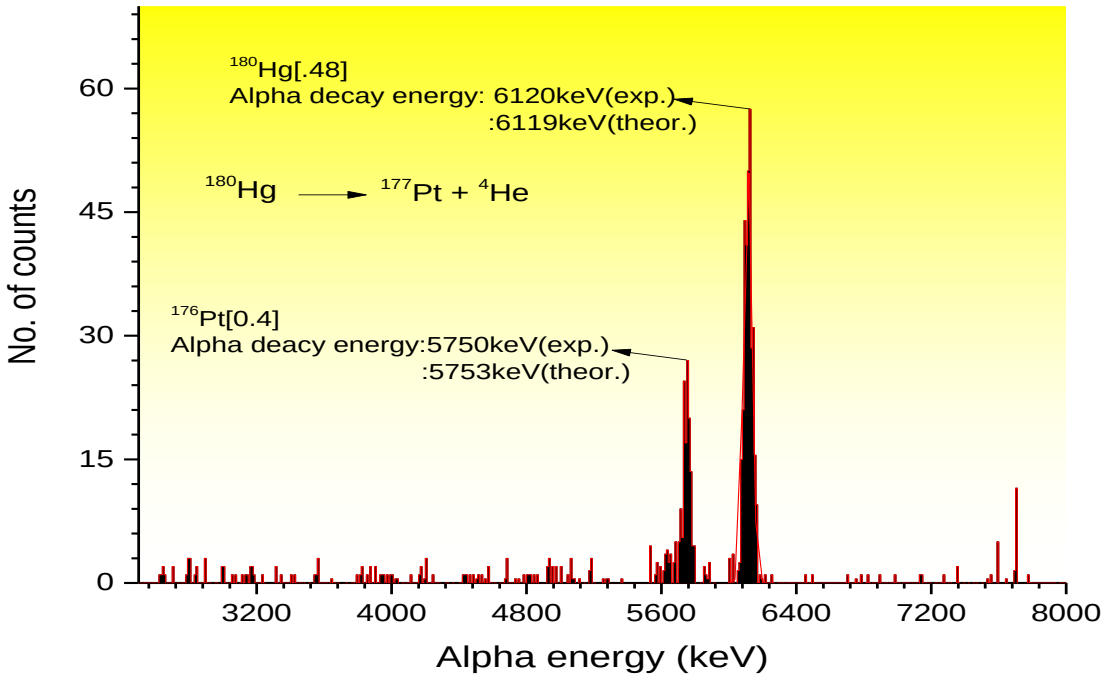
The reason behind using Hg and Rn because looking at the periodic table element 112 is from the group 12. The chemical properties of this element are similar to those of element which is above it like Hg, as 112 is found very volatile like mercury, in normal conditions. Hence it was decided to carry out the model experiments aimed at determining the separation efficiency and time of radioactive Hg isotopes synthesised in complete fusion reaction:

$$^{40}Ar + ^{144}Sm = ^{184\text{-}xn}Hg + xn$$

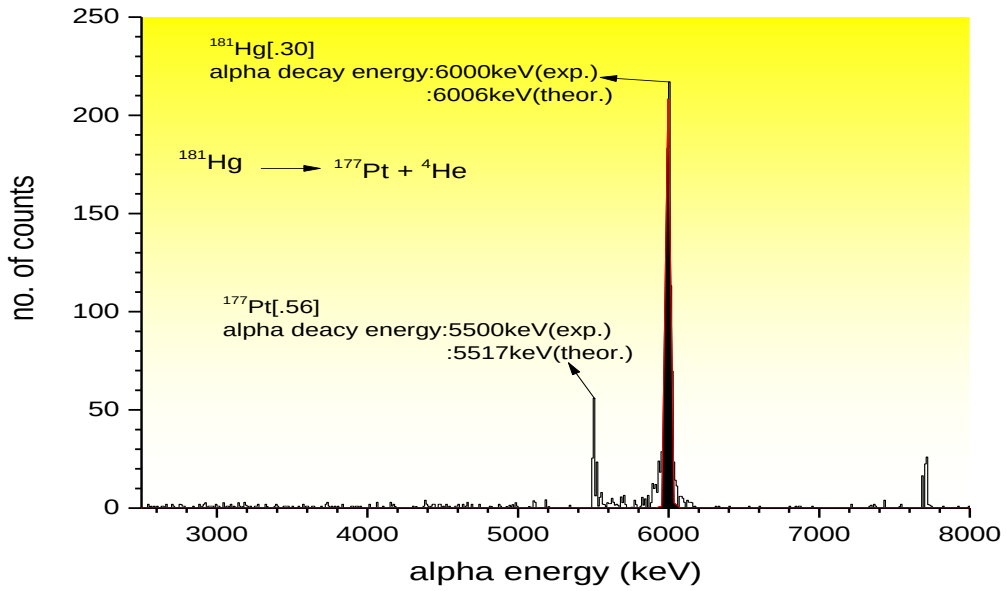
Rn is radioactive noble gas, chemically inert, compared to Hg:

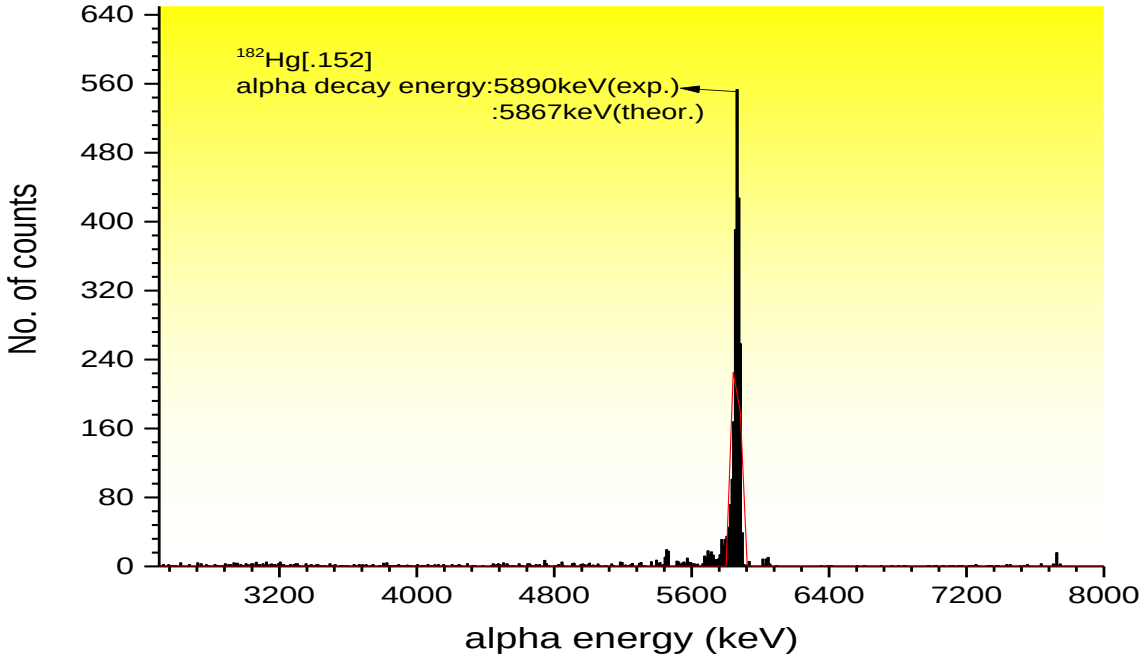
$$^{40}Ar + ^{166}Er = ^{206\text{-}xn}Rn + xn$$

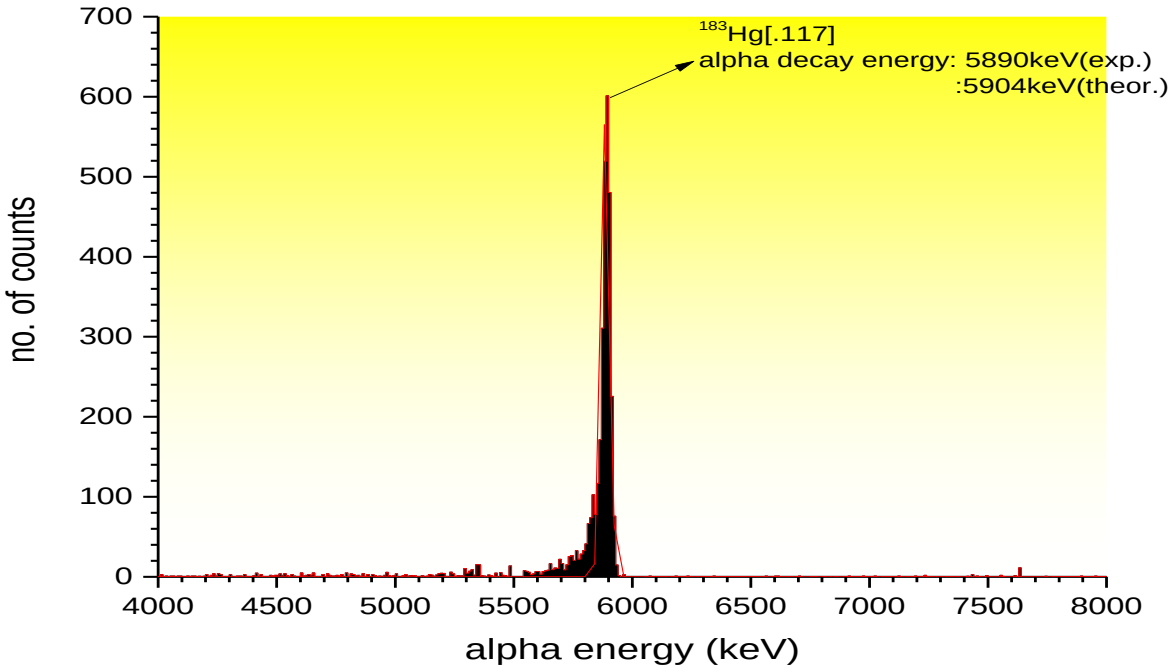
$$^{40}Ar + ^{144}Sm = ^{184\text{-}xn}Hg + xn$$

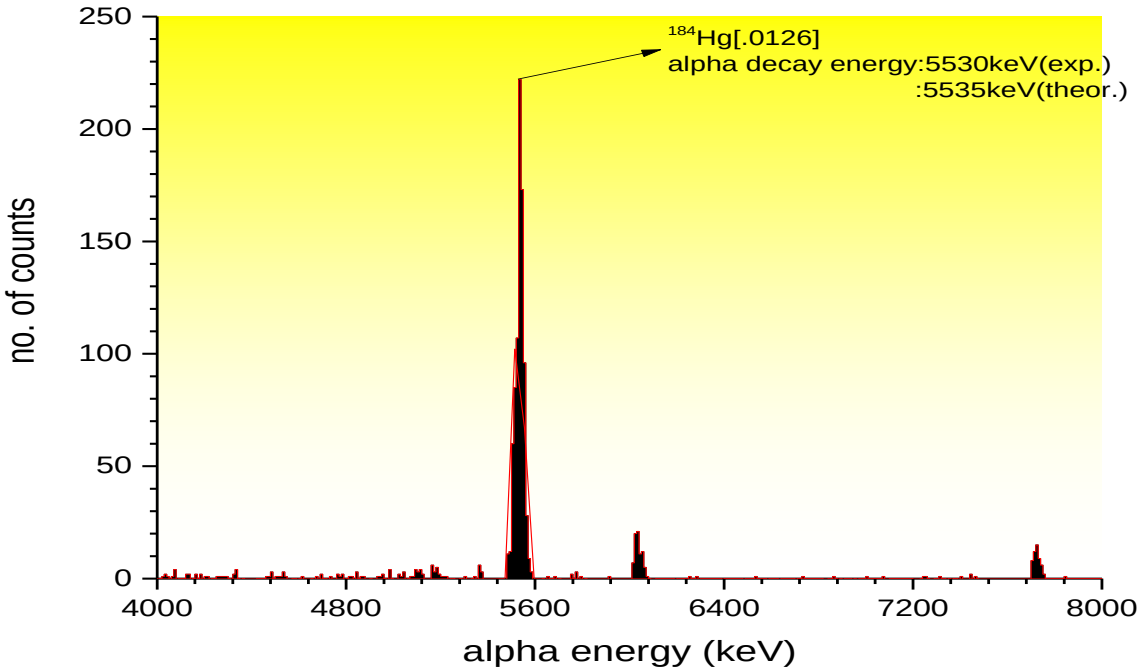


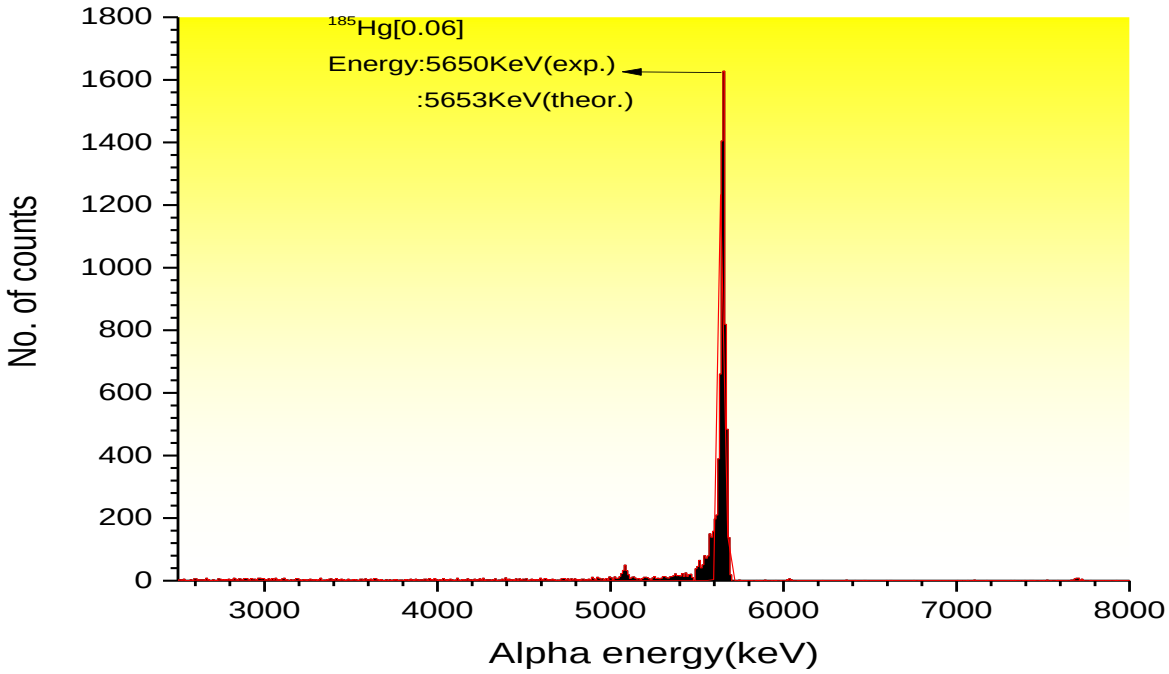
- Hg atoms undergo alpha decay on the strip of strip detector giving appropriate isotope of platinum.
- In addition, alpha particles from the daughter platinum decay could also be detected by using strip detector.


^{181}Hg[.30]
alpha decay energy:6000keV(exp.)
:6006keV(theor.)
^{181}Hg → ^{177}Pt + ^{4}He
^{177}Pt[.56]
alpha deacy energy:5500keV(exp.)
:5517keV(theor.)
no. of counts
alpha energy (keV)
0
50
100
150
200
250
3000
4000
5000
6000
7000
8000


^{182}Hg[.152]
alpha decay energy:5890keV(exp.)
:5867keV(theor.)
No. of counts
alpha energy (keV)
0
80
160
240
320
400
480
560
640
3200
4000
4800
5600
6400
7200
8000

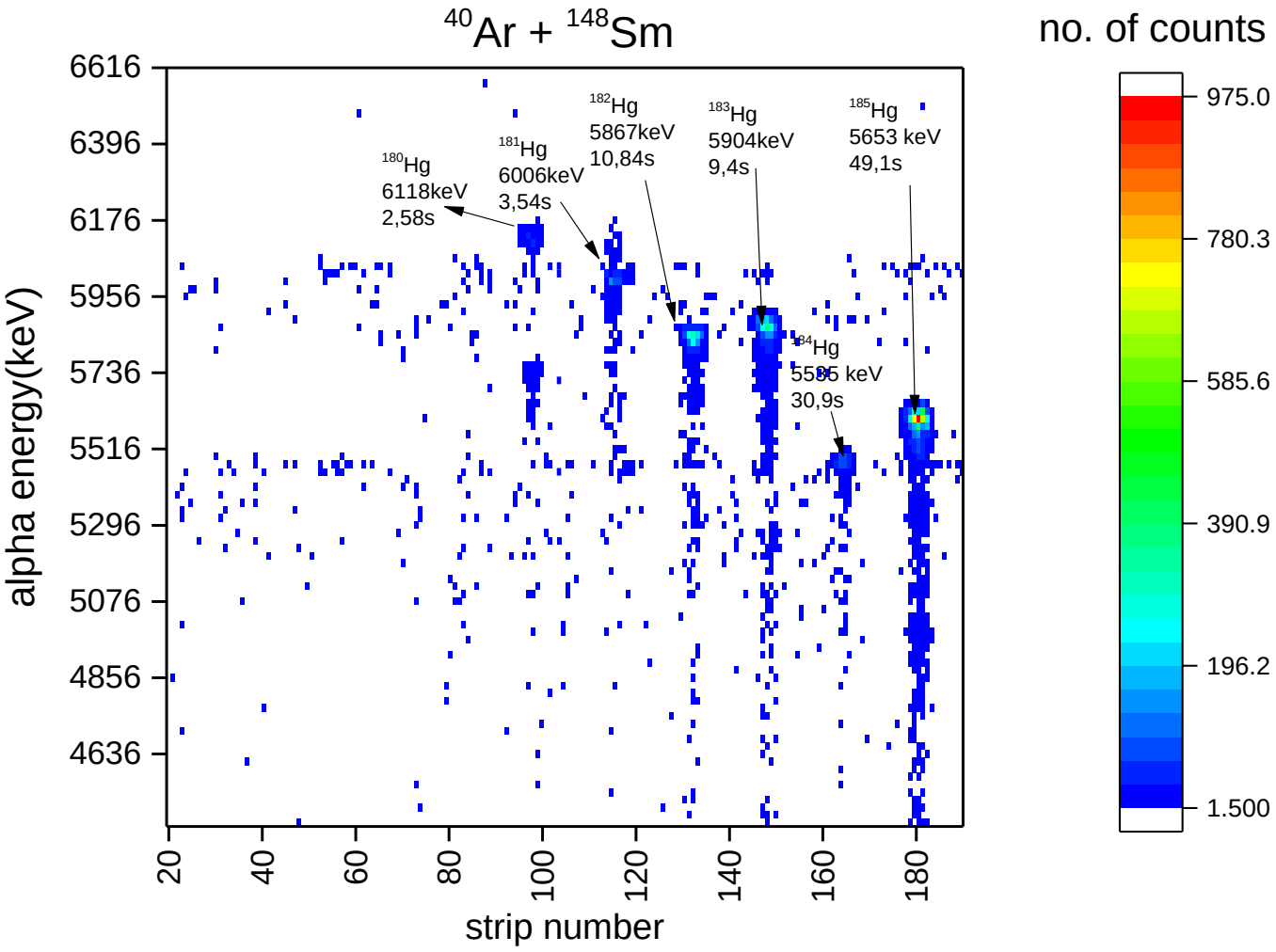

183Hg[.117]
alpha decay energy: 5890keV(exp.)
:5904keV(theor.)
no. of counts
alpha energy (keV)
0
100
200
300
400
500
600
700
4000
4500
5000
5500
6000
6500
7000
7500
8000


184Hg[.0126]
alpha decay energy:5530keV(exp.)
:5535keV(theor.)
no. of counts
alpha energy (keV)
0
50
100
150
200
250
4000
4800
5600
6400
7200
8000



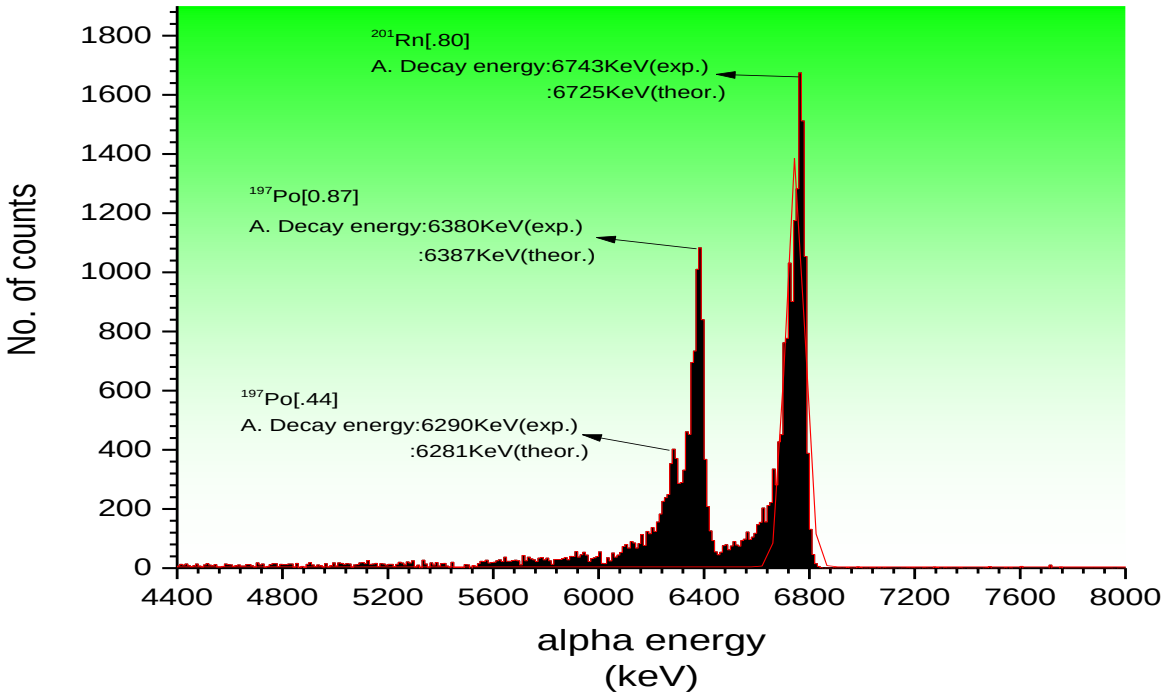
Energy spectra of Hg isotope are shown in above figures.

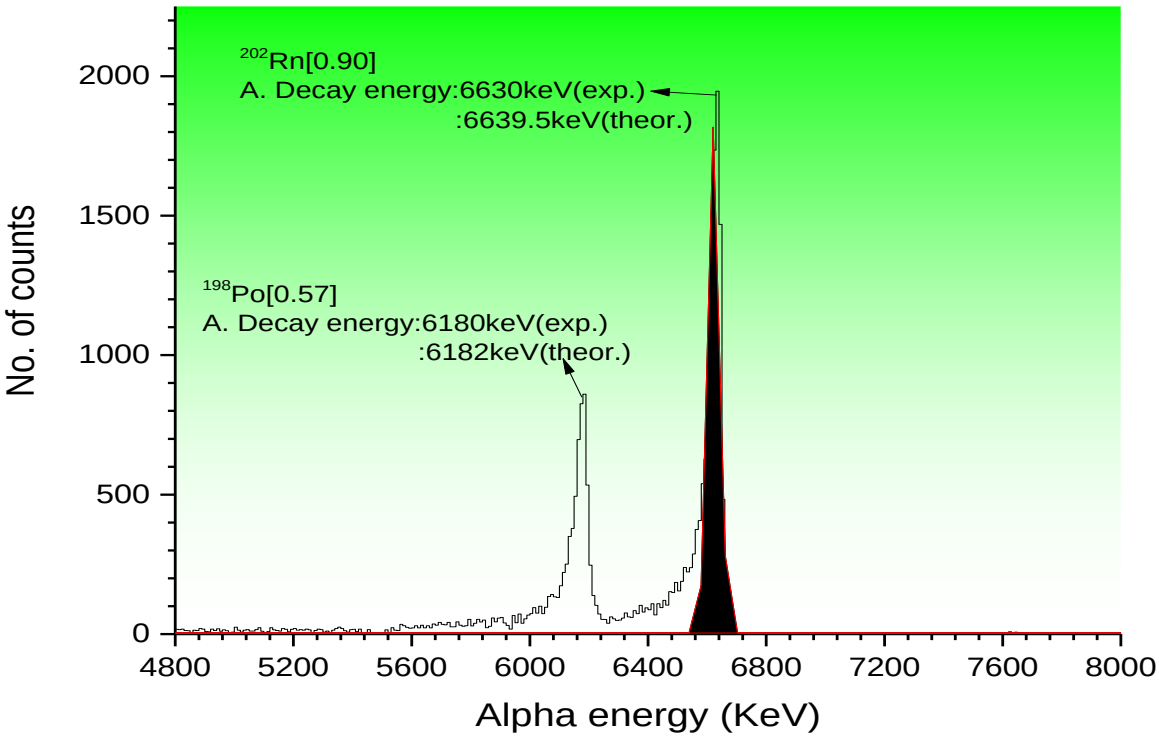
Matrix for Hg isotope

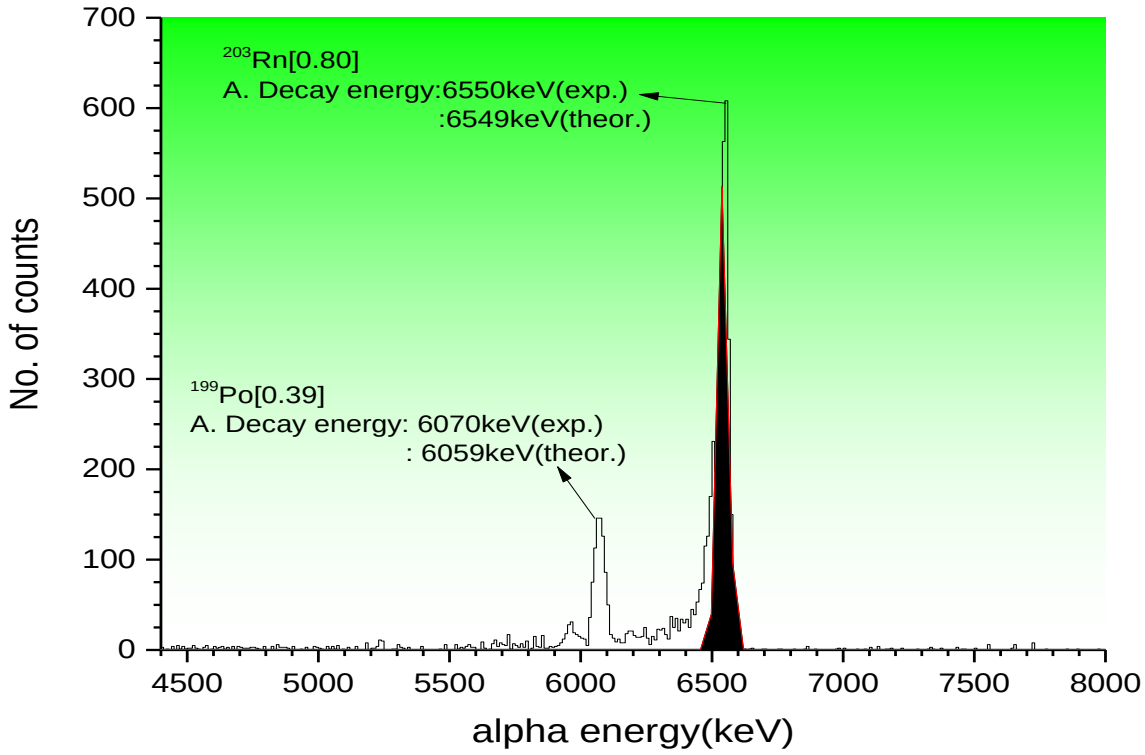


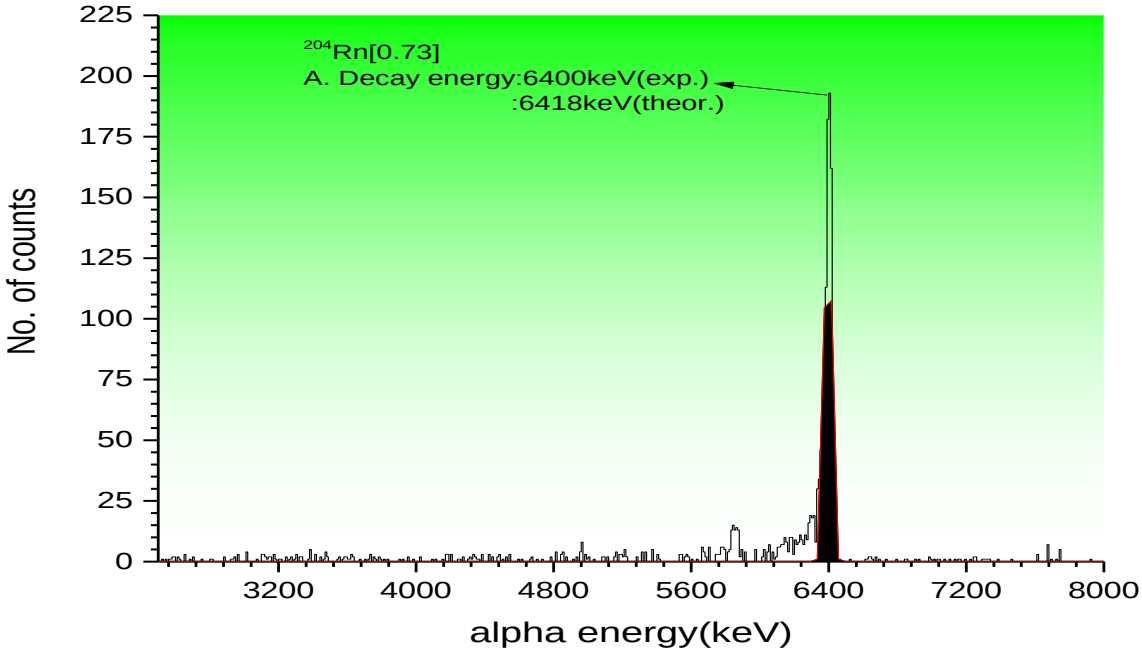
$^{40}Ar + {}^{166}Er = {}^{206-xn}Rn + xn$

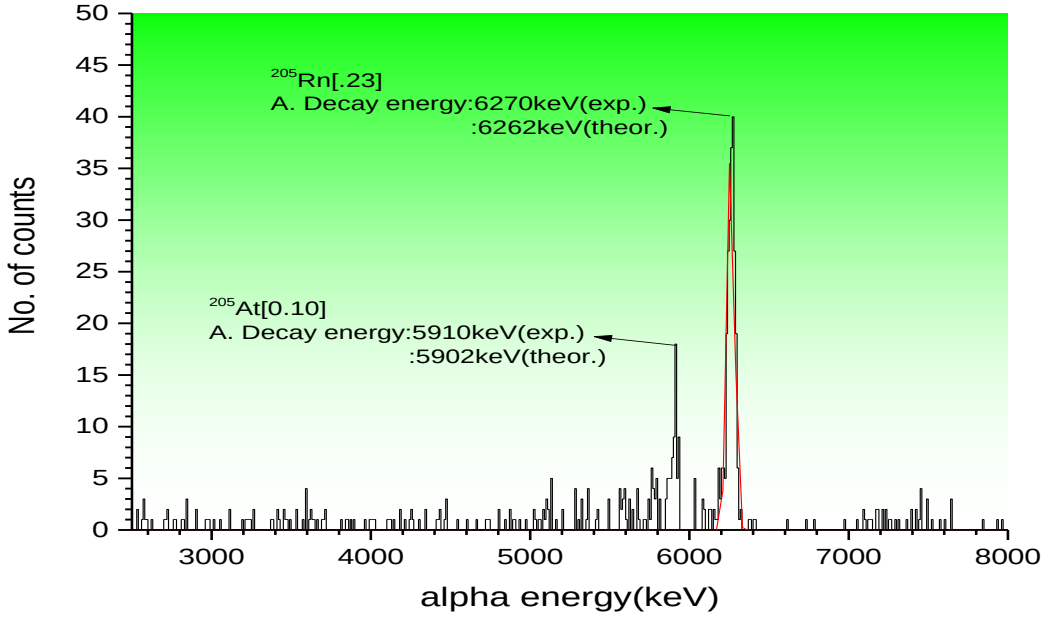
(energy spectra of Rn isotope)

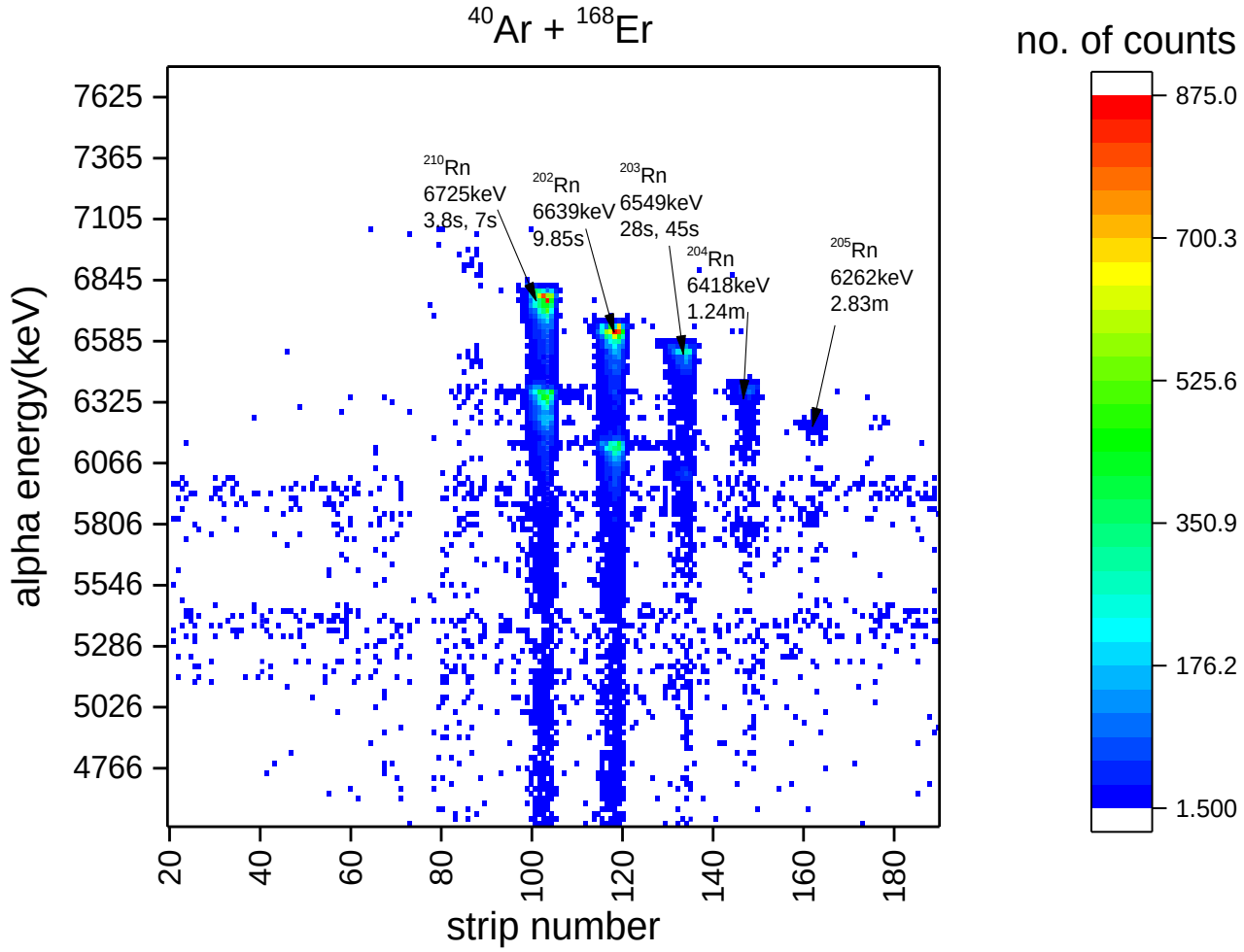



^{202}Rn[0.90]
A. Decay energy:6630keV(exp.)
:6639.5keV(theor.)
^{198}Po[0.57]
A. Decay energy:6180keV(exp.)
:6182keV(theor.)
No. of counts
Alpha energy (KeV)
0
500
1000
1500
2000
4800
5200
5600
6000
6400
6800
7200
7600
8000

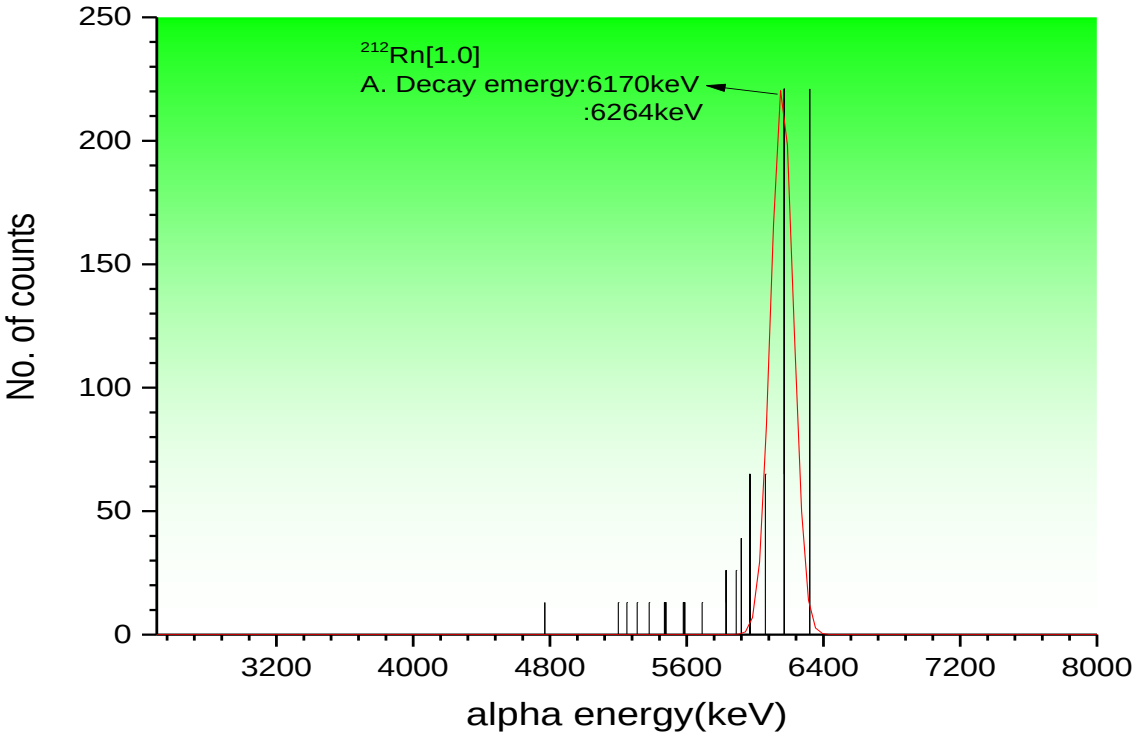

^{203}Rn[0.80]
A. Decay energy:6550keV(exp.)
:6549keV(theor.)
^{199}Po[0.39]
A. Decay energy: 6070keV(exp.)
: 6059keV(theor.)
No. of counts
alpha energy(keV)
0
100
200
300
400
500
600
700
4500
5000
5500
6000
6500
7000
7500
8000

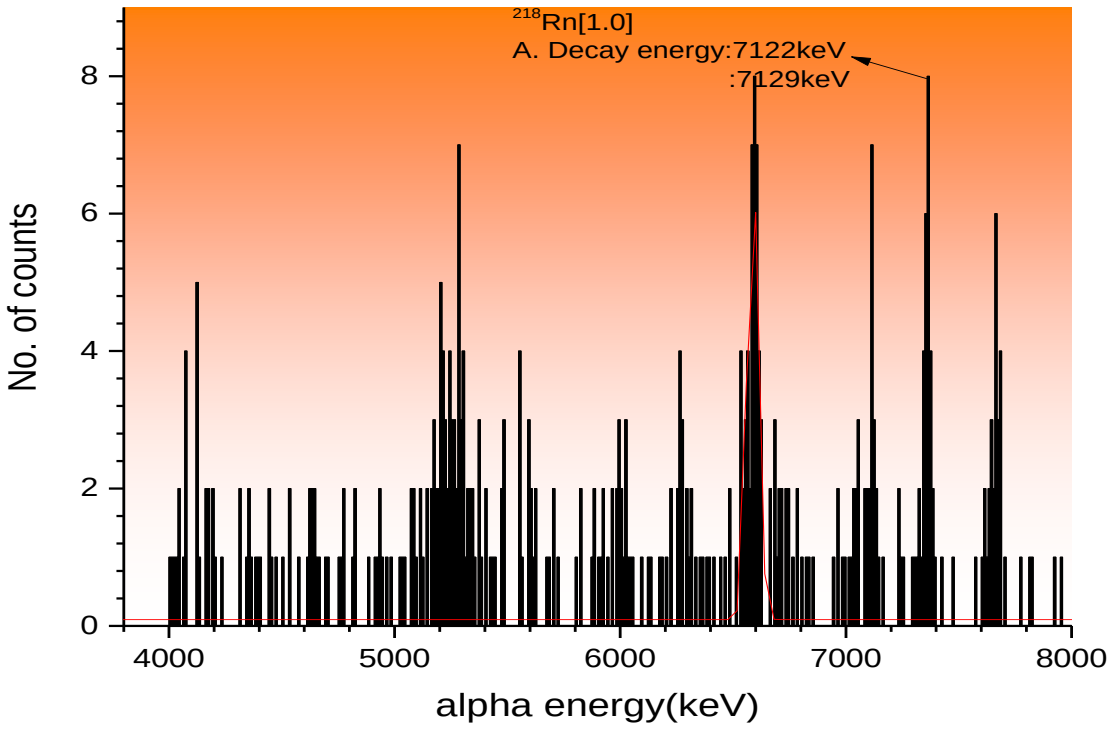

225
200
175
150
125
100
75
50
25
0
No. of counts
204Rn[0.73]
A. Decay energy:6400keV(exp.)
:6418keV(theor.)
3200
4000
4800
5600
6400
7200
8000
alpha energy(keV)

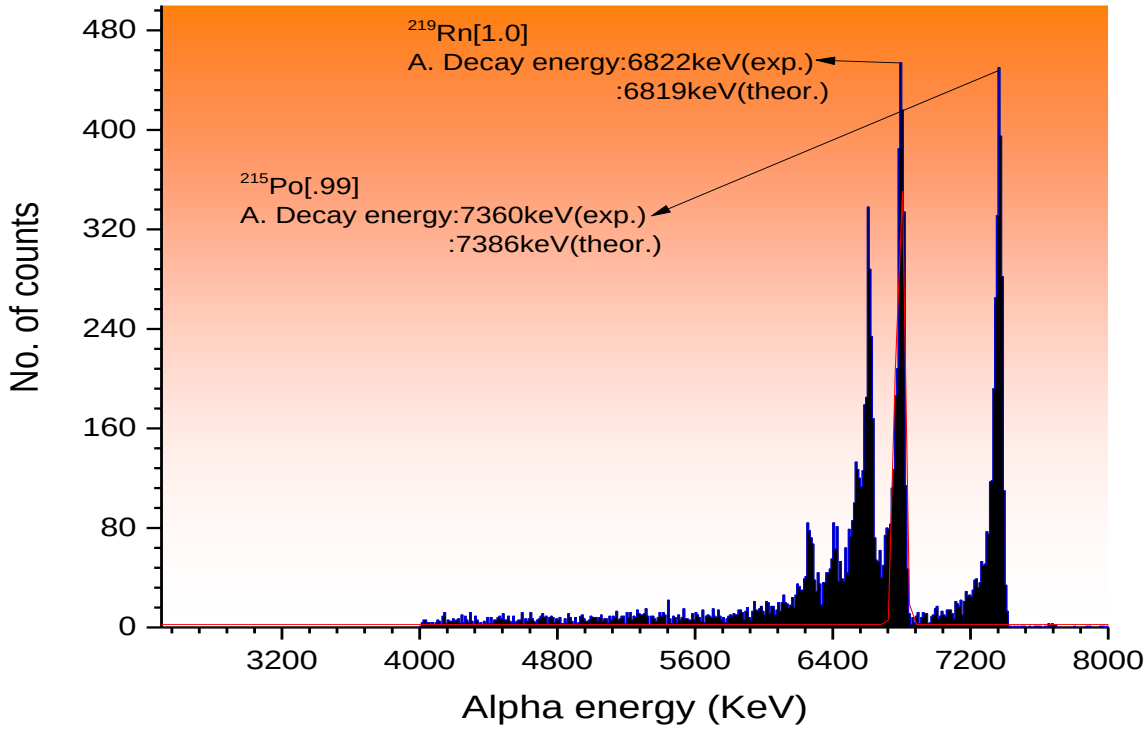

50
45
40
35
30
25
20
15
10
5
0
No. of counts
205Rn[.23]
A. Decay energy:6270keV(exp.)
:6262keV(theor.)
205At[0.10]
A. Decay energy:5910keV(exp.)
:5902keV(theor.)
3000
4000
5000
6000
7000
8000
alpha energy(keV)

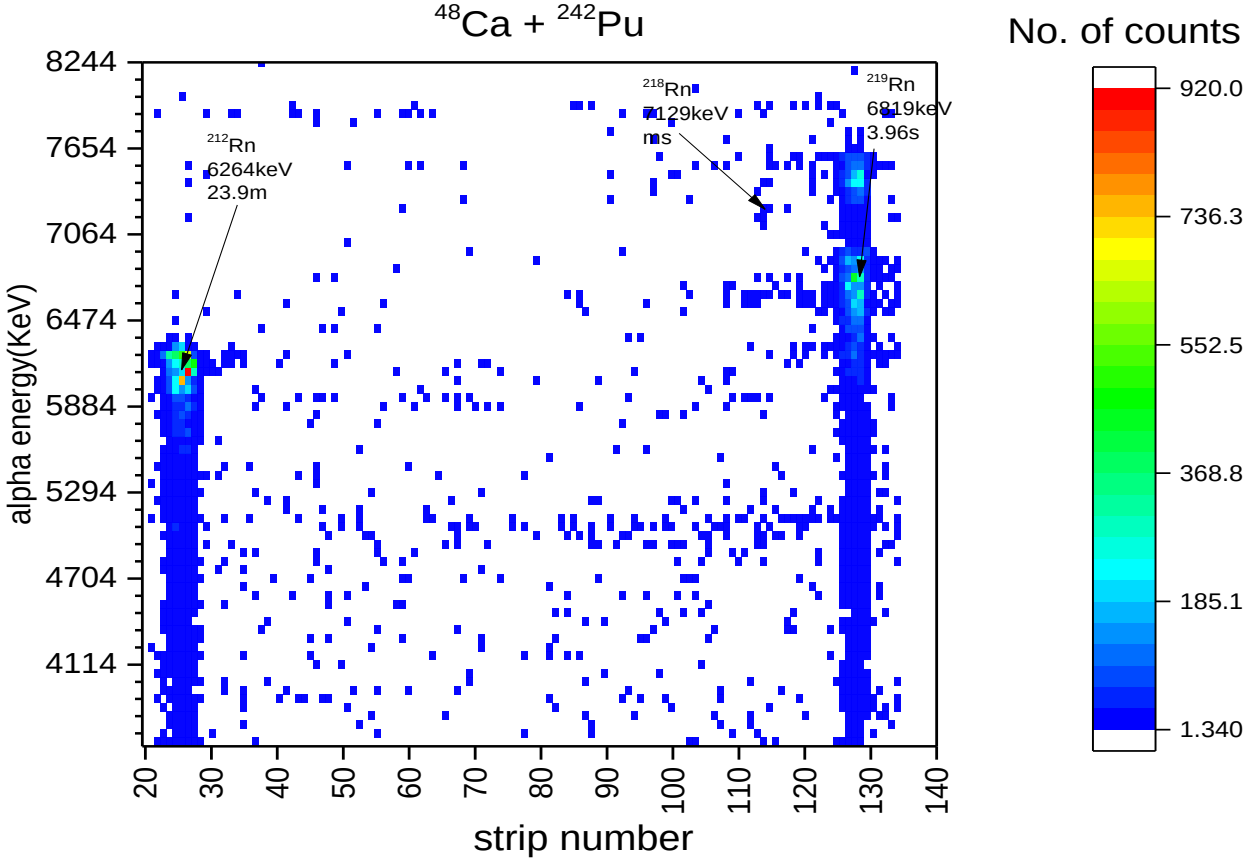

^{40}Ar + ^{168}Er
no. of counts
875.0
700.3
525.6
350.9
176.2
1.500
alpha energy(keV)
7625
7365
7105
6845
6585
6325
6066
5806
5546
5286
5026
4766
20
40
60
80
100
120
140
160
180
strip number
^{210}Rn
6725keV
3.8s, 7s
^{202}Rn
6639keV
9.85s
^{203}Rn
6549keV
28s, 45s
^{204}Rn
6418keV
1.24m
^{205}Rn
6262keV
2.83m

$^{48}Ca + ^{242}Pu$


212Rn[1.0]
A. Decay emergy:6170keV
:6264keV
No. of counts
alpha energy(keV)
0
50
100
150
200
250
3200
4000
4800
5600
6400
7200
8000

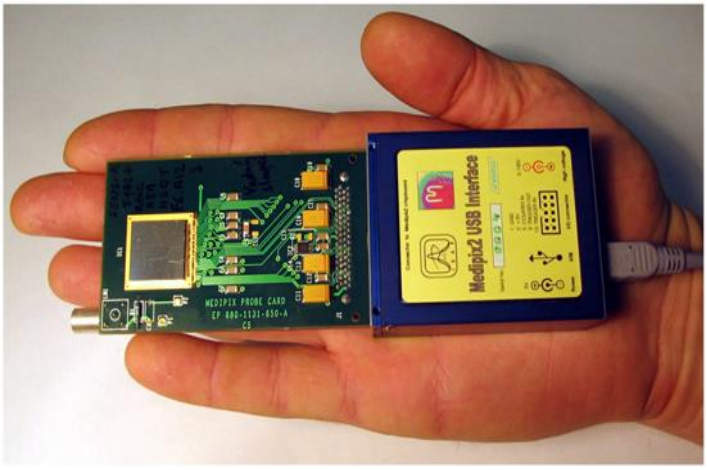

218Rn[1.0]
A. Decay energy:7122keV
:7129keV
No. of counts
alpha energy(keV)
0
2
4
6
8
4000
5000
6000
7000
8000


219Rn[1.0]
A. Decay energy:6822keV(exp.)
:6819keV(theor.)
215Po[.99]
A. Decay energy:7360keV(exp.)
:7386keV(theor.)
No. of counts
Alpha energy (KeV)
0
80
160
240
320
400
480
3200
4000
4800
5600
6400
7200
8000

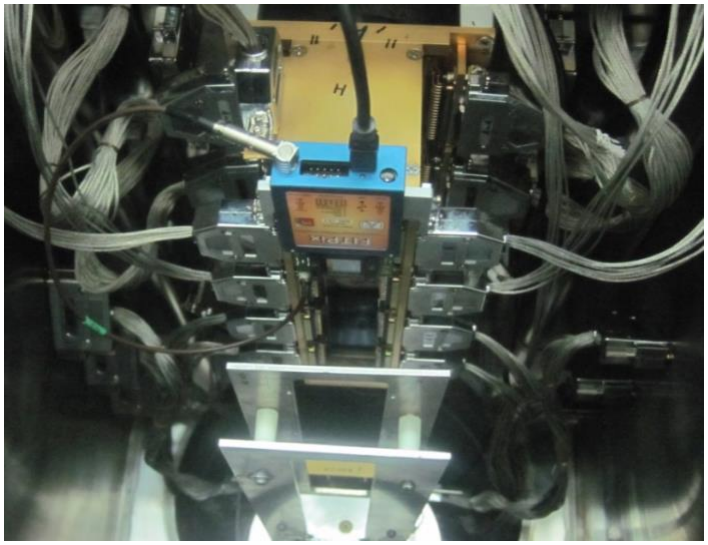

48Ca + 242Pu
No. of counts
212Rn
6264keV
23.9m
218Rn
7129keV
ms
219Rn
6819keV
3.96s
alpha energy(KeV)
strip number
8244
7654
7064
6474
5884
5294
4704
4114
20
30
40
50
60
70
80
90
100
110
120
130
140
920.0
736.3
552.5
368.8
185.1
1.340

The cross section of Ca and Pu multi-nucleon transfer reaction are quite high, so the good no. of counts are pretty much considerable. As it is shown in the matrix in a previous page. The gap in the figure is obvious because in the matrix only 212^{th}(23.9 min), 218^{th}(35ms) and 219^{th}(3.96s) isotope are visible(barely). It is because the half-life of these isotopes is greater 35ms and they are the only isotope of radon that reached the focal plane. The lifetime of 213 to 217 isotopes are much smaller than 35ms.

TIMEPIX DETECTOR



TIMEPIX detector was first constructed in Institute of Experimental and Applied Physics, Czech Technical University in Prague.

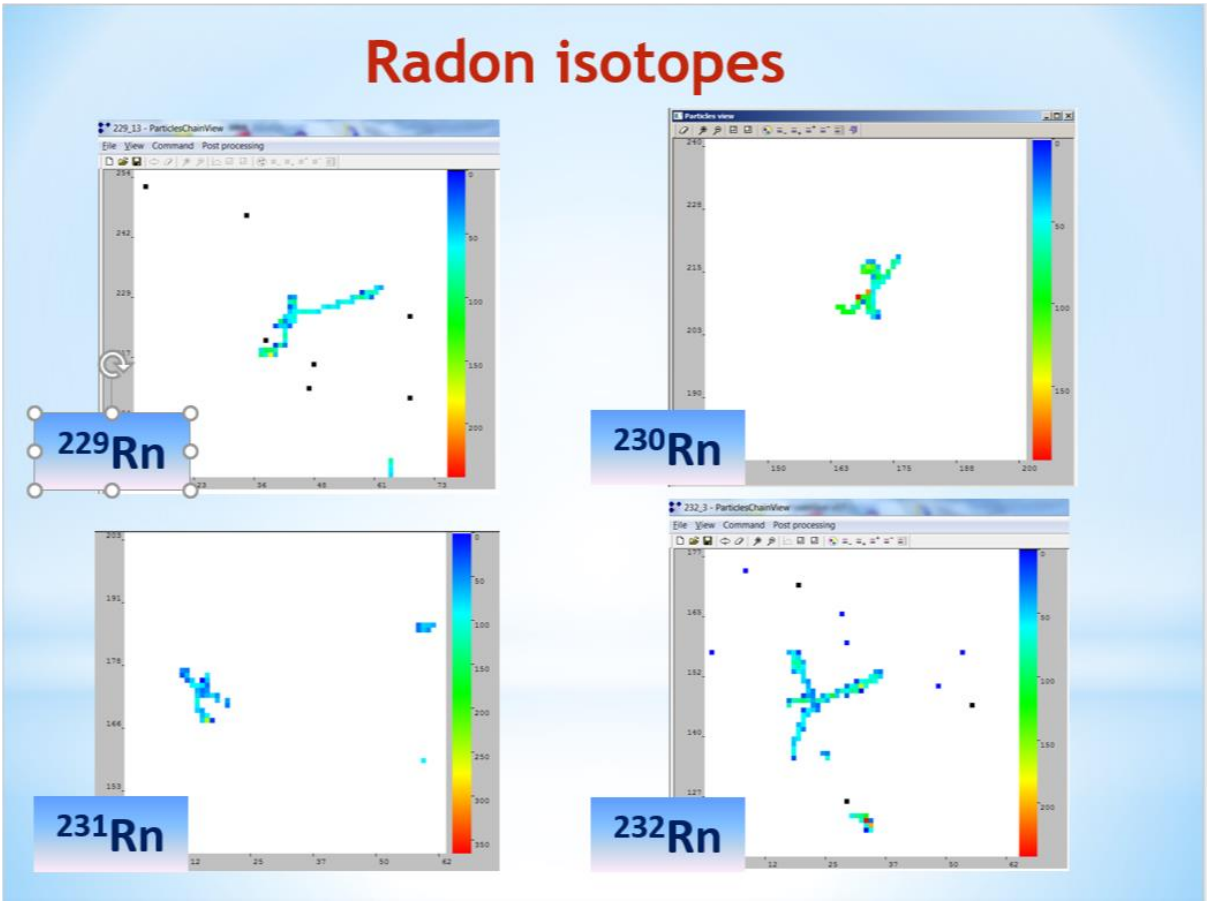


An array of 256x256 square pixels of pitch size 55mm for full sensitive area 14x14 mm^2. Silicon sensor of 300 µm thickness.

TIMEPIX represents a square 14X14 mm of sensitive area and has an array of 256X256 pixels on it(55µm step). It means that TIMEPIX has 65536 channels and each has individual ADC and preamplifier. It is enabled to detect even single alpha and beta particle, nuclear fragments and gamma or X-rays in a wide dynamic range. This detector system has an efficiency close to 100% and it performs both a noiseless digital integration and the on-line tracking visualization.

To test the MASHA and TIMEPIX some radon isotopes were produced in multi-nucleon transfer reaction $^{48}Ca + ^{232}Th$. The composite target ^{232}Th was used in the experiments. An alcohol solution of thorium nitrate was deposited into flexible graphite (thickness = 0.6 mm) and annealed at the temperature 1900°C. Finally target as ThO_2 was made and bombarded by beam of ^{48}Ca with energy E. beam = 7.3 MeV/nucleon. On a picture there are images from the TIMEPIX detector gathered in a multi-nucleon transfer reaction $^{48}Ca + ^{232}Th$ leading to the nucleon excess nuclei $^{229\text{-}232}Rn$. We can see here four beta tracks going from the implantation centers for each of the isotopes. Each decay represents every transform in the decay chain Rn→ Fr→ Ra→ Ac→ Th, which is a good visualization for four beta-decay in a row. These detectors have high spatial and energy resolution and allows to count even a single alpha or beta decay, gamma and x-rays in a wide dynamic energy range.

Radon isotopes



Conclusion

While doing this report and thoroughly doing all the steps, we now know the working of MASHA, which is continuously improved. The optimal operating mode was found. We know how hot catcher, ECR ion source and TIMEPIX detector works. We are able to determine the energies of alpha decay obtain from various fusion evaporation residue reaction which includes the reaction to produce isotopes of mercury(Hg) and radon(Rn) and also we are able to find out the masses of their respective isotopes. With the help of histograms we determine alpha energy decay of these isotopes that are produced with these isotopes(Pt and Po). The technique for online separation of nuclear reaction products using a hot catcher was used in the experiments . The energy spectra of escaped alpha particles were measured at the focal plane of silicon detector.

Acknowledgements

I tender a sincere gratitude to my scientific project supervisor Mr. Vedeneev Vyacheslav Yurievich ”Slava” for full support in this project for providing various project related research papers and giving us all necessary information. In addition resolving all of our queries through email. I would like to thank my project colleagues Oana and Andrei to help me with OriginPro software and all the help they done.

References

1. The current status of MASHA setup. V. Yu. Vedeneev, A.M. Rodin, L.Krupa. Hyperfine Interactions 238:19 (2017).
2. MASHA Separator on the Heavy Ion Beam for Determining Masses and Nuclear Physical Properties of Isotopes of Heavy and Superheavy 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.
3. Chemical characterization of element 112. R. Eichler, N. V. Aksenov, A. V. Belozerov et al. Nature. Letters. Vol. 447, May 2007.
4. Heinz W G¨aggeler. Mendeleev's principle against einstein's relativity: news from the chemistry of superheavy elements. Russian Chemical Reviews, 78(12):1139, 2009.
5. Sigurd Hofmann. Study of superheavy nuclei at ship. Romanian journal of physics, 57(1-2):214–226, 2012.
6. Yuri Oganessian, Yu Ts Oganessian, VK Utyonkov, VT Maslyuk, AV Smolyanyuk,
7. and Avazbek Nasirov. Transfer reaction studies in the region of heavy and superheavy
8. nuclei at ship. In Journal of Physics: Conference Series, volume 282, page 012007, 2011