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.

Vlad Andrei Popescu

MSc by Research Nuclear Physics

Department of Physics and Astronomy

University of Manchester

November 2020

The project was carried out under the supervision of Viacheslav Vedeneev as part of the International Remote Student Training programme at JINR

Wave 1

November 2020

Abstract

The α decay energies and branching ratios were measured for the chemical homologues of elements Cn=112 and Fl=114, namely radioactive isotopes of Hg and Rn. This was done using data acquired by the mass-separator MASHA, designed for on-line measurements of mass to charge ratios of super heavy isotopes and determine their decay modes and energies. Radioactive Hg isotopes were synthesized via the complete fusion reaction ^{40}Ar $+^{148}$ Sm, while the Rn isotopes were created in the multinucleon transfer reaction ^{48}Ca $+^{242}$ Pu and fusion reaction ^{40}Ar $+^{166}$ Er. Hg and Rn are used in test experiments to determine the total efficiency and the overall working capacity of the mass separator.The report briefly describes the installation as well as the methods used, after which the experimental results are presented.The values obtained for most of the α energies agree with the accepted values within $\sim 7 - 8$keV.

1 Introduction

Theoretical predictions of the existence of an island of stability are one of the main driving forces behind the research carried out on exotic nuclei.Heavy elements are appealing to researchers not just because they are many body nuclear systems that lack macroscopic nuclear stability, but also due to their shell effects, which cause them to be remarkably stable (for nuclei around $Z = 114$ and $N = 184$, the calculated half lives can reach 10^9s) [1]. Recent syntheses of super heavy elements (SHE) with $Z = 113 - 118$ revealed nuclei with relatively long lifetimes (> 1 s) that can be chemically identified and characterised [2]. The considerable increase in the stability of SHE points toward an initial confirmation of the existence of the island of stability [3]. However, a difficulty in measuring the properties of nuclei like $Z = 112$ or $Z = 114$ is the very low reaction cross section, which leads to a production rate of about one atom per week of bombardment [1]. While chemical characterization methods that can analyse single atoms with great precision have been developed, the calibration of the setup needs to be done with higher yield reactions to obtain statistically significant results. The choice of α radioactive Hg and Rn is justified by the predicted shared chemical properties of the two with elements $Z = 112$ and $Z = 114$ [4]. 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.

2 Brief description of the setup[1]

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 ($S_{1,2}$). The detection system is located in the focal plane of the spectrometer.

[1]The following section is a summary of the MASHA setup as presented in [2] [5] [6]. For a more detailed account please refer to the original papers.

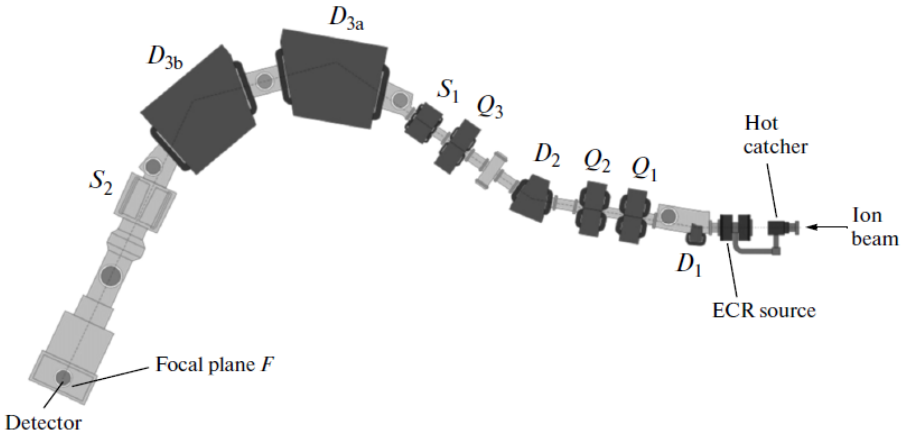


Figure 1: A schematic overview of the MASHA mass separator showing the dipole magnets, the quadrupole lenses, the sextupole lenses and the detection system [5]

2.1 Ion Source

The ECR based ion source ionizes atoms of nuclear reaction products to a charge state $Q = +1$, gathering the atoms in a a beam which is then separated by the magneto-optical system of the spectrometer. The ion currents obtained by the ECR source are formed of singly ionized atoms in a proportion of almost 100% and the ionizing efficiency for noble gasses reaches 90%. The interest for the ionising efficiency of inert gasses is that a similar inertness is expected from Cn and radioactive Hg. To drastically reduce the interaction of mercury with the the walls of the ECR, the latter are covered with TiN, thus improving the ionization efficiency for this metal.

2.2 Target assembly, hot catcher and detection

The hot catcher is used to inject fusion reaction products from the target into the ECR source and is a part of the target assembly. After the reaction products escape the target, they pass through a separating foil and stop in a thermally expanded graphite sheet which represents a porous polygraphene structure with the porosity of about 75% heated

to 1800-2000K. From there, the products diffuse in the vacuum volume of the hot catcher reaching the ECR ion source.

The detection of the nuclear reaction products decays is done via a well-type silicon detector situated in the focal plane of the spectrometer, along the normal to the beam. The frontal detector consists of 192 strips, while the side detectors are divided into 64 and 16 strips respectively (64 strips covering the top and bottom planes, and 16 for the left and right planes). The side detectors were added to increase geometrical efficiency [2] Tests performed on ^{226}Ra closed α source with the energy resolution of the detector for the energy region of α particles of $\sim$ 30keV and allow a detection of 90% of the α particles emitted in the middle of the detector. Each strip of the detector is read independently. The program used allows displaying one dimensional energy spectra from each strip and the energy spectra against the strip number.

3 Experimental method

A beam of ^{40}Ar or ^{48}Ca is accelerated in the U400M cyclotron up to $\sim 5-7$MeV/nucleon. After it passes the rotating target and the separating foil it enters the catcher, kept at a temperature of $\sim$ 1800K. The atoms diffuse from the graphite and reach the ECR ion source where they are ionized, while the beam is periodically intrerupted by the Faraday cup to allow efficient data aquisition.

Due to the chemical similarity argument brought forward in the introduction, the separation efficiency and time were measured for various α radioactive mercury isotopes, obtained in the fusion reaction reaction $^{40}\text{Ar} +^{144}\text{ Sm} \rightarrow^{184-xn}\text{ Hg} + xn$. Fusion was achieved by bombarding a stationary target Sm_2O_3 enriched to 98.5% with ^{148}Sm [5]. The fusion products, after separation would then enter a strip of the front silicon detector and α decay in the place, such that their α decay energy could be measured as a function of the strip number [5]. The separation efficiency obtained for short lived Hg isotopes is

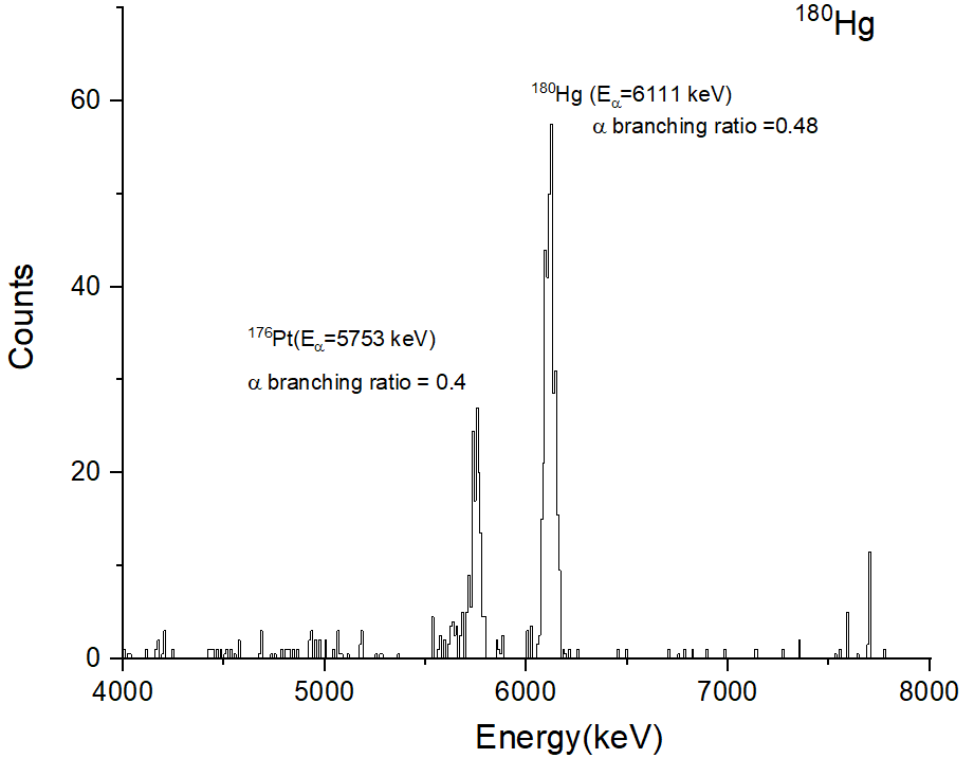
7% and a separation time of 1.8s. Similar test were performed by synthesizing Rn via the ^{40}Ar $+^{166}$ Er reaction, since radon is also expected to share similar properties (like inertness) with copernicium.

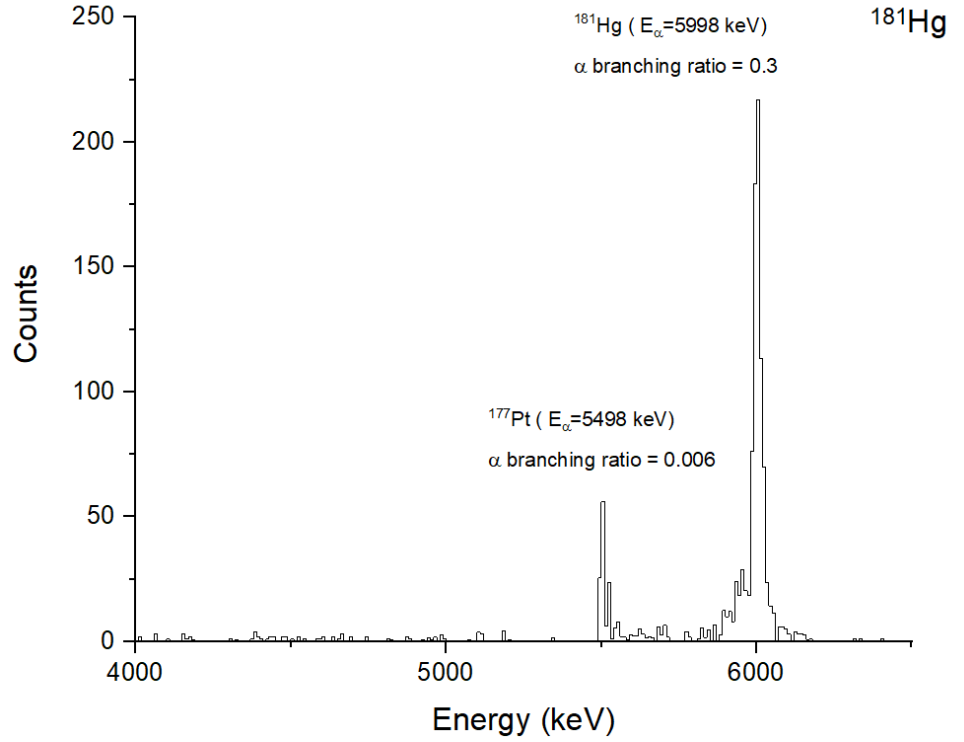
Further improvements in the experimental setup (better separation efficiency and time) allow the research of neutron rich and neutron deficit nuclei produce in transfer reactions [6], with nuclei near the neutron magic numbers $N = 126$ and $N = 152$. The main decay mode of these elements is by α emission. Rn isotopes are produced in the multinucleon transfer reaction ^{48}Ca $+^{242}$ Pu, which has a higher cross section compared to complete fusion reactions [6].

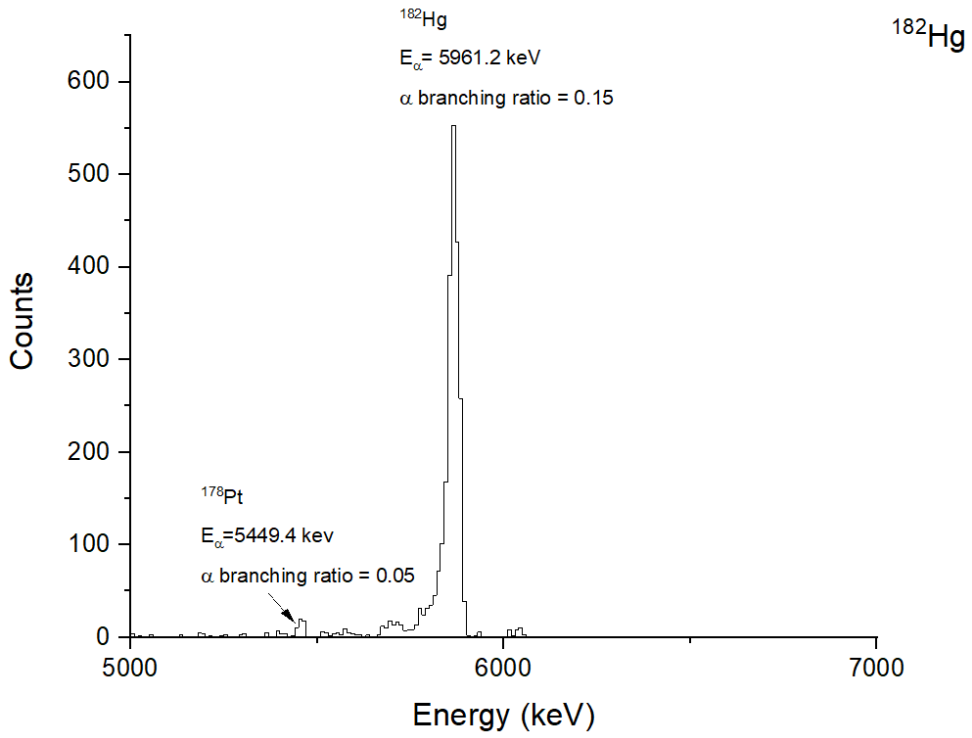
The choice of the projectiles, ^{40}Ar and ^{48}Ca aimed to remove as much as possible the irregularities in the fusion process and reduce the number of corrections that need to be made on the beam and for this purpose doubly magic nuclei have been selected. The advantage of using doubly magic nuclei is their almost perfect spherical symmetry, which ensures there is no need to make orientation corrections. A closer look at the particular isotopes used for the target reveals a progressive departure of the used nuclear species from the line of stability (excepting Er). While the samarium isotope ^{144}Sm used in the tests runs contains 82 neutrons, the samarium, erbium and plutonium have a decreasingly smaller binding energy per nucleon. Using projectile-target combinations with the highest binding energy ensures the interaction results in deep potential and the internal kinetic energy of the fusing nuclei is kept at a minimum [7]. Besides, higher intensities can be reached with intermediate heavy projectiles compared like ^{48}Ca compared to heavier ones (^{48}Ca beams can reach an intensity 100 times higher than their ^{238}U counterpart), this having a significant impact on the reaction cross section [8].

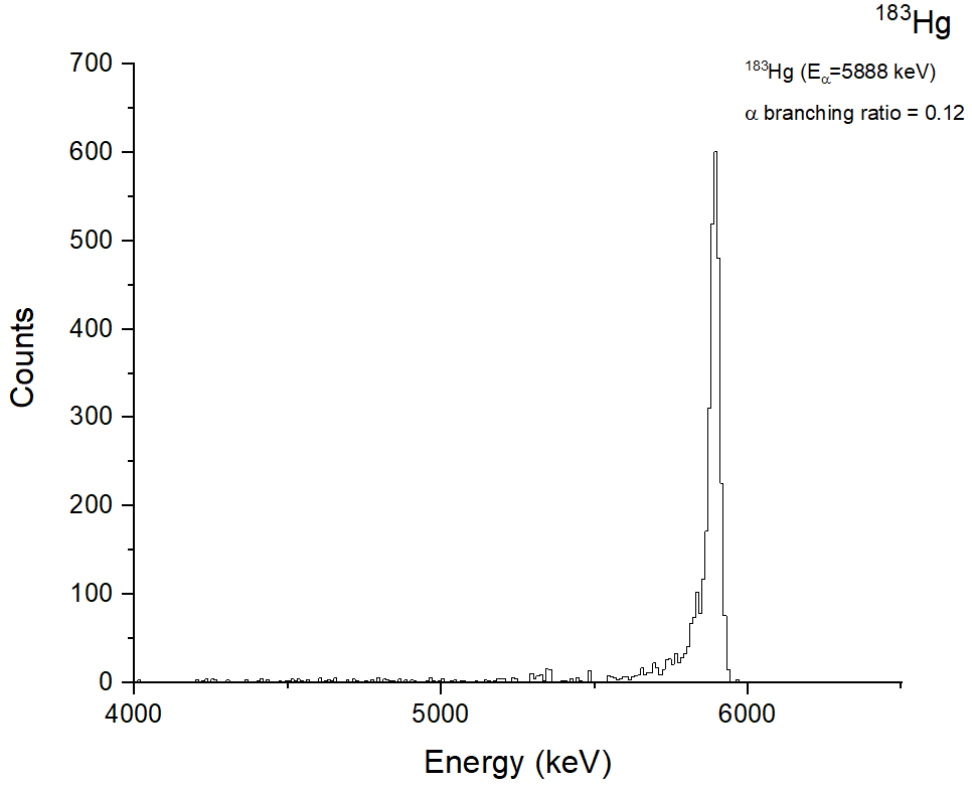
4 Data analysis

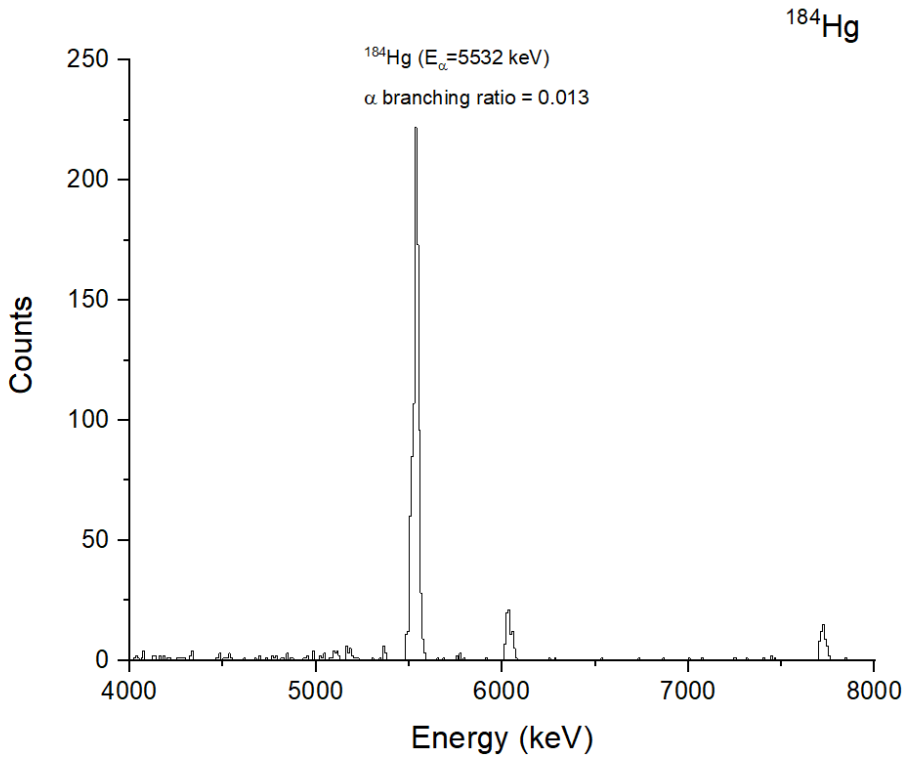
The α decay energies of Hg and Rn isotopes were plotted and the resulting isotopes were identified. Also, for each reaction the α spectrum was plotted against the strip number of the frontal detector. All three spectra display efficient mass and α separations, such that both the α decay energies of the isotopes of interest and of their daughter nuclei can be distinguished.The latter usually occur on the same strip with the parent nuclei due to the fact that 50% of the α decays are detected in the same silicon strip where they stopped. Moreover, the strip number corresponds to the X-coordinate at the focal plane, such that the mass of the detected ion can be inferred from the magnetic field values registered by the D_{3a} and D_{3b} magnets. The agreement between the calculated values and the accepted ones is mostly within 7-8keV, and σ ranges between 20-50keV. The main source of background is the incomplete release of α particles, because the layer thickness of the detectors is larger than the penetration distance of the particles. Moreover, in the case of ^{212,218,219}Rn, the absence of the intermediate isotopes is explained by their short half-life ($T_{1/2} \ll 35$ ms, where the half life of the barely visible ^{218}Rn is 35 ms), causing them to decay before reaching the detector due to the comparatively long separation time of the ISOL method.

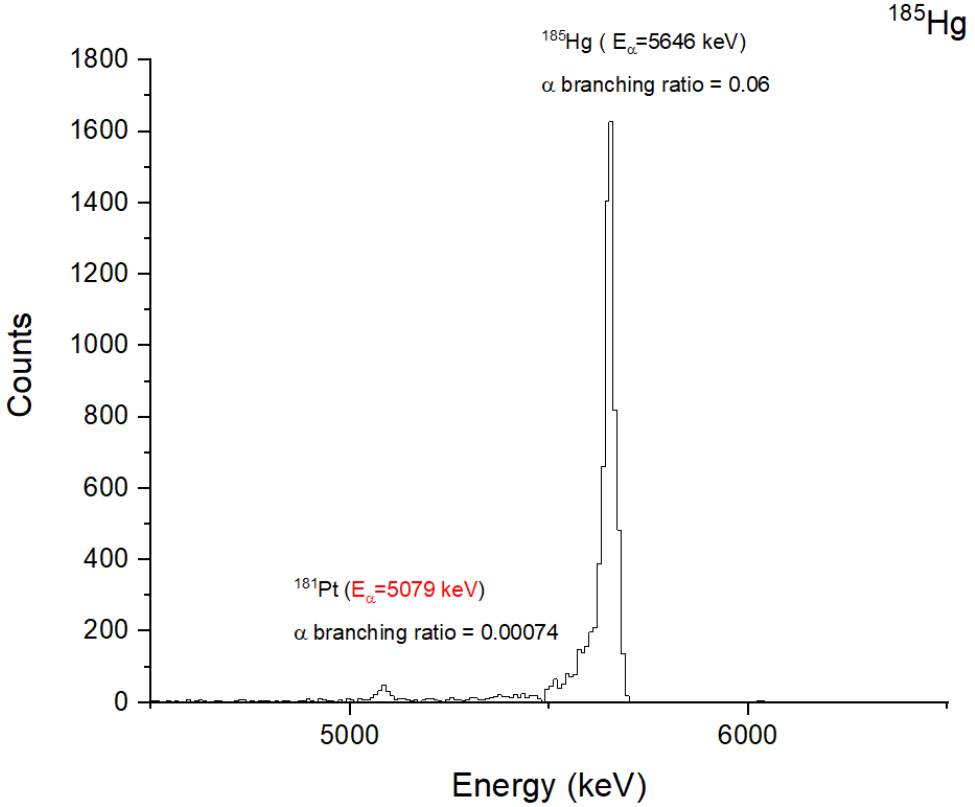

^{180}Hg
^{180}Hg (E_α=6111 keV)
α branching ratio =0.48
^{176}Pt(E_α=5753 keV)
α branching ratio = 0.4
Counts
Energy(keV)

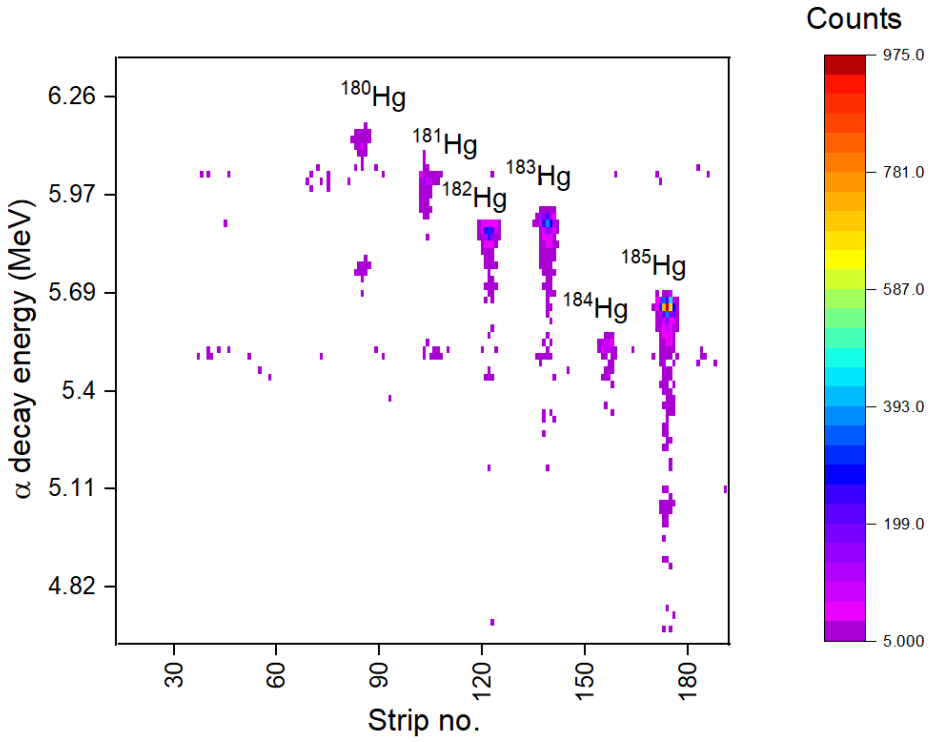

^{181}Hg
^{181}Hg (E_α=5998 keV)
α branching ratio = 0.3
^{177}Pt (E_α=5498 keV)
α branching ratio = 0.006
Counts
Energy (keV)

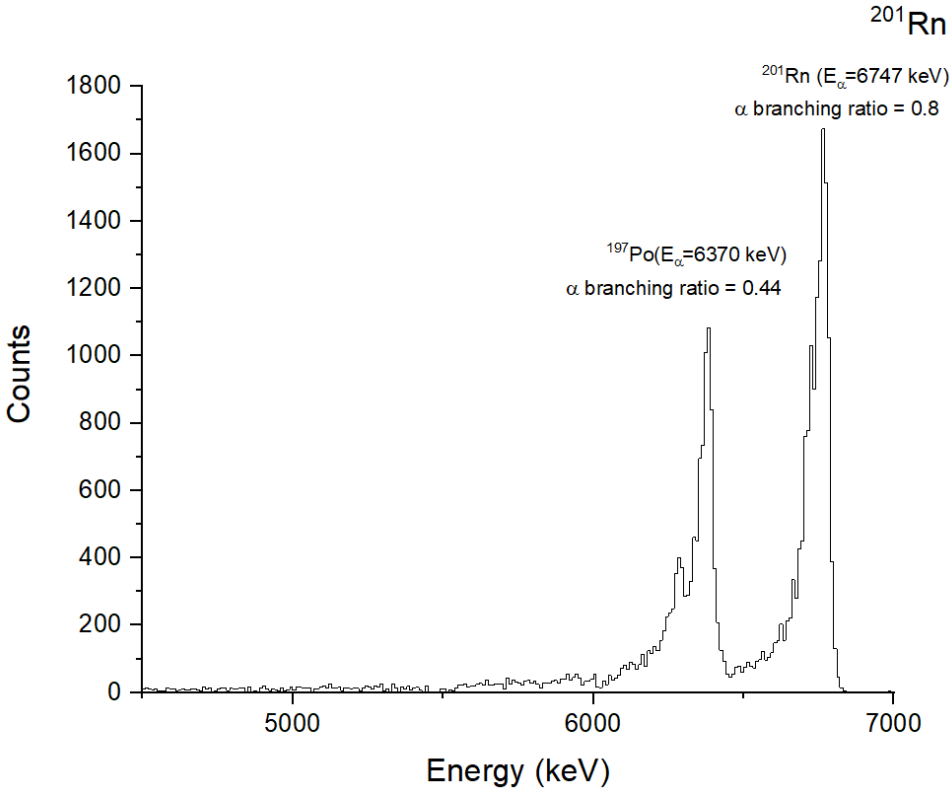

182Hg
Eα= 5961.2 keV
α branching ratio = 0.15
178Pt
Eα=5449.4 kev
α branching ratio = 0.05
Counts
Energy (keV)
182Hg

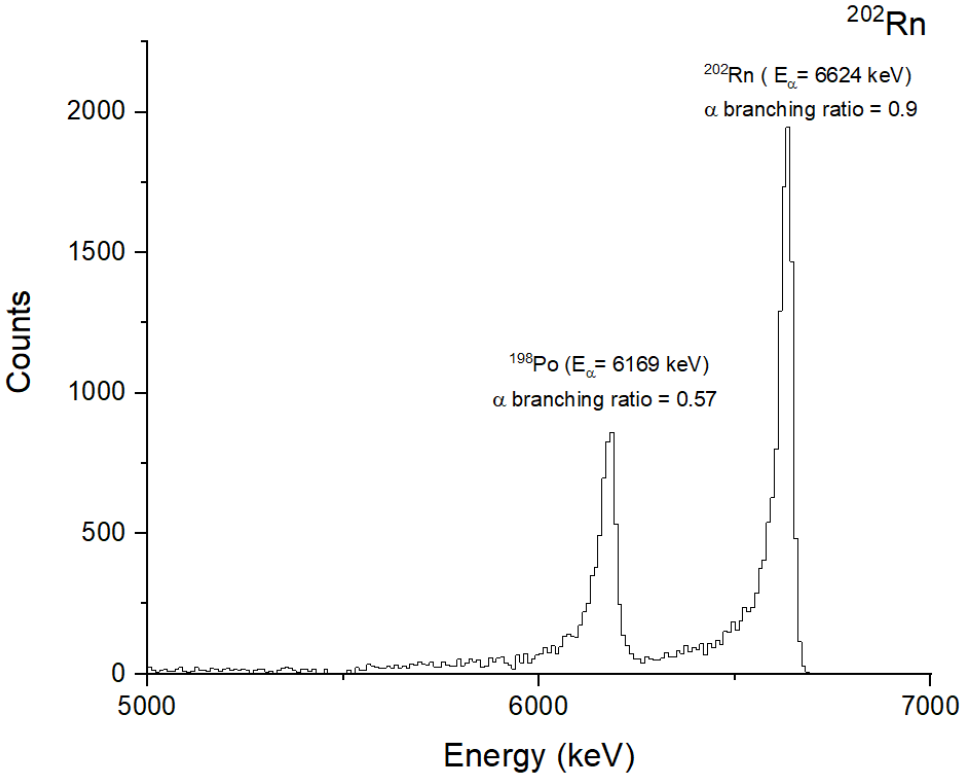

183Hg
183Hg (Eα=5888 keV)
α branching ratio = 0.12
Counts
Energy (keV)

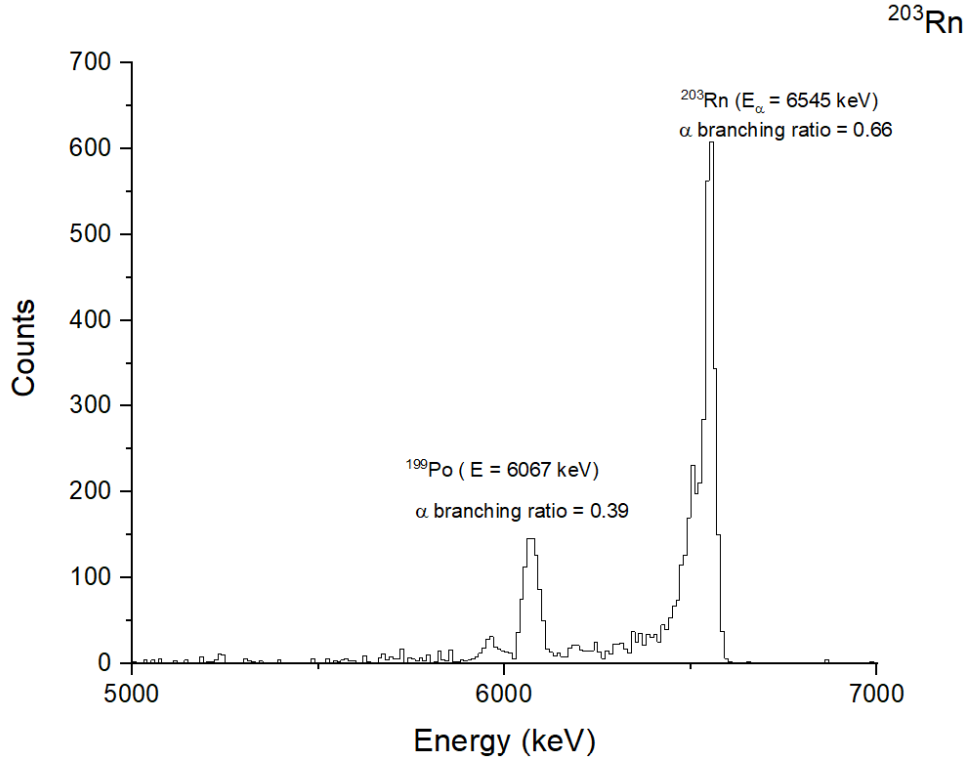

184Hg
184Hg (Eα=5532 keV)
α branching ratio = 0.013
Counts
Energy (keV)
0
50
100
150
200
250
4000
5000
6000
7000
8000

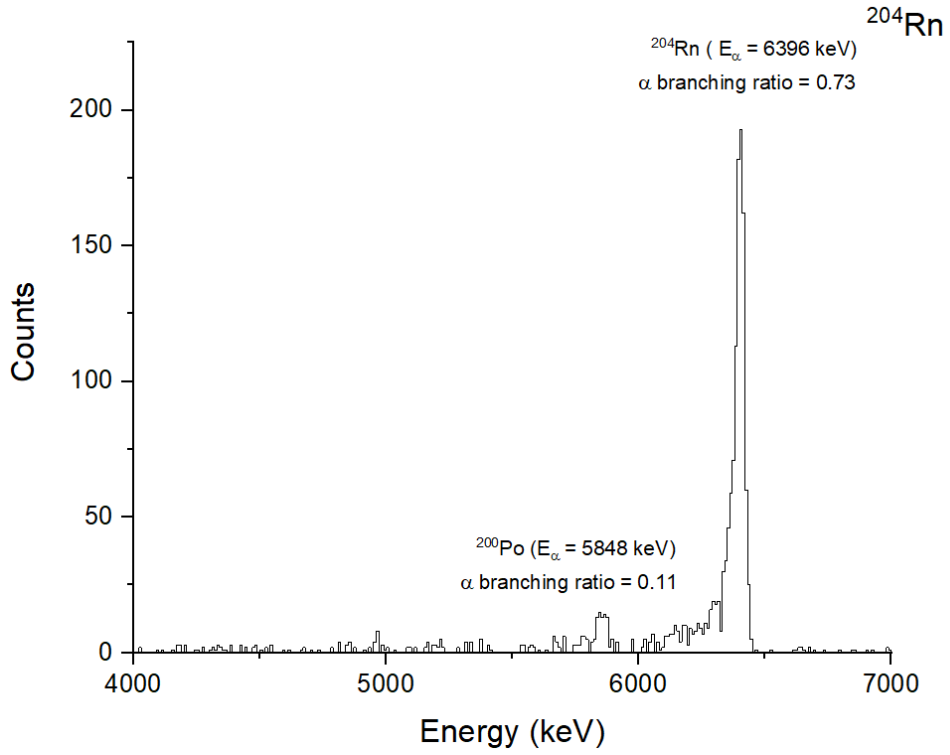

185Hg
185Hg (Eα=5646 keV)
α branching ratio = 0.06
181Pt (Eα=5079 keV)
α branching ratio = 0.00074
Counts
Energy (keV)
0
200
400
600
800
1000
1200
1400
1600
1800
5000
6000

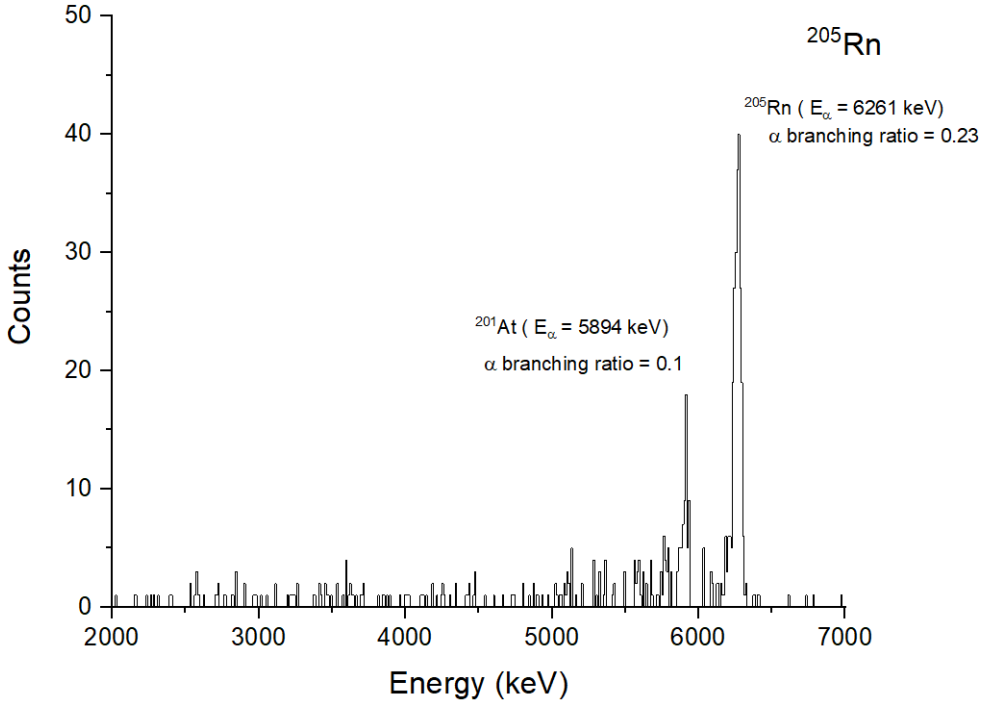

Counts
975.0
781.0
587.0
393.0
199.0
5.000
^{180}Hg
^{181}Hg
^{182}Hg
^{183}Hg
^{184}Hg
^{185}Hg
α decay energy (MeV)
6.26
5.97
5.69
5.4
5.11
4.82
30
60
90
120
150
180
Strip no.

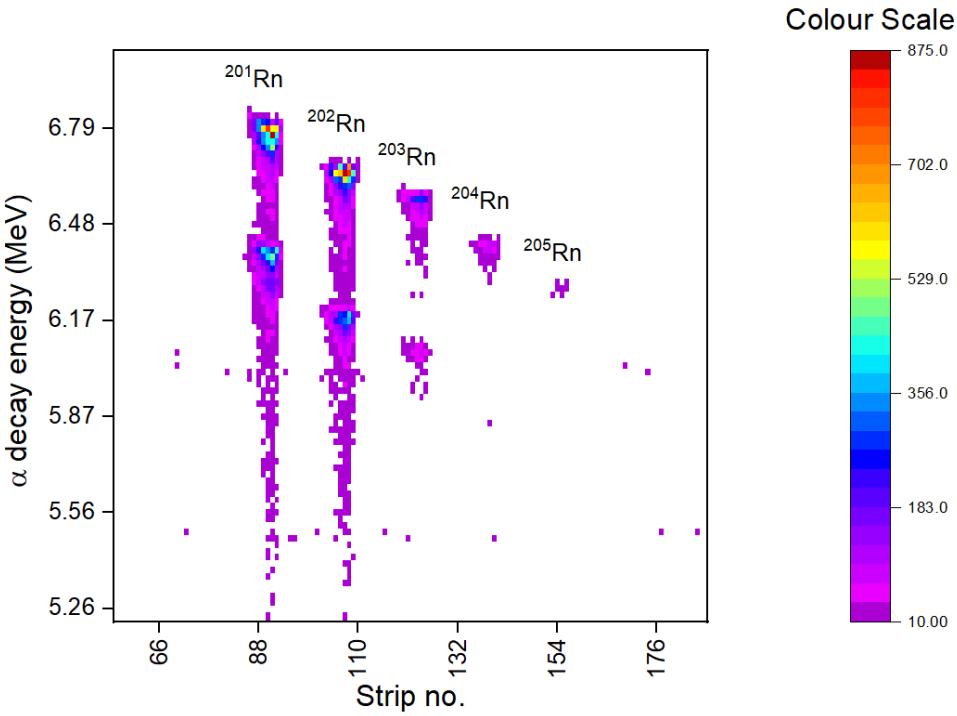

^{201}Rn
^{201}Rn ($E_α$=6747 keV)
α branching ratio = 0.8
^{197}Po($E_α$=6370 keV)
α branching ratio = 0.44
Counts
1800
1600
1400
1200
1000
800
600
400
200
0
5000
6000
7000
Energy (keV)

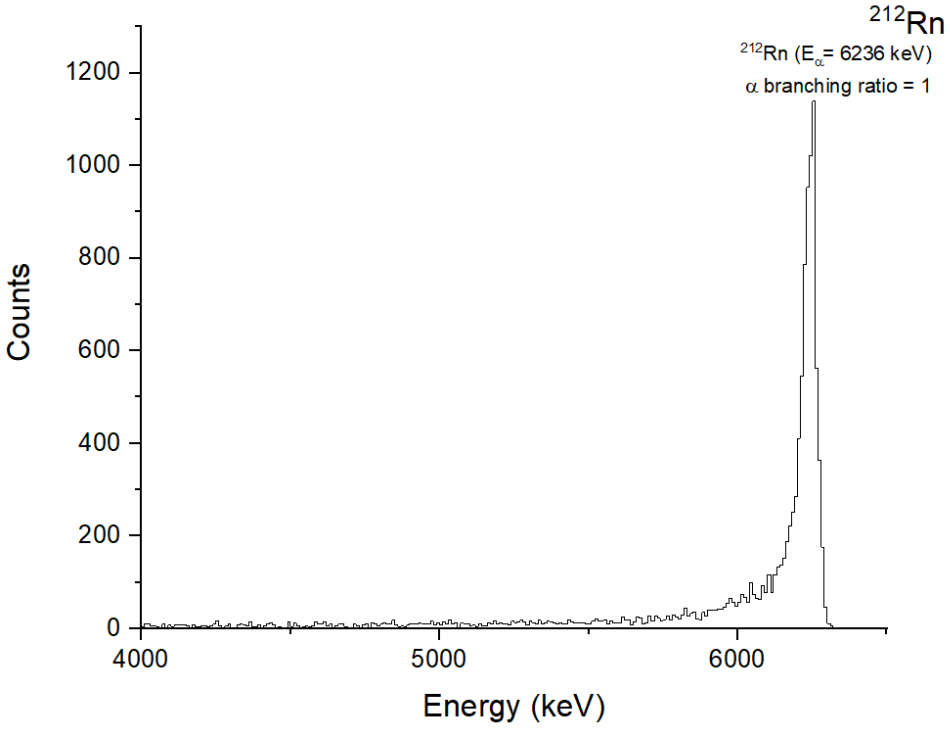

202Rn
202Rn (Eα= 6624 keV)
α branching ratio = 0.9
198Po (Eα= 6169 keV)
α branching ratio = 0.57
Counts
Energy (keV)
0
500
1000
1500
2000
5000
6000
7000

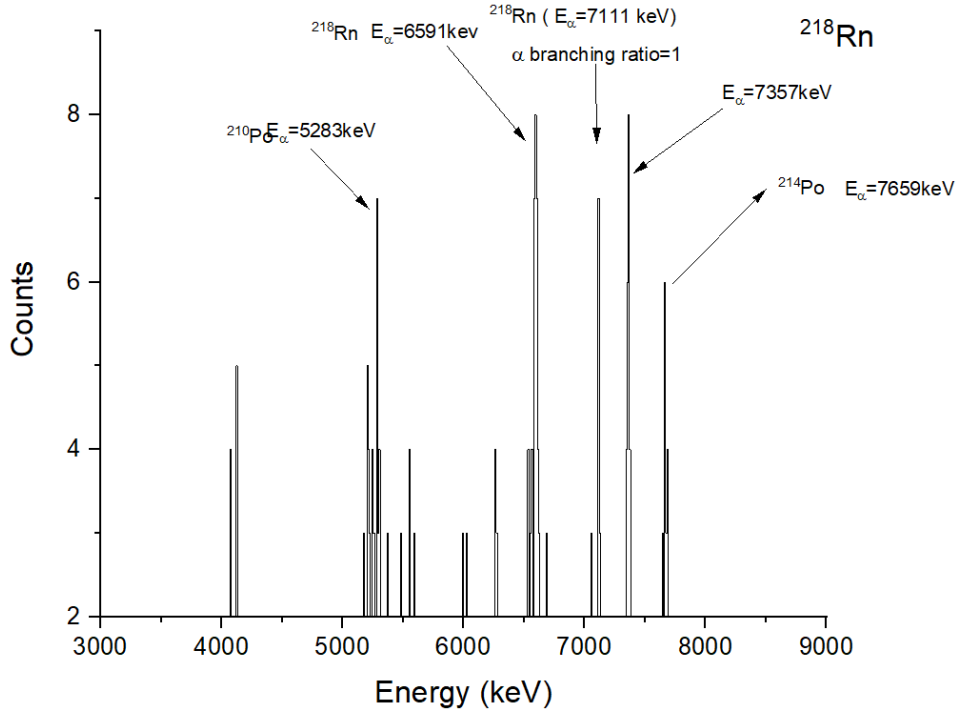

203Rn
203Rn (Eα = 6545 keV)
α branching ratio = 0.66
199Po (E = 6067 keV)
α branching ratio = 0.39
Counts
Energy (keV)
0
100
200
300
400
500
600
700
5000
6000
7000

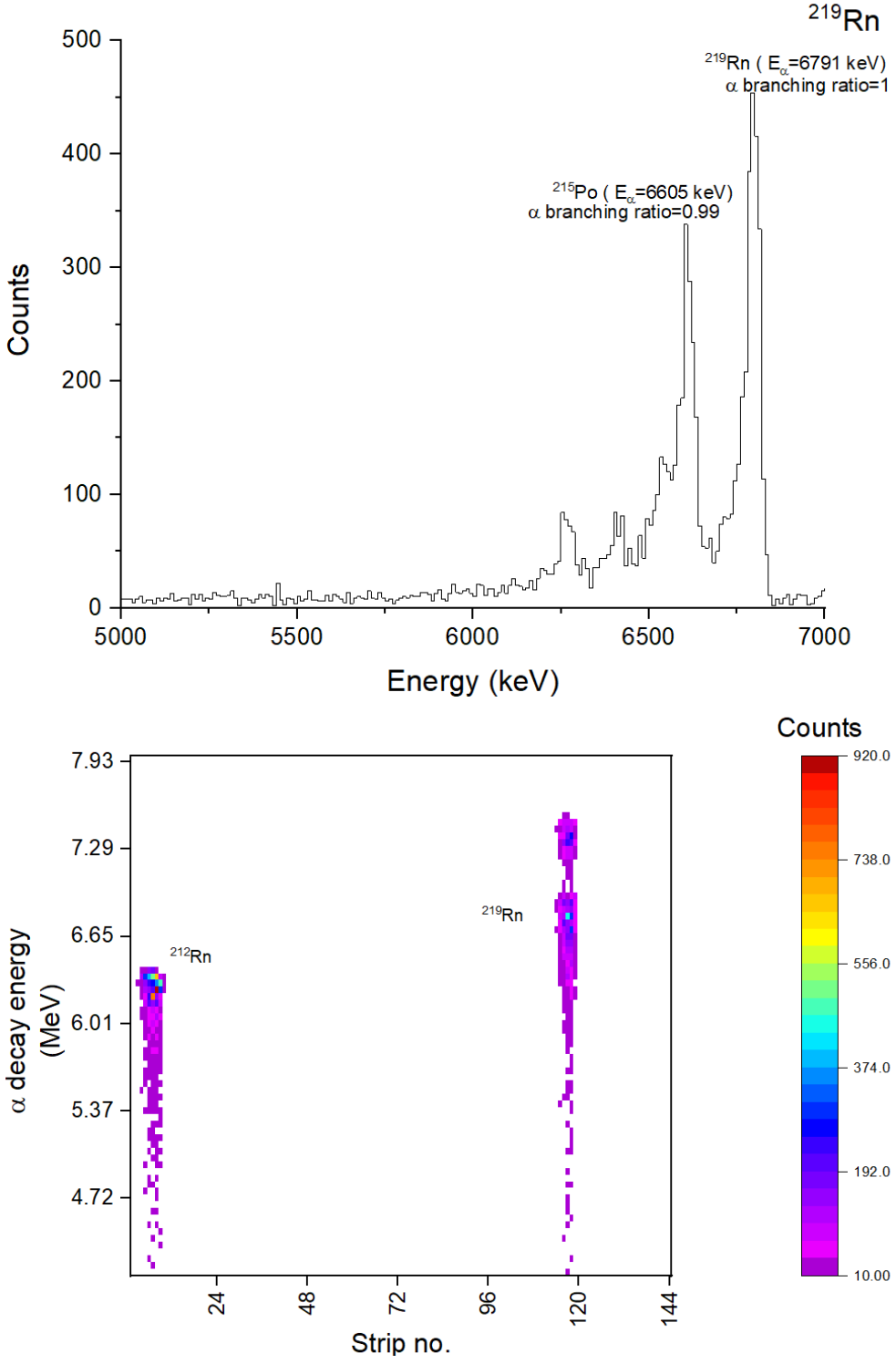

^{204}Rn
^{204}Rn (E_α = 6396 keV)
α branching ratio = 0.73
^{200}Po (E_α = 5848 keV)
α branching ratio = 0.11
Counts
Energy (keV)
0
50
100
150
200
4000
5000
6000
7000


^{205}Rn
^{205}Rn (E_α = 6261 keV)
α branching ratio = 0.23
^{201}At (E_α = 5894 keV)
α branching ratio = 0.1
Counts
Energy (keV)
0
10
20
30
40
50
2000
3000
4000
5000
6000
7000


Colour Scale
875.0
702.0
529.0
356.0
183.0
10.00
^{201}Rn
^{202}Rn
^{203}Rn
^{204}Rn
^{205}Rn
α decay energy (MeV)
6.79
6.48
6.17
5.87
5.56
5.26
66
88
110
132
154
176
Strip no.


212Rn
212Rn (Eα= 6236 keV)
α branching ratio = 1
Counts
Energy (keV)


218Rn
218Rn Eα=6591kev
218Rn (Eα=7111 keV)
α branching ratio=1
Eα=7357keV
210Po Eα=5283keV
214Po Eα=7659keV
Counts
Energy (keV)


219Rn
219Rn (Eα=6791 keV)
α branching ratio=1
215Po (Eα=6605 keV)
α branching ratio=0.99
Counts
Energy (keV)
Counts
α decay energy (MeV)
212Rn
219Rn
Strip no.

5 Conclusion

The main components of the MASHA mass separator were briefly described as well the experimental method for determining the separation efficiency and time for mercury and radon isotopes resulting from the reactions ^{40}Ar $+^{144}$ Sm, ^{40}Ar $+^{166}$ Er and ^{48}Ca $+^{242}$ Pu. Analysis of the data showed agreement within 7-8keV between the experiment and the tabulated values, as well as a σ in the range of 20-50 keV.

6 Aknowledgements

I am grateful to the INTEREST team for putting together this training programme, and to my supervisor and colleagues for constantly providing me with support and feedback.

References

[1] Heinz W Gäggeler. Mendeleev's principle against einstein's relativity: news from the chemistry of superheavy elements. *Russian Chemical Reviews*, 78(12):1139, 2009.

[2] AM Rodin, AV Belozerov, EV Chernysheva, SN Dmitriev, AV Gulyaev, AV Gulyaeva, MG Itkis, J Kliman, NA Kondratiev, L Krupa, et al. Separation efficiency of the masha facility for short-lived mercury isotopes. *Hyperfine Interactions*, 227(1-3):209–221, 2014.

[3] Sergey N Dmitriev, Yury Ts Oganessyan, Vladimir K Utyonkov, Sergey V Shishkin, Alexander V Yeremin, Yury V Lobanov, Yury S Tsyganov, Viktor I Chepygin, Evgeny A Sokol, Grigory K Vostokin, et al. Chemical identification of dubnium as a decay product of element 115 produced in the reaction 48ca+ 243am. *Mendeleev Communications*, 15(1):1–4, 2005.

[4] Robert Eichler, NV Aksenov, AV Belozerov, GA Bozhikov, VI Chepigin, SN Dmitriev, R Dressler, HW Gäggeler, VA Gorshkov, Florian Haenssler, et al. Chemical characterization of element 112. *Nature*, 447(7140):72–75, 2007.

[5] AM Rodin, AV Belozerov, DV Vanin, V Yu Vedeneyev, AV Gulyaev, AV Gulyaeva, SN Dmitriev, MG Itkis, J Kliman, NA Kondratiev, et al. Masha separator on the heavy ion beam for determining masses and nuclear physical properties of isotopes of heavy and superheavy elements. *Instruments and Experimental Techniques*, 57(4):386–393, 2014.

[6] V Yu Vedeneev, AM Rodin, L Krupa, AV Belozerov, EV Chernysheva, SN Dmitriev, AV Gulyaev, AV Gulyaeva, D Kamas, J Kliman, et al. The current status of the masha setup. *Hyperfine Interactions*, 238(1):19, 2017.

[7] Sigurd Hofmann. Study of superheavy nuclei at ship. *Romanian journal of physics*, 57(1-2):214–226, 2012.

[8] Yuri Oganessian, Yu Ts Oganessian, VK Utyonkov, VT Maslyuk, AV Smolyanyuk, and Avazbek Nasirov. Transfer reaction studies in the region of heavy and superheavy nuclei at ship. In *Journal of Physics: Conference Series*, volume 282, page 012007, 2011.