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PROPERTIES OF HEAVY AND SUPER HEAVY ELEMENTS STUDIED BY MASS SPEKTROSCOPY AND ISOL METHOD

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Association of Young Scientists and Specialists of JINR

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KEF
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Outline

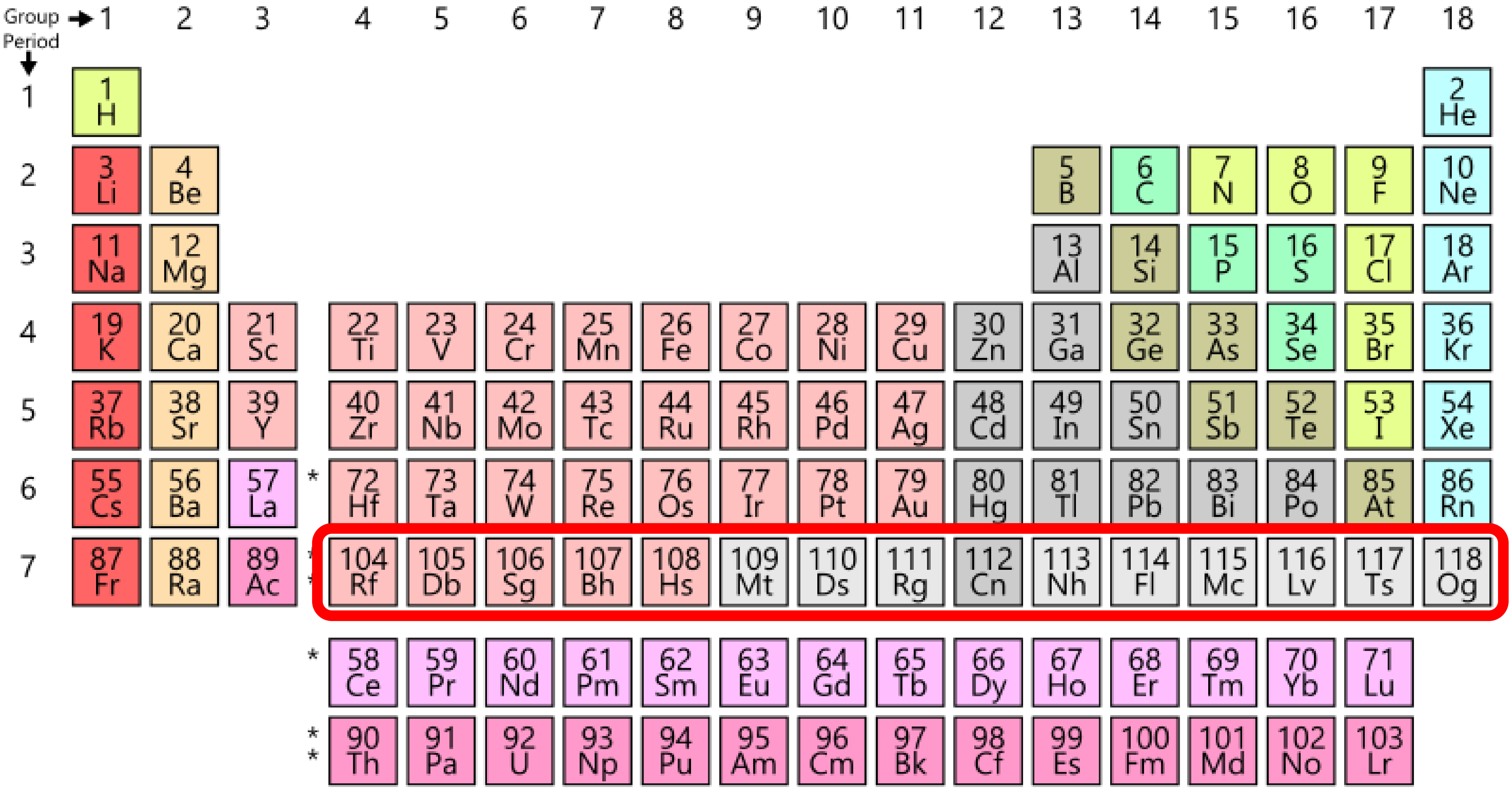
1 Intro
2 Superheavy elements and island of stability
3 Time efficiency of MASHA separator
4 Cryogenic Gas Stopping Cell
5 Purpose of simulations
6 Simulations – stopping efficiency – optimal parameters
7 Simulations - extraction time for optimal parameters
8 Conclusion

1 Briefly about me

Department of Experimental Physics

- Ph.D. Student of Applied physics, Palacky University Olomouc, Czech Republic
- Fifth year
- Supervisor: assoc. prof. Jiří Pechoušek, Ph.D.
- Joint Institute for Nuclear Research in Dubna, Russia
- Flerov Laboratory
- From February 2020
- Consultant: Mgr. Ľuboš Krupa, Ph.D.
- Head of sector: Aleksandr Mikhailovich Rodin, CSc.
- Thesis theme: **Properties of heavy and super heavy elements studied by mass spectroscopy and ISOL method, Stopping Efficiency Simulation of Cryogenic Gas Stopping Cell**

2 Superheavy elements and island of stability



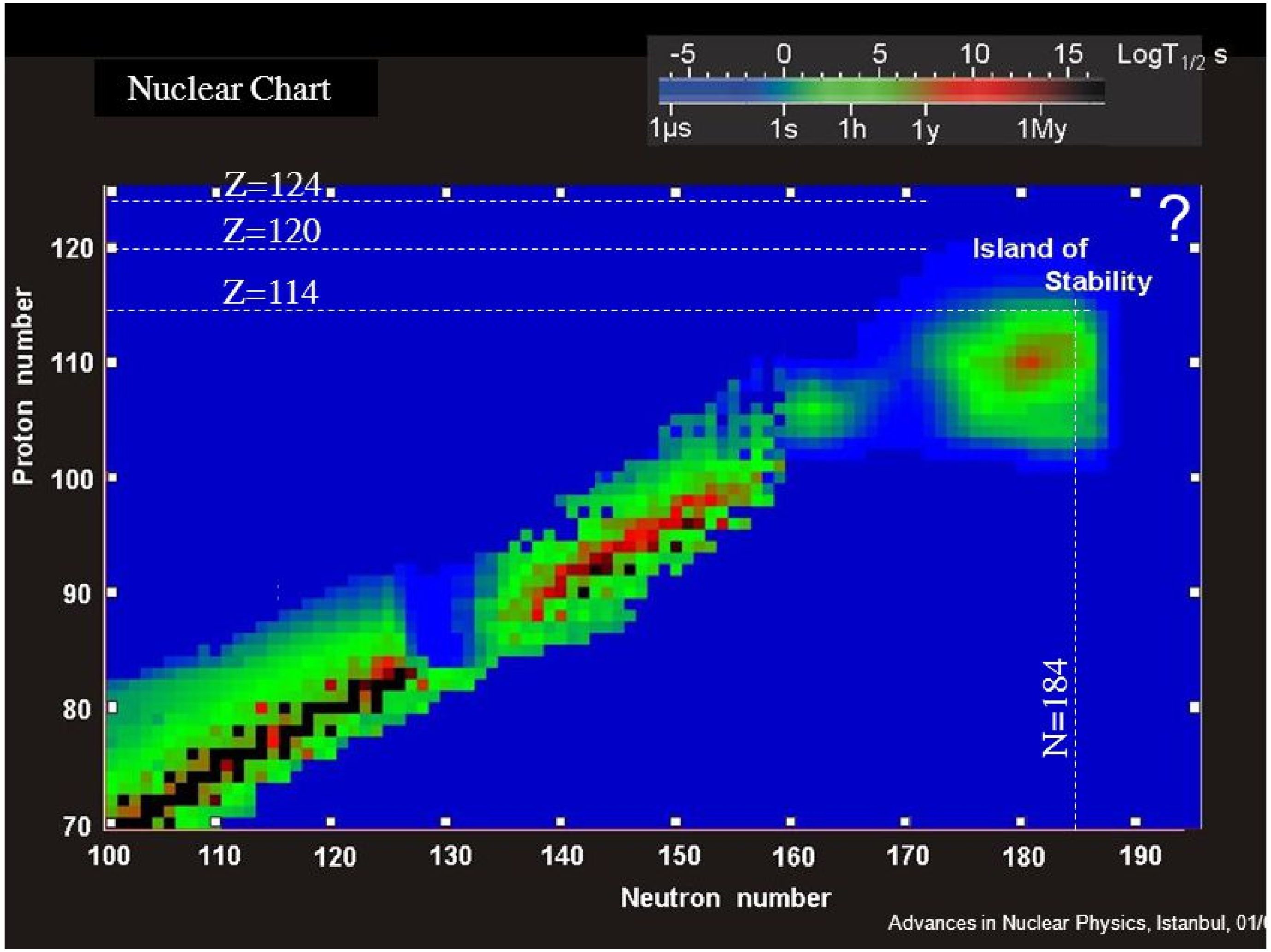
Island of stability

Superheavy elements have short half-life

Theoretically predicted island of stability

Isotopes with longer half-life than ussual

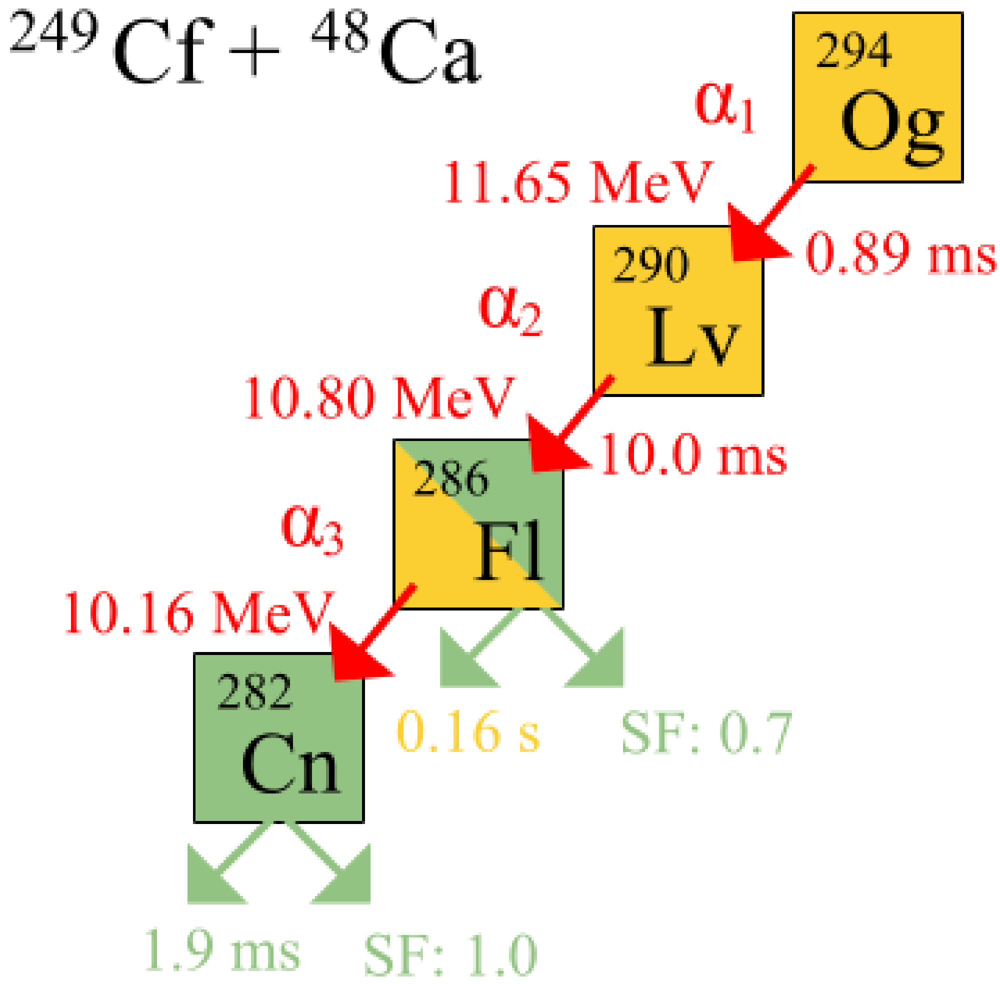
Island of stability predicted due to shell closure



[3]

Observation of new elements

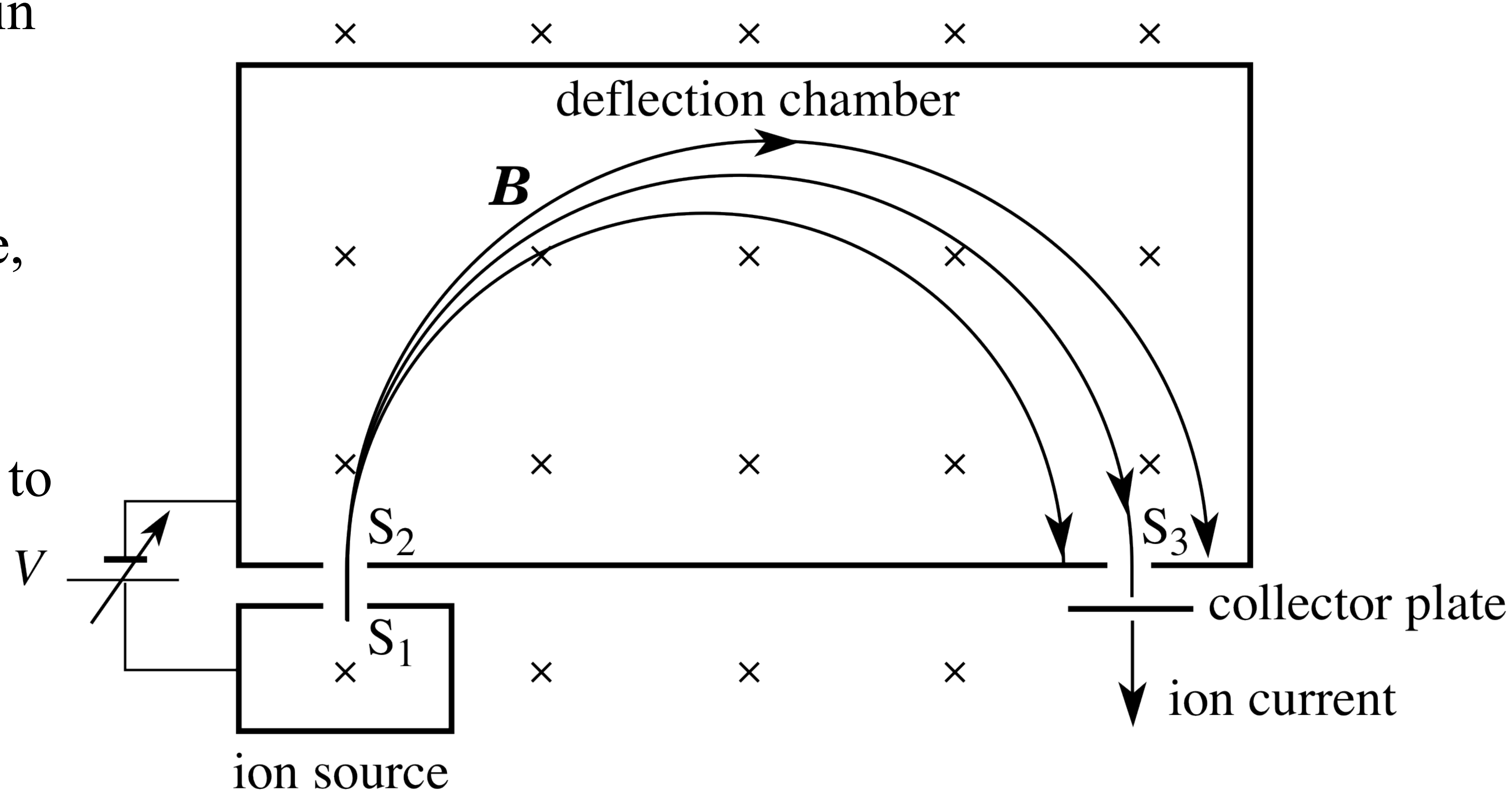
- ☢ We can observe decay chain
- ☢ We can measure mass of nuclei



[1]

How does the mass spectrometer work?

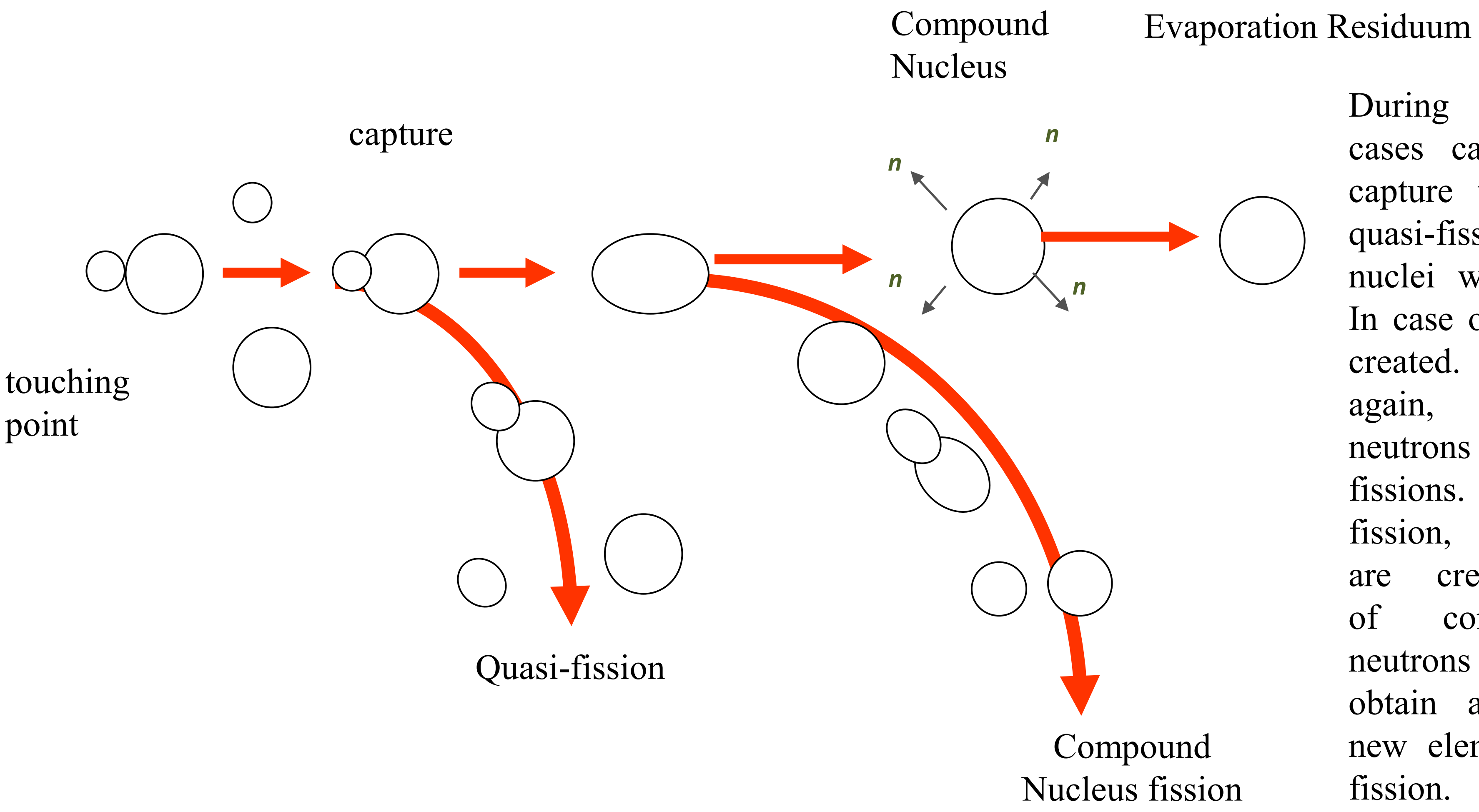
- Moving charged particle in magnetic field
- Affected by Lorentz force, which curves its trajectory
- Curvature is proportional to mass of particle



Mass

- fundamental property of an atom
- information - its constituents and their interactions, internal structure of the nucleus
- energy available for nuclear transformations in radioactive decay processes
- mass measurement allows to determine the full binding energy of the nucleus - the integral characteristic of all atomic and nuclear forces which is the key for solving the fundamental physics problems. For the determination of proton and neutron shells location, it is enough to know the nuclide mass with the relative accuracy ($\Delta M/M$) of $\sim 10^{-6}$.

More about fusion process



During collision of two nuclei, two cases can happen. Heavier nucleus can capture the lighter one or there can be quasi-fission. After quasi-fission two new nuclei with two new masses are created. In case of capture, one heavier nucleus is created. There are two possibilities again, compound nucleus evaporates neutrons or compound nucleus fissions. After compound nucleus fission, two nuclei of new elements are created. In case of evaporation of compound nucleus, neutron or neutrons are evaporated. As a result, we obtain another isotope of element, not new elements like after compound nucleus fission.

3 Extraction efficiency and extraction time of MASHA separator

- **Experiment I 2019 Autumn, reactions**
  - $^{40}Ar + ^{144}Sm \rightarrow ^{184-xn}Hg$
  - $^{40}Ar + ^{166}Er \rightarrow ^{206-xn}Rn$
- **Experimental parametres**
  - Beam energy E_0= 265 MeV
- **Absorbents:** Aluminium
  1. density 1,585 mg.cm^{-2} (thickness **5,87 µm**), foil position 41,5 mm
  2. density 2,516 mg.cm^{-2} (thickness **9,32 µm**), foil position 71,5 mm
  3. density 4,51 mg.cm^{-2} (thickness **16,7 µm**), foil position 101,5 mm
  4. density 1,585+5,55=7,135 mg.cm^{-2} (thickness 5,87+20,5=**26,37 µm**), foil position 131,5 mm
- **No absorbent:** foil position 11,5 mm
- Titan layer of target thickness: **1,5 µm**
- Sm_2O_3 layer of target thickness: **0,33 µm**
- Er_2O_3 layer of target thickness: **0,24 µm**

Cross section calculation of parental isotopes and daughter isotopes

$$\sigma = \frac{N\,M_{tg}Z\,e}{\rho\,N_A\,I\varepsilon_{parent}\varepsilon_d\,\varepsilon_{hc}\varepsilon_{tg}}, \text{ [barn]}$$

σ … cross section, [mbarn]

N … number of events(measured yield)

N_{corr} … corrected number of events (corrected yield)

$$N_{corr} = \frac{N}{\varepsilon_{parent}\varepsilon_d\,\varepsilon_{hc}\varepsilon_{tg}},\quad N_{corr\ daughter} = \frac{N}{\varepsilon_{parent}\varepsilon_{daughter}\varepsilon_d\,\varepsilon_{hc}\varepsilon_{tg}}$$

ε_{parent} … α decay fork, unique for parent isotope

$\varepsilon_{daughter}$ … α decay fork, unique for daughter isotope

ε_d … detector construction efficiency, correction ε_d =0,45

ε_{hc} … honey comb transparency, correction ε_{hc} = 0,85

ε_{tg} … target construction, correction ε_{tg} = 0,5

M_{tg} … target mass number

Z … charge of ^{40}Ar ion, $Z = 16$

e … elementary charge, $e = 1{,}6\cdot10^{-19}$C

ρ … target area density,

$\rho = 0{,}004\ \text{kg}\cdot\text{m}^{-2}$

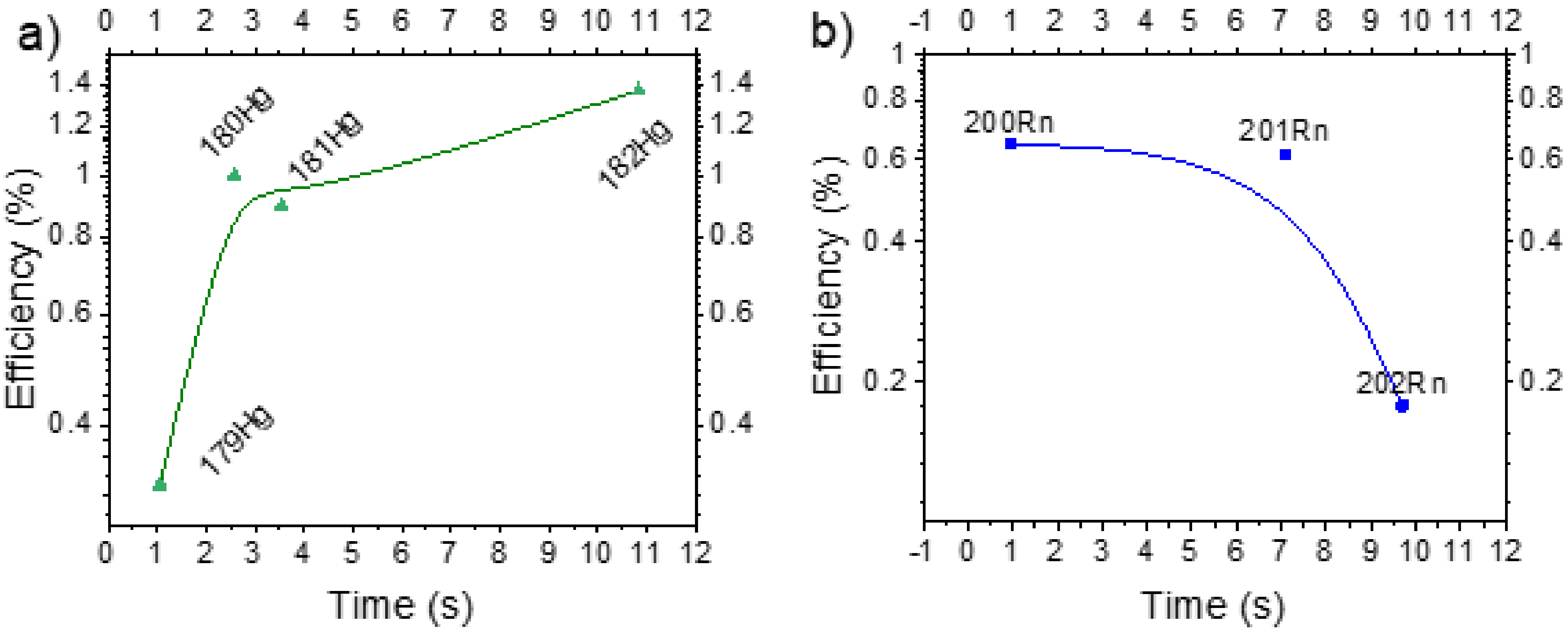
N_A … Avogadro constant, $N_A = 6{,}02\cdot10^{23}\text{mol}^{-1}$

I … beam integral, [μC]

Separation efficiency

	2n (182Hg)	3n (181Hg)	4n (180Hg)	5n (179Hg)
Time (s) for Hg	10,83	3,54	2,58	1,05
Efficiency (%) for Hg	1.3672	0.89626	1	0.32187
	4n (202Rn)	**5n (201Rn)**	**6n (200Rn)**	
Time (s) for Rn	9,7	7,1	0,96	
Efficiency (%) for Rn	0.17801	0.61215	0.645	

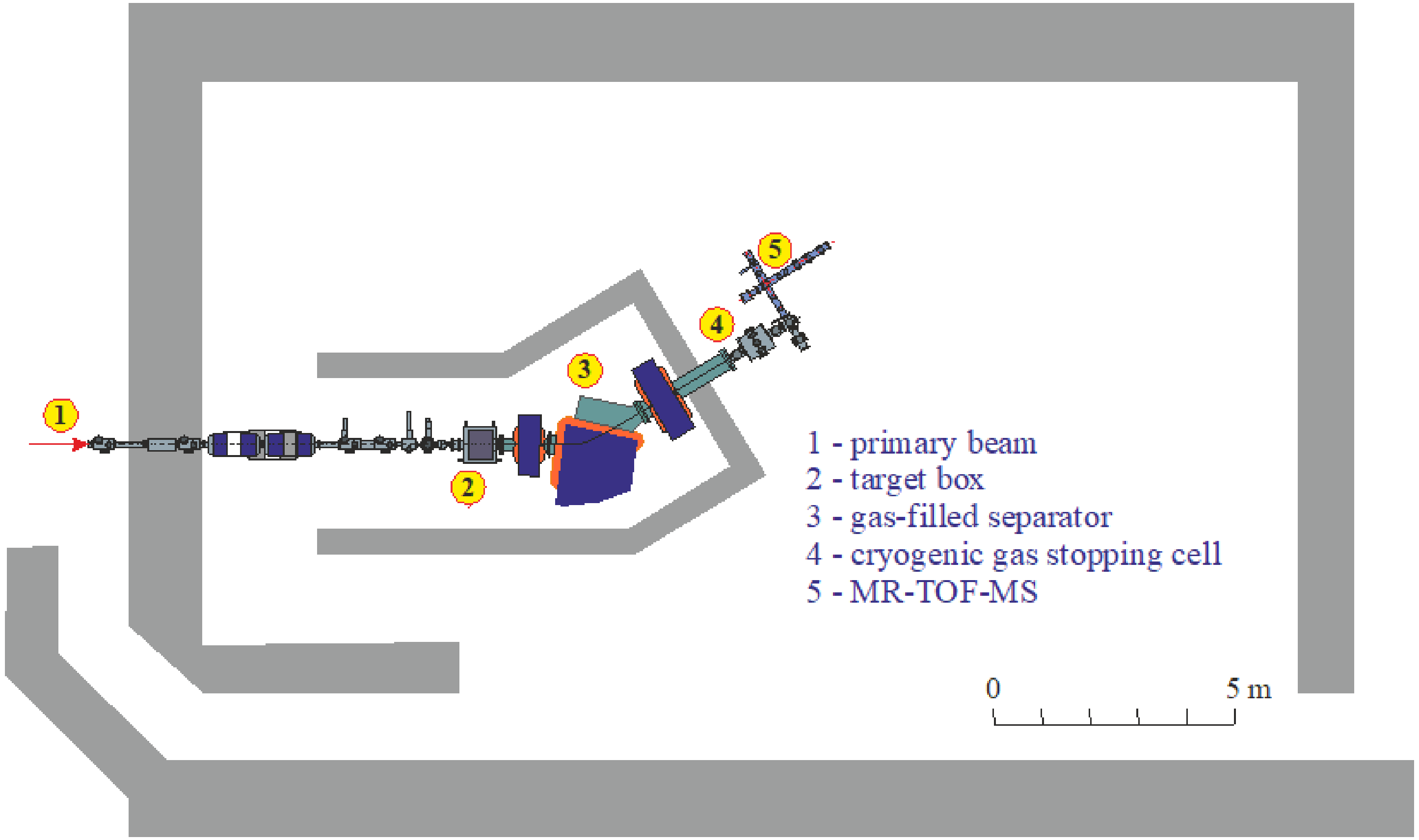
Separation efficiency of MASHA



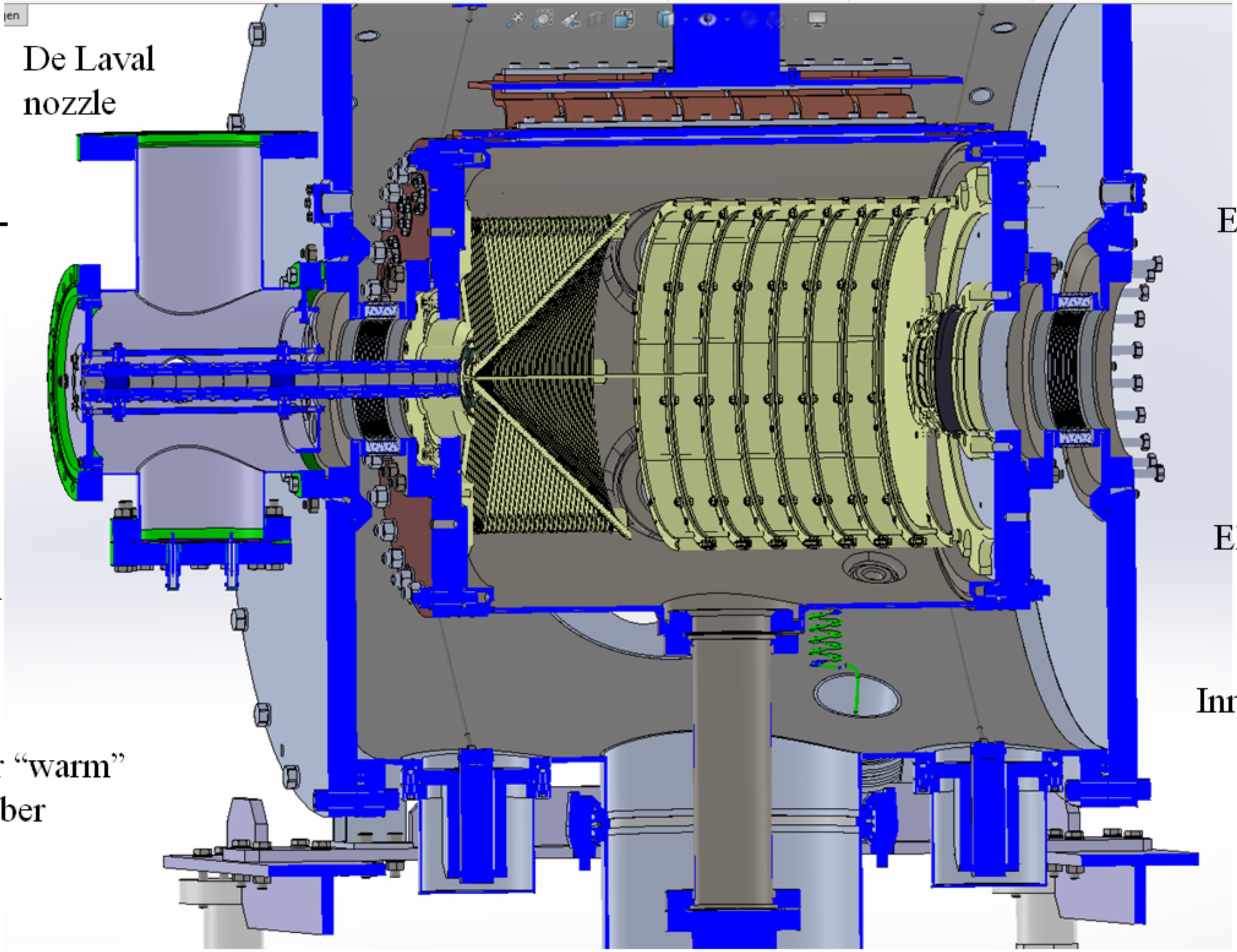
Separation efficiency of MASHA setup for mercury (left figure) and radon (right figure) isotopes.

4 Cryogenic Gas Stopping Cell Experimental Setup

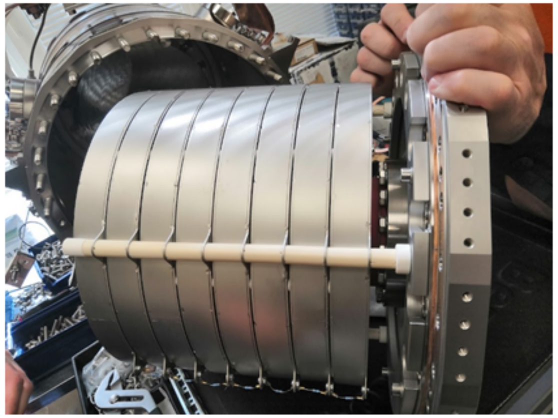
Experimental setup in new hall of cyclotrone U-400R

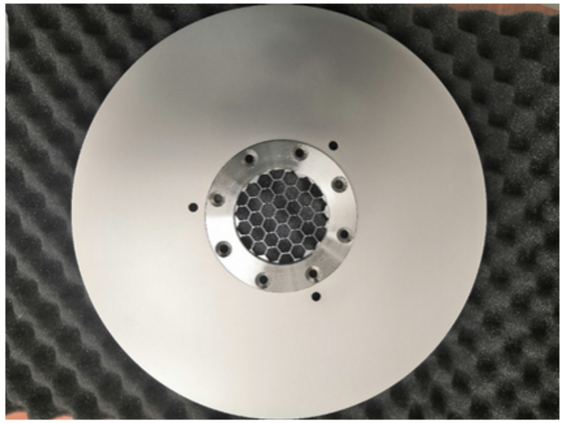


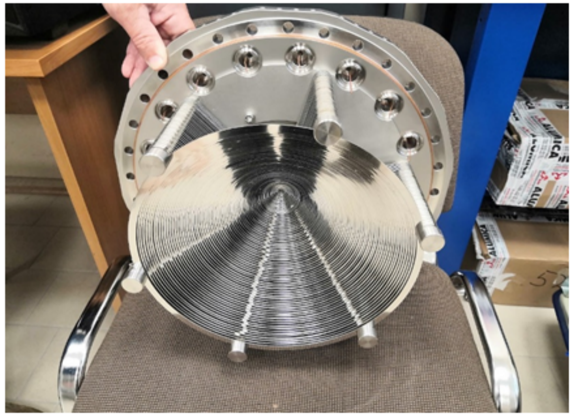
Model of axial cut

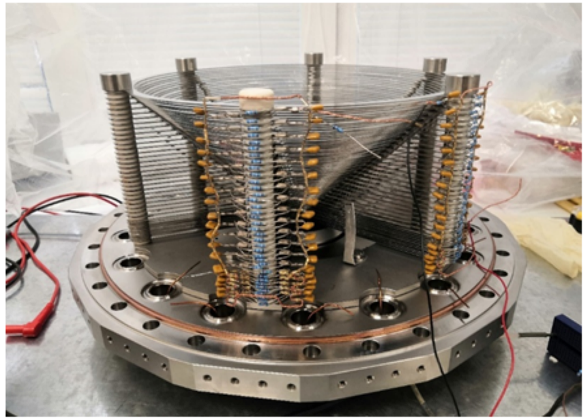


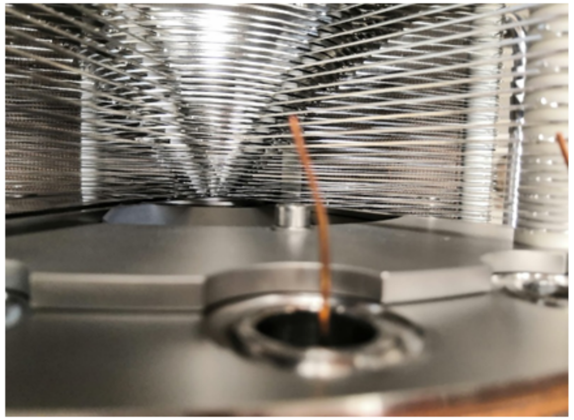
Cryogenic Gas Stopping Cell



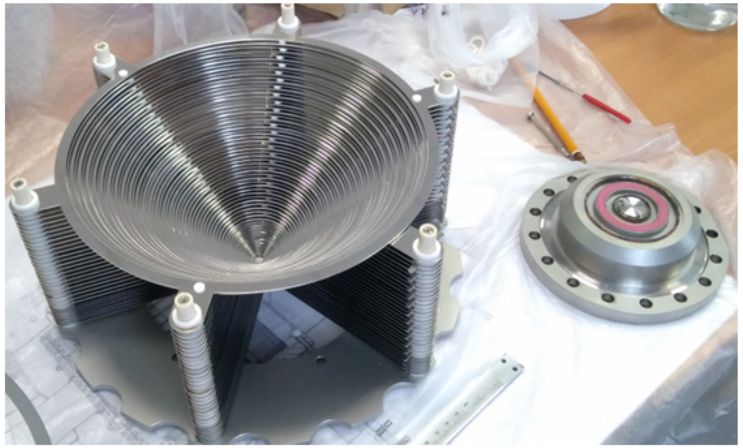


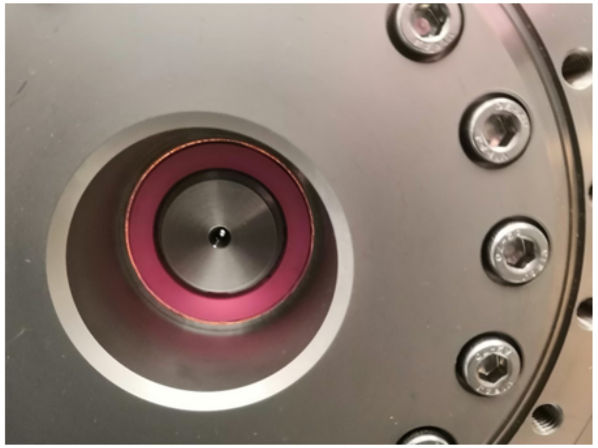


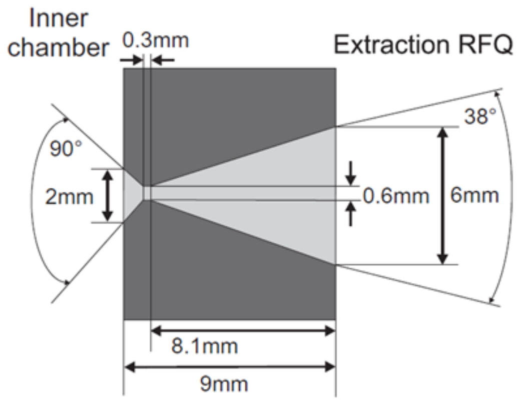


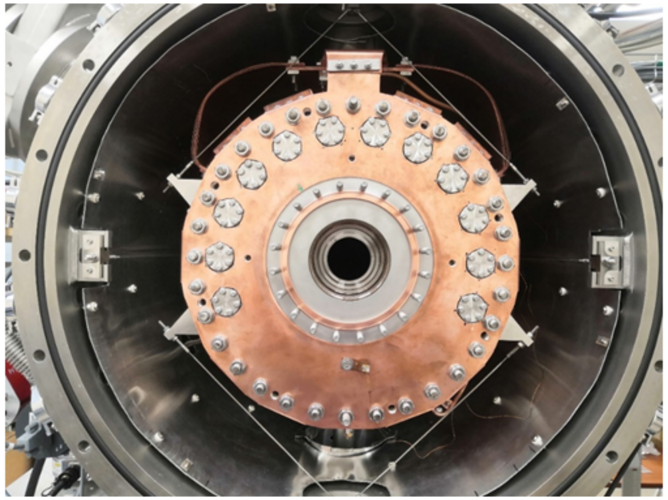


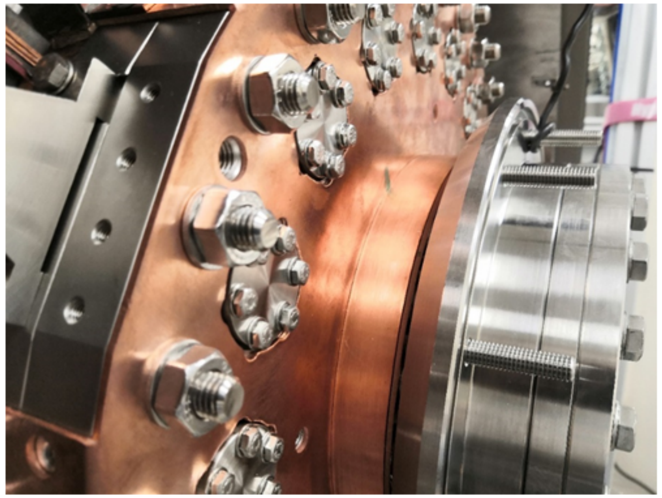
Cryogenic Gas Stopping Cell











5 Purpose of simulations

- Choosing the optimal parameters for real experiment
- Separation efficiency, Extraction Time - Impossible to measure online, directly
- Need for theoretical simulations
- 1^{st} part of simulations gave interval of optimal separation efficiency parameters – interval is then tested by 2^{nd} part of simulations for extraction time

6 Stopping Efficiency Simulation of Cryogenic Gas Stopping Cell

- Energy loss of beam particles in chamber filled by buffer-gas (helium) is proportional to stopping material electron **density** (so also buffer-gas **pressure**).

Stopping efficiency

- **Given by ratio** of the incoming ions n_{inc} that lost their entire kinetic energy within the active gas volume of the Cryogenic Gas Stopping Cell (CGSC) $n_{stopped}$:

$$\varepsilon_{stop} = \frac{n_{stopped}}{n_{inc} \cdot \varepsilon_{geom}}$$

- **Conditioned by** the kinetic energy of the incident EVR, the entrance window foil type and thickness and the buffer-gas type and density of the CGSC (only ions stopped within the active gas volume of the CGSC can be extracted)
- cannot be tested on-line - **relies on simulations**, software SRIM is used
- **WHY?** – finding reactions, width of entrance window and pressure of buffer-gas optimal for real experiment (precious and expensive experimental time)

Simulations performed:

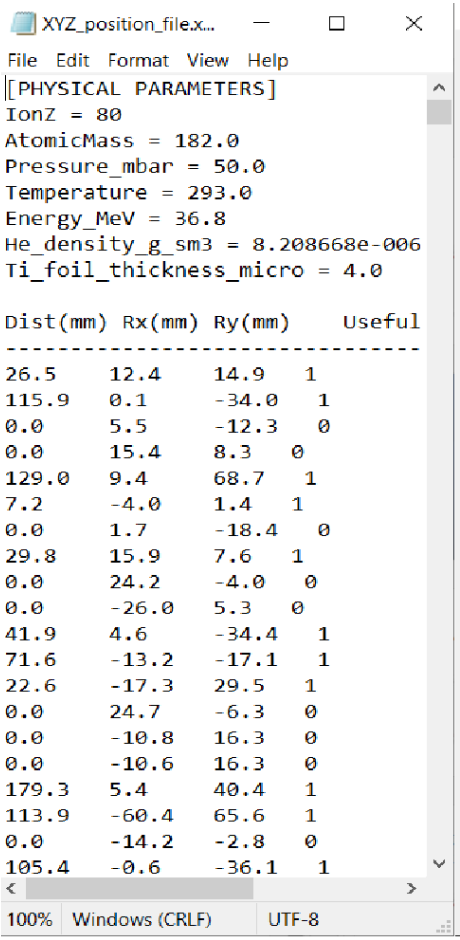
- $^{40}Ar + ^{144}Sm \rightarrow ^{184\text{-}xn}Hg$
- $^{40}Ar + ^{166}Er \rightarrow ^{206\text{-}xn}Rn$
- $^{40}Ar + ^{162}Er \rightarrow ^{202\text{-}xn}Rn$
- $^{40}Ca + ^{130}Ba \rightarrow ^{170\text{-}xn}Os$
- $^{40}Ar + ^{178}Hf \rightarrow ^{218\text{-}xn}Th$
- $^{48}Ca + ^{206}Pb \rightarrow ^{254\text{-}xn}No$
- $^{48}Ca + ^{238}U \rightarrow ^{286\text{-}xn}Cn$
- $^{48}Ca + ^{242}Pu \rightarrow ^{290\text{-}xn}Fl$

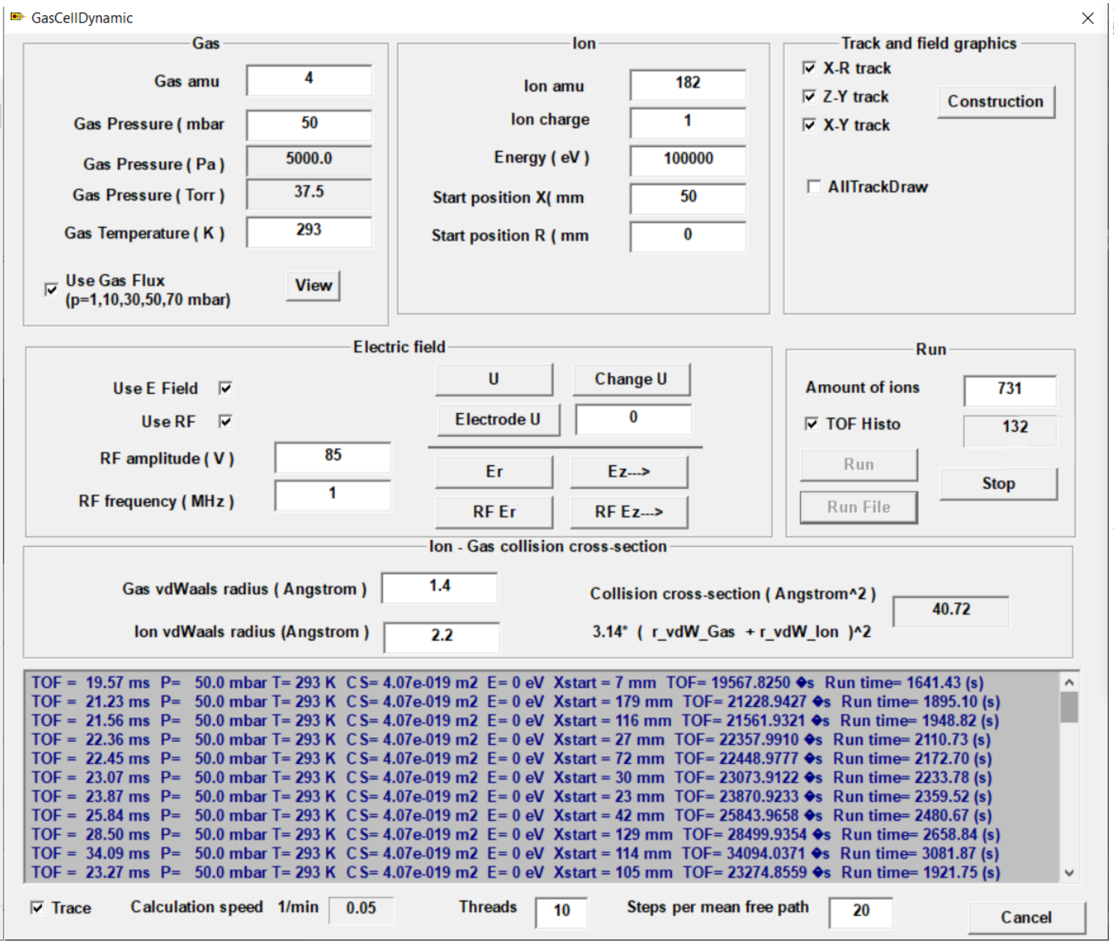
7 Extraction Time Simulations

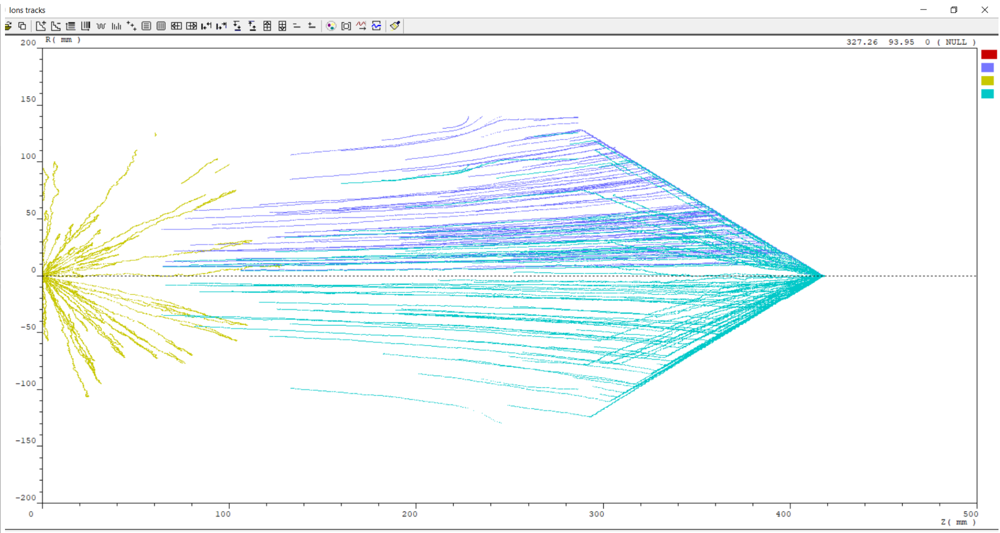
- **2nd part of simulations** (after stopping efficiency)
- **Trajectory of particles** is calculated and graphicaly captured by our **internal software** created in Root framework based on SIMION, Geant4 and COMSOL
- Simulations are based on **file of coordinates** of exact position of stopped particles (it was obtained by previous simulations of stopping efficiency)
- Performed for
  - alpha source **^{220}Rn**
  - Isotopes **^{182}Hg, ^{203}Rn, ^{286}Fl, ^{254}No, ^{255}Lr**

Extraction time simulations - example

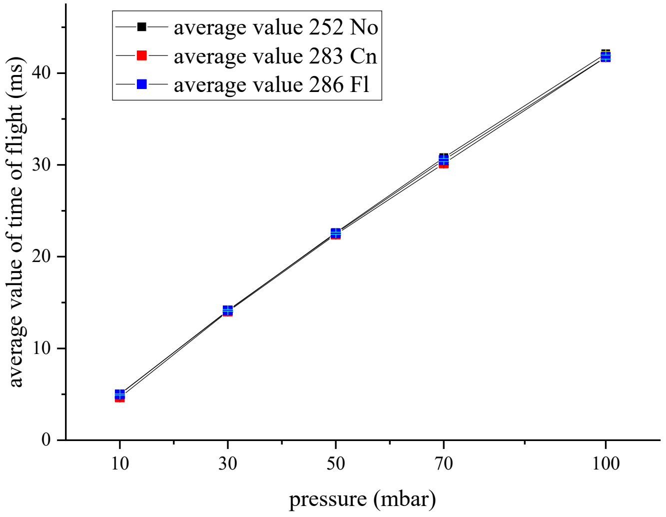
^{182}Hg, 50 mbar, 4 μm

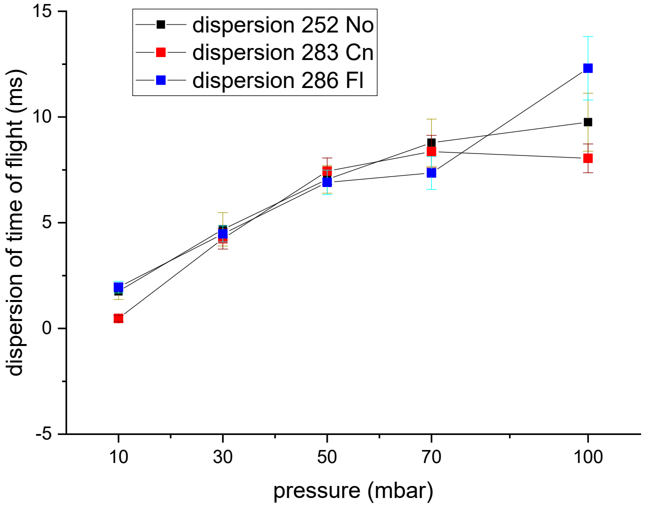


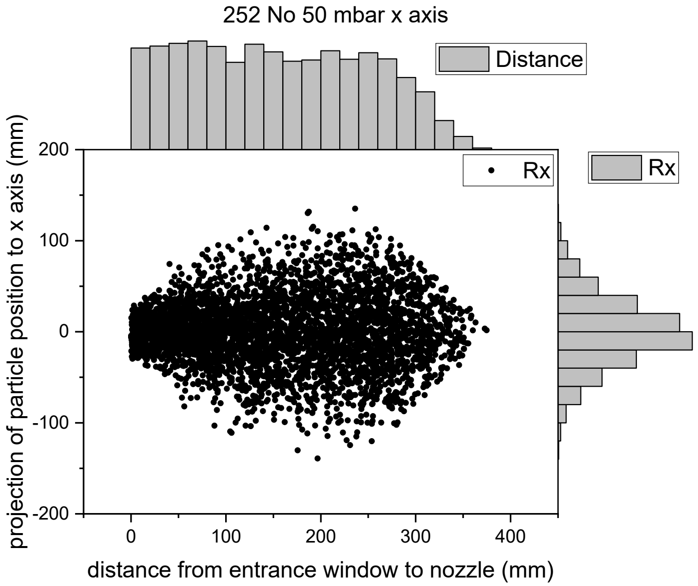


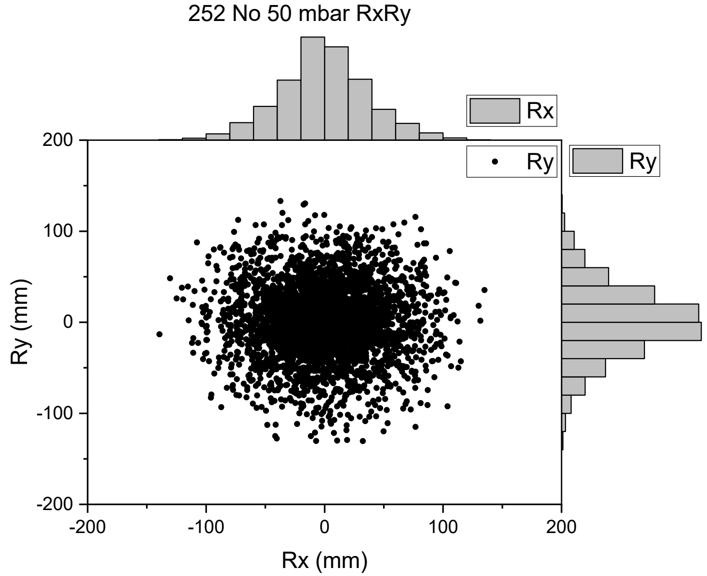


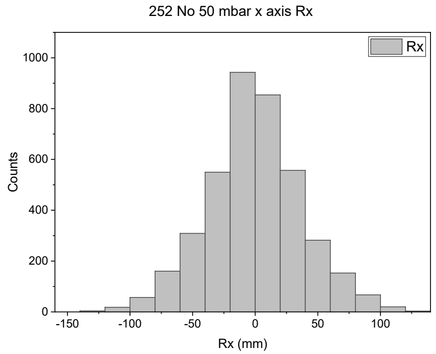
Extraction time ^{252}No, ^{283}Cn, ^{286}Fl

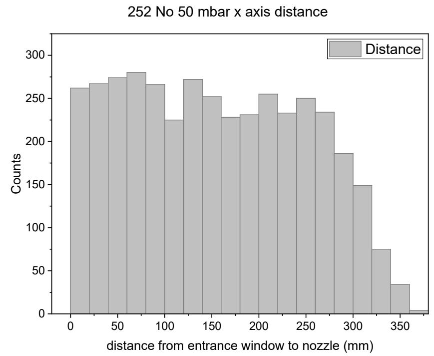


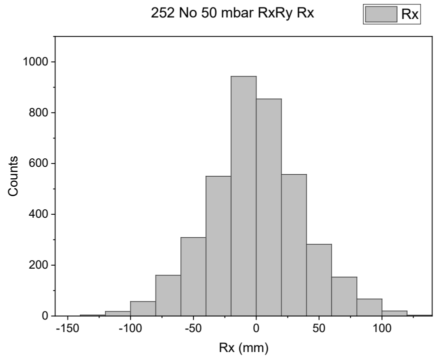


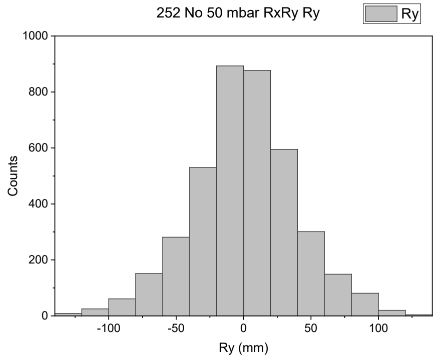








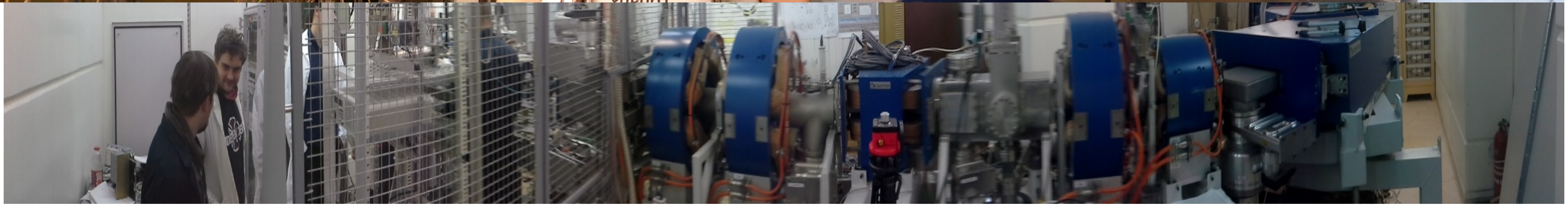




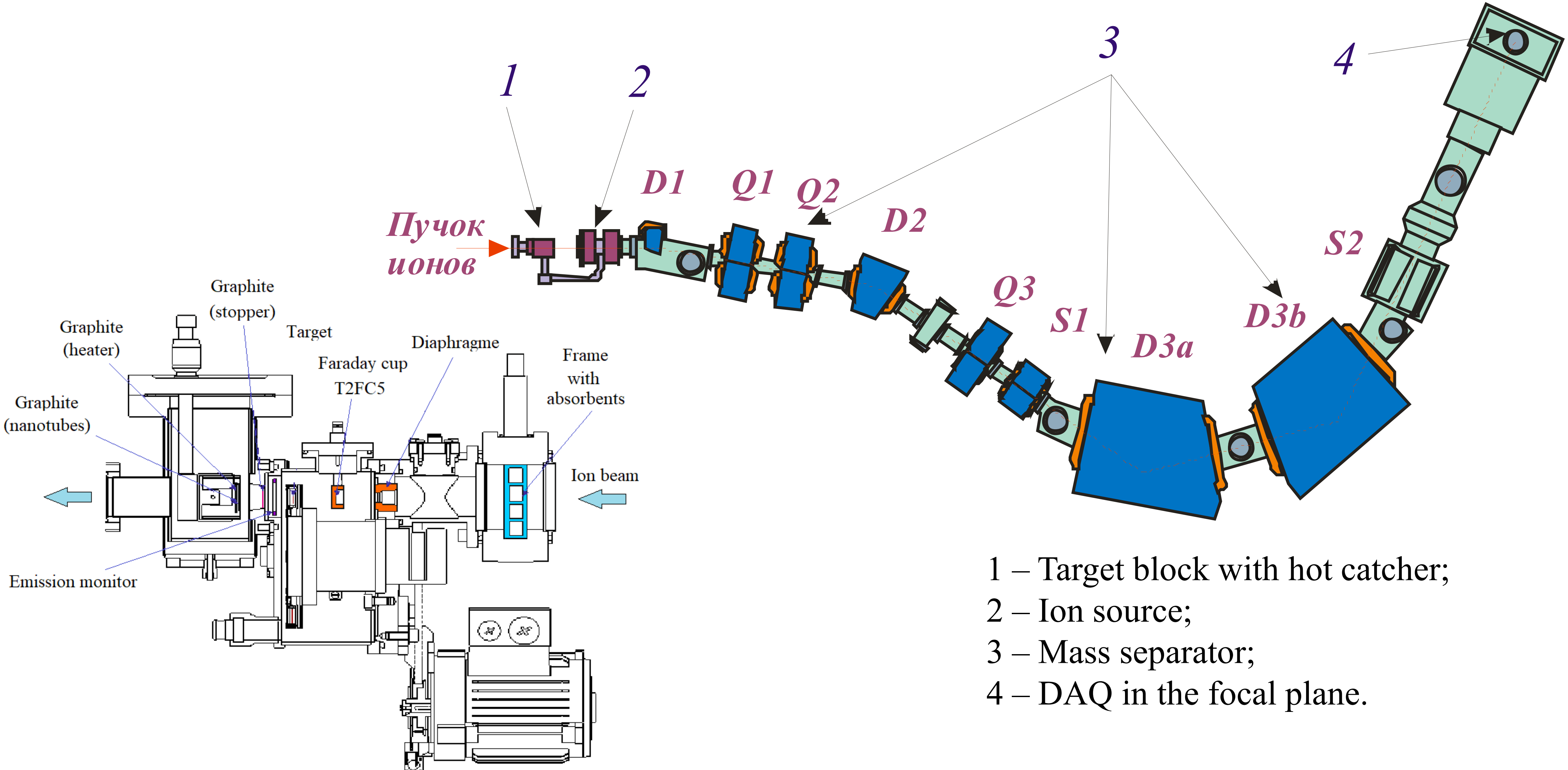
8 Conclusion

Separation efficiency and extraction time of MASHA setup was found
Optimal parameters for maximal stopping powers were found
Extraction time was simulated for optimal parameters

Thank you for your attention.



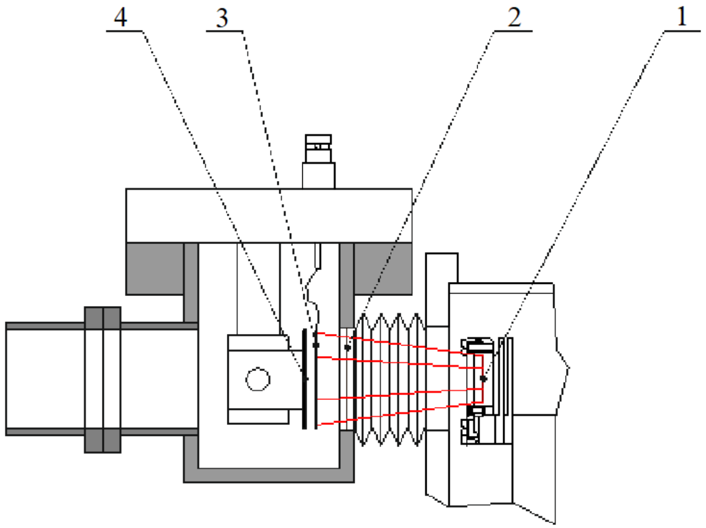
Mass Analyzer of Super Heavy Atoms



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

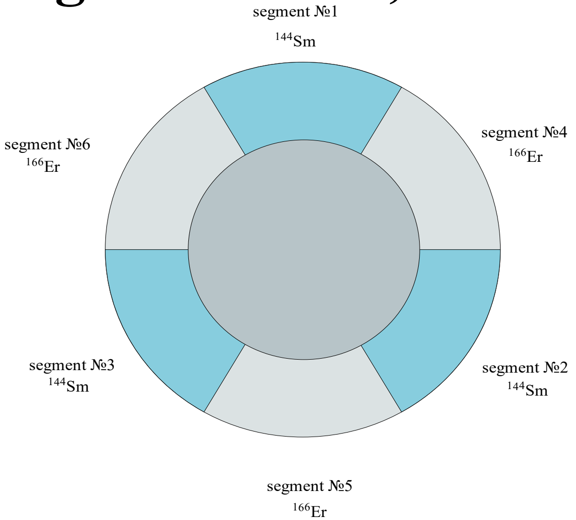
Mass Analyzer of Super Heavy Atoms

Hot cather scheme



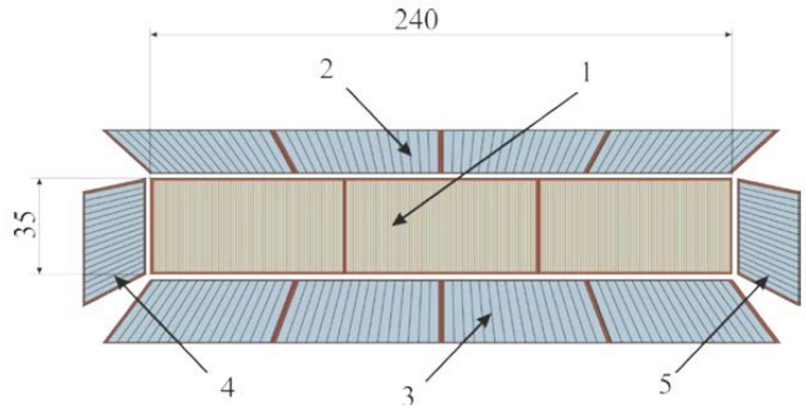
1 - Target sector on Ti foil
2 - Separate foil (graphen) 300 mg·cm^{-2}
3 - Common absorber (nanotubes or graphen) 1,5 mg·cm^{-2}
4 - Graphit foil (heater) 50 mg·cm^{-2}

Target – rotates, scheme



Nanotubes absorbent foil

Detector – scheme and picture



Experiment I 2019 Autumn

- **Experiment I 2019 Autumn, reactions**
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- **Experimental parametres**
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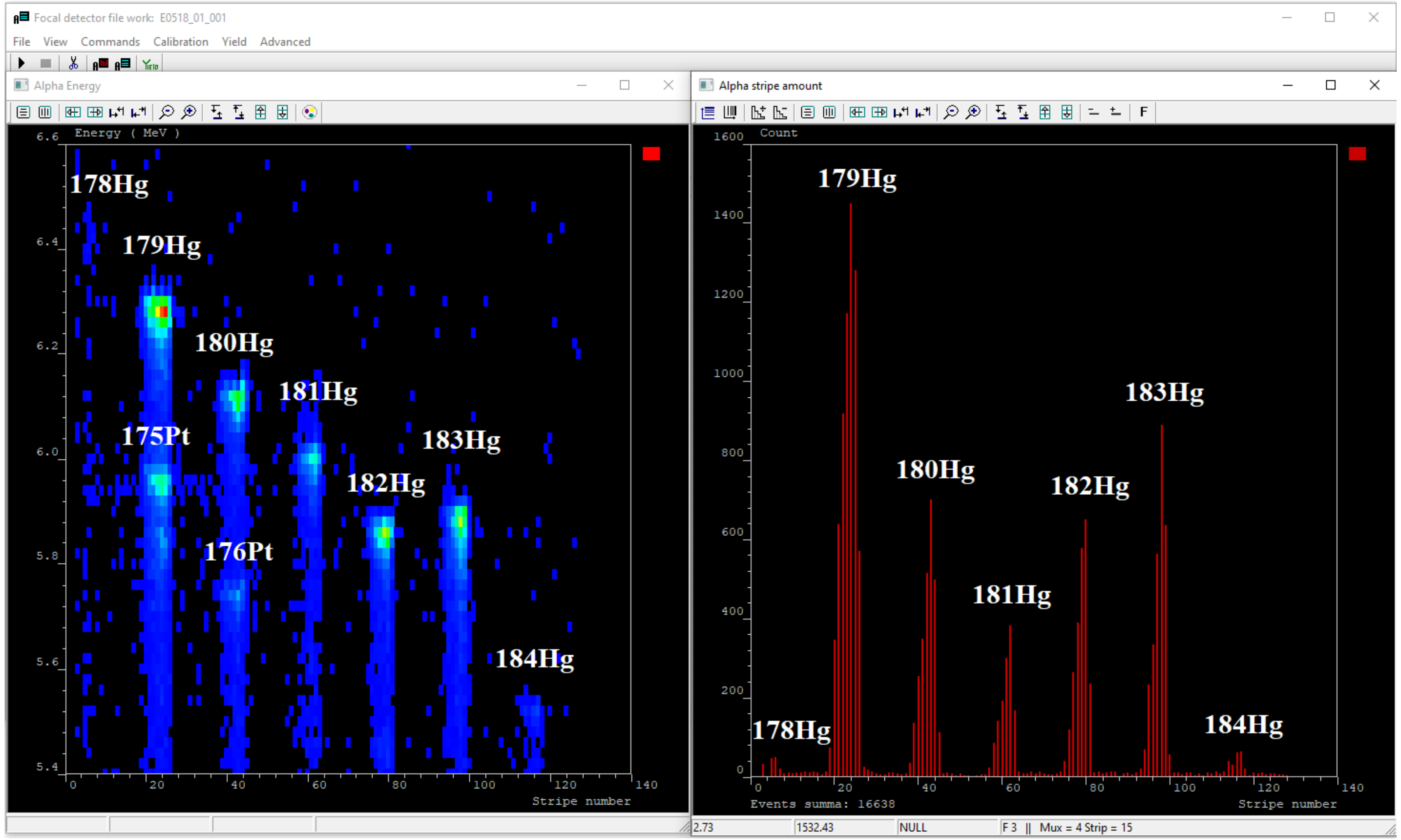
$^{40}Ar+^{144}Sm \rightarrow ^{184-xn}Hg$ reaction products

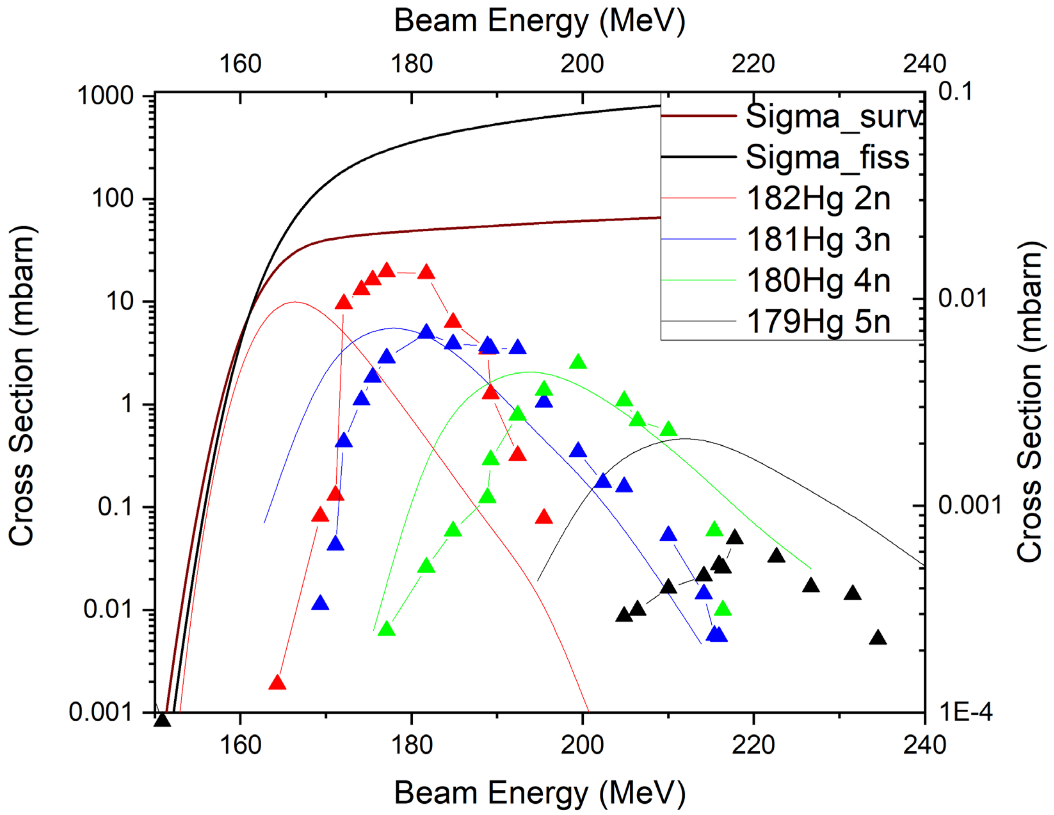


- Screenshots from Focal Detector program.
- On the left side: two dimensional matrix energetic spectrum of parental isotopes Hg and their daughter isotopes Pt (y axis – energy, x axis – mass, z axis – events).
- On the right side: mass spectrum both parental and daughter nuclei (x axis – mass, y axis – energy).

$^{40}Ar + ^{144}Sm \rightarrow ^{184-xn}Hg$ reaction products

Parental nuclei	Energy [MeV]	Probability α-decay [%]	Half Life [s]	Daughter nuclei	Energy [MeV]	Probability α-decay [%]	Half Life [s]
178Hg	6430	76,38	0,266	174Pt	6039	75	0,891
179Hg	6285	53	1,05	175Pt	6021	64	2,43
180Hg	6119	48	2,58	176Pt	5753	40	6,3
181Hg	6148	30	3,54	177Pt	5517	5,7	10,6
182Hg	5867	15,2	10,83	178Pt	5446	5	21,1
183Hg	5904	11,7	9,4	179Pt	5195	0,24	21,1
184Hg	5539	1,26	30,87	180Pt	5140	0,3	56

$^{40}Ar + ^{144}Sm \rightarrow ^{184-xn}Hg$ reaction, **parental nuclei**



- Dependence of Cross Section on Beam Energy (excitation functions).
- Hg Isotopes which nucleon number is between 179 and 182.
- Black and Brown curves are physical limits which are results of conservation laws.
- Comparison of theoretical (lines) and experimental (triangles) data.