Production cross sections of mercury and radon isotopes in complete fusion reactions with ^{36,40}Ar and ^{40,48}Ca projectiles

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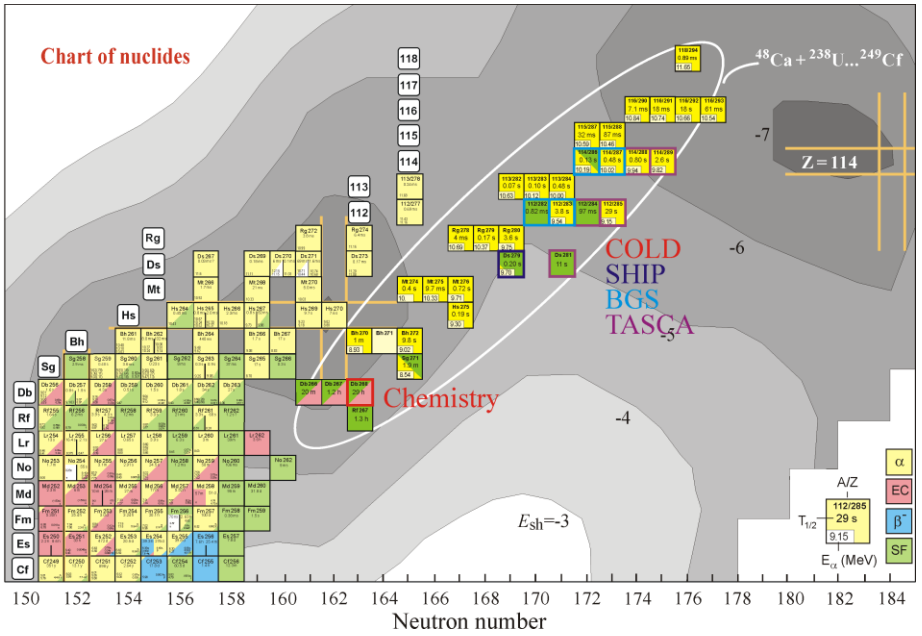
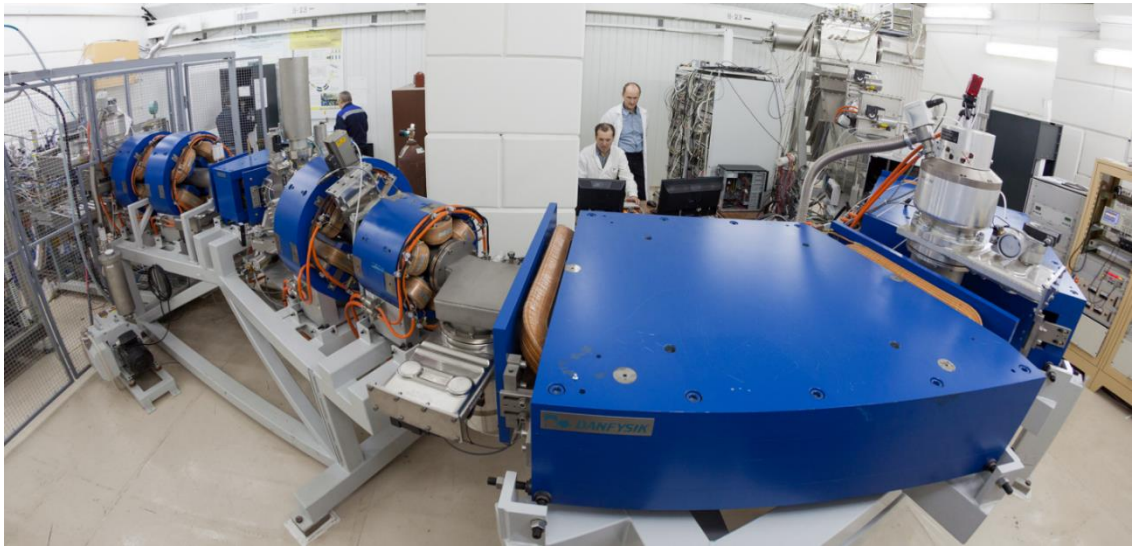
Synthesis of superheavy nuclei at FLNR JINR

A significant progress has been achieved in the nuclear physics experiments devoted to synthesis of new superheavy elements and study of their properties. The nuclides up to Z=118 (Og) were synthesized in the reactions of doubly magic ^{48}Ca ions with actinide targets.

Mass separator MASHA [1] was built in FLNR JINR, combining the ISOL method for the synthesis and separation of radioactive nuclei with the classical mass spectrometry technique.





Mass Analyser of Super Heavy Atoms (MASHA)

The life-times of some superheavy nuclei are quite long: 3.8s for ^{283}Cn, 29s for ^{285}Cn and 2.6s for ^{289}Fl.

Cn (Z = 112) is more volatile than its homolog Hg, while Fl (Z=114) differs from its light homolog Pb and exhibits the properties of noble inert gases.

[1] A.M. Rodin *et al.*, Inst. Exp.Techn. Vol. 57, No. 4, pp. 386–393 (2014)

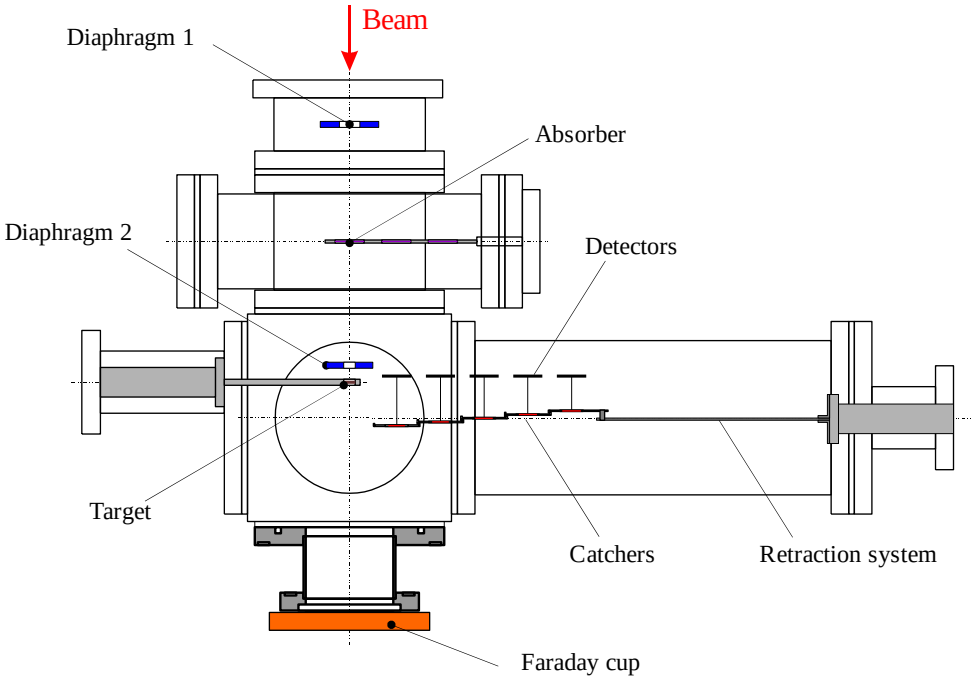
- To verify experimentally a capability of the mass-separator MASHA to measure the masses of the volatile nuclides of Cn (Z=112) and Fl (Z=114), whose production cross-sections are extremely low (about several pb), ***the efficiency of the mass spectrometer*** is proposed to measure in the experiments with ***mercury (homolog of Cn, Z=112) and radon (noble gas as Fl, Z=114)***

- The purpose of the present work was to determine ***the production absolute cross-sections of mercury and radon isotopes*** produced as evaporation residues in the complete fusion reactions of ^{36,40}Ar and ^{40,48}Ca ions with lanthanide targets of $^{144,\ 148}$Sm, ^{142,144}Nd and ^{166}Er.

- For heavy and superheavy nuclei the fusion cross-sections greatly depend on the reaction entrance channel properties, such as mass asymmetry, charges of the interacting nuclei Z_1Z_2, their deformations, as well as shell closure, where the quasi-fission process competes with the fusion one. So, an extra motivation to carry out the experiment was to study the effect of the entrance channel on production of evaporation residues of ^{184}Hg in three reactions: ^{40}Ar + ^{144}Sm, ^{36}Ar + ^{148}Sm, ^{40}Ca + ^{144}Nd.

- The effect of the neutron excess was investigated in the reactions ^{40}Ca+^{144}Nd$\rightarrow$ ^{184}Hg and ^{48}Ca+^{142}Nd$\rightarrow$ ^{190}Hg.

Experimental set-up for measurement of short-lived radon and mercury isotopes



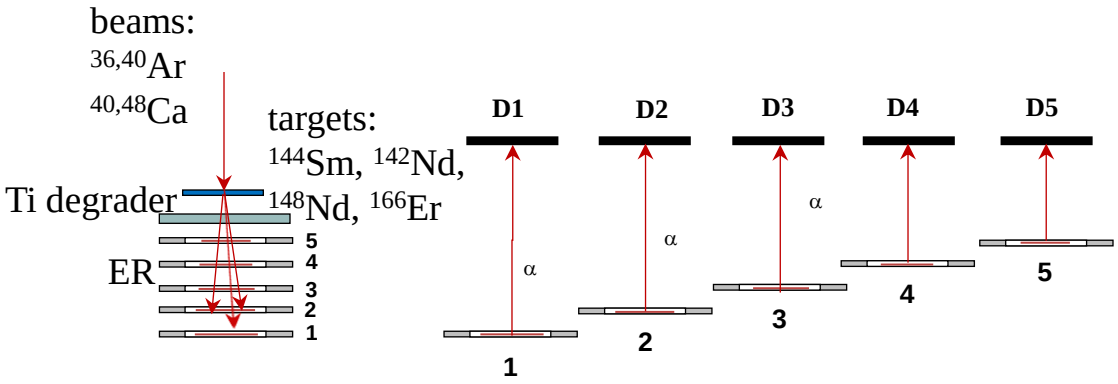
Scheme of experiment with moving catchers.

Top: pneumatic actuator with aluminum catcher foils and silicon detectors. Bottom: absorber foils in the position for registration of α-particles

The experiments were carried out at the U400M cyclotron of the FLNR, JINR (Dubna). Beams of ^{36}Ar, ^{40}Ar, ^{40}Ca, and ^{48}Ca with the energies of 250-330 MeV were used. The beam intensity in experiments was ~ 0.2 pμA. The targets were 280–330 μg/cm2 layers of ^{144}Sm, ^{166}Er, ^{148}Sm, ^{142}Nd, and ^{144}Nd. Catchers: Al foils (0.8 μm).

The beam interruption method was applied for isotope identification. Geometrical efficiencies for the semiconductor detectors were 4.90; 3.95; 3.37; 2.84 and 2.43 %.

Experiment with moving catcher foils



I. accumulation mode

II. measurement mode

To register the reaction products an ***advanced catcher-foil technique*** was applied [D. Vermeulen, *et al*., Z. Phys. A 318(1984)157].
During the experiment, the catcher foils were periodically in two positions until spectra with needed statistics were accumulated.

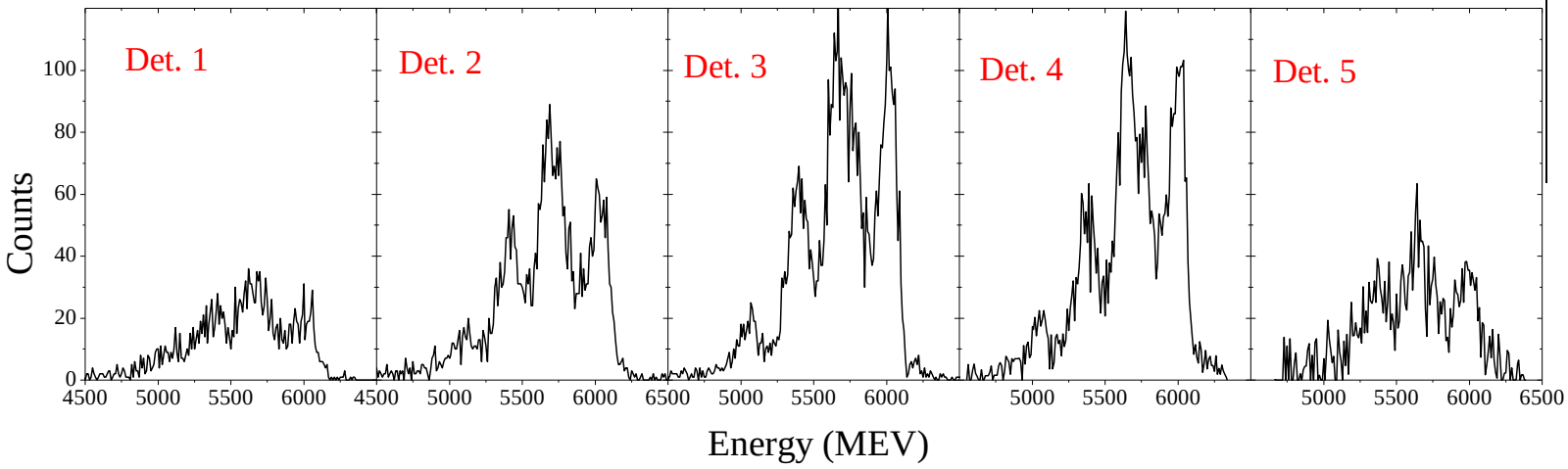
In **the accumulation mode** the foils were placed one under another, so that the reaction products were stopped at different depths in dependence of their energies.

The time of moving of aluminum absorbers between their extreme positions was 0.3 s.

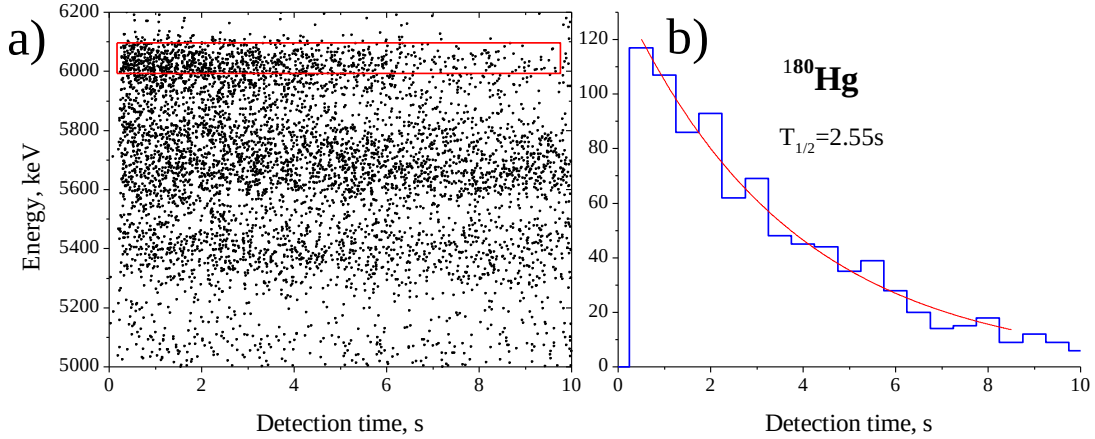
In **the measurement mode** the foil array was extended to its full width so that each foil was placed opposite to the corresponding silicon detectors registered α-decays of short-lived radon and mercury isotopes.

The accumulation and measurement times were chosen to be 10 s – 30 s according to the half-lives of the studied reaction products.

Data analysis. Isotope identification



Experimental α-particle spectra of the evaporation residues of the reaction $^{40}Ar+^{144}Sm$ at the projectile energy E_{lab} = 180 MeV for the foils 1-5, registered by corresponding semiconductor detectors.



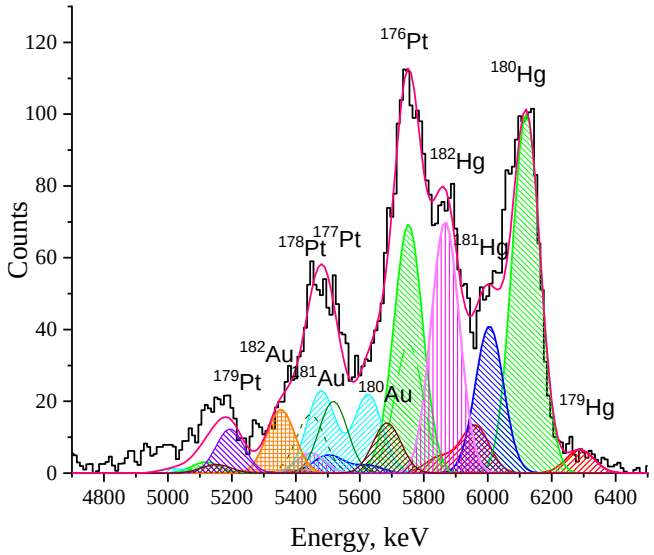
Identification of isotopes was performed using

1. α-particle energies;
2. half-lives of isotopes;
3. analysis of excitation functions.

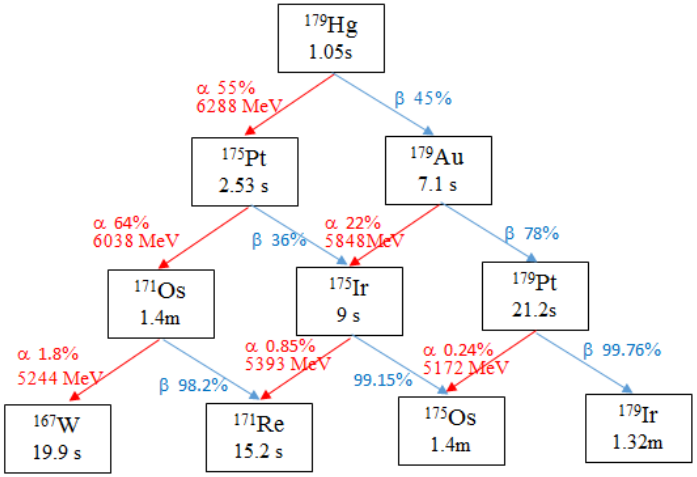
a) two-dimensional scatter-plot of α-particle energies vs. their times of registration starting from begin of measuring cycle for the reaction $^{40}Ar+^{144}Sm$ at E_{lab}=187 MeV, accumulated in third foil of catcher array;

b) decay curve for the cut in the scatter-plot .

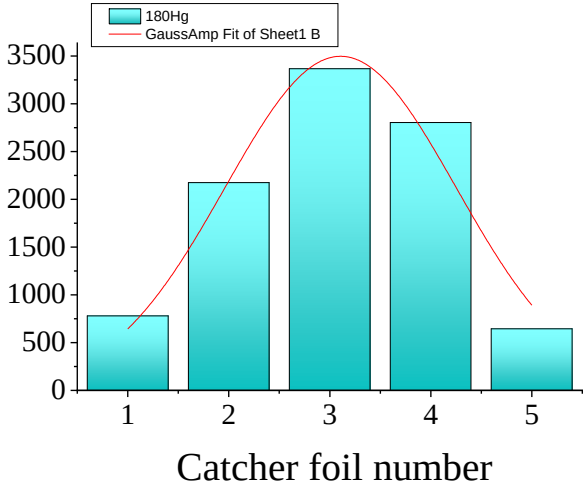
CROSS SECTION CALCULATIONS



Experimental spectrum of α-particle energy from the forth catcher foil for the reaction ^{40}Ar + ^{144}Sm at E_{lab} = 187 MeV. The yields of different isotopes with their daughter and grand-daughter nuclei are shown by colour lines.



Decay chain of ^{179}Hg with α and β branchings for each isotope in per cent.

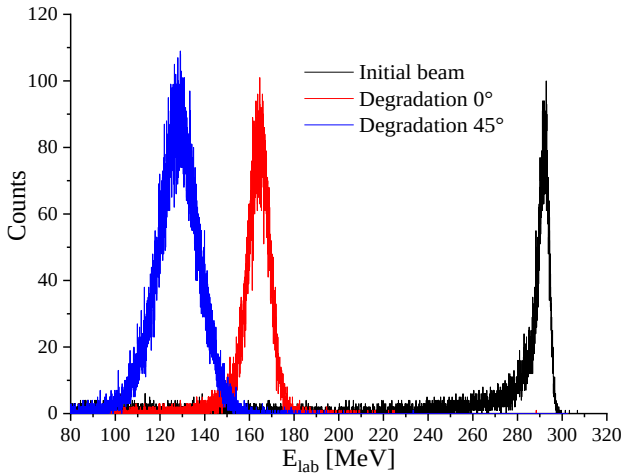


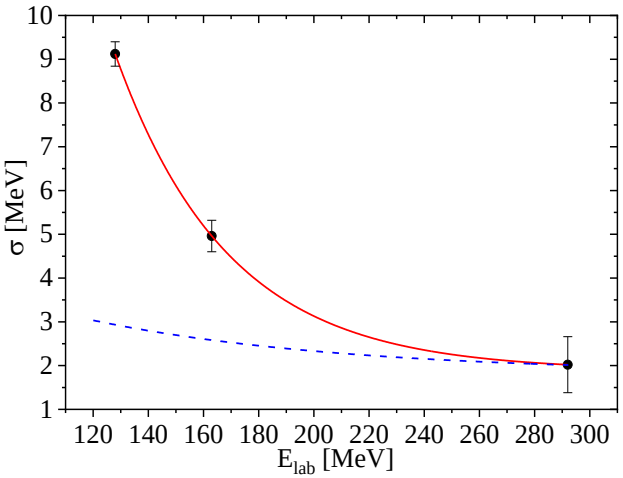
Yields of isotopes ^{180}Hg accumulated by catcher foils 1-5.

$$\sigma = \frac{N_{det}^{\alpha}\,\lambda(1-\exp(-\lambda T))}{g\beta\varepsilon_{\alpha}\, I(1-\exp(-\lambda t_B))\exp(-\lambda t_m)(1-\exp(-\lambda t_D))t_D}$$

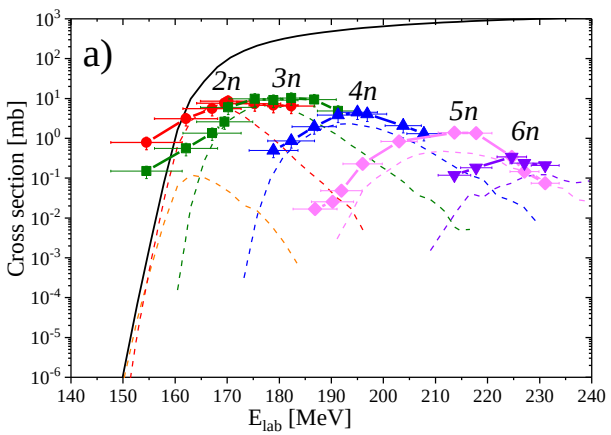
N_{det}^{α}-number of α-particles registered during one run
T-the duration of one measurement cycle; $T = t_B + 2t_m + t_D$,
t_B - accumulation time,
t_D - detection time,
t_m - the move time of the retraction system,
g – geometrical efficiency of the detector,
$\beta = dSr$ (d - target thickness, S - target area, r-target nucleus density,
λ – decay constant of studied isotope
I-integral

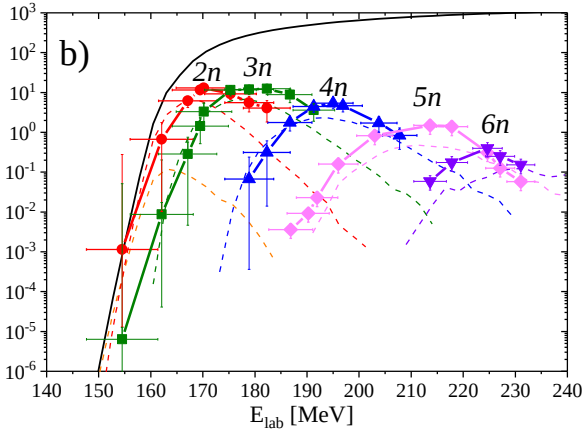
Corrections of excitation functions for beam energy spread





Left: measured energy spectrum of the ^{36}Ar beam without target and Ni foil (black), with Ni foil (10,3 μm, 0° and target, and after rotating the Ni foil by 45° (blue). Right: the dependence of the ^{40}Ar beam energy spread in the middle of the target (black squares) and its exponential fit (red line). A blue dashed line – SRIM[2] calculations.





Cross sections of xn-evaporation channels of the reaction ^{40}Ar + ^{144}Sm measured by using the catcher foil method: a) before and b) after deconvolution. Dashed curves are the cross sections calculated by the coupled-channel model nrv.

Gold deconvolution method [1]

$$D = \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{1}{2}\left(\frac{E-E_c}{\sigma}\right)^2}.$$

$$\sigma = B \cdot e^{-\frac{E_c}{t}} + \sigma_0,$$

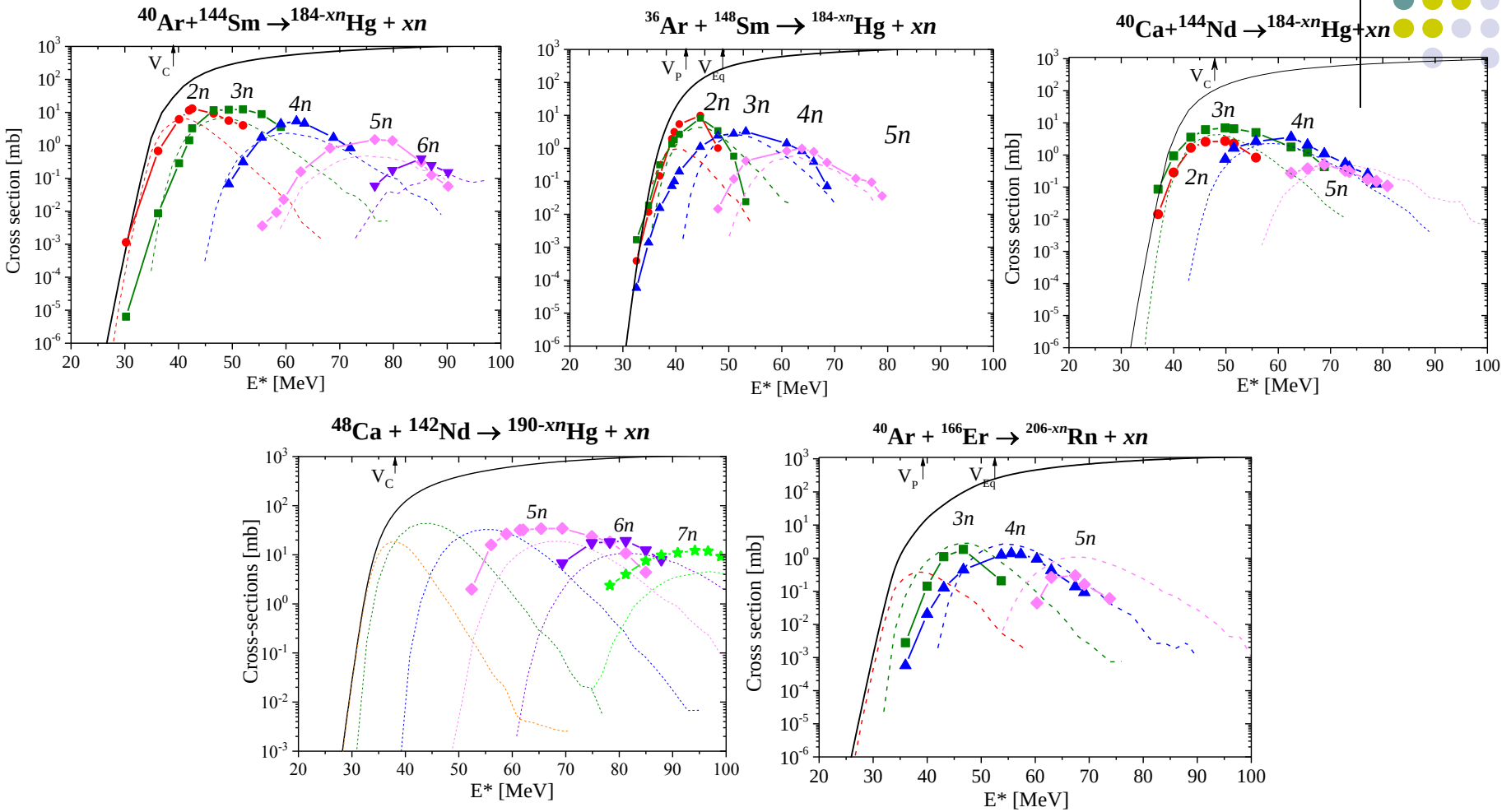
$$h^{ij} = C^j \cdot e^{-2\left(\frac{E^i - E_c{}^j}{\sigma}\right)^2}$$

$$C^j = \frac{1}{\sum_i e^{-2\left(\frac{E^i - E_c{}^j}{\sigma}\right)^2}}$$

D– response function of a beam energy spreading;
E_c – beam energy in the middle of the target;
σ – energy variance;
h^{ij} - matrix elements of response function
C^j - normalization constant

1.M. Morhac *et al.*, Nucl. Instr.Meth. A 401, 385-408 (1997)
2. J.F. Ziegler *at al.*, Nucl.Instr. Meth.B, 268, p. 1818-1823 (2010)

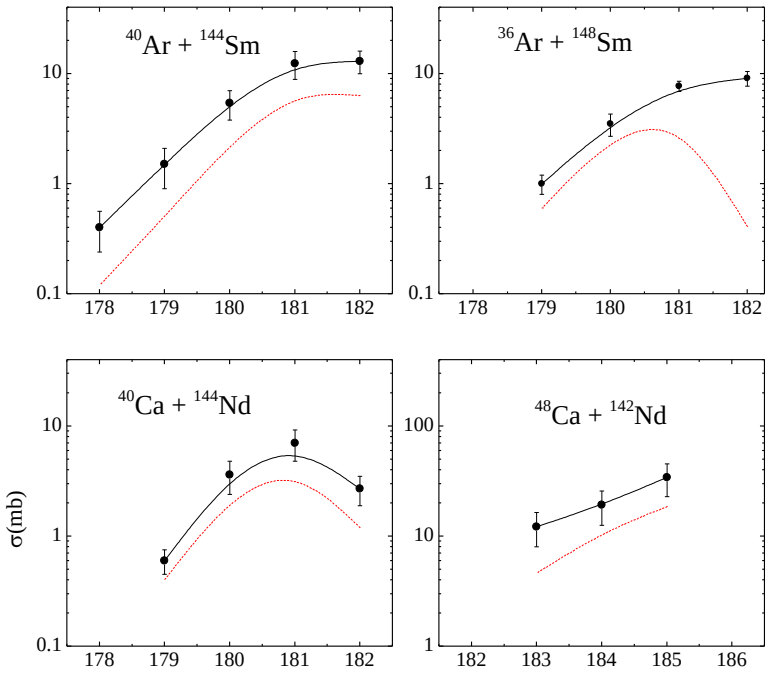
Excitation functions of the reactions $^{40}Ar+^{144}Sm$, $^{36}Ar+^{148}Sm$, $^{40}Ca+^{144}Nd$, $^{48}Ca+^{142}Nd$ and $^{40}Ar+^{166}Er$

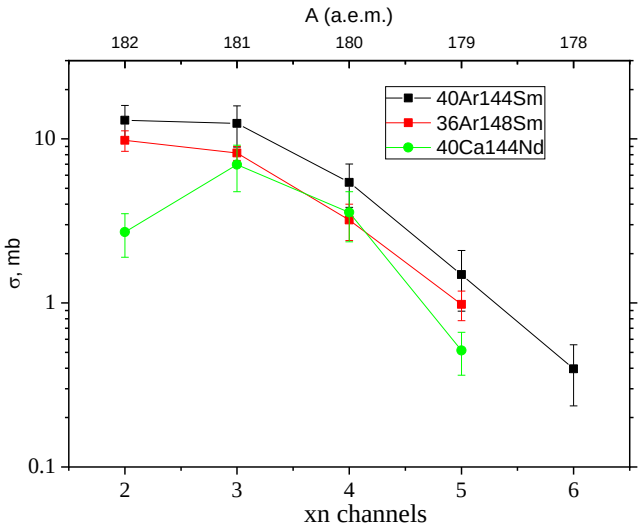


Cross sections (symbols) of *xn*-evaporation channels of the reactions measured by using the catcher foil method. Dashed curves are the cross sections calculated by the coupled-channel model nrv. V_C are the Coulomb barriers for spherical interacting nuclei, V_P and V_{Eq} are the Coulomb barriers for polar and equatorial mutual orientation of deformed ones, respectively.

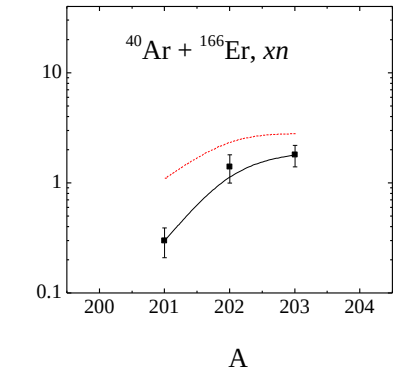
http://nrv.jinr.ru/nrv A.V. Karpov *et al.*, Physics of Atomic Nuclei 2016, V. 79, p. 749–761.

Results





The maximum values of the xn-channels of the reactions leading to the ^{184}Hg formation.



The comparison of experimental (solid lines) and theoretical [nrv] (dash lines) maxima of excitation functions for *xn*-channels of the studied reactions.

Table. Cross section maximum values in separate channels of complete fusion reactions and their position in the excitation energy scale.

σ[mb] (E*[MeV])	2n	3n	4n	5n	6n	7n
^{40}Ar+^{144}Sm →^{184}Hg	13±3 (42.5±3.3)	12.4±3.5 (52±2.6)	5.42±1.6 (62±2.3)	1.49±0.6 (76.5±2.2)	0.39±0.16 (85±2.1)	
^{36}Ar+^{148}Sm→ ^{184}Hg	9.8±1.4 (48.9±4.9)	8.3±0.8 (48.9±4.8)	3.2±0.8 (60.7±3.2)	0.98±0.2 (75.2±2.3)		
^{40}Ca+^{144}Nd→ ^{184}Hg	2.7±0.8 (49.9±5.7)	7.1±2.2 (46.1±5.7)	3.6±1.2 (62.5±4.1)	0.5±0.15 (68.8±3.8)		
^{48}Ca+^{142}Nd→ ^{190}Hg				34.4±11.3 (69.4±2.6)	19.2±6.6 (81.2±2.1)	12.2±4.2 (94.1±2)
^{40}Ar+ ^{166}Er →^{206}Rn		1.8±0.38 (46.7±3)	1.4±0.41 (55.6±2.4)	0.3±0.09 (67.4±2)		

Conclusion

Evaporation residue cross sections in the reactions ^{144}Sm(^{40}Ar,*xn*)$^{184-x}$Hg, ^{148}Sm(^{36}Ar,*xn*)$^{184-x}$Hg, ^{144}Nd(^{40}Ca,*xn*)$^{184-x}$Hg, ^{166}Er(^{40}Ar,*xn*)$^{206-x}$Rn, and ^{142}Nd(^{48}Ca, *xn*)$^{190-x}$Hg have been measured at FLNR JINR (Dubna). The improved catcher foil method was applied for the isotope identification.

The results for the reactions ^{144}Sm(^{40}Ar,*xn*)$^{184-x}$Hg,^{144}Nd(^{40}Ca,*xn*)$^{184-x}$Hg, ^{166}Er(^{40}Ar, *xn*)$^{206-x}$Rn, and ^{142}Nd(^{48}Ca,*xn*)$^{190-x}$Hg were obtained for the first time. By comparison of the ^{40}Ar + ^{144}Sm, ^{36}Ar + ^{148}Sm and ^{40}Ca + ^{144}Nd reactions leading to the same compound nucleus, the effect of the Coulomb barrier value on the position of the 2*n* channel maximum cross section was investigated.

Slightly higher values of experimentally determined cross sections in comparison with coupled-channel calculated ones were shown for all reactions leading to mercury isotopes, as opposed to the reaction ^{40}Ar + ^{166}Er leading to ^{206}Rn. The latter could be caused by a rather high values of 1*pxn*-evaporation channel cross sections in this reaction.

The largest Mendeleev Table in Eurasia on the wall of the Archimedes swimming pool was inaugurated in July 2021 to the JINR 65-year anniversary.

Thank you for your attention!

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