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YIELDS OF THE RARE-EARTH NEUTRON-DEFICIENT ISOTOPES IN THE REACTIONS OF Mo ISOTOPES WITH ^{40}Ca IONS

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The results of the joint Russian-Chinese experiment on the measurements of the reaction cross sections of the rare-earth neutron-deficient isotopes production and the study of their decay scheme are presented. The studied nuclides were obtained in the reactions $^{92}\mathrm{Mo} +^{40}$ Ca and $^{97}\mathrm{Mo} +^{40}$ Ca on the 4-meter cyclotron of the Flerov Laboratory of Nuclear Reactions, JINR. The recoil nuclei were stopped in the inert gas and transported by the gas flow to the detectors. The single and coincidence spectra of γ-, x-rays and delayed protons were measured. The enhanced yield of the reactions with the charge particle evaporation was observed.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

Выходы нейтронодефицитных изотопов редкоземельных элементов в реакциях изотопов Mo с ионами ^{40}Ca

И.Адам и др.

Представлены результаты совместного российско-китайского эксперимента по измерению сечений реакций и исследованию свойств нейтронодефицитных изотопов редкоземельных элементов вблизи границы нуклонной стабильности. Изучаемые нуклиды были получены в реакциях $^{92}\mathrm{Mo}+^{40}\mathrm{Ca}$ и $^{97}\mathrm{Mo}+^{40}\mathrm{Ca}$ на четырехметровом циклотроне Лаборатории ядерных реакций ОИЯИ. Выбитые из мишени продукты реакций тормозились в газе и переносились газовым потоком к детекторам радиоактивного излучения. Измерялись спектры γ- и х-лучей, а также запаздывающих протонов и их совпадения. Наблюдался повышенный выход продуктов реакций с испусканием заряженных частиц.

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INTRODUCTION

The heavy ion reactions are the most effective way to produce the nuclei on the boundary of the nucleon stability. These reactions are the important source of the information about the mechanism of the complicated nuclear system interactions, the peculiarities of the high excited nuclei decay and the properties of the obtained nuclides. The fusion reactions with the evaporation of some number of neutrons are used in these investigations. The largest yields of the studied nuclei are obtained, if the target and bombarding ion are the lightest neutron-deficient stable isotopes.

Such kind of the experiments is performed in the Russian-Chinese cooperation. The purpose of this work is the study of the mechanism of the reactions between the complicated nuclei and the properties of the very neutron-deficient nuclides. The objects of the investigations are the reactions between the isotopes ^{92}Mo and ^{97}Mo and ions ^{40}Ca in the energy region 4 - 5 MeV/nucl. The compound nuclei ^{132}Sm and ^{137}Sm are formed with the excitation energy of 70 - 100 MeV. They are neutron-deficient nuclei: ^{132}Sm has 12 neutron less than the lightest stable isotope ^{144}Sm and only 4 neutron more than the last proton stable isotope ^{128}Sm. A lot of neutron-deficient isotopes of the rare-earth element is formed at the decay of these compound nuclei. In the paper, the results of the first stage of this work are presented: the yields and the cross sections of the nuclides formed in the reaction ^{97}Mo + ^{40}Ca. These values allow one to refer about the competition of different reaction channels at the de-excitation of the high excited and very neutron-deficient nuclei. The decay scheme for the most produced in the reaction nuclides are known, therefore the measurements of γ-spectra of these nuclides allow one to determine their yields.

EXPERIMENTAL SET-UP

The experiments were performed on the heavy ion 4-meter isochronous cyclotron of the Flerov Laboratory of Nuclear Reactions, JINR. The experimental method was based on the transportation of the reaction products by the gas flow to the detectors of the radioactive radiation.

The block-scheme of the experimental set-up is shown on Fig.1. The irradiated target was placed inside the chamber. This chamber was isolated from cyclotron vacuum by the Al-window (the thickeness is 20 μm). The used Mo-targets were enriched by the isotopes ^{92}Mo and ^{97}Mo up to 95%. Their thickness was $\sim$ 2 mg/cm^2 and the loss of ^{40}Ca energy was $\sim$ 15 MeV. This energy loss was compared with the width of the excitation function for the production of the studied nuclides.

The intensive beam of ^{40}Ca^{+5} ions was produced in the ECR-ion source, placed outside the cyclotron [1]. The ^{40}Ca ions were accelerated up to the energy of 285 MeV and extracted from the cyclotron using a charge change by the thin C-foil. The energy of the ^{40}Ca ions was measured and controlled during the experiment. The thin scattering Au-foil and Si-detector placed before the target chamber were used for this purpose. The ^{40}Ca energy on the target was $\sim$ 200 MeV, it is the optimum energy for obtaining the studied nuclides. The intensity of ^{40}Ca beam in the target chamber was 10^{12} 1/s and does not change during the experiment.

The inert gas He flowed through the target chamber. The nuclei recoils are stopped in the gas and adsorbed by the aerosols. These aerosols were NaCl microcrystals produced in

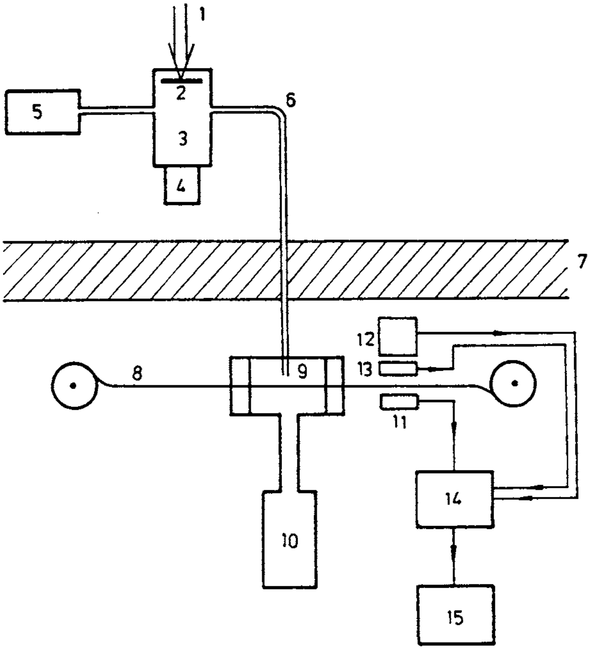

Fig. 1. Block-scheme of the experimental set-up: 1 — ion beam, 2 — target, 3 — gas chamber, 4 — Faraday cup, 5 — aerosol generator, 6 — capillar, 7 — shielding wall, 8 — moving tape, 9 — pumped chamber, 10 — pump, 11 — HpGe-detector for x-rays, 12 — HpGe-detector for γ-rays, 13 — Si-detector for the delayed protons, 14 — electronic blocks, 15 — PC

the special generator [2]. The pressure of He inside the chamber was $\sim$ 1 atm. It was enough to stop the recoils, since their energy was less than 60 MeV and the range in He — less than 10 cm.

The gas flow through the chamber was produced by the pump of the 30 l/s productivity. The aerosols with the adsorbed recoils were drown in the capillar by the flow and carried through the thick wall in the measuring room. The length of the capillar was 3 m, its diameter — 1 mm and time of the recoils transportation — 0.1 s. The nuclei recoils were collected on the moving tape inside the chamber. The pumping of the inert gas was realized through this chamber. The moving of the tape was stepwise with the stopping in front of the detectors. Three detectors were used for measurements of the nuclear radiation spectra: HpGe-detectors (100 cm^3) for γ-radiation, thin HpGe-detector (10 mm) for x-rays and thin Si-detector for the delayed protons. Usually the period of tape stopping near the detectors was 20 s and the single and coincidence spectra as a function of time were measured and accumulated in PC.

EXPERIMENTAL RESULTS

The single x-ray spectrum of the ^{97}Mo + ^{40}Ca reaction products is shown in Fig.2. The energies of the observed lines correspond to K$_\alpha$- and K$_\beta$-lines of the elements in the range $Z = 56 - 60$. It is obvious, that the origin of x-rays is the K-capture of the neutron-deficient

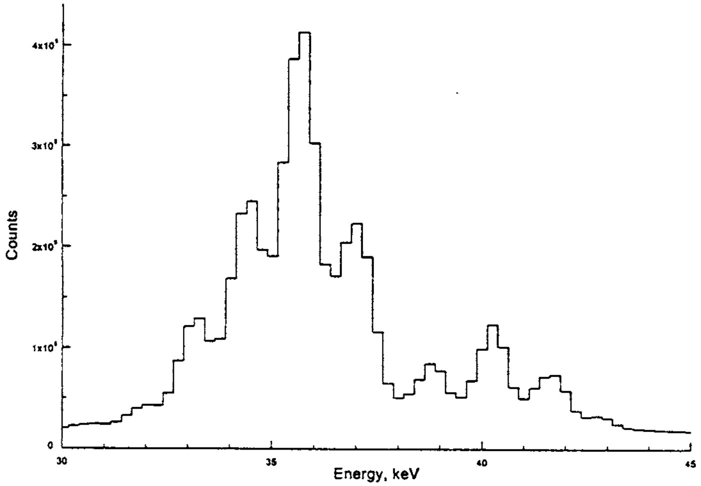

Fig. 2. Spectrum of the x-rays of the ^{97}Mo + ^{40}Ca reaction products

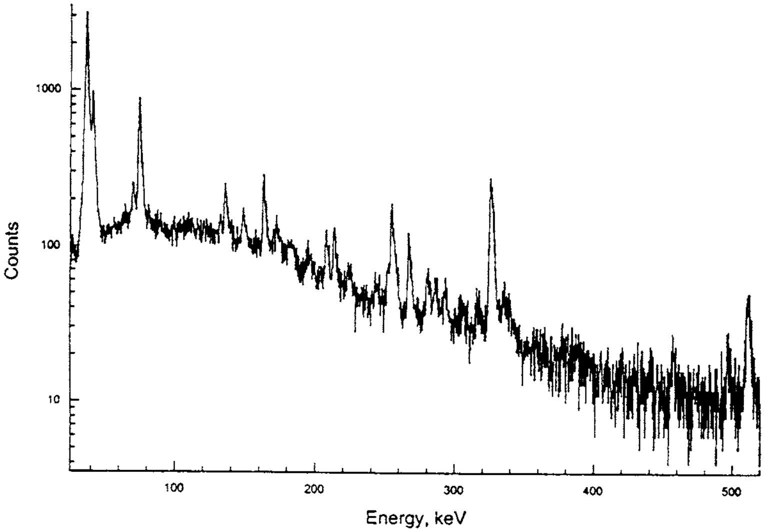

Fig. 3. Spectrum of the γ-radiation of the ^{97}Mo + ^{40}Ca reaction products

nuclides. Therefore the x-ray spectrum allows one to refer to the total element yield of the reaction products. It is seen from Fig.2, that the most intensive lines in the x-ray spectrum are the K_α- and K_β-lines of Ce, Pr, and Nd appearing after K-capture of Pr, Nd, and Pm, respectively. The weak K_α-lines after K-capture of Ce and La are observed also, but the yield of Pm x-ray is masked by the intensive line of Ce. The intensity of the K-capture branch in the decay of the produced nuclides is unknown as a rule. Therefore it is possible to get only some estimates of total yields for different elements produced in the reaction ^{97}Mo + ^{40}Ca. It is seen that the most yields have the isotopes of Pr, Nd, and Pm obtained at the evaporation from the compound nuclei of 1-3 protons of ^{137}Sm and some number of neutrons.

Table 1. The observed γ-lines, their relative intensity and identification

E_γ, keV	I_γ, %	$T_{1/2}$	Nuclide
56.0	8	5.1 m	^{127}La
68.2	11	3.5 m	^{129}Ce
87.1	12	27 s	^{131}Nd
120.0	6	31 s	^{127}Ce
131.0	9	25 m	^{130}Ce
147.8	7	5.1 m	^{128}Ce
230.3	12	5.0 m	^{131}Ce
253.8	100	40 s	^{130}Pr
255.9	21	60 s	^{126}La
266.0	25	5.7 s	^{131}Pr
279.1	11	11.6 m	^{129}La
284.0	66	4.9 m	^{128}La
325.3	57	1.6 m	^{132}Pr
357.4	5	8.7 m	^{130}La
399.5	20	3.1 s	^{128}Pr
567.0	4	88 s	^{132}Nd

Table 2. Relative yields and cross sections of the products of the reaction ^{97}Mo + ^{40}Ca

Nuclei	Evaporated particles	Y_{rel}, %	σ,mb
^{132}Sm	5n	<2.5	<0.2
^{133}Sm	4n	<2.5	<0.2
^{132}Pm	p4n	<1.2	<0.1
^{133}Pm	p3n	<1.2	<0.1
^{132}Nd	2p3n(αn)	28	2.2
^{131}Nd	2p4n(α2n)	35	2.8
^{132}Pr	3p2n(αp)	39	3.1
^{131}Pr	3p3n(αpn)	45	3.5
^{130}Pr	3p4n(αp2n)	100	8.0
^{131}Ce	4p2n(α2p)	22	1.8
^{130}Ce	4p3n(α2pn)	13	1.1
^{129}Ce	4p4n(2α)	7.5	0.6
^{130}La	5p2n(α3p)	20	1.6
^{129}La	5p3n(α3pn)	47	3.7
^{128}La	5p4n(2αp)	17	1.4
^{127}La	5p5n(2αpn)	10	0.8
^{126}La	5p6n(2αp2n)	6.2	0.5

The single γ-ray spectra are very complicated, but the spectra of γ-x–coincidence are more simple (one example of these spectra is shower in Fig.3). The analysis of these spectra allows one to identify a lot of γ-lines and attribute them to the definite nuclides. The recent table of isotopes [3] was used for this identification. The identified γ-lines, their intensities (relative to the most intensive line 253.8 keV of ^{130}Pr), the obtained nuclides and their half-lives are presented in Table 1.

For the majority of the identified nuclides, the decay scheme and the absolute intensity of the observed γ-lines are known. It is possible in these cases to determine the yields and the cross sections of the nuclei obtained in the studied reaction ^{97}Mo + ^{40}Ca. Some nuclides are formed not only at the proton and neutron evaporation from the compound nuclei, but after β^+-decay of the nuclei with the same mass number. In these cases the corrections on the population of these nuclei in the β^+-chains are induced. The identified nuclides, the evaporated in the reactions particles, the yields and the cross sections are presented in Table 2. The sum of these cross sections coincides with the total cross section calculated using ALICE code [4] for the fusion reaction ^{97}Mo + ^{40}Ca.

DISCUSSION OF RESULTS

In Fig.4 is presented the chapter of isotopes with the obtained nuclides. It is seen that the obtained nuclides are situated in the range Z = 57 - 60 (La - Nd) and A = 126 - 132. There were not observed the reaction products after the evaporation of only neutron (Sm isotopes) and only protons (^{132}La, ^{133}Ce). The largest yields have the nuclei formed at the evaporation near the same number of protons and neutrons. The lightest nuclides (isotopes Ce and La) could be formed only at the emission of the α-particles instead of the single neutrons and protons.

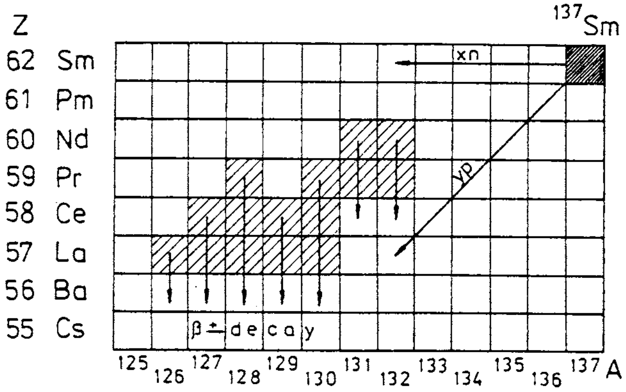

Fig. 4. Part of nuclide chapter in the region of the produced nuclei

According to the statistical model [5,6] the probability of the evaporation of any particle from the compound nuclei is expressed by the relation:

$$\Gamma_i = \hbar \int_0^{E-B_i} W_i(\varepsilon) d\varepsilon, \tag{1}$$

where E is the excitation energy of the compound nuclei; B_i and ε_i, the binding and kinetic energies of the evaporated particle

$$W_i(\varepsilon) \sim \sigma(E,\varepsilon)\varepsilon\rho(E - B_i - \varepsilon), \tag{2}$$

where $\sigma(E,\varepsilon)$ is the cross section of the back reaction; $\rho(E-B_i-\varepsilon)$, the level density of the nucleus after the evaporation of the particle (proton or neutron). In the relation (2) the most important is the value $\rho(E-B_i-\varepsilon)$, since its energy dependence is exponential. Therefore the competition between proton and neutron evaporation depends mostly on the value of residual nucleus level density $\rho(E - B_i - \varepsilon)$. This value is determined by the excitation energy of the residual nucleus and, consequently, the energy, removed by the evaporated particle $\varepsilon + B_i$. In the case of the neutrons $\varepsilon \sim$ 2T (T is the temperature of the compound nuclei), but in the case of protons $\varepsilon \sim$ 2T + B_c (B_c — coulomb barrier for the protons). Therefore the evaporation of the neutron from the compound nucleus is more probable for the nuclei with nearly the same values of proton and neutron binding energy (they are the nuclei close to the β-stability valley). But in neutron-deficient nuclei $B_p < B_n$ and evaporation protons and neutrons lead to nearly the same excitation energy of the residual nucleus. In this case the probability of the proton and neutron evaporation became near equal.

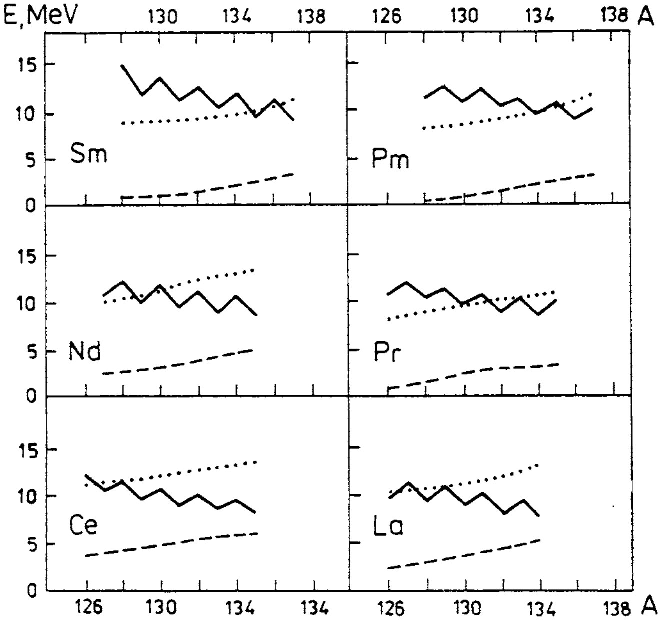

Fig. 5. Binding energies of neutrons (-) and protons (- -) including their coulomb barrier (...)

In Fig.5 are shown the binding energies of the proton and neutron in the observed isotope (La–Sm), including the coulomb barrier for the protons. The experimental values of the coulomb barrier were used [7]. It is seen that in the most Sm and Pm isotopes the removed energy is more for the neutrons. In Ce and La isotopes the opposite picture is observed. Therefore in Sm and Pm isotopes the proton evaporation is preferable, and it explains their very low yields in the reaction ^{97}Mo + ^{40}Ca $\rightarrow$ ^{137}Sm. The obtained in the reaction nuclei are well deformed. There is the indication on the lowering of the coulomb barrier for such nuclei [8]. This phenomenon increases the probability of proton emission.

The comparision of the experimental and calculated cross sections or yield ratios of the isotopes with the same mass number A allows one to obtain the new information about the level density of the very neutron-deficient nuclei close to proton drip line. This information will help to choose the optimal conditions for the production of new isotopes in this region of Z and A. It is expected that the fusion reactions ^{92}Mo + ^{40}Ca and ^{96}Ru + ^{32}S are the most perspective for this purpose.

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