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Study of the ^{242}Pu + ^{48}Ca Reaction at Super Heavy Element Factory

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Abstract—Experiments on the synthesis of isotopes of element 114 in the ^{242}Pu + ^{48}Ca reaction were carried out at a new gas-filled separator DGFRS-2 online to the DC-280 cyclotron of the Superheavy Element Factory at the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research. The decay properties of ^{286}Fl and ^{287}Fl, as well as their α-decay products, were refined. The possibility of the existence of isomeric states in successive α-decays of ^{287}Fl is discussed. The maximum cross section of $10.4^{+3.5}_{-2.1}$ pb was measured for the ^{242}Pu(^{48}Ca, $3n$)^{287}Fl reaction.

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INTRODUCTION

In this article we will discuss the results of experiments with a target made of ^{242}Pu [1], conducted at the Superheavy Element Factory (SHE Factory) [2] at the Joint Institute for Nuclear Research in Dubna. A beam of ^{48}Ca ions accelerated by the new DC-280 cyclotron, collides with the target made of enriched ^{242}Pu deposited on a titanium substrate. The reaction products ejected from the target are guided into the gas-filled separator DGFRS-2 [3], which separates them from the ^{48}Ca ion beam and background particles. These and previous experiments with ^{243}Am + ^{48}Ca [4] were conducted to test the capabilities of the SHE Factory for the production and study of new isotopes of known superheavy elements up to Og ($Z = 118$), as well as for the synthesis of new elements with $Z > 118$.

The reaction ^{242}Pu + ^{48}Ca is planned to be used for further study of the chemical properties of the element Fl ($Z = 114$). In order to prepare and conduct such experiments, it is necessary to more accurately measure the cross-section at the maximum of the excitation function of the reaction ^{242}Pu(^{48}Ca, $3n$), as well as the decay properties of ^{287}Fl ($T_{1/2} \approx 0.5$ s) and its daughter nuclei.

The reaction cross-section and nuclear properties in the decay chain of ^{287}Fl were first measured at the DGFRS in 2003 [5–8]. A total of 19 decay chains of ^{287}Fl were registered in reactions with $^{242, 244}$Pu and ^{245}Cm. The same isotopes were observed in experiments on the study of the chemical properties of the elements Cn [9] and Fl [10] (6 chains), as well as on separators SHIP (1 chain of ^{291}Lv and 4 chains of ^{283}Cn [11–13]), BGS (1 chain of ^{287}Fl [14]) and GARIS-II (2 chains of ^{283}Cn [15]).

In the reactions of ^{242}Pu, ^{245}Cm + ^{48}Ca on DGFRS, a lighter isotope ^{286}Fl was also synthesized and observed as a daughter product [6–8]. Two decay chains of ^{286}Fl were obtained on the BGS separator in the reaction of ^{242}Pu + ^{48}Ca [14, 16].

EXPERIMENTAL

The experiment on the synthesis of flerovium isotopes was conducted from March to June 2021. The main parameters of the experiment are given in Table 1.

The target consisted of enriched ^{242}Pu isotope (95.5%) and was fabricated by electrodeposition on a Ti substrate with a thickness of 0.62 mg/cm^2. The target consisted of 12 sectors, which were installed around the perimeter of a 24 cm diameter disk and rotated at a speed of 980 rpm.

Table 1. Experimental parameters for ^{242}Pu + ^{48}Ca: The thicknesses of the ^{242}Pu target, laboratory energies of ^{48}Ca at the center of the target corresponding to the excitation energies of the compound nucleus ^{290}Fl, beam doses, the number of registered decay chains of Fl isotopes, and their production cross sections are provided

Target thickness (mg/cm^2)	E_{lab}, MeV	E^*, MeV	Deam doses ($\times 10^{18}$)	Number of chains $3n/4n$	σ_{3n}, pb	σ_{4n}, pb
^{242}Pu 10×0.76, 0.56, 0.35	242.5	37.1–40.7	11.2	65/11	$10.4^{+3.5}_{-2.1}$	$1.8^{+1.0}_{-0.6}$
	247.5	41.3–44.8	5.0	4/14	$1.2^{+1.2}_{-0.7}$	$4.8^{+2.1}_{-2.1}$

The volume of the DGFRS-2 separator [3] from the differential pumping system to the detector chamber was filled with hydrogen at a pressure of 0.9 mbar. The detector chamber was separated from the DGFRS-2 volume by a 0.7 μm Mylar foil and filled with pentane at a pressure of 1.6 mbar.

The focal detector measuring 48 mm vertically and 220 mm horizontally consisted of two double-sided silicon strip detectors measuring 48 × 128 mm^2 (Micron Semiconductor, United States). They were installed one behind the other, so that the front detector covered part of the back detector. These detectors were surrounded by eight single-sided side detectors measuring 60 × 120 mm^2, each with 8 strips forming a box with a depth of 120 mm. All signals in the detectors with amplitudes above the threshold (E_{thr}) of 0.55–0.6 MeV were registered independently by digital and analog data acquisition systems, similar to those used in the DGFRS [17].

Two multi-wire proportional chambers were installed in front of the detectors for registering nuclei passing through the separator [3]. Analog electronics were designed to register in real-time the spatial, energetic, and time correlations between the signals from the implanted nuclei (ER) in the detectors and their alpha decays, which were detected with full energy and parameters expected for Fl isotopes or their daughter nuclei (namely, event energies and ER-alpha time intervals). This pair of correlated events resulted in the beam being turned off 0.1 ms after the registration of the first α particle to observe the decays of daughter nuclei under low-background conditions [18–20].

RESULTS AND DISCUSSION

The energies of alpha particles or fission fragments and the decay times of nuclei in the chains related to ^{287}Fl and ^{286}Fl are given in [1]. The energy spectra and temporal distributions of alpha particles from ^{287}Fl, ^{283}Cn, ^{279}Ds, ^{275}Hs, ^{271}Sg, and ^{267}Rf (only temporal distribution) detected in [5–15] and in this work are shown in Fig. 1. Events with an energy resolution better than 40 keV were selected for the alpha particle spectra. Only decays after the registered nearest precursor were selected for the decay time distribution.

The number of newly registered decay chains of ^{287}Fl is approximately three times higher than the number of nuclei synthesized in all previous experiments, which allows for more accurate determination of their decay properties. The half-lives measured in this work are 0.33 ± 0.04, $3.7^{+0.5}_{-0.4}$, 0.18 ± 0.02, $0.78^{+0.38}_{-0.19}$, 28^{+14}_{-7} s, and 40^{+23}_{-11} min for isotopes ^{287}Fl, ^{283}Cn, ^{279}Ds, ^{275}Hs, ^{271}Sg, and ^{267}Rf, respectively. It should be noted that only four ^{287}Fl decay chains in which ^{279}Ds undergoes α-decay were detected in previous experiments. The energy spectra measured in this experiment are in good agreement with the results of previous experiments. However, the half-life of ^{287}Fl was found to be lower than the previously measured value (0.36 ± 0.04 s instead of $0.48^{+0.14}_{-0.09}$ s), which may reduce the sensitivity of the experiment to study the chemical properties of Fl.

If we select only those α-particles from ^{287}Fl and ^{283}Cn that are accompanied by the α-decay of ^{279}Ds, a small difference can be noticed in their energy spectra compared to the total α-spectra of these isotopes. The distributions of α-particle energies and nuclear decay times in such cases are shown by the black histograms in Fig. 1. It appears that a relatively large fraction of the energies of such particles fall into the lower energy region of the spectrum. For example, 11 out of 66 events (17%) of the total ^{287}Fl spectrum were recorded with $E_\alpha < 9.94$ MeV, but a large fraction, 2 out of 8 events (25%), leading to the α-decay of ^{279}Ds, were observed in this low-energy region. For α-particles of ^{283}Cn with $E_\alpha < 9.44$ MeV, these ratios are 9/82 (11%) and 3/9 (33%), respectively. In addition, the half-lives of ^{287}Fl and ^{283}Cn in such chains are slightly smaller than those determined by summing up all events, $T_{1/2} = 0.21^{+0.10}_{-0.05}$ and $2.8^{+1.1}_{-0.6}$ s respectively (compare with the data in Fig. 1). The half-life of ^{279}Ds, determined from its α-decay, is $0.16^{+0.06}_{-0.04}$ s, which is similar to the value calculated from all events. Obviously, these observations are based on a small number of events, and further research is needed to confirm or refute them. If this is indeed the case, it may mean that the level structure of nuclei involved in alpha decay affects the probability of fission. A similar feature is observed in ^{261}Rf, which has two states with $T_{1/2} = 68$ s, $E_\alpha = 8.28$ MeV, spontaneous fission (SF) branch $b_{SF} < 0.11$, and $T_{1/2} = 3$ s, $E_\alpha = 8.51$ MeV, $b_{SF} = 0.91$ (see, for example, [21]).

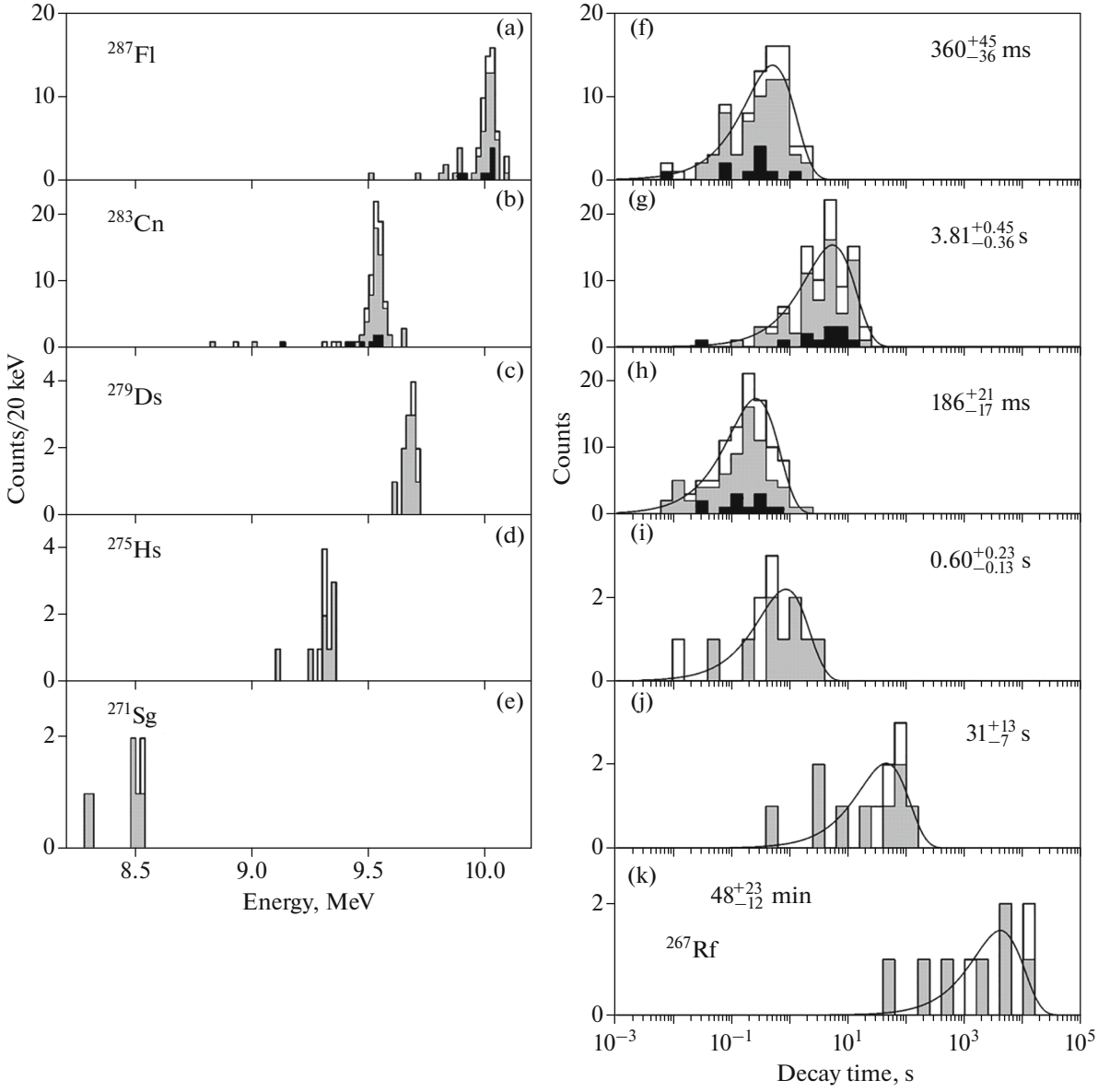

Fig. 1. Energy spectra of alpha particles (left) and decay time distributions in logarithmic scale (right) for ^{287}Fl (a, f) and its daughter nuclei ^{283}Cn (b, g), ^{279}Ds (c, h), ^{275}Hs (d, i), ^{271}Sg (e, j), and ^{287}Rf (k). The data from this work and their combination with known results are shown as gray and open histograms, respectively. The energies of alpha particles and decay times for ^{287}Fl and ^{283}Cn, followed by alpha decay of ^{279}Ds, as well as alpha decay times for ^{279}Ds, are shown in black.

In the reaction ^{242}Pu + ^{48}Ca, 25 decays of the neighboring isotope ^{286}Fl were also registered [1]. Spontaneous fission of ^{286}Fl was observed in 11 of the 25 decay chains. This number of α-decays and SF events is in good agreement with the known branching ratio for the α-decay of this isotope, $b_\alpha = 60^{+10}_{-11}\%$ [5]. The energy spectrum of ^{286}Fl and the distributions of decay times of ^{286}Fl observed in [6–8, 14, 16, 17, 22] and in this work are shown in Fig. 2. The new data are in good agreement with previously known results. The measured half-life in this work is 91^{+22}_{-15} ms for ^{286}Fl. The energy spectrum of the newly measured α-particles also agrees with the spectrum presented in [5] for ^{286}Fl.

Three alpha particles with energies of 10.003 ± 0.036, 10.050 ± 0.027, and 10.109 ± 0.016 MeV were detected for the even–even nucleus ^{286}Fl for the first time, which differ, taking into account energy uncertainties, from the energy of the main line at 10.19 MeV. Their decay times are highlighted in black in Fig. 2. The energy of the second peak, E_α = 10.054 ±

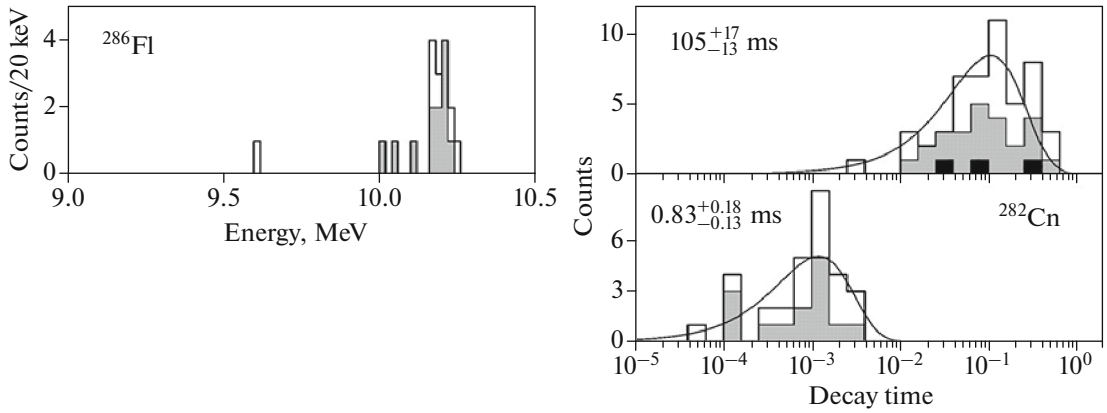

Fig. 2. The same as in Fig. 1, but for ^{286}Fl. Decay times of ^{286}Fl with low-energy α-particles are shown in black.

0.053 MeV, is lower than the energy of the main line by approximately 100–200 keV.

A possible cause of such α-transitions is the decay to the first 2^+ rotational state of ^{282}Cn. The branching ratio for α-decay to the ground state (0^+) and to the 2^+ rotational state is estimated as 67 and 33%, respectively, according to [23]. The experimental values are about 82 and 18%. The observed difference between the calculated and measured values of the decay branching ratio may be related to two factors: insufficient statistics of decays to the excited state and/or an overestimated value of the β_2 deformation used in the calculations.

Another explanation is based on predicted isomeric states. A two-quasiparticle level scheme for ^{286}Fl and its daughter nucleus ^{282}Cn was proposed in [24]. According to calculations, the energy of 10.05 MeV could be due to populating the 5^+ two-quasiparticle isomeric state in ^{286}Fl in the direct reaction ^{242}Pu + ^{48}Ca, followed by decay to the same 5^+ state in ^{282}Cn. There is good agreement between experimental and theoretical results.

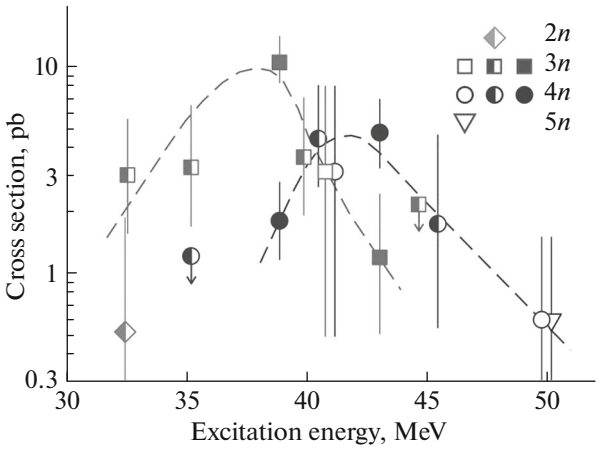

Fig. 3. Cross sections for the reaction ^{242}Pu + ^{48}Ca with the emission of 2 to 5 neutrons. The data shown with open, half-closed, and closed symbols are taken from [6, 11, 15, 16] and this work, respectively.

In the experiment with ^{242}Pu, ^{48}Ca energies were chosen close to the expected maxima of the 3*n*- and 4*n*-channels cross sections. For the 4*n*-channel, the measured cross sections do not contradict the previously known values [6, 16] (see Fig. 3). The maximum cross section of the 3*n*-channel exceeds the value measured in [6] by about three times. Such differences may be due to the small number of nuclei registered in previous experiments. In addition, the increased cross section value can be explained by the fact that the energy of ^{48}Ca in the current experiments was closer to the maximum excitation function than in [6]. The setting of the DGFRS magnetic elements, which determines its transmission, as well as the accuracy of the target thickness and beam dose estimates, also affected the calculated cross section value. A transmission of 50% was used to calculate reaction cross sections with a target thickness of 0.76 mg/cm^2 [25, 26].

CONCLUSIONS

The reaction of ^{242}Pu + ^{48}Ca was studied at two beam energies using the new separator DGFRS-2. The decay properties of ^{286}Fl and ^{287}Fl, as well as their daughter nuclei, were refined thanks to 25 and 69 new decay chains, respectively.

The maximum cross-section of the 3*n* channel leading to ^{287}Fl was found to be approximately three times larger than measured in previous experiments.

Two different alpha decays to the ground and excited states in the decay chains of ^{287}Fl, leading to alpha decay of ^{279}Ds in one case and its spontaneous fission in the other, may follow from several different alpha-particle energies and half-lives of ^{287}Fl and ^{283}Cn.

For even–even ^{286}Fl, a new alpha line was observed for the first time with an energy 100–200 keV below the main peak. The possible origin of this line is discussed, namely the population of the 2^+ rotational level in ^{282}Cn or a transition connecting isomeric states in ^{286}Fl and ^{282}Cn.

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CONFLICT OF INTEREST

The authors of this wwork declare that they have no conflicts of interest.

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