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Letter

Second experiment at VASSILISSA separator on the synthesis of the element 112

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Abstract. The upgraded separator VASSILISSA was used to confirm results of previous experiments on the synthesis of the heavy isotopes of the element 112 obtained in complete-fusion reactions of ^{48}Ca and ^{238}U. An additional reason was the non-observation of any events in the same reaction studied with the BGS separator at Berkeley. Limits of $280 \leq A \leq 286$ for the atomic mass number of the observed spontaneously fissioning isotope were measured. The obtained results on the decay mode, half-life and production cross-section are in agreement with those obtained in our first experiment.

PACS. 23.60.+e α decay – 25.70.-z Low and intermediate energy heavy-ion reactions – 25.85.Ca Spontaneous fission – 27.90.+b $A \geq 220$

1 Introduction

The synthesis of the neutron-rich isotopes of the element 112 was the aim of an investigation in 1998 employing a high-intensity ^{48}Ca beam and a ^{238}U target [1]. The experiments were performed at the electrostatic separator VASSILISSA [2]. A spontaneously fissioning (SF) isotope was measured, which was tentatively assigned to the isotope ^{283}112. The measured half-life of 3 min was relatively long and the production cross-section of 5 pb relatively high. These properties make the isotope especially attractive for further investigation of atomic properties of superheavy elements and, in particular, for the study of chemical peculiarities of the element $Z = 112$. However, the unambiguous identification of SF nuclei is a difficult problem. A possible solution could be the improvement of recoil separators into the direction of higher mass resolution.

For this purpose the separator VASSILISSA was equipped with a new dipole magnet of higher bending power and thus higher mass resolution. With the improved set-up our first experiment was repeated in order to confirm the previous results and to verify the assignment by additional mass measurement. Another reason for the repetition of our experiment was a negative result reported from a study of the same reaction at the Berkeley Gas-filled Separator (BGS) [3].

2 Experimental details

In order to obtain a reasonable mass resolution, the separator VASSILISSA was upgraded by replacing the 8° bending magnet behind the separator with a mass analyzer, based on a 37° dipole magnet. For the registration of heavy ERs in the focal plane of the new 37° dipole magnet, a new system consisting of two (start and stop) time-of-flight detectors and a 32-strip detector assembly, $60 \times 120\,\mathrm{mm}^2$ in size, surrounded by backward detectors, was developed [4]. The focal-plane assembly consists of two wafers, forming a 32-strip detector. Each strip in the focal-plane assembly is $3.525 \times 58\,\mathrm{mm}^2$ in size (a distance of 0.1 mm between the strips) and is position sensitive in the longitudinal direction. Six wafers are mounted in the backward hemisphere facing the stop detector. They measure escaping α's or fission fragments, and the total geometrical efficiency of the detector array is about 70% of 4π.

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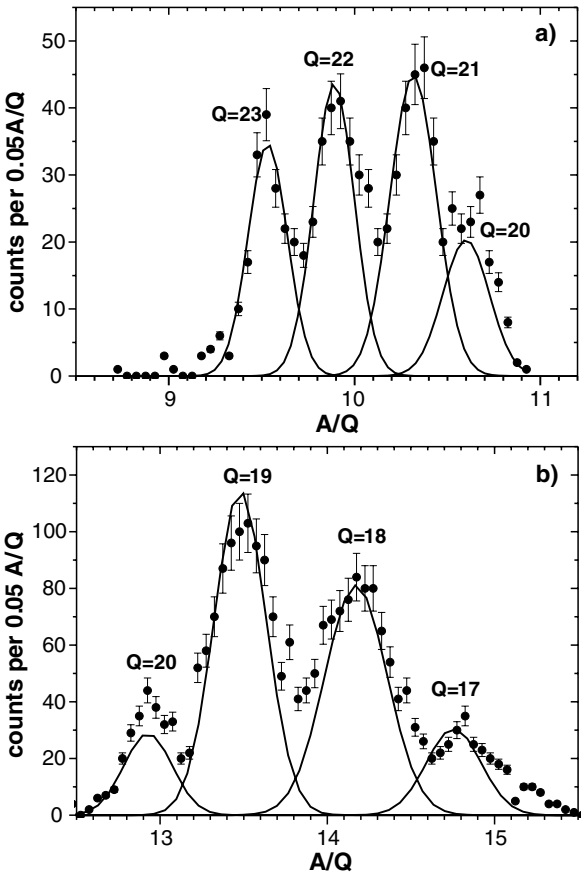

Fig. 1. A/Q distributions of ^{217}Th (a) and of ^{254}No (b) ERs produced in reactions with ^{48}Ca and ^{174}Yb and ^{208}Pb, respectively. Derived charge states are indicated. The mean charge state of the ^{217}Th ions is higher than that of ^{254}No due to the higher velocity of the ERs in the former case.

Ion optical calculations and the procedure for the mass evaluation are described in [5]. To determine the ratio of the mass number and ionic-charge state (A/Q) of ions having passed through the separator, we measure the velocity of the ions using time-of-flight (TOF) detectors and their magnetic rigidity from the position on the focal plane. In these coordinates different charge states of recoils are resolved and the mass of a single nucleus can be extracted with an accuracy of $\sigma \approx 2\%$.

The new mass analyzer was tested with various heavy-ion fusion reactions. Evaporation residues (ERs) produced in reactions between ^{40}Ar and ^{44,48}Ca beams and ^{164}Dy, ^{174}Yb, ^{198}Pt and ^{204,206,208}Pb targets were used. The produced nuclei were identified according to known decay properties using ER-α or ER-SF correlation analysis. Ratios A/Q were derived for each detected event. Knowing the masses of these nuclei, the ionic-charge distributions were determined from the ratios A/Q [6,4]. The results obtained for ^{217}Th and ^{254}No are shown in fig. 1. At the relatively high number of events collected in our test reactions, the masses of known isotopes were reproduced with an accuracy of $\sigma \approx 1\%$.

The upgraded separator is more sensitive (in comparison with the old variant of the separator) to deviations of the true mean charge state $\langle Q \rangle$ of the ERs from the predicted value. Previously, with the 8° magnet, VASSILISSA accepted 5–6 neighboring charge states [2]. With the new 37° magnet the acceptance decreased to 3–4 charge states (see fig. 1). The transmission of the separator was determined experimentally using the ^{48}Ca + ^{208}Pb $\rightarrow$ ^{254}No + 2n reaction. The yield of the 36 h half-life granddaughter isotope ^{246}Cf was obtained from periodic irradiations of the detector in the focal plane and of catcher foils moved into the beam at a distance of 0.5 cm behind the target. A transmission of 20% was measured.

Targets of U_3O_8 with an average uranium thicknesses of 350 μg/cm^2 were fabricated by electroplating the material onto 0.74 mg/cm^2 Ti backing foils. Depleted ^{238}U was used. The target design is described in detail in [6].

The ^{48}Ca beam was produced from enriched material at the ECR ion source of the U400 Cyclotron of the Flerov Laboratory of Nuclear Reactions in Dubna. The absolute beam energy was measured with an accuracy of 0.5% using the magnetic spectrometer MSP144 [7]. The projectile energy was changed by extracting the beam from appropriate radii of the cyclotron. During the experiments the beam energy was continuously controlled by detecting the time of flight of the beam particles using the signals induced by the beam bunches in pick-up coils and by measuring the energy of ions scattered in a thin Au foil using Si detectors.

The upgraded VASSILISSA provided an additional suppression of unwanted reaction products by a factor of about 100. At a beam intensity of $\sim 0.7\,\mathrm{p}\mu\mathrm{A}$, the total counting rate of all events at the focal-plane detectors was 5–10 Hz. The counting rate at a single strip in a position interval of 1.0 mm amounted to the following values: for α-decay–like events ($E > 5.5$ MeV, no signals from the TOF detectors) $< 0.075\,\mathrm{h}^{-1}$; for recoil-like events ($E > 5$ MeV, TOF signal in the time window expected for heavy ERs) $< 0.1\,\mathrm{h}^{-1}$.

3 Results

The main experiment was performed at the end of 2002 and beginning of 2003. We started the irradiations at a ^{48}Ca beam energy $E_{1/2} = (231 \pm 1.0)$ MeV ($E_{1/2}$ is the energy at half-thickness of the target). The corresponding energy from the cyclotron was 242 MeV and the excitation energy of the compound nucleus ^{286}112 at half-thickness of the target was $E^* = 33$ MeV. This value was calculated using the binding energy of the compound nucleus of ref. [8]. During a period of 29 days of pure-irradiation time a beam dose of 5.9×10^{18} projectiles was collected. No SF events were detected during this irradiation. Possible decay chains of the type $\mathrm{ER} \overset{E_{\mathrm{ER}},\mathrm{TOF}}{\longrightarrow} \alpha_1 \overset{E_{\alpha_1},t_1}{\longrightarrow} \alpha_2 \overset{E_{\alpha_2},t_2}{\longrightarrow} \cdots$ were searched for (t_i are absolute time stamps of the measured signals). In the analysis we scanned lifetimes in the interval 5 μs $\leq \tau \leq$ 1000 s and energies in the interval 8 MeV $\leq E_\alpha \leq$ 13 MeV. No such decay chains

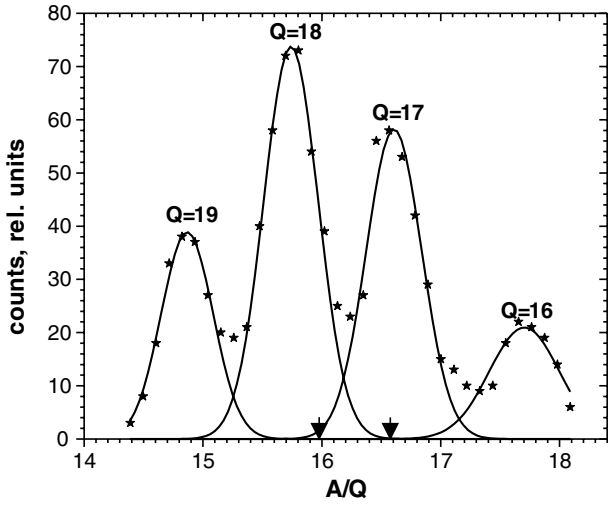

Fig. 2. Computer-simulated distribution of A/Q values of ^{283}112 ERs produced in the reaction ^{48}Ca + ^{238}U. The arrows mark the derived values of the two implanted nuclei which were correlated to subsequent SF.

were detected, from which an upper cross-section limit of 2.2 pb follows.

In the second part of the irradiation the beam energy was increased to $E_{1/2} = 234$ MeV ($E_{\rm cyclotron} = 245$ MeV, $E^* = 35.5$ MeV). During a period of 15 days a beam dose of 4.7×10^{18} projectiles was collected. Two SF events (SF1, SF2) were detected. Both events were characterized by signals of higher energies, 52 and 130 MeV, in the stop detector and coincident signals of lower energies, 13 and 40 MeV, respectively, in the backward detectors. The shared energy originates from the implantation of an ER close to the surface of the stop detector, in which one fission fragment is stopped, and from the stopping of the escaping fragment in the backward detector after some energy loss in the inactive surface layers. One of the explanations of the relatively low-energy deposition in the focal-plane detector of the first event could be that the decay took place close to the inter-strip surface and the amplitude of the signal was divided between two strips. The absence of signals from the TOF detectors identifies the coinciding signals as radioactive decays and the high-energy deposition as fission of the implanted nucleus. The first event was measured in strip number 12 and the second in strip number 32. The higher strip numbers correspond to higher magnetic rigidity of the separated ions.

The first signals preceding the two fission events originated from implanted nuclei at time differences $\tau_{\rm ER\text{-}SF1} = 180.5$ s and $\tau_{\rm ER\text{-}SF2} = 1459.5$ s. No other recoil-like or α-like signals were registered within a time interval up to 10^4 s. The position differences in vertical direction between the implanted ERs and the SF events were $\Delta y_1 = 0.6$ mm and $\Delta y_2 = 0.8$ mm and the time-of-flight values were $\mathrm{TOF}_1 = 85.1$ ns and $\mathrm{TOF}_2 = 81.0$ ns, both in the window expected for implanted ERs. The probability that the two correlations happened accidentally is 0.005 and 0.038, respectively.

As a result of the analysis described in [5], we derived from the measured values of the strip number and TOF for the first event the ratio $A_1/Q_1 = 16.0$ and for the second $A_2/Q_2 = 16.6$. These two values are marked by arrows in fig. 2, which shows the distribution of A/Q ratios expected for ^{283}112. As most probable values for the charge states we derive from fig. 2 $Q_1 = 18$ and $Q_2 = 17$. Using these numbers, we calculate from the A/Q ratios the mass numbers $A_1 = 288.0 \pm 5.8$ and $A_2 = 282.2 \pm 5.8$, from which a mean value for the mass number of 285.1 ± 4.1 follows.

4 Discussion

In our second experiment at VASSILISSA on the synthesis of the element 112 we observed two SF nuclei subsequent to implanted ERs. A direct mass analysis of these nuclei results in a mass number $A = 285.1 \pm 4.1$ which is in agreement with evaporation residues produced in the reaction ^{48}Ca + ^{238}U $\rightarrow$ ^{286}112*. The high mass number excludes fission isomers as origin of the correlated events, which are located at mass numbers of about 240 and are produced in transfer reactions. They could reach the detector system as background events.

The lifetime of the two measured SF nuclei is 3.0 and 24.3 min, respectively. The lifetimes measured in our first experiment were 3.0 and 0.9 min [1]. The nuclei were tentatively assigned to the new isotope ^{283}112. Spontaneous fission of the same isotope was measured twice after the α-decay of ^{287}114 and lifetimes of 3.8 and 9.3 min were determined [9]. The mean value from all six decays is $7.4^{+5.1}_{-2.1}$ min or $T_{1/2} = 5.1^{+3.5}_{-1.5}$ min. An α-decay branch was not measured.

The compound nuclei from the reaction ^{48}Ca + ^{238}U $\rightarrow$ ^{286}112* are produced at the Coulomb barrier with an excitation energy of ≈ 35 MeV. At this energy we expect the evaporation of 2 to 4 neutrons. It is planned to continue experiments aimed at the study of the complete-fusion reaction ^{48}Ca + ^{242}Pu at the compound-nucleus excitation energies corresponding to the evaporation of 3 and 4 neutrons, as well as the study of ^{48}Ca + ^{244}Pu at the excitation energies corresponding to the evaporation of 4 and 5 neutrons. More accurate assignment of the 5 min SF activity can be made after collecting additional experimental data.

The cross-section for the synthesis of the two events measured in our second experiment is $3.0^{+4.0}_{-2.0}$ pb. This value is in agreement with our first result ($5.0^{+6.3}_{-3.2}$ pb [1]), and a mean value of $4.0^{+3.2}_{-1.9}$ pb follows. The error bars represent only the statistical uncertainties, the absolute values have an uncertainty of a factor of 2.

In recent experiments at FLNR Dubna the reaction ^{48}Ca + ^{238}U was used to study the chemical properties of the element 112 [10]. Also in that experiment a SF activity was measured, which was detected in a highly volatile component of the chemical separation procedure in agreement with the predicted mercury-like properties of the element 112. The measured cross-section for the

activity was $2.0^{+0.9}_{-0.7}$ pb in agreement with our result for the synthesis of ^{283}112.

The chemical properties of the element 112 synthesized in the ^{48}Ca + ^{238}U reaction were also investigated at GSI Darmstadt using a cryogenic detector [11]. Condensation of a SF activity attributed to the element 112 was observed at low temperature. The reported production cross-section of about 3 pb is in agreement with the results obtained at VASSILISSA and in the chemistry experiment at Dubna.

The non-observation of any events in the reaction $^{48}\mathrm{Ca} + {}^{238}\mathrm{U} \rightarrow {}^{283}112^{*}$ at the beam energy $E_{1/2} = 231$ MeV [3] can be probably explained by the improper absolute beam energy value or/and by the choice of the separator BGS field settings according to the calculated mean charge of ERs in helium, which has an unexplainable deviation from the known systematics.

Presently a new on-line mass analyzer (MASHA) of the ISOL type is under construction at FLNR Dubna [12]. The expected accuracy of mass determination is 10^{-3} or 0.3 amu for nuclei in the region of superheavy elements. Taking into account the relatively long lifetimes of the produced nuclei and the expected high volatility of superheavy elements, we anticipate a high yield and thus accurate mass determination even at extremely low cross-sections.

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