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In-beam separation and mass determination of superheavy nuclei. Part II ☆

O.N. Malyshev[a], A.V. Yeremin[a,*], A.G. Popeko[a], A.V. Belozerov[a], M.L. Chelnokov[a], V.I. Chepigin[a], V.A. Gorshkov[a], S. Hofmann[b], M.G. Itkis[a], A.P. Kabachenko[a], Yu.Ts. Oganessian[a], R.N. Sagaidak[a], Š. Šáro[c], A.V. Shutov[a], A.I. Svirikhin[a]

[a] *Flerov Laboratory of Nuclear Reactions, JINR, Dubna 141 980, Russia*
[b] *Gesellschaft für Schwerionenforschung, Darmstadt D-64220, Germany*
[c] *Department of Physics, Comenius University, Bratislava SK–84215, Slovakia*

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Abstract

Within the past 15 years, the recoil separator VASSILISSA has been used for the investigations of evaporation residues produced in complete fusion reactions induced by heavy ions. The study of decay properties and formation of cross-sections of the isotopes of elements 110, 112 and 114 was performed using high-intensity ^{48}Ca beams and ^{232}Th, ^{238}U, ^{242}Pu targets. For further experiments aimed at the synthesis of the superheavy element isotopes ($Z \geqslant 110$) with the use of intense ^{48}Ca extracted beams, improvements in the ion optical system of the separator and the focal plane detector system have been made. The results from the test reactions and new results for the isotope ^{283}112 are presented.

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1. Introduction

Recoil in-flight separators are widely used for the synthesis and study of decay properties of heavy and superheavy nuclei. A high level of suppression of beam particles and unwanted reaction products, having high production rates in the region of charge and mass of target nuclei, has been achieved. Slow heavy evaporation residues (ERs) which are studied in the complete fusion reactions with heavy ions after passing through such experimental setups and time-of-flight detectors are implanted in the focal plane semiconductor detectors. In spite of a rather good time resolution (about 1%) of the timing detectors, the focal plane semiconductor detectors have much worse energy resolution in the case of slow

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*Corresponding author. Tel.: +7-09621-64306; fax: +7-09621-65083.
E-mail address: eremin@sunvas.jinr.ru (A.V. Yeremin).

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heavy ERs due to the big pulse height defect during the registration. The time-of-flight and energy measurements of recoil nuclei yield their mass values with an accuracy of about 10–15%, thus allowing separation of ERs from the target- and beam-like particles using two-dimensional TOF-Energy spectra. But such a resolution may not be enough for distinguishing between multi-nucleon reaction products and evaporation residues–products of complete fusion reactions.

One should mention that a method for the investigation of consistent α decays, the so-called α–α correlation analysis, has long been employed for the identification of new radionuclides. It has already been used in the works on the discovery and study of decay properties of elements from 102 (α-recoil milking experiments [1]) to 105 (delayed α correlation method [2,3]). Later this method was developed and successfully used for the identification and study of decay properties of elements 107–112 with a modern experimental setup and detection module (position sensitive detectors array) [4]. This method is based on the fact that a decay chain starting from an unknown isotope should terminate in the known region of isotopes with known decay properties. If the statistics allow one to be sure that no members in the decay chains were missed, it is possible, starting from the known nuclei, to go back to the beginning of the chain and make an assignment, i.e., to determine which isotope of what element was synthesized.

With the neutron-rich isotope ^{48}Ca used as a material for the bombarding beam, the experiments led to a completely unknown region where all decay chains are started and finished with isotopes having unknown decay properties. In addition, according to the calculations [5,6] the decay chains starting from the neutron-rich ($N = 171$–175) isotopes of elements 112–114 after a few α decays should be terminated by spontaneous fission in the region of elements 104–110.

In the case of ^{48}Ca projectiles, an additional and in some cases perhaps decisive possibility for distinguishing between the isotopes produced in complete fusion reactions from the multinucleon transfer reaction products (which can be a possible source of spontaneous fission events) and identifying new nuclides is a method of measuring the atomic mass numbers of evaporation residues synthesized during the experiment. If the mass resolution of the experimental setup reaches the value of more than 0.5% (for the heavy nuclei with masses in the region of 270–290 amu) one can make a direct identification of the obtained isotope on the basis of its mass measurement. But such a mass resolution can be achieved with rather sophisticated magnetic or combined magnetic/electrostatic (the so called Recoil Mass Spectrometers) systems having quite big deflection angles. Typically, such systems have a mass resolution $\Delta M/M$ at the level of 1/300 and not high enough transmission efficiency, which does not allow one to reach the ERs cross-section level of a few picobarns. One of the options is the use of systems which equilibrate charge states (typically to $1+$) and energies (typically to 40–60 keV) of the studied nuclei (ISOL systems, for example). In this case it is possible to achieve the mass resolution $\Delta M/M$ at the level of 1/1000. Such a project called MASHA (Mass Analyzer of Super Heavy Atoms) [7–9] is now being developed at the FLNR (JINR). Another possibility is the use of more simple and compact systems which allow the mass resolution at the level of 1.5–3% at relatively small losses of transmission efficiency. For the mass region 270–290 amu it leads to an accuracy of 3–6 amu. In this case one can establish the origin of the newly synthesized nuclide to the region of superheavy nuclei formed from compound nuclei as a result of a complete fusion reaction between a heavy ion and a target nucleus. Thus for further experiments aimed at the synthesis of the superheavy element isotopes with ($Z \geqslant 110$) using intense ^{48}Ca extracted beams the ion optical system of the separator VASSILISSA was improved which resulted in the modernization of the focal plane detector system.

2. Experimental methods

2.1. The separator VASSILISSA

The recoil separator VASSILISSA was installed in 1987 at the beamline of the U-400 heavy ion

cyclotron of the FLNR (JINR) and since then has been used in the experiments [10–12].

In the framework of the experimental program for the separator VASSILISSA "hot" fusion reactions leading to the formation of compound nuclei with atomic numbers $Z \geqslant 83$ were intensively studied. In particular, more than 30 heavy ion-target nucleus combinations from $^{40}Ca + {}^{151}Eu \rightarrow {}^{191}Bi^*$ to $^{26}Mg + {}^{208}Pb \rightarrow {}^{234}Pu^*$ for $83 \leqslant Z \leqslant 94$ were studied. The complete fusion reactions with heavy ions leading to the compound nuclei with atomic numbers $Z \geqslant 100$ (from $^{20}Ne + {}^{232}Th$ to $^{48}Ca + {}^{242}Pu$) were also studied using the separator VASSILISSA [12].

Aiming at the continuation of the experiments on the synthesis and study of decay properties of superheavy nuclei the separator VASSILISSA was upgraded. For that purpose a new dipole magnet, having a deflection angle of 37°, was installed behind the separator VASSILISSA replacing the old 8° magnet. Together with a new time-of-flight and focal plane detectors it provides a possibility to resolve masses at the level of 1.5–2% for heavy nuclei with $A \approx 300$. Ion optical calculations and the mass evaluation method were described in Part I [13]. A schematic view of the upgraded experimental setup was shown in Part I too.

2.2. Focal plane detector system

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, 60×120 mm^2 in size, surrounded by backward detectors, was developed.

Thin plastic foils (30–70 μg/cm^2 in thickness, 70×140 mm^2 in size) emitting secondary electrons and microchannel plates for detecting these electrons were used in the time-of-flight detectors. The arrangement of the microchannel plates with respect to the emitter foils is similar to that described in Ref. [14]. A typical time resolution of about 0.7 ns was achieved for slow recoil nuclei having mass numbers of about 200–250 (the total energy $E_{ER} \leqslant 40$ MeV). Typical values of the time-of-flight of heavy ERs vary from 60 to 90 ns so the resolution of the time-of-flight detectors is about 1%. The value of 99.95% was achieved for the probability of detection of such recoil nuclei by making use of a single timing detector.

The anticoincidence condition for the signals from the time-of-flight and silicon detectors is used for distinguishing between the pulses originating from the recoil nuclei and their α-decays, i.e. for obtaining "clean" α-spectra of decays of recoil nuclei implanted into the silicon detectors. To reduce the low-energy background of the scattered projectiles and to shift their energy distribution to lower energies (less then the range of 6–9 MeV that is characteristic of α-decays) a 200–400 μg/cm^2 thick mylar degrader foil was installed in front of the silicon detector array.

Having passed the time-of-flight detectors, the recoil nuclei are implanted into the silicon detectors. In order to improve the sensitivity of the experimental setup, a new detector array was manufactured and installed at the focal plane of the separator. The detector array consists of eight identical 16-strip silicon wafers each 60×60 mm^2 in size (see Fig. 1).[1]

The focal plane assembly consists of two wafers, forming 32 strip detectors. Each strip in the focal plane assembly is 3.525×58 mm^2 in size (a distance of 0.1 mm between the strips) and is position sensitive in the longitudinal direction. The position resolution along each strip was measured using the test $^{48}Ca + {}^{174,176}Yb$ and $^{48}Ca + {}^{206,208}Pb$ reactions. The value of 0.5 mm (FWHM) was obtained for sequential α-α decays, 0.8 mm for ER-α and 1.0 mm for ER–SF events. The relative position spectra for the ER-α, ER-SF and α–α correlations are very similar to those presented in Ref. [11]. A typical energy resolution of about 20 keV for the focal plane detector was obtained for α-particles in an energy range of 6–9 MeV. Fig. 2 shows the α spectra for the reaction $^{48}Ca + {}^{174}Yb \rightarrow {}^{222}Th^*$ and spectra of fission fragments from spontaneous fission of ^{252}No for the reaction $^{48}Ca + {}^{206}Pb \rightarrow {}^{254}No^*$. In the fission spectra approximately 3–5% of the events have low energy which indicates the division of the signals' amplitude between two neighboring strips.

[1] The R&D of the detectors and the housing were performed by the Canberra Semiconductor NV.

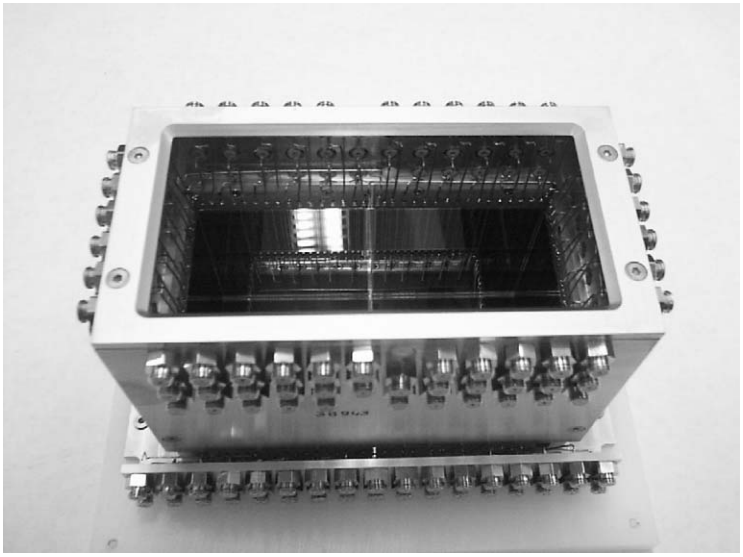

Fig. 1. A view of the focal plane detector array.

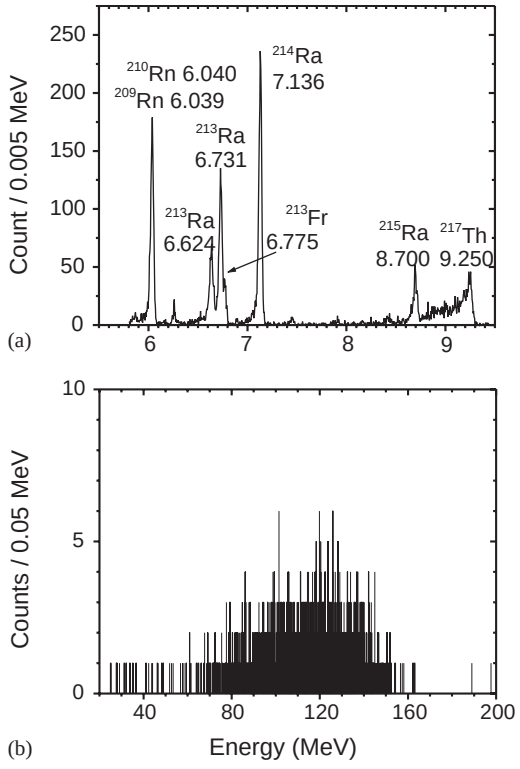

Fig. 2. (a) An example of the recorded α spectrum at the focal plane detector for the reaction $^{48}Ca + {}^{174}Yb \rightarrow {}^{222}Th^*$; (b) the spectrum of fission fragments from spontaneous fission of ^{252}No at the focal plane detector from the reaction $^{48}Ca + {}^{206}Pb \rightarrow {}^{254}No^*$.

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. As for the backward detectors, the strips do not have any position resolution and each four neighboring strips are connected galvanically so that 24 energy-sensitive segments are formed. In the case of backward detectors, we obtained an energy resolution of about 150 keV. The reason for this is a broader range of energy losses for escaping α-particles hitting the backward detectors over a wide range of angles (see Fig. 3). It is clearly seen from Fig. 3b presenting the sum of energies of both fission fragments, that the SF spectrum maximum is at about 140 MeV, whereas that of the TKE spectrum for the ^{252}No spontaneous fission is at about 200 MeV [15]. This difference can be explained by the energy losses of the second fission fragment, escaping the focal plane detector, in the entrance windows of the focal plane and backward detectors.

2.3. Electronic and data acquisition systems

Energies and positions of the events registered by the separator detector system are recorded with two different amplifications: the first one of up to

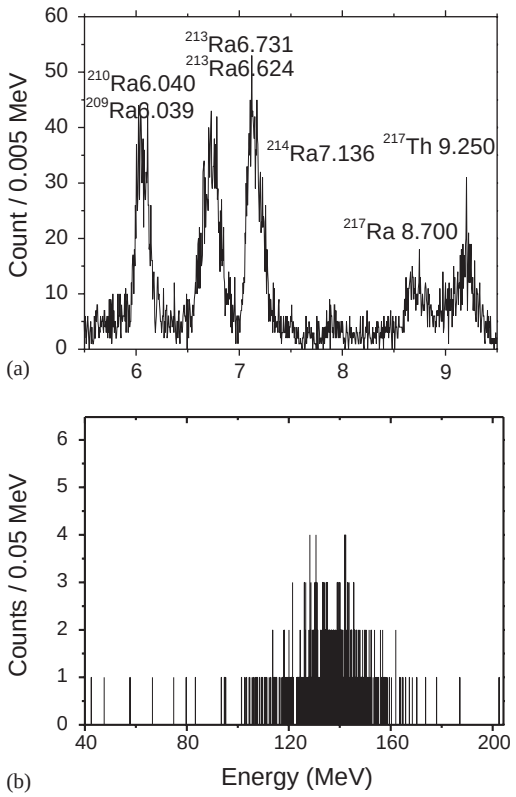

Fig. 3. (a) An example of the recorded α spectrum (sum of the pulses at the focal plane detector and backward detectors) for the reaction $^{48}Ca + {}^{174}Yb \rightarrow {}^{222}Th^*$; (b) the spectrum of fission fragments from spontaneous fission of ^{252}No (sum of the pulses at the focal plane detector and backward detectors) from the reaction $^{48}Ca + {}^{206}Pb \rightarrow {}^{254}No^*$.

200 MeV to measure the fission energies and the other one of up to 20 MeV for ERs and α particles. The spectroscopy amplifiers were designed and manufactured at the Flerov Laboratory of Nuclear Reactions. They have demonstrated an excellent stability and the deviation of the α peak position was only $\pm 0.05\%$ during a month of operation at room temperature fluctuations of $\pm 5^{\circ}C$. All the analog signals were approaching the 8-channel multiplexers and after that were converted by the 4096 channel ADCs (80 μs is the conversion time for the total range) independently for the ER-, α- and SF-signals. Thus, the dead time between the ER-, α- and SF detections was close to zero. The time differences between the consequent ER-, α- and/or SF-events of the decay chains were measured within an accuracy of time counters and shaping time of amplifiers. It was equal to 1 μs. The data acquisition system of VASSILISSA allows storing information, event by event, on the energy, position, time-of-flight and arrival time of the recoil nuclei implanted into the focal plane detector, as well as on the position, detection time and energy of the recorded alpha decay and spontaneous fission events in the focal plane and backward detectors. Some additional parameters were also recorded together with the codes of the events.

A code from each ADC is recorded independently along with the information on the strip number, time and the identification number, containing information about the type of event: energy, position/ER, alpha, SF, TOF/focal plane, backward detectors. Experimental data are transferred from CAMAC crates to the memory of the front-end PC-based computer, which collects and filters the events and sends them to LAN. The front-end PC is linked via a 100 Mbit fast ETHERNET cable to a PC in the control room, which supervises the system and stores the data to the hard disk. The distance between the PCs is 60 m. Proceeding from the fact that each primary event contains time, in the following analysis all the events with the times which differ from each other by no more than the time interval $\Delta t = 4$ μs are joined in one event-word. This event-word already contains all the information on the energy, position, time and type of the event.

3. Experimental results

The basic relations for the mass determination are: $(B\rho) \doteq \sqrt{A \cdot E} \cdot Q^{-1}$, $E \doteq A \cdot v^2$, and $A/Q = 9.6525 \cdot B\rho[\mathrm{T \cdot m}] \cdot (v[\mathrm{cm/ns}])^{-1}$, where $B\rho$, A, E, Q and v are magnetic rigidity, mass, energy, ionic charge and the velocity of the detected ion (see Part I [13]). Thus, to determine the A/Q-ratio one has to measure the velocity (TOF) and the magnetic rigidity (position on the focal plane) of the implanted ion. In these coordinates, different charge states of recoils are resolved, therefore the charge states Q can be found by solving a system

of equations combining A/Q-ratios for the set of evaluated data.

The VASSILISSA separator together with the new mass analyzer was tested with a number of complete fusion reactions induced by heavy ions. Evaporation residues produced in reactions between ^{40}Ar and ^{164}Dy, ^{208}Pb targets, as well as ^{44,48}Ca and ^{174,176}Yb, ^{198}Pt, ^{204,206,208}Pb targets, were used in the analysis. The results of the tests are presented in Refs. [16,17].

In test reactions, nuclei were identified according to known decay properties (α - energies and half-lives). From measured positions of the ERs implantation into the focal plane (detector strip number) and its time-of-flight $B\rho$ and v were calculated, and using these values corresponding A/Q ratios were obtained for each event. From these ratios, for known masses, ionic charge distributions of implanted ERs were derived (see Table 1).

3.1. Charge distributions

The upgraded separator became more sensitive and capable of providing a better accuracy in the estimations of the ERs charge states (mean charge state). Before upgrading, the separator could accept 5 charges of ERs [10], now due to a limited horizontal size of the focal plane detector (120 mm) the acceptance is 3 charge states. In that case the charge state calculations and experimental check of predictions become important. For the calculations of the ERs equilibrium charge state semi-empirical formulae from Shima et al. [18] and Nikolaev et al. [19] were used.

The charge distributions and mean charges $\langle Q \rangle$ for Ra, Th, Cf and No ERs were obtained from the test reactions indicated in Table 1. All these ERs have energies ranging from 0.15 to 0.2 A MeV or relative velocities v/v_0 from 2.45 to 2.87, where v_0 is the Bohr velocity. The dependence of $\langle Q \rangle$ on the velocity v/v_0 after passing a carbon foil is well known and is presented in all semi-empirical and empirical systematics, for example see [20] and references therein. The data from the present work are compared with previously obtained experimental results [20,21] as well as with calculations [18,19] for the ERs energy range $0.12 \leqslant E/A \leqslant 0.2$ A MeV (the relative velocity ranges from 2.2 to 2.9). This is of interest from the point of view of investigating slow heavy ERs produced in complete fusion reactions with heavy ions having masses $20 \leqslant A \leqslant 50$ (see Fig. 4). The experimental data on Ra and Th ERs from the present work are in good agreement with the data on mean charge states of Pb and Po ERs [21], ions from Ta to U [20,22] and semi-empirical systematics from Shima et al. [18]. The experimental data on $\langle Q \rangle$ for Cf, No and 112 ERs differ from these data and are more close to the experimental data, obtained at the velocity filter SHIP [23], as well as to the semi-empirical systematics from Nikolaev et al. [19]. The reason for this could be the manifestation of an oscillatory behavior of $\langle Q \rangle$ as a function of Z (atomic number of ER) described in Ref. [20] and/or transition from the region of actinide elements to that of transactinide elements; the changes in the $\langle Q \rangle$ behavior were predicted for this case in Ref. [20]. On the other hand, the experimental data on U ions from Ref. [22] showed a very wide distribution and lay outside the systematics. Unfortunately, experimental data on the ions with $Z \geqslant 92$ are very scarce, and more experimental investigations are needed in this field.

3.2. Transmission efficiency measurements

With the old 8° dipole magnet, the values of the ERs transmission efficiency through the separator varied from 3% for the ^{18}O induced reactions to 30% and 35% for the ^{40}Ar- and ^{48}Ca-induced reactions, respectively, at the optimal target thickness of 0.2–0.35 mg/cm^2. Calculations showed that with a new magnetic analyzer the transmission efficiency would decrease approximately by the factor of 1.5 with the advent of the ERs energy and charge dispersions into the focal plane. Comparing the data on the reaction ^{208}Pb(^{40}Ar, 2n)^{246}Fm with those from the literature [24], we could estimate that the transmission efficiency for ^{246}Fm ERs was about 20 ± 4%. The transmission efficiency was experimentally measured using the ^{208}Pb target (0.245 mg/cm^2, 1.6 mg/cm^2, Al backing). One of the six target segments was covered with two layers

Table 1
Charge states, A/Q values and atomic mass numbers $\langle A \rangle$ of the ^{214}Ra, ^{216}Th, ^{217}Th, ^{252}No, ^{254}No and ^{283}112 isotopes measured in the ^{48}Ca + ^{174}Yb, ^{198}Pt, ^{206,208}Pb and ^{238}U reactions

Reaction	Z_{ER} A_{ER}	E_{ER} $E_{lab(1/2)}$ (MeV)	Q_{exp}	$\langle Q_{exp} \rangle$	A/Q_{exp}	$\langle A \rangle_{exp}$
^{48}Ca + ^{174}Yb	Th 217	44.5 216	23+ (22.0%) 22+ (28.8%) 21+ (33.8%) 20+ (15.4%)	21.57	9.53±0.17 9.89±0.12 10.32±0.15 10.75±0.15	217.1±3.0
^{48}Ca + ^{174}Yb	Th 216	44.5 216	23+ (32.0%) 22+ (41.0%) 21+ (27.0%)	22.05	9.47±0.18 9.86±0.18 10.24±0.18	216.5±3.7
^{48}Ca + ^{174}Yb	Ra 214	44.5 216	22+ (66.6%) 21+ (33.4%)	21.7	9.70±0.18 10.24±0.18	214.2±3.7
^{48}Ca + ^{198}Pt	Cf 242	39.5 215	19+ (24.7%) 18+ (39.8%) 17+ (35.5%)	18.0	12.56±0.15 13.30±0.15 14.00±0.15	238.7±3.4
^{48}Ca + ^{208}Pb	No 254	38.2 218	20+ (9.9%) 19+ (42.3%) 18+ (35.9%) 17+ (11.9%)	18.5	12.93±0.17 13.48±0.18 14.17±0.22 14.76±0.20	255.1±3.4
^{48}Ca + ^{206}Pb	No 252	38.3 217	19+ (30.0%) 18+ (38.2%) 17+ (31.8%)	18.0	13.20±0.20 13.92±0.20 14.60±0.24	250.0±3.5
^{48}Ca + ^{238}U	112 283	35.7 234	18+ 17+	≈17.5	16.01±0.32 16.68±0.32	285.7±5.7

of Al foil (3 + 6 μm) for catching the ERs knocked out from the target. The ^{48}Ca beam energy was chosen close to the maximum of the 2n evaporation channel of the reaction $^{48}Ca + {}^{208}Pb \rightarrow {}^{256}No^*$. After collecting a beam dose of 7×10^{16} ions the catcher foils were placed close to the 60×60 mm^2 detector and decay of the granddaughter isotope ^{246}Cf ($E_\alpha = 6.75$ MeV, $T_{1/2} = 35.7$ h) was measured both at the focal plane detector and from the catcher foils. The measured transmission efficiency was about 20–25%.

3.3. A/Q distributions

An ability of the system to determine the masses of heavy ERs was first tested using ^{198}Po isotopes, produced in the ^{164}Dy(^{40}Ar, 6n) reaction, and ^{246}Fm produced in the ^{208}Pb(^{40}Ar, 2n) reaction. The data were collected in the reference list mode and after their sorting the "magnetic rigidity (strip number)—TOF" distributions for the implanted nuclei were derived, see Ref. [16]. It was possible to calculate the mass of the ERs detected in the focal plane. For different ^{198}Po ERs charge states ($Q = 17, 18, 19$) the results were $A = 198.1 \pm 1$, $197.8 \pm 1, 198.4 \pm 1$, respectively. Taking into account that the calculations were carried out for the isotope ^{198}Po, formed in the complete fusion reaction ^{164}Dy(^{40}Ar, 6n)^{198}Po, the obtained mass resolution could be estimated as about ±1%. Fig. 5 shows distributions of ^{198}Po ERs along the strips of the old variant VASSILISSA with the 8° magnet (16 strips) and those for the new variant with the 37° magnetic analyzer (32 strips). The

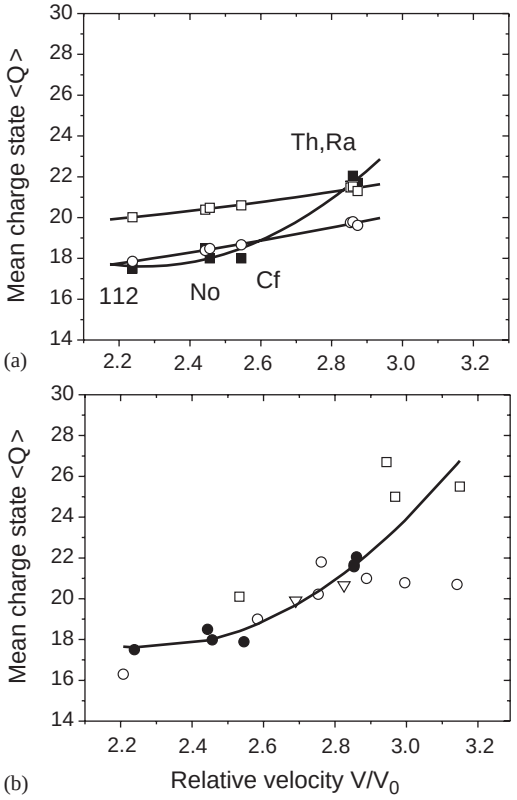

Fig. 4. Mean charges $\langle Q \rangle$ obtained in our experiments: (a) experimental data from Table 1 (filled circles) and comparison with calculations using semi-empirical systematics from Ref. [18] (open squares) and [19] (open circles). Solid curves are the polynomial fits of the experimental data to calculations for guiding the eye; (b) experimental data from Table 1 (filled circles), from [21] (open triangles), [23] (open squares), [20,22] (open circles). The solid curve is the same as in (a).

magnetic analyzer dividing different charge states (three in our case) enlarge the image of ERs in the focal plane. In the case of the $^{40}Ar + {}^{164}Dy \rightarrow {}^{204}Po^*$ reaction the cross-section values reach hundreds of microbarns. A few minutes are enough for collecting good statistics. In the case of the reactions with smaller formation cross-sections more time is needed. In this case the instability of the power supplies of the high voltage system and magnetic analyzer blurs the image in the focal plane and the resolution between different charge states of one isotope becomes much worse. For the reaction $^{40}Ar + {}^{208}Pb \rightarrow {}^{248}Fm^*$ the obtained mass resolution for ^{246}Fm ERs, calculated in accordance

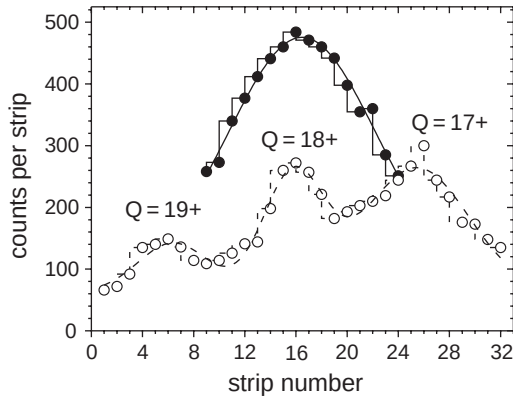

Fig. 5. Horizontal distribution (along the strips of the focal plane detector) of the implanted ^{198}Po ERs from the reaction $^{40}Ar + {}^{164}Dy \rightarrow {}^{204}Po^*$. Open circles—the focal plane detector behind the magnetic analyzer (32 strips), closed circles—the old variant focal plane detector (16 strips).

with the measured TOF and the strip number, ranged from 242.5 to 248.7 which corresponds to an accuracy of about 2%.

For a number of test reactions leading to the compound nuclei ^{222}Th, ^{246}Cf and $^{254,256}No$ positions of the implanted ERs and corresponding TOFs were extracted. The isotopes (and their masses, respectively) were identified using the known decay properties (α - energies and half-lives). From the measured $B\rho$ (strip number) and v (extracted from TOF) values the corresponding A/Q values were obtained. The results obtained for A/Q distributions of the ^{217}Th and ^{254}No ERs are shown in Fig. 6.

The accuracy of the A/Q determination is between ± 1.5 and $\pm 2\%$. For the ERs with masses heavier than 250 it leads to an uncertainty in the mass determination of ± 4–6 mass units. This is not enough for the direct identification of nuclides to be studied, but results obtained from heavy ERs mass measurements allow one to exclude transfer and incomplete fusion reaction products from the analysis and assign the observed events to the process of complete fusion.

Table 1 (two lower rows) shows results for the reaction $^{48}Ca + {}^{238}U \rightarrow 112^*$. This experiment was a repetition of the experiment performed in 1998 [25] with a new quality of the separator and was described in detail in Ref. [26]. The mean mass

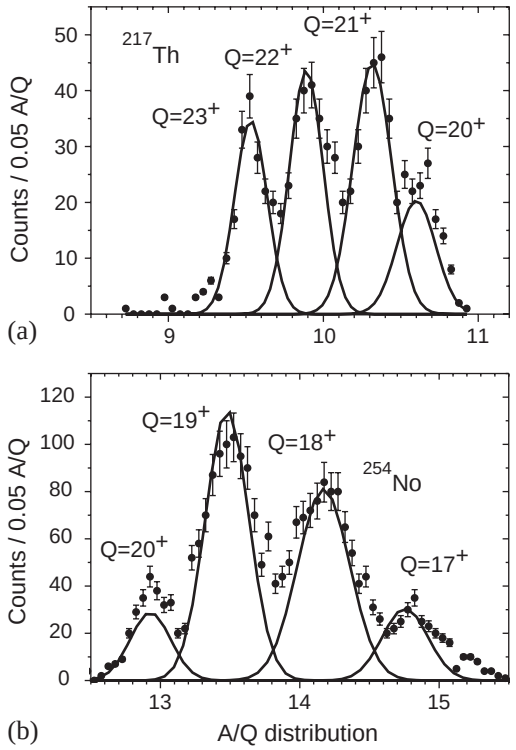

Fig. 6. A/Q distributions of the ^{217}Th and ^{254}No ERs.

value for two detected nuclei amounts to $\langle A \rangle = 285.7 \pm 5.7$. Cutting off the upper limit by the compound nucleus mass $A_{CN} = 286$, one can obtain the mass interval from $A = 280$ to $A = 286$. This result indicates, first of all, that the observed nuclides belong to the region of superheavy nuclei and their masses are close to the expected masses of the evaporation products of the reaction $^{48}Ca + ^{238}U$. Due to the relatively low excitation energy of the compound nucleus $E^*_{CN} \approx 35$ MeV the evaporation of charged particles (protons or α particles) is strongly prohibited, and it is more probable that the events measured in this work belong to the isotope $^{283}112$ produced via the $3n$ evaporation channel in the reaction $^{48}Ca + ^{238}U \rightarrow ^{286}112^*$.

Note that at an erroneous estimation of the charge states per one unit of charge to a higher or lower state leads to essential overestimates and underestimates, respectively, in the mass numbers within about ± 15 units. In this case the measured TOFs and extracted from these values ERs energies are in contradiction with the corresponding $B\rho$ values extracted from the strip numbers. So, one can conclude that the values of averaged masses of the observed SF and α activities do not differ much from those of the compound nuclei formed in the corresponding reactions and masses of nuclei produced in the few nucleon evaporation channels.

4. Discussion and conclusion

The development of the experimental technique which employs electrostatic deflectors leads to the creation of a new class of kinematic separators—mass spectrometers of recoiling nuclei (Recoil Mass Spectrometers). In these experimental setups a dipole magnet with a deflection angle of 25°–30° is placed between electrostatic condensers (deflectors), i.e. the scheme E–D–E is used (E-electrostatic deflector, D-dipole magnet). It allows one to achieve rather good mass resolution $\Delta M/M \approx 1/300$ for heavy products of nuclear reactions together with the rather high suppression factors for background products (better than 10^7 for scattered beam ions). One of the first experimental setups of this type was a recoil mass spectrometer created at Rochester [27].

Later a number of experimental setups having the familiar scheme were created at different nuclear centers, such as Legnaro (Italy) [28], Osaka (Japan) [29], Oak-Ridge (USA) [30], Argonne (USA) [31], Tokai (Japan) [32] and New Dehli (India) [33]. All these setups use the same scheme E–D–E and differ only by the number of focusing quadruple lenses in front and behind the spectrometer itself. All of them can provide the mass resolution $\Delta M/M \approx 1/300$ for nuclear reaction products in the mass region of around 200. A typical range of formation cross-sections is from a few millibarns to a few nanobarns, and it depends strongly on the value of suppression factors for the background products. Recently only two spectrometers have been used for the study of formation cross-sections and decay properties of products of reactions with heavy ions in the mass region of about and heavier than 200 amu. In Argonne, FMA [31] was used for investigating the proton

radioactivity of neutron-deficient isotopes of Pb and Bi [34], and JAERI-RMS in Tokai [32]—for investigating decay properties of Sg isotopes in the reaction $^{30}Si + ^{238}U$ [35]. But in the latter case the setup was used not in the mass resolution mode.

Recently, first test experiments have been performed with the new 37° dipole magnet installed behind the recoil separator VASSILISSA. The obtained results are very promising; it is possible now to determine masses of synthesized ERs with an accuracy of 5–6 mass units. This provides an additional reliability of identification in the experiments aimed at the synthesis of superheavy nuclei in complete fusion reactions between transactinide targets and heavy accelerated beams.

With the use of the upgraded separator VASSILISSA it is planned to continue the experiments aimed at the synthesis of superheavy nuclei in the vicinity of predicted spherical shells in complete fusion reactions between $^{34,36}S$, ^{48}Ca ions and ^{232}Th, $^{236,238}U$ and $^{242,244}Pu$ targets. Odd-Z isotopes which can be produced in reactions with ^{237}Np and ^{243}Am targets may have even longer half-lives than those of even-Z elements 112 and 114. After the upgrade of the separator the search for long correlations (up to a few hours) becomes possible.

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References

[1] B.A. Zager, et al., At. Energ. 20 (1966) 230.
[2] A. Ghiorso, et al., Phys. Rev. Lett. 22 (1969) 1317.
[3] V.A. Druin, et al., Yad. Fiz. 13 (1971) 251.
[4] S. Hofmann, Rep. Prog. Phys. 61 (1998) 639.
[5] R. Smolańczuk, Phys. Rev. C 56 (1997) 812.
[6] P. Möller, et al., At. Data Nucl. Data Tables 59 (1995) 185.
[7] Yu.Ts. Oganessian, et al., J. Nucl. Radiochem. Sci. 3 (2002) 217.
[8] Yu.Ts. Oganessian, et al., Nucl. Instr. and Meth. B 204 (2003) 606.
[9] Yu.Ts. Oganessian, Preprint JINR E7-2002-64, Dubna, 2002.
[10] A.V. Yeremin, et al., Nucl. Instr. and Meth. B 126 (1997) 329.
[11] A.V. Yeremin, et al., Nucl. Instr. and Meth. A 440 (2000) 86.
[12] A.V. Yeremin, et al., Phys. At. Nuclei 66 (2003) 1042.
[13] A.G. Popeko, et al., Nucl. Instr. and Meth. A 510 (2003) 371.
[14] A.N. Andreyev, et al., Nucl. Instr. and Meth. A 364 (1995) 342.
[15] E.K. Hulet, Yad. Fiz. (Phys. At. Nucl.) 57 (1994) 1165.
[16] Yu.Ts. Oganessian, et al., Par. Nucl. Lett. 1 (110) (2002) 5.
[17] A.V. Belozerov, et al., Eur. Phys. J. A 16 (2003) 447.
[18] K. Shima, et al., Nucl. Instr. Meth. 200 (1982) 605.
[19] V.S. Nikolaev, I.S. Dmitriev, Phys. Lett. A 28 (1968) 277.
[20] K. Shima, et al., Phys. Rev. A 40 (1989) 3557.
[21] N.K. Skobelev, et al., Z. Phys. A 314 (1983) 5.
[22] A.B. Wittkower, H.D. Betz, At. Data 5 (1973) 156.
[23] A.G. Popeko, et al., FLNR JINR Scientific Report 1995–1996, Dubna, 1997, 32.
[24] G. Münzenberg, et al., Z. Phys. A 302 (1981) 7.
[25] Yu.Ts. Oganessian, et al., Eur. Phys. J. A 5 (1999) 63.
[26] Yu.Ts. Oganessian, et al., FLNR JINR Scientific Report 2001–2002, Dubna 2003, Eur. Phys. J. A (2003) accepted.
[27] T.M. Cormier, Annu. Rev. Nucl. Part. Sci. 37 (1987) 537.
[28] P. Spolaore, et al., Nucl. Instr. and Meth. A 238 (1985) 381.
[29] S. Morinobu, et al., Nucl. Instr. and Meth. B 70 (1992) 331.
[30] J.D. Cole, et al., Nucl. Instr. and Meth. B 70 (1992) 343.
[31] C.N. Davids, et al., Nucl. Instr. and Meth. B 70 (1992) 358.
[32] H. Ikezoe, et al., Nucl. Instr. and Meth. A 376 (1996) 420.
[33] A.K. Sinha, et al., Nucl. Instr. and Meth. A 339 (1994) 543.
[34] G.L. Poli, et al., Phys. Rev. C 63 044304.
[35] H. Ikezoe, et al., Eur. Phys. J. A 2 (1998) 379.