

E15-2003-131

O. N. Malyshev, A. V. Yerebin¹, A. G. Popeko,
A. V. Belozerov, M. L. Chelnokov, V. I. Chepigin,
V. A. Gorshkov, S. Hofmann², M. G. Itkis,
A. P. Kabachenko, Yu. Ts. Oganessian, R. N. Sagaidak,
Š. Šáro³, A. V. Shutov, A. I. Svirikhin

IN-BEAM SEPARATION AND MASS DETERMINATION OF SUPERHEAVY NUCLEI

Submitted to «Nuclear Instruments and Methods in Physics Research A»

¹E-mail address: eremin@sunvas.jinr.ru

²Gesellschaft fuer Schwerionenforschung, D-64220 Darmstadt, Germany

³Department of Physics, Comenius University, SK-84215, Bratislava,
Slovakia

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 (ER's) which are studied in complete fusion reactions with heavy ions after passing through such experimental set-ups and time-of-flight detectors are implanted in the focal plane semiconductor detectors. In spite of 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 heavy ER's 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 ER's from the target-like and beam-like particles using two-dimensional TOF-Energy spectra. But such a resolution may not be enough for distinguishing between multinucleon reaction products and evaporations 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 set-up 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., determine what isotope of what element was synthesized.

With the neutron rich isotope ^{48}Ca used as a material for the bombarding beam the experiments lead 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 set-up 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 (so called Recoil Mass Spectrometers) systems having quite big deflection angles. Typically such systems have the 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 ER's 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, 8, 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 belonging 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 $Z \geq 110$ 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, 11, 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 $Z \geq 83$ were intensively studied. In particular, more than 30 heavy ion - target nucleus combinations from $^{40}\text{Ca} + ^{151}\text{Eu} \rightarrow ^{191}\text{Bi}^*$ to $^{26}\text{Mg} + ^{208}\text{Pb} \rightarrow ^{234}\text{Pu}^*$ for $83 \leq Z \leq 94$ were studied. The complete fusion reactions with heavy ions leading to the compound nuclei with atomic numbers $Z \geq 100$ (from $^{20}\text{Ne} + ^{232}\text{Th}$ to $^{48}\text{Ca} + ^{242}\text{Pu}$) 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 degrees, 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 [13]. A schematic view of the upgraded experimental set-up was shown in [13] too.

2.2 Focal plane detector system

For the registration of heavy ER's 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, $60 \times 120 \text{ mm}^2$ in size, surrounded by backward detectors, was developed.

Thin plastic foils ($30\text{--}70 \mu\text{g}/\text{cm}^2$ in thickness, $70 \times 140 \text{ mm}^2$ 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 in respect to the emitter foils is similar to that described in [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 $E_{ER} \leq 40 \text{ MeV}$). Typical values of the time-of-flight of heavy ER's

vary from 60 to 90 nsec., 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 than the range of 6–9 MeV that is characteristic of α -decays) a 200 – 400 $\mu\text{g}/\text{cm}^2$ 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 set-up, 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 $60\times 60\text{ mm}^2$ in size (see Fig. 1).*

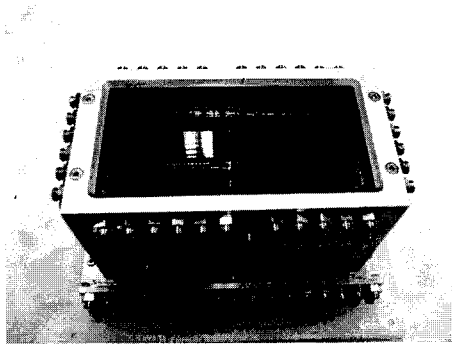


Figure 1: A view of the focal plane detector array.

The focal plane assembly consists of two wafers, forming 32 strip detector. Each strip in the focal plane assembly is $3.525\times 58\text{ mm}^2$ 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 $^{48}\text{Ca} + ^{174,176}\text{Yb}$ and $^{48}\text{Ca} + ^{206,208}\text{Pb}$ reactions. The value of 0.5 mm (FWHM) was obtained for sequential α - α decays, 0.8 mm for ER- α

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

and 1.0 mm for ER-SF events. Relative position spectra for the ER - α , ER - SF and α - α correlations are very similar to those presented in [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 $^{48}\text{Ca} + ^{174}\text{Yb} \rightarrow ^{222}\text{Th}^*$ and spectra of fission fragments from spontaneous fission of ^{252}No for the reaction $^{48}\text{Ca} + ^{206}\text{Pb} \rightarrow ^{254}\text{No}^*$. 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.

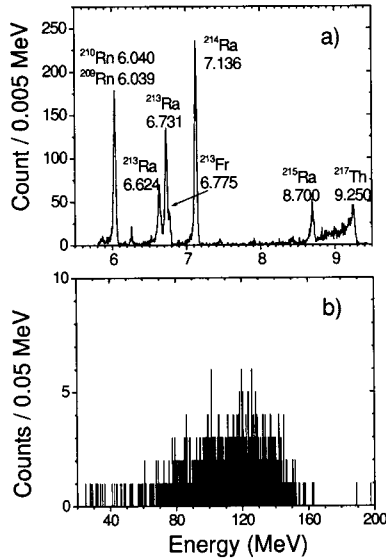


Figure 2: a) - An example of the recorded α spectrum at the focal plane detector for the reaction $^{48}\text{Ca} + ^{174}\text{Yb} \rightarrow ^{222}\text{Th}^*$; b) - the spectrum of fission fragments from spontaneous fission of ^{252}No at the focal plane detector from the reaction $^{48}\text{Ca}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

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 that is a

broader range of energy losses for escaping α -particles hitting the backward detectors over a wide range of angles (see Fig. 3-a).

It is clearly seen from Fig. 3-b 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 energy losses of the second fission fragment, escaping the focal plane detector, in the entrance windows of focal plane and backward detectors.

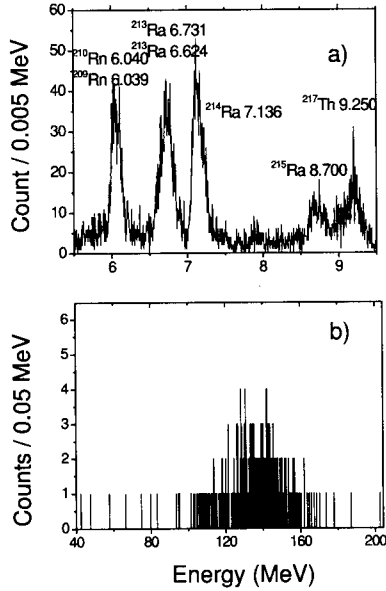


Figure 3: **a)** - An example of the recorded α spectrum (sum of the pulses at the focal plane detector and backward detectors) for the reaction $^{48}\text{Ca} + ^{174}\text{Yb} \rightarrow ^{222}\text{Th}^*$; **b)** - the spectrum of fission fragments from spontaneous fission of ^{252}No (sum of the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

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 200 MeV to measure the fission energies and the other one of up to 20 MeV

for ER's 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 ± 0.05 % during a month of operation at room temperature fluctuations of ± 5 C°. All the analog signals were arriving to the 8-channel multiplexers and after that were converted by the 4096 channel ADC's (80 μ s 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 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 μ sec. 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 meters. 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 $\Delta t = 4$ μ sec 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 $A/Q = 9.6525 \cdot B\rho[\text{T} \cdot \text{m}] \cdot (v[\text{cm/ns}])^{-1}$, where $B\rho$, A , E , Q and v are magnetic rigidity, mass, energy, ionic charge and the velocity of

of the detected ion (see [13]). Thus, to determine the A/Q - ratio one have 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.

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 $^{44,48}\text{Ca}$ and $^{174,176}\text{Yb}$, ^{178}Pt , $^{204,206,208}\text{Pb}$ targets, were used in the analysis. Results of the tests are presented in [16, 17].

In test reactions nuclei were identified according to known decay properties (α - energies and half-lives). From measured positions of the ER's 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 ER's 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 ER's charge states (mean charge state). Before upgrading the separator could accept 5 charges of ER's [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 ER's equilibrium charge state semi-empirical formulae from K. Shima et. al. [18] and V.S. Nikolaev et. al. [19] were used.

The charge distributions and mean charges $\langle Q \rangle$ for Ra, Th, Cf and No ER's were obtained from the test reactions indicated in Table 1. All these ER's 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 ER's energy range $0.12 \leq E/A \leq 0.2$ A·MeV

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

(the relative velocity ranges from 2.2 to 2.9). It is of interest from the point of view of investigating slow heavy ER's produced in complete fusion reactions with heavy ions having masses $20 \leq A \leq 50$ (see Fig. 4). The experimental data on Ra and Th ER's from the present work is in good agreement with the data on mean charge states of Pb and Po ER's [21], ions from Ta to U [20, 22] and semi-empirical systematics from K. Shima et. al. [18]. The experimental data on $\langle Q \rangle$ for Cf, No and 112 ER's 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 V.S. Nikolaev et. al. [19]. The reason for that could be the manifestation of an oscillatory behavior of $\langle Q \rangle$ as a function of Z (atomic number of ER) described in [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 [20]. On the other hand, the experimental data on U ions from [22] showed a very wide distribution and lay outside the systematics. Unfortunately, experimental data on the ions with $Z \geq 92$ are very scarce, and more experimental investigations are needed in this field.

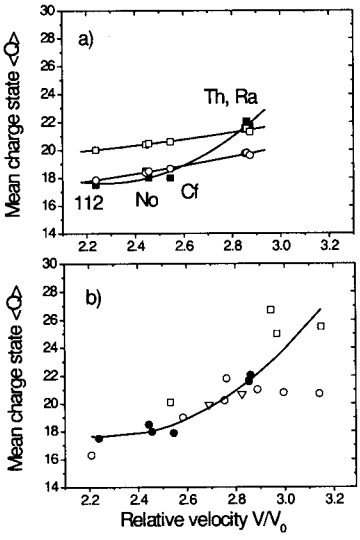


Figure 4: Mean charges $\langle Q \rangle$ obtained in our experiments. **a)** - experimental data from Table 1 (filled circles) and comparison with calculations using semi-empirical systematics from [18] (open squares) and [19] (open circles). Solid curves are the polynomial fits of the experimental 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).

3.2 Transmission efficiency measurements

With the old 8° dipole magnet, the values of the ER's 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/cm². Calculations showed that with a new magnetic analyzer transmission efficiency would decrease

approximately by the factor of 1.5 with the advent of the ER's energy and charge dispersions into the focal plane. Comparing the data on the reaction $^{208}\text{Pb}(^{40}\text{Ar}, 2n)^{246}\text{Fm}$ with those from literature [24], we could estimate that the transmission efficiency for ^{246}Fm ER's was about 20 ± 4 %. The transmission efficiency was experimentally measured using the ^{208}Pb target ((0.245 mg/cm², 1.6 mg/cm² Al backing). One of the six target segments was covered with two layers of Al foil (3 + 6 μm) for catching the ER's knocked out from the target. The ^{48}Ca beam energy was chosen close to the maximum of the 2n evaporation channel of the reaction $^{48}\text{Ca} + ^{208}\text{Pb} \rightarrow ^{256}\text{No}^*$. After collecting a beam dose of 7×10^{16} ions the catcher foils were placed close to the individual 60×60 mm² 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 masses of heavy ER's was first tested using ^{198}Po isotopes, produced in the $^{164}\text{Dy}(^{40}\text{Ar}, 6n)$ reaction, and ^{246}Fm produced in the $^{208}\text{Pb}(^{40}\text{Ar}, 2n)$ 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 [16]. It was possible to calculate the mass of the ER's, detected in the focal plane. For different ^{198}Po ER's 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 made for the isotope ^{198}Po , formed in the complete fusion reaction $^{164}\text{Dy}(^{40}\text{Ar}, 6n)^{198}\text{Po}$, the obtained mass resolution could be estimated as about ± 1 %. Fig. 5 shows distributions of ^{198}Po ER's 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 magnetic analyzer dividing different charge states (three in our case) enlarge the image of ER's in the focal plane. In the case of the $^{40}\text{Ar} + ^{164}\text{Dy} \rightarrow ^{204}\text{Po}^*$ 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 blur the image in the focal plane and the resolution

between different charge states of one isotope becomes much worse. For the reaction $^{40}\text{Ar} + ^{208}\text{Pb} \rightarrow ^{248}\text{Fm}^*$ the obtained mass resolution for ^{246}Fm ER's, calculated in accordance with the measured TOF and strip number, ranged from 242.5 to 248.7 which corresponds to an accuracy of about 2 %.

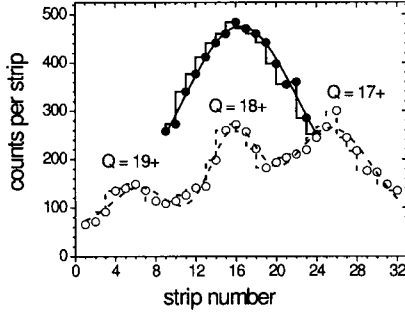


Figure 5: Horizontal distribution (along the strips of the focal plane detector) of the implanted ^{198}Po ER's from the reaction $^{40}\text{Ar} + ^{164}\text{Dy} \rightarrow ^{204}\text{Po}^*$. Open circles - the focal plane detector behind the magnetic analyzer (32 strips), closed circles - the old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

For a number of the test reactions leading to the compound nuclei ^{222}Th , ^{246}Cf and $^{254,256}\text{No}$ positions of the implanted ER's and corresponding TOF's 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 ER's are shown in Fig. 6.

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

Table 1 (two lower rows) shows results for the reaction $^{48}\text{Ca} + ^{238}\text{U} \rightarrow ^{112}^*$. This experiment was a repetition of the experiment performed

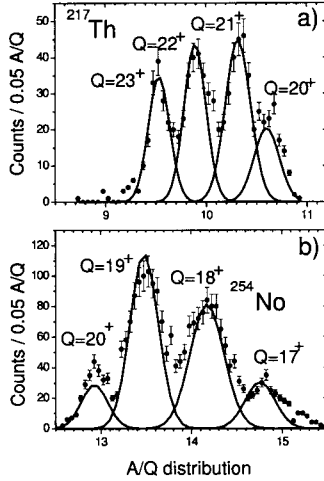


Figure 6: A/Q distributions of the ^{217}Th and ^{254}No ER's.

in 1998 [25] with a new quality of the separator and was described in details in [26]. The mean mass 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 $^{48}\text{Ca} + ^{238}\text{U}$. 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 $^{48}\text{Ca} + ^{238}\text{U} \rightarrow ^{286}112^*$.

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 TOF's and extracted from these values ER's 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 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 set-ups a dipole magnet with a deflection angle of 25 – 30 degrees 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 set-up of this type was a recoil mass spectrometer created at Rochester [27].

Later a number of experimental set-ups 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 set-ups 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 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 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 $^{30}\text{Si} + ^{238}\text{U}$ [35]. But in the latter case the set-up 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 ER's 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 $^{34,36}\text{S}$, ^{48}Ca ions and ^{232}Th , $^{236,238}\text{U}$ and $^{24,244}\text{Pu}$ 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.

Acknowledgments

The authors are grateful to A.N. Shamanin and E.N. Voronkov for the maintenance of the separator VASSILISSA and to the U-400 crew for providing stable beams of high intensity.

References

- [1] B.A. Zager et. al., *Atom. Energia*, **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.*, **C56**(1997)812
- [6] P. Möller et. al., *Atomic Data and Nuclear 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.*, **B204**(2003)606
- [9] Yu.Ts. Oganessian, Preprint JINR **E7-2002-64**, Dubna 2002, submitted to *Nucl. Instr. Meth. A*.
- [10] A.V. Yeremin et al., *Nucl. Instr. and Meth.*, **B126**(1997)329
- [11] A.V. Yeremin et al., *Nucl. Instr. and Meth.*, **A440**(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*, in press.
- [14] A.N. Andreyev et. al., *Nucl. Instr. and Meth. A***364**(1995)342
- [15] E.K. Hulet, *Yad. Fiz. (Phys. At. Nuclei)*, **57**(1994)1165
- [16] Yu.Ts. Oganessian et. al., *Particles and Nuclei, Letters*, **No.1-[110]**(2002)5
- [17] A.V. Belozarov et. al., *Eur. Phys. J.*, **A16**(2003)447
- [18] K. Shima et. al., *Nucl. Instr. Meth.*, **200**(1982)605
- [19] V.S. Nikolaev and I.S. Dmitriev, *Phys. Lett.*, **A28**(1968)277
- [20] K. Shima et. al., *Phys. Rev.*, **A40**(1989)3557
- [21] N.K. Skobelev et. al., *Z. Phys.*, **A314**(1983)5
- [22] A.B. Wittkower and 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.*, **A302**(1981)7
- [25] Yu.Ts. Oganessian et. al., *Eur. Phys. J.*, **A5**(1999)63
- [26] Yu.Ts. Oganessian et. al., FLNR JINR Scientific Report 2001–2002, Dubna 2003, submitted to *Eur. Phys. J. A*.
- [27] T.M. Cormier., *Ann. Rev. Nucl. Part. Sci.*, **37**(1987)537
- [28] P. Spolaore et. al., *Nucl. Instr. and Meth.*, **A238**(1985)381
- [29] S. Morinobu et al., *Nucl. Instr. and Meth.*, **B70**(1992)331
- [30] J.D. Cole et. al., *Nucl. Instr. and Meth.*, **B70**(1992)343
- [31] C.N. Davids et. al., *Nucl. Instr. and Meth.*, **B70**(1992)358
- [32] H. Ikezoe et al., *Nucl. Instr. and Meth.*, **A376**(1996)420
- [33] A.K. Sinha et. al., *Nucl. Instr. and Meth.*, **A339**(1994)543
- [34] G.L. Poli et. al., *Phys. Rev.*, **C63** 044304
- [35] H. Ikezoe et. al., *Eur. Phys. J.*, **A2**(1998)379

Received on July 8, 2003.

Мальшев О. Н. и др.

E15-2003-131

Сепарация и определение массы сверхтяжелых ядер

Последние пятнадцать лет сепаратор ядер отдачи ВАСИЛИСА использовался для изучения ядер-остатков испарения, образующихся в реакциях полного слияния с тяжелыми ускоренными ионами. С использованием высокоинтенсивных пучков ^{48}Ca и мишеней ^{232}Th , ^{238}U , ^{242}Pu были исследованы свойства радиоактивного распада и поперечные сечения образования изотопов элементов 110, 112 и 114. Для будущих экспериментов по синтезу изотопов сверхтяжелых элементов ($Z \geq 110$) с использованием интенсивных выведенных пучков ^{48}Ca было проведено усовершенствование ионно-оптической и детектирующей систем сепаратора. Представлены результаты тестовых реакций и новый результат для изотопа $^{283}112$.

Работа выполнена в Лаборатории ядерных реакций им. Г. Н. Флерова ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2003

Malyshev O. N. et al.

E15-2003-131

In-Beam Separation and Mass Determination of Superheavy Nuclei

Within the past fifteen 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 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 ($Z \geq 110$) 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 result for the isotope $^{283}112$ are presented.

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

Preprint of the Joint Institute for Nuclear Research. Dubna, 2003

Макет Т. Е. Попеко

Подписано в печать 30.07.2003.

Формат 60 × 90/16. Бумага офсетная. Печать офсетная.

Усл. печ. л. 1,18. Уч.-изд. л. 1,36. Тираж 300 экз. Заказ № 54030.

Издательский отдел Объединенного института ядерных исследований
141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.

E-mail: publish@pds.jinr.ru

www.jinr.ru/publish/