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KINEMATIC SEPARATION AND MASS ANALYSIS OF HEAVY RECOILING NUCLEI

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Within the past twelve years, the recoil separator VASSILISSA has been used for investigation of evaporation residues produced in heavy-ion induced complete-fusion reactions. In the course of experimental work in the region of the elements with $92 \leq Z \leq 94$, fourteen new isotopes have been identified by the parent-daughter correlations.

The study of the decay properties and formation cross sections of the isotopes of elements 110, 112, and 114 was performed with the use of the high intensity ^{48}Ca beams; ^{232}Th, ^{238}U and ^{242}Pu targets were used in the experiments. At the beam energies corresponding to the calculated cross-section maxima of the $3n$ evaporation channels, the isotopes ^{277}110, ^{283}112, and ^{287}114 were produced and identified.

For further experiments aimed at the synthesis of the superheavy element isotopes ($Z \geq 110$) with the intensive ^{48}Ca extracted beams, the improvements in the ion optical system of the separator and of focal plane detector system have been made. As a result, for heavy recoiling nuclei with masses $A \approx 250$, the mass resolution of about 2.5 % was achieved with a good energy and position resolutions of the focal plane detectors.

В течение последних двенадцати лет сепаратор ядер отдачи ВАСИЛИСА использовался для исследований ядер остатков испарения, образующихся в реакциях полного слияния с тяжелыми ионами. В рамках экспериментальной работы было синтезировано и идентифицировано, с использованием корреляций материнское–дочернее ядро, четырнадцать новых изотопов элементов с атомными номерами $92 \leq Z \leq 94$.

Исследование свойств распада и сечений образования изотопов элементов 110, 112 и 114 проводилось с использованием высокоинтенсивных пучков ^{48}Ca. В экспериментах использовались мишени ^{232}Th, ^{238}U и ^{242}Pu. При энергиях пучка, соответствующих расчетным максимумам сечений образования в каналах с испарением трех нейтронов, были получены и идентифицированы изотопы ^{277}110, ^{283}112 и ^{287}114.

Для будущих экспериментов, направленных на синтез сверхтяжелых элементов ($Z \geq 110$) с использованием интенсивных выведенных пучков ^{48}Ca, были проведены улучшения ионно-оптической системы сепаратора и детектирующей системы в фокальной плоскости. В результате для тяжелых ядер отдачи с массами $A \approx 250$ было получено массовое разрешение порядка 2,5 % наряду с хорошим энергетическим и позиционным разрешением детекторов в фокальной плоскости.

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INTRODUCTION

A method for the investigation of consistent α decays, the so-called $\alpha-\alpha$ correlation analysis, has long been employed for the identification of new radionuclides. It has already been used in the works to discover and study the 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 be ended in the known region of isotopes with the known decay properties. In the case if the statistics allows 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 to make an assignment, what definite isotope of what element was synthesized.

In the case when the neutron-rich isotope ^{48}Ca is used as a bombarding beam we have found ourselves in a completely unknown region where all decay chains are started and finished with isotopes having unknown decay properties. According to the calculations [5, 6] the decay chains started from 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. As a first step in attempt to solve the problem with the newly synthesized isotope identification we plan a number of experiments, each experiment being a basis for the following one. One of the possibilities was to use targets which differ by an α particle. It means that the isotopes which can be produced in a subsequent experiment should decay to the isotopes which were obtained in the previous experiments. These two-step experiments could be the following ones: ^{48}Ca + ^{232}Th $\rightarrow$ ^{280}110* and ^{48}Ca + ^{236}U $\rightarrow$ ^{284}112*, ^{48}Ca + ^{238}U $\rightarrow$ ^{286}112* and ^{48}Ca + ^{242}Pu $\rightarrow$ ^{290}114*, ^{48}Ca + ^{244}Pu $\rightarrow$ ^{292}114* and ^{48}Ca + ^{248}Cm $\rightarrow$ ^{296}116*.

In the first part of the experimental programme the reactions ^{48}Ca + ^{206,208}Pb $\rightarrow$ $\rightarrow$ $^{254,256-x}$No + xn were investigated. Detailed analysis of the results of these experiments will be published elsewhere, see, e. g., [7]. Using the HIVAP code [8], the excitation energies for the maxima of the $3n$ and $4n$ channels for the reactions with ^{232}Th, ^{238}U and ^{242}Pu targets, respectively, were calculated. The corresponding beam energies for the reactions in the middle of the target thickness were 228$\pm$2 and 236$\pm$2 MeV for the ^{232}Th target, 231$\pm$2 and 238$\pm$2 MeV for the ^{238}U target, 234$\pm$2 and 245$\pm$2 MeV for the ^{242}Pu target [9].

Experiments, performed at the separator VASSILISSA using ^{48}Ca beams, and obtained results are listed in Table 1.

Table 1. **Summary of experimental conditions for the irradiations with ^{48}Ca**

Reaction studied	Energy, MeV	Beam time	Beam dose	Nuclide detected	Cross section, pb
^{48}Ca+^{238}U	231	25	$3.5 \cdot 10^{18}$	^{283}112	5^{+6}_{-3}
^{48}Ca+^{238}U	238	14	$2.2 \cdot 10^{18}$	no	lim. 7
^{48}Ca+^{232}Th	238	15	$1.8 \cdot 10^{18}$	no	lim. 9
^{48}Ca+^{232}Th	228	28	$4.6 \cdot 10^{18}$	^{277}110	$2^{+4.6}_{-1.7}$
^{48}Ca+^{235}Pu	235	32	$7.5 \cdot 10^{18}$	^{287}114	$2.5^{+3.3}_{-1.6}$

EXPERIMENTAL SET-UP

The electrostatic separator VASSILISSA [10] with an upgraded detector system [11] was used in the experiments on the synthesis of the isotopes ^{283}112 and ^{287}114 using ^{238}U and ^{242}Pu targets [12, 13].

An additional (in some cases perhaps the main) possibility for the distinguishing of the isotopes produced in complete fusion reactions from multinucleon transfer reactions products and identification of new nuclides is the method of measuring the atomic mass number of the ER's, synthesized during the experiment. In the case if the mass resolution of the experimental set-up reaches the value of less than 0.5 % (for the heavy nuclei with masses in the region of 270–290 amu) one could make a direct identification of the obtained isotope on the basis of its mass measurement. But such a mass resolution needs rather big magnetic systems having deflection angles of $\geq 90°$. Another possibility is the use of more simple and compact systems which allow one to have the mass resolution at the level of 1.5–3 %. For the mass region 270–290 amu it leads to the accuracy of 3–6 amu. In this case one can establish belonging of newly synthesized nuclide to the region of superheavy nuclei formed from compound nuclei as a result of complete fusion reaction between the heavy ion and the target nucleus.

With the aim of 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 37.5 degrees, was installed behind the separator VASSILISSA replacing the old 8° magnet (see Fig. 1). The new magnet will provide an additional suppression of unwanted reaction products by a factor of about 100

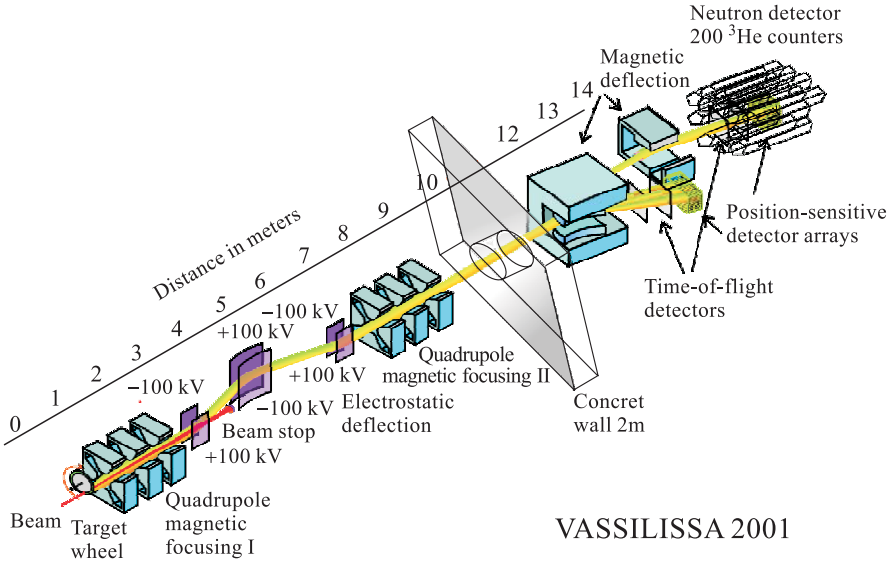

Fig. 1. A schematic view of the upgraded separator VASSILISSA

and a possibility of having the mass resolution at the level of 1.5–2 % for heavy nuclei with masses of about 300 amu. Its bending radius is 1.08 m, the effective length is 69.8 cm and the vertical gap is 114 mm. The entrance and exit boundaries of the magnetic dipole have

the values of 46° and −43°, respectively. To reduce chromatic aberrations the entrance and exit boundaries of the pole have a radius curvature of + 0.5 m and − 0.5 m.

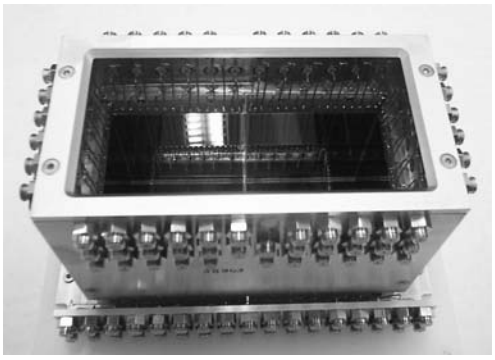

Fig. 2. The new focal-plane detector system

For the detection of heavy ER's at the focal plane of the new dipole magnet, a new detector system having a 32 strip detector assembly 60×120 mm in size and surrounded by backward detectors was also developed (see Fig. 2). Each strip is position sensitive in longitudinal direction. The position resolution along each strip was measured from test reactions. A value of 0.6 mm (FWHM) was obtained for sequential α–α decays, 1.0 mm for ER–α and 1.5 mm for ER–SF events. These values were obtained for energies of the ERs in the range from 4 to 15 MeV. It is planned to retain the old detector system [11] including the 8° dipole magnet behind the new 37° magnet, thus organizing the second detector area. Due to the compact configuration of this detector system it is possible to surround it by ^{3}He counters, thus creating the neutron detector with a high (about 50 %) detection efficiency.

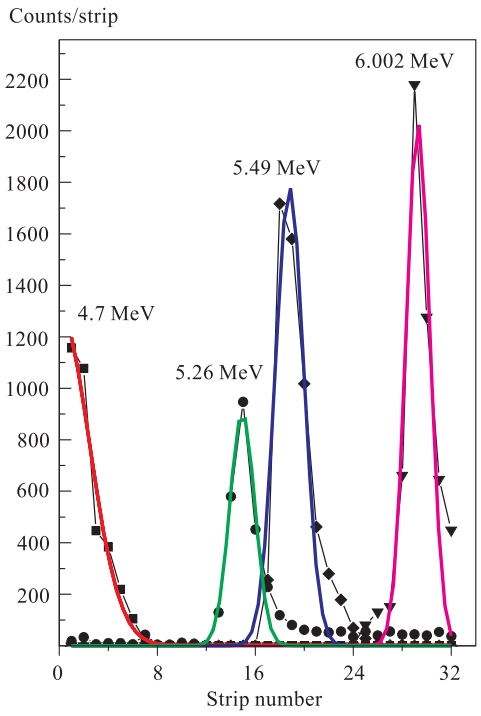

Fig. 3. The distribution of the ^{226}Ra α source; α with different energies at the focal plane of the separator. Obtained energy resolution is about 2 %, dispersion — 3.8 mm/%

For this purpose it will be necessary to build around the detector chamber an array with 200 ^{3}He counters (see Fig. 1).

Calculations show that the separator has a focal-plane inclination of $\approx 24°$, the mass (energy) dispersion D_x = 3.9 mm/% and the horizontal magnification $M_x = 1$. Measurements showed good stability ($\sim$ 0.1 %) of the effective length of the dipole up to the magnitude of the magnetic field $H = 1.15$ T. The results of the tests with the ^{226}Ra α source showed that the energy dispersion of the new magnet was about 3.8 mm/% and the resolution was about 2 % (see Fig. 3).

EXPERIMENT

In March–July 2001 the VASSILISSA separator with the new dipole magnet was tested. The analysis of the evaporation residues produced in complete fusion reactions with ^{40}Ar bombarding ions were used in the analysis. The ^{40}Ar beam was delivered from the U-400 cyclotron. The energy range of the accelerated ions varied from 190 to 210 MeV, the test ^{164}Dy and ^{208}Pb targets were used.

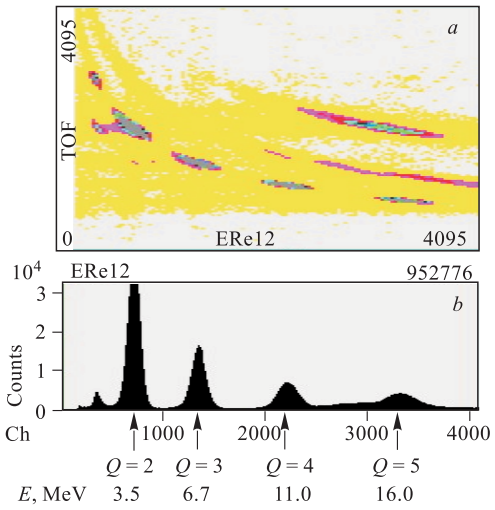

Fig. 4. The TOF-energy spectra, registered at the focal plane of the separator. The charge distribution of scattered ions is cleary seen

Using a specific ion optical regime of the separator it was possible to see at the focal plane of the separator the charge distribution of scattered ^{40}Ar ions (see Fig. 4). These data were used for the calibration of TOF-energy spectra together with the relation between the strip number (deflection angle) and $B\rho$ (magnetic rigidity) of ER's.

In Fig. 5 the experimental results obtained with the use of the ^{164}Dy target are presented. The isotope ^{197}Po was chosen and its distribution was plotted along the strip number of the focal plane detector, i. e., the deflection angle in the dipole magnet. The obtained structure in the ^{197}Po distribution allowed us to extract different charge states of ER's implanted into the focal-plane detectors.

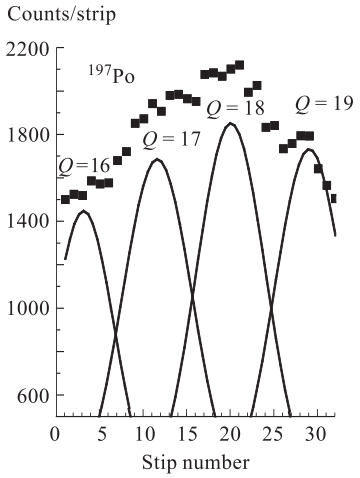

Fig. 5. The distribution of the ^{197}Po ER's along the strips of the focal-plane detector: squares — experimental values; solid lines — Gaussian fit

The time resolution of the time-of-flight system of the separator was about 0.7 ns, which corresponds to the value of about 1 % (for slow evaporation residues). For each ER, passing through the separator and detected at the focal plane, the time-of-flight (speed «v» of ER) and position of implantation/strip number (magnetic rigidity «$B\rho$» of ER) were measured. Using the high-resolution ion optical mode of the separator it became possible to separate different charge states for the Po ER's. At the two-dimensional spectrum energy-strip, three ER's peaks corresponding to different charge states were clearly seen.

It was possible to calculate the mass of the ER's, detected at the focal plane. For different charge states ($Q = 17$, 18, 19) the result was $A = 198.1 \pm 1$, 197.8 ± 1, 198.4 ± 1, respectively. Taking into account that the calculations were made for the isotope ^{197}Po, formed in the complete fusion reaction ^{164}Dy(^{40}Ar, $7n$)^{197}Po, the obtained mass resolution could be estimated as about 2 %.

In the case of the reaction ^{40}Ar + ^{164}Dy $\rightarrow^{204}$Po* the cross section values reach hundreds of microbarns. For the reaction ^{40}Ar + ^{208}Pb $\rightarrow^{248}$Fm* these values are equal to tens of nanobarns. Using the reaction ^{208}Pb(^{40}Ar, $2n$)^{246}Fm we estimated that the new dipole magnet provided an additional suppression factor of about 10 for scattered ions. Very clean α spectra were obtained. From the comparison with literature data [14] we could estimate that transmission efficiency for ^{246}Fm ER's was about 20 %. The obtained mass resolution for ^{246}Fm ER's, calculated according to the measured TOF and strip number, ranged from 244.5 to 247.2 that corresponded to the accuracy of about 2 %.

DISCUSSION

The development of the experimental technique with the use of electrostatic deflectors leads to the creation of the new class of kinematic separators — mass spectrometers of recoiling nuclei (recoil mass spectrometers). In these experimental set-ups the dipole magnet with a deflection angle of 25–30° is placed between the electrostatic condensers (deflectors), i. e., the scheme E-D-E is used (E — electrostatic deflector, D — dipole magnet). It allows one to reach a rather good mass resolution $\Delta M/M \approx 1/300$ for the heavy products of nuclear reactions together with rather high suppression factors for the background products (better than 10^7 for scattered beam ions). One of the first experimental set-ups of this type was a recoil mass spectrometer created at Rochester [15].

Later a number of experimental set-ups having the familiar scheme were created at different nuclear centres such as Legnaro (Italy) [16], Osaka (Japan) [17], Oak-Ridge (USA) [18], Argonne (USA) [19], Tokai (Japan) [20] and New Delhi (India) [21]. All these set-ups have the same scheme E-D-E and differ only in the number of focusing quadrupole lenses in front and behind the spectrometer itself. All these set-ups 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 the formation cross section varied from a few millibarns to a few nanobarns and depended 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 reaction products with heavy ions in the mass region of about and heavier than 200 amu. FMA in Argonne [19] was used for investigating proton radioactivity of neutron deficient isotopes of Pb and Bi [22], and JAERI–RMS in Tokai [20] for investigating decay properties of Sg isotopes in the reaction ^{30}Si + ^{238}U [23]. But in the latter case the set-up was used not in the mass resolution mode.

Recently the first test experiments have been performed with the new 37° dipole magnet installed behind the recoil separator VASSILISSA. Obtained results are very promising, it is possible now to define masses of the synthesized ER's with an accuracy of 5–6 mass units. This provides an additional reliability of the identification in the experiments aimed at the synthesis of superheavy nuclei in complete fusion reactions between transactinide targets and ^{48}Ca accelerated beams.

With the use of the upgraded separator VASSILISSA we plan 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 could be obtained 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 few hours) becomes possible.

The experiments performed with ^{48}Ca beams are the first step in a long-term programme aimed at the synthesis and study of decay properties of superheavy nuclei with neutron numbers close to the predicted spherical shell. The relatively long half-lives of the new isotopes with $Z = 112$, 114 (even-odd and odd-odd isotopes which could be obtained in reactions with ^{237}Np and ^{243}Am targets could have even longer half-lives), synthesized in the reactions with ^{48}Ca ions, dictate the necessity of upgrading the existing experimental set-ups and developing new ones, thus providing the possibility of direct mass measurements with an accuracy of 1 amu, but on the other hand, open new prospects for the investigation of chemical properties of superheavy elements.

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