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First experimental tests of the kinematic separator SHELS (Separator for Heavy ELement Spectroscopy)

A. Yeremin[1,a], O. Malyshev[1], A. Popeko[1], V. Chepigin[1], A. Svirikhin[1], A. Lopez-Martens[2], K. Hauschild[2], O. Dorvaux[3], B. Gall[3], and J. Gehlot[1]

[1] *FLNR JINR, Dubna, Russia*
[2] *CSNSM, Orsay, France*
[3] *IPHC, Strasbourg, France*
[4] *IUAC, New Dehli, India*

Abstract. Investigations of complete fusion reactions leading to the synthesis of heavy and superheavy nuclei have been an important part of the experimental program at the Flerov Laboratory of Nuclear Reactions (JINR, Dubna). For synthesis and decay studies of heavy nuclei, a project of modernization of the existing experimental set up VASSILISSA is now underway. The results of the first experimental tests with the modernized VASSILISSA separator are presented, in particular the experimentally measured transmission coefficients for recoil nuclei synthesized in asymmetric reactions with a ^{22}Ne beam. These results completely confirm the ion optical calculations performed during the design stage of the modernization.

1 Introduction

In the past, various types of reactions and identification techniques were applied to the investigation of formation cross sections and decay properties of transuranium elements. Fusion-evaporation reactions with heavy targets, recoil-separation techniques and identification of nuclei by parent-daughter genetic correlation after implantation into position-sensitive detectors have proven to be the most successful tools for production and identification of the heaviest elements known presently. This technique may be further improved and is very promising for the identification of new elements, the search for new isotopes and the measurement of new decay data for known nuclei. Within the past 15 years, the recoil separator VASSILISSA [1–4] has been used for the investigations of evaporation residues (ER's) produced in heavy ion induced complete fusion reactions. In the course of the experimental work a bulk of data on ER's formation cross sections, synthesized in asymmetric reactions was collected. From 2004 to 2009, experiments aimed at gamma and internal conversion-electron (ICE) spectroscopy of transfermium isotopes, produced in complete fusion reactions with accelerated heavy ions were performed using the **GABRIELA** (Gamma Alpha Beta Recoil Invetsigations with the ELectromagnetic Analyser) detector array [5]. In particular, isotopes of No and Lr were studied. The experiments using high intensity ^{22}Ne beam showed, that for slow evaporation residues, a higher transmission efficiency would be required in order to collect sufficient statistics in $\alpha - \gamma$ and $\alpha - \beta$ coincidences of heavier transfermium elements in the course of one-month experiments. Accumulated experience allowed us to perform ion optical calculations and to design a new experimental set up, based on the best parameters of existing separators and complex detector systems used at the focal planes of these installations [6, 7]. The new experimental device (the velocity filter SHELS) was developed starting from the existing VASSILISSA separator (see Fig. 1) and in May - July 2013, the first test experiments were performed using the GABRIELA focal plane detector array.

2 Experimental set up

The kinematic separator VASSILISSA had an ion optical scheme Q-Q-Q-E-E-E-Q-Q-Q-D (where Q stands for Quadrupole lens, E for Electrostatic Dipole, D for Dipole magnet) [1, 2]. It was a so called energy filter, since the main separation of the reaction products was based on the difference in E_{ion}/Q_{ion} ratio (were E_{ion} stands for energy of the recoil nucleus or reaction product, Q_{ion} - for ionic charge respectively). The set up was limited in electric rigidity of recoil nuclei to 2 MV (this means, for example, that only nuclei with energy E_{ion} - 40 MeV and charge state Q_{ion} - 20^+ can be transported through the separator). The VASSILISSA separator was used in experiments with a wide range of target-projectile combinations leading to transfermium isotopes, from ^{22}Ne + ^{238}U $\rightarrow$ ^{260}No* to ^{48}Ca + ^{208}Pb $\rightarrow$ ^{256}No*, and yielded transmission efficiencies from 2 % to 30 % respectively with acceptable factors of suppression of unwanted products.

The project of modernization of the VASSILISSA separator had two purposes: to increase the transmission effi-

[a] e-mail: eremin@jinr.ru

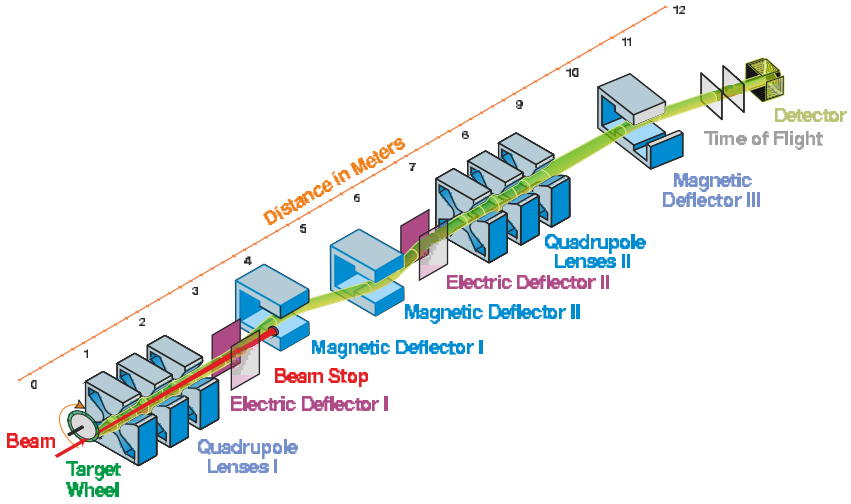

Figure 1. Schematic view of the SHELS separator.

ciency for very asymmetric combinations like ^{22}Ne + ^{238}U or ^{16}O + ^{244}Pu and to extend the region of accessible reactions by allowing the use of symmetric combinations like ^{136}Xe + ^{136}Xe, for which ER's have an electric rigidity of about 10 MV. It was planned to replace the central part of the separator, consisting of 3 electrostatic deflectors, by a combination of two electrostatic deflectors and two dipole magnets, thereby creating a velocity filter instead of an energy filter. The ion optical calculations showed that the increase in the aperture of the central separation part together with the optimization of the ion optical parameters of the focusing elements (quadrupole lenses) would allow to increase the transmission of slow ER's from asymmetric combinations by a factor of 3 at least. In order to optimize the transmission according to the asymmetry of the reaction, the new separator has been designed with movable electrostatic deflector plates.

The principal component of the modernized separator is the central part consisting of the 2 sets of electrostatic and magnetic dipoles, which accomplish the spatial filtering of recoil nuclei, multinucleon transfer reaction products and beam particles dispersing them according to their velocity and magnetic rigidity. The input focusing system consists of a triplet of magnetic quadrupoles. The triplet is located just behind the target and focuses the evaporation residues emerging from the target forming a quasi parallel beam. The ER's are then deflected in the electric field of the electrostatic dipole by an angle of 8^o whereas the trajectory of the full-energy beam is practically not affected. Each dipole magnet then bends the ER's by 22^o. The maximum dispersion of ER's occurs at the middle point between the 2 dipole magnets. The beam is dumped inside the first dipole magnet. After the dispersing system a triplet of magnetic quadrupoles is used, which serves for a better collection of ER's onto the focal plane detector. A post-separation dipole magnet installed behind the separator and before the focal plane detector provides an 8^o deflection for the ER's and gives an additional background suppression of scattered beam projectiles. The modernized separator is therefore of Q-Q-Q-E-D-D-E-Q-Q-Q-D type and operates in vacuum mode. It is 12 m long, see Fig. 1).

3 Experiment

During the experimental tests, the GABRIELA α, β, γ detector array was installed at the focal plane of SHELS. A beam of ^{22}Ne from the U400 cyclotron was used in conjunction with Au, ^{198}Pt, ^{206,208}Pb and ^{238}U targets. Fig 2 shows the typical alpha spectrum observed at the focal plane of SHELS following the complete fusion reaction ^{22}Ne + ^{198}Pt $\rightarrow$ ^{220}Ra* with a mid-target energy of E_{Ne} = 119 MeV.

In the case of the ^{198}Pt target, ER yields were measured for mid-target beam energies ranging from 115 to 125 MeV. A rotating Pt target (0.25 mg/cm^2 on a 2 μm Ti backing foil) was used. To extract the transmission efficiency for slow ER's formed in xn evaporation channels, previously obtained data for ER formation cross sections in the reaction ^{22}Ne + ^{198}Pt were used [8]. Values from 3.5 to 5 % were extracted for ER's formed in different xn channels. The accuracy of this method depends on the uncertainty in the incident-particle integral flux measurements (typically ± 10 %) and the uncertainty in the absolute cross section determination (typically ± 50 %). For evaporation residues from reactions with a Au target (standing target, 0.25 mg/cm^2 on a 3 μm Al backing foil) a transmission efficiency of the order of 6.5 % was obtained from comparison with previously measured formation cross sections [9]. The position of the standing Au target was closer to the entrance of separator (yielding a slightly bigger angular acceptance) than it was for the rotating Pt target. The measured transmission efficiency values are presented in Table 1.

In November 2013 test experiments with a newly developed ^{50}Ti beam [10] were performed. Using ^{164}Dy and

Table 1. Transmission efficiencies for different reactions and mid-target energies

Reaction	Beam energy (MeV)	Target thickness	Transmission efficiency
^{22}Ne(^{197}Au,5n)^{214}Ac	112	0.25 (metallic)	6.5 %
^{22}Ne(^{198}Pt,6n)^{214}Ra	120	0.25 (metallic)	5 %
^{50}Ti(^{164}Dy,4n)^{210}Ra	215	0.3	40 %
^{50}Ti(^{208}Pb,2n)^{256}Rf	240	0.37 (metallic)	15 - 30 %

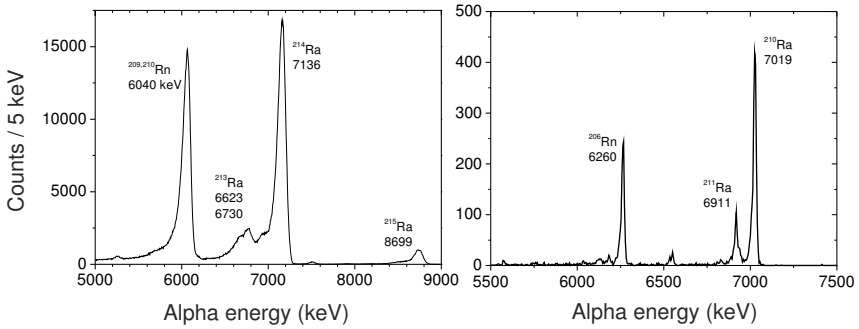

Figure 2. Left panel: Spectrum of alpha particles emitted by nuclei produced in the ^{22}Ne + ^{198}Pt → ^{220}Ra* complete fusion reaction. Right panel: Spectrum of alpha particles emitted by nuclei synthesized in the ^{50}Ti + ^{164}Dy → ^{214}Ra* reaction.

^{208}Pb targets, transmission efficiency for ER's and suppression factors for the scattered Ti beam were studied. For the reaction ^{50}Ti + ^{164}Dy, no available experimental data exists. Measured ER yields of Ra isotopes were compared with calculations, performed using the NRV-code [11]. In the case of the "cold" fusion reaction ^{50}Ti + ^{208}Pb, the ER formation cross sections have been carefully measured at the velocity filter SHIP [12]. At the U400 cyclotron, the accuracy in the beam energy measurements is ± 1.5 %. This leads to an uncertainty in the determination of the position in the excitation function of about 3 MeV. Given the narrowness of the excitation function, the accuracy of the transmission efficiency determination from comparison with the previously measured data can reach a factor of 2 or even more. The results for the transmission efficiencies of ER's produced in ^{50}Ti-induced reactions are presented in Table 1.

Acknowledgements

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