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THE VASSILISSA FACILITY FOR THE ELECTROSTATIC SEPARATION AND STUDY OF COMPLETE FUSION REACTION PRODUCTS

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1. INTRODUCTION

In recent years the use of complete-fusion reactions induced by heavy ions has resulted in considerable progress in the synthesis and study of the properties of nuclei far from the line of beta-stability. In particular, a number of new neutron-deficient isotopes has been produced in the region of heavy nuclei[1,2,3]. Some attempts to synthesize transfermium and superheavy elements have led to the production of nuclei with $Z = 107-110$[3-5].

The cross sections of the reactions leading to the synthesis of the neutron-deficient isotopes of transuranium elements far from beta stability do not exceed 10^{-30} cm^2 and decrease rapidly as the atomic number Z of the compound nuclei produced increases. Despite this fact, the high intensity of the available heavy ion beams (up to 10^{13} s^{-1}), which permits compound nucleus production in nuclear reactions having cross sections of up to 10^{-36} cm^2, makes us hopeful of the possible production of a considerable number of new nuclides.

The experimental facilities designed for studies of this kind of nuclear reactions should satisfy the following requirements: a high efficiency of transporting compound nuclei (recoil atoms) from the target to the detector, a high degree of separation of recoil atoms from background products and from the scattered projectiles.

In some studies, e.g. refs.[5,6,7], the high detection efficiency (~50%) for short-lived nuclei was achieved by means of facilities in which recoil atoms were implanted into collectors made of different materials (e.g. Al and plastic foils) and then mechanically transported to detectors. The suppression of background products was provided by collimating recoil atoms and separating them according to their ranges in the stacks of thin collector foils. Some mechanical systems for transporting recoil atoms made it possible to observe the spontaneous fission of nuclei with half-lives of up to 10^{-4} s.

The use of a gas jet for transporting recoil atoms can provide the delivery of nuclear reaction products to detectors with an efficiency of 40-80%.The gas-jet technique allows the study of the spectra and kinetic energies of spontaneous fission fragments from atomic nuclei with half-lives $T_{1/2}>10^{-1}$ s[8,9]

A mass-separator ion source based of the processes of recoil atoms stopping and charge exchange in a gas flow was described in ref./10/. This type of ion source (IGISOL) provided a speed of operation of 10^{-3} s and an efficiency ranging from 10^{-2}% to about 5% depending on the projectile mass. It is noteworthy that mass separators, operated in conjunction with ion sources, have had so far limited applications for the synthesis of short-lived transfermium nuclides.

Kinematic separators seem to be the most versatile facilities for investigating nuclei far from stability, as well as for synthesizing and studying new elements. In connection with the synthesis of heavy nuclei using complete-fusion reactions the following experimental setups are of greatest interest. These are the velocity filter SHIP/11/, electrostatic separators/12,13/ and gas-filled electromagnetic separators/14,15/. These facilities furnish a fairly high efficiency (20-60%), a short time ($\geq 10^{-6}$ s) required for transporting recoil nuclei from the target to the detectors, and a high degree of suppression of the scattered projectiles and background products. For example, the velocity filter SHIP provides the separation factors for Ar, Kr, and Xe beams equal to 10^{12}, 10^{10} and 10^{8}, respectively. This made it possible to implant recoil atoms directly into semiconductors. The recoil atomic mass can be roughly ($A/\Delta A \sim 10$) determined by measuring their energy and time-of-flight. The energy measurements for the particles emitted by the nuclei implanted into the detector and of the time interval between the successive α decays offer the possibility of establishing recoil - α-α correlations and of identifying with a sufficient reliability the compound nucleus formed in a heavy ion-induced reaction.

2. DESCRIPTION OF THE ION-OPTICAL SYSTEM OF THE VASSILISSA FACILITY

The VASSILISSA facility was designed at the Laboratory of Nuclear Reactions of JINR, Dubna. The principal component of the facility is an electrostatic separator of nuclear reaction products/16/ which provides the spatial separation of the trajectories of recoil atoms and projectiles by virtue of some differences in their energy.

Complete-fusion reaction products with the mass $A=A_1+A_2$ escape from the target in the beam direction and have the energy $E = E_1A_1/(A_1+A_2)$, where E_1 is the projectile energy, and A_1 and A_2 are the mass numbers of the projectile and the target nucleus, respectively. Thus for the comlete-fusion reactions induced by heavy ions with A_1 randing from 20 to 60 on target nuclei with the mass $A_2 > 100$ the ratio E_1/E exceeds 5.

Some literature data (see, e.g./17,18/)permit rather accurate calculations of charge spectra and average charges for the projectiles and recoil atoms after their passing through thin foils (q_1 and q, respectively). In a wide range of complete fusion reactions between heavy ions with masses from 20 to 60 and target nuclei with masses $A_2 > 100$ the ratio of average charges, q/q_1, lies between 1.1 and 1.4.

The deflection angle of ions in an electic field is proportional to the quantity q/E and, consequently,

$$\alpha/\alpha_1 \sim \frac{(A_1+A_2)}{A_1} \times \frac{q}{q_1},$$

where α and α_1 are the deflection angles for recoil atoms and projectiles, respectively. The deflection angle of an ion in a magnetic field is proportional to q/p, where p is the ion momentum. Hence $\alpha/\alpha_1 \sim q/q_1$ since the momenta of the projectile and recoil atom are approximately equal in complete-fusion reactions.

The principle of electrostatic separation was chosen because the difference between the deflection angles of recoil atoms and projectiles is much greater in an electic field than in a magnetic one. For example, in the reaction ^{208}Pb(^{40}Ar, 2n)^{246}Fm in which an excitation function maximum lies at $E_\ell \approx 200$ MeV, the recoil atom energy is $E \approx 33$ MeV, the average charge of recoil atoms is $q = 20$ and that of the projectiles is $q_1 = 16$, the ratios of the deflection angle are $\alpha/\alpha_1 \approx 8$ and $\alpha/\alpha_1 \approx 1.25$ in electric and magnetic fields, respectively.

The products of complete fusion reactions are emitted from the target in the beam direction with some spread in angles, energies, moments and charge states. The evaporation from the compound nucleus of neutrons, protons and α particles and multiple scattering in the target material contribute to the variance of the angular distribution of the recoil nuclei. The width of the angular distribution depends on the mass ratio of the projectile and target nuclei, on the number and kind of the light particles evaporated, on the target thickness, and on the bombarding energy. The angular distribution observed in the (HI,xn)-type reaction is considerably narrower than that of a (HI,αxn) reaction. In fig.1 one can see the angular distributions calculated for recoil atoms formed in bombardments of a 0.5 mg/cm^2 Pb target with 200 MeV Ar and with 120 MeV Ne ions.

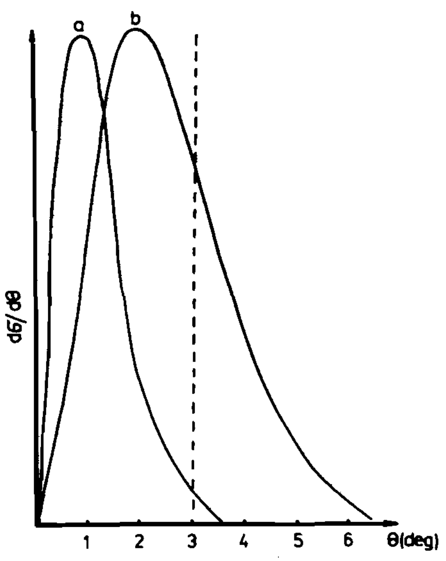

Fig.1. (a) The angular distribution of recoil atoms in the $^{208}Pb(^{40}Ar,2n)^{246}Fm$ reaction. (b) The angular distribution of recoil atoms in the $^{208}Pb(^{22}Ne,4n)^{226}U$ reaction. The dashed line shows the angular acceptance of the VASSILISSA facility.

The energy and momentum dispersions of recoil atoms are determined mainly by the target thickness and by the chromaticity of the ion beam.

A fairly high efficiency of transporting recoil nuclei is achieved if the experimental facility has a large angular acceptance and provides the transmission of recoil nuclei having a sufficiently large dispersion in $\Delta E/E$, $\Delta P/P$ and $\Delta q/q$. In designing the VASSILISSA facility we aimed at achieving a 10-40% transport efficiency for a wide range of complete-fusion reactions. The angular acceptance was chosen to be $\pm 3^{\circ}$ that provided for 30%-80% of all target recoils to pass through the facility aperture (see,e.g., fig 1). Calculations for the ion-optical system of the facility were carried out using the TRANSPORT/19/ and DECAY TURTLE/20/ computer codes. The calculations showed that a sufficiently high efficiency is provided by the facility if it transports recoil atoms with relative dispersions in energy, $\Delta E/E \sim \pm 10\%$, in momentum, $\Delta p/p \sim \pm 5\%$, and in charge, $\Delta q/q \sim \pm 10\%$. For example, 60% of the recoil atoms produced in the reaction $^{208}Pb(^{40}Ar,2n)^{246}Fm$ on a 0.5 mg/cm^2 thick target at bombarding energy $E_\ell \approx 200$ MeV fall into the range characterized by energy, momentum and charge dispersions of ±10%, ±5% and ±10%.

A schematic view of the VASSILISSA facility is shown in fig.2. The facility consists of a rotating target device, a separator system including three electrostatic dipoles, a focusing system comprising two triplets of electromagnetic quadrupoles located on the beam exis in front of and behind the electrostatic dipole system, and a detector array for recording recoil atoms and their radioactive decay products. The main parameters of the ion-optical system of the VASSILISSA facility are given in table 1.

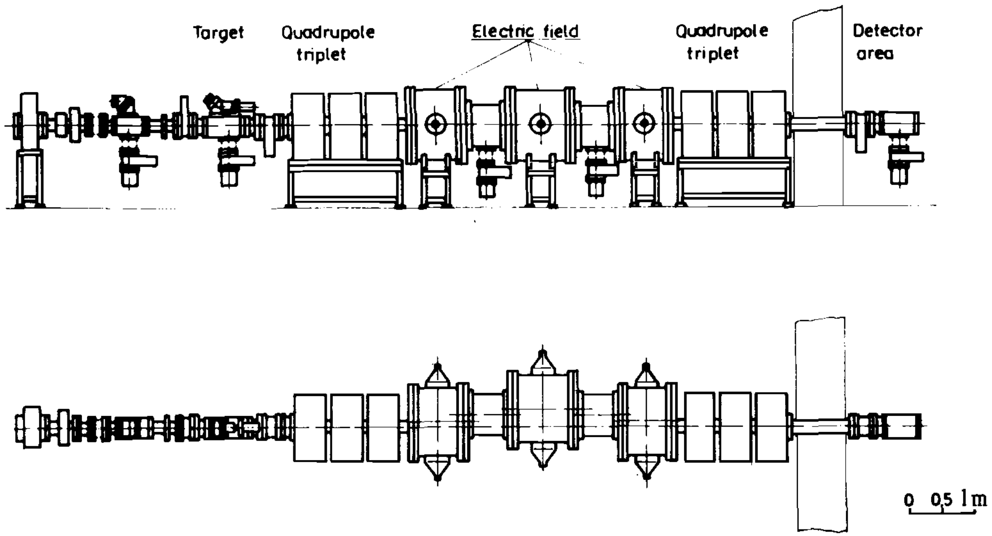

Fig.2. Schematic view of the VASSILISSA facility.

Table. Parameters of the ion-optical system

Angular acceptance	$\pm 3^{\circ}$
$\Delta E/E$	±10%
$\Delta q/q$	±10%
$\Delta p/p$	±5%
Transport time	3×10^{-6} s
Distances between:	
target and 1st triplet	0.4 m
target and 1st condenser	3.5 m
target and 2nd triplet	7 m
target and detectors	12 m
Effective length of quadrupole lenses	35 cm
Aperture radius	10 cm
Maximum field gradient	10 T/m
Effective lengths of 1st and 3rd condensers	47 cm
Effective length of 2nd condenser	82 cm
Distance between plates	15 cm
Maximum value of electric field strength	20 kV/cm
Target diameter	1 cm

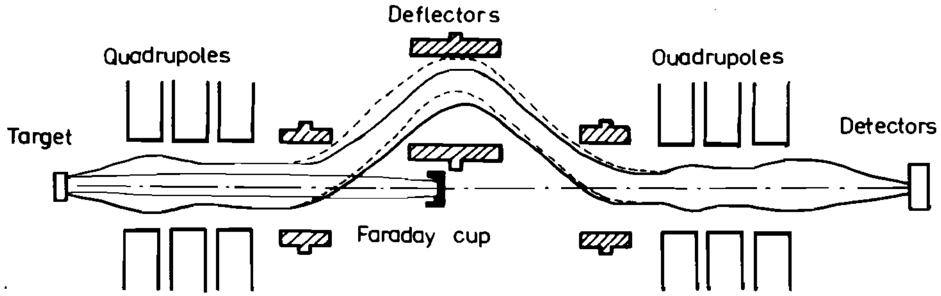

Fig.3. The envelopes of recoil nuclei beams. Full and dashed lines stand for the ions having the energy to charge state ratios $(E/q)_1$ and $(E/q)_2$ respectively ($(E/q)_1=1.05(E/q)_2$).

The separation of recoil atoms from the ion beam is performed using a system consisting of three electrostatic dipoles. The maximum dispersion in energy is achieved in the central plane which passes through the second dipole. Recoil atoms are deflected through an angle of 8^0 and reach the aperture of the second dipole whereas the projectiles pass through the first dipole almost undeflected and then stop in a Faraday cup (see fig.3). Further separation of recoil atoms from scattered projectiles takes place in the second and third dipoles.

The focusing system of the VASSILISSA facility consists of two triplets of broad aperture magnetic quadrupoles. The first triplet located behind the target collects the recoil atoms escaping from the target and shapes them into a quasiparallel beam 8 cm x 10 cm in size. This beam of recoil atoms passes through the aperture of electrostatic dipoles practically without losses. The focusing action of the electrostatic dipoles is weak. The second triplet of magnetic quadrupoles serves for focusing the beam of recoil atoms into the detection device. Fig.3 shows the envelope of the recoil atom beam produced in the reaction $^{208}Pb(^{40}Ar,2n)^{246}Fm$, which has been calculated for three charge states of recoil atoms and for the relative momentum spread $\Delta p/p \sim \pm 5\%$.

3. TECHNICAL DESCRIPTION OF THE VASSILISSA FACILITY

As is seen from fig.2, the main part of the facility is located in an experimental hall inaccessible during heavy ion bombardments. The detector array and electronics are shielded by a 2-m thick concrete wall, which allows operation during the experiment.

3.1. Target Device

The facility employs target fastened on a rotating disc provided with 6 holes. The target disc is rotated by a motor with fine control of the number of revolutions. The electronic system synchronizes the phase and frequency of disc rotation with those of the cyclotron beam pulses. The frequency of beam pulses from the U-400 cyclotron ranges between 100 and 150 Hz, the duration of one beam pulse varies from 1 to 2.5 ms. Each beam pulse reaches the corresponding aperture of the target disc and passes through it without touching the disc body. The target material is deposited on Al, Cu or Ti backing foils 1-5 μm thick or on 50 $\mu g/cm^2$ graphite layers which are glued upon the apertures available in the target disc. The targets have a thicknesses ranging from 0.2 to 0.8 mg/cm^2. The doublet of magnetic quadrupoles placed at a distance of 3 m in front of the target provides a beam spot smaller than 1.2 cm in the target plane. The bombarding energy can be varied within 1-2 MeV by a set of rotating degraders. The energy is measured with an accuracy of 1% by recording scattering ions by semiconductor detectors.

3.2. Magnetic Quadrupoles

Standard 20 cm full-aperture magnetic quadrupole lenses 25 cm in length are used. To facilitate the technology of their manufacture the shape of the magnetic poles was chosen to be stepwise. To reduce the influence of the multipole components of the magnetic field the step-shaped poles were calculated using the Poisson computer code/21/. Magnetic field measurements were carried out using a Hall gauge. The distance between the magnetic lenses is equal to 30 cm. The mutual influence of the lenses is not great and is taken into account in the calculations. The optical axes of the lenses coincide with geometrical ones within 0.1 mm and these axes were aligned with the projectile beam axes with an accuracy of 0.1 mm.

3.3. High-Voltage System

High voltage is supplied to each pair of the condenser plates symmetrically from a separate high-voltage source. The maximum voltage on the plates is ±150 kV. The electric network of the high-voltage power supplies includes ballast resistors which limit leakage currents in the case of 100 μA breakdowns on the condenser plates. The high voltage stability is 0.5%, ripple is 2.5% at 50 Hz. Taking into account the energy and charge spread of the recoil atoms the ripple does not produce a noticeable effect on the transport efficiency. Positive potential is applied to the plates made of stainless steel. Negative potential is applied to aluminium plates. The plates of the first and the third condenser are 35 cm in length and the length of the second condenser is 70 cm. The effective length of the plates was calculated according to the Poisson code /21/ and was tested experimentally with a calibration alpha source.

During 6-8 hours prior to operation the plates were conditioned so that the leakage currents did not exceed 1.5 μA on the plates at a voltage of ±100 kV. Breakdowns occur on the plates not more than once in five hours in a vacuum of $1\cdot 10^{-6}$ Torr. The primary beam passing through the first condenser does not affect the occurrence of breakdowns at an intensity of up to $3\cdot 10^{12}$ pps.

3.4. Vacuum System

All the components of the vacuum system, which is 3.5 m^3 in volume, are made of stainless steel. A pressure of $1\cdot 10^{-6}$ Torr is provided by five turbine pumps with an evacuation rate of 500 l/s each. The vacuum system has an inleakage rate of the order of $8\cdot 10^{-4}$ l•Torr/s. The limiting vacuum is determined mainly by gas release from the surfaces of the system. A spectral analysis indicates almost the entire absence of water or nitrogen in the vacuum volume of the facility. To reduce gas release the inner surfaces of the system were conditioned using a glow-discharge in argon.

3.5. Detector System

The time-of-flight technique consisting of two (start and stop) detectors based on microchannel plates is used to determine the velocity of recoil atoms. The detectors are 60 mm in diam. and the path length is equal to 50 cm. The time resolution for ~ 30 MeV recoil atoms with the mass A ~ 250 is 1 ns. The detection of recoil atoms and their radioactive decay products (α particles and fission fragments) is performed using an array of semiconductor detectors or a double ionization chamber.

4. CALIBRATION MEASUREMENTS

Calibration measurements are carried out using a ^{249}Cf α source covered with a 10 μm Al foil and placed in the target plane. The α particles passing through the foil have an energy of 3.9 MeV and a relative energy spread of 15%. The α detection is performed by a 75-mm diam. semiconductor detector placed in the focal plane of the separator. The calculated alpha particle transmission through the facility is 90%; the experimental value is equal to 75%. The values of potentials on electrostatic condensers and of currents in the magnetic quadrupoles coincide with the calculated ones within 5%. In the first experiments using Ne, P and Ar ion beams the separation factors for scattered ions were obtained to be equal to 10^{12}, 10^{11} and 10^{10}, respectively.

5. CONCLUSION

The first results obtained using the VASSILISSA facility make us hopeful that it will be a good instrument for studying complete fusion reactions. The high speed of recoil transport and high beam separation factors of the facility will permit experiments to investigate new short-lived nuclides formed in nuclear reactions with cross sections smaller than 10^{-34} cm^2.

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Еремин А.В. и др. E15-88-137
Экспериментальная установка для изучения характеристик
продуктов реакций полного слияния с электростатической
сепарацией от пучка тяжелых ионов /ВАСИЛИСА/

Описана экспериментальная установка ВАСИЛИСА, главной частью которой является электростатический сепаратор продуктов реакций полного слияния от ионов пучка. Установка способна пропускать ядра отдачи, вылетающие из мишени в направлении пучка в угол 10^{-2} стер. и имеющие распределение по энергии и ионному заряду ±10%. Время транспортировки ядер от мишени к детекторам составляет $3\cdot10^{-6}$ с. Сепарация рассеянных ионов производится системой из трех электростатических конденсаторов. Факторы очистки от ионов Ar, P, Ne составляют 10^{10}, 10^{11}, 10^{12} соответственно.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

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Yeremin A.V. et al. E15-88-137
The VASSILISSA Facility for the Electrostatic Separation
and Study of Complete Fusion Reaction Products

The VASSILISSA facility is described, the main component of which is an electrostatic separator of complete-fusion reaction products from the ion beam. The facility is capable of transmitting recoil nuclei emitted by the target in the beam direction within a solid angle of 10^{-2} ster and having a ±10% spread in energy and ionic charge. The time required to transport the nuclei to detectors is $3\cdot10^{-6}$ s. The separation of scattered ions is performed using a system of three electrostatic condensers. Separation factors are obtained for Ar, P and Ne to be equal to 10^{10}, 10^{11} and 10^{12}, respectively.

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

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