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The Dubna Gas-Filled Recoil Separator: a Facility for Heavy Element Research

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The Dubna gas-filled recoil separator was put into operation in 1989. Its D-Q-Q design, main parameter values as well as first tests at the U400 cyclotron were described in Ref. [1]. Since then many significant improvements and numerous model experiments were accomplished to develop the separator into a facility for heavy element research. Owing to its underlying principle, the separator shows excellent qualities for fusion-evaporation reactions induced by ^{40}Ar and similar projectiles. Therefore the main goal of our recent developments was to achieve a reliable application of the separator to highly asymmetric fusion-evaporation reactions induced by much lighter projectiles like ^{18}O or ^{22}Ne on targets of the transuranium nuclides. Special emphasis was laid on the possibility of applying very intense beams of these lighter projectiles to strongly radioactive and rather exotic target species like ^{242}Pu or ^{248}Cm (see also Refs. [2, 3]).

Being very attractive from the viewpoint of heavy element research, the highly asymmetric fusion-evaporation reactions represent the most difficult case for studying these with recoil separators. In fact, as compared, e.g., to ^{40}Ar-induced reactions, the asymmetric reactions are characterized by much broader angular distributions of evaporation residues (EVRs) recoiling out of a target of a finite thickness; thus, from the very beginning, only some 15 to 30% of the EVRs are accepted by the D-magnet (see Fig.1). The large angular divergency of the EVRs restricts effective target thicknesses by values of about 0.2 mg/cm^2 or less. Other complications originate from low kinetic energies $<E_R^0>$ of EVRs recoiling out of the target (typically $<E_R^0>$ are below 10 MeV) as well as from large dispersions of E_R. Perceptible $<E_R^0>$ losses occur in the 3.7-m long path of EVRs through the gas filling the separator (usually H_2 at 0.7 to 1 Torr), as well as in the exit window and in the pentane gas filling the detection module. As it was shown in our measurements (Fig.2), the transmission of EVRs through the separator and hence the efficiency ϵ_c of the EVR collection onto the focal plane Si detector array falls down rapidly with decreasing $<E_R^0>$. Furthermore, a decrease in $<E_R^0>$, i.e., in the average EVR velocity, causes a lowering of the average charge state <q> of EVRs in the gas media and seems to give rise to significant fluctuations of q. For the data shown in Fig.2, the <q> value of the polonium EVRs decreases from 3.6 at $<E_R^0>$=12.5 MeV down to 2.1 at $<E_R^0>$=4.5 MeV. Appreciable q fluctuations concurrent with the low <q> values characteristic of EVRs from very asymmetric reactions are supposed to give additional reasons for fairly low EVR collection efficiencies ϵ_c in these cases as well as for extended image sizes at the focal plane (see Fig.3).

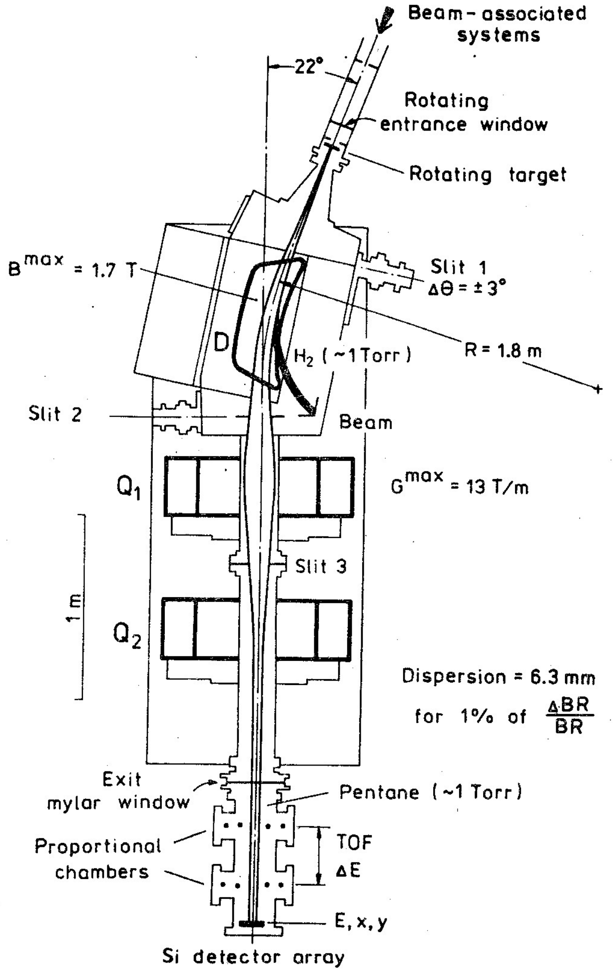

Fig.1. Lay-out of the Dubna gas-filled recoil separator. The detection system of the separator involves six individual 20 mm wide by 30 mm high Si detectors covering an area of 120×30 mm^2 at the focal plane. Two large-area (140×60 mm^2) multiwire proportional chambers placed in pentane at a pressure of about 1 Torr are used for time-of-flight measurements of EVRs and background particles arriving at the Si detector array (see also Ref. [4]). The 0.5-micron mylar exit window separates the detection module from the gas media of the separator.

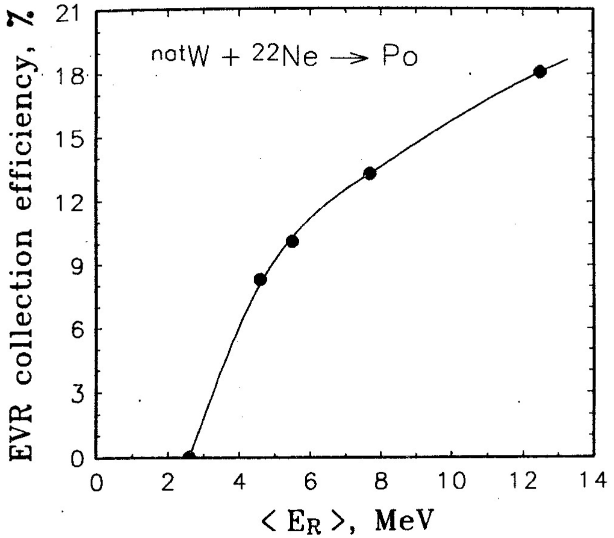

Fig. 2. The dependence of the EVR collection efficiency ϵ_c on the average initial kinetic energy $<E^0_R>$ of the EVRs produced by the ^{nat}W+^{22}Ne reaction.

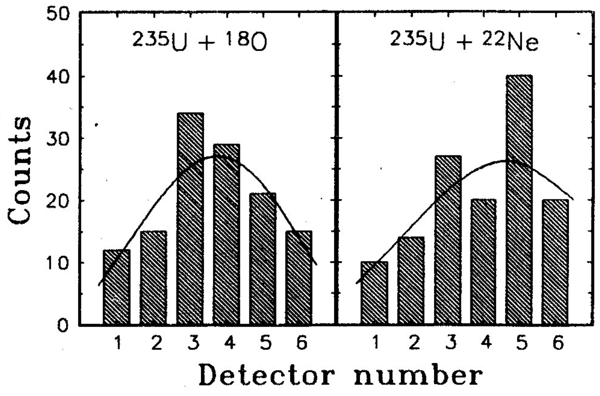

Fig.3. Measured distributions of EVRs with Z=100 and Z=102 over six Si detectors at the focal plane.

Table 1. Summary of measured or estimated (*) characteristics of separation

$<E^0_R>$ values are given for EVRs recoiling out of the middle of the target used in a particular experiment. Collection efficiencies ϵ_c are given for an area of 120×30 mm². The ϵ_c values do not involve any detection efficiencies and are not corrected for "geometrical" EVR losses associated with the detection module (i.e., for those caused by scattering of EVRs on the mylar window, by the ≈90-% geometrical transparency of the module, and by some other minor reasons). Image sizes are specified by FWHM values (in cm).

Target Projectile Z of EVRs	^{nat}W ^{22}Ne Po	^{235,238}U ^{18}O Fm	^{235}U ^{22}Ne 102	^{242}Pu ^{22}Ne 104	^{238}U ^{26}Mg 104	^{206,207}Pb ^{34}S Cf	^{207}Pb ^{40}Ar Fm
Beam energy, MeV	112	93	122	114	134	170	196
$<E^0_R>$, MeV	11.0	5.7	8.7	7.6	11.5	21.8	28.2
<q>	3.3±0.1	2.1±0.1	2.3±0.1	$1.9^{+0.1}_{-0.2}$		4.8±0.2	5.9±0.2
ϵ_c, %	16±3	3±1	6±2*	6±2*	10*	35±10	45±10
Suppression of							
-full energy projectiles	>10^{15*}	>5·10^{16}	>10^{17}	>2·10^{18}	>4·10^{17}	>3·10^{15}	
-scattered projectiles with E>35 MeV			2·10^{16}	7·10^{16}	5·10^{15}	10^{14}	5·10^{12}
-target-like products	>10^{3*}			≥10^{4}			5·10^{4*}
Image size							
-horizontal	6.8±0.2	8.7±1.4	12±3			7±1	
-vertical	2.1±0.1	3.5±0.2					

A summary of measured or estimated characteristics of separation for a number of highly asymmetric fusion-evaporation reactions is presented in Table 1. It is seen here that collection efficiencies ϵ_c for heavy EVRs produced by these reactions range between 3% and 10%. However, despite the fairly low ϵ_c values, the net sensitivity of experiments can be essentially improved by applying very intense beams of ^{18}O, ^{22}Ne and other lighter projectiles, up to (2-4)·10^{13} pps, which are provided by the Dubna U400 cyclotron. To accept such intense beams, the separator is equipped with beam wobbling systems, fast rotating entrance windows, rotating target wheels, etc. We stress also that for asymmetric reactions a very favourable separation quality lies in the extremely strong suppression of both full energy projectiles and scattered beam particles.

The potentialities of the separator for heavy element research with asymmetric fusion-evaporation reactions can be exemplified by our recent experiments on the production of isotopes of element 104 in the ^{242}Pu+^{22}Ne and ^{238}U + ^{26}Mg reactions [2]. In these experiments, the ^{22}Ne beam with a typical intensity of 1.5·10^{13} pps applied to a rotating target of ^{242}Pu [3] allowed us to reach, in several days, a total beam dose of 3.6·10^{18}. As is shown in Fig.4 and Table 2, as a result of this beam dose, we have detected between cyclotron beam pulses 38 α decays of ^{259}104, seven correlated α-α events of $^{259}104 \xrightarrow[3s]{\alpha} {}^{255}102 \xrightarrow[3.3m]{\alpha\ 62\%} {}^{251}$Fm, as well as 37 SF decays coming from ^{260}104 and, partially, ^{259}104. At the given ^{22}Ne

Table 2. Summary of observations made between cyclotron beam pulses in the ^{242}Pu+^{22}Ne and ^{238}U+^{26}Mg reactions

	^{242}Pu+^{22}Ne	^{238}U+^{26}Mg
Beam energy	114 ± 2 MeV	134 ± 2 MeV
Typical beam intensity	1.5·10^{13} pps	1.6·10^{12} pps
Total beam dose	3.6·10^{18}	0.5·10^{18}
N_{sf}	37	3
N_α for ^{259}104	38	3
N_α for ^{255}102	40	3
$N_{\alpha-\alpha}$ for ^{259}104→^{255}102	7	0
N_α for [^{256}102]	21	1

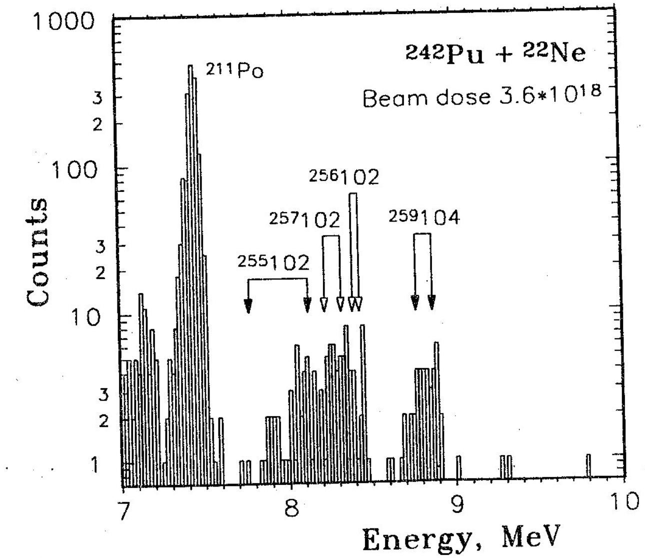

Fig.4. The beam-off α-particle-energy spectrum from the ^{242}Pu+^{22}Ne reaction at the ^{22}Ne bombarding energy 114 MeV. Most of α activities with E_α below 7.7 MeV (e.g., ^{211}Po) originate from the ^{197}Au+^{22}Ne reaction used for calibrations.

bombarding energy, the production cross section of $^{259}104$ in the ^{242}Pu + ^{22}Ne reaction could be evaluated to be roughly 1.5 nb. A remarkable long-term stability of the separator operation was revealed in the 104 experiments.

In April 1993, the separator was employed in the collaborative Dubna–Livermore experiments aimed at the synthesis of the heaviest isotopes of element 106 in the ^{248}Cm + ^{22}Ne reaction. In these experiments, a Livermore position-sensitive Si detector system [5] has been used. The Dubna–Livermore ^{248}Cm + ^{22}Ne experiments have led to the discovery of the two new, α-decaying nuclides $^{265}106$ and $^{266}106$ [6] with neutron numbers close to the theoretically predicted neutron-deformed shell N=162.

One of the main current developments of our technique is associated with the improvement of the focal plane Si detector array. The present set of six ordinary Si detectors is replaced by an array of position-sensitive PIPS detectors produced by Canberra Semiconductor. The new detector array of 120×40 mm^2 will be composed of three 40×40 mm^2 detectors each one involving four 10 mm wide strips with a position sensitivity in vertical direction. A corresponding electronic system was designed and its construction is now under way. The implementation of the position-sensitive focal plane detector array will make it possible to suppress backgrounds by two more orders of magnitude and thus radically extend the possibilities of revealing and identifying the rarest decay chains in heavy element studies.

Another prospective development of the separator we associate with constructing behind it a mass separation system. For this purpose, the best choice seems to be the IGISOL technique similar to that developed in Jyväskylä [7] or at RIKEN in Tokyo [8]. The involvement of mass separation would essentially widen the scope of possible research.

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A Neutron Multidetector spectrometer "HENDES"

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The main goal of the "HENDES" project (High Efficiency Neutron DEtection System) is to build the large solid angle neutron detector facility for the investigation of neutron emission mechanisms in different heavy ion-induced reactions. Neutron energy spectra, angular distributions, mean value and neutron multiplicity distribution will be measured in coincidence with fission fragments or reaction products. The measurements of neutron energy spectra and fission fragment velocities will be carried out by means of the time-of-flight method.

The basic element of this experimental set-up is the position sensitive neutron detector (PSND) – quartz tube 100 cm long and 6 cm in diameter filled with liquid scintillator. Scintillator is viewed from both butt-ends by two photomultipliers (PM's). In order to avoid light attenuation PM's are coupled directly to the liquid. The detector is placed in totally light-tight titanium container. The full weight of PSND-module is near 9 kg. 48 PSND are mounted around the reaction chamber in a distance 46 cm and 55 cm from beam axis. (See Fig.1).

The reaction chamber consists of two 2 mm thick stainless steel semi spheres 80 cm in diameter and central Ti-ring. Fission fragment detectors, light charged particles telescope and target device are mounted inside the vacuum volume on the central ring.