TIME-OF-FLIGHT SPECTROMETER FOR MEASURING THE REACTION PRODUCTS*

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The heavy-ion reactions are characterized by a large number of channels, differing in various characteristics (angular distributions, mass distributions, kinetic energy, reaction cross sections, *etc.*). The major characteristics of two complex nuclei interaction processes is the mass distribution of reaction products. Therefore, one of the main features of the experiment is a direct measuring of the reaction products masses. This is directly achieved by measuring the masses of the forming nuclei. This paper describes the results of direct measuring of the reaction products masses using a precision time-of-flight technique. Tn this technique, microchannel plates (MCP) are used as the start and stop detectors. Using the 25 cm path length, time resolution of 240 ps was obtained, which made it possible to determine the nuclei masses with an accuracy of ±5 amu. The technique is applied in experiments to measure the heavy nuclei fission fragments characteristics (mass distribution and total kinetic energy), in reactions of complete and incomplete heavy ions fusion with nuclear targets.

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1. Introduction

Studying the characteristics of nuclear reaction products, their kinetic energies and masses are of particular importance. To detect them in a modern physical experiment, the time-of-flight products measurements of such reactions can be used. With the beginning of the use of low-intensity radioactive nuclei beams in nuclear physics experiments, it is necessary to solve the problems of obtaining the required intensity beams, accelerating them to the required energy, and detecting the nuclear reaction products. Special conditions are imposed on the detecting equipment's characteristics:

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high energy and time-of-flight resolutions, high purification coefficient of reaction products from the primary beam, *etc.* The time-of-flight method is one of the most effectively used techniques for determining the particle energy [1, 2]

$$E_K = E_0 \left(\frac{1}{\sqrt{1-\beta_2}} - 1 \right), \tag{1}$$

where $E_0 = m_0 c^2$ — ion rest energy, $\beta = \frac{V}{c}$ — relative speed ions, $V = \frac{L}{t}$ — speed of ions [2].

Time-of-flight systems are most effectively used at detecting heavy nuclei fission fragments [3–5]. At the present stage of experimental nuclear physics development, a combination of various registration methods and identification of nuclear reaction products is used.

As a part of detecting the time-of-flight in experiments at the high-resolution magnet analyzer (MAVR) facility of the Flerov Laboratory of Nuclear Reactions (FLNR) JINR, a time-of-flight system was created. The system allows to carry out the correlation measurements of fission fragments with particles detected in the focal plane of the magnetic spectrometer.

2. Detector based on MCP

The time-of-flight technique requires the starting detector with a high time resolution, low sensitivity to the light particles background, minimal braking losses at detecting heavy reaction products, and resistance to radiation damage. The detector based on microchannel plates (MCP) meets all these conditions [6–8]. The detector consists of an input foil (lavsan) of 160 μg/cm^2 with an aluminum sputtering thickness of 20 μg/cm^2, an accelerating grid, an electrostatic mirror, and an assembly of microchannel plates 32.5 mm in diameter. The particle, passing through the foil, knocks out electrons from the MCP detector, whereas, the electrons are accelerated

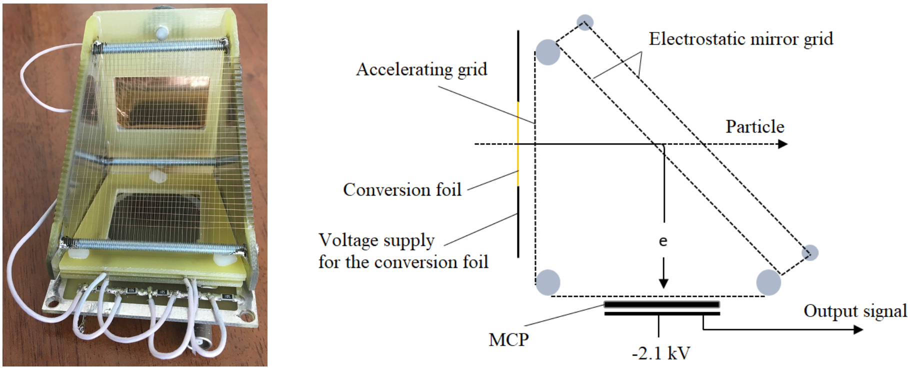

Fig. 1. MCP detector (left) and its scheme (right).

in the electric field between the foil and the accelerating grid. In the space between two electrostatic mirrors, the accelerated electrons rotate by 90 degrees and then are registered by the MCP (see Fig. 1).

3. Time-of-flight system for measuring charged particles

To study the time-of-flight technique, a system for implementing time-of-flight test measurements was created. The system consists of a vacuum chamber, data acquisition (DAQ) system, and data analysis software (Fig. 2).

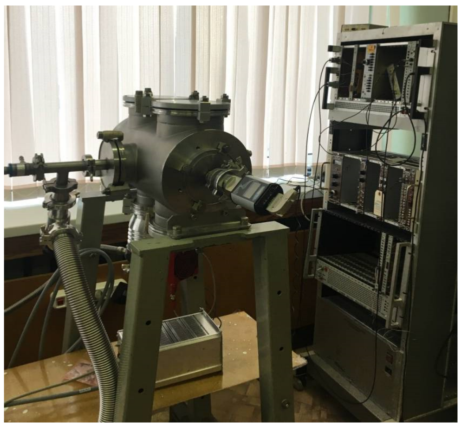

Fig. 2. The time-of-flight system.

The time-of-flight spectrometer operation results are presented in Fig. 3 on the 2D-matrix. The matrix shows the α-particles yield, emitted by ^{226}Ra, depending on their energy and time of flight.

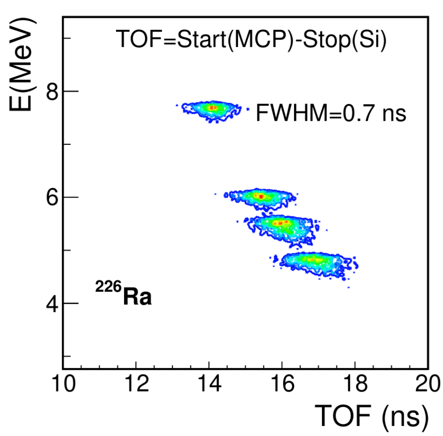

Fig. 3. 2D-matrix of α-particles yield.

The system included the start and stop MCP detectors and the total energy absorption Si detector. The distance l between the two detectors was set at 250 mm. The obtained results show a good time resolution of 240 ps (see Fig. 4).

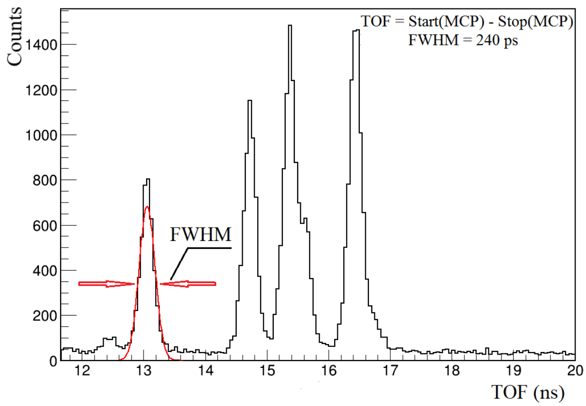

Fig. 4. Time resolution of α-particles emitted by ^{226}Ra.

4. Fission fragments time-of-flight measurements technique

In nuclear fission fragments studies, the time-of-flight technique is used to measure the paired fragments velocities [9, 10]. From the law of conservation of momentum in the case of fission, the paired fragments velocities are inversely related to their masses, which can be replaced with sufficient accuracy by their mass numbers. The fragment velocity v is determined from measurements of the path length of a fragment t in distance l. From the measured velocity values in this work, the masses of the detected products were obtained by an independent calculation according to formula (1).

Analyses have been carried out on the study of spontaneous fission fragments of ^{252}Cf using a time of flight system. Despite the fact that the main decay mode of ^{252}Cf is through α-emission, 97%, the contribution of spontaneous fission is also quite high — 3.08%. This allows us to study ^{252}Cf fission fragments at our facility.

As a result of the energy measurements and time-of-flight, the masses and kinetic energies of ^{252}Cf fission fragments were obtained: the light fragment mass $M_{\mathrm{l}} = 116$ amu and the heavy fragment $M_{\mathrm{h}} = 140$ amu, the kinetic energies of the fragments $E_{\mathrm{l}} = 105.33$ MeV and $E_{\mathrm{h}} = 80.7$ MeV, respectively. Figure 5 shows the mass distribution of ^{252}Cf fission fragments in comparison with the results of work [11], in which the mass values were obtained: the light fragment $M_{\mathrm{l}} = 108.6$ amu, the heavy fragment $M_{\mathrm{h}} = 143.4$ amu, as well as $E_{\mathrm{l}} = 104.6$ MeV and $E_{\mathrm{h}} = 79.7$ MeV energy values.

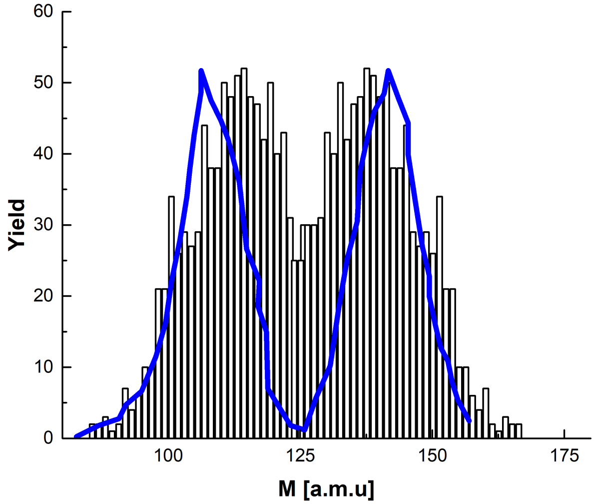

Fig. 5. (Colour on-line) The mass distribution spectrum of ^{252}Cf fission fragments. Experimental data — histogram, mass distribution results of [11] — black/blue line.

5. Two-arm time-of-flight spectrometer of the fission fragments of the MAVR

The results of the work were established as the basis for the fission fragments study at the MAVR facility, FLNR JINR. The experiment was carried out on the ^{48}Ca ion-beam at 310 MeV energy on ^{238}U target thickness of 1.05 μm and titanium substrate thickness of 1.5 μm. The reaction products were detected by two time-of-flight systems (Fig. 6). The first system is represented by the radio-frequency RF generator and Si detector. The second one includes MCP and Si detectors.

After the interaction of an ion beam (*e.g.* ^{48}Ca) with a target, fragmentation-like products and elastically scattered ions are detected using time-of-flight arms. Other products that have flown out at an anterior angle (*e.g.* α-particles) are detected by detectors placed in the focal plane of the magnetic analyzer MSP-144.

In addition to obtaining a time stamp from our MCP detector, a signal from the U-400 radio-frequency accelerator system was also used [12, 13]. Figure 7 shows 2D yields of the ^{48}Ca+^{238}U reaction products from the time of flight and their energies: (a) time matrix using an affixment based on the RF accelerator system, (b) time stamp detector based on microchannel plates.

From Fig. 7 (b), the time resolution of using MCP detector is higher than obtaining a "time" stamp from the RF system (Fig. 7 (a)). The time resolution was measured by the elastic scattering peak of ^{48}Ca and equal 1.5 ns.

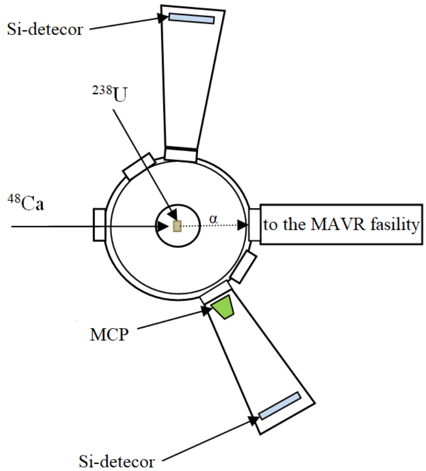

Fig. 6. Two-arm time-of-flight spectrometer's scheme.

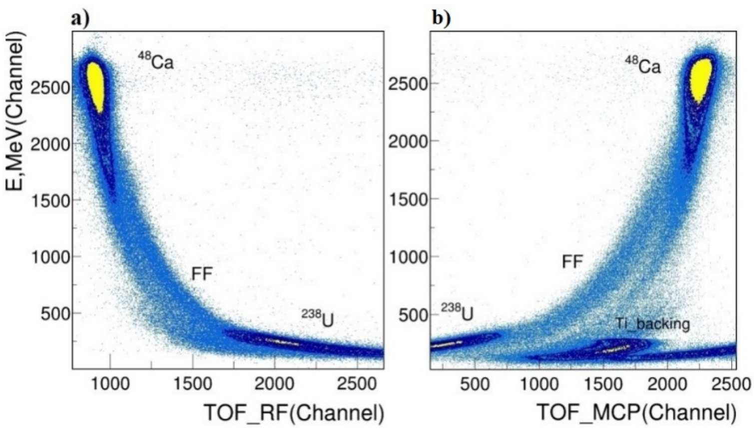

Fig. 7. 2D-matrix of the products yield of ^{48}Ca+^{238}U reaction depending on the time of flight and their energies.

It is explained by the contribution of the intrinsic energy spread of the ^{48}Ca ion beam (1%) and the effect of absorption and re-scattering in the target. It should also be taken into account that the use of a semiconductor detector as a "start" signal detector leads to a deterioration in its time resolution to a value of 0.4 ns due to a longer pulse rise front. In both cases, a good separation of elastic scattering products and fragments of forced fission FF is visible. However, in the second case (Fig. 7 (b)), the best reaction products separation is seen through their channels: FF — fission fragments, ^{48}Ca — elastic scattering of the beam, ^{238}U — elastic scattering of uranium.

The detected product masses were calculated according to the measured values of the time of flight and energies. Figure 8 shows the products mass distribution of the ^{48}Ca+^{238}U reaction. The area corresponding to the fission fragments is highlighted. The elastically scattered resolution of ^{48}Ca ions was obtained with an accuracy of FWHM = 5 amu. Such a low value is explained by the use of a thick target ^{238}U (2 mg/cm^2).

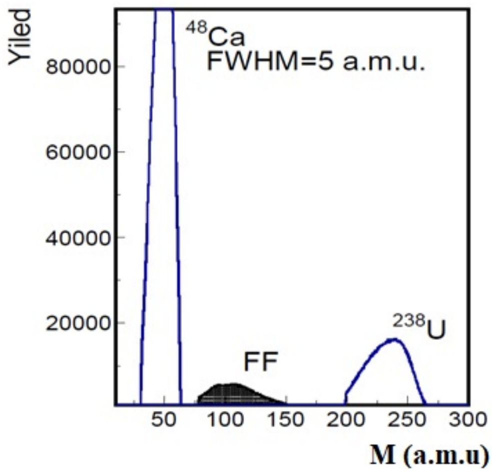

Fig. 8. The products mass distribution of the ^{48}Ca+^{238}U reaction: elastically scattered ions ^{48}Ca and ^{238}U, fission fragments (FF) are well separated from quasi-elastic products.

6. Summary

In this paper, a technique for studying the nuclear reaction products by detecting the time-of-flight of fission fragments was demonstrated. Two techniques of measuring the time of flight were used: the RF accelerator system and MCP detector. The advantage of measuring the time-of-flight by the second method was shown, *i.e.* using a time stamp detector based on microchannel plates.

Another purpose of the described system is to register elastically scattered ions, which is used as a monitoring system for the quality and composition of the beam, falling on the target of the MAVR facility. This makes it possible to measure the ion beam energy and the integral of particles flux passing through the target.

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