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GENERAL EXPERIMENTAL TECHNIQUES

A Time-of-Flight Detector of Low-Energy Ions for an Accelerating Mass-Spectrometer

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Abstract—The results of experiments with a time-of-flight detector for detecting rare ions at the output of the accelerating mass spectrometer of the Institute of Nuclear Physics (Siberian Branch, Russian Academy of Sciences) are described. The operation of this detector is based on detection of electron emission from thin films by means of microchannel plates. Owing to the small thickness of films, ions can sequentially pass through several films—this is the basis of the time-of-flight system for identifying isotopes. The high time resolution of detectors allows a significant decrease in the external-radiation background compared to one semiconductor complete-absorption detector that measures the ion energy.

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INTRODUCTION

The reliable separation of background events arising during passage of the analyzed ion beam through a spectrometer's vacuum channel is the main problem in studies of rare isotopes in samples. Scattering of ions by atoms of a residual gas and processes of charge exchange of ions with either a loss or capture of electrons lead to the appearance of a background beam together with an extracted isotope. For example, in measuring the ^{14}C isotope amounting to $<10^{-12}$ of the main ^{12}C isotope, the background from charge-exchange processes must be suppressed to a level of $<10^{-14}$–10^{-15}. The charge-exchange cross section for carbon ions at a residual gas may be 10^{-15} cm^2 [1], and for a traversed distance of 1 m in a vacuum of 10^{-6} Torr, the charge-exchange probability is $\geq 10^{-3}$. Even after multiple stages of filtering by magnetic and electrostatic spectrometers, a sufficiently high background may remain in the detecting channel and serious requirements for its separation are imposed on the final detector. The first experiments on the background detection were performed with semiconductor detectors with expectations that, after the final magnetic spectrometer, background particles with another masses but the same momentum can be discriminated if the energy resolution of the detector is high enough. However, it turned out that the resolution of available semiconductor detectors is insufficient for ion energies of ~1 MeV. The energy spread is probably caused by the input conducting film on the semiconductor detector. In addition, noise and background from cosmic rays remain quite high and do not allow reliable extraction of a signal from ^{14}C. The background-counting level at the detector was on the order of 0.10–0.01 s^{-1}. Semiconductor detectors turned out to be sensitive to doping with ion beams and quickly become disabled.

DESIGN OF TIME-OF-FLIGHT DETECTOR

To detect ions, we have developed a detector of emission from a thin film. This detector uses the well-known principle [2] of isochronous electrostatic reflection of electrons to a microchannel plate (MCP). The design of the detector schematically shown in Fig. 1 ensures simultaneous arrival of electrons at the MCP regardless of the place of emission in the transverse position of the film. Emitted electrons knocked out by an ion from film *1* are accelerated in the electric field applied between accelerating grid *2* and the film (1.5 kV across a gap of 5 mm). After being accelerated, secondary-emission electrons enter the interior of a prism and drift there in a zero field to the entrance to the region of electrostatic mirror *3*, where they are reflected at an angle of 90° and again enter the zero field in the prism, in which they drift in the direction of a tandem of two MCPs. Gilded-tungsten filaments with a thickness of ~30 μm are stretched with a pitch of 1.5 mm on the windows of the electrostatic mirror and two sides of the prism. The gap between the grids forming the electrostatic mirror is 7 mm, and the voltage across the gap is 3 kV. The prism faces are manufactured from 1-mm-thick stainless steel; the prism base and edges have the same size of 45 mm. The transparency of one detector is ~95%; the channel diameter is 20 mm.

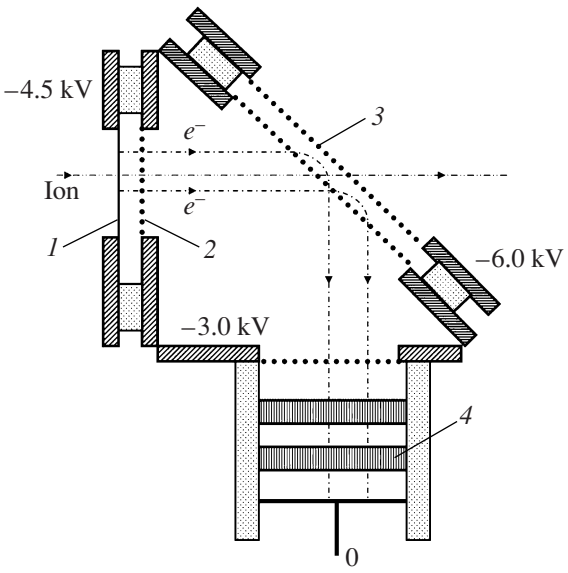

Fig. 1. Time-of-flight detector: (*1*) film, (*2*) accelerating grid, (*3*) electrostatic mirror, and (*4*) MCP.

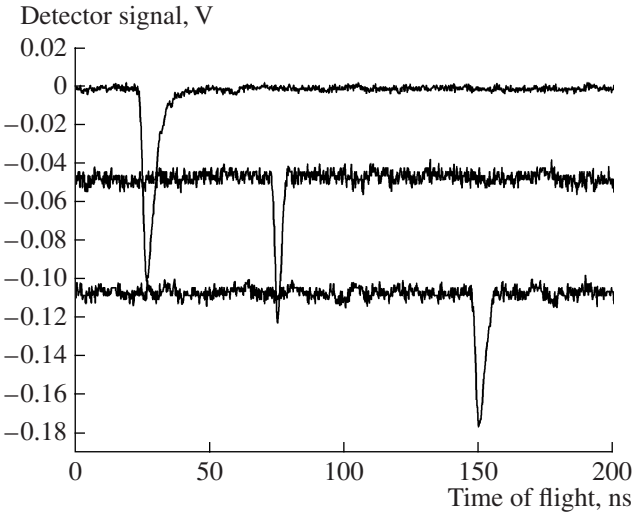

Fig. 2. Signals of three TOF detectors sequentially passed by an ion with an energy of 1 MeV.

The film was manufactured by means of a known technology [3]: a droplet of a solution spills into a thin film with a diameter of ~10 cm over the water surface. The film was deposited on a ring with a diameter of 20 mm with grid of W filaments stretched with a 1-mm pitch. The first experiments showed that even an ion flow with an intensity of 1000 ions/s rapidly charges such a film and leads to a decrease in the efficiency of the detector because of a distortion of the electric field that pulls out secondary electrons. To remove electrostatic charges, magnesium evaporated by means of an electric discharge was additionally deposited on the films. The second problem was the electron-emission background from the W grids stretched for the formation of the electrostatic mirror. Even at 6 kV, a background with a counting rate of 10–100 s^{-1} was observed that strongly depended on the potential distribution at the grids and rapidly increased with the voltage. Optimizing the pulling out and reflecting voltages with a decrease in the field strength between the grids allowed limitation of this background source within a reasonable range.

Figure 2 shows signals corresponding to ion transmission through three sequentially positioned detectors (the distances between neighboring detectors are 22 and 32 cm). The last detector is a MCP assembly the surface of which was hit by ions. It is seen that the typical pulse amplitude is 100 mV and the signal far exceeds noise, thereby ensuring digital processing of signals without preamplifying.

Signals were detected using discriminators, pulse formers, a coincidence circuit, time-to-digital converters, and pulse counters developed in the CAMAC standard at the Budker Institute of Nuclear Physics (Siberian Branch, RAS) for experiments in high-energy physics. Signals from three detectors were fed to the discriminator and then to the delay formers and the coincidence circuit. The discriminator threshold was 15 mV. The duration of pulses at the input of the coincidence circuit increased to 300 ns. The coincidence circuit triggered the time-to-digital converters; signals from the discriminators delayed by ~400 ns by means of cable lines served as signals of the ends of the measured time intervals. In such a system, triggering occurs upon arrival of a pulse from the last counter and slower ions have a shorter time interval measured with the time-to-digital converter. The time-interval measurement sampling was ~0.5 ns. Each channel was calibrated with a pulse generator. After operation, digital signals were written in a computer through a CAMAC crate. The data-acquisition rate of such a system was limited by the PC–CAMAC interaction and did not exceed 10 Hz. In principle, this limited the background radiation but was sufficient for acquisition of rare ions arriving at frequencies <1 Hz.

RESULTS OF EXPERIMENTS OF ION DETECTION

Experimental studies of the capabilities of the time-of-flight (TOF) detector in recording the spectrum of ions at the output of the accelerating mass spectrometer were performed on the facility at the Budker Institute of Nuclear Physics (Siberian Branch, RAS) [4]. The analyzed ions are produced as a result of bombardment of graphite by cesium ions. The settings of the accelerating mass spectrometer corresponded to 1 MeV of the beam energy at the input to the TOF detector. Boron ions contained in graphite at a level of 10^{-6} were used to test the detector.

Curve *1* in Fig. 3 shows the TOF histogram for ^{11}B ions traversing a 32-cm free-space segment. By approx-

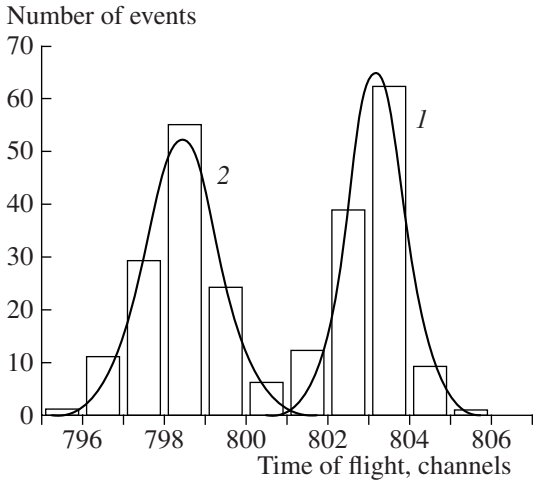

Fig. 3. Ion TOF distribution (0.5 ns per channel) (*1*) without a film and (*2*) with an additional film at the detector input.

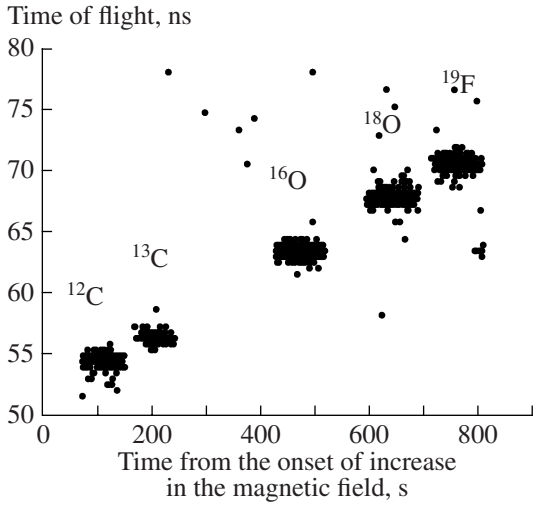

Fig. 4. Sequential changes in the time of flight with a change in the magnetic field in the spectrometer's output magnet.

imating the histogram with a Gaussian function, we obtain an rms TOF spread of 0.35 ns, which corresponds to an energy spread of 9.1 keV. To assess the influence of the film used in the detector on the beam energy spread, another film manufactured according to the same procedure was placed at the input (on a movable probe) of the TOF detector. When this film is introduced (curve *2*), the average ion time of flight increases by 2.39 ns, which corresponds to a loss of ~60 keV in the energy of particles passing through the film. Such a particle-energy loss corresponds to a thickness of 13 μg/cm^2 of the C film [5]. The additional film increases the TOF spread to 0.46 ns; i.e., the measured ion-energy spread becomes equal to 11.8 keV. Hence, the energy spread introduced by the film is 7.5 keV. Simulating according to the SRIM program [6] for ^{11}B ions transmitted through the C film 13 μg/cm^2 thick yields an average loss in the particle energy of 63 keV and an energy spread of transmitted ions of 5.4 keV. The distance of the film to the last detector was 54 cm, and a 20% decrease in the acquisition rate caused by the introduced film allowed evaluation of the transverse scattering. The above simulation yields a 13% decrease in the number of ions that hit the last detector owing to the scattering process at a zero initial beam emittance without taking into account the film placed on the first detector. Hence, the energy spread resulting from the passage of ions through the film makes the main contribution to the time resolution. Experiments with an increased distance between the detectors showed that the resolution did not improve and the detection efficiency decreased owing to scattering at the films. If it is necessary to improve the time resolution, thinner films should be used. Note that, in the case of a small energy spread in the ionization loss during passage of ions through the film, the influence of the energy spread owing to the ion charge exchange at the film being at an electric potential may become predominant. This leads to the necessity of reducing the voltage applied to the film and, probably, to picking off a signal from the MCP anode at a positive potential.

In mass spectrometry of carbon, the TOF detector of particles must separate masses close to 14 amu. The number of such ions before the last 90° magnetic filter is quite large. Figure 4 shows the signals recorded by the system during slow scanning of the magnetic field (from 4.0 to 5.4 kG) of the output magnet that changes the range of the momentum permitted for ion passage. We see the change in the time of flight corresponding to a change in the mass, which changes from 12 to 19 amu. In this case, the main part of the system of the accelerating mass spectrometer (to the output magnet) is adjusted for passage of ^{14}C knocked out from a graphite sample (note that graphite is classified as a dead sample because the content of radiocarbon in it is insignificant). The corresponding time histograms are shown in Fig. 5. The time resolution is ~0.4 ns, which is sufficient for ion identification. The background from scattered ions with other masses was ~0.10–0.01 s^{-1}, which amounts to 10^{-12}–10^{-13} in relative units at an output flow of primary ^{12}C ions of 10^{11} s^{-1}. A resolution of 0.4 ns at a distance to the neighboring peak of 2 ns ensures an additional suppression (at a Gaussian distribution) of 3×10^{-6}. However, this estimate is too optimistic, and we propose a double system for measuring time intervals based on three consecutive counters. Such a system of several sequentially positioned detectors of passing particles allows an appreciable decrease in the number of random coincidences. Figure 6 shows the resulting TOF distribution for ^{11}B and ^{10}B ions in the plane of two flight gaps (the TOF distances are 54 and 22 cm for TOF1 and TOF2, respectively). The TOF telescope consisting of three sequentially positioned detectors allowed almost complete suppression of random coincidences and reliable measurement of the ion

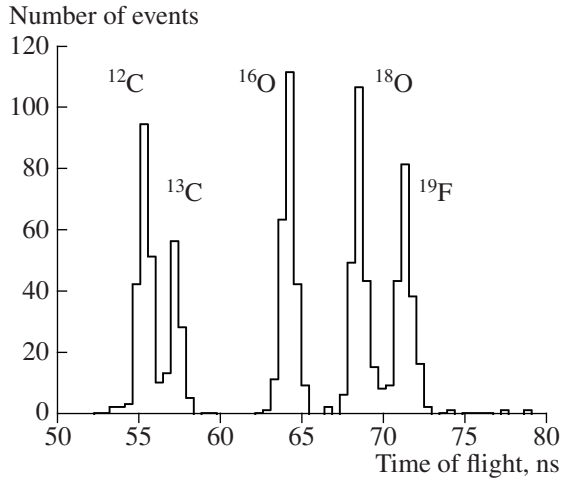

Fig. 5. Spectrum of time intervals for a mixed ion beam.

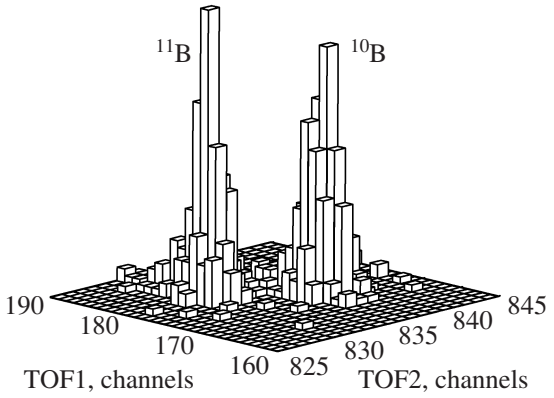

Fig. 6. Ion distribution in the plane of two time intervals (0.5 ns per channel).

velocity. Note that the ion flow was also measured for high-intensity beams and that the detectors efficiently operated at counting rates of up to 50 kHz.

CONCLUSIONS

The experience with detecting ions by detectors with thin films has shown that they correspond to the requirements for final detectors of the accelerating mass spectrometer. Although the expenditure for the development of the detector was relatively low, its energy resolution is ~1% and allows reliable differentiation between isotopes in an ion beam. The use of strong deceleration of ions in a series of consecutively installed films can serve as one of the methods for filtering ion beams, which extends the possibilities of the accelerating mass spectrometer in selecting isobar, such as ^{14}C and ^{14}N.

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