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LARGE AREA HIGH-EFFICIENCY TIME-OF-FLIGHT SYSTEM FOR DETECTION OF LOW ENERGY HEAVY EVAPORATION RESIDUES AT THE ELECTROSTATIC SEPARATOR VASSILISSA[1]

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Широкоапертурная высокоэффективная система
для измерения времени пролета тяжелых ионов и ядер отдачи
для электростатического сепаратора ВАСИЛИСА

В работе описан широкоапертурный тонкий временной детектор для регистрации тяжелых ионов. Конструкция детектора основана на транспорте вторичных электронов с помощью магнитного и электрического полей на сборку из микроканальных пластин (МКП), где происходит усиление электронного сигнала. Для увеличения эффективности регистрации сбор вторичных электронов осуществляется с обеих сторон эмиттера. Собственное временное разрешение детектора временной отметки (380 ± 30) пс и эффективность регистрации (95 ± 5) % были получены в опытах с α-источником ^{226}Ra. При измерениях с тяжелыми ионами собственное временное разрешение детектора временной отметки составляет (400 ± 30) пс и эффективность регистрации близка к 100 %. Система измерения времени пролета, состоящая из двух таких временных детекторов, используется в экспериментах с тяжелыми ионами, проводимых на кинематическом сепараторе ВАСИЛИСА [1,2].

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Large Area High-Efficiency Time-of-Flight System
for Detection of Low Energy Heavy Evaporation Residues
at the Electrostatic Separator VASSILISSA

A large-area thin timing detector for slow heavy nuclei was developed. The apparatus is based on the transport of secondary electrons by crossed electric and magnetic fields with subsequent amplification by micro-channel plate multipliers. To increase the registration efficiency secondary electrons are coollected from the both sides of the emitter foil. An intrinsic time of (380 ± 30) ps and registration efficiency of (95 ± 5) % were obtained for the single TOF detector using ^{226}Ra α-source. A time resolution of (400 ± 30) ps and registration efficiency close to 100 % were measured for heavy ions for the single TOF detector. A time-of-flight system consisting of two such detectors is extensively used in the experiments with heavy nuclei at the kinematic separator VASSILISSA [1,2].

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

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1 Introduction

Heavy ion collisions and, in particular, fusion evaporation, fusion-fission and deep inelastic reactions are usually characterized by a large mass and charge transfer and, consequently, by a large number of different residual fragments with broad kinetic energy and mass distributions. Therefore complicated and sophisticated apparatus are needed, especially in cases when nuclides with very short lifetimes are investigated. So far a lot of setups for heavy ion identification have been built, which use divers methods like kinematic coincidence technique, different time-of-flight (TOF) and ΔE-E telescopes or counters (see, for example, refs.[3, 4, 5] and refs. therein). Coupled with different kinds of kinematic separators and spectrometers, the advanced multidetector systems allow to improve the reliability and quality of the data and to obtain extra possibility for the identification of different reaction products.

Among various techniques, exploiting in experiments with heavy ions, TOF systems play an important role due to their relative simplicity and large range of particles and energies which may be covered at the same time. For example, such devices are extensively used in the study of heavy ion induced complete fusion reactions at the velocity filter SHIP (GSI, Darmstadt) [6] and at the electrostatic separator VASSILISSA at Flerov Laboratory of Nuclear Reactions (JINR, Dubna) [1, 2]. In these facilities the in-flight separation of the evaporation residues (EVRs) from the beam projectiles and from the products of different background reactions is performed according to their velocity or energy difference by a combination of magnetic and electric fields. After separation the reaction products are registered by detector telescopes, installed at the focal plane of the separators. The detector systems of these separators consist of two timing detectors and an array of position sensitive silicon strip detectors for the measurements of the pulses from impinging nuclei and from their subsequent alpha/fission decays. Unambiguous identification of the separate reaction channels can be carried out by the α-spectroscopy methods, making use of the genetic time and position correlations of α-decays.

One should note that in the region of nuclei, studied at such facilities, time signals from TOF detectors together with the energy signal from the silicon detector allow only for a rough mass identification of the nuclei. This is explained by specific properties of the EVRs under studies, and

in particular, such as:

- low energy of the products, typically of 0.05-0.2 MeV/u,
- large mass of the reaction products, (A >200 amu),
- the energy response (pulse height defect) of the silicon detectors for such heavy and slow nuclei is not known with a sufficient precision,
- large spot size of the EVRs at the focal plane, usually 25-50 cm^2

For instance, a typical mass resolution of about 5% was measured in the experiments on the identification of the new element with Z=109 at SHIP [7].

Although, such a mass resolution does not provide the possibility to distinguish between different products of the complete fusion reaction (typically - xn-, pxn- and αxn-channels with the masses of M_{EVR}=(0.95-0.99)$\times M_{CN}$, where M_{CN} - is the mass of compound nucleus), the use of the TOF system allows for a clear distinction between these products and low energy scattered projectiles (typically, in the O-Ni region, with the masses of M_{Proj}=(0.1-0.3)$\times M_{CN}$).
Even more important use of TOF systems in experiments with these separators is the exploiting of an anticoincidence condition between pulses from the TOF-detectors and from the silicon detectors. This condition allows to distinguish between heavy ions, coming from the separator (scattered projectiles, EVRs or products of different background reactions) and their subsequent decays after the implantation into the silicon detector. As a result, due to high efficiency of TOF detectors (>99%), "clean" decay spectra can be obtained [2].
Thus, taking into account these requirements, the time-of-flight detectors for such separators should satisfy at least the following requirements:

- to avoid losses and scattering of the low energy, large mass EVRs in the entrance windows, very thin start and stop timing detectors must be used, usually 10-30 $\mu g/cm^2$ thick and the time-of-flight base should be kept as short as possible. One should stress, that the last condition is in evident contradiction with the requirement of a good mass resolution,
- the entrance window of the detector should not be smaller then the beam spot at the focal plane of the separator, typically 25-50 cm^2,

- to permit at least rough mass identification rather good time characteristics should be provided, typically not worse than 400-500 ps,
- the registration efficiency for very slow heavy ions must be close to 100%.

Following all these conditions a new time-of-flight detector was developed and used in the TOF system at the focal plane of the kinematic separator VASSILISSA. The basic detector design followed those, presented in [8, 9], but some special features were developed, which enable us to improve the performance.

The principle of the operation of those setups is that a charged ion passing through a thin foil produces a few secondary electrons (SEs) which are then accelerated and transported by a combination of electric and magnetic fields to a set of microchannel plates where the electron pulse is amplified and the timing signal is derived from the anode.

The aim of this paper is to describe the main features of such a device and to present some characteristics, measured in the experiments with this detector. Section 2 gives a general overview of the construction of the detector and in section 3 we discuss the performance of this system in the test experiments with α-particles and heavy ions.

2 Detector Design

The time-of-flight system of the separator VASSILISSA consists of two identical (start and stop) timing detectors with the flight path of 40 cm. The total view of one of the detectors and the principle of the operation are presented in Fig.1 and Fig.2, respectively. Some basic parameters are given in Table 1 and will be discussed later.
One of the main requirements for any TOF detector is a good time resolution which can be achieved if the trajectories of SEs are isochronous. To fulfill this condition the systems, described in [9, 10], exploit crossed electric and magnetic fields which provide nearly isochronous 180° cycloidal trajectories for the SEs. In the case of the separator VASSILISSA, to increase the transport efficiency of reaction products from target to the focal plane detectors one has to deal with rather large EVRs beam spot of about 70 mm in diameter. The use of a system with 180°-angle image rotation would result in a considerable enlargement of the whole detec-

tor setup and in additional difficulties due to necessity to create uniform magnetic and electric fields in a large active volume.
As a compromise we took into account the fact that the beam of EVRs is nearly parallel at the focal plane of the separator [2] where both, start and stop, detectors are installed.

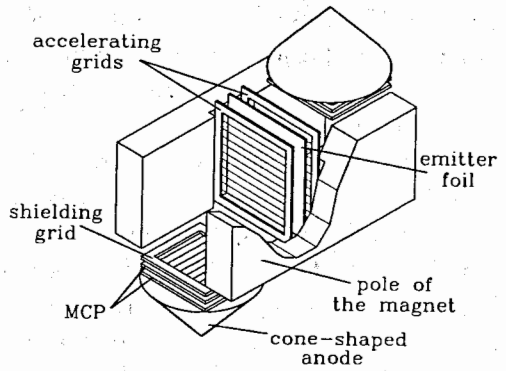

Fig. 1. Total view of the single timing detector. For simplicity the coil, winded on the external C-shaped part of the magnet, is not shown.

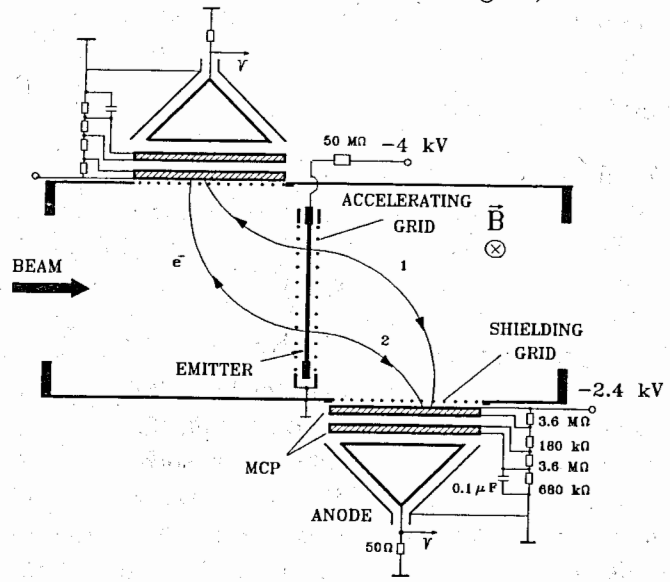

Fig. 2. Principle of the operation of the detector. The trajectories of SEs for two ions 1 and 2 are shown.

Under this condition the flight paths of SEs will be isochronous (for instance, flight paths E1-E1′, and E2-E2′ for the ions 1 and 2 in Fig.2,3) for any ion crossing the emitter foils in both detectors parallel to the beam axes. Thus, instead of a rather complicated system with the 180° image rotation, the system with the image rotation angle of 90° was developed. Also, in this case the resulting image will be reduced in size and one can use micro-channel plates with the smaller dimensions then the size of the EVRs beam spot.

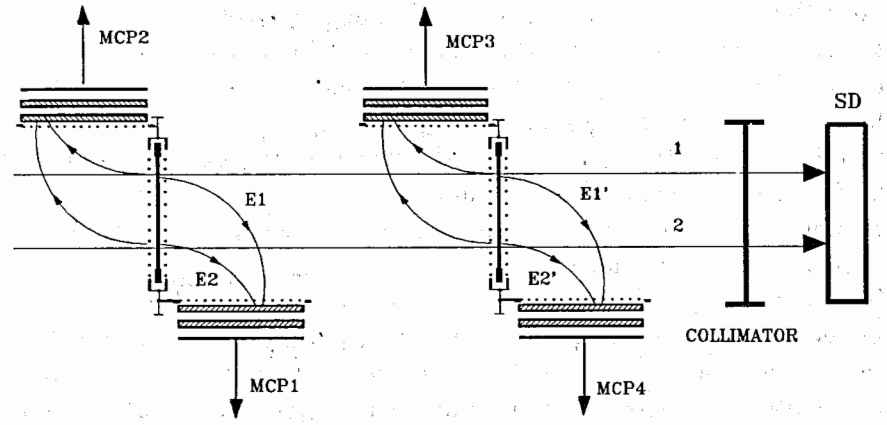

Fig. 3. Detector arrangement used in the measurements. The flight paths of SEs will be isochronous for the ions 1 and 2 (flight paths E1-E1' and E2-E2′, correspondingly) crossing the emitter foils in both detectors parallel to the beam axes.

Thin self-supported formvar foil of about 20-30 $\mu g/cm^2$ covered by evaporated gold layer (10-20 $\mu g/cm^2$) was mounted on a brass square frame with a 82 mm diameter hole. The frame was inserted between the poles of an electric magnet, perpendicularly to the incident beam of EVRs and insulated by means of teflon insulators (see Fig.1,2). The poles of the magnet are rectangular plates with the size of 90×180×20 mm. The magnetic field is created by a coil, winded on the external C-shaped part of the magnet core, protruding out of the vacuum box.

The inhomogeneity of the magnetic field in the active detector volume was calculated by the computer code POISSON [11] and did not exceed 0.3%. To avoid additional scattering and losses of passing ions gridless accelerating systems are usually used and the electric field is created by rather complicated combinations of equipotential plates and rings [8, 9]. However, it is resulted in increasing of the geometric sizes of the detector and, consequently, in increasing of the inhomogeneity of magnetic and electric fields. To keep the size of our TOF-detector quite small we preferred to use accelerating grids with high transparency.

Two grounded grids, installed on both sides of the emitter foil (under potential of -4kV) at the distance of 5 mm apart from the foil were used to create the electric field which accelerates SEs. Thus, because of the electric field exists only in a limited area between foil and grids, its uniformity is very high. A transparency of each accelerating grid is 97.5%, yielding a total transparency for the whole start-stop system of about 90%. Such a system of electric and magnetic fields then transports SEs to a electron multiplier based on two microchannel plates assembled in a "chevron" configuration.

To increase the detection efficiency SEs are collected from both sides of the emitter foil and the corresponding pulses are then proceeded by independent sets of the MCP1-MCP4 multipliers, see Fig.2,3. Such a configuration is especially important to avoid the losses of SEs produced very close to the edges of the foil frame. One has to mention, that it is possible to collect SEs only from one side of the emitter by exploiting only a half of each detector. In this way one can remove one acceleration grid, thus increasing the transparency of the detector.

The choice of the field magnitudes E and B is mainly stipulated by the equations of motion of SEs in electric and magnetic fields [5], by the time dispersion and transit time of secondary electrons and by the restrictions on the geometrical size of the detectors. The transit time of the SEs should be minimized to reduce their time-of-flight uncertainties due to field inhomogeneities. The time dispersion in electron's flight time is mainly due to initial velocity spread of the electrons, emitted from the foil. Thus, the magnitudes of both fields have to be as large as possible within the geometrical limitations on the detector and constraints from the equations of motion. Heaving all these arguments in mind the dimensions and power supplies, given in Table 1 were chosen.

Table 1. Parameters of the time-of-flight detector.

Parameter	
SEs multiplier	
MCP size	60×90 mm^2
Bias on MCP	1000 V
MCP separation	1 mm
MCP-MCP bias	200 V
MCP -anode separation	1 mm
MCP - anode bias	200 V
Anode	
Diameter	60 mm
Potential	0 V
Emitter foil	
Diameter	82 mm
Thickness	20 μg/cm^2
Potential	– 4 kV
Electric Field	
Grid's wire diameter	50 μm
Grid's wire step	2 mm
Grid potential	0 V
Uniformity $(\delta E/E)^{a)}$	0.1%
Magnet	
Field	(40–100)×10^{-4} T
Gap Diameter	90 mm
Uniformity $(\delta B/B)^{a)}$	0.3 %

$^{a)}$ Calculated uniformity.

Two additional shielding grids under ground potential were installed in parallel to the surface of the MCPs to suppress the defocusing influence from MCP's electric field on the secondary electrons.

Using the resistor chain only 3 high voltage supplies were necessary for each timing detector: one of them (-4 kV) was applied to the emitter foil and two others at the voltage of -2.4 kV were used as a power supply for the MCP detectors (see Fig.2). The necessity to use separate power supplies for the MCP detectors was due to some differences in the MCP's characteristics, mainly, in their resistance values.

Specially cone-shaped 50 Ω impedance anode was exploited in the detectors to match the input impedance of the following electronics.

3 Experimental arrangement

3.1 Test measurements with a ^{226}Ra α-source

Time resolution and registration efficiency were investigated with a system consisting of two (start and stop) timing detectors and a silicon detector as a counter of ions, see Fig.3. An ion-implanted silicon detector with a diameter of 68 mm, divided into 8 independent vertical strips with the energy resolution of 25 keV for each strip has been chosen for the measurements. The measurements have been carried out with a ^{226}Ra α-source of 10 mm in diameter installed at the distance of 200 mm in front of the first timing detector. To avoid the registration of the α-particles which had slope trajectories a collimator with eight horizontal rectangular holes, each of 1×7 mm in size, was installed in front of the silicon detector.

A block diagram of the electronics used is shown in Fig.4. Anode signals from the MCPs multipliers were typically characterized by 300-500 ps rise time, 2 ns full width and (0.4-0.6)V peak amplitude. The pulses from the MCPs were directly fed into two fast constant fraction discriminators (CFD1-CFD2) (ORTEC 745 CFD) operating in a slow time rejection mode. The optimization of the discrimination fraction and delay values has been done for each CFD. Summing of the pulses for each pair of MCP1/MCP2 and MCP3/MCP4 was performed directly on the input of CFD1 and CFD2, respectively.
Although due to a small difference in timing signals from MCP1-MCP4

the time resolution is slightly deteriorated, better total registration efficiency can be obtained. As a time-to-amplitude convertor a TAC ORTEC 457 was used in the experiments.

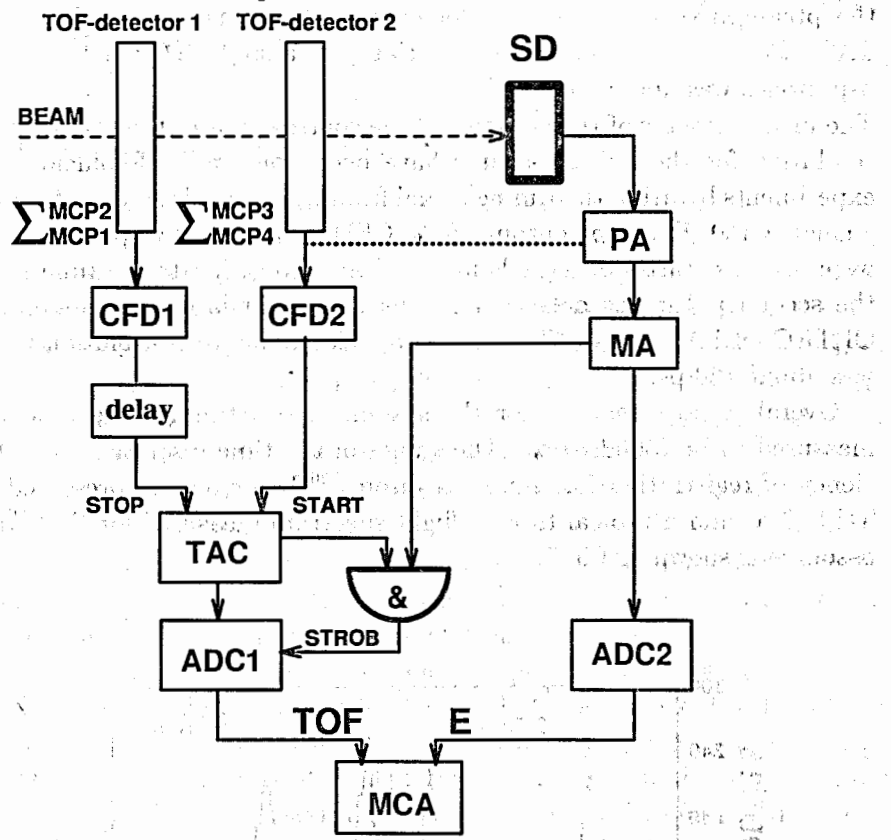

Fig. 4. Block diagram of the electronics used in the experiments. **SD**- Silicon detector, **CFD**- Constant fraction discriminator, **PA**- Preamplifier, **MA**= Main amplifier, **TAC**- Time to amplitude convertor, **MCA**- Multi-channel analysator, **ADC** - Analog-to-digital convertor.

The total registration efficiency for the whole TOF-system, consisting of two (start and stop) TOF detectors, can be deduced from the ratio:

$$\epsilon = \frac{N_{TOF}}{N_{Total}},$$

where N_{TOF} and N_{Total} - are the numbers of counts recorded by the ADC1

and ADC2 analog-to-digital convertors, correspondingly. The measured value was obtained to be 90±5%. To measure registration efficiency of the single TOF detector a fast timing signal (dotted line in Fig.4) from the preamplifier of the silicon detector was used as a start signal for TAC. The measured registration efficiency of a single TOF detector for α-particles was about (95±5)%.

The measurements of the electronic time contribution to the overall time resolution for the ^{226}Ra α-source have been done in "self-coincidence" experiments by using the timing signal from the single TOF detector and a single CFD. From the output of the CFD we derived two pulses which were used as start-stop signals for the TAC. To calibrate the time scale the second pulse was delayed for 2 ns using standard delay module (ORTEC DELAY 425A). Thus measured electronic time resolution value was about 120 ps.

Overall time resolution for the system of two timing detectors was measured to be (560±40)ps. The values of the time resolution and efficiency of registration for α-particles from ^{226}Ra source are presented in Table 2(a) and a typical time-of-flight spectrum measured for the ^{226}Ra α-source is shown in Fig.5.

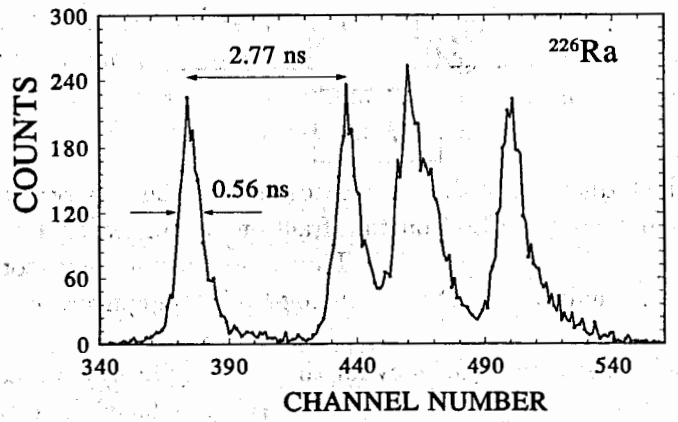

Fig. 5. Time-of-flight spectrum for the ^{226}Ra α-source.

One can derive the intrinsic time resolution for the single TOF detector using measured values of the electronics time resolution and of the

time resolution of the whole TOF system. Neglecting very small addition due to the finite α-particle energy (25 ps) and quadratically subtracting corresponding values, a value of (380±30)ps for the time resolution of the single TOF detector can be deduced.

3.2 Heavy ion induced reactions

Because of the heavy ions produce larger number of SEs than α-particles [12] registration efficiency of the system should be better than in case of α-particles registration.

The measurements were carried out using the above described methods with heavy ions from different complete fusion reactions and from elastically scattered target nuclei. The typical time characteristics of the anode pulses from the MCPs multipliers were very close to those measured with α-particles, but the peak amplitudes were 3-5 times higher. The registration efficiency of a single TOF detector was measured to be 99.95% for heavy ions.

Due to uncertainties with the determination of the pulse height defect values of the silicon detector for such heavy EVRs, we could derive only an estimated value for the time resolution of the system.

A typical time-of-flight versus energy spectra for the reactions : ^{22}Ne+^{182}W$\rightarrow^{204}$Po* and ^{40}Ar+^{164}Dy$\rightarrow^{204}$Po* are presented in Fig.6(a.b). One can clearly distinguish the areas corresponding to evaporation products and to low energy scattered projectiles. Projecting the two-dimensional spectrum to the "TOF"-axis for the narrow region of about 0.5 MeV alone the "Energy"-axis gives us a value of (600±40)ps for the time resolution of the whole system. After correct estimation of the pulse height defect it would be possible to obtained better value. As for the case of α-particles one can deduce the intrinsic time resolution of a single TOF detector measured with heavy ions. The obtained value was about (400±30)ps. The total registration efficiency of the system of two TOF detectors was close to 100%, see Table 2(a).

As it was mentioned in the Section 1, one of the most important applications of a such TOF system is the exploiting of the anticoincidence condition between pulses from TOF detectors and from the silicon detectors which helps to get "clean" decay spectra in the silicon detectors. In our case, the use of the pulses from all four MCP1-MCP4 multipliers

in anticoincidence with the pulses from the silicon detectors provides an increased registration efficiency for heavy ions. In fact, the probability ϵ_{ac} to get an anticoincidence signal from the whole TOF system is given as follows:

$$\epsilon_{ac}=1-(1-\epsilon_{sm})^4 ,$$

where ϵ_{sm} - is the probability to register the ion by any single MCP1-MCP4 multipliers. As in the case of heavy ions registration the value of ϵ_{sm} is close to 1, it results in a very high efficiency of the anticoincidence condition. One has to stress that in this case it is enough to register the ion at least by one of the MCP1-MCP4 multipliers and the condition of the coincidence between different MCP1-MCP4 is not strictly necessary.

Table 2. Measured values of the registration efficiency and time resolution for the system of two TOF detectors (see Fig.3,4)
a) - with the summing pulses from the pairs MCP1/MCP2 and MCP3/MCP4, correspondingly;
b) using only MCP1/MCP4 or MCP2/MCP3 pairs of multipliers.

	α-source ^{226}Ra		Evaporation Residues, E=10 MeV	
	Time Resolution	Efficiency	Time Resolution	Efficiency
a)	560±40 ps	90±5%	600±40 ps	>99.99%
b)	440±30 ps	65±5%	480±30 ps	99.9%

3.3 Special applications of the TOF detector

In the cases when better time resolution is required one can use only corresponding pairs of MCP1/MCP4 or MCP2/MCP3 multipliers (see Fig.3,4) and not to sum the pulses from the pairs MCP1/MCP2 and MCP3/MCP4 at the inputs of CFD1 and CFD2 discriminators. Besides, one can remove one accelerating grid from each TOF detector, allowing for better transparency of the whole system. Although it results in a slight decreasing of the registration efficiency of the whole system, better time resolution could be obtained due to better timing characteristics of the pulses from the anodes of multipliers.

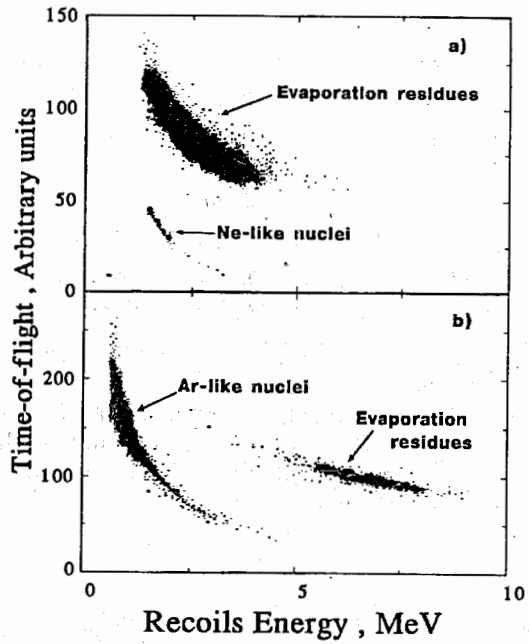

Fig. 6. Two-dimensional TOF-E spectra measured in the reactions with heavy ions.
a) ^{22}Ne+^{182}W→^{204}Po* reaction; b) ^{40}Ar+^{164}Dy→^{204}Po* reaction.

The measurements with the α-particles from a ^{226}Ra source were performed for a system of two TOF detectors using only MCP1 and MCP4 multipliers. Time resolution and registration efficiency for such a system were measured to be about (440±40) ps and 65%, correspondingly. Similar measurements were performed with the beams of heavy ions and the measured values are given in the Table 2(b).
An intrinsic time resolution and registration efficiency of a single TOF detector in this mode was deduced to be (280±30) ps and 80±5%, correspondingly.

4 Conclusion

Following the design of Bowman and Heffner [8] we developed and tested a large-area thin timing detector for slow heavy nuclei. An intrinsic time resolution of (380±30)ps and registration efficiency of (95±5) % were

measured for a single TOF detector using ^{226}Ra α-source. Comparable values are obtained in the experiments with heavy nuclei.

The system, consisting of two such detectors is extensively exploited in the study of heavy ion induced complete fusion reactions at the electrostatic separator VASSILISSA. The use of the anticoincidence condition between TOF detectors and silicon detectors results in considerable improvement of the background conditions for the recording of decay spectra at the focal plane of the separator. The obtained time resolution gives a reasonable (5%) mass resolution for the reaction products, providing more reliable identification.

The whole setup is rather simple, inexpensive and easy to operate in the broad region of energies and masses of heavy nuclei which makes this system very attractive and particularly suitable for the applications in heavy ion identification systems.

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