TIME-OF-FLIGHT SPECTROMETRY OF HEAVY IONS IN THE WIDE RANGE OF ENERGIES AND MASSES. DATA PROCESSING

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The use of the Si-semiconductor detectors in time-of-flight-energy (TOF-*E)* spectrometry of heavy ions or fission fragments (FFs) is known to have delicate methodological problems due to the "amplitude (pulse-height) defect (PHD)" and "plasma delay (PD)" effects in the *E* and TOF channels, respectively. Correct accounting for both effects needs rather complicated procedure of the FF mass reconstruction. The task becomes extremely complicated if we deal with heavy ions in the wide range of energies and masses far from those typical for conventional binary fission. This is a case of the experiments dedicated to studying of the collinear cluster tri-partition (CCT) of heavy nuclei [1, 2]. We present the modified algorithms and new methodical results compared to our previous publication [3].

The layout of the COMETA setup used in our recent experiments is shown in fig. 1.

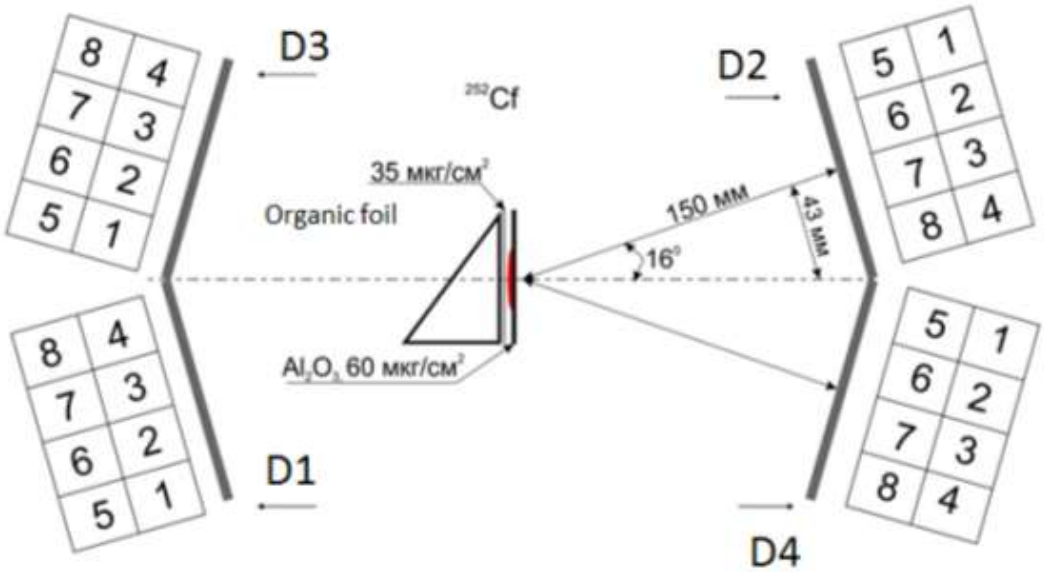

FIGURE 1. Layout of the COMETA setup (without "neutron belt"). D1-D4 -mosaics of PIN diodes. The MCP based "start" detector is located in the center of the system.

The overall view of the spectrometer is presented in fig. 2. The spectrometer consists of four mosaics of eight PIN diodes each and micro-channel plates (MCP) based "start" detector. The "neutron belt" [2] located in the plane perpendicular to the system axis is not shown here. Each PIN diode provides both energy and time-reference signals. The masses of the fragments can be estimated both in the frame of "two-velocities" and "velocity (time-of-flight) – energy" approaches, but only the latter one is used in the studies of multi-body decays including collinear cluster tri-partition (CCT [1, 2]).

An example of the mass-correlation plot and corresponding energy-correlation plot for the events with big missing mass associated with CCT is presented in fig. 3. The masses of the fragments (fig. 3a) form regular linear structures to be the manifestation of spherical and deformed magic nuclei. As can be inferred from the figure the CCT products indeed are observed in the wide range of masses and energies.

FIGURE 2. Mosaics of PIN diodes and “start” detector of the COMETA setup (a), overall view of the spectrometer (b).

The problem of adequate reconstruction of the FFs parameters such as velocity, energy and mass measured with the help of semiconductor detectors has a long lived history. The detailed review of physical treating and parametrizationz o PHD and PD for heavy ions can be find in [4].

Practical procedure of taking into account of both effects in reconstruction of the FFs masses is presented in [5]. As a starting point, the authors assumed the mass and energy dependence of PHD to be the same as that of Schmitt et al. [6]:

$$\mathrm{PHD} = (a - 1 + a'm)*Em + b + b'm, \tag{1}$$

where a, a', b, b' are the PHD parameters to be determined, m is the mass and Em is the measured energy when the diode is calibrated with α particles.

It was assumed that the resolution function g_i of the spectrometer for the mass ”i” is Gaussian. Another assumption was that the width of the resolution function ϭ, can be expressed as a polynomial function of the mass as

$$\sigma_i = C1 + C2i + C3i^2 + C4i^3$$

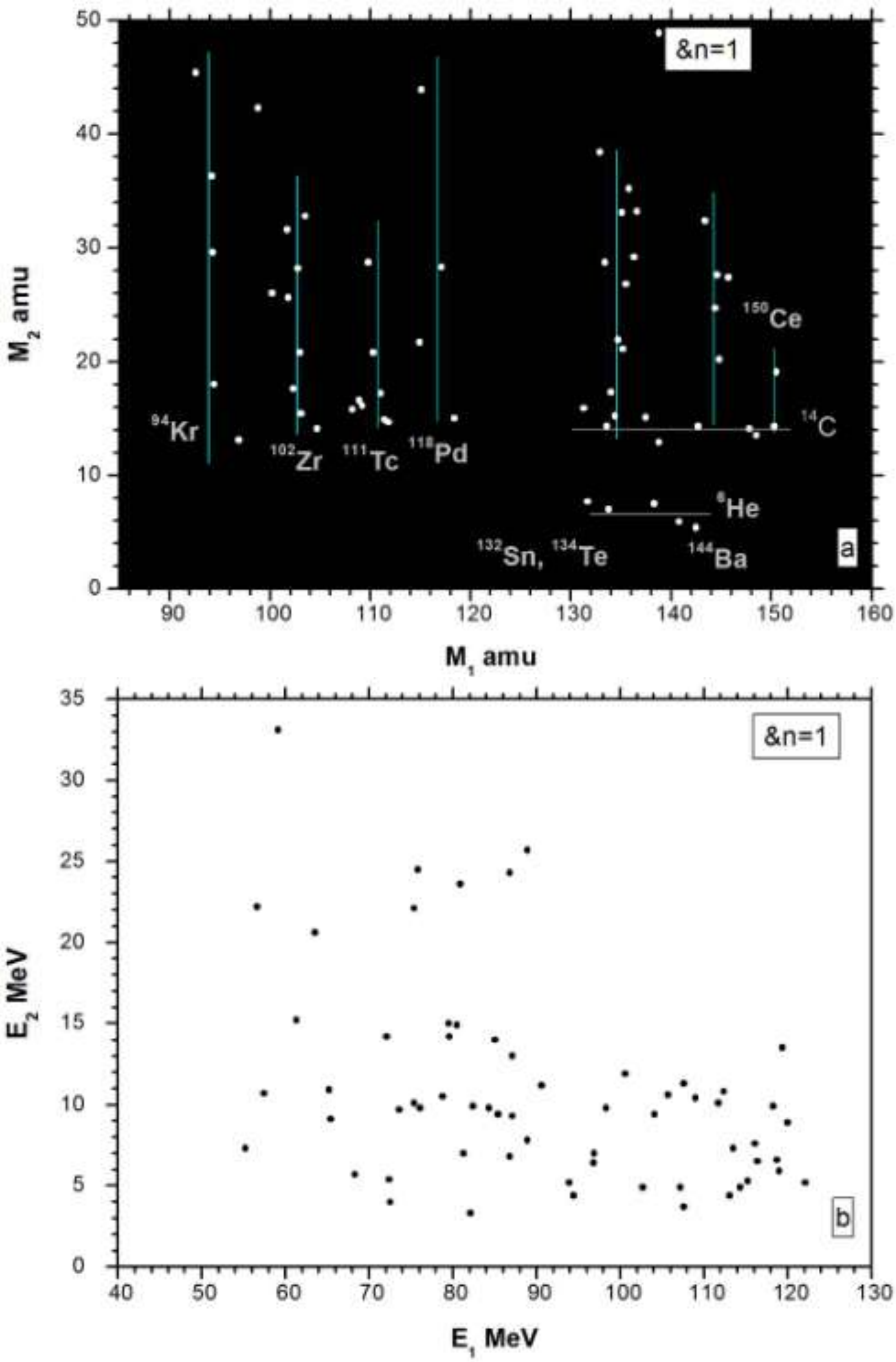

FIGURE 3. Mass correlation plot for the neutron gated fission events (one neutron was detected in each event) – a). The lines mark the positions of magic nuclei or light ions. Energy correlation plot for the same events – b. The data were obtained at the COMETA setup in the version shown in fig. 1. Additional Cu foil of 0.8 mkm was placed in the arm D2/D4 (fig. 1) in the vicinity of "start" detector.

The mass distribution of the radiochemical measurement (Y^{rad}) was dispersed by $g_{i.}$ in order to take into account experimental mass resolution. The resultant spectrum Y^{dis} than compared with the experimental one (Y^{exp}) to get the parameters *a*, *a'*, *b*, *b'* and Cl, C2, C3, C4. This was done by minimizing χ^2 which is

$$\chi^2 = \sum_{j=1}^{\infty} \frac{(Y_j^{\exp} - Y_j^{dis})^2}{Y_j^{\exp}}$$

It should be stressed that the measured value of the velocity V_{exp} without any correction on the PD was used at this stage. Earlier similar procedure was proposed in our work [7].

The plasma delay of fission fragments in PIN diodes can be estimated according to the empirical formula of Neidel and Henschel [8]:

$$t_p = 1.33*(m^{1/6*}E^{1/2})/F, \qquad (2)$$

where F is the electrical field strength in a diode.

In order to take into account simultaneously both factors namely PHD and PD the authors searched for solution of the system consisting of three following expressions:

$$mV^2/2 = E$$
$$m(l/t)^2 = E_{ex} + \mathrm{PHD}$$
$$t = t_{ex} - t_p$$

where t_{ex} is the measured TOF. m and E can be determined to a sufficient accuracy within 2 or 3 steps of iteration with three equations above.

It is not surprising that such rather inconsistent procedure of mass reconstruction gives biased values of the parameters. For instance, in the frame of the presented procedure mass resolution for the FFs appeared to occur about 8 amu while that one followed from the measurements with monochromatic ions does not exceed 3.3 amu.

Another example of measuring masses of ions lighter than typical FFs is presented in [9]. Mass and velocity distributions have been measured for the evaporation residue and fusion-fission products from the ^{16}O + ^{40}Ca reaction at 214 MeV. The pulse-height correction of Kaufman et al. [10] was used, where the scaling factor was established for each Si detector using the pulse heights induced by the fission fragments of Cf. Plasma-delay corrections were applied to the timing measurement of each detector following the set of empirical formulae established by Bohne et al. [11]. Unfortunately, it is not clear from the text how both corrections were simultaneously applied.

Thus, we have not find in the literature suitable algorithm of mass reconstruction to be adequate to our methodically more complicated task namely once again: ***wide range of both masses and energies of heavy ions, necessity to take into account not only PHD but PD as well due to short flight path used. It means essential distortion of TOF due to PD.***

We use three different approaches in the reconstruction of the TOF–*E* FF masses. At the first stage, a simplified approach is used as follows. Two coefficients of the time calibration are calculating using the velocity spectrum of the known FFs from the literature. The energy calibration dependence is presented as a parabolic curve passing via three points (we call such calibration version “3 point calibration”), namely through the known centers of the energy peaks for the light and heavy fragments, and the energy of the alphas of natural radioactivity of ^{252}Cf nucleus. Such approach gives quite satisfactory results for the reconstruction of the FF masses, at least, near the loci of binary FFs. It is using mainly for the on-line control of the collecting data.

In the linear calibration of tracts of E and TOF measurements, corresponding generators are used for the slope determination while the position of alpha peak let find corresponding calibration constants.

In the most adequate procedure of "true calibration" distortions due to both PHD and PD are taken into account.

It is known the energy E of the registered FF to be the sum of the detected energy E_{det} and the pulse-height defect denoted by $R(M,E)$:

$$E = E_{\mathrm{det}} + R(M, E), \tag{3}$$

where the detected energy of fission fragments is given by:

$$E_{\mathrm{det}}[\mathrm{MeV}] = E[\mathrm{ch}] \cdot dE / dk + E_0$$

dE/dk and E_0 are the linear calibration parameters.

The parameterization for the pulse-height defect in equation (3) was chosen instead of expression (1) in the version proposed by Mulgin et al. [12] as the following empirical expression:

$$R(M, E) = \frac{\lambda \cdot \mathrm{E}}{1 + \varphi \cdot \dfrac{E}{M^2}} + \alpha \cdot ME + \beta \cdot E \ , \tag{4}$$

where $\{\lambda, \varphi, \alpha, \beta\}$ are the parameters. In addition we know that:

$$E = \frac{M \cdot V^2}{1.9297}, \tag{5}$$

where E is the energy of the FF in *MeV*, M is the mass of the FF in *amu* and V is the velocity of the FF in *cm/ns*. The velocity for this purpose is calculating using the parameters obtained from the linear time calibration.

In order to find the correct values of the parameters $\{\lambda, \varphi, \alpha, \beta\}$ a special iteration procedure has been designed. This procedure consists in obtaining the numerical solution of the following equation:

$$G(\{\lambda, \varphi, \alpha, \beta\}, M, V) = 0$$

Combining equation (3), (4) and (5), we obtain:

$$G = \frac{MV^2}{k} - [E_{\mathrm{det}} + \frac{\lambda \cdot \dfrac{MV^2}{k}}{1 + \varphi \cdot \dfrac{V^2}{Mk}} + \alpha \cdot \frac{M^2 V^2}{k} + \beta \cdot \frac{MV^2}{k}] = 0 \ , \tag{6}$$

where $k = 1.9297$.

The correct value of the velocity V could be obtained using formula (2) in the following form:

$$V = \frac{L}{\gamma V M^{2/3} + \text{tof}_{lin}}, \tag{7}$$

where tof_{lin} – experimental TOF value obtained using linear calibration, L – the length of the flight-path, γ-additional parameter to be find together with {λ, φ, α, β}. At each fixed vector of parameters we find numerical solution of the set of expressions (6) and (7) in other words, quasi-mass M found to be the root of the equation (6).

After processing an amount of data, a spectrum of quasi-mass is obtained. The vector of parameters changes by the MINUIT package in order to minimize the following criterion function by changing the parameters {λ, φ, α, β}:

$$F = [(< ML_T > - < ML >)^2 + (< MH_T > - < MH >)^2] + \mu \sum_{M_{TE}} \frac{(Y(M_{TE}) - Y_T(M_{TE}))^2}{Y(M_{TE})} \tag{8}$$

Where μ is a free parameter that is chosen by the user and it is used as an input parameter to the MUNUIT minimization procedure. This parameter plays a role of specific relative weight of the second term in the criterion function F. The values $<ML>$ and $<MH>$ are average masses of light and heavy fragments calculated from the experimental mass spectrum $Y(M_{TE})$. In the above equation the known values from literature are denote by "T". It is worth noting that the first square bracket term in equation (8) is sensitive to the difference between the centers of the mass peaks for the fission fragments while the second term is responsible for the agreement in shapes between the experimental mass spectrum $Y(M_{TE})$ and the mass spectrum from literature $Y_T(M_{TE})$.

The comparison of different approaches to the FF mass reconstruction is presented in fig. 4.

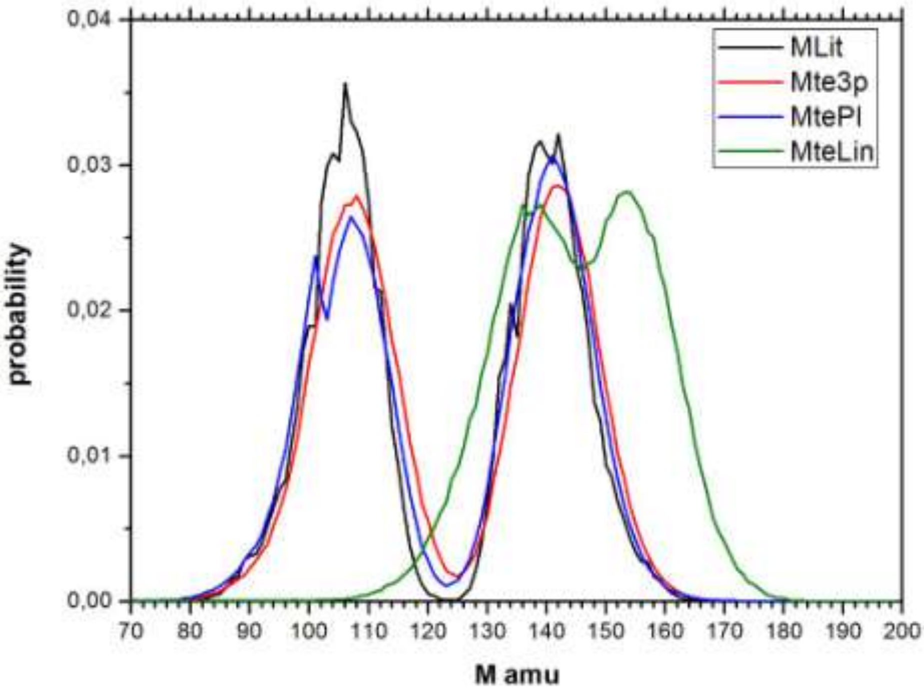

FIGURE 4. Comparison of different calibration procedures namely 3-point, linear and "true" (marked as Pl) used for the FFs mass reconstruction in the frame of the TOF-E method. The inclusive spectra over 32 PIN diodes of the COMETA setup are shown.

Fig.5 demonstrates the quality of calibration in the mass range of the lightest CCT products. It is clearly seen that only true calibration gives unbiased position (a priory known) of the mass peaks.

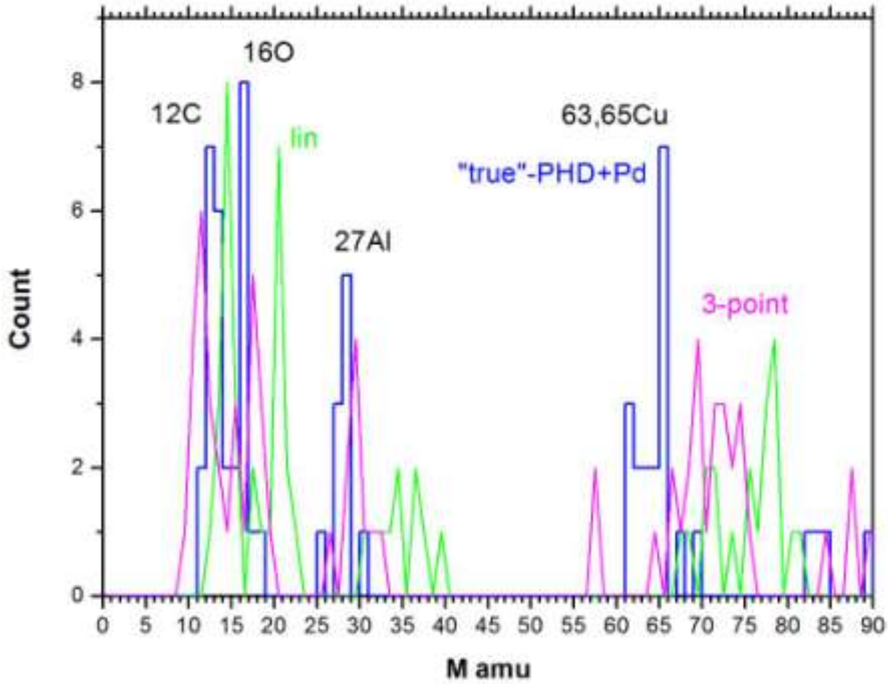

FIGURE 5. Comparison of the mass spectra for the knocked-out ions in the ternary events. Only "true" calibration gives unbiased position of the mass peaks.

Summing up, we would like to state that the worked out procedure based on the "true calibration" proves to be an adequate instrument in the CCT studies.

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