Experimental testing of heavy ions mass search procedure in the measurements with PIN diodes

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**Abstract.** We discuss the quality of heavy ions (HI) mass reconstruction in the wide range of HI energies and masses using Si PIN diodes for measuring both energy and time-of-flight. The results are based on the experimental data obtained at the IC-100 accelerator in the Flerov Laboratory of the JINR (Dubna, Russia).

1. **Introduction**

Using of the semiconductor detectors for spectrometry of heavy ions is known to have several methodological obstacles, which are necessary to be overcome. First of them is pulse-height defect (PHD), which is manifested in the form of apparently less energies than particles actually have. Second is plasma delay effect (PD), which prevents precise measurements (TOF technique) due to creation of plasma in detectors, which is obstructing the charge collection. 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 our experiments dedicated to studying of the collinear cluster tri-partition (CCT) of heavy nuclei [1, 2].

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 parametrization of PHD and PD for heavy ions can be find in [3]. We have not find in the literature [4–9] 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.

2. **Experiment**

A special experiment aimed at testing of the mass reconstruction procedure was performed at the IC-100 accelerator in Flerov Laboratory of the JINR. The beam of \(^{132}\)Xe ions with the energy of about
1 MeV/A bombarded thin metal targets (foils) made of Al, Ti, Cu, Nb, Ag and Au. Both the scattered Xe ions and the ions knocked out from the foils were detected by a time-of-flight spectrometer. The layout of the experiment is presented in figure 1.

![Diagram of experimental setup](image)

**Figure 1.** Layout of the experimental setup. Position of the detectors (a) and electronics used (b). The flight passes do not exceed correspondingly $L_1 = 500 \text{ mm}$, $L_2 = 173 \text{ mm}$, $L_3 = 31 \text{ mm}$.

The time-of-flight spectrometer consists of two microchannel plates based time pick-of detectors TD-Start, TD-Stop and one PIN diode. Evidently, microchannel plates based detectors are free from plasma delay effect that allows using them for measuring of "true" time-of-flight. The PIN diode serves for measuring of both the FF energy ($E$) and time-of-flight (TOF). The data acquisition system consists of the fast digitizer CAEN DT5742 and a personal computer. In order to measure the knocked out ions of four different energies in the range of $(7-115) \text{ MeV}$ in the same run a special multi-section degrader was placed before the start detector.

3. Data processing

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

$$E = E_{\text{det}} + R(M,E),$$  \hspace{1cm} (1)

where the detected energy of fission fragments is given by:

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

$dE/dk$ and $E_0$ are the linear calibration parameters.

The parameterization for the pulse-height defect in equation (1) was chosen in the version proposed by Mulgin et al. \cite{10} as the following empirical expression:

$$R(M,E) = \frac{\lambda \cdot E}{1 + \varphi \cdot \frac{EM}{M^2}} + \alpha \cdot ME + \beta \cdot E,$$  \hspace{1cm} (2)

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

$$E = \frac{M \cdot V^2}{1.9297},$$  \hspace{1cm} (3)

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:
Combining equation (1), (2) and (3), we obtain:

\[ G(\lambda, \varphi, \alpha, \beta, M, V) = 0 \]

where

\[ k = 1.9297 \]

The correct value of the velocity \( V \) could be obtained [6] in the following form:

\[ V = \frac{L}{\gamma \sqrt{MV^2} + \text{tof}_{\text{lin}}} \]

where \( \text{tof}_{\text{lin}} \) – experimental TOF value obtained using linear calibration, \( L \) – the length of the flight-path, \( \gamma \) - additional parameter to be find together with \( \{ \lambda, \varphi, \alpha, \beta \} \). At each fixed vector of parameters we find numerical solution of the set of expressions (4) and (5) in other words, quasi-mass \( M \) found to be the root of the equation (4).

4. Results

Masses of the ions detected in the experiment at the IC-100 accelerator were calculated in the frame of the procedure presented above in section 3. Parameters \( \lambda \) and \( \varphi \) in formula (4) were chosen according recommendations of work [10]. The results are presented in figure 2.
Figure 2. Estimated masses of the detected ions at different energies. Mean mass of natural mix of isotopes for each element involved is marked by a vertical line with a label.

As can be inferred from the figure estimated mass values are in good agreement with the expected ones in a wide range of masses and energies. Systematic deviation of the experimental points from the vertical line for Xe beam ions is presumably due to the influence of the randomly scattered component of the beam. The mass of the heaviest ions of Au is overestimated on approximately four units.

5. Conclusions
Using of both new “parabolic” time pick-of algorithm and mass reconstruction procedure based on the PHD parametrization proposed in [10] let us to reproduce quite satisfactory HI masses in a wide range of masses and energies.

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References

[1] Pyatkov Yu V et al. 2010 Eur. Phys. J. A 45 29
[2] Pyatkov Yu V et al. 2012 Eur. Phys. J. A 48 94.
[3] Akimov Yu A et al. 1967 (In Russian) Semiconductor detectors of nuclear particles and their application (original Russian text: Poluprovodnikovye detektory yadernyh tchastits i ih primenenie. (Moscow: Atomizdat))
[4] Kim Y S et al. 1993 Nucl. Instrum. Meth. A 329 403.
[5] Schmitt H W, Kiker W E and Williams C W 1965 Phys. Rev. 137 13837.
[6] Alexandrov A A et al. 1991 Nucl. Instrum. Meth. A 303 323.
[7] Neidel H O and Henschel H 1980 Nucl. Instrum. Meth. 178 137.
[8] Beck C et al. 1989 Phys. Rev. C 39 2202.
[9] Kaufman B et al. 1974 Nucl. Instrum. Meth. 115 47.
[10] Bohn W et al. 1985 Nucl. Instrum. Meth. A 240 145.
[11] Mulgin S I et al. 1997 Nucl. Instrum. Meth. A 388 254.