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New semi-automatic method for reaction product charge and mass identification in heavy-ion collisions at Fermi energies

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ABSTRACT

This article presents a new semi-automatic method for charge and mass identification of charged nuclear fragments using either $\Delta E - E$ correlations between measured energy losses in two successive detectors or correlations between charge signal amplitude and rise time in a single silicon detector, derived from digital pulse shape analysis techniques. In both cases different nuclear species (defined by their atomic number Z and mass number A) can be visually identified from such correlations if they are presented as a two-dimensional histogram ('identification matrix'), in which case correlations for different species populate different ridge lines ('identification lines') in the matrix. The proposed algorithm is based on the identification matrix's properties and uses as little information as possible on the global form of the identification lines, making it applicable to a large variety of matrices. Particular attention has been paid to the implementation in a suitable graphical environment, so that only two mouse-clicks are required from the user to calculate all initialization parameters. Example applications to recent data from both INDRA and FAZIA telescopes are presented.

1. Introduction

In the intermediate energy regime, violent heavy-ion collisions produce many nuclear species with a large range of charge (Z), mass (A), and kinetic energy (E_k) [12]. Studying this kind of reactions requires detectors with almost 4π solid angle coverage, high granularity, low energy thresholds, large dynamic range in energy and capable of characterizing reaction products on an event by event basis. The first generation of 4π multi-detectors focused on complete collection of charged particles produced in a reaction [3–7], providing little isotopic information for heavy fragments ($Z > 5$). More recently detectors have evolved to provide isotopic resolution for a broader range of products [8–10], by improving existing detectors and identification techniques, or developing new methods such as the Pulse Shape Analysis (PSA) in silicon detectors [11–13].

Such multi-detectors are generally made of telescopes (stacks of detector material layers) measuring the energy lost by charged particles in the different stages. Several combinations of detectors have been used for this purpose, such as ionization chambers (IC), silicon detectors (Si), plastic scintillators, and thallium-activated cesium-iodide scintillators (CsI(Tl)). When a charged particle passes through such a telescope, its charge, mass, and kinetic energy determine the number of detectors it can cross before stopping, and the energy loss in the different layers. Charged particles are then identified by plotting the energy loss in one or several layers of the telescope (ΔE) versus the residual energy released in the detector in which the particle is stopped

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(E). Within this representation, called $\Delta E - E$ matrix, different particles populate identification lines characteristic of their charge and mass (see for example Fig. 1(a)).

Three main methods are then used to identify such particles:

(i) Interactive drawing of lines in order to discriminate between the ridges corresponding to a given charge and/or mass. Particles are then identified from their relative distance between pairs of ridge lines.
(ii) Fit of a limited set of ridge lines with a functional describing the relation between ΔE and E, in which Z and A enter as parameters [14–17]. In this case, particle identification is obtained by inversion of the functional for given ΔE and E, in order to extract Z and possibly A.
(iii) Fit of detector calibration parameters on a limited set of ridge lines using energy loss table to generate all identification lines [20,27,10,21]. Particles are then identified from their relative distance between pairs of ridge lines.

The method (i) is probably more powerful and allows to face any situation, such as complex detector responses, but it suffers from two main limitations: it does not provide any extrapolation in regions of low statistics, and it is time consuming because each line has to be accurately drawn.

Methods (ii) and (iii) allow extrapolation and suffer less from this latter inconvenience, since only a subset of ridge lines have to be drawn by hand. It may still become problematic when using multidetectors composed of thousands of identification telescopes. In both cases, identification performances rely on the precise knowledge of the detector response, which can be very complex in the case of CsI(Tl) scintillators light output-energy conversion [18] or in presence of pulse-height defect in silicon detectors [19]. These two methods are very efficient in reproducing Z lines but are generally not accurate enough to reproduce isotopic lines over a large range of elements.

With increasing numbers of identification matrices to treat which include information on increasing numbers of individual isotopes of different elements, it becomes essential to develop automatic or semi-automatic methods to extract identification lines in $\Delta E - E$ matrices. The need for automation was already evident with the advent of the first large charged particle arrays, and some methods were developed at that time, using for example image processing [22,25,26], or artificial neural networks [23]. More recently, neural networks have been applied directly to digital current signal [13] for isotopic identification. Cluster algorithms have also been used for proton-γ discrimination [24].

The evolution of computer resources, and the availability of powerful libraries dedicated to large scale data analysis [28,29] allow us to consider new types of algorithms. In this article we present a new method, called SPIDER[1] identification (for Spider Particle Identification in $\Delta E - E$ Representation) for semi-automatic ridge line determination in two-dimensional matrices. This method has been developed avoiding as much as possible the use of *a priori* information on the exact form of identification lines, in order to be applicable to a large variety of identification matrices. Particular attention has been payed to the implementation in a suitable graphical environment. The extracted lines can then be directly used to identify charged particles (i), or set as an input of a functional fit (ii) or energy loss fit (iii).

2. SPIDER identification

2.1. Algorithm

Determining ridge lines in two-dimensional matrices (x, y) is a hard task, whereas powerful algorithms for peak localization in N-dimensional matrices are available [30]. The main idea of the present method is then to transform our problem into a problem of peak localization in one-dimensional histograms. To do so, we have to project a part of the matrix onto a relevant axis. It is the shape of the identification lines and their relative population that guided the choice of this projection. The one-dimensional histogram shown in Fig. 1(b) is obtained by projecting all points between $D(\theta - \alpha/2)$ and $D(\theta + \alpha/2)$ onto the straight line $D(\theta)$, passing through (x_0, y_0) and making an angle θ with respect to Ox (see Fig. 1(a) where x stands for E and y for ΔE). Each peak appearing on this projection corresponds to the intersection between $D(\theta)$ and a ridge line of a given Z and A.[2] The angle of the first projection, θ_0, and the pedestal coordinates (x_0, y_0) are input parameters of the algorithm.

To localize the peaks in Fig. 1(b), the binning of the histogram should be chosen carefully. The number of bins n_b of the projection is defined as:

$$n_b = d_\theta \times \rho(\theta) \times \beta, \tag{1}$$

with d_θ the length of the projection, β a binning parameter to be provided by the user, and $\rho(\theta)$ an internal parameter given by:

$$\rho(\theta) = \begin{cases} \sqrt{2} & \text{if } \theta > \theta_0 \\ 1 & \text{if } \theta = \theta_0 \\ 5/4 & \text{if } \theta < \theta_0. \end{cases} \tag{2}$$

The choice of $\rho(\theta)$ is purely phenomenological.

Maxima are then located using the algorithm described in Ref. [30], and their position in the two-dimensional matrix (Fig. 1(c)) is used as starting point for all subsequently generated identification lines, making crucial the choice of θ_0.

The operation of projection/localization is then repeated in order to cover the full matrix, varying θ from θ_0 to 90°, and then from θ_0 to 0° by steps of $\delta\theta$. In practice, $\delta\theta$ and α slightly depend on θ, and can be modified by the user in order to adapt the algorithm to a specific situation (very low statistics for example). Each new point $P(x_p, y_p)$ is associated to the line Z, so far containing n_Z points and whose end point coordinates are (x_Z, y_Z), if:

$$\begin{cases} |y_p - y_Z| < \delta y, & \text{for } n_Z < 10, \\ |y_p - f_Z(x_p)| < \delta y, & \text{for } n_Z \geq 10, \end{cases} \tag{3}$$

with $f_Z(x) = a_Z^0 \times (x + a_Z^1)^{-a_Z^2}$ a function fitted to the n_Z points already associated to the line Z, and $\delta y = y_Z \times Z^{-1}$. The choices of $f_Z(x)$ and δy are purely phenomenological.

Once the spiderweb is woven (see Fig. 1(d)), identification lines that do not fulfill the following criteria:

$$\begin{cases} n_Z > 10 \\ a_Z^1 < 3000 \\ 0.35 < a_Z^2 < 1 \end{cases} \tag{4}$$

are rejected, where n_Z is the final number of points associated to the line Z, and ($a_Z{}^0$, $a_Z{}^1$, $a_Z{}^2$) are the parameters of $f_Z(x)$. This procedure aims at eliminating lines with a form completely incoherent with the Bethe-Bloch formula, without being too restrictive in order for this method to be applicable to different types of identification matrices.

It is then possible to build the identification grid from each of the individual functions $f_Z(x)$, either limited to the range where peaks were found (see Fig. 2 for example), or extrapolated over the whole residual energy range (see Fig. 4(a) for example).

[1] not to be confused with the "SpiderWeb" surface construction algorithm.

[2] The ridge lines of individual isotopes are indistinguishable in these data, due to insufficient resolution of the ΔE detectors. In this case ions of different Z populate broad ridges around the mean value <A> of their isotopic distribution.