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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 correla-

tions 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.

Key words: Silicon Detector, Computer Data Analysis, Charged Particle Identification

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) [1,2]. 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 [3,4,5,6,7], providing little isotopic information for heavy fragments ($Z > 5$). More recently detectors have evolved to provide isotopic resolution for a broader range of products [8,9,10], by improving existing detectors and identification techniques, or developing new methods such as the Pulse Shape Analysis (PSA) in silicon detectors [11,12,13].

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 (E). Within

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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 [14,15,16,17]. 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 SPIDER¹ 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 paid 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:

$$n_b = d_\theta \times \rho(\theta) \times \beta, \quad (1)$$

with d_θ the length of the projection, β a binning parameter to be provided by

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 $\langle A \rangle$ of their isotopic distribution.

the user, and $\rho(\theta)$ an internal parameter given by:

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

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

Maxima are then located using the algorithm described in [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 .

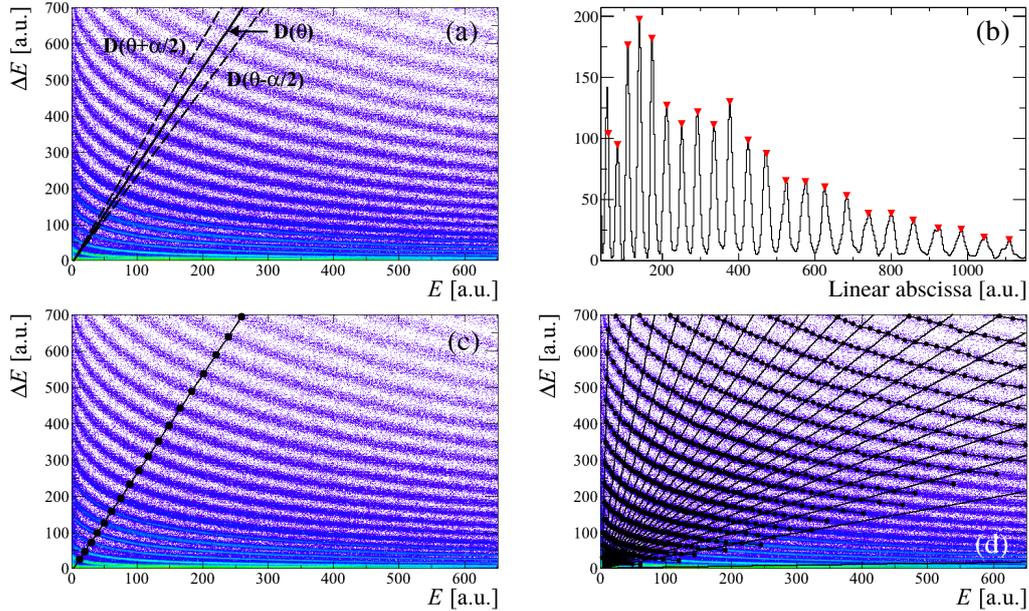


Fig. 1. Illustration of the different steps of the SPIDER identification: (a) definition of the projection; (b) projection on line $D(\theta)$ and localization of maxima; (c) positioning of the maxima on the $\Delta E - E$ matrix; (d) weaving of the spiderweb.

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:

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

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:

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

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).

2.2 Implementation

In order to run the algorithm presented above, several input parameters should be provided by the user: the pedestal coordinates (x_0, y_0) , the first projection angle θ_0 , and the binning parameter β . These parameters are generally difficult to estimate, which makes our method unusable without an implementation in a suitable graphical environment. It has therefore been included in the identification grid editor of KaliVeda [29], which is a graphical user interface dedicated to the creation and editing of identification grids developed initially within the INDRA Collaboration [4].

The pedestal coordinates (x_0, y_0) can be set by the user with a simple click on the $\Delta E - E$ matrix. Our algorithm needs also another point, (X_0, Y_0) , situated approximately in the middle of a high- Z line; and the knowledge of the charge Z_0 associated to this line. The values of θ_0 and β are then calculated as follows :

$$\tan(\theta_0) = \frac{Y_0 - y_0}{X_0 - x_0} \quad (5)$$

$$\beta = \frac{1}{20Z_0} \sqrt{(X_0 - x_0)^2 + (Y_0 - y_0)^2}. \quad (6)$$

Thanks to the implementation in a “user friendly” graphical environment, our method needs only two mouse-clicks from the user to calculate all initialization

parameters, making it very easy to use.

2.3 Examples of use

The present method has been initially developed to treat INDRA Si-CsI(Tl) matrices [4]. Since it uses as little information as possible on the exact form of Z lines, it can be applied to different types of identification telescopes. Here are several examples of use on Si-CsI(Tl), IC-Si, Si-Si matrices; and also matrices from Pulse Shape Analysis of the charge signal in silicon detectors.

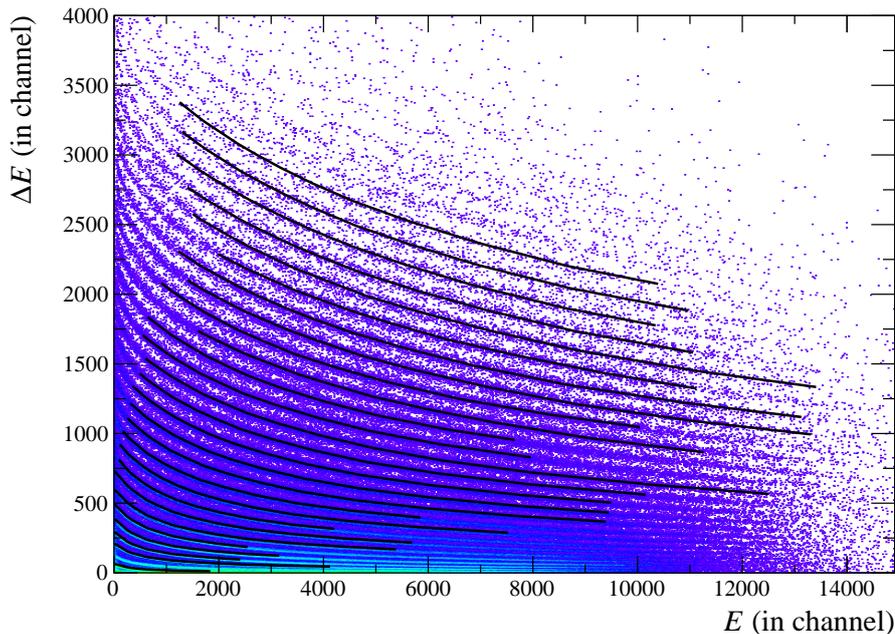


Fig. 2. Application of the SPIDER identification method on a Si-CsI(Tl) matrix of INDRA ($\theta \sim 17^\circ$). Data come from the Ta+Zn at 39 MeV/A reaction measured at GANIL.

Fig. 2 presents the result of the SPIDER identification on a $\Delta E - E$ matrix coming from a Si-CsI(Tl) telescope of the INDRA multidetector. In this example, Z lines up to $Z = 29$ were found by our algorithm. Since extrapolation using individual functions is not safe in the case of Si-CsI(Tl) matrix, because of the strong curvature of Z lines at low residual energy (E), identification lines have been generated on the range where points were found by the algorithm. The obtained identification grid cannot be used directly. It has to be completed by hand, or can be used as input to constrain a fit using some functional. This point is discussed in Section 2.4.

Fig. 3 presents the results of the SPIDER identification on a $\Delta E - E$ matrix coming from an INDRA IC-Si telescope. In this kind of matrix, Z lines are

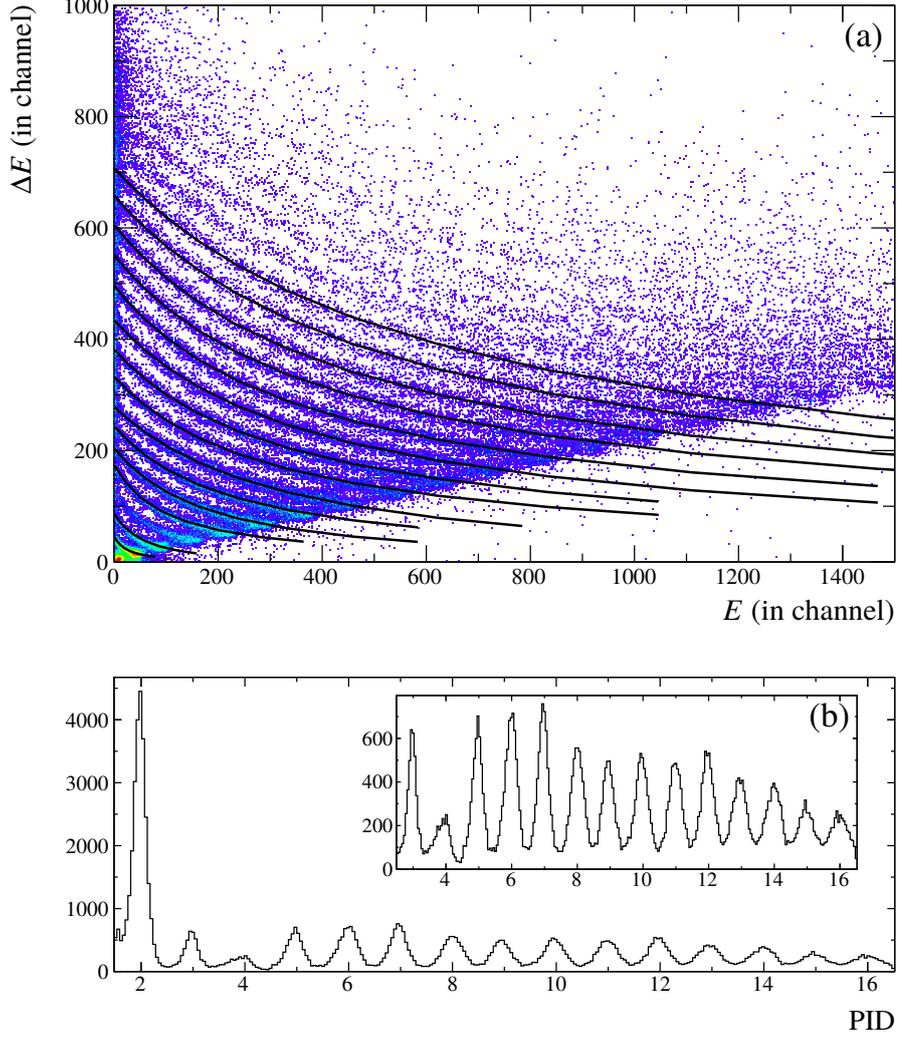


Fig. 3. Application of the SPIDER identification method on a IC-Si matrix of INDRA ($\theta \sim 17^\circ$). PID stands for particle identification obtained after linearization of the matrix with the identification grid. Data come from the Ta+Zn at 39 MeV/A reaction measured at GANIL.

generally broad due to the poorer energy resolution of such large-area ionization chambers operated at low pressure, and rarely homogeneously populated. Nevertheless, our algorithm has extracted ridge lines from $Z = 2$ to $Z = 16$ (Fig. 3(a)), providing a good charge identification (Fig. 3(b)). It can be noted that, in this example, the $Z = 4$ line was not generated because it did not satisfy the criteria of Eq. (4).

The result of the SPIDER identification on a $\Delta E - E$ matrix coming from a Si-Si telescope of FAZIA [9] is presented in Fig. 4. In this kind of matrix, ridge lines corresponding to different elements are clearly separated thanks to the very good quality of FAZIA silicon detectors. In addition, the line curvature is quite slight, making the SPIDER identification very efficient (Fig. 4(a)). Even

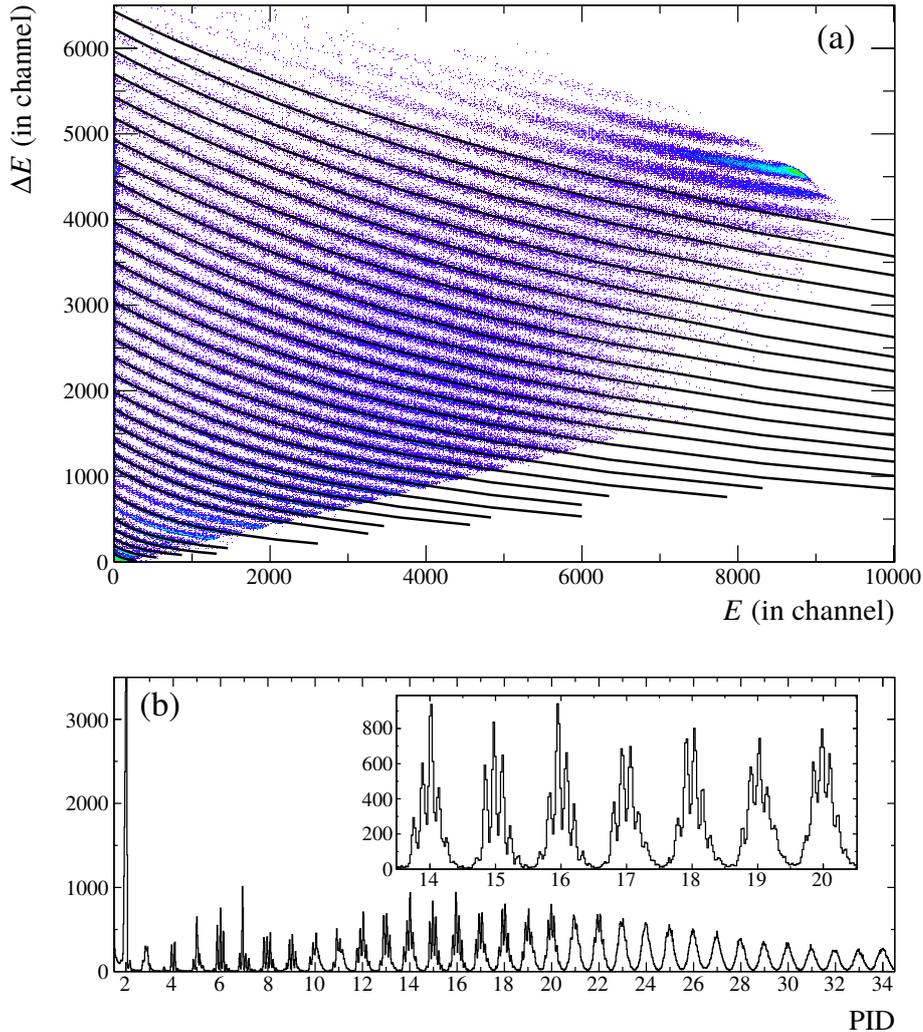


Fig. 4. Same as Fig. 3 for Si-Si matrix of FAZIA ($\theta \sim 7^\circ$). Data come from the Kr+Sn at 35 MeV/A reaction measured at LNS [31,32].

if a few lines ($Z = 7$ and $Z = 9$) have not been generated, the grid provides a very good charge identification, up to $Z = 34$ (Fig. 4(b)). For each integer value of Z , several peaks appear on the identification spectrum up to $Z \sim 20$. These peaks correspond to different isotopes of each element, and allow to discriminate particles of different masses. The charge-identification grid can then be used as a starting point to generate a mass-identification grid. This point is discussed in sec. 3.

Previous examples all concern the $\Delta E - E$ method. Identification matrices obtained by Pulse Shape Analysis of the charge signal in FAZIA silicon detectors [9] present a form quite similar to that obtained with the $\Delta E - E$ method. Since the SPIDER identification method uses little *a priori* information on the ridge line form, it can also be applied to this type of matrix. In the example shown in Fig. 5, the generated grid provides a satisfying charge

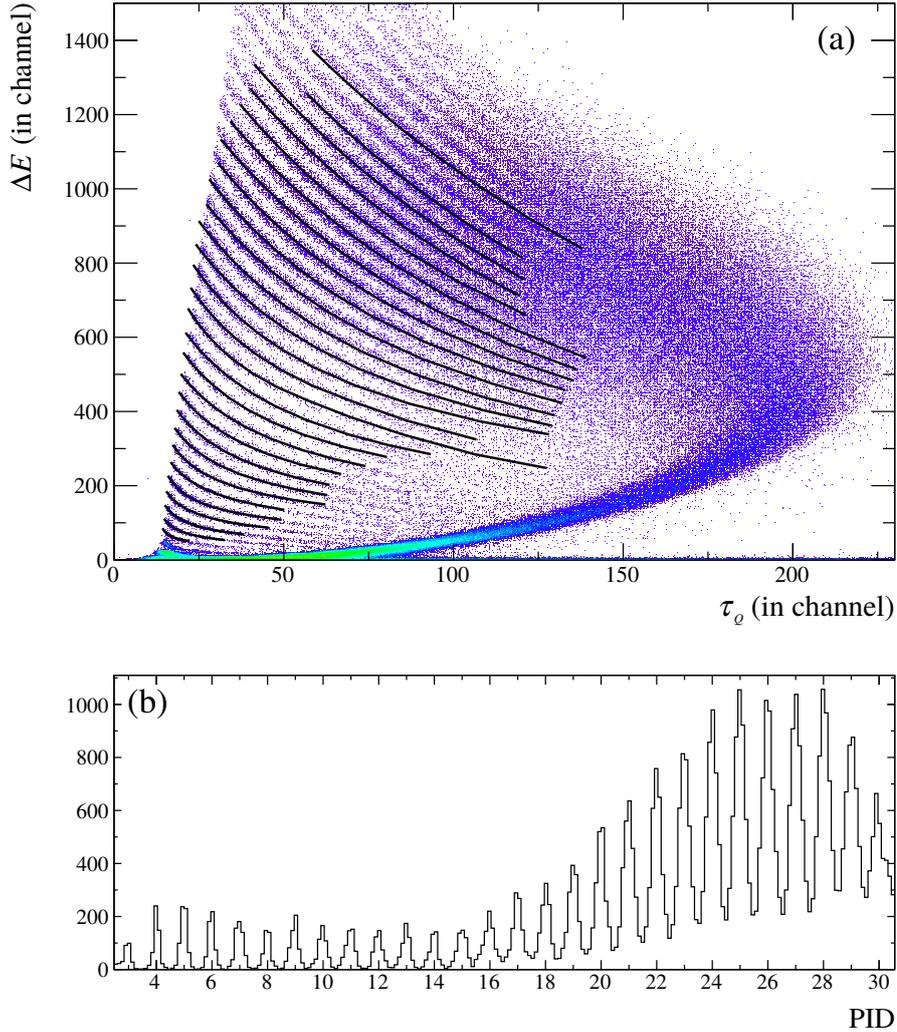


Fig. 5. Same as Fig. 3 for energy versus rise time of the charge signal in the first silicon layer matrix of FAZIA ($\theta \sim 7^\circ$). Data come from the Kr+Sn at 35 MeV/A reaction measured at LNS [31,32].

identification from $Z = 3$ up to $Z = 30$ (Fig. 5(b)), even if identification lines do not cover the full matrix range (Fig. 5(a)).

2.4 Coupling with a fitting procedure

We have shown in previous examples that Z -lines generated by the SPIDER identification, possibly extrapolated using individual functions, can be directly used to identify particles. This procedure is efficient but does not allow to extrapolate the identification to higher Z . These lines, without extrapolation, can also be used as input to fit functional parameters. In the present example, we used the functional proposed in [16].

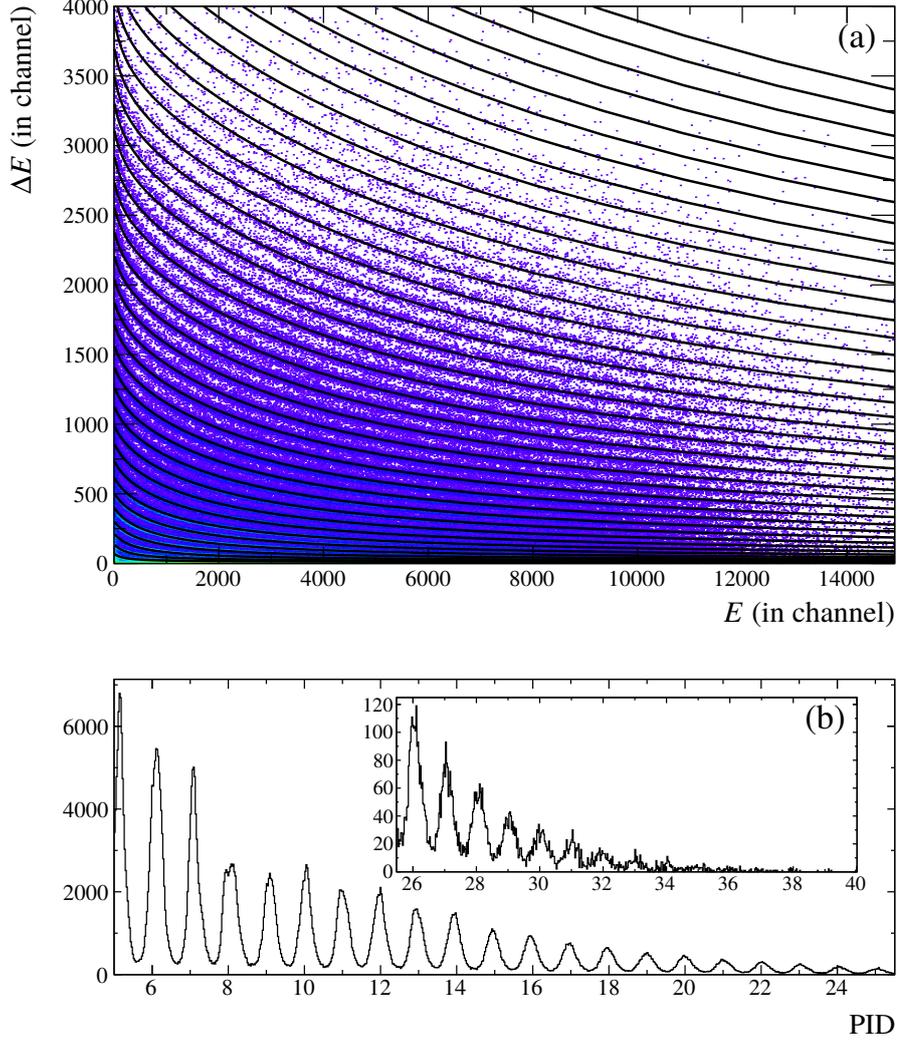


Fig. 6. Example of coupling between the SPIDER identification method and a functional fit [16]. The identification grid used as input is shown in Fig.2.

Raw Z -lines obtained with the SPIDER method on an INDRA Si-CsI(Tl) matrix are those previously presented in Fig. 2. These lines, which do not cover the whole residual energy range, are used to fit the 9 parameters of the functional [16]. The result of the fit is shown in Fig. 6. It can be seen that a satisfactory agreement is obtained for all charges and over the full matrix. The quality of the charge identification can be checked in Fig. 6: a good charge identification is achieved up to $Z \sim 36$, even if the statistics for high Z is very poor. The coupling between the SPIDER method and a functional fit allows to obtain a full charge identification in a very short time. This procedure was used during the data reduction of the INDRA experiment presented in [33].

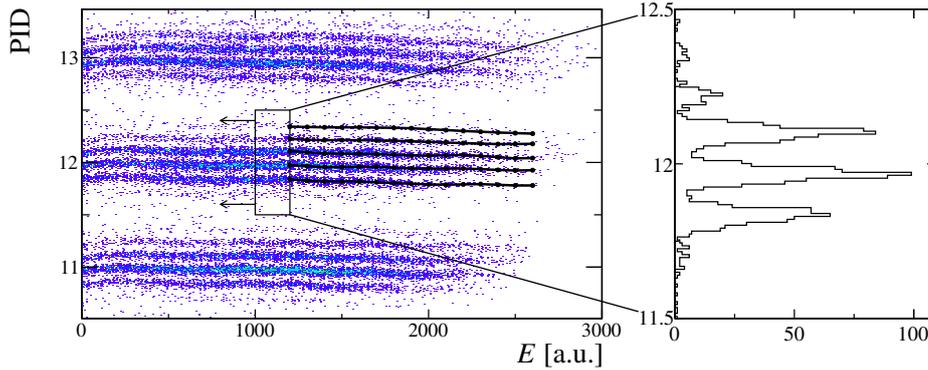


Fig. 7. Illustration of the isotopic identification method in PID- E matrices.

3 Isotopic identification

The method presented above, and its possible coupling with a fitting procedure, facilitate a lot the extraction of Z -identification lines. As illustrated in Fig. 4(b), the good quality of FAZIA silicon detectors allows also isotopic identification of charged particles up to $Z \sim 25$. In order to carry out an isotopic identification, ridge lines corresponding to each (Z, A) couple have to be drawn. This is again a very fastidious task. We propose here a method to extract these lines in a fully automatic way. The only input of the algorithm is a charge-identification grid that can be easily generated using the SPIDER identification method, which is particularly efficient for the case of Si-Si matrices (see Fig. 4).

In $\Delta E - E$ matrices, lines corresponding to a given atomic number Z are regularly spaced and populated. The scheme for isotopic lines is much more complex: the relative population of each isotope depends strongly on the considered element, on the studied reaction, and isotopes with short lifetimes (typically lower than 1 ns) are never detected. The extraction of isotopic (Z, A) -lines from the raw $\Delta E - E$ matrix is therefore very complex. To simplify the treatment, we have to transform the matrix in order to extract masses Z by Z . The first stage of the algorithm is then to linearize the $\Delta E - E$ matrix according to the Z -identification grid provided by the user, in order to obtain a PID- E matrix (Fig. 7). If the quality of the grid is good enough, A -lines associated to a given Z are almost horizontal and lie in the PID range $[Z-0.5, Z+0.5]$.

All points contained in the range $\text{PID} = Z \pm 0.5$ and $E = E_i \pm \delta E$ (rectangular box in Fig. 7) are projected on the PID axis. Peaks corresponding to the intersection of A -lines and the vertical line $E = E_i$ appear in the projection histogram. The binning of this projection is set to 60 bins whatever the Z considered. Peaks are located and replaced in the PID- E matrix. Each new point is simply associated to the closest A -line. The operation is then repeated

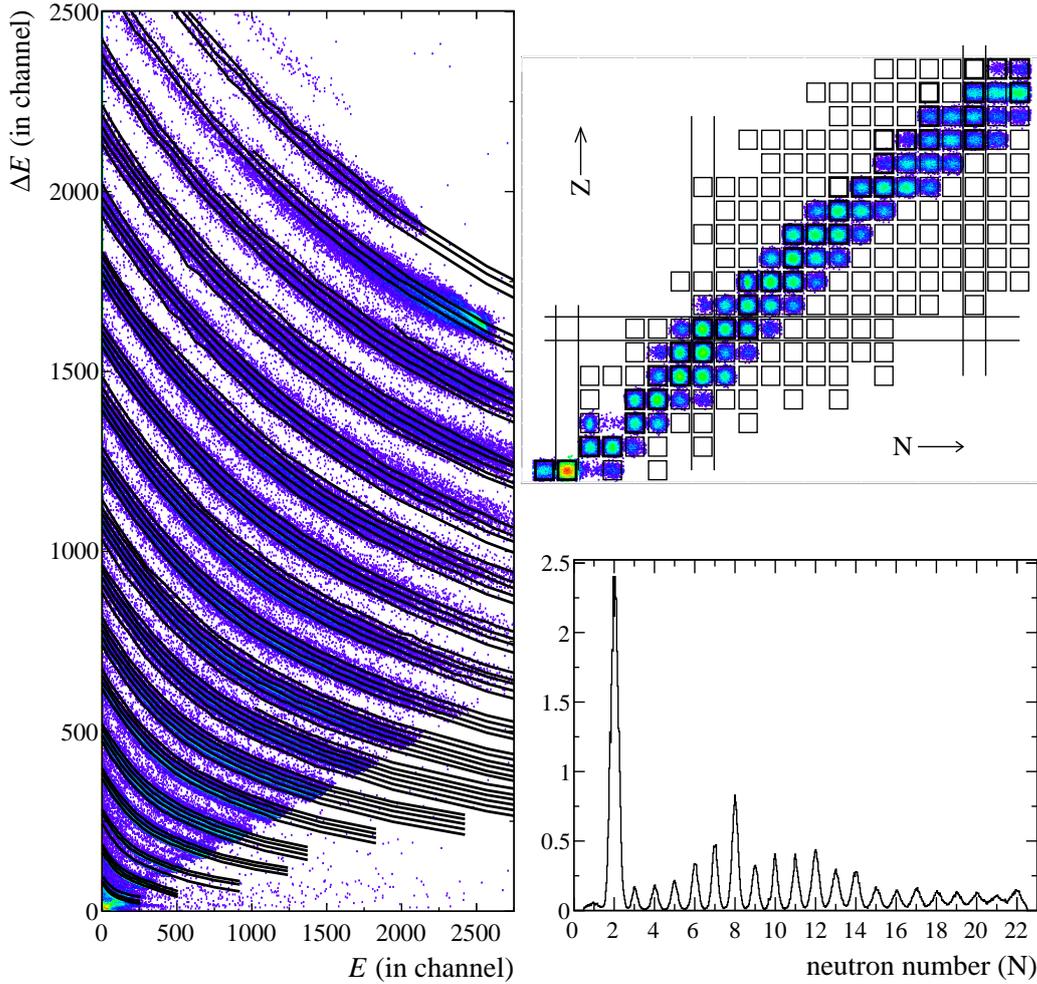


Fig. 8. Result of the automatic isotopic line extraction applied to a Si-Si matrix of FAZIA ($\theta \sim 7^\circ$) in the Ar+Sn at 25 MeV/A reaction: isotopic identification grid, isotopic and neutron number distribution after linearization.

by varying E_i in order to cover the whole residual energy range, and for all Z (Fig. 7). The obtained identification grid in the PID- E plane is finally transformed in the $\Delta E - E$ plane (Fig. 8). The corresponding isotopic identification matrix is presented in Fig. 8.

This algorithm has also been implemented in the identification grid editor of KaliVeda [29].

4 Conclusion

In this article, we proposed a new method (SPIDER identification) for generating Z and A identification grids 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. It has been successfully tested on various types of matrices obtained with $\Delta E - E$ and Pulse Shape Analysis techniques. Particular attention has been paid to the implementation in a suitable graphical environment, so it needs only two mouse-clicks from the user in order to calculate all initialization parameters. Extracted lines can then be directly used to identify charged particles, set as an input of a functional fit, or used to extract isotopic lines in a fully automatic way.

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