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A procedure to calibrate a multi-modular telescope

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Abstract

A procedure has been developed for the charge, mass and energy calibration of ions produced in nuclear heavy ion reactions. The charge and mass identification are based on a ΔE–E technique. A computer code determines the conversion from ADC channels into energy values, atomic number and mass of the detected fragments by comparing with energy loss calculations through a minimization routine. The procedure does not need prior measurements with beams of known energy and charge. An application of this technique to the calibration of the MULTICS apparatus is described.

1. Introduction

In the last several years new detectors with large solid angles and geometrical efficiencies have been developed to investigate heavy ions reactions at intermediate energies (10 MeV/u to 1 GeV/u) [1–4]. The new experimental apparatus allow the simultaneous detection of energy, emission angle, atomic number and mass of several fragments by using a large number of multimodular telescopes. To extract this kind of information from the detector signals long and tedious calibrations are usually required. This is due to the high number of different detectors (ionization chambers, semiconductors and scintillators) and to the large number of nuclear species in a wide energy range which are produced in the reactions. It is important to note that these large experimental apparatus allow relatively fast data collection and are able to detect also rare events due to their high detection efficiency. On this basis it is possible to measure with different projectile + target systems at different beam energies with the same experimental setup in the available beam-time. Furthermore since different amplification gains of the electronic chain may be needed during a single experiment (because of different beam energy and projectile + target combination) a longer calibration procedure may result.

Part of the beam-time is typically used for the collection of known-energy experimental points (as Rutherford diffusion on targets or direct exposition to low-intensity beam) from which the detectors calibration is then determined.

In this paper we will present the implementation of a new time-saving calibration method to minimize the time dedicated to detector calibration, thus allowing the collection of more data, hence smaller statistical uncertainties. Furthermore in all the cases when known-energy beams are not available or it is not possible, using elastic scattering, to cover all detectors and telescopes, the procedure we will describe allows one to obtain the angular coefficient (slope) and constant term (offset) of the straight-line calibration.

It must be considered also that possible instabilities of the electronics may cause amplification drift making it difficult to use the same set of calibration data in two measurements made at different times. It is then extremely useful to have a calibration procedure which can be applied to each run independently. In order to optimize the experimental potential of a quick data analysis a fast data reduction must also be implemented along with fast data collection.

Last but not least the procedures commonly used for the charge (mass) calibration are based on graphical cuts or on Particle Identification Functions (PIF) which, because of their manual nature, automatically introduce a limitation into the calibration. On the contrary a minimization procedure makes it possible to reduce the human "subjectivity" of the results and to achieve higher precision.

With this technique pre-calibration procedures can be skipped and human participation is required only to check the results. This technique is made possible by the high computational abilities to modern computers.

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2. The calibration procedure

The calibration procedure here described may be applied to the multi-modular detectors with resolution sufficient to separate the curves relative to single atomic number (mass) in a (ΔE, E_{res}) matrix, where ΔE and E_{res} are, respectively, the energy losses in two successive detectors of an incident ion with total energy $E = \Delta E + E_{res}$.

Every single section in the program compares the data to the energy loss calculations. Specific energy loss (dE/dx) of a charged particle in matter depends on the characteristics of the incident ion (mass, charge and energy) and of the absorber medium (volumetric density and atomic number) and is well described by the classical Bethe–Bloch formula [5]. Energy loss calculation, based on the Anderson studies [6,7], are able to reproduce experimental data with good accuracy in a large energy and atomic species spectra. This can be seen in Fig. 1 where the energy loss curves overlap experimental data relative to ion species of beams with known energy.

The calibration program consists of three different sections:

i) a first introduction section that deals with energy losses in detectors;

ii) a second section dedicated to energy calibration; in this section the offsets and amplification gains of electronic chain are computed for the various detectors of each telescope;

iii) a final event-by-event calibration in energy, charge and mass.

As an example, we will describe the application of the procedure to a telescope of the MULTICS array, which consists of a ionization chamber (IC), a 500 μm, thick silicon (SI), a 4 mm lithium drifted silicon (SILI) and a CSI(Tl) scintillator (CSI).

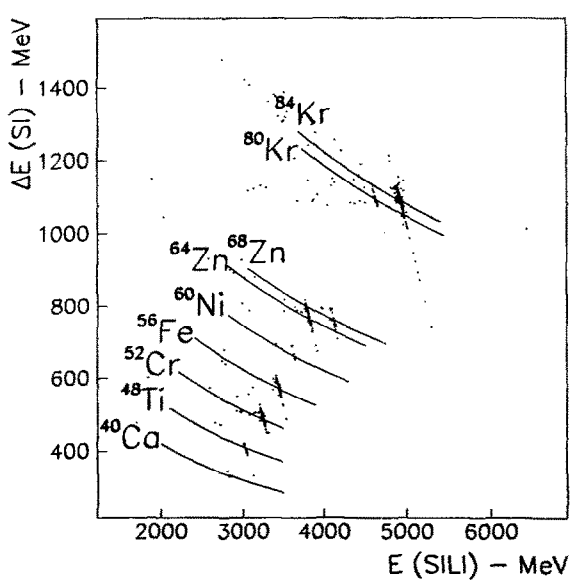

Fig. 1. Matrix ΔE vs. E_{res} from direct exposure to energy-known beams (500 μm silicon as ΔE detector (SI) and 4 mm of lithium drifted silicon as stop detector (SILI)).

2.1. Energy loss tables

Part i) deals with the preparation of tables containing the data for the energy loss of various ions at several energies in each pair of ΔE–E_{res} detectors. For an accurate calibration it is extremely important to know with good precision each ΔE detector's active thickness and dead layer. If the telescope is not able to determine the ion mass A, the most probable isotope associated with the atomic number Z, $A = aZ + bZ^2$ ($a = 2.08$, $b = 0.0029$ for fragments produced in heavy ion reactions [8,9], $b = 0.0059$ for the most probable isotopes on the periodic table) can be used in the energy loss calculation. The differences in the b values take into account the fact that the reaction products tend to be lighter than the most probable isotopes in nature because of the preferential emission of neutrons.

The aim of this first procedure is to obtain an analytical expression for the energy-loss tabulated points. This can be done also before the experiment and remains valid during all the measurements done using the same detectors.

For every given ion the following analytic form connects the various energy losses in the telescope:

$$\Delta(E)_{Z,A} = f_{Z,A}(E_{res}) = -d_1 E_{res}^{-d_2} \exp\left(1 - \frac{E_{res}^{d_3}}{d_4}\right), \qquad (1)$$

where d_1, d_2, d_3, and d_4 are the parameters to be determined for each (Z, A) pair in the energy range $0 \leqslant E_{res} \leqslant E_{MAX}$.

In Fig. 2a we show the good agreement between the curves $\Delta(E)_{Z,A} = f_{Z,A}(E_{res})$ and the points calculated through Eq. (1) for different values of atomic number Z.

2.2. Energy calibration of the telescopes

After the determination of the $f_{Z,A}(E_{res})$ parameters, the program then deals with the energy calibration of each telescope.

A set of points is extracted for every ΔE–E_{res} matrix. Data sampled on the curves are shown in Fig. 2b; one has to assign arbitrarily a temporary Z value (Z_{TEMP}) to each curve in the right order given by subsequent curves. With the program the correct correspondence between Z and the relative curve will be done through the option that allows to add or subtract a constant value Z_{plus} to each Z_{TEMP}.

The marked points shown in Fig. 2b are extracted from the $\Delta E = E_{res}$ matrix and the coordinates are put in a table. Each of these points is characterized by its ΔE(Ch) and E_{res}(Ch) coordinates (expressed in channels) and by a Z_{TEMP} value. Once the first is fixed, a $Z_{TEMP} + 1$ value must be assigned to the next curve and so on. The angular coefficients and the known-terms of the calibration curves

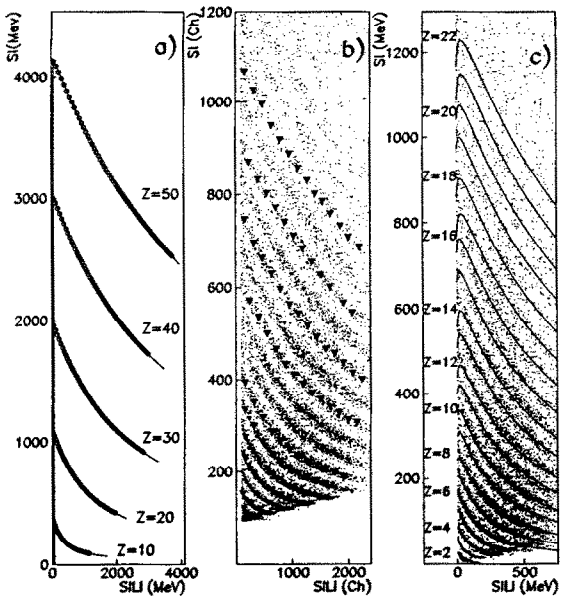

Fig. 2. (a) Curves ΔE–E_{res} for the matrix ΔE (silicon, 500 μm thick, SI) vs. E_{res} (4 mm lithium drifted silicon, SILI). The points come from the output of the ENLOSS code while the overlapped curves come from the fit with the analytic function (1). One can see the good capability of the function to fit the large range of data. (b) Example of sampled point. It is not important to sample all the curves. The number of sampled points is about 90. (c) Calibrated data overlapped by energy-loss curves from $Z = 2$ up to $Z = 22$. One can see the good agreement between the curves and the experimental calibrated points, demonstrating the good accuracy of the calibration method.

for the various detectors in the telescope are treated as parameters in the minimization routine (we use the MINUIT D505 routine from the CERN Program Library).

Through a minimization process the program determines the angular coefficients and the offsets of the energy-channel curves that yield the best agreement between sampled points and the energy-loss curves from Eq. (1).

The method consists of minimizing the distance between the sampled points and the $\Delta(E)_{Z,A} = f_{Z,A}(E_{res})$ curves associated with the relative Z value (Z_{TEMP}).

The χ^2 value for each event is given by the squared difference between the value of the temporary calibration of an experimental ΔE value and the valued predicted from the energy-loss curves corresponding to a chosen Z_{TEMP} value and to an E_{res}-experimental-calibrated-value. The code makes a comparison between the different ΔE values, that correspond to a fixed value E_{res} for the temporary assigned Z_{TEMP} value.

The final parameters, obtained by the χ^2 fit, give the offsets and angular coefficients best able to match the energy-loss $\Delta(E)_{Z,A} = f_{Z,A}(E_{res})$ curves to sampled data (therefore to experimental data) for a particular choice of the assigned Z_{TEMP}-values.

Using Z_{plus} as a variable the minimization procedure is repeated with different Z values assigned to the sampled data; the χ^2 shows an evident minimum corresponding to the correct assignment of the Z value to each curve.

In Fig. 2c we show a ΔE–E_{res} matrix calibrated with the coefficients obtained from the minimization method discussed above. The $\Delta(E)_{Z,A} = f_{Z,A}(E_{res})$ curves for different Z values overlap the experimental data.

It should be noted that when dealing with a multimodular telescope the calibration of the middle detectors (those that act as passing and stopping detectors) applies heavy constraints to the calibration quality if one wants good $f_{Z,A}(E_{res})$ fits on two different matrices, since the choice of offset and slope values for the middle detector impose a constraint on both the matrices.

The good capability of the method is clearly shown in Fig. 3, where the curves corresponding to different Z values are overlapped onto the experimental calibrated data. In this figure the abscissa E_{res} is obtained from the sum of the output of the two following detectors.

2.3. Event by event calibration

After the energy calibration the atomic number Z has to be assigned to each experimental point, event by event.

Starting from the energies, obtained as described before or from energy-known beams, the program estimates the distance of the experimental point to the curve $\Delta E = f_{Z,A}(E_{res})$ for all the possible Z values. The shortest distance between the (E_{res}, ΔE) point and a curve $f_{Z,A}(E_{res})$ determines the choice of the appropriate assignment of the

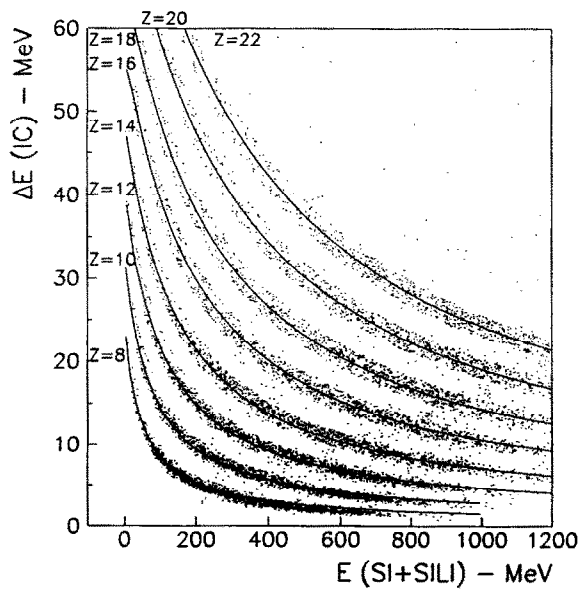

Fig. 3. Curves ΔE–E_{res} for the matrix ΔE (Ionization chamber, 8.5 cm long, CF_4 gas filled at a pressure of 90 mbar, IC) vs. E_{res} (silicon + lithium drifted silicon, SI + SILI) for $Z = 8$ up to $Z = 22$ in steps of 2; energy loss curves are overlapped. In this case silicon acts as passing and stopping detector.

Z-value. The Z-value is evaluated in the matrix corresponding to the detector which works as stop detector for that particular event. This detector can be determined as the one where the subsequent detector measures zero energy.

We have applied the same calibration procedure to a CsI(Tl) scintillator through a calibration curve which is able to reproduce the light-response of the scintillator as a function of the energy and charge of the incident ion [10,11]. By implementing this function in a routine we could consider the scintillator in a manner similar to the other linear detectors.

The whole calibration procedure has been tested by comparing it with results obtained through standard methods (e.g. PIF for the charge calibration). The precision of the calibration has also been checked with the calibration obtained from known energy experimental points which have been measured by low-intensity beam impinging directly on the detectors. The excellent consistency of the results shows the quality of our procedure.

Exploiting the possibility of accelerating simultaneously ions with a charge/mass ratio roughly constant, several "cocktail" beams have been obtained at the Superconducting Cyclotron of the Michigan State University (18 different ion species have been accelerated). With this "cocktail" beams a very accurate calibration was obtained independently. We checked the data calibrated with the previously described procedure with data calibrated by the cocktail beams. A very good agreement between the two calibration methods was found. The excellent agreement found for the calibration parameters obtained with these two different methods gives added credibility to the capability of the technique described here.

In Fig. 2c the agreement between the experimental calibrated data with the procedure discussed above and the corresponding energy-loss curves confirms the accuracy of the method.

3. Conclusions

The advantages obtained with this automatic calibration procedure may be summarized in the following points.

- Known-energy beams or target elastic diffusion calibration are not needed. This results in more beam time available for experimental data collection.
- The time dedicated to offline calibration is greatly reduced.
- Results are very accurate, comparable with those obtained with procedures based on the collection of a large number of known-energy experimental points and using PIF.
- The procedure can be easily extended to any experimental apparata with multi-modular telescopes based on ΔE–E_{res} technique for the evaluation of the ion atomic number and/or mass.

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