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Efficiency of a large solid angle detecting system for heavy ions

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A study is presented on the evaluation of the detection efficiency of a modular apparatus, covering a large solid angle, to be used in experiments with heavy ions at intermediate energies. Calculations are performed for the reaction Xe + Cu at 45 MeV/A simulated by means of the Gemini code.

1. Introduction

The improvements on accelerators of the last few years have provided high intensity beams of heavy ions with energies between 20 and 100 MeV/A. This opens the possibility to collect more data at several energies and with a sufficiently large variety of heavy ions. A complete description of the mechanisms of projectile–target interaction can be obtained only with kinematically complete measurements [1,2], i.e. with an experimental apparatus covering the whole solid angle in the center of mass and detecting all the fragments emitted in each reaction. This goal can be achieved by covering a laboratory solid angle much smaller than 4π taking advantage of the forward focusing of the reaction products when an asymmetric projectile–target combination is used, with the lighter ion as target (inverse kinematics).

In the MULTICS collaboration [#1] a detecting system with about 50 telescopes is under construction to be used mainly for measurements of intermediate mass fragments ($A \geq 5$, $Z \geq 3$).

Each telescope, with truncated pyramid shape, consists in an axial ionization chamber, an xy position-sensitive silicon detector and a CsI crystal. The front face of each telescope is a square of side $L = 52$ mm with a frame having a width $\delta = 5$ mm and is located 50 cm from the target.

The ionization chamber can be operated with different gas pressures, up to 400 mbar. A typical energy threshold is 1.5 MeV/A for any Z at 100 mbar.

The xy position sensitive detector, with angular resolution $\Delta\theta \approx 0.2°$ has been chosen in order to have detailed information on the angular correlation between fragments emitted in the same event.

A 25 mm thick CsI detector can stop any fragment up to 80 MeV/A.

The Z-resolution of this kind of telescope $\Delta E_1 - \Delta E_2 - E_{\mathrm{residual}}$, has been tested with a xenon beam, showing a good discrimination of all the Z-values in the range 3–55. Details and performances of the apparatus will be described elsewhere.

We plan to use this apparatus in measurements at GANIL laboratories and at the Laboratori Nazionali del Sud of INFN once the superconducting post-accelerator cyclotron will be in use.

The analysis of the experimental data which will be taken in these experiments requires a preliminary accurate evaluation of the efficiency of the system mainly to see whether the apparatus introduces distortion in the measured spectra owing to the loss of events in some preferential region of the phase space.

It should be noted that the "a priori" calculation of the efficiency of the detection system depends on the

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[#1] INFN-Sezione di Bologna, Sezione di Catania, Sezione di Milano, Sezione di Trieste, Laboratori Nazionali di Legnaro, GANIL Laboratories.

assumptions made for the dynamics of the reaction, i.e. the same apparatus has different efficiencies for a different reaction mechanism.

In this respect we here describe a procedure which allows us to calculate the efficiency of the apparatus and therefore to know how the experimental system "filters" the data whatever the reaction mechanism is.

This procedure has the advantage, with respect to geometrical considerations, of taking into account the behavior of cross sections for the production of n fragments predicted by any theory, from an isotropical emission (corresponding to pure geometrical assumption) to a more complicated one, such as statistical assumptions or dynamical models, without losing any information on the correlation of the emitted fragments.

Furthermore this procedure can be "inverted", i.e. one can use inverse formulae in order to have a straightforward determination of the emission angles from the positions of the detected fragments.

In section 2 we present a basic geometrical arrangement of the telescopes and provide a set of formulae allowing to determine whether a particle could be revealed by the apparatus or it is lost in dead regions. Section 3 deals with the evaluation of the efficiency, particularly with respect to three-fold events simulated by the Gemini code [3] for the reaction Xe + Cu at 45 MeV/A. Possible improvements of the apparatus are also discussed. In section 4 we present our conclusions.

2. Geometry of the apparatus

The apparatus has been built in such a way that the front face of each telescope is tangent (in its center) to a sphere of radius $R = 50$ cm centered in the target, so that it could fit the existing scattering chambers, i.e. Nautilus at GANIL laboratories or the scattering chamber under construction at the Laboratori Nazionali del Sud, Catania.

Dividing the spherical surface in parallels and meridians, seven telescopes are put on each meridian and seven telescopes on each parallel, except for the central one where the beam goes through a hole as big as a telescope. The front faces of adjacent telescopes meet at one vertex on the highest and lowest parallel, and at one side on each meridian, leaving dead regions between adjacent telescopes on the same parallel (see fig. 1).

To specify the position of the centre of each front face (henceforth called detector) on the sphere we refer to the cartesian coordinate system Oxyz shown in fig. 2 with the origin O in the target position and the z-axis in the beam direction.

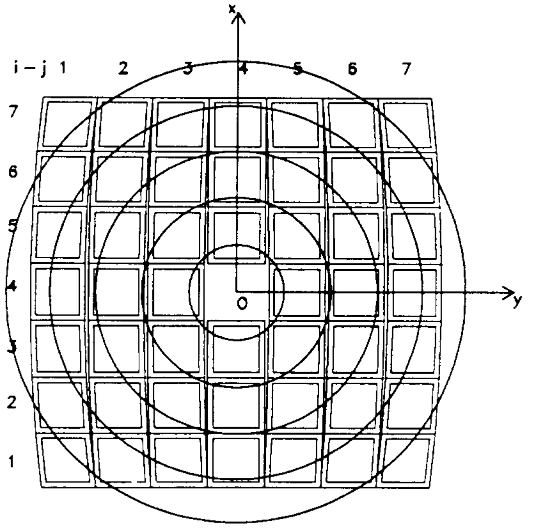

Fig. 1. Schematic picture of the system of detectors (front view). The circles are the intersections between a plane parallel to the xy one, at $z = 50$ cm, and cones with aperture $\theta = 5°$, $10°$, $15°$, $20°$, $25°$.

If β and α are the colatitude (measured from x axis) and the longitude (measured from z axis in the yz plane) and i and j are integers labelling (as shown in fig. 1) the parallels and the meridians on which the centres of the detector lie, then:

$$\beta_i = 90° - (i - i_c)\ \Delta\beta, \tag{1}$$

$$\alpha_j = (j - j_c)\ \Delta\alpha, \tag{2}$$

where $i_c = 4$ and $j_c = 4$ are the central parallel and the central meridian respectively, $\Delta\beta = 2\ \mathrm{artg}(L/2R)$ is the angular aperture between two consecutive parallels and

$$\Delta\alpha = 2\ \mathrm{artg}\frac{L}{2(R\sin\beta_{\min} - L/2\cos\beta_{\min})}$$

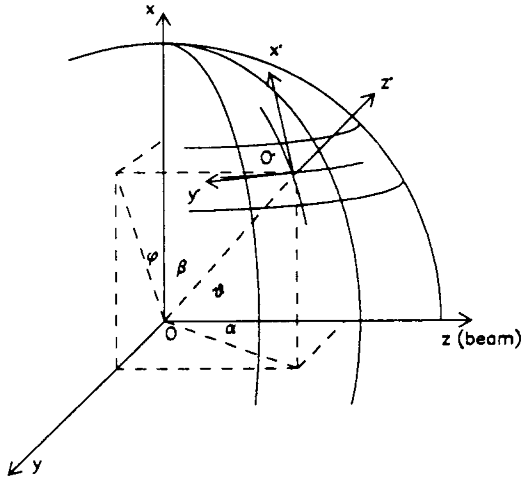

Fig. 2. Reference frames used for the description of the apparatus: O′ is the centre of the detector (i, j).

is the angular aperture between two consecutive meridians ($\beta_{\min}$ being the colatitude of the highest detector centres). Let us now consider a fragment emitted from the origin O with polar angles θ_{ev}, ϕ_{ev} and let α_{ev} and β_{ev} be the colatitude and longitude, given by:

$$\operatorname{tg} \alpha_{ev} = \operatorname{tg} \theta_{ev} \sin \phi_{ev}, \tag{3}$$

$$\cos \beta_{ev} = \sin \theta_{ev} \cos \phi_{ev}. \tag{4}$$

A comparison among α_{ev}, β_{ev} and all the α_j, β_i from eqs. (1) and (2) allows to determine the detector (i, j) closest to the straight line $(\alpha_{ev}, \beta_{ev})$.

Then, in order to know if the particle is detected or not, we check if the fragment strikes the active area of the (i, j) detector.

We first calculate the distance R_{ev} from the target to the intersection point between the straight line $(\alpha_{ev}, \beta_{ev})$ and the plane of the closest detector:

$$R_{ev} = \frac{R}{\cos \beta_i \cos \beta_{ev} + \sin \beta_i \sin \beta_{ev} \cos(\alpha_{ev} - \alpha_j)}; \tag{5}$$

then the Cartesian absolute coordinate of the event:

$$x_{ev} = R_{ev} \cos \beta_{ev},$$

$$y_{ev} = R_{ev} \sin \beta_{ev} \sin \alpha_{ev},$$

$$z_{ev} = R_{ev} \sin \beta_{ev} \cos \alpha_{ev}, \tag{6}$$

and finally we transform them in the reference frame of the (i, j) detector, having its origin in the detector centre, the z' axis perpendicular to the detector and the x' and y' axis tangent to the meridian and to the parallel respectively (see fig. 2).

The transformation can be written as:

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = A \begin{pmatrix} x_{ev} - x_{ij} \\ y_{ev} - y_{ij} \\ z_{ev} - z_{ij} \end{pmatrix}, \tag{7}$$

with x_{ij}, y_{ij}, z_{ij} the absolute coordinates of the center of the (i, j) detector and:

$$A = \begin{pmatrix} \sin \beta_i & -\sin \alpha_j \cos \beta_i & -\cos \alpha_j \cos \beta_i \\ 0 & \cos \alpha_j & -\sin \alpha_j \\ \cos \beta_i & \sin \alpha_j \sin \beta_i & \cos \alpha_j \sin \beta_i \end{pmatrix}. \tag{8}$$

A particle hitting a detector in a point with relative coordinates x' and y' ($z' = 0$) is detected only if its falls in the sensitive area of the detector, i.e. if,

$$|x'| \le \frac{L}{2} - \delta, \qquad |y'| \le \frac{L}{2} - \delta.$$

With this procedure we are able to evaluate the detecting efficiency for any kind of event characterized by n particles as the ratio between the number of the events detected by the apparatus and the total number of events of the same kind produced in the reaction. This will be done for some specific cases in the next section with simulated events.

In addition, as already mentioned in the introduction, the inversion of eq. (7) allows the determination of the laboratory polar angles of the emitted fragments (θ_{ev}, ϕ_{ev}), starting from the experimental x', y' and z'.

3. Efficiency

First of all we evaluated the "geometrical" efficiency of the apparatus defined as the ratio between the active solid angle and the total solid angle subtended by the boundaries of the apparatus.

Pure geometrical considerations give the value of 61%, and consequently an efficiency of ~ 37% and ~ 23% for two-fold and three-fold coincidences of uncorrelated particles emitted within the whole solid angle subtended by the apparatus. However these numbers give only a guess of the importance of dead regions: the detection efficiency with respect to a given event of a given reaction (and hence the possible distortion in the event distributions) depends on the reaction itself due to the angular dependence of the cross sections.

Therefore, for any specific case, one has to simulate events in the most realistic way. This can be done using some specific model describing how two or more intermediate mass fragments are generated and emitted in an intermediate-energy heavy-ion reaction.

A reasonable simulation can be achieved exploiting the Gemini code. In fact, this code, based on a statistical decay of a compound nucleus, gives observables which agree quite well with experimental data in the energy range here considered.

Calculating the efficiency for the events (n-fragments) generated by the Gemini program for the reaction Xe + Cu at 45 MeV/A, we obtained an efficiency $\epsilon_2 = 22\%$ for the two-fold, $\epsilon_3 = 12\%$ for three-fold coincidences and ϵ_4 of a few percent for four-fold coincidences.

We are mainly interested in these last two types of events, which could give more information on the reaction mechanism, but since the cross section of four-fold events is quite low, we focalize the discussion about the three-fold events.

Beside the loss of events, the most important thing is to check how this loss reflects on the shape of the distributions of some observables. Here we limit ourselves to consider only the variables $A_3/(A_1 + A_2 + A_3)$, and $A_1/(A_1 + A_2 + A_3)$, which appear very suitable [4] for the description of three-fold events (A_1, A_2, A_3 are the mass of the heavy, intermediate and light fragments, respectively).

Fig. 3a shows the bidimensional $A_3/(A_1 + A_2 + A_3)$ vs $A_1/(A_1 + A_2 + A_3)$ spectrum of three-fold events generated by the Gemini code for the reaction here

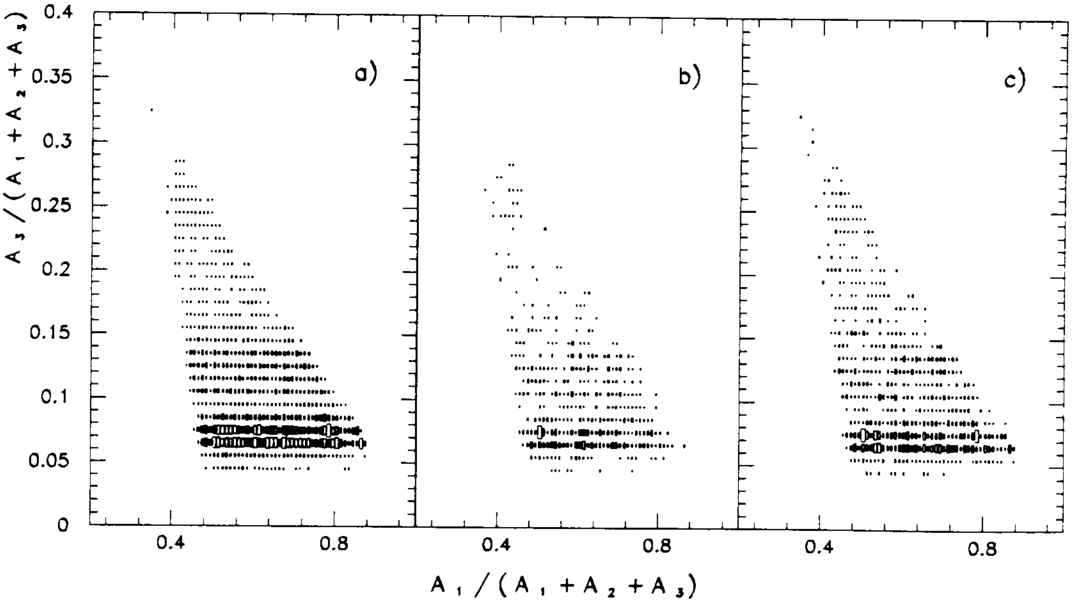

Fig. 3. Bidimensional plot of $A_3/(A_1+A_2+A_3)$ vs $A_1/(A_1+A_2+A_3)$ for three-fold coincidences: (a) from Gemini code; (b) detected by the apparatus; (c) detected by the apparatus with the improvement described in the text.

considered; fig. 3b shows the same spectrum filtered by the apparatus described in the previous section. The right corner at the bottom of fig. 3 represents evaporation events i.e. a quite big and two very small fragments); going to the left one goes to a symmetric binary fission with a very small fragment as a companion. The corner on the top of the triangle, where the masses of the three fragments are similar, corresponds to events due to two sequential binary fissions. The latter region could be populated experimentally also by a ternary breakup.

The shape of the spectra for events in this region could be particularly interesting as far as the transition between a sequential decay mechanism and a multifragmentation process is concerned. It is then important that no distortion is introduced by the apparatus. In

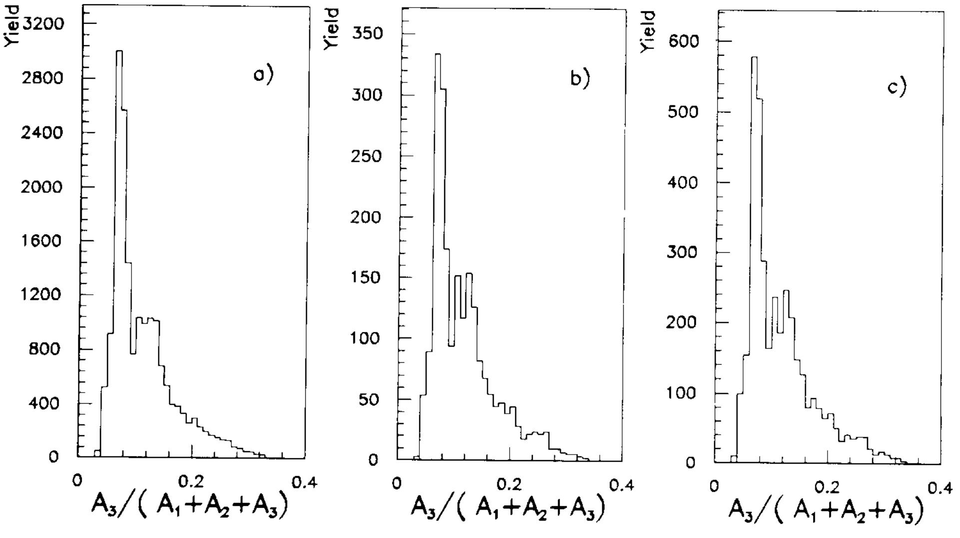

Fig. 4. Three-fold coincidences spectrum vs $A_3/(A_1+A_2+A_3)$: (a) from Gemini code; (b) detected by the apparatus; (c) detected by the apparatus with the improvement described in the text.

figs. 4a and 4b the spectra of the generated and filtered events are shown as a function of $A_3/(A_1+A_2+A_3)$. Apart from a considerable loss of events the shape of the filtered spectrum is substantially unchanged especially in the high $A_3/(A_1+A_2+A_3)$ region. Kinematical considerations clearly show that the observed loss of events mainly depend on the big central hole ($\pm 3°$) where the heaviest fragments go through.

To measure in particular processes of evaporation or fission, one has therefore to increase the angular range toward small angles, i.e. to reduce the central aperture. This can be done in different ways. One of them consists on adding four detectors at a distance of the order of $2R$, symmetrically placed with respect to the beam axis with their centers on the diagonals of the square corresponding to the central missing detector. This arrangement allows to leave unchanged the description of the old detectors and to describe the additional detectors with equations similar to eqs. (1) and (2).

Another arrangement consists in making some mechanical modifications to the system, moving toward the beam the detectors of the central parallel (or meridian), leaving an aperture smaller than the size of one detector and adding, at a distance $2R$, only two more detectors covering small angles. In this way one has to treat only two additional detectors and, consequetely, also the electronics is not much increased; on the other side the analysis of the data is more complicated, due to the loss on symmetry of the detectors.

The arrangements have been studied taking into account the maximal rate the detectors can stand, due to the large value of the Rutherford cross section at small angles. The efficiency for the three-fold events is of the order of 20% for both of them. Figs. 3c and 4c show, respectively, the A_3–A_1 triangular plot and its projection on the A_3 axis corresponding to the arrangement with four additional detectors. Similar spectra are obtained with the other arrangement.

4. Conclusions

A study has been performed in order to determine the efficiency of a detecting system with respect to events with n-fragments, in heavy ion reactions at intermediate energies. Events have been simulated using the predictions of the Gemini code.

Although the shape of the spectra of three-fold coincidences depends on the particular reaction here considered and on the reaction mechanism inherent to the Gemini code, the procedure here described allows to have more insight on the possible distortions produced by the detecting system with respect to the predictions of any model describing the reaction.

With this kind of arrangement and for the particular reaction and mechanism considered, we obtained as main result that only the number of events is affected by the detector apparatus, whereas the main features such as coincident distributions are affected only to a minimal extent.

In conclusion we are confident that this kind of apparatus can give significant information in the investigation of the reaction mechanism in the intermediate energy regime.

Acknowledgement

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