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EFFECTIVE SOLID ANGLE IN THE ^{8}Be DETECTION(x)

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ABSTRACT.

The effective solid angle for the detection of the unstable ^{8}Be nucleus exibited by a simple system which consists of two circular surface barrier detectors is discussed and calculated. The results are compared with the experiments. The computation method of such an effective solid angle can be used for applications also for the more sophisticated systems presently used.

1. - INTRODUCTION.

The multinucleon correlations in nuclei reveal themselves by the important and frequent occurrence of the α-clustering. To the calculation of their extents, as expressed by the so called α-spectroscopic factors, a lot of theoretical work has been devoted. To verify experimentelly these calculations, the angular distributions of ^{6}Li, ^{7}Li and ^{7}Be nuclei coming from the (d, ^{6}Li), (t, ^{7}Li) and (^{3}He, ^{7}Be) reactions have been measured, and the α-spectroscopic factors of the populated nuclear states of the residual nuclei have been extracted by fitting the experimental data with the theoretical appropriate angular distributions. However, also when a simple transfer mechanism can be postulated for the above reactions, an unambigue determination of the interesting quantities has been rarely possible. This is due to the lack of know-

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ledge of the optical parameters to be inserted in the required DWBA calculations, as well as to the uncertainties associated with the finite range corrections[1-4].

With the advent of the position sensitive detectors, the detection of the unstable ^{8}Be nucleus with relatively large efficiency has become possible[5, 6]. Therefore (α, ^{8}Be), (^{12}C, ^{8}Be) etc. reactions have become another possible tool for investigations of the above kind[7]. Now, because of the decay of the ^{8}Be nucleus in two α-particles, the detection of this nucleus is easy also when it is emitted in the beam direction. This is a very important circumstance because, as shown in ref. (8, 9), in some cases, from processes like X(^{12}C, ^{8}Be) Y(α)X, a determination of the α-spectroscopic factors, pertaining to the states of the Y nucleus, can be done, independently of the reaction mechanism, simply by measuring the angular correlation between the ^{8}Be nucleus emitted at 0^o and the α-particles leaving the Y nucleus.

Different systems have been realized up to now in order to detect ^{8}Be nuclei. Beside other problems which such devices give, one of the most important is a good knowledge of their effective solid angle for ^{8}Be detection. Now, a detecting system for unstable nuclei is a good one if it is able to discriminate the contributions of the unstable nucleus, which is of concern, from those coming from other reaction products and from contributions due to chance coincidences. When the simple identification of the unstable nuclei is sufficient, the system generally consists of a position sensitive detector (PSD) shielded by a screen with two apertures as scehmatically indicated in Fig. 1. This screen is devoted to eliminate the events due to stable particles which

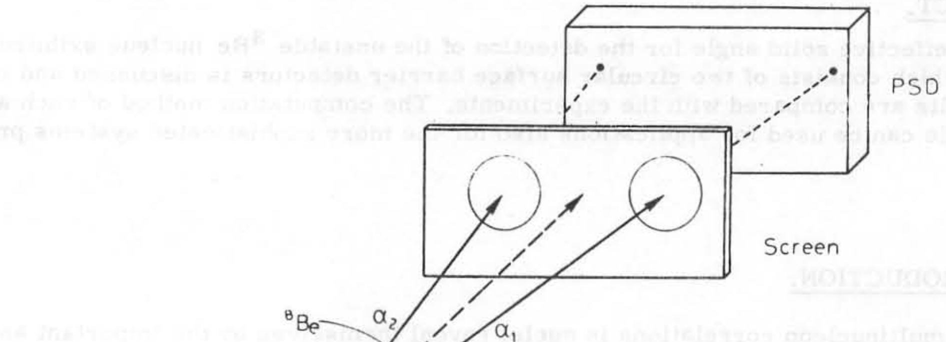

FIG. 1 - Sketch showing a PSD screened by a shield with two circular holes.

can simulate unstable nuclei and to prevent the beam particles to reach the surface of the detector when the system is used at 0^o. Obviously the detection efficiency and the effective solid angle of such a system have to be egual to the corresponding ones of a system employing two sim ple detectors with sensitive surfaces having the same dimensions and shapes of the apertures of the above mentioned screen. However, when the knowledge of the parameters of each particle produced in the decay of the unstable nucleus is necessary, e.g. when different energy levels of the unstable nucleus are to be identified, it needs to use or two PSD or an array of simple solid state detectors[10].

In both cases every calculation regarding the detection efficiency of the detecting system can be experimentally tested by using a corresponding system of two simple solid state detectors with apertures of the same dimensions and shapes as in the ones actually used. With this in mind we calculated the effective solid angle of ^{8}Be detection for a system consisting of two circular surface detectors and we tested the goodness of this calculation by using the system to detect the $^8Be_{g.s.}$ produced in the $^{10}B(d, {}^8Be)\alpha$ reaction at $E_d = 2.5$ MeV.

The calculation method is valid in all the conditions one can imagine, if, as already said, the apertures are well chosen. That is, the method is well applicable also to the best case of the system consisting of two PSD in coincidence.

2. - KINEMATICS OF ^{8}Be BREAK-UP AND DETECTION SYSTEM.

2.1 Given the reaction $M_i + M_t \rightarrow {}^8Be^* + Y^* \rightarrow \alpha_1 + \alpha_2 + Y^*$, if T_{α_1} and T_{α_2} are the kinetic energies of the two α-particles, θ_1 and θ_2 are their emission directions, $Q_o = 0.094$ MeV the energy released in the two α-particles decay of the $^8Be_{g.s.}$ nucleus, the energy and momentum conservation gives, for the kinetic energy, excitation energy and angle of emission of the ^{8}Be nucleus respectively, the following relations :

$$T^*_{Be} = \frac{1}{2}\left[T_{\alpha_1} + T_{\alpha_2} + 2\sqrt{T_{\alpha_1} T_{\alpha_2}}\cos(\theta_1 - \theta_2)\right], \tag{1}$$

$$E^*_{Be} = \frac{1}{2}(T_{\alpha_1} + T_{\alpha_2}) - \sqrt{T_{\alpha_1} T_{\alpha_2}}\cos(\theta_1 - \theta_2) - Q_o , \tag{2}$$

$$\tan\theta = \frac{\sqrt{T_{\alpha_1}}\,\mathrm{sen}\,\theta_1 + \sqrt{T_{\alpha_2}}\,\mathrm{sen}\,\theta_2}{\sqrt{T_{\alpha_1}}\cos\theta_1 + \sqrt{T_{\alpha_2}}\cos\theta_2} . \tag{3}$$

In such a way the measurement of the kinetic α-particles energies and their emission directions enable one to determine the kinetic, excitation energy and flying direction of the ^{8}Be nucleus.

If the total energy of the reaction that produces the ^{8}Be is sufficient, besides the ^{8}Be itself, the residual nucleus Y can be formed in an excitated state also. Again the above measurements on the α-particles allow the determination of the excitation energy E^*_Y of the Y nucleus. Indeed one finds :

$$-E^{*}_{Y} = \frac{M_t M_Y(M_i+M_t) - (M_{Be}+M_Y)\,M_{Be}\,M_i}{M_Y(M_i+M_t)^2}\,T_i - \frac{M_{Be}+2M_Y}{2M_Y}\,(T_{\alpha_1}+T_{\alpha_2})$$

$$-\frac{M_{Be}}{M_Y}\sqrt{T_{\alpha_1}T_{\alpha_2}}\,\cos(\theta_1-\theta_2) + \frac{2(M_{Be}+M_Y)\,M_{Be}\,M_i}{M_Y(M_i+M_t)}\;\cdot \tag{4}$$

$$\cdot\sqrt{\frac{T_i\left[T_{\alpha_1}+T_{\alpha_2}+2\sqrt{T_{\alpha_1}T_{\alpha_2}}\,\cos(\theta_1-\theta_2)\right]}{2\,M_i\,M_t}}$$

$$\cdot\ \cos\tan^{-1}\frac{\sqrt{T_{\alpha_1}}\ \mathrm{sen}\,\theta_1+\sqrt{T_{\alpha_2}}\ \mathrm{sen}\,\theta_2}{\sqrt{T_{\alpha_1}}\ \cos\theta_1+\sqrt{T_{\alpha_2}}\ \cos\theta_2} + Q_o + Q_{oo}\ ,$$

where Q_{oo} is the Q-value for the producing ^{8}Be nucleus reaction and T_i is the incident particle kinetic energy.

2.2 As already said in Sect. 1, perhaps the best detecting system is constitued by two position sensitive detectors coupled in coincidence. Each pair of strips, that one can delimit on these PSD, can, however, be simulated by two simple detectors with apertures of the same size and shape of the two strips. We utilized two detectors of this sort and choose circular apertures. As one will see in Sect. 3, the computation of the efficiency of the system gets considerable simplicity when the two α-partilces are about symmetrically emitted with respect to the detected ^{8}Be direction. In this case the two α energies are about equal in the Laboratory System (LS) and there is a privileged relative angular position of the detectors for each excitation energy of the ^{8}Be. In fact the angles θ_1 and θ_2 of the detectors are given by (see Fig. 2):

$$\theta_1 = \theta - \Delta \quad \text{and} \quad \theta_2 = \theta + \Delta$$

with

$$\tan\Delta = \sqrt{\frac{E^{*}_{Be} + Q_o}{T^{*}_{Be}}}\ . \tag{5}$$

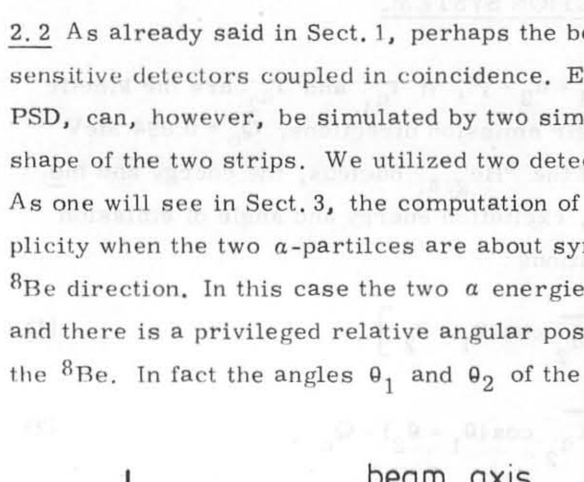

FIG. 2 - Velocity diagram for the emission of the two α-particles from a ^{8}Be nucleus with the same energies in the LS. This is the only case of symmetrical emission.

In the present experiment we used two surface barrier detectors to detect the α-particles produced in the decay of the ^{8}Be from the reaction ^{10}B(d, ^{8}Be)α. The outputs of the two detectors were analised in bidimensional mode. The details of the assembly are given in Sect. 4. The relative angles between the centers of the detectors were chosen in order to detect the α-particles from the ground state of the ^8Be.

2.3 In regard to the produced bidimensional spectra of two α-particles from the $^{10}B(d, ^8Be)\alpha$ reaction, the centers of the accumulation regions are at the intercepts between the unique possible kinematical curve for the two α's:

$$T_{\alpha_1} + T_{\alpha_2} + \sqrt{T_{\alpha_1} T_{\alpha_2}} \cos(\theta_1 - \theta_2) - \sqrt{\frac{T_d}{2}} (\sqrt{T_{\alpha_1}} \cos\theta_1 + \sqrt{T_{\alpha_2}} \cos\theta_2) - \frac{T_d}{4} - \frac{Q_{oo}}{2} = 0$$

and the curves (one for each ^8Be excited state):

$$T_{\alpha_1} + T_{\alpha_2} - \frac{T_d}{6} - \frac{\sqrt{2T_d}}{3} (\sqrt{T_{\alpha_1}} \cos\theta_1 + \sqrt{T_{\alpha_2}} \cos\theta_2) - \frac{2E^*_{Be}}{3} - \frac{Q_{oo}}{3} - Q_o = 0$$

representing the relation between the energies of the two α-particles coming from the ^8Be break-up, with T_d the deuteron bombarding energy.

3. - DETECTION EFFICIENCY AND EFFECTIVE SOLID ANGLE.

The ^8Be detection efficiency of the two detectors system depends on the Θ and Φ angles (Figs. 3, 4) which, inside the acceptance solid angle of the system, individuate the flying direction of the ^8Be nucleus. If $\varepsilon(\Theta, \Phi)$ represents such an efficiency, the effective solid angle Ω_{eff} for the ^8Be detection is:

$$\Omega_{eff} = \int \varepsilon(\Theta, \Phi) \operatorname{sen} \Theta \, d\Theta \, d\Phi \quad , \tag{6}$$

where the integration is done over the acceptance solid angle of the system.

The problem regarding the effective solid angle is, then, the calculation of the $\varepsilon(\Theta, \Phi)$ function. This involves both the kinematics and the dinamics of the ^8Be decay. The situation becomes easier when the ^8Be is left at the ground state, because, in such a case, the angular distribution of the break-up α-particles in the Center Mass System (CMS) is isotropic. Even in this case the main computation difficulty remains. This is constituted by the dependence of the detectors areas, which are effective for the detection of the break-up α-particles, on the ^8Be flying direction, that is from Θ and Φ.

At low ^8Be kinetic energy, due to the importance of the asymmetry between the α-particles emission angles with respect to the ^8Be nucleus flying direction, a further difficulty arises to determine the above mentioned areas. A remarkable simplification in the definition of these areas occurs when $T_{Be} \gg Q_o$ and the TC distance (Fig. 3) between the target T and the centre C of the detection system is large with respect to the detectors diameter. The simplification arises because, when these conditions are satisfied, the above asymmetry can be neglected and, calling π the plane normal to the TC direction and containing the centre C, it

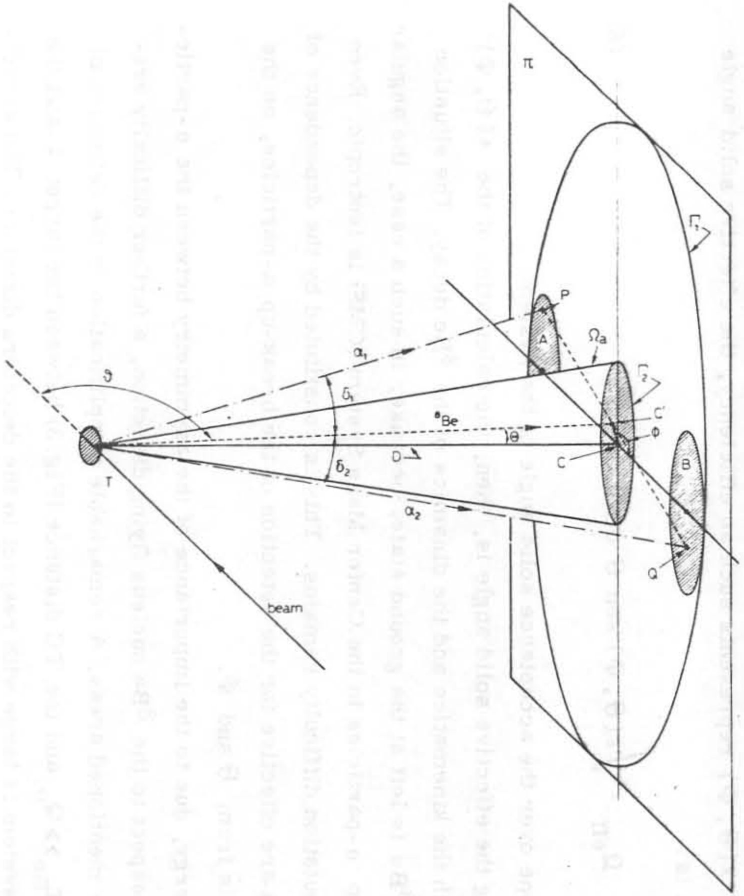

FIG. 3 - Sketch showing the section of the central break-up cone on the π plane (circle Γ_1) and the cone Ω_a defining the acceptance solid angle. For symmetrical α-particles emission the section of Ω_a on the π plane (circle Γ_2) results with a radius equal to that one of the detector surface projections (circles A and B) on the same π plane. Dashed line : flying direction of a ^{8}Be nucleus emitted within the acceptance solid angle. Dashed-dotted lines (α_1 and α_2) : flying direction of the ^{8}Be break-up α-particles. See text for other symbols meaning.

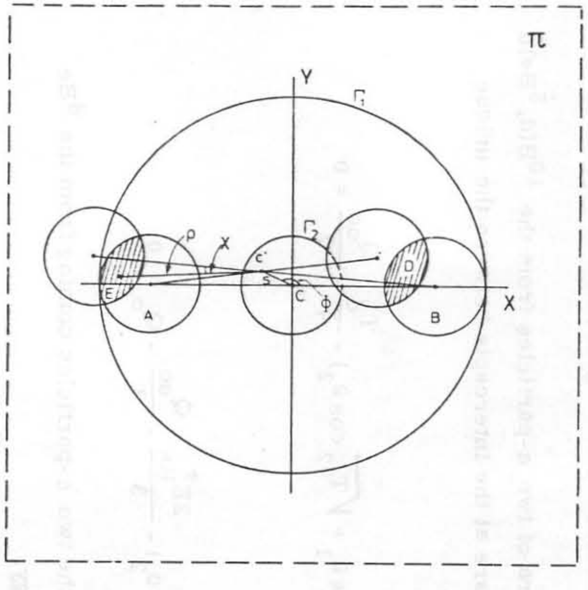

FIG. 4 - The shaded areas (E and D) are the parts of the A and B areas which are effective to detect a ^{8}Be nucleus emitted within the acceptance solid angle in the (θ, Φ) direction (see Fig. 3) intercepting the π plane in the C' point. These parts are determined by the specular image method. See text for other symbols meaning.

is possible to consider the various surfaces cut on this π plane by the break-up cones of the different detectable ^{8}Be nuclei all circular and having the same radius.

When this is true, in order to calculate the effective areas, it is enough to bear in mind that a ^{8}Be has a non-vanishing probability to be detected when the following conditions are satisfied:

a) The flying direction of the ^{8}Be nucleus has to lay within the acceptance solid angle of the system, i.e. within the cone having TC as an axis and cutting on the π plane a surface Γ_2 equal to that of the least one between the A or B areas which the above plane cuts on the detector cones (Fig. 3).

b) The P and Q points where the flying directions of the break-up α-particles intercept the π plane have to lay on the A and B areas respectively. Moreover these points have to be symmetrical with respect to C', which is the point where ^{8}Be nucleus would impact the π plane if this nucleus did not decay.

If the break-up cone of the ^{8}Be emitted in the TC direction entirely contains the A and B areas (Fig. 4), simple geometrical considerations show that the effective areas to detect a ^{8}Be nucleus emitted in the acceptance solid angle of the system (that is the areas D and E in Fig. 4) can be obtained by overlapping to each of the A or B areas the specular image of the other with respect to the C' point.

When the A and B areas are not entirely contained in the above break-up cone, the effective areas are part of those obtained by the specular overlap; this part is depending on the break-up cone aperture and C' impact point.

As an extreme case, if one assumes the break-up α-particles uniformly distributed in the break-up cone, the detection efficiency $\varepsilon(\Theta, \Phi)$ is simply the sum of the effective areas (the dashed E and D zones of Fig. 4) divided by the area of the break-up cone (the circle Γ_1 of Fig. 4) on the π plane.

When this is not the case, the distribution of the α-particles in the break-up cone needs to be taken into account. This distribution can be obtained easily when the ^{8}Be nucleus is produced at its ground state. Then, in the ^{8}Be CMS the α-particles angular distribution is isotropic, and their distribution inside the break-up cone is given by the well known CMS-LS solid angle transformation.

Observing (see Fig. 5) that an α-particle, emitted at an angle δ with respect to the ^{8}Be emission direction, appears flying, in the ^{8}Be CMS, either along Θ' or Θ'' directions, we have:

$$P(\Omega(\delta)) \,\mathrm{sen}\,\delta \,d\delta \,d\Phi = \left| P(\Omega(\Theta'))\,\mathrm{sen}\,\Theta' \,d\Theta' d\Phi \right| + \left| P(\Omega(\Theta''))\,\mathrm{sen}\,\Theta'' \,d\Theta'' \,d\Phi \right| .$$

Here, each P denotes the probability that an α-particle is emitted in the unit solid angle in the direction given by the angles.

The isotropy of the angular distribution in the ^{8}Be CMS allows to write:

$$P(\Omega(\Theta')) = P(\Omega(\Theta'')) = \frac{1}{4\pi} .$$

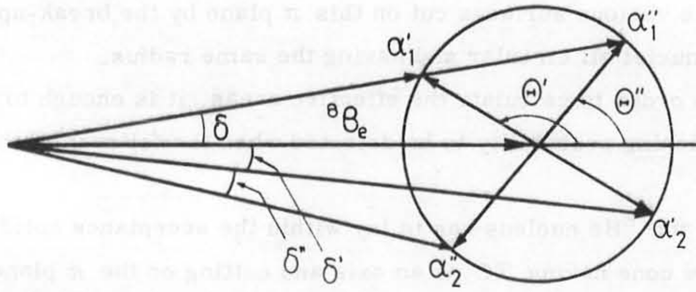

FIG. 5 - Velocity diagram showing as, dependently on the energy, a break-up α-particle emitted in the δ direction, with respect to the emitted ^{8}Be one, can appear flying along either the Θ' or the Θ'' direction in the CMS. Note that the companion α-particle (α'_2 or α''_2) is emitted along the δ' or δ'' direction no one being symmetrical to the δ direction.

Therefore, for the probability which an α-particle has to be emitted in the unit solid angle along the direction δ, one obtains:

$$P(\Omega(\delta)) = \frac{1}{4\pi}\left[\left|\frac{\mathrm{sen}\ \Theta' d\Theta'}{\mathrm{sen}\,\delta\, d\delta}\right| + \left|\frac{\mathrm{sen}\ \Theta'' d\Theta''}{\mathrm{sen}\,\delta\, d\delta}\right|\right],$$

with the well known relations :

$$\left|\frac{\mathrm{sen}\ \Theta' d\Theta'}{\mathrm{sen}\,\delta\, d\delta}\right| = 2K\cos\delta + \frac{1+K^2\cos 2\delta}{\sqrt{1-K^2\,\mathrm{sen}^2\delta}},$$

$$\left|\frac{\mathrm{sen}\ \Theta'' d\Theta''}{\mathrm{sen}\,\delta\, d\delta}\right| = -2K\cos\delta + \frac{1+K^2\cos 2\delta}{\sqrt{1-K^2\,\mathrm{sen}^2\delta}}$$

where :

$$K = \Delta^{-1}.$$

Therefore the $P(\Omega(\delta))$ probability is given by :

$$P(\Omega(\delta)) = \frac{1+K^2\cos 2\delta}{2\pi\sqrt{1-K^2\,\mathrm{sen}^2\delta}} \tag{7}$$

and it is peaked near the edges of the break-up cones. From this we obtain the probability per unit plane angle as :

$$P(\delta) = \mathrm{sen}\,\delta\ \frac{1+K^2\cos 2\delta}{\sqrt{1-K^2\,\mathrm{sen}^2\delta}}\ . \tag{8}$$

When the acceptance solid angle is not too large, one can write :

$$\varrho = D\tan\delta\ , \tag{9}$$

where D is the TC (target-π plane) distance, and ϱ is the polar coordinate of a generic point within the pertinent effective area with respect to the point C' (Fig. 4).

Using the relation (9), equation (8) becomes:

$$P(\varrho)\, d\varrho = \frac{1 + K^2\left[(D^2 - \varrho^2)/(D^2 + \varrho^2)\right]}{D\sqrt{D^2 + \varrho^2(1 - K^2)}}\;\varrho\, d\varrho \; . \qquad (10)$$

With the (10), the efficiency to detect a ^{8}Be nucleus emitted in (Θ, Φ) direction is:

$$\varepsilon(\Theta, \Phi) = \frac{1}{\pi}\iint P(\varrho)\, d\varrho\, d\chi \; , \qquad (11)$$

where the integral has to be evaluated on the effective areas (E or D of Fig. 4) which of course are function of Θ and Φ.

Fig. 6 shows the effective solid angle Ω_{eff} obtained by numerical integration of eq. (11) and (6) for different ^{8}Be kinetic energies when the two detectors are placed on the peripherical region of the central break-up cone, as shown in Fig. 4, where the α yield is at a maximum.

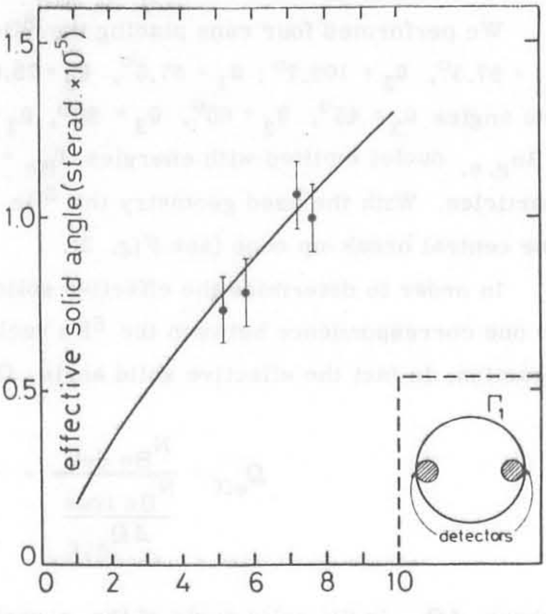

FIG. 6 - Calculated effective solid angle vs. $^8Be_{g.s.}$ kinetic energy for a system of two circular detectors at 120 mm from the target and each one diaphragmed by a shield with a 4 mm diameter hole. At each ^{8}Be kinetic energy, the external edge of each hole lies on the surface of the break-up cone (see inset). The points correspond to the experimental determined effective solid angle. The bars indicate the statistical and geometrical errors.

4. - EXPERIMENTAL SET-UP, RESULTS AND CONCLUSIONS.

In order to test the goodness of our effective solid angle computation method, we used a system of three circular surface barrier detectors, which detected the three α-particles emitted in the ^{10}B(d, ^{8}Be)α reaction at E_d = 2.5 MeV. Two of them were connected in coincidence to observate the ^{8}Be nuclei through the detection of the two break-up α-particles; the third one detected independently the α-particles emitted at the angle kinematically corresponding to that of the ^{8}Be emission.

The deuteron beam was produced by a 2.7 MeV V.d.G. accelerator. The target was obtained by evaporation of B_2O_3 on a carbon backing and it was 100 μg/cm^2 thick.

The three detectors, placed at 120 mm from the target, could be rotated independently around the target and allowed to detect the ^{8}Be nuclei and the associated α-particles at various angles.

The pulses coming from the two ^{8}Be detectors fed the X-Y inputs of the double ADC of a 4096 channels analyser, where they were biparametrically analysed. A 30 ns coincidence circuit, piloted by the same pulses, gated the analyser and it allowed a remarkable reduction of the chance coincidences.

Two circular Al shield with a 4 mm diameter hole at the centre, placed in front of each the two detectors of the ^{8}Be nuclei, while defined the acceptance solid angle $\Delta\Omega_{acc}$ of the system, allowed the entrance only to those break-up α-particles which at the used ^{8}Be energies were emitted within about $\pm 35^o$ around the 90^o ^{8}Be flying direction in the CMS.

We performed four runs placing the ^{8}Be detectors at the angles $\theta_1 = 114.3^o$, $\theta_2 = 127.7^o$; $\theta_1 = 97.3^o$, $\theta_2 = 109.7^o$; $\theta_1 = 67.6^o$, $\theta_2 = 78.6^o$; $\theta_1 = 58.6^o$, $\theta_2 = 69.2^o$ and the third detector at the angles $\theta_3 = 45^o$, $\theta_3 = 60^o$, $\theta_3 = 90^o$, $\theta_3 = 100^o$ respectively. In such a way we observed the $^8Be_{g.s.}$ nuclei emitted with energies $T_{Be} = 5.14$; 5.77; 7.2; 7.6 MeV and the companion α-particles. With the used geometry the ^{8}Be detectors resulted on the peripherical region of the central break-up cone (see Fig. 3).

In order to determine the effective solid angle of the ^{8}Be detecting system we used the one to one correspondence between the ^{8}Be nuclei and the companion α-particles emitted in the reaction. In fact the effective solid angle Ω_{eff} is defined by:

$$\Omega_{eff} = \frac{N_{Be\ det}}{\dfrac{N_{Be\ true}}{\Delta\Omega_{acc}}} = \frac{N_{Be\ det}}{\dfrac{N_\alpha}{\Delta\Omega_\alpha}\ \dfrac{d\Omega_\alpha}{d\Omega_{acc}}}, \tag{12}$$

where $\Delta\Omega_\alpha$ is the solid angle of the α-particles detector, that is of the third detector, and:

$$\frac{d\Omega_\alpha}{d\Omega_{acc}} = \frac{\mathrm{sen}^2\,\theta_3 \cos(\Theta_3 - \theta_3)}{\mathrm{sen}^2\,\theta \cos(\Theta - \theta)}, \tag{13}$$

where θ_3 is the emission angle of the third α-particle in the LS and Θ_3 is the corresponding angle in the CMS, θ and Θ are the ^{8}Be emission angles in the LS and CMS respectively.

To eliminate the chance coincidences which localized their contribution in the same region where the ^{8}Be nuclei events appeared, we made after each run another one in the same experimental conditions but with a decay on the X arm of the coincidence circuit. The background of the chance coincidences resulted always less than 10% of the events in the region of the ^{8}Be pulses.

The points reported in Fig. 6 represent the effective solid angle determined by the measured data after the application of the relation (12). The indicated errors refer to the statistical and geometrical ones.

The values of the effective solid angle experimentally determined at the various ^{8}Be kine tic energies appear consistent, within the errors, with the corresponding ones evaluated by the underlained method.

The above consistency shows that although the system accepts α-particles which fly in the ^{8}Be CMS within a cone with a relative large aperture ($\pm$ 35^o), the method appears to work well.

Although we have used the system at the best working condition its efficiency is low. One could increase such an efficiency by using a circular array of similar system and connecting in coincidence the couples of the detectors which are diametrically opposed.

The authors wish to thank the staff of the V. d. G. accelerator for his assistance during the measurement runs.

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