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Influence of the detection geometry in the analysis of experimental observables in projectile breakups

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The effect of geometrical considerations in the detection of flying spectator particles in projectile fragmentation processes is discussed. It is shown that different Fermi momenta have different probabilities of being detected in a detector of finite opening. A comparison of experimental inclusive deuteron spectra from the (^{3}He,d) reaction on ^{59}Co with the spectator particle mechanism, including the corrections for the probabilities of detection of various Fermi momenta, shows that very good agreement can be found for the centroid position, width, and angular dependence of the peak due to the projectile fragmentation.

The projectile breakup mechanism has been extensively studied in recent years both experimentally and theoretically.[1-10] In inclusive spectra from nuclear reactions with composite particles, this mechanism results in a bump whose centroid corresponds to particles that have velocities corresponding to the one of the incident beam. Although very early qualitatively understood and treated,[11] the description is still not completely satisfactory despite the recent calculations of Baur *et al.*[9] and Aarts *et al.*[10] Notably, disagreement still exists in the behavior of the following parameters: position of the centroid of the bump, its width, and angular dependence of the integrated cross section. In the present work we consider corrections to the form of the spectra obtained using the simplest projectile breakup mechanism when the distortions due to geometrical effects are taken into account, that to our knowledge have not been considered so far.

A particle belonging to the projectile shall be detected under an angle α with respect to the beam if the sum vector resulting from the particle momentum in the beam and its particular Fermi momentum points toward the detector. The resulting geometrical situation is shown in Fig. 1. For ease of presentation a two-dimensional detection geometry has been chosen, but the extension to three dimensions does not introduce qualitative changes. We have shown two cases of Fermi momenta p_1 and p_2. Due to the opening angle of the detector, Ψ, particles with a Fermi momentum p_1 shall be detected if emitted in a region of angular opening θ. If we assume that particles with p_2 have the same probability of entering the detector it means that the same angular range of particles with p_2 shall be accepted by the detector. However, from Fig. 1 we clearly see that in this case the angular range of acceptance shall be much smaller. This decrease of the angular aperture reflects itself in nonuniform "detection efficiency" of the detector for different Fermi momenta. From Fig. 1 we can infer that, also, the particles with the same Fermi momenta but resulting in different sum vectors (low and high values) will have different "detection efficiencies" for the same detection angle α. We point out that such a distortion is not to be assimilated to a trivial center of mass—lab frame transformation. This is visible from the fact that the maximum "detection efficiency" in the sense described, i.e., the largest angle θ is achieved for the values around minimum Fermi momentum allowed at the angle of detection. For higher Fermi momenta the efficiency decreases regardless of whether it results in a higher or lower energy in the detector. Furthermore, for a given Fermi momentum the efficiency is a function of the angle of detection. This is visible from the following argument: increasing α to a value at which the p_2 value from Fig. 1 is close to the kinematically allowed Fermi momentum (similar to the situation for p_1 in Fig. 1), the corresponding arc length located inside the angular opening defined by the detector will be much larger, implying a larger efficiency of detection.

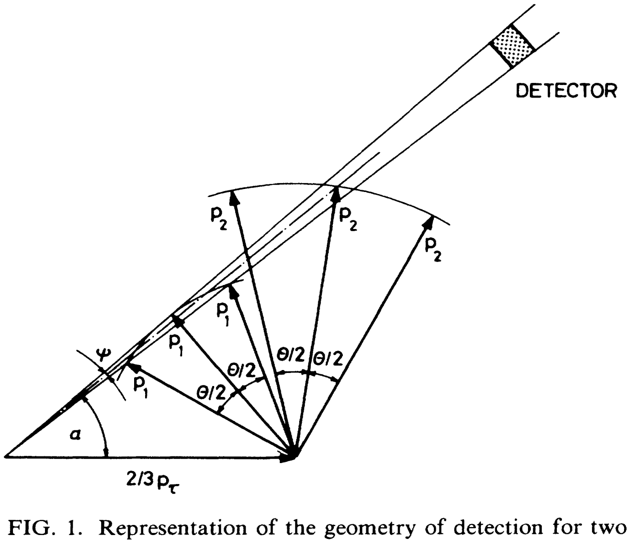

FIG. 1. Representation of the geometry of detection for two different values of Fermi momentum p_1 and p_2 in the case of projectile breakup. p_T is the momentum of the incoming ^{3}He particle. α, θ, and Ψ are explained in the text.

Having established the fact that the efficiency is not equal for all Fermi momenta detected at the same angle, we have quantitatively calculated the effect for inclusive spectra created by the breakup of ^{3}He projectiles ($E_{^3\mathrm{He}}=130$ MeV) on ^{59}Co measured by Djaloeis *et al.*[3] We have applied our correction for efficiency to the spectra generated by the spectator mechanism, the simplest and often used approximation (e.g., Ref. 2) where in the uncorrected form the spectral shape is given by

$$\frac{d^2\sigma}{d\Omega_d dE_d} \sim |G(P)|^2(\mathrm{PS}) . \qquad (1)$$

$G(P)$ is the Fourier transform of the Yukawa-type wave function of the relative motion of the proton and deuteron in ^{3}He given by

$$G(P)=\frac{4}{\pi}\hbar^3\alpha^3\frac{1}{(P^2+\hbar^2\alpha^2)} , \qquad (2)$$

where $\alpha=(2\mu\epsilon_T)^{1/2}/\hbar$ with μ being the reduced mass and ϵ_T the separation energy of the deuteron in ^{3}He.

The momentum of the emitted deuteron $\mathbf{P}_d$ is the sum of the momentum due to the internal motion in the ^{3}He at time of breakup ($\mathbf{P}$), that is, $\mathbf{P}_d=\frac{2}{3}\mathbf{P}_T+\mathbf{P}$. (PS) is the phase space factor for three particles in the final state—the proton, deuteron, and ^{59}Co.

The spectra calculated according to Eq. (1) may be assimilated to *emitted* spectra, which, however, as we have explained are not identical to the particle energy spectra detected in a detector of final opening. To obtain the shape of the *detected* spectra the emitted spectra were processed through the detection system calculating by a Monte Carlo simulation the effect of the geometry for each event generated by Eq. (1), taking into account the full three-dimensional case, and the full momentum range. Calculations were made using $\Psi=1.0$ and 0.2 deg. The magnitude of Ψ did not affect in any visible way the shape of the spectra.

In Fig. 2 we show the result of our simulation compared with the prediction of Eq. (1) for inclusive deuteron

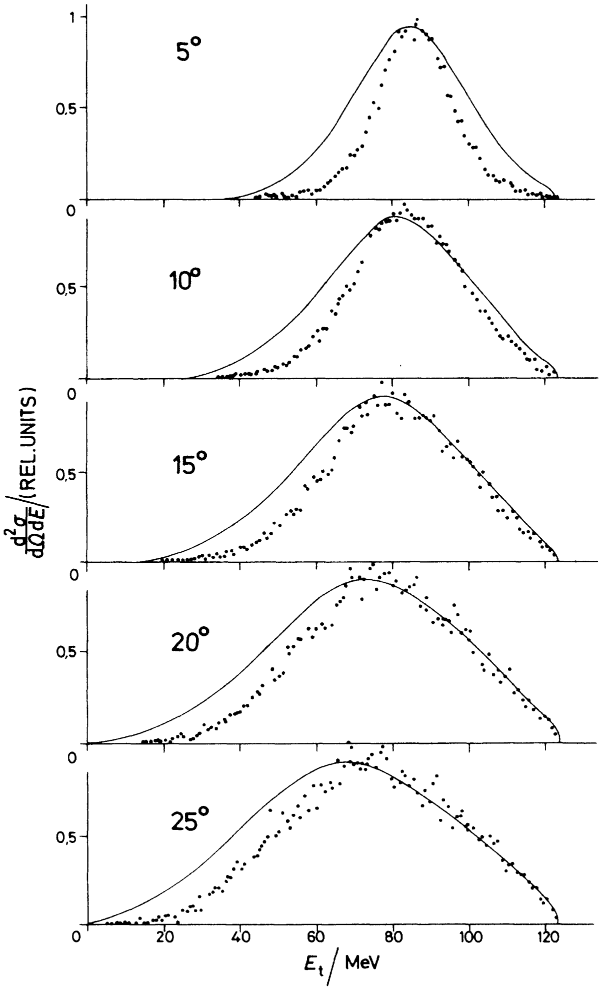

FIG. 2. Geometry corrected simulated deuteron inclusive spectra (points) at $\alpha=5$–25 deg compared with the spectra obtained using Eq. (1) with a Fourier transform of the form (2) (solid curve).

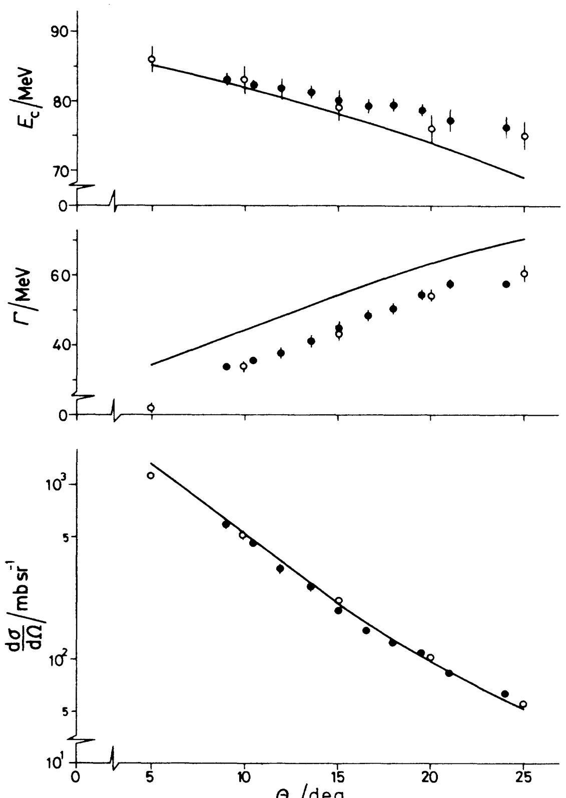

FIG. 3. Comparison of experimental data for the centroid energy, E_c, width Γ, and integrated cross section $d\sigma/d\Omega_d$ (dots) from Ref. 3 with the results of our geometry corrected simulation (circles) and with the prediction of Eq. (1) using the Fourier transform (2). The integrated cross section data obtained with calculation and simulation were normalized independently to the data with a single value for the whole angular range.

spectra in the angular range 5—25 deg. The latter is the form that is usually compared directly to experimental data[2,4] when using this approximation. The two curves have been arbitrarily normalized to the same peak value to emphasize the difference in shape. It is visible that the inclusion of the efficiency correction plays a non-negligible role in the deformation of detected spectra at forward angles. In Fig. 3 we show the comparison of the dependence of the centroid energy, width, and integral cross section with the angle of detection obtained by Eq. (1), for our simulation, and experiment.[3] For all three parameters the Monte Carlo simulation agrees very well with experimental data. In the angular dependence of the cross section, the difference between our treatment and Eq. (1) seems small but note that the ordinate is in logarithmic scale and that our simulations predict a slightly slower decrease usually born out by data. Besides the comparison with experimental data given above the difference between the curves and our Monte Carlo simulation is typical of the disagreements found in many different cases of analyses of projectile fragmentation spectra in the literature (Ref. 8 and references therein). Complex mechanisms are then invoked to remove to a certain extent the discrepancies, but the present work shows the importance of including the effect of mechanism-induced detector efficiency before comparing any theoretical prediction of data, since as visible from the results, the correction introduced reflects itself as a virtual deformation of the wave function in momentum space of the fragmenting system because all momentum components of the wave function are not detected with the same efficiency—the efficiency being lower for high components than for low components. We have demonstrated that the inclusion of this correction allows us to use the simplest approach to reconcile experimental data and theoretical calculations in all the parameters that were so far in disagreement, namely, the position of the centroid of the bump, its width, and the integrated cross section. Also the difference in the shape of the experimental bump on the low and high side of the maximum are reproduced by the present correction.

We conclude that the effect described in this work has to be taken into account whenever the spectator particle is observed in the final channel in projectile fragmentation processes. The underlying treatment may be more sophisticated than the one used here, but the implication of the efficiency effect shown is the same. It seems that it is not possible to take this effect analytically into account in the calculations so that one has to resort to Monte Carlo simulation.

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