Evaporation recoil effects: Asymmetries in neutron, projectile-fragment coincidences for 35 MeV/nucleon $^{14}N + ^{165}Ho$ reactions

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(Received 22 April 1986)

Simulations of neutron evaporation from light heavy ions are presented to illustrate experimental biases present in coincidence experiments. In particular, the case presented involves neutrons observed in coincidence with quasi-elastic boron fragments from collisions of ^{14}N with ^{165}Ho at a bombarding energy of 35 MeV/nucleon. The left-right asymmetry observed experimentally in the high energy neutron spectra at angles of $\pm 60°$ and $\pm 90°$ cannot be reproduced together with the correct angular distribution if only a projectile-like source is assumed to create the observed spectra, and this suggests that some other process is required to explain the data. Some general features of the simulations will be compared with results of moving-source analyses.

I. INTRODUCTION

An experiment[1] conducted at the National Superconducting Cyclotron Laboratory observed neutrons emitted in coincidence with projectile-like fragments in $^{14}N + ^{165}Ho$ reactions at $E(^{14}N) = 490$ MeV. The neutron energy spectra were obtained at several angles between 10° and 110° in the laboratory system, and were in coincidence with either strongly damped or quasielastic projectile-like ($A < 14$) fragments at $\theta = 10°$. A notable feature of these spectra in quasielastic events was that neutrons detected at, say, 60° on the side of the beam axis opposite the detected fragment were more numerous than those observed at 60° on the same side of the beam axis as the fragment. This asymmetry appeared for the higher energy neutrons ($E_n > 10$ MeV) and could not be associated with evaporation from the target-like fragment, which produces neutrons predominantly in the low energy portions of the observed spectra. The purpose of this study was to determine whether the asymmetry observed in Ref. 1 could arise from neutron evaporation from the projectile-like fragment if recoil effects were included and if account were taken of the experimental bias introduced by the requirement of a neutron-fragment coincidence.

Discussion of the simulations will begin in Sec. II by mentioning some of the features of the moving source model, since this will be used in the simulation algorithm. Then, in Sec. III the effects of recoil upon emission of neutron will be discussed and will be followed in Sec. IV by a discussion of the details of the simulation routine. Section V will give a brief synopsis of the general features which were examined in these simulations of neutron evaporation including recoil effects, and Sec. VI will be devoted to some final comments about the conclusions which are reached from comparison of the simulated spectra with experimental data.

II. MOVING SOURCE MODEL

First, consider the moving-source model, which does not include recoil effects. Excited target-like and projectile-like fragments emerge from a two-body rearrangement collision. Both will have, in general, some finite velocity in the laboratory and can emit neutrons as they travel in straight-line trajectories (that is, they have both been fully accelerated by their mutual Coulomb repulsion and are simply de-exciting to the final state fragments). The emission of neutrons in these cases is assumed in the model to be isotropic in the rest frame of the emitter. The motion of the emitters in the laboratory frame gives some initial velocity to which the neutron decay velocity, relative to the emitter, is added vectorially. Hence, the neutrons are "kinematically focused" along the directions of motion of the fragments, and the degree of focusing depends on the fragment speed. In this model one would expect that neutrons coming from the projectile fragment would have a laboratory angular distribution which is peaked in the fragment direction of motion. A similar statement applies to neutrons from the target fragment. In fact, the neutrons would be symmetrically distributed about the directions of fragment motion. Indeed, this is exactly what is observed at lower bombarding energies.[2–4]

The experiment reported in Ref. 1 would be well suited to observing neutrons from such moving sources. If attention is restricted to quasielastic scattering, where the projectile-like fragment is near beam velocity, then the target-like fragment recoils with only a small velocity.

Hence, the neutrons from the former are focused toward the projectile-like fragment directions of motion, while neutrons from the target-like fragment have a nearly isotropic laboratory angular distribution. In fact, a moving source analysis performed in Ref. 1 gives the nearly isotropic laboratory angular distribution expected for such a slow-moving target-like source. The slope parameter obtained for this source is $T \approx 3$ MeV. However, the kinematic focusing of neutrons evaporated from the projectile-like source cannot explain the asymmetry. This is because such focusing would have led to an angular distribution that was symmetric about 10°, which is where the fragment detector was located. This would imply that for polar angles larger than 10°, more neutrons would be detected on the same side of the beam axis as the fragment than at the same angles on the opposite side. Instead of neutrons being more numerous on the same side of the beam as the projectile fragment, Ref. 1 shows that there were more neutrons on the opposite side of the beam axis. Thus one concludes from this that the simple two-moving-source model cannot describe the data of Ref. 1.

The moving source model has proven useful as a convenient parametrization of light-particle (n, p, d, t, ^{3}He, and α) emission spectra.[5,6] But at beam energies above ~ 5 MeV/nucleon the two source model no longer fits the data. A third source is required. This additional source suggests that either another mechanism for neutron production developed as the energy increases, or the model used to analyze the data is not entirely correct. That is, the two-moving-source model might be missing some relevant physics. For example, when neutrons are evaporated the emitter recoils. While insignificant for the heavy target-like piece, the recoil may be significant for light projectile-like fragments, such as those reported in Ref. 1 and elsewhere. This is especially true when high energy neutrons are emitted.

III. RECOIL EFFECTS IN COINCIDENCE SPECTRA

Recoil of the projectile-like fragment can create an asymmetry of the sign observed in Ref. 1 if the fragments have a forward peaked angular distribution. Figure 1 shows strong fragment angular distributions that are peaked in the forward direction. A fragment detector placed at 10° will detect not only those fragments emitted toward the detector, but will also detect fragments emitted in neighboring directions that recoil toward the fragment detector upon emission of a neutron. Fragments at angles forward of 10° can recoil into the detector only if neutrons are emitted toward the opposite side of the beam axis from the fragment detector, whereas fragments emitted at angles behind 10° can recoil into the detector if the coincident neutrons are emitted toward the same side of the beam axis. The angular distribution of emitters (excited projectile-like fragments) shown in Fig. 1 would give more fragments at $\theta < 10°$ than at $\theta > 10°$, which would give more neutrons detected in coincidence with projectile-like fragments on the opposite side of the beam axis. In this way an asymmetry which is qualitatively in agreement with that observed in Ref. 1 can be produced by moving sources.

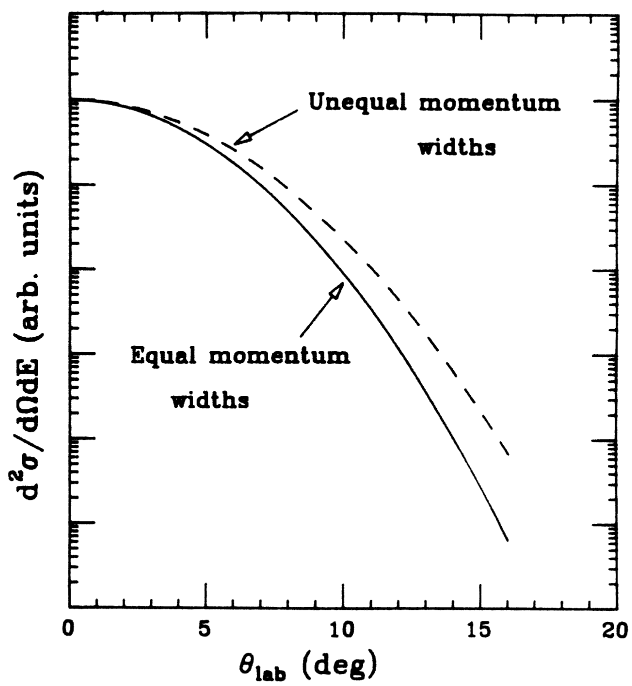

FIG. 1. Angular distribution of neutron emitters (projectile-like fragments). The solid line is for equal longitudinal and transverse momentum widths, $\xi = 1.0$, and the dashed line is for $\xi = 1.25$ (see text Sec. IV C). In each case, fragments emitted to smaller angles are more numerous than those emitted to larger angles.

Neutron emission exhibiting a left-right asymmetry has been reported[7] in coincidence of neutrons with evaporation residues in collisions of ^{20}Ne with ^{165}Ho at various energies at and below 20 MeV/nucleon. Their asymmetric neutron emission showed a peaking in the angular correlation of neutrons in a direction other than that of the detected evaporation residue. The evaporation residue was detected at 10° and the peak in the neutron angular correlation was at a small angle on the other side of the beam axis. They attributed this emission pattern to effects of recoil upon evaporation of a neutron, but they did not quantitatively justify this conclusion. In fact, it is not at all clear that their observed neutron emission, which was responsible for the peaking toward the opposite side of the beam axis, did not arise from an entirely different process, such as pre-equilibrium emission. In that case the empirical bias of requiring a heavy ion to be detected at 10° could simply be selecting those events in which conservation of momentum requires neutrons to be emitted to the opposite side of the beam axis. The results of the simulation presented below may shed some light on whether evaporation plays any significant role in the asymmetry observations of Holub *et al.*[7]

IV. SIMULATIONS

To quantitatively understand the significance of incorporating recoil effects, consider the quasielastic reaction ^{165}Ho(^{14}N, ^{10}B n)X at a bombarding energy $E(^{14}\mathrm{N}) = 490$

MeV. We assume that the initial boron isotopes, which will decay by neutron emission(s) to $^{10}B_{g.s.}$, have an angular distribution characteristic of fragmentation reactions, viz.[8]

$$\frac{d^2\sigma}{d\Omega\,dE} \propto P_F(\epsilon,\theta_F^0) = \sqrt{\epsilon}\exp\{-A^2u[\epsilon+\epsilon_0-2(\epsilon\epsilon_0)^{1/2}\cos\theta_F^0]/\sigma^2\} , \tag{1}$$

where ϵ_0 is the fragment energy parameter in MeV/nucleon corresponding to the centroid of the Gaussian momentum distribution. The mass number of the fragment is $A=10$, ϵ is its kinetic energy per nucleon, θ_F^0 is the fragment direction of motion in the lab system before recoil, σ^2 is the Gaussian variance of the momentum distribution [in units of $(\mathrm{MeV}/c)^2$] of the projectile-like fragments, and $u=931.5016$ MeV is the unified mass unit. This distribution is peaked at $\theta_F^0=0°$ and $\epsilon \cong \epsilon_0$. We assume for simplicity that the $^{11}B^*$ excited fragment distribution is the same as the ^{10}B detected fragment distribution, since the initial $^{11}B^*$ distribution is unknown. One may question whether this assumption is realistic, but the essential feature is the strong angular distribution of emitters. A fragment detector placed at $\theta=10°$, as in Ref. 1, will, of course, detect those fragments initially heading toward 10° but which are not deflected out of the detector's acceptance by recoil upon emitting a neutron. The number of these fragments will be given by Eq. (1) with $\theta=10°$. However, there will also be contributions from fragments initially headed at angles forward (backward) of 10°, which will recoil into the 10° detector acceptance if the neutron is emitted toward the opposite (same) side of the beam axis as the fragment. Note that Eq. (1) gives more fragments at the more forward angle and this, in turn, gives more neutrons to the side of the beam axis opposite the side where the fragment is detected.

A simple technique was used to simulate recoil effects. Equation (1) served as the fragment angular and energy distribution function with $\epsilon_0=28$ MeV/nucleon and $\sigma=130$ MeV/c, as given by fits of the inclusive ^{10}B data of Ref. 1. A center of mass neutron energy spectrum of

$$P_n(E_n)=(E_n)^{1/2}e^{-E_n/T} \tag{2}$$

was assumed with T a fixed parameter which was set to values between 3 and 8 MeV for various trials. The computer program itself was constructed as shown schematically in Fig. 2. Instead of looping through the various angles and energies, one could select them randomly—this would then be a Monte Carlo simulation—but the programming time would be substantially longer. The present method is sufficient and more efficient. The simulation presented here assumes coplanar geometry. This is justifiable in the simple two-moving-source model only if multiple neutron emission is excluded. However, most of the recoil effects arise from high energy neutrons, of which there are seldom more than one per event. Data and calculations at ±10° are not included to avoid regions where sequential decay and knock-out are expected to dominate.

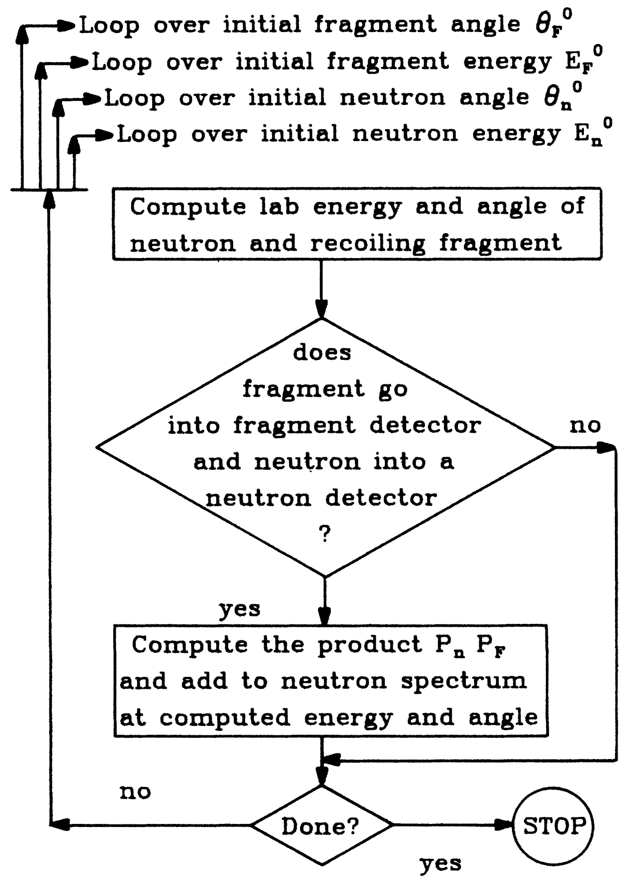

FIG. 2. Flow chart of evaporation recoil computer program. Coplanar geometry is assumed in all cases.

A. $T=3$ MeV

The simulation results are shown in Fig. 3, superimposed on the data of Ref. 1, for $\epsilon_0=28$ MeV/nucleon, $\sigma=130$ MeV/c, and $T=3$ MeV. Calculations at −45° were normalized to the data at that angle by eye, and the same normalization was applied to calculations at all other angles. Data at only +30° and −45° are reasonably described by the calculation. At 30° the calculation overpredicts the "opposite-side" cross sections, but for $|\theta| \geq 60°$ the simulations underpredict the data by orders of magnitude. This latter observation is a reflection of the fact that the neutron-fragment angular correlation is strongly influenced by the fragment speed, even if recoil is included.

B. $T=8$ MeV

Various changes in simulation parameters were made in attempts to more closely match the neutron spectra. One such change is to set the projectile-like source temperature to a value of 8 MeV. The motivation for this is that a three-moving-source fit to the data of Ref. 1 required one of the sources to have a temperature of about 8 MeV (the

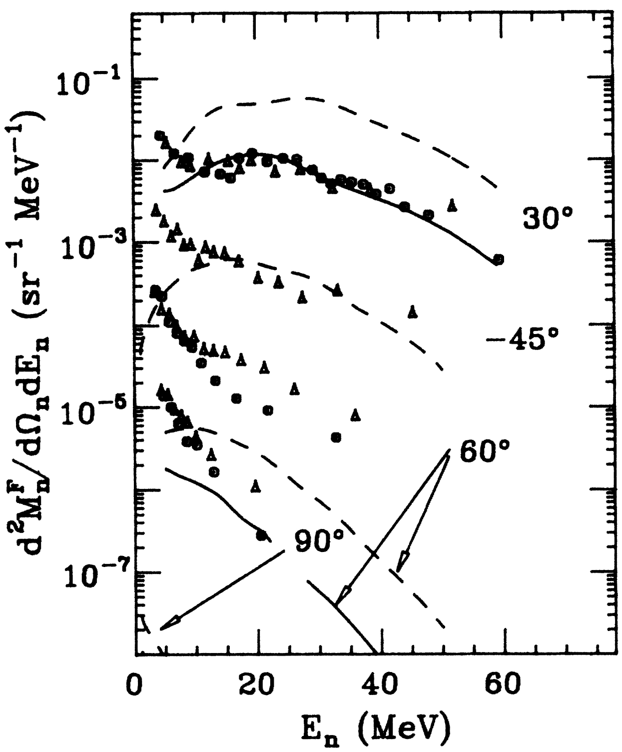

FIG. 3. Neutron multiplicity data from Ref. 1 and calculation for a projectile-like source temperature $T=3$ MeV, fragmentation peak momentum width $\sigma=130$ MeV/c, and a centroid kinetic energy $\epsilon_0=28$ MeV/nucleon. Circles (solid lines) are data (calculations) on the same side of the beam as the projectile-like fragment and triangles (dashed lines) are on the opposite side of the beam axis. Data at successive angles are offset by factors of 10 for clarity, and some of the data points are not plotted to avoid congestion. If all data were plotted on the same scale, the low energy portion of the spectra would have the same magnitude for all angles, indicating a nearly stationary target-like source that was evaporating neutrons. Angle labels are placed near the end of the spectra they represent, and, when necessary for clarity, arrows point to the calculations for given angles.

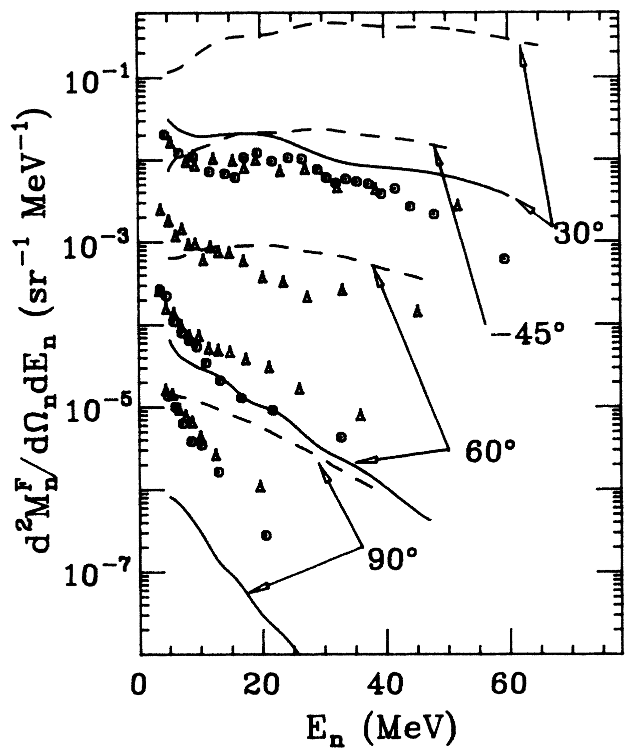

FIG. 4. Similar to Fig. 3, except that the source temperature is 8 MeV. Also, the simulation was normalized to the data at +60°, rather than −45° as in Fig. 3, for clarity.

fit also required a source kinetic energy of only 9 MeV/nucleon or about half the beam velocity). Such a simulation, with the other parameters held fixed ($\sigma=130$ MeV/c and $\epsilon_0=28$ MeV/nucleon), is shown in Fig. 4, again with the data of Ref. 1. Calculations in Fig. 4 were normalized by eye to the data at +60° (the same side of the beam axis as the fragment detector angle), rather than at −45° as in Fig. 3, for clarity.

Figure 4 displays much of the same qualitative features shown in Fig. 3, but the computed asymmetries are much larger than those in the data. Also, the angular distribution is, overall, not much better reproduced than in Fig. 3. Inspection of the solid lines and the corresponding circles shows that at 30° the calculations exceed the data, while at 90° the simulated spectrum gives too few neutrons to match the data. Once again, the angular distribution of the simulation is stronger than that of the data, and this is a reflection of the speed of the emitters.

C. Shallower fragment angular distribution

Fragment angular distributions are generally softer than implied by Eq. (1). In the fragmentation formulas this is expressed by allowing a transverse momentum width, $\sigma_\perp$, which differs from the longitudinal width, $\sigma_\parallel$. It is, then, useful to see what effect allowing $\sigma_\perp \neq \sigma_\parallel$ has on the simulated neutron spectra. In particular, consider the momentum distribution of fragments in the laboratory system to be

$$\frac{d^2\sigma}{d\Omega\, dE} \propto \sqrt{E}\, e^{-(p_\parallel - p_0)^2/2\sigma_\parallel^2} e^{-p_\perp^2/2\sigma_\perp^2} , \tag{3}$$

where $p_\parallel$ and $p_\perp$ are the longitudinal and transverse components of the fragment momentum, p_0 is related to the beam momentum and is a fitted parameter (again the centroid of the assumed Gaussian fragmentation spectrum for ^{10}B), and $\sigma_\parallel$ and $\sigma_\perp$ are the longitudinal and transverse momentum widths, respectively. If the relationship between the two widths is given by the expression $\sigma_\perp/\sigma_\parallel = \xi$, then the fragment distribution reduces algebraically to that of Eq. (1) multiplied by a factor $F(\xi)$, where $F(\xi)$ is given by

$$F(\xi) = \exp[A^2 u \epsilon \sin^2(\theta)(1 - 1/\xi^2)/\sigma_\parallel^2] , \tag{4}$$

where A, u, ϵ, and θ are as in Eq. (1), $\sigma_\parallel = 130$ MeV/c, and $\xi = 1.25$ (for this test). Figure 1 illustrates how this fragment distribution is softer than that given by Eq. (1) alone. The fundamental change here is a softening

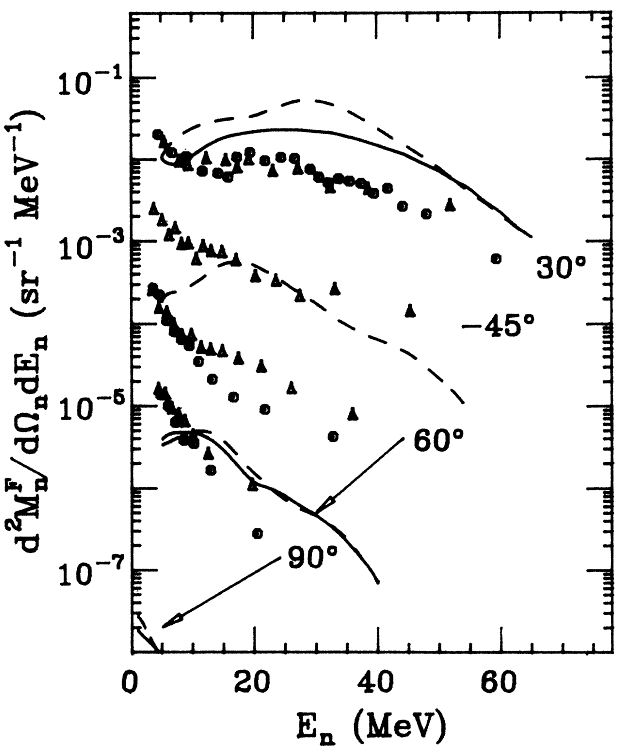

FIG. 5. Similar to Fig. 3, except the longitudinal and transverse momentum widths are unequal ($\xi = 1.25$; see Sec. IV C).

of the angular distribution of neutron emitters while maintaining the energy distribution to a large degree. Figure 5 shows the resulting simulated spectra, again with the data. The result is similar to Fig. 3 in that the angular distribution of the calculation is again stronger than the data. However, the softening of the fragment angular distribution has eliminated much of the left-right asymmetry in neutron emission.

V. GENERAL FEATURES

The popularity of the moving-source analysis has rested primarily on the simple analytic properties which seem to be connected to physical processes at lower energies. That is, the temperature is connected to the excitation energy of the source, and the source kinetic energy per nucleon reflects the emitter's speed and direction. At higher energies, where such a connection is not so directly established, moving source parameters such as temperature provide a convenient means of systematizing a large body of data for which there exists no complete theory, or at least no readily accessible theoretical framework for analysis. But is there anything which we can learn from moving source analyses at these intermediate energies? The above simulations showed that the details of neutron emission spectra, in coincidence with projectile-like fragments, can indeed be altered by including effects which are not part of the standard multiple moving source analyses. However, the basic features of the simulations are almost the same as the moving source analysis would give. The high energy neutron emission could not be ascribed to two moving sources where one is a projectile-like and the other a target-like source. This became clear upon examination of the angular distribution of the neutron emission. Both the present analysis and the moving source analysis[1] require, within this moving source framework, a quite different source which moves slower (to give a less forward peaked angular distribution of neutrons than a quasielastic fragment) and has a temperature higher than that of the target-like fragment.

These simulations have been useful, then, in determining that simple two-body equilibrium reactions are apparently not able to describe the data. So, the origin of the high energy neutrons has not yet been determined.

VI. CONCLUSIONS

These failures in reproducing the neutron spectra make it plausible that with only two sources no reasonable set of parameters can be chosen to reproduce the data of Ref. 1, even including recoil effects. Since incorporating reasonable fragment energy and angular distributions and accounting for recoil effects in evaporation will not reproduce the data of Ref. 1, the high energy and large angle neutrons must arise from some other mechanism. This is not too surprising since it is known[7,9] that pre-equilibrium neutron emission begins to be obvious even at energies much lower than 35 MeV/nucleon. The assessment of the origin of the neutrons in Ref. 1 is beyond the scope of this study, but it promises to be of interest in determining the reaction mechanism for these coincidence experiments.

This work was supported by the National Science Foundation under Grant Nos. PHY-83-12245 and INT-80-15333.

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[8]This expression derives from the expression $d^2\sigma/d\Omega\, dp \propto p^2 e^{-(p-p_0)^2/2\sigma^2}$ in the case that the longitudinal and transverse momentum widths are equal. For the purpose of these simulations, the magnitude of p_0 is taken from fits to experimental data of Ref. 1 and the direction is assumed to be 0° in the lab. It may be more realistic to assume that p_0 is directed toward the grazing angle, and this would soften the angular distribution and change the asymmetry in neutron emission.

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