Evolution of Nucleus-Nucleus Collision Mechanisms from the Barrier to Beyond the Fermi Energy

M. Fatyga, K. Kwiatkowski, and V. E. Viola
Departments of Physics and Chemistry and Indiana University Cyclotron Facility, Indiana University, Bloomington, Indiana 47405

C. B. Chitwood, D. J. Fields, C. K. Gelbke, W. G. Lynch, J. Pochodzalla, and M. B. Tsang
Department of Physics and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824

and

M. Blann
Lawrence Livermore National Laboratory, Livermore, California 94550
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Systematic measurements of linear-momentum-transfer distributions have been performed for ^{6}Li-, ^{12}C-, and ^{14}N-induced reactions on ^{238}U at energies up to $E/A = 45$ MeV. The data establish a limitation in linear momentum transfer at 200 MeV/c per projectile nucleon, which occurs near a beam energy of $E/A \approx 35$ MeV. This limitation is interpreted in terms of precompound particle emission, and calculations based on this concept reproduce the global energy dependence of the data.

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As the relative energy of nucleus-nucleus collisions increases from the Coulomb barrier to beyond the Fermi energy, one expects the influence of the dinuclear mean field on the reaction dynamics to be significantly modified by the effects of individual nucleon-nucleon collisions. The qualitative understanding of this transitional energy region requires systematic experimental studies of the global reaction properties as a function of bombarding energy. These, in turn, should provide valuable guidance for the future development of microscopic theories which consider the effects of both mean-field and nucleon-nucleon processes on the reaction dynamics.[1-3]

In this Letter we investigate the energy dependence of linear-momentum-transfer distributions which characterize collisions between light complex projectiles (^{6}Li, ^{12}C, and ^{14}N) and a heavy target nucleus (^{238}U). Linear-momentum-transfer distributions were determined by measurement of the angular correlation between coincident fission fragments.[4] Experiments were performed at the National Superconducting Cyclotron Laboratory at Michigan State University with ^{14}N beams of $E/A = 30$, 35, 40, and 45 MeV, ^{12}C beams of $E/A = 20$, 25, 30, and 35 MeV, and ^{6}Li beams of $E/A = 30$ and 35 MeV. These new measurements cover the region in the immediate vicinity of the Fermi energy and, combined with previous data,[5-8] map out the detailed energy dependence of linear momentum transfer in collisions between complex nuclei.

Coincident fission fragments emitted from a 300-μg/cm^2 ^{238}U strip target were measured with two position-sensitive parallel-plate avalanche detectors of active area approximately 19 cm in the horizontal plane and 15 cm in the vertical plane.[8] One detector was positioned with its center at $+85°$ with respect to the beam axis and at a distance of 19 cm from the target. For the data reported here a gate was placed on a region of this detector which spanned $\pm 4°$ both in and out of the reaction plane, centered at 90° with respect to the beam axis. The second detector was placed 15 cm from the target with its center at an angle of $-65°$. This permitted 100% coincidence efficiency for fragments detected in the gated region of the defining detector.

In the off-line analysis two-dimensional spectra of the fission-fragment coincidence yields were generated as a function of the relative in-plane angle θ_{AB} between the two fragments and the out-of-plane angle ϕ. In this report we will focus on the in-plane angular correlation function, which can be directly related to the longitudinal component of the linear momentum transferred to the fissioning system. For this purpose all out-of-plane events detected at angles θ_{AB} and ϕ were projected onto the reaction plane ($\theta_{AB}, \phi = 0°$), defined by the beam axis and the center of the gating detector.

Figure 1 shows the folding-angle distributions, $d^2\sigma/d\Omega_A d\theta_{AB}$, for the ^{14}N + ^{238}U system. Previous results at lower energies[5,8] are included in the figure to demonstrate the evolution of the folding-angle distributions over the energy range from $E/A = 7$ to 45 MeV. For each energy we have indicated the ratio $p_{\parallel}/p_{\rm beam}$, where $p_{\parallel}$ and $p_{\rm beam}$ denote the linear momentum transfer to the fissioning nucleus and the beam momentum, respectively. Qualitatively similar

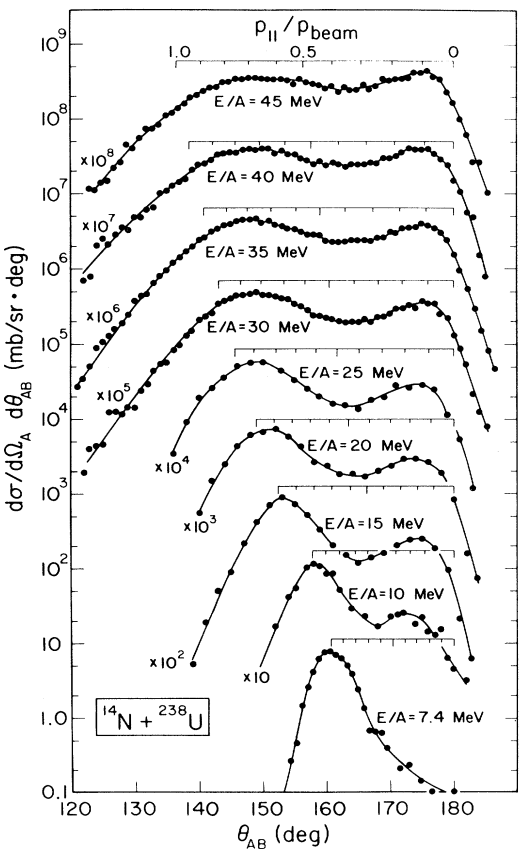

FIG. 1. Fission-fragment folding-angle distributions for the $^{14}N + ^{238}U$ reaction. Data at $E/A = 30$, 35, 40 and 45 MeV are from this work; data at $E/A = 7.4$ and 10.4 MeV are from Ref. 5, and data at $E/A = 15$, 20, 25 MeV are from Ref. 8. For each measurement a linear-momentum-transfer scale, $P_{\parallel}/P_{beam}$, is shown immediately above the data.

results are obtained for ^6Li and ^{12}C projectiles.

At incident energies near the Coulomb barrier the reactions are dominated by complete fusion processes, corresponding to full momentum transfer. Small contributions from low-momentum-transfer events are due to peripheral collisions such as inelastic scattering or transfer reactions. At higher beam energies two distinct components are observed, one associated with large momentum transfers (or peripheral processes). For energies above $E/A \simeq 20$ MeV, the most probable folding angle of the large-momentum-transfer component remains essentially constant near $\theta_{AB} \approx 149°$ for ^{14}N, corresponding to a limiting value of the maximum linear momentum transfer of $p_{\parallel}^{max} \approx 2800$ MeV/c. (For ^6Li- and ^{12}C-induced reactions these limiting values are $p_{\parallel}^{max} \approx 1200$ MeV/c and $p_{\parallel}^{max} \approx 2400$ MeV/c, respectively.) For all three cases the maximum linear momentum transfer per projectile nucleon is limited to 200 MeV/c. At higher energies the folding-angle distributions become rather structureless, corresponding to a broad continuum of linear momentum transfers and deposition energies in the residual system.

The peak angle of the low-momentum-transfer component does not exhibit a pronounced energy dependence. However, the relative importance of these peripheral processes increases strongly with bombarding energy and beyond $E/A \approx 40$ MeV, the fission cross section becomes dominated by peripheral interactions.[6,7,9] Qualitatively similar observations have been made for ^{40}Ar-induced reactions between $E/A = 27$ and 44 MeV.[10-12]

For a more detailed analysis we have extracted the following quantities:

(1) The most probable value of the linear momentum transfer for the fusionlike component, $P_{\parallel}^{mp}$. This quantity is most relevant to the properties of central collisions, but becomes difficult to extract for energies $E/A > 40$ MeV because of the dominance of the fission cross section by peripheral processes.

(2) The average value of the linear momentum transfer for the entire distribution, $\langle p_{\parallel} \rangle$. For uranium targets this quantity has the advantage of unambiguous definition and of including the total reaction cross section in the energy domain studied here. However, it does not separate fusionlike and peripheral interactions and, hence, for lighter nuclei depends strongly on the fissility of the decaying nucleus.

(3) An upper limit for the ratio σ_{CF}/σ_R, where σ_{CF} and σ_R denote complete fusion and total reaction cross sections, respectively. Because of the increasing dominance of preequilibrium emission processes, the concept of complete fusion becomes increasingly ill defined at higher energies. We stress that we cannot establish the existence of complete fusion beyond $E/A \approx 30$ MeV, but only an upper limit for this process. In deriving σ_{CF}/σ_R the complete-fusion component in the θ_{AB} plane has been approximated by the out-of-plane (ϕ) distribution at the most probable folding angle for complete fusion. Corrections have been included to account for the effects of fission-fragment mass and energy asymmetry.[4]

Figure 2 shows the average and most probable values of the linear momentum transfer per projectile nucleon, $p_{\parallel}^{mp}/A$ and $\langle p_{\parallel} \rangle/A$, as a function of the beam velocity parameter, $[(E-V)/A]^{1/2}$ (bottom scale), and the beam energy per nucleon (top scale), where E and V are laboratory values of the beam energy and of the Columb barrier. The departure of the results from full linear momentum transfer (solid line) becomes more pronounced with increasing beam energy. For ^{12}C and ^{14}N projectiles both the most probable and the average linear momentum transfer per nucleon exhibit a maximum near $E/A \approx 35$ MeV; for ^6Li (not shown in Fig. 2) this maximum occurs nearer

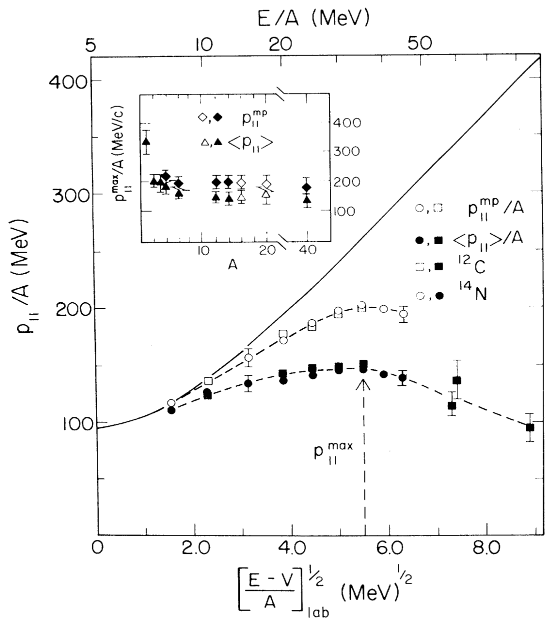

FIG. 2. Longitudinal momentum transfer per projectile nucleon as a function of laboratory beam velocity parameter $[(E-V)/A]^{1/2}$ (bottom scale) and projectile energy per nucleon (top scale). Squares and circles correspond to the ^{12}C- and ^{14}N-induced reactions on ^{238}U, respectively. Open points designate most probable values of the linear momentum transfer and solid points designate average values. Data below $E/A=45$ MeV are from this work and Refs. 4, 5, and 8 with typical systematic errors indicated for the data at $E/A=15$ and 45 MeV; data at $E/A=58$ and 84 MeV are from Ref. 7, and the $E/A=60$ MeV result is from Ref. 16. The inset shows the maximum value of the linear momentum transfer per projectile nucleon as a function of projectile mass (Ref. 8); lozenges and triangles represent most probable and average values, respectively. Solid points indicate established upper bounds; open points represent the largest values observed over a more restricted range of energies.

$E/A \approx 30$ MeV. Similar limitations have previously been observed in light-ion–induced reactions,[13] where the maxima occur at higher values of E/A.

Upper bounds for $p_{\parallel}^{mp}/A$ and $\langle p_{\parallel}\rangle/A$ are now established for a variety of light complex projectiles up to ^{40}Ar. To illustrate the present experimental situation, maximum values of $p_{\parallel}^{mp}/A$ and $\langle p_{\parallel}\rangle/A$ are shown in the inset in Fig. 2 as a function of projectile mass.[8] Light-ion data are from Ref. 13; limits for ^{6}Li, ^{12}C, and ^{14}N have been determined here; estimates for ^{16}O and ^{20}Ne are based on data presented in Refs. 7 and 8, and ^{40}Ar data are from Refs. 10–12. It appears that the most probable values of the linear momentum transfer for all ions with $6 \leq A \leq 40$ are limited to values less than 200 MeV/c per projectile nucleon.

The ratios of $p_{\parallel}^{mp}/p_{beam}$ and $\langle p_{\parallel}\rangle/p_{beam}$ and the maximum values of σ_{CF}/σ_R are shown as functions of laboratory values of $[(E-V)/A]^{1/2}$ in Figs. 3(a)–3(c), respectively. Nearly identical values are extracted for ^{12}C- and ^{14}N-induced reactions. For ^{6}Li projectiles, values of $p_{\parallel}^{mp}$ and σ_{CF}/σ_R agree well with ^{12}C and ^{14}N results while the $\langle p_{\parallel}\rangle$ values are about 10% higher. At energies above $E/A \approx 45$ MeV, the maximum contribution of complete fusion to the fission cross section has become negligible [Fig. 3(c)].

Incomplete momentum transfer in the fission channel must be associated with processes which account for the missing momentum; e.g., precompound particle emission, absorptive breakup of the projectile, or fragmentation of the target nucleus. Previous experimental studies have indicated the importance of particle emission prior to the attainment of full statistical equilibrium as an important mechanism for incomplete momentum transfer in central collisions.[14,15] In order to investigate the connection between precompound particle emission and incomplete linear momentum transfer, we have performed two model calculations for the ^{14}N + ^{238}U system which estimate the average linear momentum carried away by precompound particle emission in central collisions.[16,17] The dashed line in Fig. 3(a) shows the results obtained with a Boltzmann master-equation approach which includes emission of H and He precompound particles.[16] These calculations tend to overestimate the amount of energy carried away by precompound particles at lower beam energies, but with increasing energy they yield increasingly better agreement with the data.

The solid lines in Fig. 3(a) show the results of calculations which assume emission of particles with $Z=1-10$ from a localized region of excitation which is in the process of equilibrating with the remainder of the composite system.[17] Calculations are shown for three values of the rate at which nucleons are accreted to the localized region of excitation. An accretion rate of 2–3 nucleons per fm/c reproduces the energy dependence of the linear momentum transfer reasonably well. This value also provides a reasonable description of light-particle and intermediate-mass fragment emission ($Z \leq 10$) for ^{12}C-induced reactions on gold at $E/A=30$ MeV. In the context of intermediate-mass fragment studies, both the disappearance of complete fusion and the broad distribution of deposition energies inferred from the linear-momentum-transfer results underscore the necessity for exclusive measurements in order to define the source excitation energy associated with production of these fragments.

In summary, we have extended measurements of linear momentum transfer in ^{6}Li-, ^{12}C-, and ^{14}N-induced reactions on ^{238}U up to energies of $E/A=45$ MeV. Over the energy region from $E/A=20$ to 45 MeV the distribution of linear momentum transfer is spread over a broad continuum, with the maximum

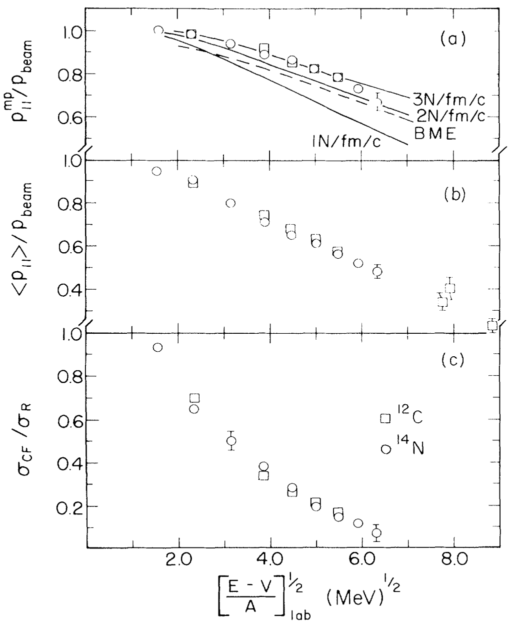

FIG. 3. Properties of linear-momentum-transfer distributions as a function of the laboratory beam velocity parameter for the same data as in Fig. 2. Squares represent ^{12}C data and circles are ^{14}N results. (a) The ratio of the most probable linear momentum transfer to the beam momentum. The solid curve represents a theoretical calculation of Ref. 17 for three different values of the nucleon accretion rate: 1.0, 2.0, and 3.0 nucleons per fm/c. The dashed line shows the Boltzmann master-equation prediction for precompound decay from Ref. 16. (b) The ratio of the average linear momentum transfer to the beam momentum, with typical errors as in Fig. 2. (c) The ratio of the upper limit for the complete-fusion cross section to the total reaction cross section.

possible contribution from complete fusion decreasing to a negligible level at the highest energy. For these projectiles we establish a limitation in linear momentum transfer at 200 MeV/c per projectile nucleon for the most probable value and 150 MeV/c for the average. These maximum momentum transfers occur at beam energies of $E/A=35$ MeV for ^{12}C and ^{14}N projectiles and $E/A=30$ MeV for ^{6}Li beams. The approximate correspondence of these limiting values with the Fermi momentum and average nucleon interaction energy in nuclei[18] suggest the increasing importance of individual nucleon-nucleon collisions in determining the reaction dynamics at these energies.

The origin of incomplete momentum transfer in central collisions is examined in terms of models which postulate particle emission prior to the attainment of full statistical equilibrium in the heavy residue. Consistent with this interpretation, these precompound models[16,17] are found to reproduce the global energy dependence of the most probable linear momentum transfer. Comparison of the full folding-angle distribution with microscopic models which include a more rigorous treatment of the effects of the mean field, nucleon-nucleon collisions, Pauli-blocking, etc., will be of considerable interest in the future interpretation of these results.[1-3]

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