INFLUENCE OF NUCLEON FERMI MOTION ON INCOMPLETE FUSION

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Velocity spectra were measured for evaporation residues produced in fusion reactions induced by 5–35 MeV/A ^{14}N. The results, together with published data for ^{16}O and ^{20}Ne induced fusion, are shown to reveal a projectile dependence of incomplete fusion processes. The data can be qualitatively described in terms of a picture which takes into account the vector addition of the center-of mass velocities of the interacting nuclei with the intrinsic Fermi velocities of the nucleons.

At energies near the Coulomb barrier, interactions between heavy ions are dominated by a complete fusion process in which the two nuclei fuse into a statistically equilibrated compound nucleus which subsequently decays by particle evaporation or fission. There now exists a substantial body of data indicating that at higher energies ($\geqslant$ 7–10 MeV/A) reactions occur in which only part of the projectile and target fuse, with the remaining nucleons being emitted on a time scale shorter than that for equilibration. The evidence for such "incomplete fusion" reactions comes primarily from two experimental observations. One is the detection of energetic, non-statistical, light particles in coincidence with evaporation residues (i.e. reaction products close in mass to the compound nucleus) or fission fragments [1–6]. The other observation is that the velocities of the fused system, inferred from evaporation residue velocities or fission fragment angular correlations, are different from those expected for complete fusion [3,7–12]. For example, the evaporation residue velocities are observed to be lower (higher) than expected when the projectile is lighter (heavier) than the target [9,10].

At present, the mechanism responsible for these incomplete fusion processes is not understood.

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Recently, Morgenstern et al. [13], used an assumed shape for the complete fusion component of the velocity spectra to estimate the relative magnitude of complete versus incomplete fusion for systems with differing mass asymmetry in the entrance channel. Incomplete fusion was found to be more likely for an asymmetric system than for a symmetric system at the same relative velocity. A common onset of incomplete fusion for different systems was found only when the data were plotted versus the center-of-mass velocity of the lighter reaction partner at contact:

$$v_L = [A_H/(A_H + A_L)]\, v_{rel},$$
$$v_{rel} = [2(E_{cm} - V_C)/\mu]^{1/2},$$

where A_H and A_L denote the masses of the heavier and lighter reaction partners, respectively, E_{cm} and V_C are the center-of-mass kinetic and Coulomb energies, respectively, and μ is the reduced mass. As suggested by Morgenstern et al., the observed trend can be qualitatively understood if the incomplete fusion processes are associated with those reactions in which nucleons obtain large velocities as a result of the vector addition of their Fermi velocities with the velocity of the nucleus with respect to the center of mass.

In this letter, we present results of velocity measurements of evaporation residues produced in reactions induced by ^{14}N. A comparison with previously reported ^{16}O and ^{20}Ne results is shown to display a projectile dependence for incomplete fusion which is apparent in the shift of the velocity centroids alone, without resorting to any decomposition of the spectra. We describe this dependence qualitatively in the framework of a simple velocity addition picture.

Experiments were performed using ^{14}N beams on targets of ^{24}Mg, ^{27}Al, ^{28}Si, ^{40}Ca, and ^{48}Ti. Measurements between 5 and 9 MeV/A were made at the Argonne Superconducting Linac. Higher energy measurements at 15, 25, and 35 MeV/A were carried out at the Michigan State University Superconducting Cyclotron. Velocities of the reaction products were measured using a time-of-flight detector system at small angles (typically 5–8 degrees). Channel plate detectors were used to obtain timing information and energies were measured with Si surface-barrier detectors. Centroids of the velocity spectra ($v^{-2}\, d^2\sigma/d\Omega\, dv$) were extracted for individually resolved residue masses. In agreement with refs.[9,10], the centroids were found to be roughly independent of residue mass. The quoted centroids are the average of the values obtained for the heaviest 5–10 masses with sufficient statistics in the peak.

In fig. 1a, the results of the present velocity measurements are compared to those obtained in studies of ^{16}O and ^{20}Ne induced reactions on targets of comparable mass [9,10]. Two features can be noted in the figure. First, the ratios of the observed velocity centroids to those expected for complete fusion, show evidence of a threshold velocity above which the velocities fall off from that expected for a fully fused system. This has been discussed previously [9,10], and an essentially identical behavior has been noted in the results of studies using different techniques in different mass regions [3,8,11,12].

The second feature in fig. 1a, which has not been explicitly discussed in the literature, is that the observation, at the same v_{rel}, of similar ratios for different projectiles implies that either the multiplicity or the average velocity of the emitted non-equilibrium light particles must be different. Using conservation of linear momentum, one can show that emission of the same number of nucleons from projectiles with different masses results in different shifts in the velocity centroids. The magnitude of the difference can be seen by calculating the number of emitted nucleons, N_{em}, necessary to reproduce the observed velocity centroids, assuming the same velocity for all emitted nucleons; i.e.

$$A_p v_p = (A_p + A_t - N_{em})\, v_{CS} + N_{em} v_{em},$$

where the subscripts p, t, CS, and em refer to the projectile, target, composite system, and emitted nucleons, respectively. This is shown in fig. 1b where the number of emitted nucleons calculated for the data of fig. 1a are plotted, this time as a function of the velocity of the lighter reaction partner, v_L. The escaping nucleons are assumed to move with the velocity of the projectile at the point of contact. Fig. 1b simply illustrates that different mass losses for the different projectiles

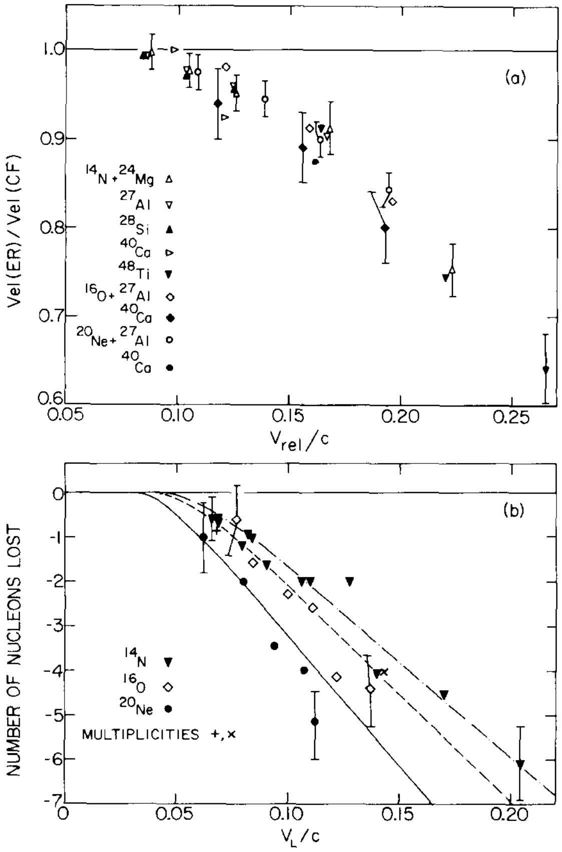

Fig. 1. Results of evaporation residue velocity measurements for reactions induced by ^{14}N (present work), ^{16}O (ref. [10]), and ^{20}Ne (ref. [9]). See the text for details. For clarity, only representative error bars are shown. Vertical and diagonal crosses are the results of multiplicity measurements for $^{14}N + ^{27}Al$ (ref. [4]) and $^{16}O + ^{48}Ti$ (ref. [6]), respectively. The results of the calculation discussed in the text are shown as solid, dashed, and dot-dashed lines for ^{20}Ne, ^{16}O, and ^{14}N, respectively.

are necessary to explain the observed velocity centroids. The quantity shown in fig. 1b is the mean mass loss averaged over all fusion-like reactions and not that for incomplete fusion alone which could be significantly larger.

The projectile dependence apparent in fig. 1b is also present when the mass loss is plotted versus v_{rel}, however, a systematic target dependence is also present (i.e., a larger mass loss for heavier targets). This is similar to the asymmetry effect observed by Morgenstern et al. [13] in their extraction of complete fusion yields, and might be interpreted as additional evidence that v_L is the relevant parameter for interpreting the reaction mechanism. It should be noted, however, that for systems with similar v_L and asymmetry, but involving different projectiles, the mass loss is not the same.

Also shown in fig. 1b are the results of measurements of the multiplicities of "fast" protons and alphas in coincidence with evaporation residues for $^{14}N + ^{27}Al$ (ref. [4]) and $^{16}O + ^{48}Ti$ (ref. [6]). Extraction of these quantities requires the subtraction of large evaporation components from the observed light-particle yields and thus the uncertainties are large. However, it is clear that the extracted multiplicities are consistent with the mass loss implied by the velocity centroids. Similar observations for ^{16}O induced fission data have been made by Vandenbosch [14].

The observed projectile and bombarding energy dependence with v_L can be qualitatively described in terms of a simple picture considering the addition of the center-of-mass momenta of the projectile and target nuclei with the intrinsic Fermi motion of individual nucleons. At higher bombarding energies, this addition produces nucleons with momenta well above the Fermi momentum in the frame of the compound nucleus (i.e., the center of mass). Such nucleons can escape the effective potential generated by the remainder of the projectile and target. This is illustrated in fig. 2 where the Fermi spheres for the projectile, target, and compound nucleus are shown for the reactions $^{16}O + ^{40}Ca$ and $^{28}Si + ^{28}Si$ at the same v_{rel}. Above a threshold velocity, some fraction of the projectile and target Fermi spheres extend outside that of the compound nucleus. This picture differs from those discussed by Bondorf [15] and Vandenbosch [14] in that the potential from which the nucleons escape is that defined by the composite system.

Since the relative velocities are comparable to the Fermi velocity, we assume that the velocity distribution in the composite system can be derived from the individual Fermi distributions of the projectile and target without rearrangement. If the nucleons outside the compound Fermi sphere are not captured and the momentum-space

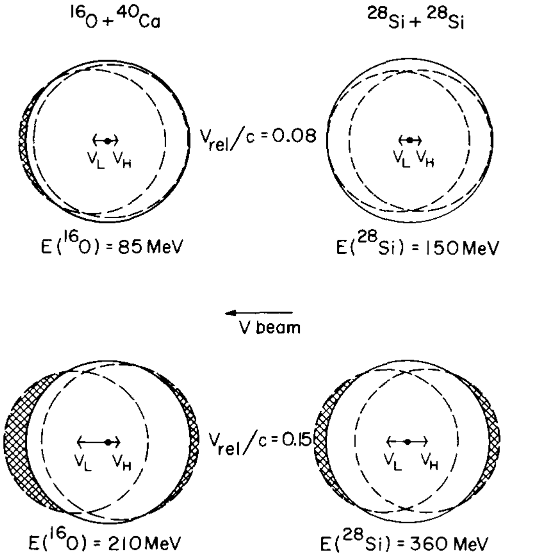

Fig. 2. Fermi spheres in the center of mass for the systems and energies indicated. The compound nucleus is shown as a solid line and dashed lines are used for the target and projectile. Cross-hatches are used to indicate regions of excess momentum. See the text for discussion.

nucleon density is that of a Fermi gas, then the number of escaping nucleons can be calculated using the fraction of the volume outside the sphere. Based on estimates of the barrier a nucleon must overcome in order to escape the nuclear interior [15], one can calculate that the laboratory velocity of these nucleons will be reduced to roughly that of the projectile at contact, thus allowing a comparison with the data of fig. 1b. The probability for complete fusion (i.e., no nucleons lost from either nucleus) depends on the distribution about the average number of nucleons lost from the projectile and target and hence no prediction can be made without additional assumptions. Although our picture does not consider angular momentum explicitly, this does not imply a lack of impact parameter dependence for incomplete fusion. A bias for peripheral collisions could be revealed by more detailed dynamical calculations.

The curves shown in fig. 1b are the results of the calculations for ^{14}N, ^{16}O, and ^{20}Ne which include only the effect of emission from the projectile (the lighter reaction partner in all cases). The momentum distributions were taken to be sharp spheres using the values of Fermi momentum, k_F, extracted from e^- scattering [16] when available or obtained from interpolation. Fermi energies of 26.6, 27.2, and 28.7 MeV were used for ^{14}N, ^{16}O, and ^{20}Ne, respectively. In order to reproduce the threshold velocity for the onset of incomplete fusion, the compound nucleus Fermi energy was adjusted to be 38 MeV (as compared to ≈ 37 MeV from ref. [16]).

The projectile dependence predicted arises partially from the differences in assumed Fermi momenta for the different projectiles and partially from the different masses of the projectile. Emission from the target was found to reduce the magnitude of the predicted effect from that shown in fig. 1b although the projectile dependence remained. Assuming the momentum distribution of a Fermi gas with a non-zero temperature was found to increase the number of escaping nucleons. Variations in the values of k_F will, of course, also change the quantitative predictions. Because of the simplicity of the picture, the influence of these additional effects was not pursued. What is striking, however, is the number of features in the data that appear naturally in the framework of this picture: namely, the appearance of a v_L threshold, the linear dependence on v_L (or v_H) rather than v_{rel}, the importance of the lighter reaction partner in asymmetric systems, and the dependence on the projectile.

To summarize, the investigation of incomplete fusion reactions has been extended by using beams of ^{14}N. Comparison of the present data to previous data obtained with ^{16}O and ^{20}Ne beams shows that the number of emitted nucleons necessary to explain the observed velocity centroids depends strongly on the projectile. The projectile and energy dependences of this process can be qualitatively described using a picture which takes into account the Fermi motion of nucleons in the interacting nuclei. This suggests that incomplete fusion processes may arise from the coupling of the center-of-mass motion of the interacting nuclei to the intrinsic Fermi motion of the nucleons within the nuclei. More detailed calculations which include explicitly the reaction dynamics need to be performed, especially in the region of onset of incomplete fusion when effects of breakup and transfer Q-values might be important.

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References

[1] T. Inamura et al., Phys. Lett. 68B(1977) 51.
[2] K. Siwek-Wilczynska et al., Phys. Rev. Lett. 42 (1979) 1599;
J. Wilczynski et al., Nucl. Phys. A373 (1982) 109.
[3] B.B. Back et al., Phys. Rev. C22 (1980) 1927.
[4] R. Billerey et al., Phys. Rev. Lett. 47 (1981) 639.
[5] T. Udagawa, D. Price and T. Tamura, Phys. Lett. 118B (1982) 45.
[6] P.L. Gonthier et al., Nucl. Phys. A373 (1983) 289.
[7] T. Sikkeland, E.L. Haines and V.E. Viola, Phys. Rev. 125 (1962) 1350.
[8] V.E. Viola et al., Phys. Rev. C26 (1982) 178.
[9] H. Morgenstern et al., Phys. Lett. 113B (1982) 463;
H. Morgenstern et al., Z. Phys. A313 (1983) 39.
[10] Y. Chan et al., Phys. Rev. C27 (1983) 447.
[11] B. Tsang et al., Phys. Lett. 134B (1984) 169.
[12] J. Jastrzebski et al., Phys. Lett. 136B (1984) 153.
[13] H. Morgenstern et al., Phys. Rev. Lett. 52 (1984) 1104.
[14] R. Vandenbosch, in: Nuclear Science Research Conference Series, Vol. 6, Nuclear physics with heavy ions, ed. P. Braun-Munzinger (Harwood Academic, New York, 1984) p. 447–469.
[15] J.P. Bondorf et al., Nucl. Phys. A333 (1980) 285.
[16] E.J. Moniz et al., Phys. Rev. Lett. 26 (1971) 445.