Fusion and Emission of ^{1}H and ^{4}He in Reactions between Complex Nuclei at High Energies

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We have measured cross sections for evaporation residues, fission, and direct and evaporative ^{1}H and ^{4}He in reactions of 222–340-MeV ^{40}Ar with ^{116}Sn, ^{154}Sm, ^{164}Dy, and ^{197}Au. Fusion cross sections are also presented for 77–167-MeV ^{12}C + ^{182}W and 187-MeV ^{40}Ar + ^{116}Sn. The Z dependence of the evaporative H/He indicates a breakdown of phase-space models for fission-evaporation competition. The large cross sections observed for direct H/He emission force serious consideration of energy dissipation by H/He ejection during the initial impact.

Since 1960, ^{1}H and ^{4}He have been found to be emitted with large cross sections in many reactions between complex nuclei.[1] Forward-peaked (direct) emission[2] seems to dominate for projectiles of ^{12}C, ^{14}N, and ^{16}O and evaporative emission[3] (symmetric about $\theta_{c.m.} = 90°$) for ^{40}Ar + ^{77}Se. First interpretations were that the direct H/He came from projectile breakup,[2] but more recent evidence[4] is for massive transfer or incomplete fusion (capture of the projectile residue). Currently there is great interest in gaining an understanding of complete fusion at high energies, and it is natural to ask about the possible role of the incomplete-fusion events. Experimentally, can one adequately distinguish complete from incomplete fusion in the measurements, and, correspondingly, do the reaction models take adequate account of the fast ejection of H/He during the impact processes? Models currently in use assume that complete fusion occurs prior to significant loss of energy or angular momentum from the composite system. Our new results along with other data strongly suggest that this assumption is not valid. We discuss the trends of a body of new data on fusion cross sections for several reactions induced by ^{12}C and ^{40}Ar. Also, we show a pattern of new results on the emission of H/He in ^{40}Ar reactions. Extensive direct and evaporative emission are observed. We discuss the possible relationships between direct-emission and fusion cross sections and between evaporative emission and fission.

The experimental arrangement is described elsewhere[5,6] so we shall give only a sketch here. Beams of ^{12}C and ^{40}Ar were obtained from the Lawrence Berkeley Laboratory 88-in. cyclotron and SuperHILAC, respectively. Self-supporting targets of ^{116}Sn, ^{154}Sm, ^{164}Dy, ^{182}W, and ^{197}Au were used. Three member solid-state telescopes (Si of 45 μm, 500 μm, and 5 mm at solid angles $\approx$ 8 msr) identified and measured H/He; gas-ionization telescopes (methane at $\approx$ 20 Torr with stopping detector of 500 μm Si at 0.2 or 1 msr)[7] determined evaporation residues (ER) and fission. Data were recorded event by event on magnetic tape, and we now report some of the results taken in the singles mode.

In Fig. 1 we show angular distributions at two incident energies for ^{1}H/^{4}He and fissionlike events for a ^{164}Dy target. Also, we show the

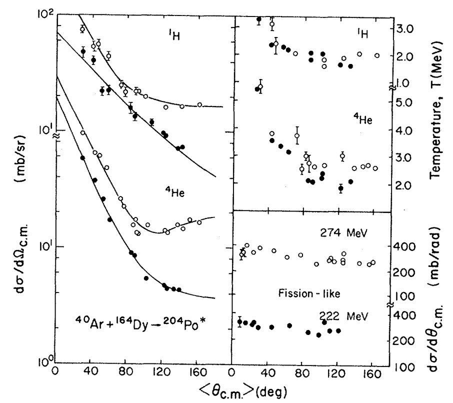

FIG. 1. Measured angular dependence of $d\sigma/d\Omega$ and T for ^{1}H, ^{4}He, and $d\sigma/d\theta$ for fissionlike events from ^{40}Ar $+^{164}$Dy. The open points are for 274 MeV and the filled points are for 222 MeV. Results for ^{116}Sn and ^{154}Sm targets are similar; for Au, see Ref. 6.

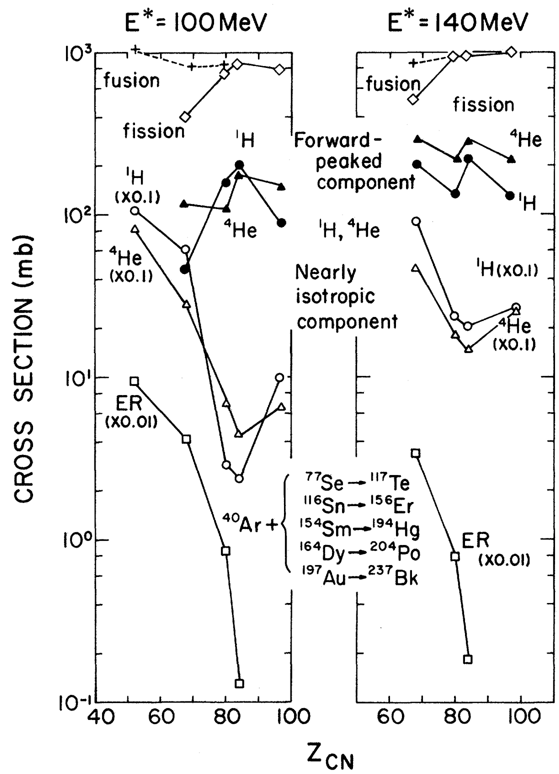

FIG. 2. Integrated cross sections at two excitation energies for fusion, fission, ^{1}H, ^{4}He, and ER vs charge of the composite nucleus, Z_{CN}. Data for a target of ^{77}Se are from Ref. 3.

angular dependence of the effective temperatures obtained by fitting the spectra to the equation $P(\epsilon)\propto(\epsilon-B)\exp(-\epsilon/T)$, with barrier parameters B from McMahan and Alexander.[8] Results for the ^{154}Sm and ^{116}Sn targets are similar. In contrast with the data[3] for ^{40}Ar + ^{77}Se, there is a clear forward-peaked component with a high effective temperature. We have attempted to resolve the direct and evaporative components by fitting to the function, $W(\theta)=A\exp(-\gamma\theta)+B+C\times\cos^2$. We assign to evaporative processes the integral of the symmetric part $(B+C\cos^2\theta)$ and the rest to direct processes. The symmetric emission could be the result of evaporation from the composite nuclear system or perhaps from fission fragments with symmetric distributions. As can be seen from Fig. 1, the direct processes at 222 MeV so dominate the integrated cross sections that the evaporation cross sections can be assigned only with large uncertainties.

The angular distributions for fissionlike events (as taken from ΔE-E contour maps[9]) are not quite symmetric about $\theta_{c.m.}=90°$. This is probably due to the difficulties of separating the so-called "fission" and "deeply inelastic" reactions.[9] Near $\theta_{c.m.}=90°$ one finds that the heavy-fragment energy spectra resolve into three well-defined groups that one is tempted to call projectilelike, targetlike, and fissionlike fragments. Therefore we assign to the fission cross section the value $\sigma_f=2\pi^2(d\sigma/d\Omega)_{c.m.}$ (at $\theta_{c.m.}=90°$). These values provide upper limits to the symmetric part of the fission cross sections.

In Fig. 2 we present the cross sections for ^{40}Ar reactions at two excitation energies as functions of Z of the composite system. As the incident energies are well over the barrier, the fusion cross sections (fission plus ER) are relatively constant (≈ 0.6 to ≈ 1.0 b). However, with increasing Z_{CN}, the fraction of ER drops dramatically (lower curve). The direct component of ^{1}H/^{4}He emission is relatively constant (with Z_{CN}) at ≈ 120 and ≈ 200 mb for excitations of 100 and 140 MeV, respectively. Presumably, direct H/He ejection occurs much faster than the subsequent fission or evaporative decays and is unaffected by them. By contrast the evaporative component of H/He must compete with fission and its cross sections decreases drastically from $Z_{CN}=52$ to 84. However, from $Z=84$ to 97 there are actually increases in the evaporative H/He while the ER cross sections have been reduced tremendously by fission. These increases are contrary to statistical-model expectations for evaporation prior to fission. In Ref. 6 we show that even for the very fissile system with $Z_{CN}=97$ the bulk of this evaporative H/He component must be emitted prior to scission and cannot be attributed to emission from the fission fragments. One must conclude that it comes from the composite system with intrinsic rate comparable to fission regardless of the rapid dependence of the number of open fission channels on Z. It would then appear that the fission-evaporation competition is determined primarily by the reaction dynamics rather than the available phase space. Hence, the energy spectra of H/He should reflect the temperatures and barriers of the composite system prior to fission and be largely unmindful of it. The experimental spectra are consistent with this argument. Thus, it would appear that these emissions of H/He are very powerful, if not unique, reflectors of the early life of the composite system. They may allow testing of many interesting questions such as the possible persistence of shell effects to very high excitations.[10]

In Fig. 3 our new data for ER and fission cross sections are compared to other similar data[5,6,9,11] and to calculated curves from the semiempirical systematics of Vaz and Alexander.[12] These curves simply provide a common reference and are not intended as sophisticated models for the fusion process at high energies. Let us summarize the pattern in Fig. 3. (1) All the data approach the reference curves at low energies simply because the calculations were taken from empirical fusion barriers. (2) With increasing energy, the data seem to flatten out compared to the reference curves. This tendency is especially clear for ^{12}C and ^{14}N projectiles and for ^{40}Ar + Sn, Sm, Dy, and Au. (3) For ^{40}Ar + Pd, Ag and Sb, there are only small deviations from the reference curves, while our new measurements for ^{116}Sn fall below the curve at 222 and 274 MeV, but agree with the curve at 187 MeV. In the model of Ref. 12, and others presented so far, the fusion decision is presumed to precede significant particle emission. However, particle ejection during impact and from a band of l waves near l_{crit} would present an element so far unaddressed in the models for complete fusion.

Our purpose here is to emphasize the possible importance of energy dissipation by H/He ejection during the impact stage. First consider reactions with the lighter projectiles ^{12}C and ^{14}N. For energies well over the barrier we know that forward-peaked H/He emission is very large.[2,4] Also, we now believe that the projectile residue often fuses with the target.[4] For ER measure-

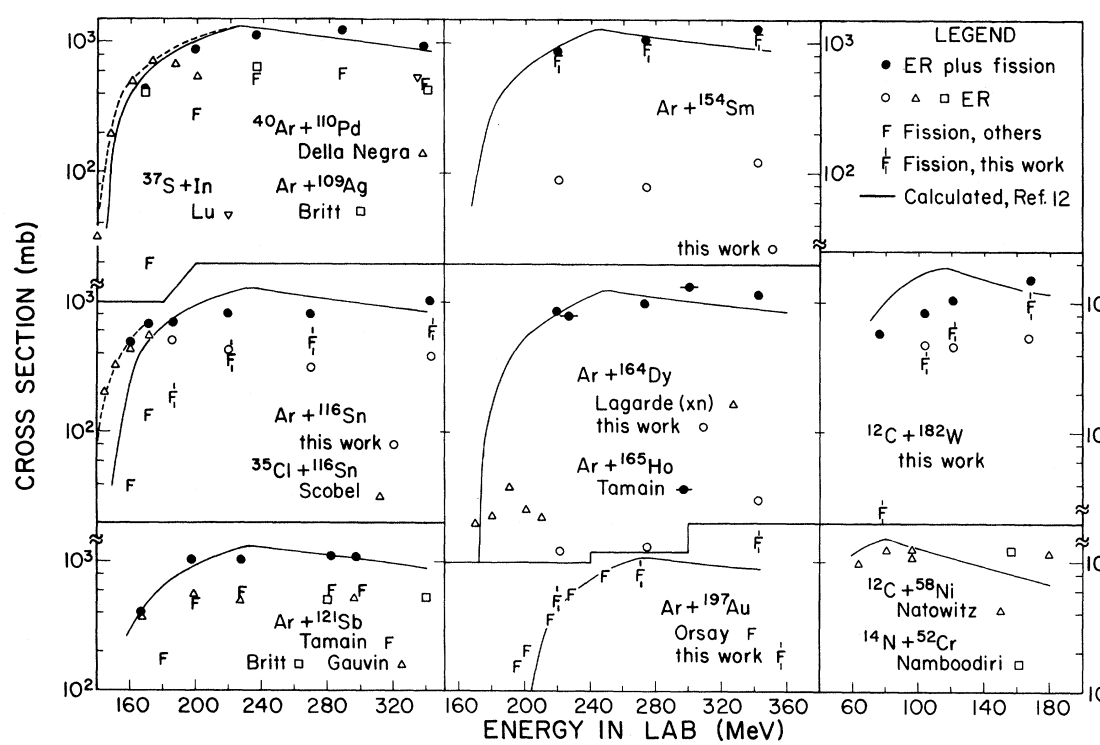

FIG. 3. Excitation functions for fusion (filled circles), fission (F), and ER (open symbols as indicated) from this work (open circles) and other studies (triangles, Ref. 5; inverted triangles, Ref. 9; squares, Ref. 11).

ments near the detection threshold of a gas telescope (e.g., recoils of a few MeV from reactions such a ~100-MeV $^{12}C + ^{182}W$), the heavy residuals after forward-peaked direct ^4He emission may not be detected.[5] As the projectile energy is increased, however, such residual nuclei will often be detected and possibly included in the integrated cross section assigned to ER. One possible experimental complication of the trends in Fig. 3 for the ^{12}C and ^{14}N reactions (and for most published data) is as follows. For energies near the calculated cross-section maximum, the observed ER cross sections could suffer from competition with incomplete-fusion reactions that are largely undetected. For higher energies the observed ER cross sections could increase as a result of an increased detection efficiency for the incomplete fusion residues. In the case of ^{40}Ar-induced reaction, the experiments probably include most incomplete-fusion reactions along with the complete fusion; at high energies there may also be some confusion of fission with deeply inelastic reactions.[9]

What do we actually want to include in the experimental fusion cross section? This clearly depends on the reaction model that we want to test.[13] References 4 and 6 give evidence that the probability for direct ^4He emission is greatest for l waves near to or greater than the high-l cutoff for fusion (l_{crit}). Therefore, a model calculation of l_{crit} must consider in detail both the nucleon transfers and the particle emissions for l near l_{crit}. Energy dissipation by nucleon transfer alters both the energy and angular momentum of the relative motion and therefore the calculated values of l_{crit}.[14] Experiments show that the cross sections for direct H/He emission are often quite large (~1000 mb for 126-MeV ^{12}C + Bi; ~200 mb each for H/He for 274-MeV ^{40}Ar), and could thus perturb collision trajectories for many l values. Therefore, the role of the incomplete-fusion residues *vis-à-vis* a "fusion" cross section of ~1000 mb has obvious importance. To our knowledge no current reaction model for fusion includes this aspect; i.e., energy dissipation and perturbation of the assumed potential barrier due to direct particle ejection during the impact.

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