Influence of the Mass Asymmetry on the Onset of Incomplete and the Limit to Complete Fusion

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Velocity spectra of evaporation residues deviate characteristically from the mean velocity of complete fusion, indicating that the lost momentum (mass) in incomplete fusion originates perferentially from the lighter partner. By varying the energy in the range 10–25 MeV/u the authors determine the onset of incomplete and the limit to complete fusion, and they discuss dependence on the mass asymmetry in the entrance channel.

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Heavy-ion–induced reactions below 10 MeV/u have in common the fact that the reaction cross section is shared predominantly among the following competing processes: those leading to complete fusion (CF), deep-inelastic collisions, and quasi-elastic collisions. As the energy increases, one observes in addition light particles that evidently are emitted at an early stage of the reaction. This phenomenon is known as incomplete fusion (ICF), breakup fusion, or massive transfer, and various models attribute it to "precompound" or "preequilibrium" emission, the formation of "hot spots," "Fermi jets," the "prompt emission of particles," or a transferlike process. The common feature is that essentially these light particles are spectators having little interaction with the nucleons of the compound system. The existence of direct light particles was proven by Britt and Quinton,[1] and Alexander and Winsberg[2] were the first to comment on partial momentum transfer. As the velocities of the colliding nuclei approach the mean Fermi velocity of nucleons in nuclear matter, one finds that a nucleon can be emitted at an early stage of the reaction by adding up both velocities in an appropriate way. If followed by fusion, the "reduced" compound nucleus obviously does not absorb the full linear momentum of projectile and target. Hence, the measurement of the linear momentum transferred to the compound nucleus (CN) will give an insight into the reaction mechanism. A heavy CN will predominantly undergo fission and the correlation angle (folding angle) of the two fragments is taken as a measure for the degree of momentum transfer.[3]

In this Letter we report on reactions leading to lighter CN ($A_{\rm CN} < 100$) where the formation of evaporation residues (ER) is the main decay mode. Following our previous work we relate the degree of momentum transfer to the mean ER velocity, and by adopting the width of the velocity distribution according to Morgenstern *et al.*[4,5] and Lehr *et al.*,[7] we extract the ratio of complete to all fusionlike processes.

The experiments were performed at the VICKSI facility of the Hahn-Meitner-Institut, Berlin. Self-supporting thin (200–500 μg/cm^2) targets of ^{12,13}C, ^{26}Mg, ^{27}Al, ^{40,44,48}Ca, and ^{58,60,62}Ni were bombarded with ^{12}C, ^{20,22}Ne, ^{35}Cl, and ^{36,40}Ar ions of 10–25 MeV/u. Two channel-plate arrays 118 cm apart provided the time-of-flight T while the energy E was derived from a surface barrier detector. Two-dimensional T vs E and mass $M \propto ET^2$ vs E spectra were accumulated on-line. The flight path was determined from measurements with a Th-α source to within ± 0.2 cm. The time axis was normalized by means of a precision pulser and a known precision delay line to within ± 10 psec and the ion energy was known to an accuracy of better than 0.1%. Finally, the absolute time value was deduced from elastic scattering on a thin (100 μg/cm^2) Au target. Taking into account the energy losses of projectile and ER in the target and detector foil, we obtain the absolute ER velocity to an accuracy of ± 0.01 cm/nsec.

This high precision enables us to analyze the experimental velocity distributions with respect to the mean velocity for full momentum transfer $v_{\rm CN}$. Representative examples are shown in Fig. 1. It is striking that (i) mass symmetry in the entrance channel leads to mean ER velocities $\bar{v} \approx v_{\rm CN}$ (this is *a priori* true for identical target and projectile at $\theta = 0°$); and (ii) mass asymmetry leads to $\bar{v} < v_{\rm CN}$ for a light projectile and a heavy target, and $\bar{v} > v_{\rm CN}$ vice versa.

Our data clearly show that the momentum (mass) lost at an early stage of the fusion process preferentially originates from the lighter partner of the colliding nuclei. We can express the ratio $\bar{v}/v_{\rm CN}$ as follows[4]:

$$\frac{\bar{v}}{v_{\rm CN}} = \left(\frac{m_P - \Delta m_P}{m_P - \Delta m_P + m_T - \Delta m_T}\right) \Big/ \left(\frac{m_P}{m_P + m_T}\right), \qquad (1)$$

where the indices P and T denote projectile and target, and Δm represents the mass lost prior to fusion. It is obvious that we cannot determine the degree of momentum transfer without referring to the mass ratio in the entrance channel, as pointed out previously.[7] However, in the case of a light projectile on a heavy target we can extrapolate the fraction of the transferred momentum to the velocity axis, providing an upper limit to fusionlike (incomplete) reactions.

We have demonstrated[4-6] how one can deduce the fraction of complete fusion. If we assume a Maxwellian velocity distribution of the ER's and an isotropic or $1/\sin\theta$ angular distribution (to cover the extreme cases) the transformation into the laboratory yields the Lorentz-invariant cross section as a function of v,

$$(1/v^2)\, d^2\sigma/d\Omega\, dv = N[(v - v_{\rm CN}\cos\theta)^2 + v_{\rm CN}^2 \sin^2\theta]^{1/2} v^{-1} \sin^{-1}\theta \times \exp\{-[(v - v_{\rm CN}\cos\theta)^2 + v_{\rm CN}^2\sin^2\theta]/2s^2\}, \tag{2}$$

with the laboratory scattering angle θ, a normalization constant N, and the standard deviation s. We have shown[5,6] that the "width" $s_{\rm CF}$ for complete fusion at higher energies can be extrapolated from low-energy data (where CF is predominant) in excellent agreement with statistical model calculations. The data can then be fitted by Eq. (2) with N the only free parameter. The components of incomplete fusion are obtained in an analogous way with the velocity $v'_{\rm CN}$ of the reduced CN and with allowance for a variation of up to -10% in $s_{\rm ICF}$. It should be noted that the partition into various incomplete-fusion components is somewhat ambiguous. However, this does not affect the complete-fusion part. Essentially the deduced fraction of complete fusion is not altered by a change in scattering angle or a variation in residue mass. Though there is a notable trend (in the case of a light projectile on a heavy target) of decreasing $\bar{v}/v_{\rm CN}$ with decreasing residue mass, this is to a large extent balanced by a simultaneously increasing width s. In any case these variations are within the quoted errors.

The colliding nuclei approach with the relative velocity $v_{\rm rel} = [2(E_{\rm c.m.} - V_B)/\mu]^{1/2}$, μ being the reduced mass and V_B the fusion barrier, and come to rest in the c.m. frame after complete fusion. The relative velocity is shared in inverse proportion to the masses and consequently the lighter partner A_L will be faster than the heavier A_H prior to fusion:

$$v_L = \frac{A_H}{A_L + A_H} v_{\rm rel}; \quad v_H = \frac{A_L}{A_L + A_H} v_{\rm rel}. \tag{3}$$

We find that for a fixed $v_{\rm rel}$ the fraction of complete fusion decreases with increasing mass asymmetry (see right-hand side of Fig. 2). We therefore do not relate the degree of momentum transfer and the fraction of complete fusion to $v_{\rm rel}$ (or an equivalent) as is usually done.[3,7,8] Instead it appears more appropriate to assume a strong dependence on v_L, as the lost momentum (mass) mainly originates from the lighter partner (Fig. 1). The

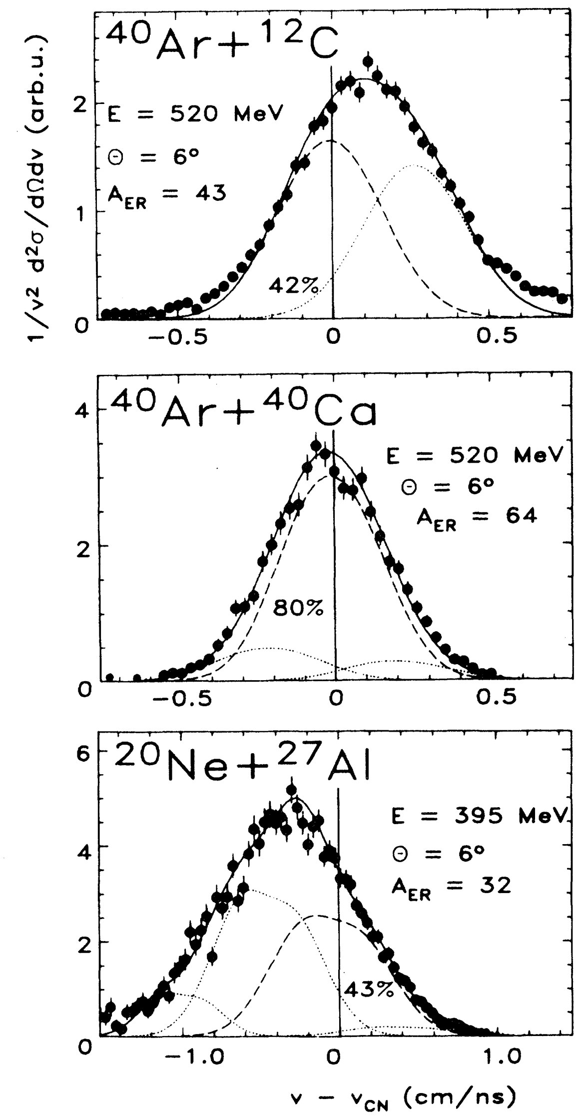

FIG. 1. Velocity spectra of evaporation residues (ER) suggesting that the lighter nucleus loses momentum (mass). The quoted numbers indicate the fraction of complete fusion (CF). Fits are calculations with Eq. (2).

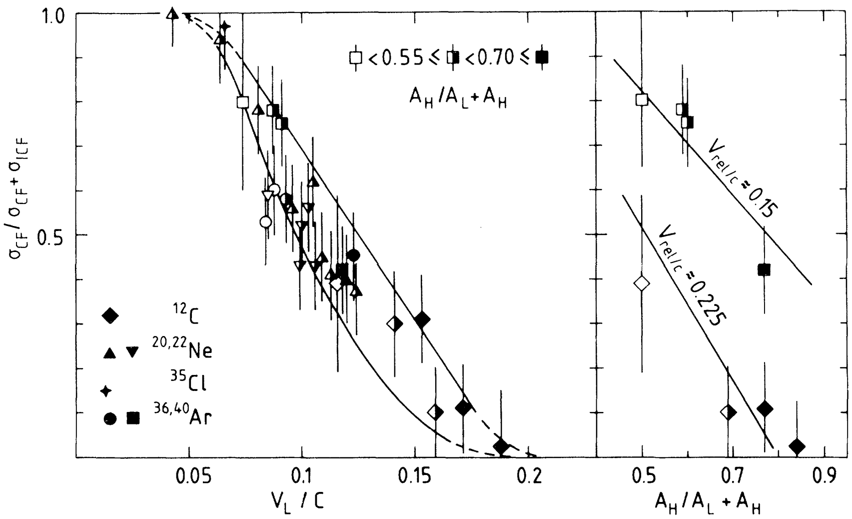

FIG. 2. The fraction of complete fusion displayed as a function of the velocity of the lighter nucleus, v_L/c. The symbols representing projectiles are filled in according to the degree of mass asymmetry. The right-hand side shows that complete fusion strongly depends on the asymmetry in the entrance channel. For further explanations see text.

fraction of complete fusion then decreases almost linearly with v_L revealing an onset to ICF and a limit to CF, v_{onset} and v_{limit}, respectively. Simply, the nuclei A_L and A_H lose momentum (mass) with certain probabilities $P_L,P_H \leq 1$ once v_L or v_H (or both) exceed the threshold velocity v_{onset}. The product $(1-P_L)(1-P_H)$ defines the fraction of complete fusion. Thus the strongly asymmetric case $A_L << A_H$ reduces to the exclusive loss of momentum (mass) from the lighter nucleus A_L since we always have $v_H < v_{\text{onset}}$.

Figure 2 demonstrates that such a picture is consistent with the systematic trend of our data. Strong asymmetry in the entrance channel yields ratios close to the upper line, $(v_{\text{limit}}-v_L)/(v_{\text{limit}}-v_{\text{onset}})$, while more symmetric systems cluster at the lower curve, $(v_{\text{limit}}-v_L)^2/(v_{\text{limit}}-v_{\text{onset}})^2$. From our data we extract an onset of ICF at $v_L/c=0.06\pm0.02$ and a limit to CF at $v_L/c=0.19\pm0.02$. The latter corresponds to a limitation of the transferred momentum of 180 MeV/c per nucleon, in accordance with Galin *et al.* and Rana *et al.*[9] The onset of ICF is in good agreement with Refs. 3, 7, and 8. On the contrary, relating $\sigma_{\text{CF}}/(\sigma_{\text{CF}}+\sigma_{\text{ICF}})$ to v_{rel} does not yield a common limit to CF, as $v_L \approx v_{\text{rel}}$ for $A_L << A_H$ but $v_L < v_{\text{rel}}$ otherwise.

We conclude that the velocity of one partner (the lighter one, A_L) is decisive for the onset of incomplete and the limit to complete fusion. Both the onset and the limit are smooth since we deal with probabilities, but nevertheless are well defined. Finally, an extrapolation of existing data[5,7] of the transferred momentum [Eq. (1)] to the velocity axis provides an upper limit to incomplete-fusion reactions of $v_L/c=0.38\pm0.05$ for the case of exclusive loss of momentum from the light projectile.[5,7]

It is suggestive to give an interpretation within the framework of a simple Fermi gas. For the sake of simplicity we proceed in the following in a nonrelativistic manner although the quoted numerical values include relativistic corrections. By adding the Fermi velocity v_{F} of a nucleon m_0 collinearly to the nuclear velocity v_L, we obtain a lower limit for the onset of incomplete fusion:

$$\tfrac{1}{2}m_0(v_{\text{F}}+v_L)^2 \geq \epsilon_{\text{F}}+E_S, \tag{4}$$

with the Fermi energy ϵ_{F} and the separation energy of a nucleon (or nucleon cluster) E_S. Typical values of $25 \leq \epsilon_{\text{F}} \leq 40$ MeV and $8 \leq E_S \leq 12$ MeV result in a numerical value of $v_L/c \geq 0.03\text{–}0.05$ for the onset of incomplete fusion. The mean energy of a nucleon in a cold Fermi gas is $\frac{3}{5}\epsilon_{\text{F}}$. Adding the nuclear velocity vector, we arrive at

$$\tfrac{1}{2}m_0\left(\left(\tfrac{3}{5}\right)^{1/2}\vec{v}_{\text{F}}+\vec{v}_L\right)^2 = \tfrac{3}{5}\epsilon_{\text{F}}+\tfrac{1}{2}m_0v_L^2+m_0\left(\tfrac{3}{5}\right)^{1/2}v_{\text{F}}v_L\cos\alpha, \tag{5}$$

α being the angle between the Fermi velocity vector and the nuclear velocity. By averaging over α we obtain a limit to complete fusion:

$$\tfrac{3}{5}\epsilon_{\text{F}}+\tfrac{1}{2}m_0v_L^2 \geq \epsilon_{\text{F}}+E_S, \tag{6}$$

taking into account that on the average any nucleon can be emitted. In other words, at least one nucleon is lost prior to fusion with a high probability—that is, complete fusion of the colliding nuclei ceases to exist above $v_L/c \geqslant 0.21$–0.24. We can speculate that the cross section for incomplete fusion becomes negligibly small when antiparallel addition of nucleus and mean Fermi velocity exceeds the maximum velocity in the Fermi gas:

$$\frac{1}{2} m_0 \left(- \frac{3}{5}^{1/2} v_\mathrm{F} + v_L \right)^2 \geqslant \epsilon_\mathrm{F} + E_S. \quad (7)$$

Thus an upper limit to fusionlike reactions is reached at $v_L/c \approx 0.40$–0.50.

In conclusion, incomplete fusion increasingly competes with complete fusion at 10–25 MeV/u. The onset of ICF and the limit to CF strongly depend on the degree of mass asymmetry in the entrance channel. Incomplete fusion contributes significantly above $v_L/c \approx 0.06$ and complete fusion ceases to exist above $v_L/c \approx 0.19$, corresponding to a limitation of the transferred momentum of 180 MeV/c per nucleon.

[1]H. Britt and A. Quinton, Phys. Rev. C 124, 877 (1961).

[2]J. Alexander and L. Winsberg, Phys. Rev. C 121, 529 (1961).

[3]V. E. Viola, Jr., *et al.*, Phys. Rev. C 26, 178 (1982), and references therein.

[4]H. Morgenstern *et al.*, Phys. Lett. 113B, 463 (1982).

[5]H. Morgenstern *et al.*, Z. Phys. A 313, 39 (1983).

[6]H. Lehr *et al.*, to be published.

[7]R. G. Stockstad *et al.*, Lawrence Berkeley Laboratory Report No. LBL-15874, 1983 (unpublished); Y. Chan *et al.*, Phys. Rev. C 27, 447 (1983).

[8]W. Henning, Nucl. Phys. A400, 295c (1983).

[9]J. Galin *et al.*, Phys. Rev. Lett. 48, 1787 (1982); G. L. Rana *et al.*, Nucl. Phys. A407, 233 (1983).