INCOMPLETE MOMENTUM TRANSFER IN HEAVY-ION FUSION AT 14 MeV/u

H. MORGENSTERN, W. BOHNE, K. GRABISCH, D. KOVAR+, H. LEHR
Hahn-Meitner-Institut für Kernforschung Berlin

Abstract: Evaporation residues have been studied for reactions induced by 291 MeV ^{20,22}Ne ions on ^{12,13}C, ^{26}Mg, ^{27}Al, ^{40,48}Ca and ^{60}Ni targets. The analysis of many velocity spectra of individually resolved residue masses shows clear evidence for fusion-like residues with incomplete momentum transfer.

Already 20 years ago, studies of compound nucleus formation with the recoil technique by Alexander[1] showed evidence for "partial momentum transfer" at 10 MeV/u. The present investigation is the first attempt to determine directly the average momentum transfer of some lighter fusion systems by measuring the average velocity of the resulting evaporation residues. The experiment was performed at the VICKSI facility of the Hahn-Meitner-Institut Berlin. The energy and the time-of-flight (flight path 134 cm, overall time resolution about 100 psec) of the evaporation residues were measured to obtain mass-velocity distributions (see Figure 1). The discussion will focus on the velocity spectra of the heaviest masses observed where the reaction products have the basic characteristics expected for evaporation residues and have little or no contributions from other possible reaction processes.

The evaporation residues resulting from compound nucleus formation and subsequent light-particle emissions have velocity spectra and angular distributions which reflect the degree of linear-momentum transfer from the projectile to the projectile-plus-target system as well as the details of the kinematics of the evaporation process. This can be seen in the predictions of Monte Carlo calculations, however, it can most easily be understood in terms of analytic expressions derived using simple arguments. In particular a simple relationship exists between the average recoil velocity of the evaporation residues in the laboratory system and the velocity of the compound nucleus from which it originated. This relationship is obtained[2,3] by assuming specific forms for the velocity and angular distributions (generally isotropic angular and Maxwellian velocity distributions) of the evaporation residues in the center-of-mass system and then transforming into the laboratory system. The derived velocity distribution

+present adress Argonne National Laboratory of the residues is[3]:

$$d^2\sigma/d\Omega dV = N V^2 \exp(-(V-V_C\cos\theta)^2/2\sigma^2) \exp(-V_C^2\sin^2\theta/2\sigma^2) \quad (1)$$

with the recoil velocity V and the angle θ in the laboratory system, the compound nucleus velocity V_C and the standard deviation σ. From equation (1) it can be seen that the observed velocity spectrum divided by V^2 (i.e., the quantity $V^{-2}d^2\sigma/d\Omega dV$) should be a Gaussian centered at $V_C\cos\theta$ and therefore provides information on the velocity of the compound system from which the residue originated. The degree to which the experimental results are well described by Eq(1) is shown in Figure 2. The shapes are well reproduced, but the observed velocity centroids show increasing deviations from the expected compound nucleus velocities (indicated in the figure by arrows) as the target mass increases. Also shown in Figure 2 are the velocity spectra predicted by the evaporation codes JULIAN and CASCADE (dashed curves). Their basic shape is in agreement with that of Eq(1) and the average velocity is equal to the compound nucleus velocity for 100% momentum transfer; the variances σ^2 are smaller than observed.

The observation of compound velocities $\bar{V}_C$ which are smaller (and variances σ^2 which are larger) than that expected for the projectile-plus-target compound nucleus is indicative of the presence of pre-equilibrium emission or incomplete fusion processes. If one tries to extract the evaporation residue cross section after complete fusion by fitting the velocity spectra (see Figure 3) with two or three Gaussians, one of which has a velocity centroid at 100% momentum transfer and a variance equal to calculated values (JULIAN,CASCADE), one obtains the given percentages for complete- and incomplete-fusion cross section for the given angle and residue mass. One may try to discuss these results in the framework of the "incomplete-fusion" picture of Wilczynski[4]. This implies that a light fragment of the projectile nucleus, (or a fragment of the target), is emitted during the reaction with a velocity near to the projectile (or target) velocity, respectively, while only the remainder of the projectile (target) fuses with its partner. In Figure 4 these velocities for neutron, proton and α-particle break-up of projectile and target with due consideration of separation energies and Coulomb forces are indicated by short lines. The velocity tendency of the lighter residue masses seems to indicate that increasingly larger fragments are emitted prior to fusion.

In summary we have investigated the feasibility of using the recoil velocity spectra of evaporation residue masses to provide information as to whether the residues are produced in complete- or incomplete-fusion reactions by determining whether full momentum transfer has occured. Significant departures from full momentum transfer were observed. The results obtained indicate that the recoil velocity spectra of evaporation residues can be an extremly valuable information especially when measured in coincidence with energetic forward-emitted light particles for establishing the complete- and incomplete-fusion yields for light- and medium-weight systems at high bombarding energies.

References:

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2. A. Ewart and M. Kaplan, Phys. Rev. 162 (1967) 944
3. J.Gomez del Campo et al., Phys. Rev. C19 (1979) 2170
4. K. Siwek-Wilczynska et al., Nucl. Phys. A330 (1979) 150

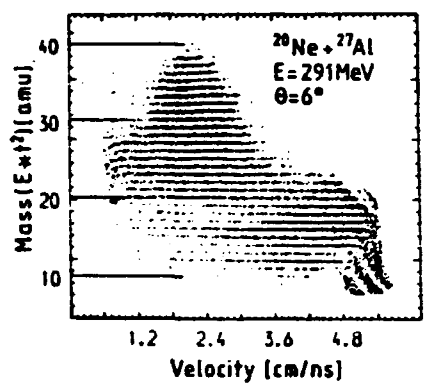

Figure 1: Typical mass-velocity diagram

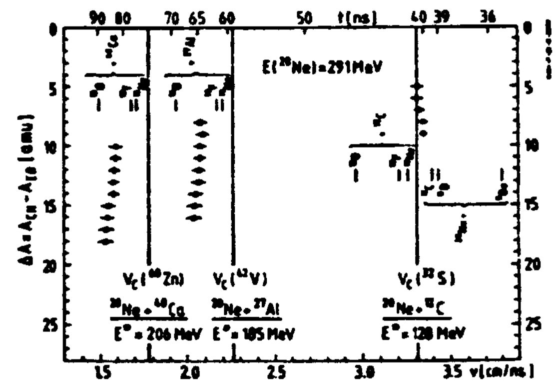

Figure 4: Plot of averaged velocities $\bar{V}_C$ extracted from fits of Eq(1) to the spectra.

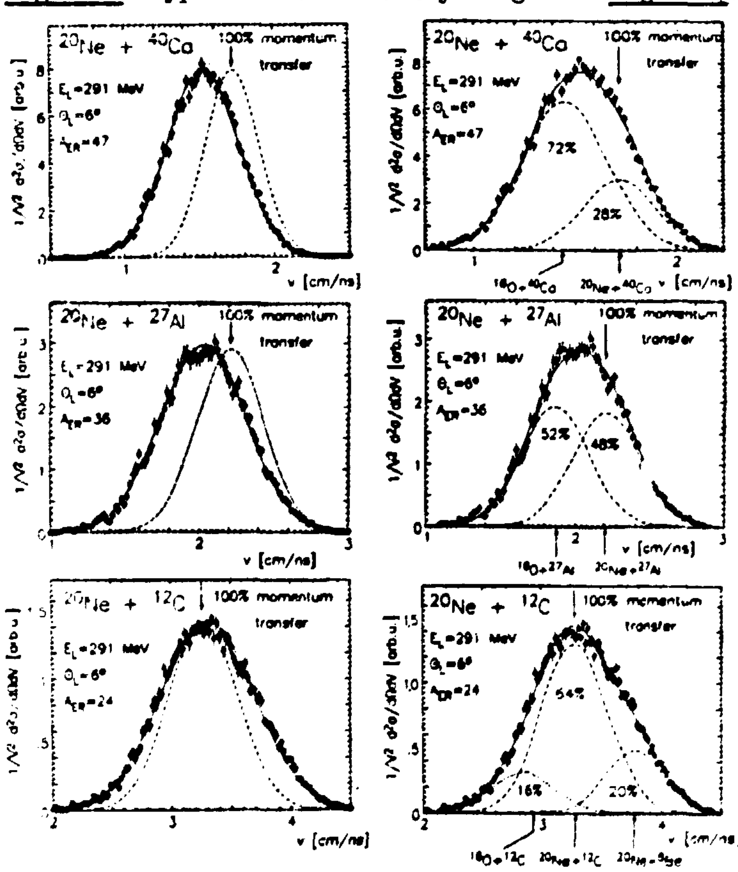

Figure 2 (left) and 3 (right): Velocity spectra divided by V^2 for some residue masses. The solid lines (left) are fits with Eq(1) and the dashed lines are the predictions of evaporation calculations. The solid lines (right) are the sum of the dashed lines. See the text for further discussion.