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Experimental Studies of Quasi-fission Reactions

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Experimental Studies of Quasi-fission Reactions

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In recent years, a number of experimental studies have shown that a substantial fraction of the total reaction cross section is found in fission-like processes, which do not result from the fission decay of a completely fused system[1]. Similar to the quasi-fission process predicted by Swiatecki[2] these reaction products have total kinetic energies typical of those found in the fission decay of compound nuclei but may be distinguished from compound fission products on the basis of their angular and mass distributions. The quasi-fission products also exhibit substantially more net mass transfer than seen in deep inelastic scattering. Thus, the quasi-fission processes can be viewed as bridging the gap between complete fusion and deep inelastic scattering in heavy systems.

A large body of experimental data on these fission-like processes have become available in recent years using a number of different target-projectile combinations. None of these experimental studies are specifically addressing the question of entrance channel effects. These effects are expected to play an important role if the dynamics in the approach phase of the reaction is responsible for the occurrence of quasi-fission. An alternate interpretation in terms of the disappearance of the fission barrier at large partial waves, which is entirely a property of the completely fused system independent of the formation process, has also been proposed. In order to address these questions we have studied the system ^{214}Th via three different entrance channels, namely ^{32}S+^{182}W, ^{48}Ti+^{166}Er and ^{60}Ni+^{154}Sm. The analysis of the ^{48}Ti+^{166}Er data is, as yet, incomplete and we shall therefore report only on the results of the ^{32}S+^{182}W and ^{60}Ni+^{154}Sm reactions in this paper.

The experiments were carried out at the ATLAS facility at Argonne using beams of 136, 177, 222, and 260 MeV ^{32}S and 339, 390, and 421 MeV ^{60}Ni. Singles reaction products were measured in an array of eight Si surface barrier detectors over the angular ranges of θ_{lab}=10°-170° and θ_{lab}=10°- 90° for the ^{32}S and ^{60}Ni beams, respectively. Fragment masses were deduced from the measured energy and flight-times after applying suitable corrections for the pulse height defect and plasma time delay associated with the detection of heavy ions in Si-detectors.

In the fission decay of a compound nucleus it is expected that the mass distributions are symmetric around half the total mass of the system irrespective of the center-of-mass angle at which it is measured. Any deviation from this symmetry therefore may be taken as a clear indication that non-compound reactions contribute to the measured mass distributions. In Fig. 1 we show the angular dependence of the mass centroids for fission-like products from the $^{32}S+^{182}W$ reaction at four different bombarding energies. At the two lowest bombarding energies, E_{lab}=166, 177 MeV, the mass distributions are clearly centered at half the total mass at A=107 at all angles, as expected for compound nucleus decay. At the two higher energies, E_{lab}=222, 260 MeV, there appears, however, to be a weak preference for heavier fragments to be emitted at forward angles (and lighter fragments at backward angles). This trend is, however, very weak and may well be of instrumental origin, i.e. inadequate corrections for the energy and time response of Si detectors to heavy ions. A deviation from the expected behavior for compound fission would, however, be consistent with the fact that partial waves for which the fission barrier has vanished ($\ell > \ell_{Bf=0}$=65 h) contribute to the fission-like cross section at these beam energies.

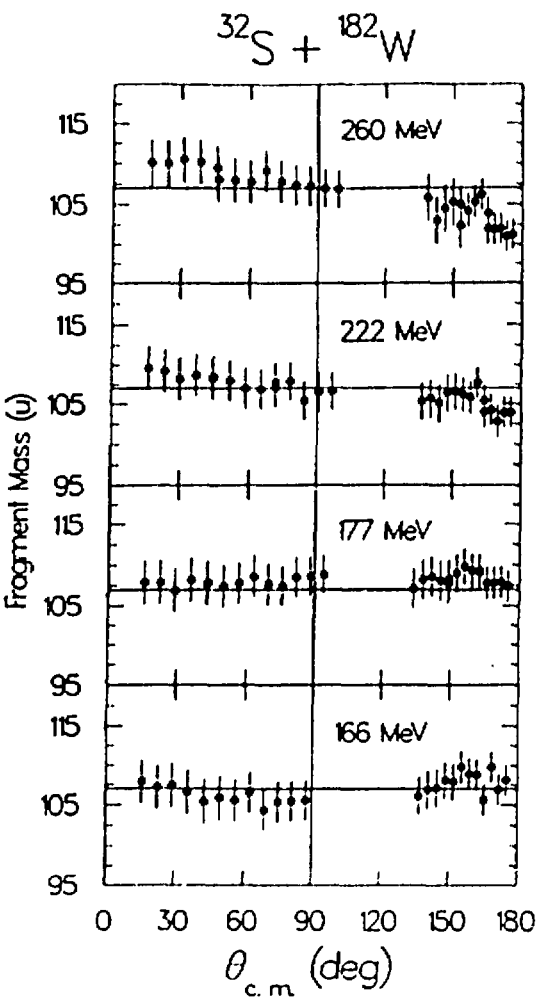

Fig. 1: Angular dependence of the centroids of the fragment mass distributions are shown for the $^{32}S+^{182}W$ reaction.

In the $^{60}Ni+^{154}Sm$ reaction we observe a strong component of non-compound fission-like reaction products. In Fig. 2 we show the angular distributions for fragments belonging to different mass bins for the beam energy of E_{lab}=339 MeV. The mass bin A=106-110 corresponding to symmetric mass splits is strictly forward-backward symmetric as required for binary exit channels. Going to lighter fragment masses we find a progressively stronger preference for emission at forward angles. This behavior is inconsistent with the binary decay of a compound system and it shows that the reaction time is shorter or

comparable to the rotational period of the interaction complex. The solid curves are calculated on the basis of the standard formalism for fission angular distributions[3]. The angular asymmetry is achieved by multiplying the standard expression with an exponential function such that the full expression is

$$W(\theta) \simeq \sum_{I=0}^{\infty} (2I+1)\ P(I)\ \exp[\beta(\theta - \tfrac{\pi}{2})] \sum_{K=-I}^{I} \frac{1}{2}\ (2I+1)\rho(K)\ |d^{I}_{0,K}(\theta)|^{2} \qquad (2)$$

where P(I) is the partial wave distribution, β is a parameter controlling the angular asymmetry, $\rho(K)$ is the K-distribution (K is the axial component of the total spin I) and $d^{I}_{0,K}(\theta)$ is the θ-dependent part of the symmetric top wave function. The partial wave distribution P(I) is taken from model calculations[3] which reproduce the excitation function for fission-like processes whereas the K_o^2 value (the variance of the gaussian K-distribution, $\rho(K)$) is obtained from a fit to the angular distribution for the A=46-50 mass bin. The solid curves for the other mass bins are obtained by adjusting the slope parameter β and the overall normalization. We observe that this single choice for the K_o^2-value gives a good representation of the data for all mass bins. This indicates that, within the experimental sensitivity, the variance of the K-distribution is not strongly dependent on the mass split in the process. These data are, however, not sufficiently accurate in the extreme forward region to rule out a weak mass dependence of the K_o^2 value as observed in the ^{50}Ti,^{56}Fe + ^{208}Pb reactions by Kratz et al.[4].

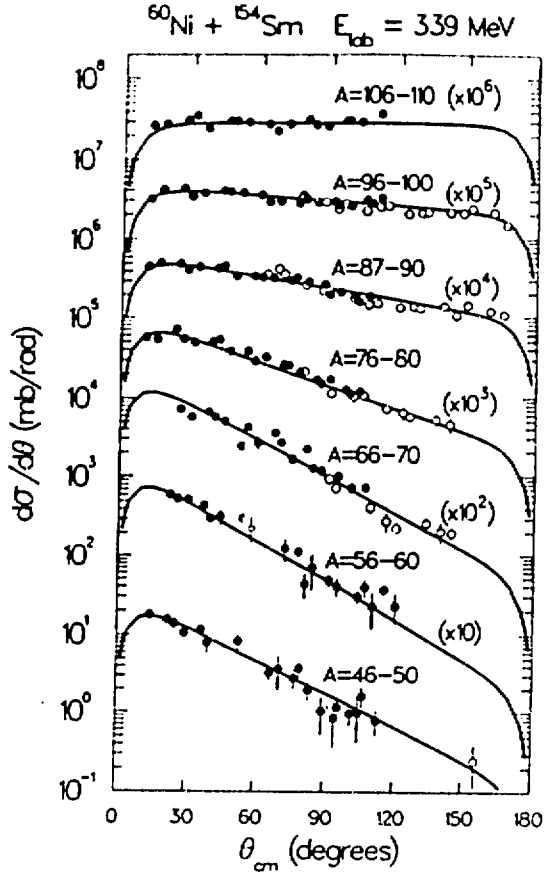

Fig. 2: Angular distributions for fragments falling into different mass bins are shown for the $^{60}Ni+^{154}Sm$ reaction at E_{lab} = 339 MeV. The solid points are data for the mass bin indicated in the figure. Open circles correspond to the complementary fragment plotted at the supplementary angle.

Another effect of the entrance channel mass asymmetry is evident in the width of the mass distributions of fission-like products as illustrated in Fig. 3. The standard deviations of the mass distributions, all normalized to the same scission point temperature of T_{scis}=2.0

MeV, are here shown as a function of the mean square angular momentum contributing to the fission-like processes. We observe that the angle-integrated mass distributions for the $^{60}Ni+^{154}Sm$ products (solid squares) are substantially wider than the ones for the $^{32}S+^{182}W$ reaction (solid circles). The mass distribution of products emitted only at $\theta_{cm} = 90^{o}$ (open squares) is also substantially wider than seen for the ^{32}S induced reaction. This increase in the width of the mass distribution for the more mass asymmetric entrance channel again leads to the conclusion that these products are the result of a reaction involving a rapid net transfer of mass from the heavy to the light reaction partner during a time period, which is shorter or comparable to the rotational period of the system.

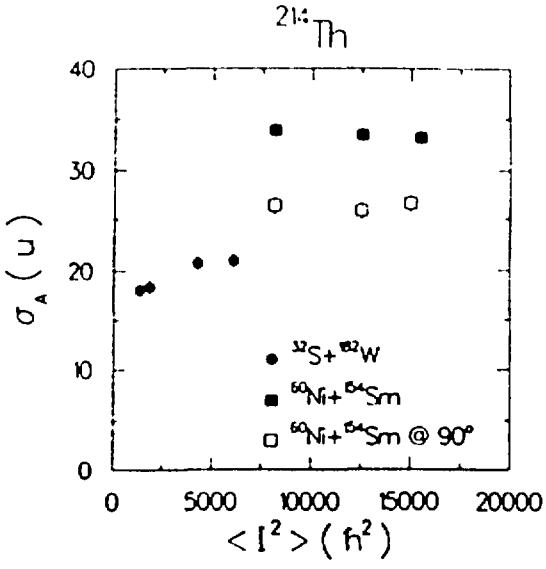

Fig. 3: The standard deviation of the mass distributions of fission-like fragments are shown as a function of the mean square spin of the system.

We find that the observed differences in angular and mass distributions for the two reactions lead to the following conclusion. Whereas the $^{32}S+^{182}W$ products essentially display the characteristics expected for the fission decay of a compound system (although small deviations are found for the two highest energies, where partial waves above the vanishing point for the fission barrier are populated), these characteristics are not found for the $^{60}Ni+^{154}Sm$ system. On the contrary, the angular distributions for asymmetric mass splits in the $^{60}Ni+^{154}Sm$ reactions show evidence of short reaction times and fast mass transfer rates, which are characteristic of quasi-fission processes.

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