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FUSION-FISSION IN THE $^{16}O+^{40,44}Ca$ AND $^{32}S+^{24}Mg$ REACTIONS

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In measurements of fully-damped yields for the $^{16}O+^{40,44}Ca$ and $^{32}S+^{24}Mg$ reactions, we find evidence for a fusion-fission reaction mechanism. The experiments were performed at the Argonne tandem-linac booster facility. Reaction products with masses 22 < A < 36 for the $^{16}O+^{40,44}Ca$ reactions and 10 < A < 28 for the $^{32}S+^{24}Mg$ reaction were detected and identified using the time-of-flight technique. The $^{16}O+^{40,44}Ca$ reactions were measured at several center-of-mass energies from 49.5 to 62.5 MeV, while the $^{32}S+^{24}Mg$ data were obtained at a single energy of E_{cm} =60 MeV. The resulting total kinetic energies (calculated assuming two-body kinematics), angular distributions, and mass distributions of the fragments are found to be consistent with a fusion-fission reaction mechanism. An alternative explanation of the yields in terms of a deep-inelastic scattering mechanism is ruled out by the asymmetric nature of the mass distributions: the maximum cross section for the $^{32}S+^{24}Mg$ reaction is detected in the mass 12 channel whereas the maximum cross sections for deep-inelastic scattering would be expected to occur near the target-projectile mass partition. For the $^{32}S+^{24}Mg$ reaction at E_{cm} = 60 MeV, the fission cross section is found to be approximately 6% of the evaporation-residue cross section. These results indicate that at higher energies fission competes with light particle evaporation in compound nuclear decay -- even in these light systems.

I. INTRODUCTION

In discussions of the limitations to fusion in light nuclear systems, a body of data which has received little attention, and yet may be significant to the question of fusion limitations, comes from studies of fully-damped yields in these systems. Examples of studies where, to varying degrees, the systematics of the fully-damped yields have been investigated include the work of Grotowski et al.[1] on the $^{6}Li+^{40}Ca$, $^{9}Be+^{40}Ca$, and $^{12}C+^{40}Ca$ reactions, the work of Ritzka et al.[2] on the $^{16}O+^{48}Ti$ reaction, and the $^{20}Ne+^{40}Ca$ reaction studies of Nguyen Van Sen et al.[3]. We have investigated the fully-damped yields in the $^{16}O+^{40}Ca$ and $^{16}O+^{44}Ca$ systems, and have recently completed a preliminary measurement on the $^{32}S+^{24}Mg$ system. In even lighter systems, many of the systematics developed by Shapira et al.[4] on the 'orbiting' phenomenon in systems such as $^{12}C+^{28}Si$, are common with what is observed in the heavier systems, and it seems possible that all of these yields result from a common reaction mechanism. Some general properties of these fully-damped yields include: 1) angular distributions which follow a $1/\sin(\theta)$ angular dependence, 2) average total kinetic energies which can be characterized by the sum of the nuclear, Coulomb, and rotational energies of two spheroids in close proximity, 3) a relatively weak dependence of the average total kinetic energies on the incident beam energy, and 4) mass distributions which favor asymmetric mass partitions. These systematics, with the possible exception of that for the mass distributions, suggest the formation of a relatively long-lived composite system. In terms of a partial-wave decomposition of the reaction cross section, the reaction mechanism responsible for these yields is almost certainly intermediate between those responsible for fusion-evaporation residue yields and quasi-elastic scattering yields and as such reflects the transition stage between compound nucleus formation and more direct reaction processes.

One key question concerning these fully-damped yields is whether they should be viewed as resulting from a deep-inelastic scattering mechanism, a picture embodied in discussions of 'orbiting',[4] or if instead they correspond to the decay of a compound nucleus. In measurements employing asymmetric entrance channels, the observation of an asymmetric trend in the mass distributions of the reaction fragments can be used to argue that a general mass drift is occurring from the target-projectile mass partition -- as would be expected in a deep-inelastic scattering process. However, it is also possible that in these light systems the asymmetric mass partitions are favored by the fission process. In fusion-fission the final mass distribution should be independent of the entrance channel (except for details of the compound nucleus spin distribution) which suggests that a possible way to distinguish between these two mechanisms might be to compare the final mass distributions from two entrance channels reaching the same compound nucleus, one symmetric or nearly symmetric and the other asymmetric.

We have studied the $^{16}O+^{40}Ca$ and $^{32}S+^{24}Mg$ systems, both of which reach the same ^{56}Ni compound system, and also $^{16}O+^{44}Ca$ system. In this contribution we will first discuss the details of our measurements and then develop some of the systematics observed for the fully-damped yields of these systems, indicating how these can be understood in terms of a fusion-fission mechanism.

II. EXPERIMENTAL ARRANGEMENT

The $^{16}O+^{40,44}Ca$ and $^{32}S+^{24}Mg$ reactions were studied using beams from the Argonne superconducting tandem-linac facility. The ^{16}O+Ca measurements were done at a number of incident beam energies from 69.3 to 87.3 MeV; the $^{32}S+^{24}Mg$ measurement was done using a 140 MeV, ^{32}S beam. For the ^{16}O

measurements, Si(surface-barrier) detectors were located at laboratory angles of 30°, 40°, 50°, and 60°, whereas the ^{32}S measurement was done with detectors located at 10°, 15°, 25°, 35°, 45°, 55° and 65°. The time structure of the beams from the superconducting linac was used for mass identification, with approximately 2 mass unit resolution obtained for the ^{16}O runs, and about 1.2 mass unit resolution for the ^{32}S run.

The targets used in these experiments consisted of isotopically-enriched, self-supporting ^{40}Ca(180 μg/cm^2; 99.9% enrichment), ^{44}Ca(150 μg/cm^2; >85% enrichment), and ^{24}Mg(100 μg/cm^2; 99.9% enrichment). For the ^{16}O runs, reaction products from the carbon and oxygen target contaminants were clearly resolvable from the fully-damped products of interest. The buildup of these contaminants was monitored for the $^{32}S+^{24}Mg$ experiment, and is believed to be responsible for less than 5% of the observed yields in this system (no corrections have been applied to the cross sections quoted here).

III. RESULTS AND DISCUSSION

In this section we will try to illustrate the behaviors which seem to characterize the fully-damped yields in light systems with examples from our data. These results will be discussed in the context of the two competing pictures of fusion-fission and deep-inelastic scattering. It should be noted that part of the difficulty in distinguishing between these pictures is that, at some point, they merge into one another: there must be a smooth transition between the formation of an equilibrated compound nucleus and the formation of a composite system where most, but not quite all, of the degrees-of-freedom have equilibrated. It then becomes a question as to how well 'standard' models describe the bulk of the experimental data, and to what extent new models need to be developed to describe the data.

Center-of-mass angular distributions of dσ/dθ are shown in Fig. 1 for different mass partitions resulting from the $^{32}S+^{24}Mg$ reaction at E(cm)=60MeV. In deriving these center-of-mass cross sections, two-body kinematics has been assumed with the lighter fragment mass indicated in the figure. It is evident that cross sections of constant dσ/dθ are observed (corresponding to angular distributions of dσ/dΩ with 1/sin(θ) angular dependences): this suggests the formation of a long-lived, rotating complex which has equal probability of decaying in all directions perpendicular to the spin vector. The only deviation from this trend occurs for the most symmetric mass partitions, where at forward angles a clear separation of the fully-damped yields from the more quasi-elastic events was not achieved. Such constant angular distributions would be expected from the fission decay of

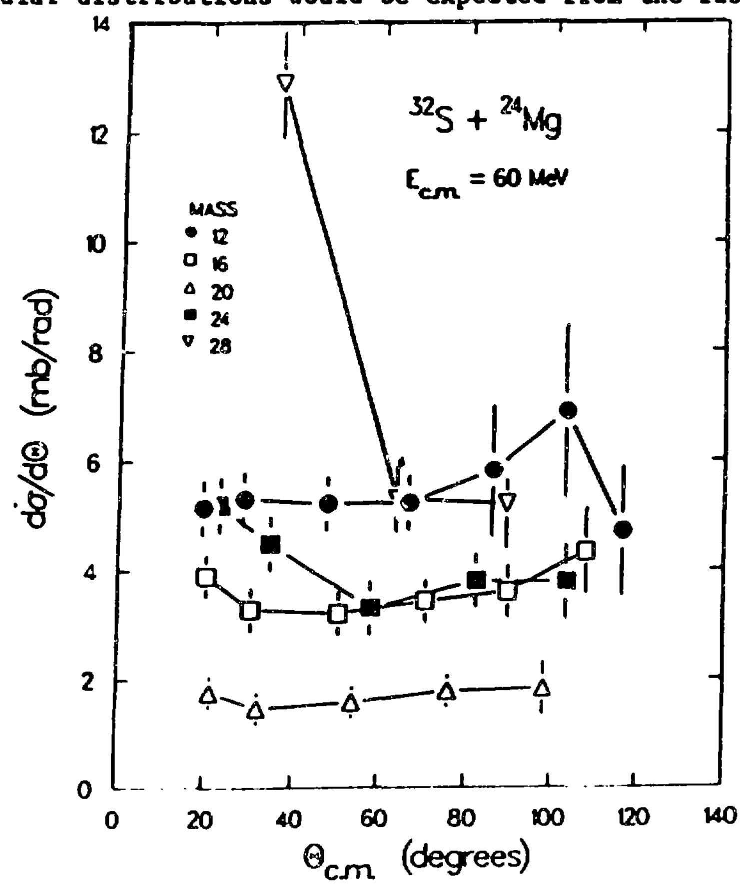

Fig. 1. $d\sigma/d\theta_{cm}$ for the $^{32}S+^{24}Mg$ reaction at E_{cm} = 60 MeV. The mass of the detected reaction fragment is indicated.

high-spin states in the compound ^{56}Ni nucleus. For light systems all fission decay is likely to originate from high spin states since it is only for these states that the barrier for fission is sufficiently small to enable it to compete favorably with particle-evaporation as a deexcitation mechanism of the compound system.

We have also calculated the scattering angle predicted for the deep-inelastic scattering process as a function of impact parameter using the computer code developed by Feldmeier[5]. This calculation follows the evolution of the shapes of the interacting nuclei as they come together, form a connecting neck, and then either reseparate or fuse into a compound system. Using this model of the deep-inelastic scattering process, forward-peaked angular distributions are predicted, with relatively narrow mass distributions concentrated near the target-projectile mass partition. Our data would require an additional 'orbiting' component not present in the model. It should be noted ,however, that the applicability of deep-inelastic scattering models developed for much heavier systems in these lighter systems has not been established.

Another indication that long-lived intermediate systems are formed is the full relaxation of the energy as evidenced by the angle independence of the observed total kinetic energy (TKE) values. In Fig. 2 the average TKE values are shown for different final mass partitions of the $^{32}S+^{24}Mg$ reaction as functions of the average center-of-mass scattering angles. With the exception of the symmetric mass partition, the TKE values are constant within the experimental uncertainties. This result is a necessary condition for a fusion-fission process and might also be expected for a long-lived, orbiting component of deep-inelastic scattering.

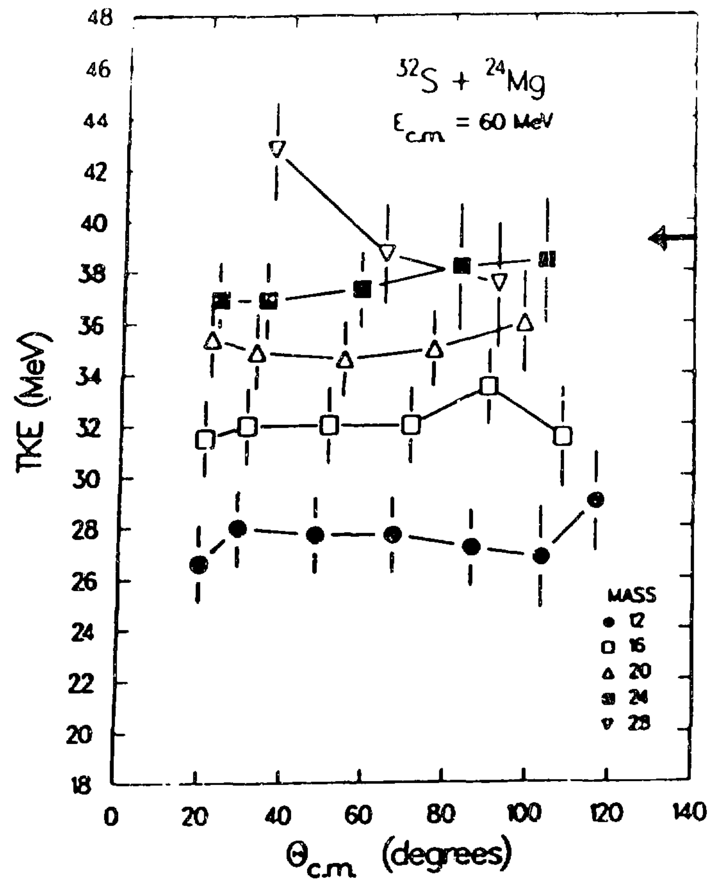

Fig. 2. Angular dependence of the total kinetic energies observed in different mass partitions for the $^{32}S+^{24}Mg$ reaction at E_{cm} = 60 MeV.

In Fig. 3, the most-probable TKE values for the symmetric mass partitions are shown for the $^{16}O+^{40,44}Ca$ reactions as functions of the incident beam energy. The TKE values predicted for the fusion-fission process can be estimated by approximating the liquid-drop saddle-point configuration by two spheroids (see Fig. 3 insert) and then calculating the relative interaction energy. These calculations of the saddle-point shapes and the relative interaction energies were done including diffuse surface and finite-range effects using the formalism developed by Krappe, Nix, and Sierk[6]. For these light systems the saddle- and scission-point configurations are thought to be similar, and in our calculations the relative, attractive nuclear interaction between the two spheroids was found to be less than 2 MeV. The

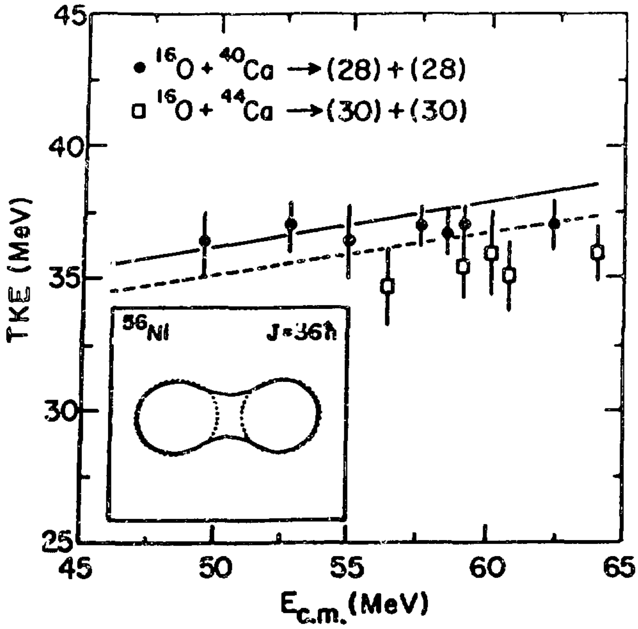

Fig. 3. The total kinetic energies observed in the symmetric-mass breakup channel of the $^{16}O+^{40}Ca$ reaction (solid circles) and the $^{16}O+^{44}Ca$ reaction (open circles). The sketch indicates the geometry of the two-spheroid approximation (dashed curves) and the corresponding liquid drop model saddle-point shape (solid curve) as indicated in the text.

relative rotational energy can be substantial compared to the relative Coulomb energy and must be included in the calculations. We have assumed an average angular momentum for fission corresponding to the critical angular momentum for fusion in the sharp-cutoff approximation: this approximation is supported by Cascade calculations[7] which model the competition between fission-decay and light-particle evaporation. The solid and dashed curves in Fig. 3 show the results of our calculations for the $^{16}O+^{40}Ca$ and $^{16}O+^{44}Ca$ systems, and the arrow in Fig. 2 notes the TKE value calculated for the symmetric partition in the $^{32}S+^{24}Mg$ reaction. Good agreement is achieved with the measured TKE values. Since the saddle-point configurations look very much like two fragments in close proximity, very similar results would be expected from an 'orbiting' picture of the interaction.

Perhaps our strongest evidence in favor of a fusion-fission picture as

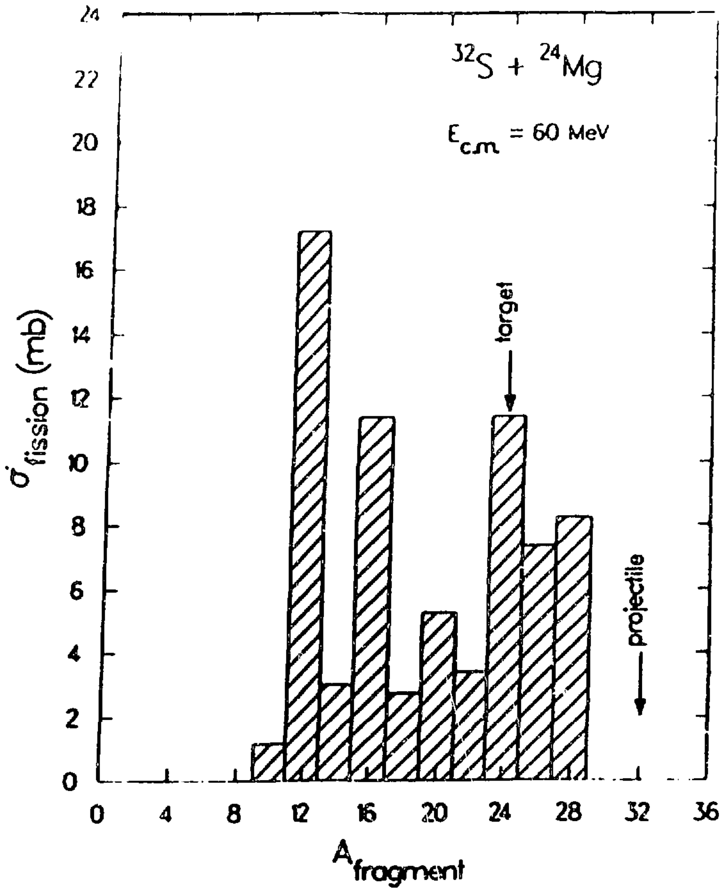

Fig. 4. Angle-integrated cross sections for the fission-like yield in the $^{32}S+^{24}Mg$ reaction.

opposed to a deep-inelastic scattering model is shown in Fig. 4 where we plot the angle-integrated cross-sections for the different mass partitions of the $^{32}S+^{24}Mg$ reaction. There is clear evidence of the cross section increasing in going away from the target-projectile mass partition. Such behavior might be expected from the asymmetric fission of the ^{56}Ni compound system, but would be very surprising in terms of a deep-inelastic scattering picture where one would expect the cross-section to reflect some memory of the entrance channel. The enhancement of the cross sections for every fourth mass unit may indicate shell effects felt by the fissioning system at the scission point -- an increase in pre-scission binding energies of the fragments of only a few MeV, resulting in greater phase space being available in certain partitions, can easily account for the observed effect. Very similar behavior was also observed in the $^{16}O+^{40}Ca$ system, but not in the $^{16}O+^{44}Ca$ system where decay of the compound nucleus into two favored 'alpha-particle'-like nuclei is not possible.

Summing the partial cross sections in Fig. 4 we obtain a total fission cross section of 72 mb for the $^{32}S+^{24}Mg$ system at E_{cm}=60MeV. This is to be compared with an evaporation-residue cross section of about 1050 mb as measured by Kovar et al.[8] -- approximately 6% of the total fusion cross section at this energy is found in the fission channel; at higher energies an even greater portion of the fusion cross section would be expected to lead to fission. This fission component, which has been largely ignored in discussions of the fusion of light, heavy-ion systems, results in larger partial waves contributing to fusion than would be indicated by evaporation-residual measurements alone.

IV. CONCLUSIONS

We have studied fully-damped yields from the reactions $^{16}O+^{40,44}Ca$ and $^{32}S+^{24}Mg$, and have shown that these yields are consistent with a fusion-fission reaction mechanism. The observation of an asymmetric mass distribution of these yields in the $^{32}S+^{24}Mg$ reaction is at odds with the alternative deep-inelastic scattering picture; for deep-inelastic scattering some memory of the entrance channel would be expected to be retained. Fission decay is found to account for about 6% of the total fusion cross section in the $^{32}S+^{24}Mg$ system at E_{cm}=60 Mev. This suggests that the fission process should not be ignored in obtaining higher energy fusion cross sections, even for relatively light systems.

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