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ABSTRACT

Evidence that the fully energy-damped binary products observed in the $^{18}O+^{10,11}B$ reactions originate from a fusion-fission process, rather than through a deep-inelastic orbiting mechanism, is presented. The relative importance of the fusion-fission process in these very light systems is supported by experimental results that indicate a statistically equilibrated fission process and also by model calculations. This conclusion is contrary to that reached in a recent publication discussing the same data.

Nuclear Reactions: $^{10,11}B$ (^{18}O,X), $E_{LAB} \simeq 55$ MeV, measured $\sigma(\theta)$ and $\sigma(Z)$, for fusion and strongly damped binary processes.

Recent measurements have demonstrated the presence of strongly energy- damped binary processes in heavy-ion reactions reaching very light compound nuclei of mass $A_{CN} < 30$[1-3]. As in the case of similar yields observed in somewhat heavier systems with A_{CN}=40, a controversy has developed concerning the reaction dynamics leading to the emission of these complex fragments[4-6]. Two competing processes, deep-inelastic orbiting and compound nucleus fusion followed by fission, have been suggested as possible mechanisms. Both processes are expected to produce fully energy damped binary residues with $1/\sin\theta_{CM}$ angular distributions characteristic of long-lived rotating nuclear systems. In a recent publication[7], Lépine-Szily et al. have argued that the large-angle binary yields observed in the $^{18}O+^{10,11}B$ systems at Ec.m. = 18.8 and 19.9 MeV, respectively, arise from a deep-inelastic orbiting mechanism. In this paper we show that the same experimental features used in ref. 7 to support an orbiting mechanism actually favor a compound nucleus explanation for the observed yields.

The main experimental observable that can be used to distinguish between a direct-reaction orbiting mechanism and a compound nucleus fusion-fission process is the presence or absence of an entrance channel dependence for the energy-damped yields. The orbiting mechanism, where the colliding nuclei form a di-nucleus complex without reaching the more compact configuration of an equilibrated compound nucleus, is expected to be strongly dependent on the specific nature of the entrance channel. The fusion-fission process, alternatively, assumes the formation of a compound nucleus where the only memory of the entrance channel is through the conserved quantities, such as total charge, energy, and angular momentum. In heavier systems with $40 \leq ACN \leq 60$ both of these processes have been identified. In these heavier systems fusion-fission cross sections have been observed in all systems explored at the level predicted by the fission transition-state model. Clear evidence has been found for a second, orbiting mechanism, however, only in systems having a small number of open channels[8-10], and principally systems reaching the ^{40}Ca compound system.

The experimental features that characterize the energy-damped yields in the $^{18}O+^{10,11}B$ systems have been discussed elsewhere. To summarize the relevant features:

a.) The lithium, beryllium, boron, and carbon angular distributions, shown in Fig. 1 for the $^{18}O+^{10}B$ reaction at $E_{lab}(^{16}O) = 55$ MeV, all show a $1/\sin q\theta_{CM}$ angular dependence, as expected for the decay of a spinning, long-lived intermediate configuration. This behavior is expected for either an orbiting or a fusion-fission origin.

b.) The nitrogen and fluorine angular distributions, also shown in Fig. 1, are strongly forward peaked and suggest a more peripheral reaction mechanism. In extracting the nitrogen cross sections corresponding to a binary breakup process for the $^{18}O+^{10}B$ reaction it was necessary to correct for an evaporation-residue component to these yields. This was accomplished[2,11,12] using a model calculation of the evaporation-residue energy distribution in the nitrogen channel to estimate the fraction of total nitrogen yield resulting from this process. This unfolding procedure is illustrated in Fig. 2. The cross sections shown in Fig. 1 are only for the binary reaction component. A similar correction was not found necessary for the $^{18}O+^{11}B$ reaction, as seen in Fig. 2.

The nitrogen angular distribution requires somewhat further discussion as the reverse kinematics encountered in this reaction has clearly led to some confusion on the part of the authors of ref. 7. In that reference it is claimed that the forward rise in the nitrogen distribution can only be explained in terms of non-binary processes, such as the evaporation residue component discussed above. This argument is based on the correct idea that the nitrogen and carbon angular distributions must be identical for the binary breakup of the aluminum compound system. What these authors have failed to recognize is that the observed nitrogen and carbon yields do not correspond to the same center of mass angles. The kinematics and center-of-mass angle definition used in this paper are illustrated in Fig. 3 for the $^{18}O+^{10}B$ reaction leading to ^{15}N and ^{13}C fragments. The observed nitrogen yields, which show a forward angle enhancement, correspond to the "small-angle scattering" case. It is seen that the corresponding ^{13}C fragments are also scattered to a small center of mass angle, leading to very small laboratory energies for these particles, as indicated in the corresponding velocity schematic[1-3,11]. The observed carbon particles correspond to the "large-angle scattering" case shown in this figure. Contrary to the claim of ref. 7 there

is no difficulty in reconciling the carbon and nitrogen angular distributions. The large center-of-mass angle yields in this channel, corresponding to the carbon measurements, indicate a process involving a long time scale. The small center-of-mass angle yields, corresponding to the nitrogen measurement, are dominated by a much faster process. Similar behavior is also observed in the oxygen+boron channel where the elastic and inelastic scattering processes dominate the forward center-of-mass angle yields.

As the nitrogen and oxygen angular distributions are dominated by more peripheral reaction mechanism, it is interesting to extract an effective time scale for these processes using the Regge-pole[2,14] model to determine the "life-angle" of the rotating dinuclear complex. (A smaller "life-angle" corresponds to a faster process). The angles deduced from this analysis are indicated in Fig. 1 and 4 for three different reactions reaching the ^{28}Al compound nucleus. As expected, the results indicate longer lifetimes as the charge and mass exchange increases.

Fully energy-damped heavy-ion reactions result in angular distributions that are isotropic in the reaction plane and, for a binary x-y exit channel, have anisotropies $A(x\text{-}y) = d\sigma(0°)/d\sigma(180°) \simeq 1$. According to the Regge-pole model, the emission probability for the decay of short-lived complexes and direct reaction components lead to anisotropies which can be associated with the lifetime of the process. Theoretical predictions that consider the direct reaction mechanism, as is the case with explicit coupled channel calculations or algebraic scattering model calculations[7], should be able to reproduce the observed anisotropies. In fact, calculations presented in ref. 7 for the direct components, predicting anisotropies $A(O+B) \simeq 50$ and $A(N+C) \simeq 15$ are in agreement with the experimental findings and support the argument that direct processes dominate the forward angle oxygen and nitrogen angular distributions.

c.) The most convincing argument for a compound nucleus origin for the observed energy-damped yields results from studying their entrance-channel dependence. The angular distributions for the binary reaction products from the $^{18}O+^{10}B$, $^{19}F+^{9}Be$, and $^{17}O+^{11}B$ reactions, all reaching the ^{28}Al compound nucleus, are shown in Figures 1 and 4. The reactions were studied at energies leading to similar compound nucleus excitation energies of 48 MeV, 46 MeV, and 47 MeV, respectively. Because of the

similar entrance channel mass asymmetries it is expected that these reactions also lead to similar compound nucleus spin distributions. In Fig. 5 the ratio of the carbon to boron cross sections $R = \sigma_C/\sigma_B$ are shown for the three systems as a function of excitation energy. This ratio should have little dependence on the entrance channel if the underlying process is one of compound nucleus formation and decay, but should show a strong dependence, particularly in comparing the $^{19}F+^{9}Be$ to the $^{18}O+^{10}B$ and $^{17}O+^{11}B$ reactions, if an deep-inelastic orbiting mechanism is involved. The data show very little entrance channel dependence and thus support the compound nucleus mechanism.

We find, then, that the experimental evidence points to a compound nucleus fusion-fission process as the origin of the large angle yields observed in these very light systems. The absence of an orbiting process in these systems is consistent with the the general observation that systems that do show evidence of an orbiting mechanism also tend to demonstrate molecular resonance behavior in excitations functions of their large angle elastic and inelastic yields. The systematics of anamolous large angle scattering, such as molecular-resonance behavior, suggest that these processes are related to the number of open channels in the decay process[10,16]. According to these systematics reactions between α-particle nuclei, which tend to have the highest binding energies and corresponding lower level densities in the fragments, are expected to the prime candidates for molecular resonance and, hence, orbiting reactions. For example, the number of open channels per unit of flux of the grazing partial wave for two systems that show molecular resonance behavior are $\simeq 10^{-1}$ for the $^{12}C+^{12}C$ system and $\simeq 1$ for the $^{12}C+^{16}O$ system. This should be compared to a value of $\simeq 10^{3}$ for the $^{18}O+^{10}B$ reactions. Although this "number of channels" argument is model dependent, and is therefore not as strongly based as the direct experimental evidence, it does further support a fusion-fission origin for the yields in the $^{18}O+^{10,11}B$ systems.

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FIGURE CAPTIONS

Figure 1 Q-value integrated angular distributions for target-like (Z=6,5,4) and projectile-like (Z=7) components from the $^{10}B+^{18}O$ reaction. The dashed lines correspond to fits to the prediction for the decay of a dinuclear complex with "life-angle" α (for details see the text).

Figure 2 Unfolding of the $^{10}B(^{18}O,N)$ Q-value converted spectrum (left), assuming the ^{15}N-^{13}C binary exit channel. The full line corresponds to the raw data; the dotted spectrum corresponds to the evaporation residues contribution (calculate using the statistical model code LILITA[13]); the hatched spectrum corresponds to the resultant subtracted spectrum associated to the non-fusion Nitrogen component. The $^{11}B(^{18}O,N)$ Q-value spectrum (right) obtained from the raw data. No evaporation residues contribution is predicted or observed in this channel.

Figure 3 Schematic description of the scattering in the center of mass frame (upper) and velocity diagram defining the scattering angle for projectile-like (^{15}N) and target-like (^{13}C) products for the $^{18}O+^{10}B$ reaction.

Figure 4 Same as figure 1 for the $^{19}F+^{9}Be$ and $^{17}O+^{11}B$ reactions.

Figure 5 Ratio of Carbon to Boron cross-sections versus excitation energy of the residual nuclei for the different entrance channels forming the ^{28}Al compound nucleus. Fluctuations at very low excitation energies are due to contribution of discrete states populated via direct processes.

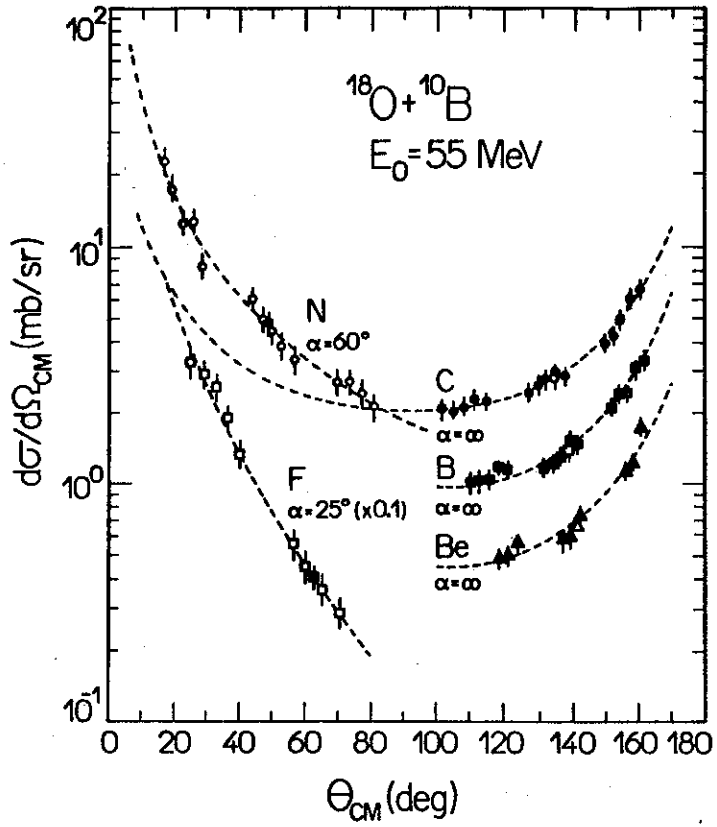

Figure 1

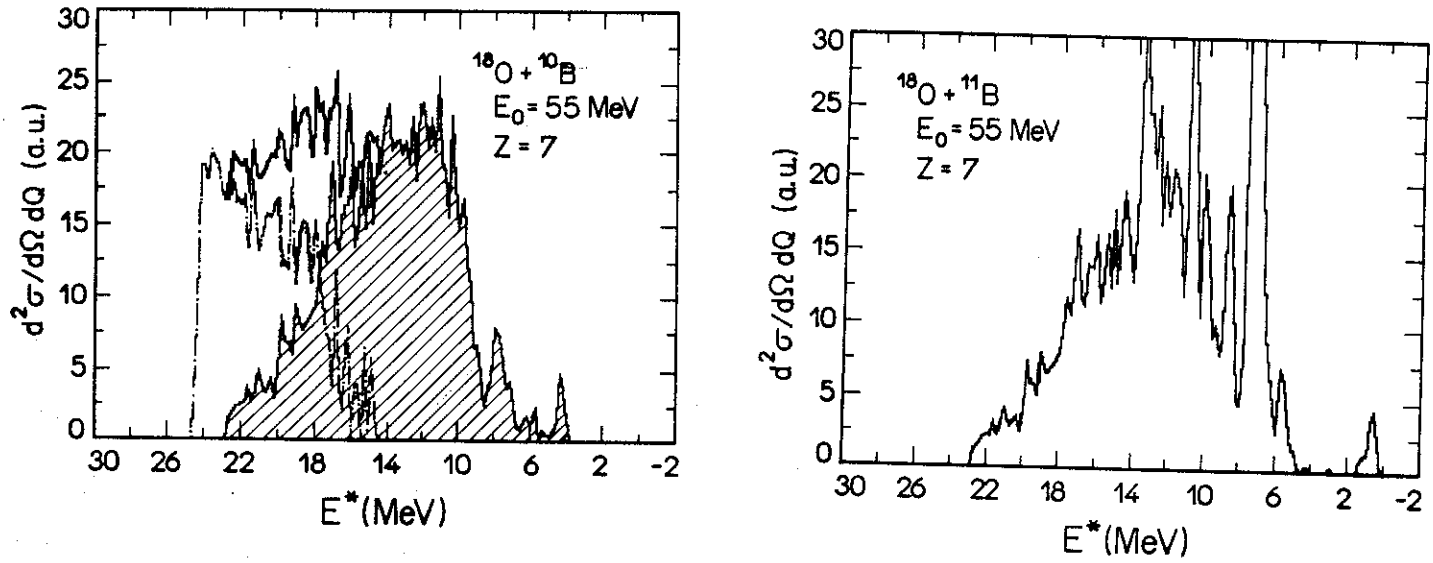

Figure 2

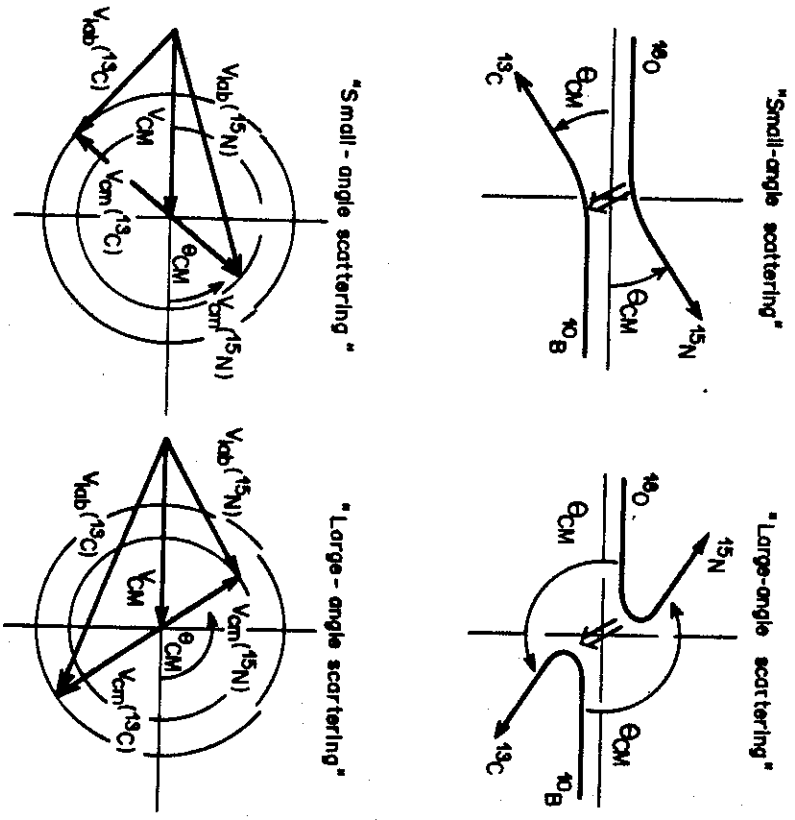

Figure 3

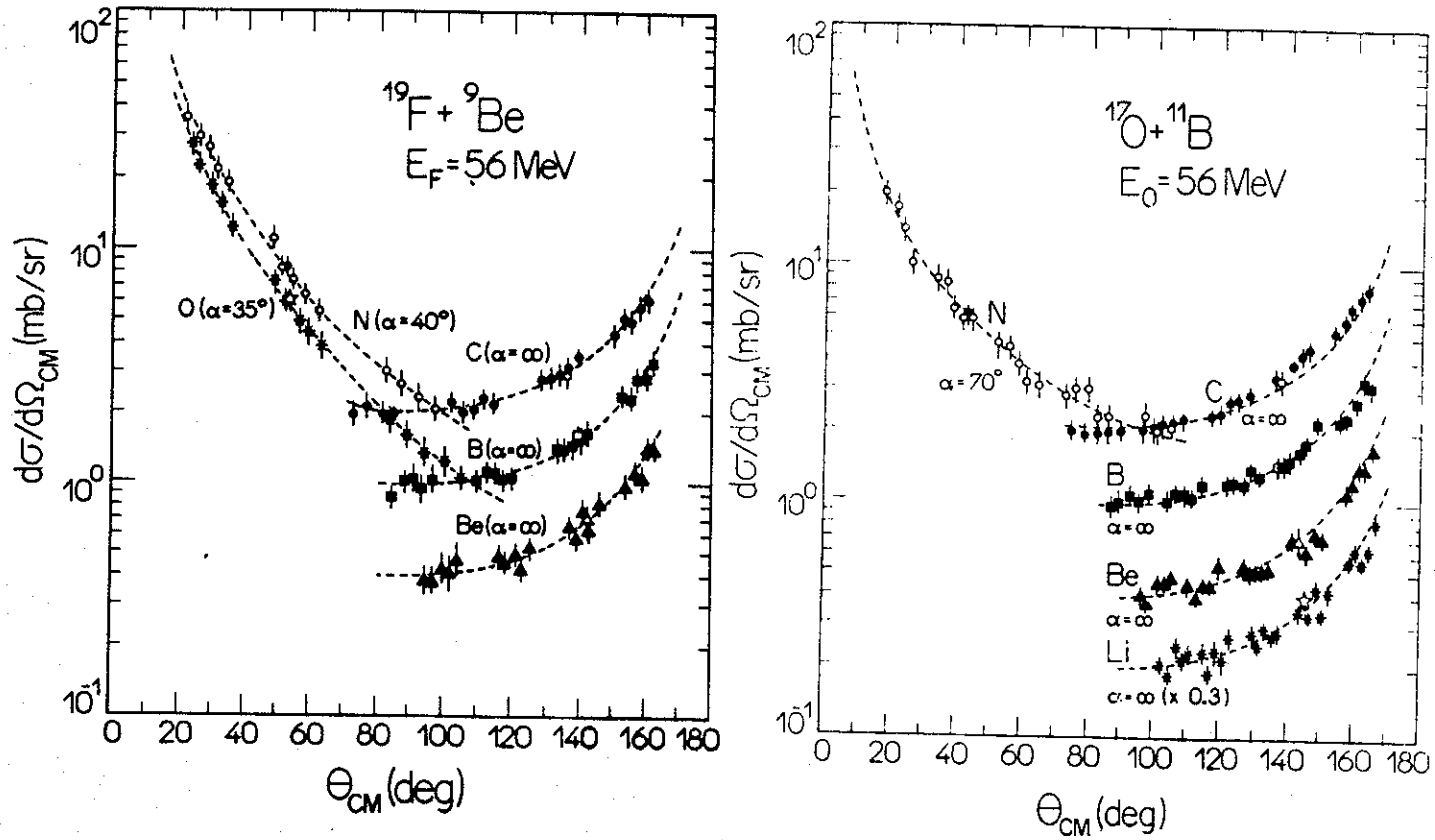

Figure 4

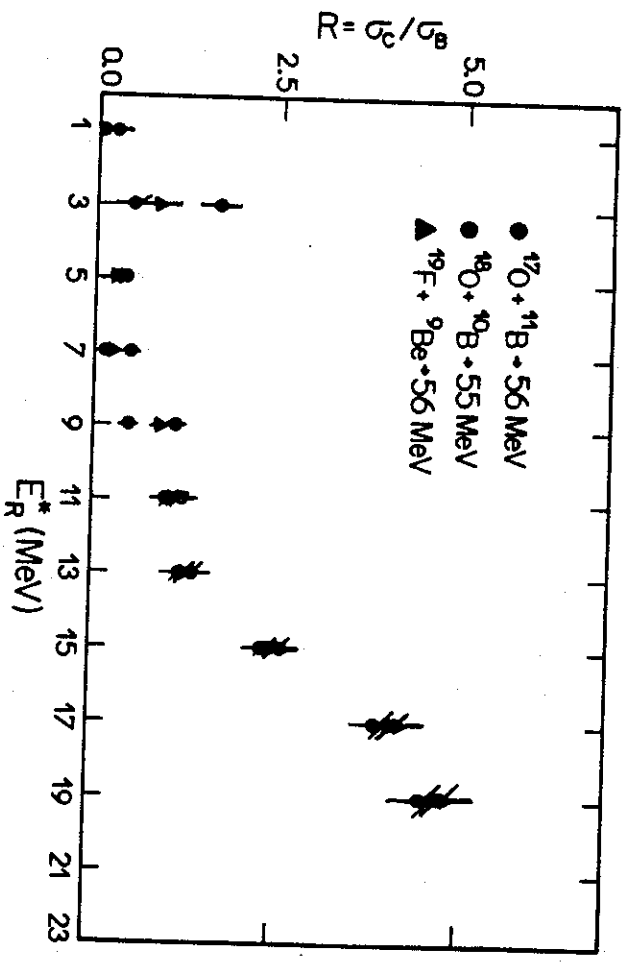

Figure 5