Correlations between α particles and evaporation residues for the $^{14}N+^{12}C$ reaction at $E(^{14}N)=180$ MeV

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(Received 18 September 1986)

Angular correlations between α particles and evaporation residues have been measured to study the equilibrium versus nonequilibrium effects on the fusion process. Measurements with α-particle detectors were carried out to extreme forward angles (4°) to maximize the sensitivity to nonequilibrium components. The results are consistent with complete fusion and equilibrium decay, in contrast with recent systematics that predict large amounts of incomplete fusion at this energy.

I. INTRODUCTION

Recent work on heavy-ion fusionlike reactions[1,2] has indicated that for energies close to or above 8 MeV/nucleon sizable effects of incomplete momentum transfer occur which make the extraction of fusion cross sections difficult at these energies. On the other hand, the study of fusion in this energy domain is extremely important in order to study saturation effects on the angular momentum,[3] relations between the fusion cross section and the nucleus-nucleus potential,[4,5] and the stability of the compound nucleus at high energies.[6] One usual approach to determining the amounts of incomplete momentum transfer consists in the measurement of the centroids of the invariant velocity spectra[1,2,8] of evaporation residuelike fragments. For asymmetric systems this technique has been employed to detect small deviations (5%) from full momentum transfer. Nevertheless, there are many cases reported in the literature for which such variations are not seen up to 17 MeV/nucleon,[7–10] involving primarily collisions between p-f shell nuclei. One possible explanation for the lack of change of the centroids of the velocity distributions is that due to the very similar nuclei (p-f shell), and similar light particle thresholds, the same amounts of prefusion particles are lost from target and projectile, keeping the average momentum transfer the same and equal to the full momentum transfer value. For these cases the only information left concerning incomplete momentum transfer is on the width of the velocity distributions, which should deviate significantly from statistical model calculations. For the $^{14}N+^{12}C$ reaction at $E(^{14}N)=248$ MeV,[7] about 10% incomplete fusion contribution has been suggested by analyzing the width of the energy spectra; however, for this and other reactions[7–10] the energy spectra agree very well with statistical model calculations for bombarding energies below 17 MeV/nucleon.

The present experiment has been designed to provide a more stringent test of incomplete fusion for energies below 17 MeV/nucleon, and consists of a detailed measurement of the in-plane correlation of α particles emitted in coincidence with evaporation residuelike fragments. Previous measurements of α particle correlations with heavy fragments were carried out at lower bombarding energies and restricted to angles larger than 12° for the $^{10}B+^{12}C$ (Ref. 11) and $^{14}N+^{12}C$ (Ref. 12) systems. The authors show theoretical as well as experimental (in coincidence with low Z ions $Z<5$) correlations that peak at the beam direction (zero degrees) and thus could be taken as an indication of preequilibrium emission, since these α-particle correlations follow a simple scaling of the singles cross sections.[11,12] However, the experimental correlations in coincidence with the heavier evaporation residues show a maximum away from zero degrees, and to determine whether or not this feature is consistent with complete fusion and equilibrium decay, data taken at more forward angles are necessary.

II. EXPERIMENTAL PROCEDURE AND RESULTS

In the present study we used a 180 MeV beam extracted from the ORIC cyclotron to bombard a 100 $\mu g/cm^2$ carbon target. The angular correlation was measured down to $\pm 4°$. A total of seven ΔE-E solid state detectors were placed on the reaction plane, with two of them having thin (10 μm) ΔE detectors that were used to detect the evaporation residues of nuclear charge $Z=5$–9. The two evaporation residue detectors were fixed at $\pm 9°$ and the rest of the telescopes were rotated to cover a total of 20 angles from -60 to 22 deg. The pulse height of all the detectors were recorded via multichannel analog to digital converters (ADC's) and time pulses were recorded using multichannel time to digital converters (TDC's) with the rf pulse of the cyclotron used as reference time. The data were recorded event by event on tape for off-line analysis. The tapes were scanned with the proper E-ΔE and time gates ($\Delta t \approx 100$ ns) in order to construct the α-particle heavy residue coincidences.

Results for the angular correlation between the α particles and the residues of N, O, and F are shown in Fig. 1. The correlation for $Z=8$ and 9 includes all the events without a gate placed on the kinetic energy of the evaporation residue, whereas for $Z=7$ a two-dimensional gate on the ΔE vs E map was necessary to exclude the clearly quasielastic events present on the high energy part of the nitrogen spectra. The vertical scale in Fig. 1 gives the α-particle differential multiplicity $(dM_\alpha/d\Omega_\alpha)$ defined by

$$\frac{dM_\alpha}{d\Omega_\alpha}=\frac{\int\int(d^4\sigma/d\Omega_\alpha d\Omega_Z dE_\alpha dE_Z)dE_\alpha dE_Z}{(d\sigma/d\Omega_Z)_{\theta_Z}},$$

where $(d\sigma/d\Omega_Z)_{\theta_Z}$ is the singles evaporation residue cross section measured at the laboratory angle θ_Z (9 deg in this experiment).

A simple inspection of the data in Fig. 1 reveals that the angular correlation does not peak at zero degrees, which in itself can be taken as an indication that no sizable prefusion emission of α particles from the ^{14}N projectile occurs. This is also consistent with the fact that for this and lower bombarding energies[7] the centroids of the velocity distributions are centered around the full momentum transfer value.

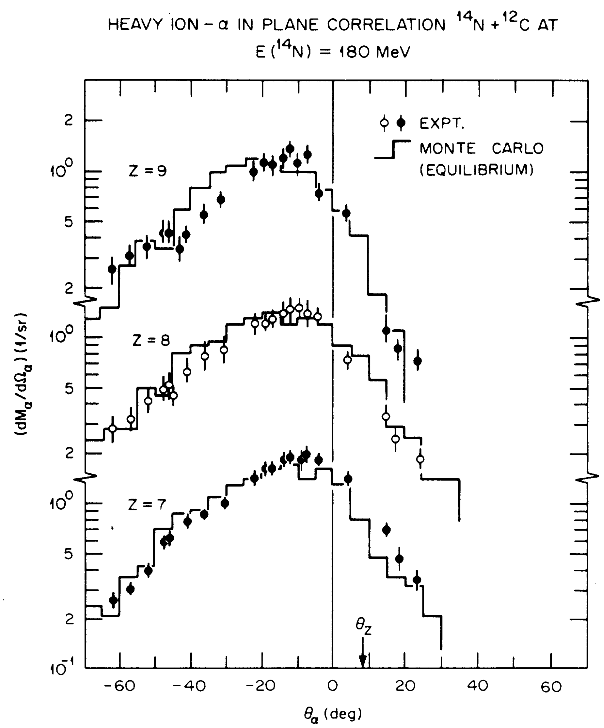

FIG. 1. In-plane angular correlation between α particles and evaporation residues of F, O, and N ions. The evaporation residues were detected at a laboratory angle $\theta=9°$. The histograms are the results of the complete fusion and equilibrium decay calculations performed with the code LILITA.

III. DISCUSSION

The modeling of the complete fusion and equilibrium decay process has been made with the code LILITA,[13] which uses the Monte Carlo method in conjunction with probability distributions derived from the Hauser-Feshbach formula. The present calculations for the $^{14}N+^{12}C$ complete fusion reaction were done using the same set of statistical model parameters used for similar calculations.[7–10] The α-particle heavy residue correlations have been calculated in an event-by-event fashion in which the evaporation residue mass, charge, angles, kinetic energy, and the kinematical quantities of their associated light particles are written on a large file for further processing. After about 20 000 compound nucleus trials the file was scanned to construct the α-particle residue correlations. The solid histograms drawn in Fig. 1 are the results of the calculations for the angular correlation of evaporation residues of fluorine, oxygen, and nitrogen in coincidence with α particles, resulting from a complete fusion and equilibrium decay mechanism. As can be seen from the figure, they account very well for both the shape and magnitude of the angular correlation. For these calculations the total excitation energy reached in ^{26}Al is 98 MeV, corresponding to a temperature of 5 MeV, and the total angular momentum reached is $26\hbar$, equal to the saturation value for ^{26}Al.[3]

A similar conclusion can be drawn by studying the energy correlations between the α particles and the heavy residues. In Fig. 2 we show the energy spectra of α particles (left side) and oxygen ions (right side) measured in coincidence, for the α-particle laboratory angles of $-4°$ and $-15°$. The histograms are the results of the statistical model calculations which again, due to the agreement with the experiment, indicate that the dominant reaction mechanism for the production of these $Z=8$ fragments is

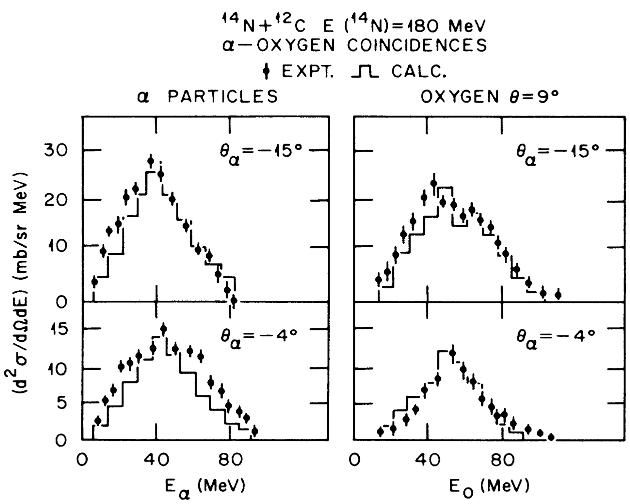

FIG. 2. Coincidence energy spectra between the α particles (left side) and oxygen ions (right side). The α particles were detected at the laboratory angles of $-4°$ and $-15°$ and the oxygen ions at 9°. The histograms are the LILITA calculations for the complete fusion and equilibrium decay process.

that of complete fusion and equilibrium decay.

Following a recent study of systematics[1] of fusion versus incomplete fusion for slightly heavier systems ($A=40$), we have determined that a total of 30% incomplete fusion should be expected for the $^{14}N+^{12}C$ reaction at $E(^{14}N)=180$ MeV. To simulate the incomplete fusion angular correlations, assumptions have to be made concerning the loss of α particles prior to fusion. One possible quantity which can control the amounts of α-particle emission from the target or projectile is the minimum excitation energy that has to be given to produce a short-lived ($\sim 10^{-22}$ s) α-particle unstable state in the target or projectile. From the compilation given in Ref. 14 we find that this energy is 10.3 MeV ($\Gamma=3$ MeV) for ^{12}C and about 13.3 MeV ($\Gamma=1$ MeV) for ^{14}N, and therefore to produce an incomplete fusion reaction these amounts of energy have to be given by the available center of mass energy. From the expected 30% of incomplete fusion we have to assume that only one α particle is lost at a given time, otherwise no evaporation residues of fluorine or oxygen can be produced. Two simulations of incomplete fusion have been made, and the results for the α-oxygen correlation are shown in Fig. 3. The first simulation (solid histograms) is done assuming that the α particles are lost with equal chance from target or projectile, and the second (dashed histogram) was done reducing the α-particle loss from the projectile to a 25% chance. Both correlations are calculated with the assumption that the angular distribution of the lost α particles is symmetric in the rest frame of the emitter (this produces essentially an isotropic correlation between the α particles lost from the ^{12}C and the $Z=8$ residues and a sharp forward peak angular correlation for the case of the alphas lost from ^{14}N). As can be seen from the figure, the solid histogram gives too much alpha emission in the forward angles and the dashed one too much at angles >30 deg, and neither account for the data as well as the complete fusion case can (see Fig. 1).

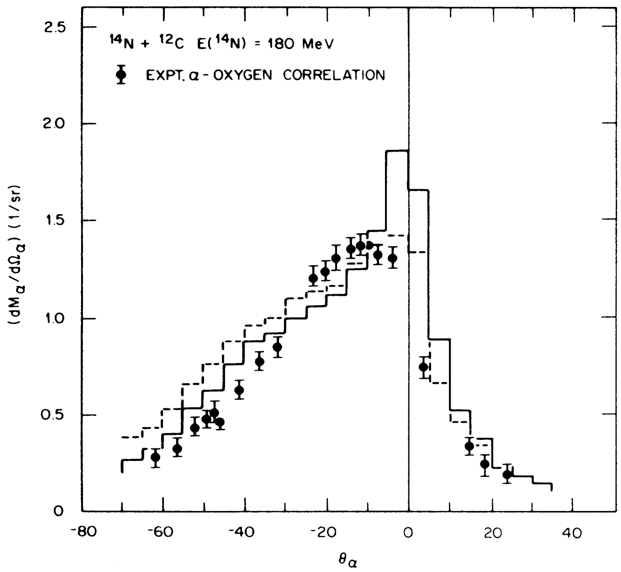

FIG. 3. In-plane angular correlation between α particles and evaporation residues of oxygen. A linear scale for the vertical axis is used to emphasize the differences between the data (solid points) and the calculations (histograms). The solid histogram is a calculation of incomplete fusion assuming equal probabilities of losing α particles from target or projectile, and the dashed histogram corresponding to a 25% probability of losing α particles from the projectile and 75% from the target.

IV. CONCLUSION

By a detailed analysis of the angular correlation between α particles and evaporation residues of $Z=7,8,9$ produced in the bombardment of 180 MeV ^{14}N on ^{12}C we have shown that no sizable effects of incomplete fusion occur at this energy. This result is consistent with previous inclusive measurements for the $^{14}N+^{12}C$ reaction[3,7,8] as well as with other fusion measurements of light systems[9,10] and is in disagreement with recent incomplete versus complete fusion systematics[1] reported for slightly heavier systems like $^{20}Ne+^{27}Al$.

The persistence of complete fusion at energies as high as 13 MeV/nucleon and the ability to produce equilibrated systems at temperatures as high as 5.6 MeV certainly require further theoretical as well as experimental studies. In addition, the drastic changes observed in the fusion cross sections with the addition or removal of small number of nucleons[7,15,16] remain as challenging problems for study in the fusion of light systems. Recent developments in the study of fusion and its connection to the orbiting process[16,17] show encouraging progress towards the understanding of heavy-ion reaction mechanisms in the light systems.

This research was sponsored by the U.S. Department of Energy under Contract DE-AC05-840R21400 with Martin Marietta Energy Systems, Inc.

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