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Preequilibrium Emission in the Fusion Reactions in the System ^{14}N + ^{27}Al at 100 MeV

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Light-particle emission in the fusion reactions in the system ^{14}N + ^{27}Al at 100 MeV has been studied with use of coincident techniques. Comparison of the data with a statistical model accounts for the energy and angular distributions of the products, the particle multiplicities, and the dealignment in the evaporation cascade. However, (18 ± 5)% of the evaporation residue cross section is of nonequilibrium origin and is interpreted in the framework of preequilibrium emission from complex configurations.

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Several studies of heavy-ion reactions have been made recently where light-particle–heavy-fragment coincidence techniques have been employed to explore the reaction mechanism, especially questions regarding the existence of nonequilibrium phenomena. Althought the statistical model is very useful in such studies to simulate the equilibrium decay of compound nuclei, detailed application of the model has been made only in a few cases.[1] In this Letter, we report the results of a coincidence study of the light charged particles emitted in the fusionlike reactions of 100-MeV ^{14}N projectiles with ^{27}Al. From a comparison of the experimental energy spectra and angular correlations with the predictions of a multistep Monte Carlo statistical-model calculation,[2] we conclude that a significant nonequilibrium component exists in the α emission leading to evaporation residues (ER). This component is interpreted as preequilibrium emission from complex configurations.

The experiment was performed at the isochronous cyclotron of the Institut des Sciences Nucléaires at Grenoble. Heavy ions produced in the reaction of 100-MeV ^{14}N with ^{27}Al were detected with use of a telescope consisting of a gas-ionization ΔE detector and a Si E detector. The H and He particles were detected (in and out of the plane defined by the heavy-ion detector and the beam axis) with use of a silicon detector telescope consisting of three or four detectors. Both singles and coincident events were tagged and written on magnetic tape, and were analyzed off-line on the HP-21MX computer at the Institut de Physique Nucléaire, Lyon.

Statistical-model calculations were made with use of a multistep Monte Carlo Hauser-Feshbach code which allowed the particle emission probabilities and kinematics to be followed over all the steps in a large number of evaporation cascades.[2] The semiclassical formalism of Ericson and Strutinski[3] was employed to calculate the angular distributions and to follow the direction of the angular momentum of the evaporation residues along the cascade. The parameters chosen were those of Ref. 2 which gave a good fit to the ER mass distributions and energy spectra in light–heavy-ion reactions. In our calculation, the only free parameters were the critical angular momentum for fusion, which was set equal to $27\hbar$ to reproduce the ER cross section, and the radius parameter for the moment of inertia (1.43 fm) which has been chosen to fit the back-angle light-particle spectra.

We discuss certain aspects of the inclusive ER data first. The magnitude and shape of the angular distribution of the evaporation residues are reasonably well reproduced by the statistical model. The angle-integrated yield distribution of the ER can also be predicted well by the calculation, except for the lightest elements. Data from a carbon target bombardment and a careful analysis of all the results allow us to exclude a possible oil contamination of the Al target as the reason for the discrepancy in the light-element yields. In fact, fragment-fragment coincidence results show that contributions from deep-inelastic processes (DIP) to the lightest products explain the data adequately.[4] For Mg nuclei detected at angles backward of 15° in the laboratory this contribution has been estimated to be 30%.

Turning now to light-particle–ER coincidence results, we discuss the particle multiplicities, the out-of-plane angular correlations, and the energy distribution of the emitted particles.

The particle multiplicity as a function of the Z of the ER can be deduced by integrating the angular correlations over all the angles in and out of plane. The results are presented in Fig. 1. The ratio of the He width to the H width varies from 2 for Na to 0.4 for S nuclei. The observed charge multiplicity is in good agreement with the charge loss of the compound nucleus. These results constitute an overall test of the statistical model. We see from Fig. 1 that we have satisfactory agreement between the experiment and the calculation. After a correction for the DIP contribution,[4] the total He and H cross sections leading to all ER products amount to 1070 ± 200 and 1420 ± 200 mb, respectively. With the 830-mb total ER cross section, we get an average multiplicity of 1.3 ± 0.3 (theory, 1.5) for He and 1.7 ± 0.4 (theory, 1.9) for H.

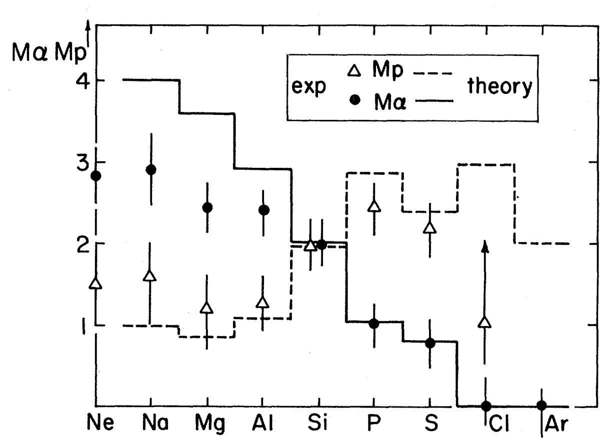

FIG. 1. Experimental and calculated H and He particle multiplicities.

The angular correlations give further insight into the mechanism of particle emission. For the in-plane He angular correlation with different ER elements, we have observed a flattening of the distribution with particle loss which is reproduced well by the statistical model. The flattening is even more drastic for the H data. The out-of-plane correlations shown in Fig. 2 are more interesting from the point of view of the mechanism of particle emission. It can be seen from Fig. 2 that there is an overall agreement between the experiment and the theory for H and He in coincidence with different evaporation residues. In this figure, φ is the angle the light-particle detector makes with the plane containing the ER detector and the beam axis. The detector angles are given in the figure caption. The solid lines in the figure are the results of the statistical-model calculation. Out-of-plane correlations are generally used to measure the preservation of the spin direction where an initial alignment with respect to a given plane is expected. Although the original spin of the compound nucleus is distributed uniformly in a plane perpendicular to the beam direction, we use here a quantity $P_J = \frac{3}{2}\langle\cos^2\theta\rangle - 1$ (analogous to the usual alignment factor) to denote the average component of the final spin in the direction of the original spin, θ being the angle between the initial and final spin directions. The calculated values of P_J are indicated in Fig. 2. It is seen that a large anisotropy is associated with large values of P_J. There is a progressive dealignment along the evaporation cascade in the sense of increasing departure of the final spin from the initial spin direction. The spin direction is essentially preserved in nucleon evaporation steps whereas with the emission of more than two He particles substantial dealignment is obtained. In view of this, it is not a surprise that in γ-DIP-fragment correlation experiments where a few particles are emitted one still observes a strong alignment up to the γ cascade.[5]

Although there is an overall agreement between the experimental correlations and the statistical model in the case of the lighter ER, the heaviest evaporation residues show a larger anisotropy than calculated, corresponding to a larger value of P_J than expected (see Fig. 2). This suggests a contribution from a nonevaporation process involving He emission in the grazing direction which might preserve an almost complete align-

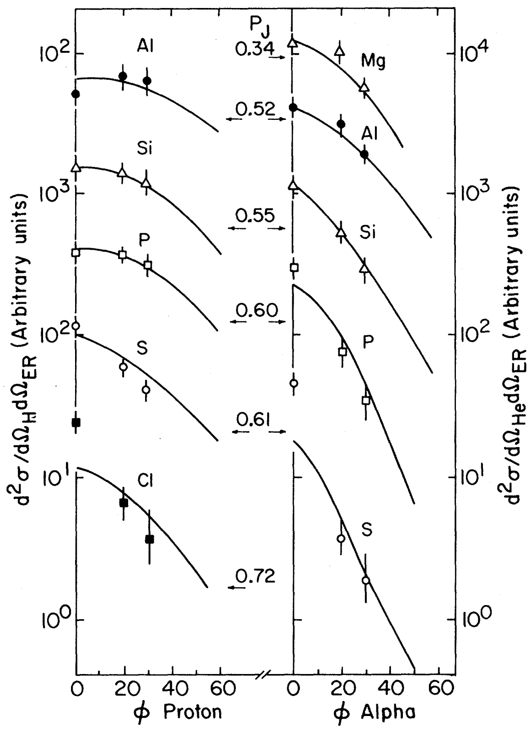

FIG. 2. Experimental and calculated out-of-plane light-particle—ER correlations and associated P_J values. The abscissa is the out-of-plane angle of the light particle (LP). $\theta_{ER} = 10°$; $\varphi_{ER} = 0°$. $\theta_{LP} = 15°$ for $\varphi_{LP} = 0$. (Negative angles denote the opposite side of the beam from the light-particle telescope.)

ment. In the case of the He-S correlation, for example, the initial nonequilibrium He emission would be followed by evaporation of two protons and possibly one or more neutrons. In the case of the Cl-H correlation, there could be a similar nonequilibrium particle emission followed by a proton and possibly neutron evaporation steps. The inclusive center-of-mass angular distributions of H and He presented in Fig. 3(a) and the coincidence He spectra in Fig. 3(b) confirm such a preequilibrium mechanism. In Fig. 3(a), an "extra" cross section is seen in the forward hemisphere, in excess of the back-angle cross sections and, as seen in the inset, this is concentrated in the grazing direction. In the H distribution, however, no such forward peaking could be seen. The anisotropies in the H and He angular distributions in the backward hemisphere are well described by the statistical-model calculation with the critical angular momentum for fusion equal to $27\hbar$ derived from ER cross section.

The α energy spectra change drastically as a function of the out-of-plane angle [Fig. 3(b)]. The small change in the in-plane angle θ from 15° to 32° as one varies φ from 0° to 30° cannot explain this change in the spectrum. The spectrum at $\varphi = 30°$ agrees well with the statistical-model evaporation spectrum. The model calculations also reproduce the in-plane coincidence spectra at backward angles as well as the inclusive spectra and angular distributions at back angles with the single set of parameters adopted in this work. But an extra cross section with a harder spectrum is observed at forward angles, e.g., at $\theta = 15°$, $\varphi = 30°$ [Fig. 3(b)] which cannot be explained by the statistical model with the same parameters. This corroborates the results in Fig. 2 and stresses the strong alignment of the nuclei responsible for the preequilibrium emission suggested above. Comparing the energy spectra and angular distributions with the model predictions,

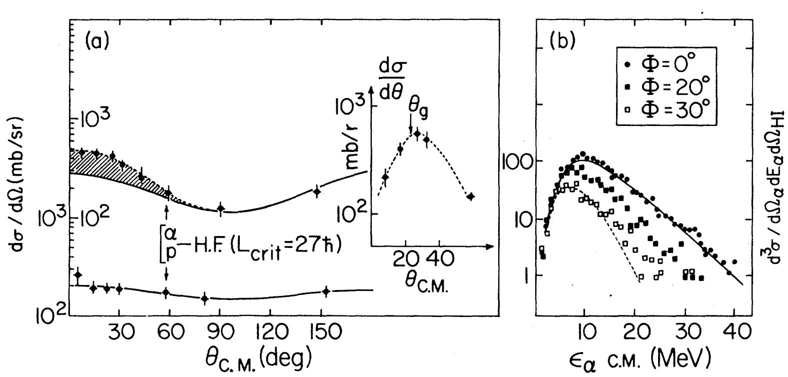

FIG. 3. (a) Experimental and calculated c.m. He and H angular distributions (singles). The extracted "direct" He cross section is shown as an inset. (b) In- and out-of-plane experimental He energy spectra. The broken line is the calculated evaporation spectrum. The solid line is a preequilibrium plus evaporation calculation. $\theta_{He} = 15°$ for $\varphi = 0°$.

we extract a preequilibrium cross section of 150 ±40 mb for He and an upper limit of 40 mb for H. As we have reported recently, the α emission in the deep-inelastic collisions in this system includes a similar nonequilibrium component whose origin has not been determined.[4] The origin of the fast particles measured in coincidence with the evaporation residues, however, can be interpreted in the well-known framework of preequilibrium emission as discussed below.

Nonequilibrium particle emission leading to incomplete fusion has been observed in several systems.[1,6-10] However, a quantitative explanation has not been proposed yet. In the present work we interpret the results using the preequilibrium model,[11-13] which has recently been applied to heavy-ion reactions at higher energies.[14] It predicts fast particle emission during the equilibration phase; but the primary configuration has to be known before calculations can be made. Using the particle-hole level-density expression, Griffin[11] has deduced an analytical formula for the high-energy slope of the particle spectra. The slope as a function of the residual excitation energy U gives a value for n, the particle-hole number, close to 11 for our case. Such a configuration can be assimilated to a state of 5 neutrons, 5 protons, plus a He. It corresponds to a He preformation factor of the order of 10%.[15] In the preequilibrium-model calculation the equilibrium transition rate must be corrected for complex configurations. The relation required for this was obtained by Harp, Miller, and Berne[12] by solving the master equation for the relaxation of two independent Fermi gases as a function of time. Applying the model to our case, we obtain[13] a preequilibrium He cross section of 180 mb and a H cross section of 25 mb. These values compare well with the experimental results $\sigma_{He} = 150$ mb and $\sigma_H \leq 40$ mb. The theoretical spectrum obtained from the preequilibrium model agrees well with the in-plane experimental spectrum [see Fig. 3(b)].

The light-particle spectra measured in coincidence with ER, DIP fragments, and in singles all show a remarkable similarity. In view of the ability of the preequilibrium model to describe the spectra accompanying incomplete fusion, one question remains: Would the preequilibrium model be able to interpret such a fast emission followed by a DIP mechanism?

In conclusion, we note that a Monte Carlo evaporation-model code is a very convenient tool in unraveling different reaction mechanisms. Correlation measurements are necessary to separate the contributions of DIP fragments to light-particle emission. With the aid of these techniques we have been able to distinguish an incomplete fusion contribution of (18±5)% of the ER cross section in the present reaction. It is attributed to the preequilibrium emission of H and He. We have here, and more effectively at higher energies, a unique opportunity to test the validity of the preequilibrium model for the emission of light particles from complex configurations.

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