Alpha emission at the Fermi energy

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Alpha particles have been measured in coincidence with both projectile-like fragments ($Z=5-8$) and light fragments ($Z=3-4$) in the reactions of 35 MeV/nucleon ^{16}O with ^{58}Ni. These results provide an extension of previous systematics studying the evolution of nonequilibrium emission of α particles from reactions at 6 to 20 MeV/nucleon. Two nonequilibrium components can be identified: one consists of beam velocity α particles and the other consists of intermediate velocity α particles. Compared to lower bombarding energies, no drastic change in the reaction mechanism has been observed at the Fermi energy.

Recent studies[1-8] have shown that nonequilibrium emission of light particles in coincidence with projectile-like fragments is an important feature of heavy ion reactions. The emission of light particles, therefore, can be used to probe the early stages of the reaction mechanism. Careful systematic studies, in which exclusive measurements are performed, are necessary to establish clear trends in order to arrive at a unified description of heavy ion reactions. In this respect, we have extended into the Fermi energy regime the previous systematics of the systems ^{16}O+^{58}Ni at 6 MeV/nucleon,[5,6] 9 MeV/nucleon,[6] and 13 MeV/nucleon,[8] and ^{16}O+^{nat}Ti at 20 MeV/nucleon.[7,9] We find that there is no dramatic change in the reaction mechanism at the Fermi energy. As in the lower bombarding energy data, two nonequilibrium components of α particles can be observed. One component consists of fast, beam velocity α particles focused in the most forward direction, while the other component consists of α particles having velocities intermediate between the beam and the center-of-mass velocities.

The experiment was performed using 35 MeV/nucleon ^{16}O projectiles accelerated at the National Superconducting Cyclotron Laboratory to irradiate an 850 μg/cm^2 target of enriched ^{58}Ni. Alpha particles were detected in eight telescopes located at 15°, 30°, 45°, 60°, 75°, 90°, 113°, and 135° with respect to the incident beam. The four most forward α telescopes consisted of Si ΔE surface barrier detectors with thicknesses between 90 and 150 μm backed by 10 cm NaI(TI) detectors. The three most backward angle α telescopes had 20 to 35 μm Si ΔE detectors and were backed by 5 mm Si(Li) detectors. Projectile-like fragments (PLF's) of $Z=5-8$ and light fragments (LF's) of $Z=3$ and 4 were detected in three telescopes, made up of 100 μm ΔE Si and 5 mm Si(Li) detectors, all located at 10° relative to the incident beam. Two of these PLF telescopes were positioned in the plane of the α telescopes one on each side of the beam. The third PLF telescope was located out of this plane and measurements were made at $\phi=45°$ and 60°.

Evidence for the sequential decay of PLF's can best be seen in the energy correlation of the α particles observed close to the PLF's. A plot of E_α vs E_C is displayed in Fig. 1 for α particles at $+15°$ in coincidence with carbon at $+10°$. The pattern of two lobes seen in this plot is typical of the sequential decay of the PLF's.[10] The upper lobe results from the forward emission of α particles slowing down the recoiling carbon while the lower lobe results from the backward emission of α particles. The average relative energy between the ^{12}C and the α particle is 4 MeV leading to an average excitation energy in ^{16}O of 11 MeV. Also on the average about 120 MeV of the incident kinetic energy has been dissipated by prompt emission of light particles or by exciting the target-like fragments (TLF's). The widths of levels in ^{16}O around 11 MeV excitation energy are narrow and, therefore, long-lived, resulting in the sequential emission from fully accelerated fragments. This assumes that the Coulomb field of the TLF's does not affect the level structure in ^{16}O and change the lifetime of the levels in this excitation energy region. These prominent patterns reflecting a strong correlation indicate that essentially all of the yield at this angle results from the sequential breakup of ^{16}O. The same pattern is typical for PLF's of $Z=5-7$. Therefore, the data suggest that projectile fragmentation occurs via an inelastic collision exciting the PLF's which then decay by sequential breakup after the PLF's and TLF's have been fully accelerated away from each other.

Representative energy spectra of α particles in coincidence with carbon are presented in Fig. 2. The two prominent bumps in the energy spectrum at $\theta_\alpha=+15°$, which is closest to the observed PLF's at $+10°$, correspond to the two lobes seen in Fig. 1. Most of the yield at this angle results from the decay of the projectile. We have performed simple calculations which simulate the sequential α emission from both PLF's and TLF's. Simple functions are used to parametrize the energy and angular distributions of the primary PLF's before they decay. The relative energy distributions between the α particles and the PLF's or TLF's are parametrized by Maxwellian functions. Also included in the model is a component of fast, beam velocity α particles. This component is

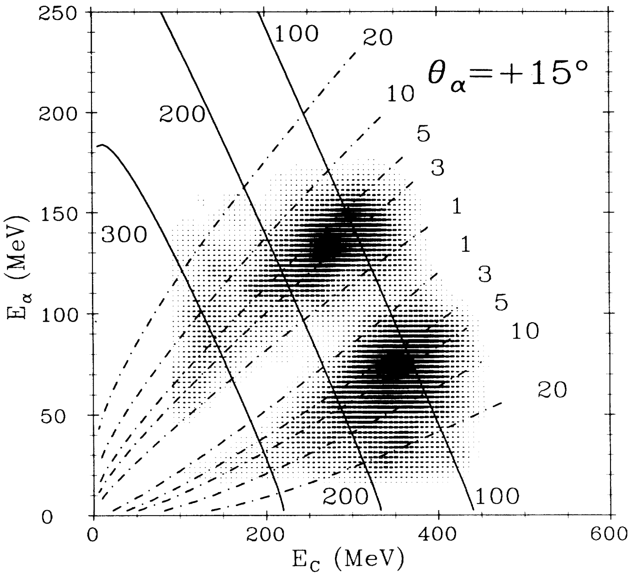

FIG. 1. Density plot for α particles at $\theta_\alpha=+15°$ in coincidence with carbon at $\theta_C=+10°$ with the intensity varying linearly. Curves represent three-body kinematic calculations. The dot-dash curves correspond to the relative energy (MeV) between C-α, while the solid curves correspond to the total excitation energy, $-Q_3$ (MeV).

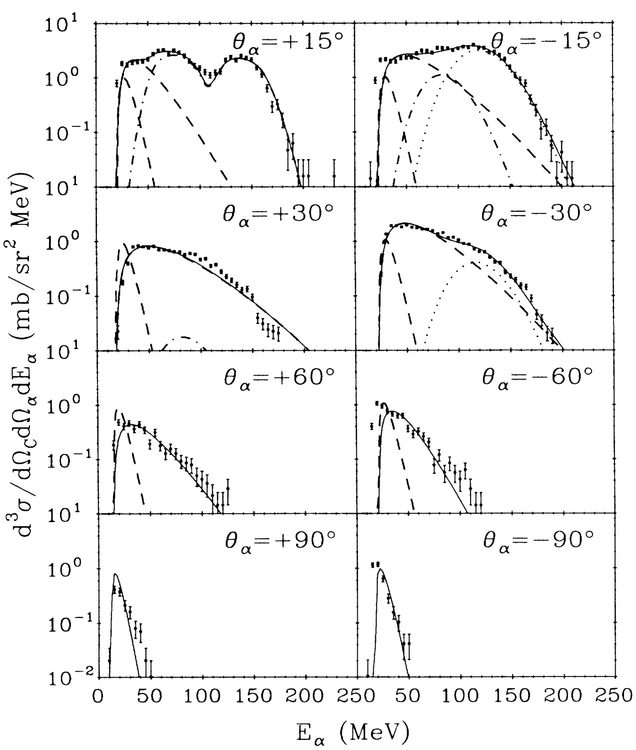

FIG. 2. Energy spectra of α particles at angles indicated in coincidence with carbon at 10°. Model calculations represented by curves; see the text for an explanation. Positive angles indicate the same side of the beam as the observed PLF's, while negative angles indicate the opposite side.

parametrized by Gaussian functions for the laboratory velocity distribution and angular distribution. The model was fit to the data using the nonlinear least squares method. These calculations are shown in Fig. 2 as dashed curves (the narrower dashed curves) for decay of TLF's and dot-dash curves for the decay of PLF's. The extracted temperature parameter for the decay of the TLF's is 4.1 MeV, and for the decay of the PLF's is 1.4 MeV. These temperatures are consistent with the average excitation energies extracted from Fig. 1. In a microscopic diffusion model of heavy ion interactions, during the initial stages of the collision the number of nucleons exchanged by the two nuclei is the same leading to the equal excitation energies. Therefore, the lighter partner would have a higher temperature. As the interaction continues the excitation energy is equilibrated and the two partners have equal temperatures. However, it is difficult to understand how the PLF's would have a lower temperature than the TLF's. Perhaps it is a result of the sampling of the excitation energy distribution of the PLF's which is imposed by the demand that a carbon survives or the role of prompt particle emission in the dissipation of the excitation energy.

On the opposite side of the beam from the detected PLF's at $\theta_\alpha=-15°$ and $-30°$ there is an excess of beam velocity α particles which has been observed in other studies at various bombarding energies.[6–9] This fast component does not arise from the sequential breakup of ^{16}O as it would require an excitation energy of 20 MeV, and from Fig. 1 we note that the probability for populating this excitation energy region is very low. In order to explain this component in terms of sequential emission processes a very broad decay energy distribution would be required in our model calculation which then would not fit the data at $\theta_\alpha=-15°$. This beam velocity component of α particles has been fitted by the model and is shown as dotted curves contributing only at $-15°$ and at $-30°$. These fast α particles presumably are emitted during the initial moment of interaction, and the mechanism is independent of the later stages of the collision as one also finds this component in coincidence with fusion-like residues.[7,9] Most α-particle—PLF coincidence experiments indicate an enhancement of this fast component on the opposite side of the beam from the detected PLF, suggesting a momentum correlation between the fast α particle and the PLF.

We have converted the energy spectra of α particles in coincidence with carbon into Galilean invariant cross section as a function of laboratory velocity and plotted the cross section as a contour polar plot shown in Fig. 3(a). Figure 3(b) is the result of the model calculation which includes the sequential decay of PLF's and TLF's and the fast component. The observed distribution [Fig. 3(a)] reveals a circular ridge of high intensity in the backward hemisphere arising from the decay of TLF's and is centered about the average velocity of the TLF's. For this component of α particles emitted by equilibrated TLF's, one expects an isotropic circular ridge similar to the one seen in the calculated plot [Fig. 3(b)]; however, there is a strong enhancement at $\theta_\alpha=-140°$ in the observed distribution which cannot be understood in terms of sequential decay. The distribution remaining after the subtraction of only the forward hemisphere from the model calculation is presented in Fig. 3(c). This velocity plot reflects the emission pattern of the nonequilibrium intermediate component of α particles. This component having half the beam velocity has been observed also for a similar system at 20 MeV/nucleon.[7] An asymmetry about the beam is suggested by the enhancement in the α yield of the intermediate component on the opposite side of the beam from the detected PLF's seen in Fig. 3(c).

An interpretation of the data can be done in terms of the hot spot model. For example, the α energy spectra in Fig. 2 at $\theta_\alpha = \pm 60°$ are broader than the calculated spectra (dashed curves). However, these α particles seem to feel the Coulomb barrier of the TLF's as the lower energy portions of the spectra agree with the calculated spectra. A calculation in the same spirit as one performed by Awes *et al.*[11] in which only the temperature parameter for the decay of the TLF's is allowed to vary for $|\theta_\alpha| \leq 60°$ is represented by the broader dashed curves in Fig. 2. The sum of this calculation for the decay of TLF's and the

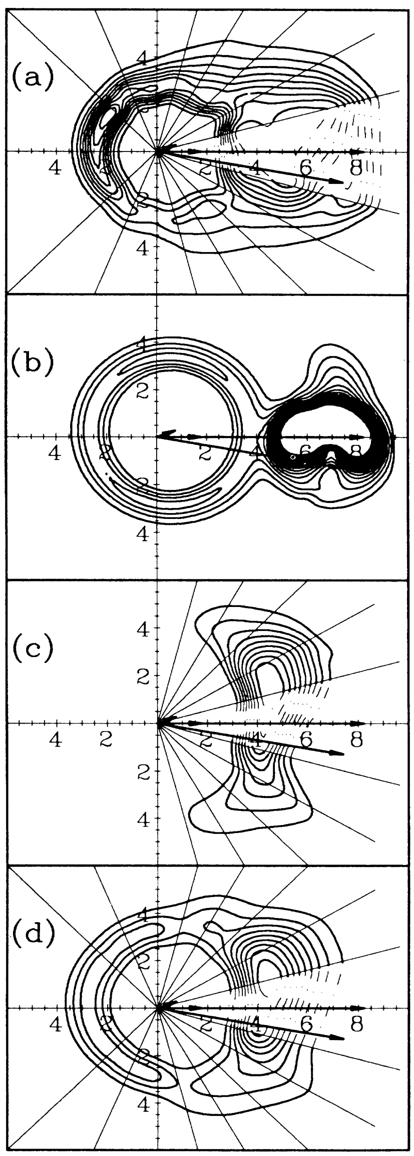

FIG. 3. Contour polar plots for the velocity distribution (a) of α particles in coincidence with carbon, (b) for model calculation of the sequential decay of PLF's and TLF's and of the fast component, (c) difference between (a) and (b), and (d) the calculated decay of TLF's with a varying temperature parameter. Lines indicate the position of α telescopes. Velocity vectors are indicated for the primary beam, the center of mass, and the mean velocities of the PLF's and TLF's. The units of the axes are in cm/ns.

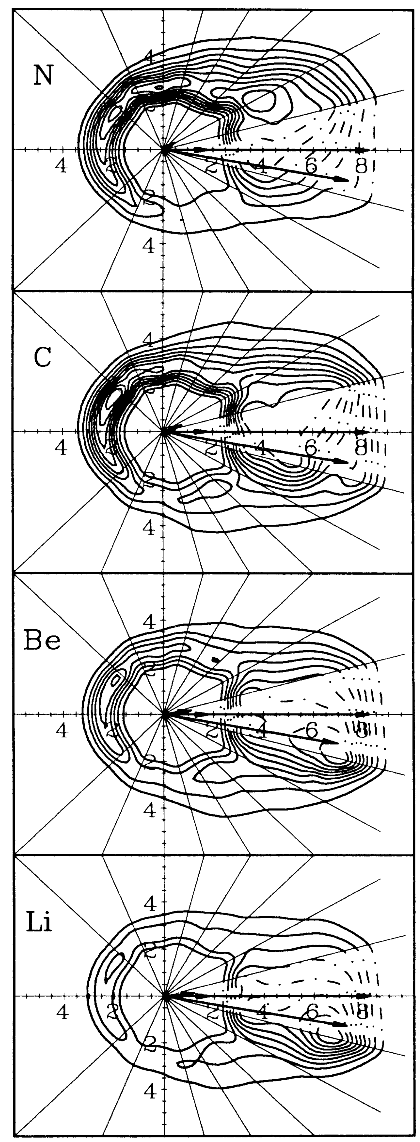

FIG. 4. Contour polar plots of the velocity distribution of α particles in coincidence with $Z = 7$, 6, 4, and 3 observed at 10°. Lines indicate the position of α telescopes. Velocity vectors are indicated for the primary beam, the center of mass, and the mean velocities of the PLF's and TLF's. The units of the axes are in cm/ns.

contributions of the PLF's (dot-dash curves) and of the fast component (dotted curves) is represented by solid curves. Such a calculation accounts well for the data. This calculation for the decay of the TLF's simulates the decay of a hot spot or hot zone on the TLF's which decays first in the forward hemisphere cooling down before decaying isotropically. The velocity distribution of this component is plotted in Fig. 3(d).

Integrating the in and out of plane angular correlations, we estimate the average multiplicity to be 0.5 for α particles associated with the observance of carbon at 10°. If we assume that the experimental angular correlation would follow the calculated correlation between $\theta_\alpha = \pm 15°$, then the average multiplicity increases to 0.8 α particles per carbon. Using the model calculation, we decompose the overall multiplicity into the various contributions: 0.32 for the sequential decay of the PLF's, 0.16 for sequential decay of the TLF's, 0.06 for the fast component, and 0.22 for the intermediate component (we estimate 15% error in these values).

Velocity plots for α particles in coincidence with representative PLF's and LF's are shown in Fig. 4. The plots are generally very similar; however, there are some differences to be noted. First, the contribution from the decay of the PLF's, more evident at $\theta_\alpha = +15°$, increases dramatically for LF's, as can be seen in the case of Li by comparing the ratio of the α component from the PLF's to the α component from the TLF's as observed at backward angles. This increase of the yield of the α component from the PLF's suggests that these LF's are produced by the fragmentation of the projectile. Second, the contribution of the intermediate component is asymmetric with respect to the beam axis (suggested by the enhancement on the opposite side of the beam from the detected PLF's) for the case of nitrogen but becomes symmetric for the LF's. This indicates that the mechanism for this component may depend on the later stages of the interaction.

In conclusion, we find that the energy spectra and angular correlations of α particles in coincidence with PLF's are very similar to those at lower bombarding energies. As in the case at 20 MeV/nucleon,[7] two nonequilibrium components can be identified. One component is characterized by beam velocity α particles in the very forward direction. These fast α particles are emitted during the early phases of the interaction. The other intermediate component consists of α particles having half the beam velocity. The velocity and angular distributions of these α particles depend on the Z of the observed PLF's, suggesting that this component reflects the dynamics of the collision.

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