Alpha-Particle Emission in Deeply Inelastic Reactions of 204-MeV $^{16}O + ^{93}Nb$

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Angular and energy correlations have been measured for α particles emitted in coincidence with projectilelike fragments from deeply inelastic collisions of 204-MeV ^{16}O with ^{93}Nb. Anisotropic emission of fast α particles is observed; however, the main results of this and similar experiments can be reproduced by model calculations which assume the α particles are evaporated from fully accelerated fragments and take the angular distribution of projectilelike fragments into account.

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Recent results of heavy-ion (HI) -neutron coincidence measurements[1] and of correlated mass and charge measurements[2] indicate that the kinetic-energy loss in deeply inelastic collisions (DIC) is transformed to excitation energy, which is shared by two heavy fragments in proportion to their mass. These fragments then deexcite by evaporating light particles. However, results of HI-α-particle coincidence measurements[3-8] for DIC at bombarding energies of 4-20 MeV/nucleon with projectiles of $A \leq 32$ have exhibited strongly anisotropic angular correlations which peak between the directions of the projectilelike (PL) and targetlike (TL) fragments. Interpretations in terms of hot-spot formation,[3,9] fast α-particle knockout,[6] and α-particle emission from the contact zone between PL and TL fragments[7,8] have been suggested for some of the results. If such interpretations were correct, one could use the correlations of α particles with the heavy fragments to probe the early stages of DIC before the kinetic energy damping is complete.

A simple, alternative interpretation of such HI-α-particle correlations is presented here. We have measured angular correlations between α particles and PL fragments for DIC of 204-MeV ^{16}O and ^{93}Nb and find they are forward peaked. These earlier results can be reproduced by Monte Carlo calculations assuming evaporation of α particles from the two primary fragments in DIC, if the angular distributions of PL fragments are included in the analysis.

The experiments were carried out by bombarding a 1-mg/cm^2 ^{93}Nb foil (containing less than 5 $\mu g/cm^2$ of carbon or oxygen) with a 204-MeV ^{16}O beam produced by the Oak Ridge isochronous cyclotron. Products with $Z \geq 4$ were detected by a ΔE-E telescope which had a gas-ionization ΔE section. Coincident α particles were detected with use of eight particle telescopes consisting of 50-70-μm-thick ΔE and 1500-μm-thick E silicon surface-barrier detectors. Four such light-ion (LI) telescopes were placed at various angles in the reaction plane defined by the beam and the detected HI, and four were placed at various out-of-plane angles. Data were taken with the HI telescope at $-12°$ and at $-21°$ (the laboratory quarter-point angle is $\theta_{1/4} = 14°$). (We define $\theta > 0$ for angles in the reaction plane on the side of the beam opposite to the direction of the detected HI.)

Energy-integrated α-particle multiplicities and energy spectra of the coincident α particles were extracted for each pair of HI and LI telescope angles and for each element from $Z = 4$ to 10. The multiplicity was calculated as $M = dE_\alpha \times dE_{HI} Y_c / dE_{HI} Y_s / \Delta\Omega_d$, where Y_c and Y_s are the coincident and singles HI yields, and $\Delta\Omega_d$ is the α-particle detector's solid angle. The in-plane multiplicity versus α-particle detection angle, θ_α, for α particles in coincidence with $Z = 6$ ions (the HI with largest yield) is shown in Fig. 1(a) for the $\theta_{HI} = -21°$ HI telescope setting. Angular distributions for other elements and for the θ_{HI}

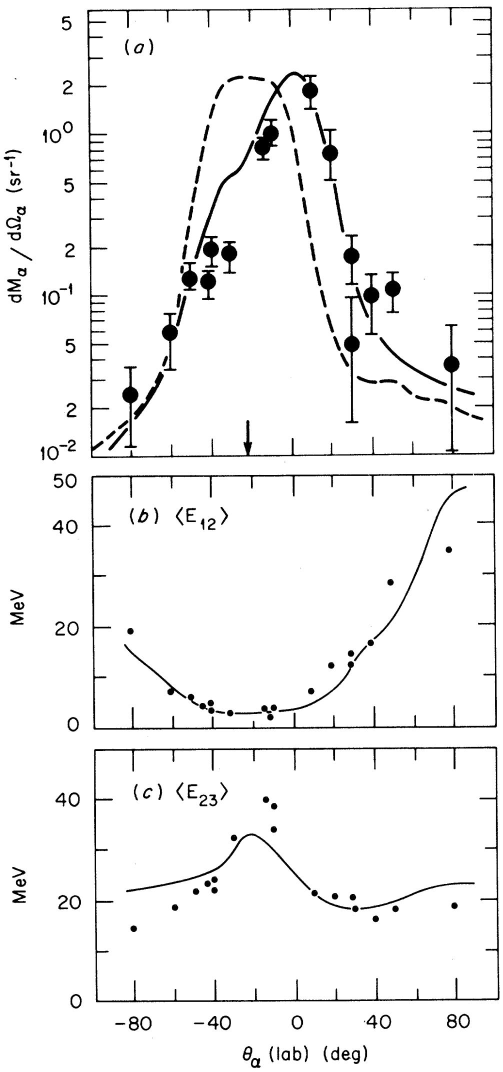

FIG. 1. (a) Differential α-particle multiplicities, $dM_\alpha/d\Omega_\alpha$, and mean values of (b) E_{12} and (c) E_{23} for carbon–α-particle coincidences at $\theta_{HI} = -21°$ in the reaction 204-MeV $^{16}O + {}^{93}Nb$. The results of calculations described in the text are given by dashed line, emission angle of the PL fragment taken as near the HI detector's direction; solid line, emission angle of the PL fragment chosen with use of $d\sigma/d\Omega_{HI}$ measurements.

$= -12°$ HI telescope setting have similar shapes. The distributions are forward peaked and are nearly symmetric about the beam direction, with a full width at half maximum of 30°–40°. There is no obvious symmetry about the direction of either the detected or the undetected HI. Integration of the in-plane distributions and the out-of-plane measurements yields total α-particle multiplicities of 1.2 for the carbon and 0.8 for the nitrogen deeply inelastic groups.

Following the methods of Ohlsen,[10] a three-body kinematic analysis was made. Mean values of E_{12} and E_{23} were calculated for the various elements and telescope angle pairs; E_{ij} is the relative energy of particles i and j in their common center-of-mass system. Here, 1, 2, and 3 refer to the detected HI, the α particle, and the undetected HI, respectively. If the α particles were emitted sequentially with a narrow range of energies from the detected (undetected) HI, then the mean value of E_{12} (E_{23}) would vary little with laboratory detection angle of the α particle. The mean values of E_{12} and E_{23} are shown in Figs. 1(b) and 1(c) for events in coincidence with carbon. Both exhibit trends similar to those noted by Gelbke *et al.*[5] and Bhowmik *et al.*[6] The variation of $\langle E_{23}\rangle$ with θ_α is in contrast to results obtained at lower bombarding energies per nucleon.[3,4] There, $\langle E_{23}\rangle$ was found to be nearly independent of θ_α; this was taken as evidence that the α particle was emitted sequentially from the TL fragment.

Energy spectra and angular distributions resulting from evaporation of α particles from the excited PL and TL fragments were modeled with use of a Monte Carlo computer code with the assumption that neutron, proton, and α-particle emission takes place from fully accelerated PL and TL fragments. Center-of-mass energy spectra, angular distributions, and multiplicities for the light particles emitted by excited ^{16}O and ^{93}Nb nuclei were determined with use of a modified version of the statistical-model code JULIAN.[11] The mean excitation energies and spins of the primary fragments were obtained by dividing the average total–kinetic-energy (TKE) loss according to fragment mass[1,2] and by use of sticking-model values,[12] respectively. TKE and mass distributions for PL fragments were taken from our experimental results.

If we assume that the original emission angle of the PL fragment is within a small cone centered about the HI detector direction, the calculation yields the dashed line in Fig. 1(a), which is symmetric about θ_{HI} and does not correspond to observation. However, the angular distribution of PL fragments causes the α particles emitted by them and detected in coincidence to be asymmetric about the direction of the HI detector. This occurs because an α particle emitted by a PL fragment such as ^{16}O imparts a substantial recoil velocity to the residual HI, which can change its direction by as much as 10°. Since $d\sigma/$

$d\Omega$ for PL fragments increases rapidly with decreasing θ, the observed α-particle–HI coincident yield is dominated by PL fragments which were traveling initially at an angle smaller than $\theta_{\rm HI}$, emitted an α particle, and subsequently recoiled into the HI detector. The associated α particles are thus concentrated between the directions of the PL and TL fragments and give rise to a forward-angle peak in the coincidence cross section. Similar observations have been made recently by Gomez del Campo[13] and by Gelbke.[13] The values of $dM_\alpha/d\Omega_\alpha$, $\langle E_{12}\rangle$, and $\langle E_{23}\rangle$ shown as the solid lines in Fig. 1 were obtained from calculations by use of our results for $d\sigma/d\Omega$ for PL fragments. These results are seen to reproduce the main features of the measurements and also are found to reproduce the out-of-plane results for these quantities. The calculations also reproduce the magnitude and shape, including the decrease at high energy, of the α multiplicity as a function of laboratory energy and angle $dM_\alpha/dE_\alpha d\Omega_\alpha$, and reproduce the shape of the PL fragment angular distribution. Comparison of calculated and measured velocity spectra for specific LI detector angles indicates that for the most forward LI detector positions at least 85% of the yield is accounted for by statistical emission of α particles. Within the precision of the measurements, all the yield for $|\theta_\alpha| \geq 30°$ is reproduced by the calculation. The total α-particle multiplicities in the model were 0.9 from the PL and 0.4 from the TL fragments.

To test whether such a model can account for other observed HI–α-particle correlations, we performed calculations for the reactions of 92-MeV ^{16}O with ^{58}Ni[3] and 310-MeV ^{16}O with ^{197}Au.[5] Mass, TKE, and angular distributions, and detector thresholds and positions were taken from Refs. 3 and 5. If the division of excitation energy is taken to be proportional to the fragment masses, the PL fragment is near threshold for particle emission for these two cases. We assume the excitation energy division to have a Gaussian distribution about its mean value, with a width calculated following Ref. 14. (Including such a width has little effect on the ^{16}O + ^{93}Nb results, as there the PL fragment is excited several megaelectronvolts above threshold.) On the basis of evaporation calculations,[11] the probability of α emission from the PL fragment was assumed to increase linearly with fragment excitation energy above emission threshold up to unity at 15 MeV. The resulting α multiplicities are shown as a function of θ_α for the two reactions in

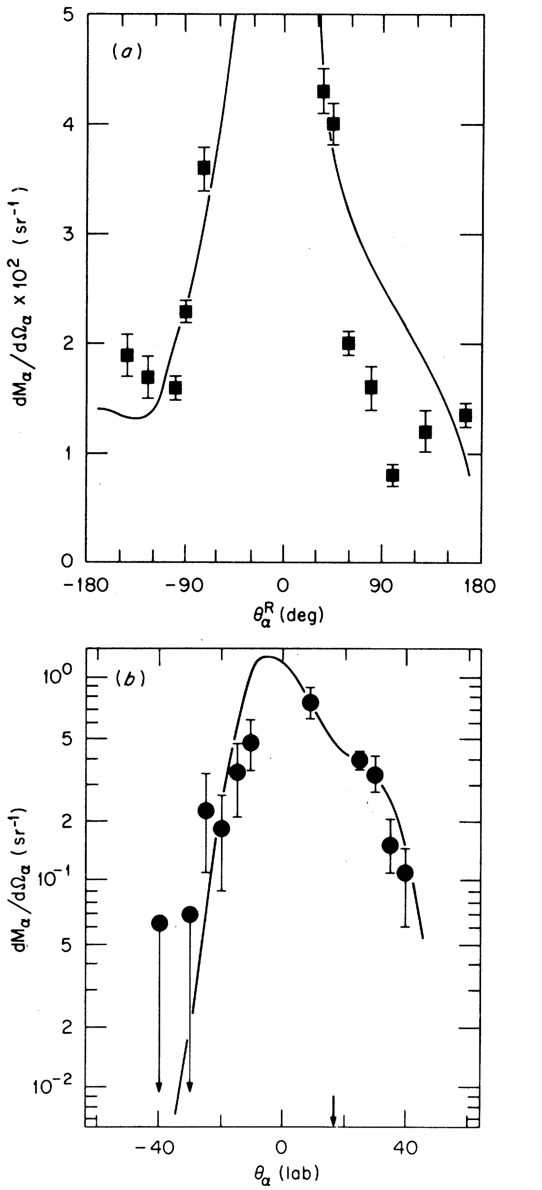

FIG. 2. Results of calculations (solid lines) and measured values (points) of $dM_\alpha/d\Omega_\alpha$ for carbon–α-particle coincidences for (a) 92-MeV ^{16}O + ^{58}Ni (Ref. 3) and (b) 310-MeV ^{16}O + ^{197}Au (Ref. 5). The ^{16}O + ^{58}Ni results are given in the rest frame of the recoiling targetlike fragment with 0° defined as the beam axis. The ^{16}O + ^{197}Au results are in the laboratory frame. For the latter case, the calculated multiplicity was arbitrarily normalized to the measured cross sections at $\theta_\alpha = 25°$ and a range of three-body Q value from -100 to -60 MeV was used.

Fig. 2. The shape of the multiplicity distribution is reproduced in both cases, as well as the absolute value of the multiplicity for the O + Ni reac-

tion.[3] The calculations also qualitatively reproduce the shapes of the α-particle spectra and the angular variation of the quantity[3] R for the O + Ni reaction.

In summary, we have observed anisotropic emission of α particles in deeply inelastic reactions induced by 13-MeV/nucleon ^{16}O projectiles on ^{93}Nb. Both the anisotropic HI–α-particle angular correlations and the high energies of the coincident α particles are reproduced by model calculations assuming evaporation from fully accelerated fragments, as are features of other HI–α-particle correlations previously ascribed to nonequilibrium emission of α particles in DIC. It is important in analyzing results of this and similar experiments to perform model calculations and identify kinematical effects in the results of a three-body analysis and in the variation of $dM_\alpha/d\Omega_\alpha$ with θ_α. The importance of performing such an analysis has also been noted by Gomez del Campo, who made an extensive Monte Carlo analysis, similar in philosophy to ours, of the PL fragment singles and α-particle coincident data from the DIC of 168-MeV $^{20}Ne + {}^{63}Cu$.[13]

Note added.—Recent results of Rauch *et al.*[15] indicate the excitation energy distribution used for the PL fragment in the $^{16}O + {}^{58}Ni$ reaction[3] is too broad; a more realistic one[15] slightly decreases the calculated forward-angle yield.

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