excited 0^+ energies. The model also fails to account for the asymmetric population of the excited 0^+ state in ^{182}W. It is hoped, however, that numerical calculations incorporating differences between neutron and proton bosons will be able to correct these differences while retaining the other features of the model predictions which agree so well with the data.

In summary and conclusion, we have presented a body of data for two-particle transfer reactions between W nuclei which show some simple systematic features. The data show some of the characteristics of both the PR and PV schemes but are better described by the SU(3) limit of the IBA model which still leaves the possibility for improvement when numerical calculations in this framework are performed. One expectation, independent of any model, is that there should exist[11] a 0^+ state in ^{180}W at about 1 MeV excitation. This state, were the target stable, should be strongly populated in the ^{178}W(t,p) reaction—it might therefore be expected to be seen in α-particle transfer on ^{176}Hf.

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Pre-emission of α Particles in Deep-Inelastic Reactions

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In-plane angular and energy correlations between α particles and heavy ejectiles have been measured for the reaction ^{14}N + ^{58}Ni at 148 MeV. The coincidence cross sections may be parametrized as a product of singles cross sections for the detection of α particles and heavy ejectiles. The observed correlations indicate that the α particles are emitted at an early stage, prior to the formation of the deep-inelastic fragments.

One of the most interesting aspects of interactions between complex nuclei is the study of deep-inelastic reactions. It has been shown experimentally[1-7] that a large fraction of heavy ejectiles (HI) coming from deep-inelastic reactions are accompanied by α particles. In a recent α-HI correlation measurement for the system ^{11}B + ^{58}Ni at 116 MeV energy, it was shown that α particles are emitted in a fast process on a time scale comparable to the collision time.[2] In the present investigation, we have extended these measurements to the ^{14}N + ^{58}Ni system at 148 MeV. It has been found that the α-HI energy and angular correlations may be parametrized as a product of the singles cross sections for α particles and heavy ejectiles. This result combined with the strongly forward peaked angular correlations indicate that the α particles are emitted at an early stage of the reaction by a direct process prior to the emission of the deep-inelastic-reaction fragments.

The experiment was performed by bombarding a ^{58}Ni foil of 2.5-mg/cm^2 thickness with 148-MeV ^{14}N beam from the Variable Energy Cyclotron at the Atomic Energy Research Establishment (Harwell, England). The heavy ejectiles ($Z = 3-8$)

were detected in a ΔE-E counter telescope consisting of a 30-μm-thick ΔE and a 1.5-mm-thick E detector. The coincident α particles were detected in a coplanar geometry with a 50-μm-thick ΔE and 1.5-mm-thick E counter telescope. Details of the experimental set up are given in Ref. 2.

Coincident cross sections have been measured for two different HI angles: $\theta_{HI} = 13°$, the classical grazing angle for $^{14}N + ^{58}Ni$; and $\theta_{HI} = 26°$. Coincident α particles were detected in the angular range $-70° < \theta_\alpha < 70°$, where positive θ_α corresponds to the HI and α counters on opposite sides of the beam. For some α angles the out-of-plane correlations were also measured. The coincidence cross sections have been corrected for "random" events which were typically < 10% of "real" events.

For light ejectiles ($Z < 6$) the impurity contribution from carbon and oxygen on the Ni target is estimated to be < 10% for both HI angles. For $Z = 6$ ejectiles the impurity contributions are ~15% and ~30% at $\theta_{HI} = 13°$ and 26°, respectively. No corrections for impurities in the Ni target have been made.

The in-plane energy-integrated angular correlations of α particles with HI are shown in Fig. 1. These differential α multiplicaties are obtained by dividing the α-HI coincidence cross sections by the singles deep-inelastic HI cross sections. The angular correlations observed for $\theta_{HI} = 13°$ and $\theta_{HI} = 26°$ are quite similar. For $Z < 6$ the angular correlations are symmetric about the beam axis and have a full width at half maximum ~40°. The angle integrated α multiplicities, corrected for out-of-plane anisotropy, have been estimated to be in the range 0.4 to 0.8.

Analysis of the energy correlations (E_{HI} vs E_α) reveals an important feature which is also to a large extent seen in the $^{11}B + ^{58}Ni$ data[2]: The projected coincidence α energy spectra are independent of ejectile type and have the same shape as the singles α spectra. Typical coincidence energy spectra in the center-of-mass frame for heavy ejectiles ($E_{HI}{}^c$) and α particles ($E_\alpha{}^c$) are shown in Fig. 2. The solid curves are singles measurements at the corresponding HI and α angles. The projected energy spectra for HI in coincidence with "fast" α's ($E_\alpha{}^c > 22.5$ MeV) and slow α's ($9 < E_\alpha{}^c < 22.5$ MeV) are also found to be similar in shape to the corresponding singles HI spectra. A similar analysis for α spectra gated by "low"- and "high"-energy ejectiles shows a lack of dependence of $\langle E_\alpha{}^c \rangle$ on HI energy.

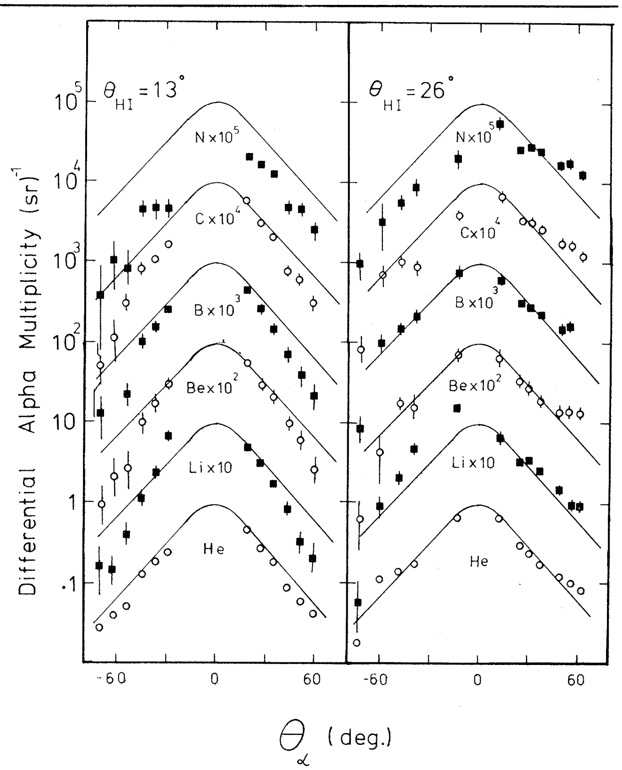

FIG. 1. Differential α multiplicities $dM_\alpha/d\Omega$ for different ejectiles (solid and open circles) for the reaction $^{14}N + ^{58}Ni$ at 148 MeV. The solid curves are derived from singles α angular distributions as described in the text.

The apparent independence of $E_\alpha{}^c$ and $E_{HI}{}^c$ and the similarity of the coincidence and singles energy spectra indicate that the two-dimensional energy correlation cross section may be factorized in the form

$$\frac{d^4\sigma(E_{HI}, \theta_{HI}, E_\alpha, \theta_\alpha)}{d\Omega_{HI}\, d\Omega_\alpha\, dE_{HI}\, dE_\alpha} \simeq K \frac{d^2\sigma(E_{HI}, \theta_{HI})}{d\Omega_{HI}\, dE_{HI}} \frac{d^2\sigma(E_\alpha, \theta_\alpha)}{d\Omega_\alpha\, dE_\alpha}, \qquad (1)$$

where $d^2\sigma(E_{HI}, \theta_{HI})$ and $d^2\sigma(E_\alpha, \theta_\alpha)$ correspond to the singles energy spectra for heavy ejectiles and the singles energy spectra for the α particles at angles θ_{HI} and θ_α, respectively, and K is a constant of proportionality. A comparison between the calculated[8] and experimental two-dimensional energy correlation plots shows that they are within statistical error. For $Z = 6$ and 7 at $\theta_{HI} = 13°$ the singles spectra contain a strong quasielastic component that is absent in the coincidence data. For this reason, the coincidence data for these ejectiles could not be reproduced

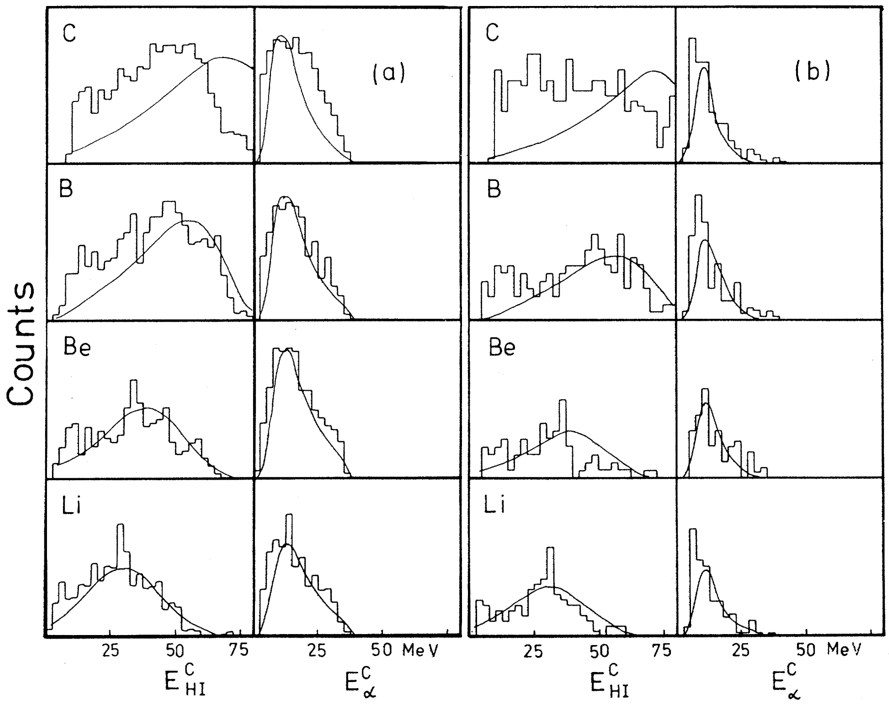

FIG. 2. Projected coincidence energy spectra for α particles and different ejectiles at (a) $\theta_{HI} = 13°$, $\theta_\alpha = 26°$, and (b) $\theta_{HI} = 13°$, $\theta_\alpha = 51°$. The solid lines indicate the shapes of the singles spectra at the corresponding HI and α angles.

by use of the singles cross sections. Reasonable agreement could, however, be obtained by replacing the singles $d^2\sigma_{HI}$ and $d^2\sigma_\alpha$ by the projected coincidence cross sections.

The factorization of the coincidence cross sections implies that the differential α multiplicities are proportional to the singles α angular distributions. The solid curves in Fig. 1 are obtained from the experimental distributions $d\sigma_\alpha/d\Omega_\alpha$ measured in the angular range $7° < \theta_\alpha < 65°$ and extrapolated smoothly through 0°. The same normalization constant $K = 0.5$ sr/b has been used for all the curves. The agreement between the calculation and data implies that the shape of the α-HI correlations are largely dictated by the shape of the singles α angular distributions and the multiplicities for different ejectiles are roughly independent of Z and θ_{HI}.

For a comparison between different models for α emission, the energy correlation data have been analyzed in terms of the three-body kinematics. Figure 3 shows the spectra of Q_3, E_{12}, and E_{23} for two α angles. E_{ij} is the relative energy between the particles i and j in their common center-of-mass frame, where 1, 2, and 3 refer to the HI, α, and the recoiling nucleus, respectively. These shapes are reproduced quantitatively by the factorization procedure (solid curves). The dashed curves for $Z = 6$ are obtained by replacing the singles spectra by the corresponding projected spectra for C and α particles in coincidence.

The success of factorization in describing the energy and angular correlation data implies that the α particle and HI are formed at different times so that the probabilities for the detection of α particle and HI are independent of each other. Emission of α particles from a projectilelike fragment is therefore ruled out as the dominant reaction mechanism. Similarly, the observed variation of the average value $\langle E_{23}\rangle$ with θ_α (Fig. 4) cannot be explained by α emission from a targetlike fragment.

The strongly forward-peaked angular correlations and the independence of α energy with Z and θ_{HI} suggests that the majority of α particles are emitted at an early stage in a fast direct process. However, the factorization of cross sections indicates that the reaction may be assumed to proceed in two stages. First the α particle is emitted in the forward direction by a process similar to a knockout mechanism. The

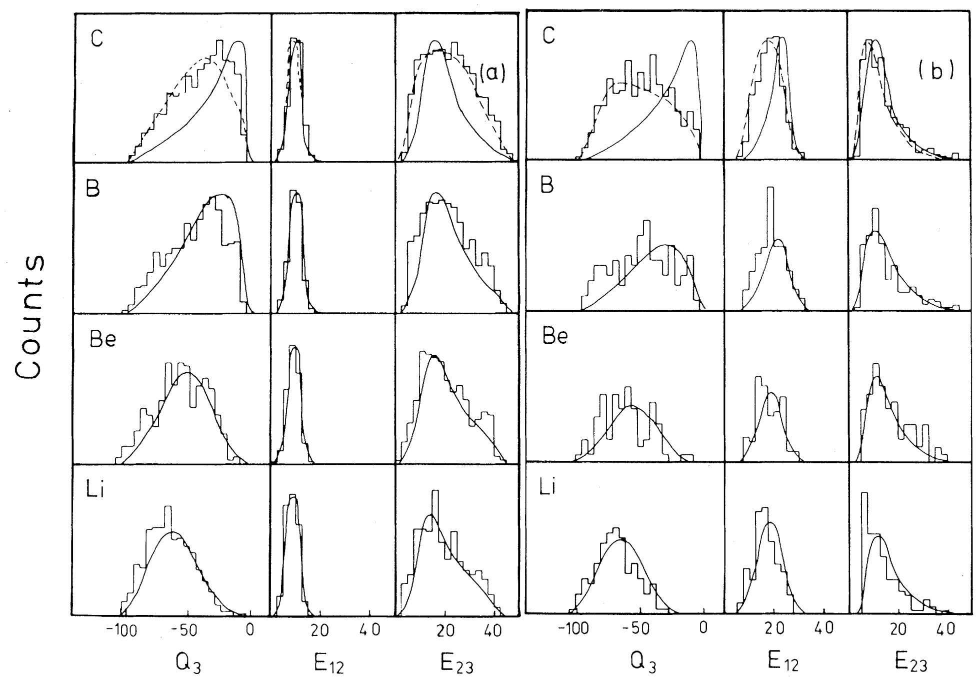

FIG. 3. Energy distribution of Q_3, E_{12}, and E_{23} at (a) θ_{HI} = 13°, θ_α = 26°, and (b) θ_{HI} = 13°, θ_α = 51°. The solid and dashed curves are calculated from the factorization parametrization (see text) and are normalized to the experimental data.

projectile-target combination, after losing the α particle, forms a dinuclear complex that exchanges mass and energy between its constituents and finally breaks up producing the deep-inelastic-reaction fragments. Because of the statistical nature of these exchanges, the fragments retain no memory of the energy and the direction of the α particle emitted and the cross section may be written as a product of the probabilities for

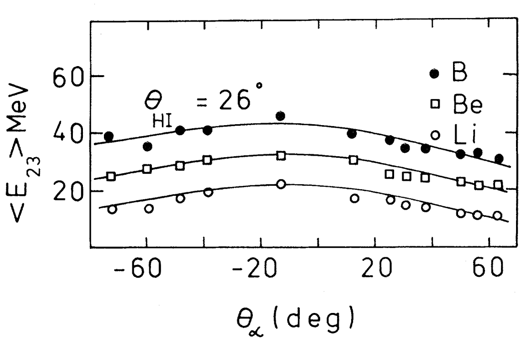

FIG. 4. Variation of $\langle E_{23} \rangle$ with θ_α at θ_{HI} = 26°. Data points for different ejectiles have been shifted 10 MeV upwards with respect to each other. The solid curves are calculated from singles cross sections with the factorization procedure.

separately detecting the α particle and the ejectile.

It must be stressed that although the above process implies a time ordering of events, the break up of the dinuclear complex is also a fast process as the energies of the heavy ejectiles are well above the Coulomb barrier. Since the α multiplicities are close to unity, a major fraction of the ejectiles observed in singles are formed by such a three-body process.

In conclusion, the observed energy and angular correlations for a large range of θ_α and Z have been reproduced by a simple parametrization of the data in terms of singles cross sections. The proposed reaction model in which the α particle is emitted in the first stage of the reaction can account for the narrow angular correlations and the factorization of cross section. Such a model, if proven correct, would have an important implication for the energy-dissipation mechanism in deep-inelastic reactions.

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Anisotropy of Yrast Gamma Transitions from ^{16}O on ^{48}Ti: Angular Momentum Dissipation and Alignment in Deep-Inelastic Reactions

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The intensities and angular correlations of yrast transitions measured in coincidence with light fragments from 96-MeV $^{16}O + ^{48}Ti$ reactions are used to determine amount and alignment of the angular momentum transferred to the heavy fragment as a function of the reaction Q value. It is found that fluctuations of the spin axis about the scattering normal are small at the most probable Q value of -32 MeV but increase strongly with increasing inelasticity.

The angular momentum transfer in deep-inelastic heavy-ion collisions is presently much studied by measuring the multiplicity M_γ of the deexcitation γ rays[1-4] or the anisotropy of particle emission from the excited fragments.[5,6] A shortcoming of the former method is its indifference to the separate contributions from the light and the heavy fragment and, for fragment masses $A \lesssim 70$, the rather weak dependence of M_γ on the initial fragment spin.[3] On the other hand, the fragment spin determined by the anisotropy of light-particle emission[5] or sequential fission[6] depends on assumptions about the spin orientation. Therefore, a complementary method appears desirable. In this Letter we use the population pattern of the heavy-fragment yrast states observed in a high-resolution γ-spectroscopic study of the 96-MeV $^{16}O + ^{48}Ti$ reaction to determine the angular momentum transfer.

In contrast to the approximate isotropy of the energy-integrated γ radiation noted in some recent studies[1-4] of deep-inelastic reactions, considerable out-of-plane anisotropies have been observed for γ rays from the decay of first and second excited states of $^{16}O + ^{27}Al$ and $^{16}O + ^{58}Ni$ reaction products.[7,8] However, these studies did not yield quantitative conclusions about the dealigned component of the initial fragment spin because of the large effect of the preceding statistical particle and γ decay at low spin[7,8] which may reduce the anisotropy of the observed final decay drastically even in the case of a complete initial spin alignment. In contrast, the anisotropy of a stretched cascade starting at high spin reflects the initial spin alignment. In the example of the ^{50}Cr ground-state band, presented in this Letter, it is possible to follow the fluctuations in the direction of the spin of the primary fragment as a function of the reaction Q value.

We have bombarded ^{48}Ti targets of 2-mg/cm^2 thickness with a 96-MeV ^{16}O beam from the Munich MP tandem accelerator. Light fragments were detected at 35° using a ΔE-E telescope consisting of an axial field ionization chamber and a 9-cm^2 surface-barrier Si detector subtending a solid angle of 30 msr. Element numbers Z were clearly resolved. The coincident γ radiation was measured with a 120-cm^3 Ge(Li) crystal positioned 8 cm from the target at 45°, 90°, and 180° with respect to the mean recoil direction in the in-plane geometry, and normal to the reaction plane in the out-of-plane geometry.

