Direct Evidence for a Narrow Window at High Angular Momentum in Incomplete-Fusion Reactions

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Alpha-gamma coincidence measurements have been made with reactions of 142-MeV ^{16}O on ^{146}Nd leading to the noncollective nuclei ^{152}Dy and ^{151}Dy. The side-feeding pattern in coincidence with forward energetic alpha particles peaks at $J = 30$ with full width at half maximum ~10, indicating that central collisions do not participate, while that for backward alpha particles extends down to $J = 0$. The data are consistent with the generalized critical-angular-momentum model of incomplete fusion.

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Energetic charged particles peaked at forward angles have been observed in a number of heavy-ion reactions leading to fusionlike products.[1-4] These have been interpreted in terms of an incomplete fusion process[1,3] (or "massive transfer").[2,5] The simple pictures of this reaction mechanism available to date[3,5] imply that this process occurs for a narrow range of entrance-channel angular momenta, l, beginning near the maximum angular momentum, l_{cr}, that participates in complete fusion. The γ-ray multiplicity data[4] confirm the expectation that average l values $> l_{cr}$ are involved. Unfortunately, the most distinctive feature predicted for the process, the suppression of contributions from $l < l_{cr}$ and the consequent narrow range of participating l values, could not be demonstrated with the data of Ref. 4, nor is this question directly addressed by measurements[1,2] of side-feeding patterns for rotational nuclei.

We report here measurements of the side-feeding pattern of discrete states up to very high spins in the noncollective nuclei ^{152}Dy (Ref. 6) and ^{151}Dy (Ref. 7) in coincidence with α particles from $^{146}Nd(^{16}O, \alpha xn)$ reactions at 142 MeV. These observations provide the first direct evidence that states with low spin are not populated in fusionlike reactions emitting energetic forward α particles.

The choice of the final nuclei for this experiment was based on the following considerations. It is generally believed that the initial spin population in a residual nucleus prior to its γ-ray deexcitation is transferred to the yrast states via statistical transitions which carry away excitation energy but little angular momentum on the average. In a prolate rotational nucleus, enhanced collective transitions appear to compete favorably with these statistical transitions even several megaelectronvolts above the yrast line.[8] As a result, the transfer of the spin population from the entry states to the yrast states may involve many paths through collective bands nearly parallel to the yrast line. The experimentally observable side feeding into the yrast band therefore tends to occur at spins much lower than the initial values and is as characteristic of the (largely unknown) properties of these parallel bands as it is of the entry-state population.[8,9]

Interpretation of the side-feeding patterns is much simpler for noncollective residual nuclei. Statistical-model calculations[10] for the reaction $^{124}Sn(^{32}S, 4n\gamma)^{152}Dy$ at 145 MeV show reasonable agreement with the observed[6] singles side-feeding patterns if zero or rather small collective enhancement is included.[11] This indicates that in such nuclei competition by nonstatistical transitions is minimal and therefore the relative intensities of the yrast transitions should be a direct measure of the entry-state population. Accordingly, a reaction leading to noncollective final nuclei by way of α emission was chosen. The final nuclei ^{152}Dy and ^{151}Dy have been studied in great detail recently.[6,7] Their yrast levels are known to extremely high J values and appear to show little or no collectivity.

A 148.8-MeV $^{16}O^{5+}$ beam from the Oak Ridge isochronous cyclotron bombarded a 10.3-mg/cm^2 target of Nd metal enriched to 97.54% in ^{146}Nd. The mean energy in the target was 142 MeV. A Ge(Li) detector at 125° was operated in coincidence with six ΔE-E silicon surface-barrier telescopes. The telescopes were in the same plane as the Ge(Li) detector at −18°, +22.5°, −28°, +38.3°, −57°, and +164°. For each particle-γ coincidence, the pulse heights in the Ge(Li) detector and the relevant ΔE and E counters, and the time delay between the pulses were recorded on magnetic tape. The event tapes were later scanned with $(\Delta E, E)$ masks appropriate for α particles, ultimately producing six Ge(Li) spectra in coincidence with α particles in each telescope. Delay times as long as 300 ns between the telescope signal and the Ge(Li) pulse were accepted, allowing for essentially complete decay of all the isomeric levels.[6,7] The characteristic known γ lines clearly identified the yrast transitions in the various residual nuclei, principally ^{151}Dy and ^{152}Dy. Transitions among the low-lying levels of ^{150}Dy ($\alpha 8n$ channel) and ^{153}Dy ($\alpha 5n$ channel) were weak; in the sum of the spectra for all six telescopes their intensities are about 16% and 12%, respectively, of the low-J intensities for ^{152}Dy.

The angular correlations of the α particles from various energy bins for the $\alpha 6n$ and $\alpha 7n$ exit channels were very similar to those of Ref. 4, namely a smooth gradation from strong forward peaking for the high energies to symmetry about 90° c.m. for energies near the Coulomb barrier for α evaporation. In Figs. 1(a) and 1(b) we show the relative population of levels in ^{152}Dy and ^{151}Dy deduced from transition intensities obtained in coincidence with predominantly nonstatistical α particles of c.m. energies ≥ 32 MeV in the four most-forward telescopes. The yields are remarkably constant up to $J = 28$ in ^{152}Dy and $J = \frac{37}{2}$ in ^{151}Dy. The smooth curves represent least-squares fits to Fermi functions adopted as the simplest analytic representations of the data. Figures 1(c) and 1(d) present similar data and fits for level yields obtained in coincidence with α particles of all energies in the 164° telescope; these α spectra show the characteristics of evaporation from an equilibrated system. The patterns for low-energy alpha particles in the forward telescopes were similar.

To illustrate the side-feeding pattern more clearly, we present in Figs. 2(a) and 2(b) the intensity differences for successive J values from the fits of Fig. 1. The solid curve in Fig. 2(a) gives the sum of the ^{152}Dy and ^{151}Dy differential yields for the α particles emitted backward, while that in Fig. 2(b) is the corresponding sum in coincidence with forward high-energy α particles.

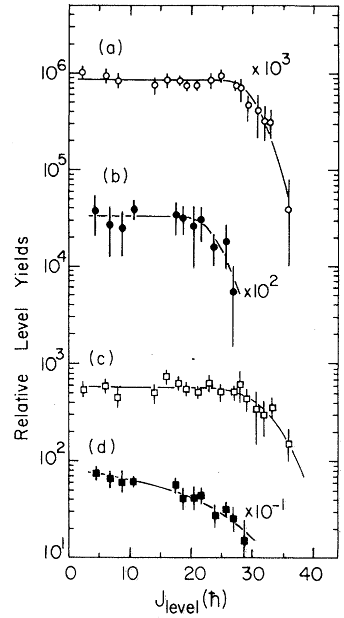

FIG. 1. Relative level yields from 142-MeV ^{16}O on ^{146}Nd for (a) ^{152}Dy and (b) ^{151}Dy in coincidence with α particles with $E_{c.m.} \geq 32$ MeV at 18°, 22.5°, 28°, and 38.3° (laboratory system); and for (c) ^{152}Dy and (d) ^{151}Dy in coincidence with α particles of all energies at 164° (laboratory system). The curves are least-squares fits to the function $A/\{1+\exp[(J-J_0)/\Delta]\}$ with the parameters $(A, J_0, \Delta) = (865, 31, 2)$, $(340, 24.5, 2)$, $(580, 33, 2.8)$, and $(830, 21, 6.5)$ for (a), (b), (c), and (d), respectively. The yields for (a) and (b) should not be compared with those for (c) and (d) since no allowance was made for the solid angles.

Some inferences concerning the entrance-channel l values can be made directly from Figs. 2(a) and 2(b). (1) Since the entry-state population in Fig. 2(b) is confined to a narrow range at high J, central collisions play essentially no role in the emission of fast forward α particles in these reactions. (2) The fast α particles should carry away more angular momentum than evaporated ones; hence the peak in Fig. 2(b) should correspond to l near the maximum l value contributing in Fig. 2(a). To illustrate these points more quantitatively, the entry-state J distributions of Figs. 2(a) and 2(b) were transformed to entrance-channel l distributions [Fig. 2(c)] by taking into account the angular momentum carried off by parti-

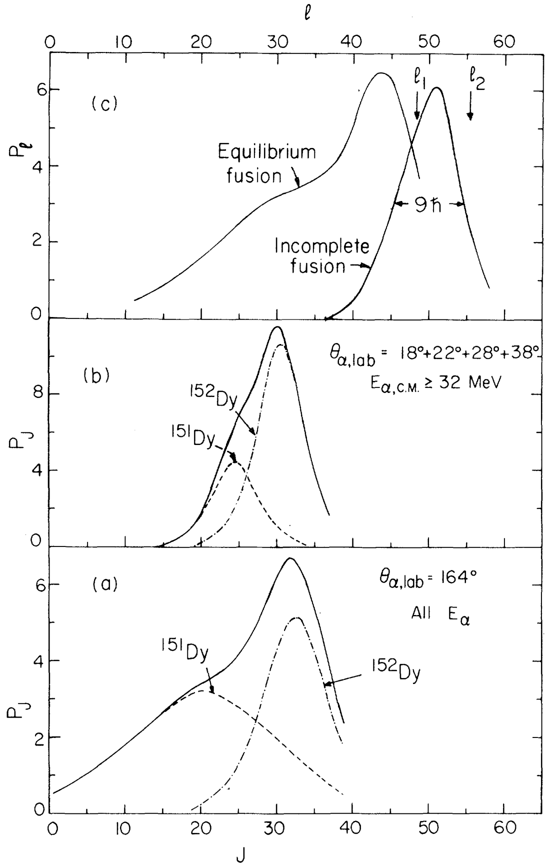

FIG. 2. (a) Angular momentum distribution of Dy entry-state population, P_J, as deduced from side-feeding intensities. The solid curve represents equilibrium αxn emission obtained from the differential of the sum of the curves in Figs. 1(c) and (d); their separate contributions are also indicated. (b) Similar distributions for Dy products associated with forward-emitted energetic alpha particles, from Figs. 1(a) and (b). (c) Entrance-channel populations, P_l, deduced from the solid curves of (a) and (b). The relative normalization of the two curves is arbitrary. The angular momentum carried away by the emitted particles was taken into account as described in the text. The arrows mark l_{cr} for complete fusion (l_1) and the maximum l value for incomplete fusion associated with escape of one α particle (l_2).

cle emission. The curve labeled "Equilibrium fusion" was obtained from Fig. 2(a) with statistical-model calculations[12] for αxn evaporation from ^{162}Er. These gave $\Delta l_\alpha \cong 4\hbar$ and $\sum \Delta l_n \cong 7\hbar$ ($6\hbar$) for $\alpha 6n$ ($\alpha 7n$), where Δl_i is the average angular momentum removed per particle of type i. The data of Fig. 2(b) were also treated with the statistical model to find the average spin before neutron emission which would leave an average $J \sim 30$ after evaporation of six or seven neutrons from ^{158}Dy; an internally consistent estimate of $\Delta l_n = 1.4\hbar$ removed per neutron was obtained. To estimate Δl_α for the fast α particles we made use of the experimental observation[4] that the projectile fragments carry angular momentum nearly in proportion to their masses. [This may be recognized as a natural consequence of the impact-parameter localization implied by the narrow peak in Fig. 2(b).] This gives $\Delta l_\alpha = \frac{4}{16} l$; combining this with the dashed curves of Fig. 2(b) corrected for neutron evaporation, we obtained the curve in Fig. 2(c) labeled "Incomplete fusion."

We now compare this curve with the predictions of the model of Ref. 3. The arrow at $l_1 = l_{cr}(^{16}\mathrm{O} + {}^{146}\mathrm{Nd})$ corresponds to the largest angular momentum allowed for complete fusion.[13] The arrow $l_2 = l_{cr}(^{12}\mathrm{C} + {}^{146}\mathrm{Nd}) \times \frac{16}{12}$ marks the maximum l value possible for fusion of ^{12}C + ^{146}Nd with escape of one fast α particle from the ^{16}O projectile.[3] Most of the initial population leading to energetic α emission is confined to the region between the two arrows. We note that the true l distributions for incomplete fusion should be narrower than the curve shown in Fig. 2(c) because the transformation does not allow for fluctuations in the angular momentum removed by the particles. The evaporation calculations indicate that an initial width $\sim 7\hbar$ would be consistent with the value $\sim 9\hbar$ that we observe.

In summary, we have obtained direct evidence that in fusionlike reactions leading to emission of energetic forward α particles, the entry states are restricted to a narrow range at high J. Transforming to l space in the entrance channel, we find that the data agree well with the generalized critical–angular-momentum model of incomplete fusion.[3] This work was supported in part by U. S. Department of Energy. Oak Ridge National Laboratory is operated for the U. S. Department of Energy by Union Carbide Corporation.

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Accurate Determination of the Ground-State Level of the ^{2}He Nucleus

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Combining certain well-known facts from low-energy scattering theory leads to the accurate determination of the ground-state level $(0^+, T=1)$ of the ^{2}He nucleus at energy $E = -140 - i467$ keV.

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The development of Coulomb-modified effective-range (ER) theory started almost half a century ago.[1] In this Letter it is shown that this theory can be used to determine accurately the position of the ground-state level of the ^{2}He nucleus. To my knowledge this has not been done before.

The ER function $K_l(k^2) = k^{2l+1}\cot\delta_l(k)$ is important in the theory of scattering by a short-range potential V_s. I confine myself to $l=0$. Under certain conditions on the potential, K_0 is real analytic at $E \equiv k^2 = 0$,

$$K_0(k^2) = -1/a_0 + \tfrac{1}{2}r_0 k^2 + \dots, \tag{1}$$

where a_0, r_0, ... are real. If the potential is $V_C + V_s$, where V_C is the *repulsive* Coulomb potential $e^2/r \equiv 2k\gamma/r$ (taking $\hbar = 1$ and $2m=1$), the ER function is modified, and may be taken as[2-5]

$$K_{Cs,0}(k^2) = \frac{2\pi k\gamma}{\exp(2\pi\gamma)-1}(\cot\delta_0{}^C - i) + 2k\gamma H(\gamma), \tag{2}$$

$$H(\gamma) \equiv \psi(i\gamma) + (2i\gamma)^{-1} - \ln(i\gamma). \tag{3}$$

Here ψ is the digamma function, γ is Sommerfeld's parameter, and $\delta_0{}^C$ is the Coulomb-modified S-wave phase shift. Now $K_{Cs,0}(k^2)$ is real analytic at $k^2=0$ for certain local[3,5] and nonlocal[2] potentials. The expansion coefficients are related to the Coulomb-modified scattering length $a_{Cs,0}$, effective range $r_{Cs,0}$, and shape parameters P and Q,

$$K_{Cs,0}(k^2) = -1/a_{Cs,0} + \tfrac{1}{2}r_{Cs,0}k^2 - Pr_{Cs,0}{}^3k^4 + Qr_{Cs,0}{}^5k^6 - \dots. \tag{4}$$

Bound states and resonances of $V_C + V_s$ correspond to poles of the Coulomb-modified t matrix in the k plane. At these poles,[2]

$$\cot\delta_0{}^C = i, \quad \delta_0{}^C = -i\infty, \tag{5}$$

so that (here $k = i\kappa$ is the position of the bound state or resonance; $a_B \equiv me^2/\hbar^2$ is the Bohr radius)

$$\tfrac{1}{2}a_B K_{Cs,0}(-\kappa^2) = H[(i\kappa a_B)^{-1}] \tag{6}$$