tion initiated by a $\pi^- + p$ scattering both in the $I = \frac{1}{2}$ and $\frac{3}{2}$ isospin states. The ratio between $I = \frac{1}{2}$ and $\frac{3}{2}$ resonances is estimated to be 1:4 for $\pi^- pn \to nn$ ($I_{pn} = 1$), compared to 1:16 for $\pi^- d \to nn$. It seems clear that the $I = \frac{1}{2}$ πN resonances would contribute more in $^{3,4}He(\pi^-, n)^{2,3}H$ than in $\pi^- d \to nn$ with the result that the minimum would be shallower in $^{3,4}He$ than in ^2H. In order to assess quantitatively these isospin effects in nuclear pion absorption, calculations are needed that take into account contributions from absorption on $I = 0$ as well as $I = 1$ NN states including the possible complications due to interfering amplitudes.

In conclusion, this paper has presented new data on nuclear pion absorption above the (3,3) resonance region. The energy dependence is found to be different from that of $\pi d \to pp$ when the nuclear form factor dependence is taken out. We suggest that this observation indicates the importance of $\pi + N$ (off-shell) scattering in the absorption process where the selective formation of intermediate $I = \frac{1}{2}$ and $I = \frac{3}{2}$ πN resonances depends on the isospin of the initial nucleon state involved. Calculations should be attempted on these (π, N) reactions in $^{3,4}He$ to assess the role of $I = \frac{1}{2}$ and $I = \frac{3}{2}$ πN resonances in nuclear pion absorption which would help clarify the elusive question of the reaction mechanism.

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Selective Population of High-*j* Orbitals in Er Nuclei by Heavy-Ion-Induced Transfer

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Selective population of high-j and high-K states in $^{167,169,171}Er$ nuclei has been observed in heavy-ion—induced single-neutron—transfer reactions. γ rays in coincidence with outgoing particles have been used to aid in level assignments and several previously unobserved high-j states have been identified.

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The backbending phenomenon and high-spin isomers are two examples of the unique role played by high-spin single-particle states in the structure of nuclei. Identification of these states with the (d, p) reaction can be made only in isolated cases since the reaction mechanism strongly favors low spin states.[1] The location of high-j neutron hole states has been extensively studied with the selective $(^3He, \alpha)$ pickup reaction,[2] while the inverse reaction leading to particle states has been rarely studied. In this Letter we report the use of two heavy-ion—induced stripping reactions to selectively populate high-spin particle states in deformed nuclei, specifically in $^{167,169,171}Er$. In addition to populating known low-lying levels, several other high-spin states, not observed in an earlier (d, p) study,[3] have been identified. These results demonstrate that heavy-ion—induced transfer reactions can play an important role as a spectroscopic tool to locate high-spin single-par-

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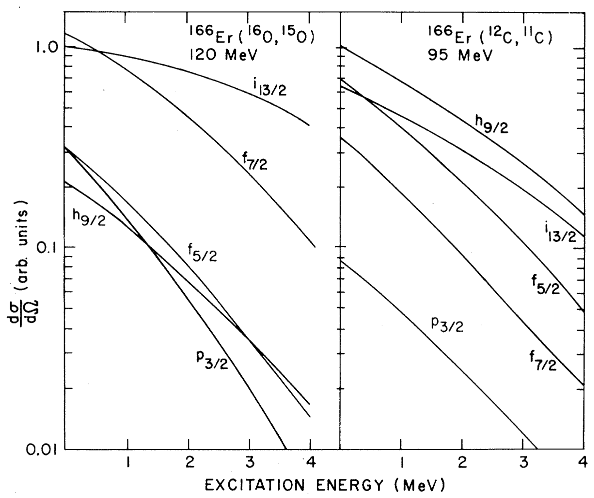

FIG. 1. Expected relative cross sections for active single-particle levels as a function of excitation energy for the reactions ^{166}Er(^{16}O, ^{15}O) and ^{166}Er(^{12}C, ^{11}C) calculated with the distorted-wave Born-approximation code PTOLEMY (Ref. 4). Unit spectroscopic factors were assumed for all states.

ticle states.

The choice of the reactions studied here, (^{16}O, ^{15}O) and (^{12}C, ^{11}C), is based upon two factors. Their large negative Q values mismatch the incoming and outgoing grazing angular momenta so that small angular momentum transfers are strongly suppressed (see Fig. 1). The consequences of these kinematic conditions and selection rules which result from the transferred neutron in the projectile being $p_{1/2}$ for ^{16}O and $p_{3/2}$ for ^{12}C lead to a strong favoring of high-spin final states with spin $j_>$ ($j_f = l_f + \frac{1}{2}$) for ^{16}O projectiles, while high spin $j_<$ ($j_f = l_f - \frac{1}{2}$) and $j_>$ states are comparable for ^{12}C (Fig. 1). The strong difference in the relative population of $j_>$ and $j_<$ final states for these two reactions is used below to distinguish $\frac{9}{2}^-$ from $\frac{13}{2}^+$ states which the (α, ^{3}He) reaction has difficulty doing from either strength or angular distribution measurements.

The strength with which levels are populated also depends upon the amplitudes, $C_j(\Omega)$, of the spherical basis states in the Nilsson wave functions. This also enhances final states in bands arising from high-j orbitals like $i_{13/2}$ and those with high-Ω values because of the small admixture of more than one j component in their Nilsson wave functions. For example, positive-parity bands in odd Er nuclei have $C_{13/2} \cong 0.90$. In each of the rotational bands with $C_j \approx 0.9$ it is expected that only one state (that with $j_f = j$) should be populated strongly for transfer on a spin-0 target.[5]

Targets of enriched ^{166,168,170}Er of 50–200 μg/cm^2 evaporated on thin C backings were bombarded with 120-MeV ^{16}O and 95-MeV ^{12}C ions from the Brookhaven National Laboratory tandem facility and outgoing ^{15}O and ^{11}C ions were momentum analyzed by the quadrupole–triple-dipole spectrometer and identified in a position sensitive ΔE-E gas proportional counter. Typical resolutions for ^{15}O ions ranged from 100–150 keV and for ^{11}C from 80–120 keV.

Heavy-ion–induced transfer reactions on heavy nuclei have bell-shaped angular distributions, a shape independent of angular momentum transfer. As a result a large fraction of the transfer yield can be subtended by the spectrometer at a single setting (typical solid angles used were 12 msr) and relative intensities of states are approximately angle independent. Spectra of outgoing ^{15}O and ^{11}C ions, taken at the peak of the angular distribution and converted to excitation energy for ^{167,169,171}Er final nuclei, are shown in Fig. 2.

Both reactions are seen to be very selective for all the isotopes, and a comparison of the two reactions for each isotope shows a dramatic difference in the population of some states. The classification of states as $j_>$ or $j_<$ comes directly from this comparison. For example, compare the spectra for ^{167}Er. The peak at 0.29 MeV is strong in both reactions and indicates $\frac{13}{2}^+$ strength, while the peak at 0.43 MeV is reduced relative to the 0.29-MeV peak in (^{12}C, ^{11}C) and is likely $\frac{7}{2}^-$. The peak at 1.32 MeV is very strong in (^{12}C, ^{11}C) but is absent in (^{16}O, ^{15}O) which implies a $\frac{9}{2}^-$ assignment. In the (^{16}O, ^{15}O) reaction the peak at 1.53 MeV is strong but because it appears as a doublet in the C reaction it cannot be assigned as $\frac{13}{2}^+$ from the particle spectrum alone.

These assignments, of course, cannot be regarded as definitive. In order to determine their validity for ^{167}Er a γ-ray coincidence measurement was made between ^{15}O particles detected in the spectrometer and γ rays detected at 130° in a Ge(Li) counter. This measurement, which improved the effective energy resolution to 3 keV, confirmed that the states which are populated in ^{167}Er between 0.25 and 0.5 MeV by the (^{16}O, ^{15}O) reaction are the $\frac{13}{2}^+$ member of the $\frac{7}{2}$[633] band at 0.294 MeV and two $\frac{7}{2}^-$ levels at 0.413 and 0.430 MeV (Ref. 3) with approximate relative population of 2.2:0.4:1.0, respectively. In addition, the $\frac{15}{2}^+$ member of the $\frac{7}{2}$[633] band at 0.432 MeV is weakly populated, presumably by multi-

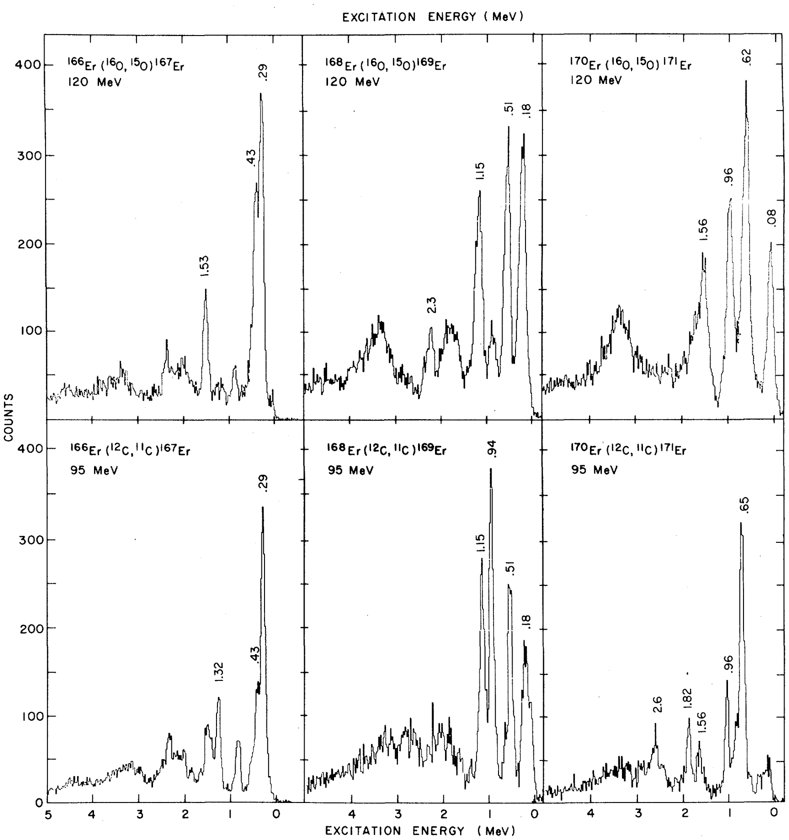

FIG. 2. Outgoing-particle spectra at 42° from the reactions $^{166,168,170}Er(^{16}O, ^{15}O)$ (top) and $^{166,168,170}Er(^{12}C, ^{11}C)$ (bottom). Excitation energies are listed above the peaks and have an uncertainty of about 0.02 MeV.

step processes, with a cross section less than 10% of the $\frac{13}{2}^+$ state.[6]

The state at 1.53 MeV in ^{167}Er yields γ rays exclusively from low-lying members of the $\frac{7}{2}[633]$ band. This observation is consistent with the state being the previously unobserved $\frac{13}{2}^+$ member of the $\frac{9}{2}[624]$ band, as decay of this level is expected to be primarily by high-energy γ rays (≥ 1 MeV which have low detection efficiency) to members of the $K=\frac{7}{2}$ band. This assignment also fits very well with the extension of a band tentatively assigned as $\frac{9}{2}[624]$ from a (d, d') experiment[7] where only the $\frac{9}{2}^+$ and $\frac{11}{2}^+$ members were identified at 1.253 and 1.382 MeV, respectively. A γ-ray coincidence experiment has not been made with the much weaker $(^{12}C, ^{11}C)$ reaction, but systematics of known energy levels through the Er isotopes are additional evidence that the 1.32-MeV level in ^{167}Er is the $\frac{9}{2}^-$ member of the $\frac{7}{2}[514]$ band (see Fig. 3).

In addition to the known $\frac{7}{2}^-$ state at 0.18 MeV in ^{169}Er the $\frac{13}{2}^+$ member of the $\frac{7}{2}[633]$ band[3] is seen at 0.51 MeV (Fig. 2). The previously unobserved

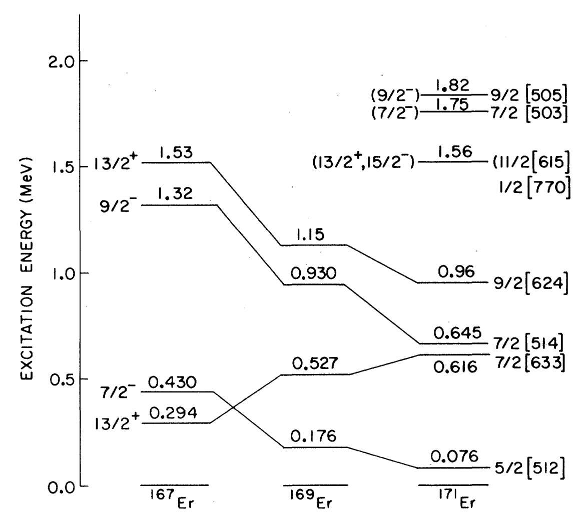

FIG. 3. Deduced single-particle high-spin levels for the erbium isotopes studied here. Spins of the levels appear to the left-hand side, energies on top, and Nilsson band assignments to the right-hand side. Levels whose energies are given in keV have been established in previous work.

$\frac{13}{2}^+$ member of the $\frac{9}{2}[624]$ band at 1.15 MeV is much more prominent than in ^{167}Er. The (^{12}C, ^{11}C) spectrum clearly shows the previously assigned $\frac{9}{2}^-$ member of the $\frac{7}{2}[514]$ band[3] at 0.94 MeV but does not unequivocally allow assignment of $j_<$ strength at high excitation energy or near the ground state.

The strong $\frac{13}{2}^+$ state at 0.62 MeV in ^{171}Er and the low-lying $\frac{7}{2}^-$ state have been previously assigned.[3] The second $\frac{13}{2}^+$ state, which has not been previously observed, appears at an excitation energy of 0.96 MeV. A third strong peak at 1.56 MeV could be the $\frac{13}{2}^+$ member of the $\frac{11}{2}[615]$ band, or the $\frac{15}{2}^-$ member of the $\frac{1}{2}[770]$ band ($j_{15/2}$ parentage), which comes down in energy from the next shell very rapidly with increasing deformation. A comparison of the ^{15}O and ^{11}C spectra indicates $f_{7/2}$ strength at 1.75 MeV as the tail on the peak at 1.56 MeV is strongly suppressed in the ^{11}C reaction. The most likely assignment for this latter state is the $\frac{7}{2}^-[503]$ bandhead.

The (^{12}C, ^{11}C) spectrum for ^{171}Er identifies $j_<$ peaks at 1.82 MeV and 2.6 MeV in addition to the previously known $\frac{9}{2}^-$ state at 0.645 MeV,[3] which is not resolved from the $\frac{13}{2}^+$ state at 0.616 MeV. The state at 1.82 MeV is most likely the $\frac{9}{2}^-[505]$ bandhead and the state at 2.6 MeV is likely to be the $\frac{5}{2}^-[503]$ bandhead.

A large broad peak at 3.4 MeV in excitation for the (^{16}O, ^{15}O) reactions on the heavier Er isotopes is clearly seen in Fig. 2. Kinematic considerations indicate the strength can be attributed to Er but its origin is not yet understood.

The observed high-j and high-K states and their tentative assignments are summarized in Fig. 3. The lower $\frac{13}{2}^+$ state in ^{171}Er has the largest transfer strength and was previously assigned as a member of the $\frac{9}{2}[624]$ band[3] since the $\frac{7}{2}[633]$ band should be nearly filled. With use of the present data from ^{167,169}Er, it is clear that the two lowest $\frac{13}{2}^+$ states would be nearly degenerate in ^{171}Er were it not for Coriolis mixing. Nilsson-model calculations indicate that the lowest-lying $\frac{13}{2}^+$ state at 0.62 MeV probably has a larger component of $\frac{7}{2}[633]$ and the $\frac{13}{2}$ state at 0.96 MeV has as its major component $\frac{9}{2}[624]$. Regardless of the precise structure of these states the strong Coriolis mixing puts more of the transfer strength into the lower state.

In summary, through the strong selective population of known high-spin levels and the identification of previously unobserved high-j states in Er nuclei, this experiment has clearly demonstrated that the unique features of heavy-ion-induced transfer make these reactions invaluable in spectroscopic studies of nuclei.

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