BNL-31327

Conf-820588--1

BNL--31327

DE82 010142

Selective Population of High-j States Via Heavy-Ion-Induced Transfer Reactions

P. D. Bond

Brookhaven National Laboratory, Upton, New York 11973 USA

MN ONLY

Invited Talk

Presented at

Binational Workshop and Symposium on Nuclear Physics
at Cyclotron and Intermediate Energies

Bombay, India

May 24 - June 2, 1982

MASTER

The submitted manuscript has been authored under contract DE-AC02-76CH00016 with the U.S. Department of Energy. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

97-18

SELECTIVE POPULATION OF HIGH-j STATES VIA HEAVY-ION-INDUCED TRANSFER REACTIONS

P. D. BOND
Brookhaven National Laboratory, Upton, New York 11973, USA

One of the early hopes of heavy-ion-induced transfer reactions was to populate states not seen easily or at all by other means. To date, however, I believe it is fair to say that spectroscopic studies of previously unknown states have had, at best, limited success. Despite the early demonstration of selectivity with cluster transfer to high-lying states in light nuclei$^{1)}$, the study of heavy-ion-induced transfer reactions has emphasized the reaction mechanism. In this paper the value of using two of these reactions for spectroscopy of high spin states is demonstrated. The transfers discussed are not exotic; they are single neutron transfer, but the results are new, and the use of heavy-ion-induced transfer for spectroscopic purposes shows great promise for the future. The examples are chosen from the region of nuclei for which the neutron number is $82 < N < 105$, where the active neutron shell model states are $2f_{7/2}$, $1i_{13/2}$, $3p_{3/2}$, and $1h_{9/2}$, and the nuclei range from near spherical to deformed. The focus here is on the location of $\nu i_{13/2}$ strength in these nuclei.

We begin with nuclei near $N = 82$ where there has been a recent flurry of (HI,xn) activity because the nucleus ${}^{146}_{64}\mathrm{Gd}_{82}$ has characteristics of a closed shell nucleus$^{2)}$. Both the proton and neutron shell model states include some of high spin, so the structure of many high spin states should have simple configurations, and yet earlier studies with the (d,p) reaction to both ^{144}Nd $^{3)}$ and ^{148}Sm $^{4)}$ found little or no $i_{13/2}$ strength in these nuclei. The major reason for these negative results is that the (d,p) reaction favors small values of the angular momentum transfer.

Since heavy-ion-induced reactions are generally performed with poorer energy resolution than those with light ions and for the nuclei in this region have predominantly bell-shaped angular distributions, one might wonder, why use heavy ions? One reason is that heavy-ion-induced single neutron transfer can be chosen to have a selectivity for high j states not possible with light ion reactions. Shown in fig. 1 are single neutron transfer spectra, taken at the peak of the cross section, to states in ^{149}Sm for three reactions: (^{13}C,^{12}C), (^{12}C,^{11}C), and (^{16}O,^{15}O). The (^{13}C,^{12}C) reaction is well matched (incoming and outgoing grazing angular momenta are nearly equal) and tends to populate low spin states, much as the (d,p)

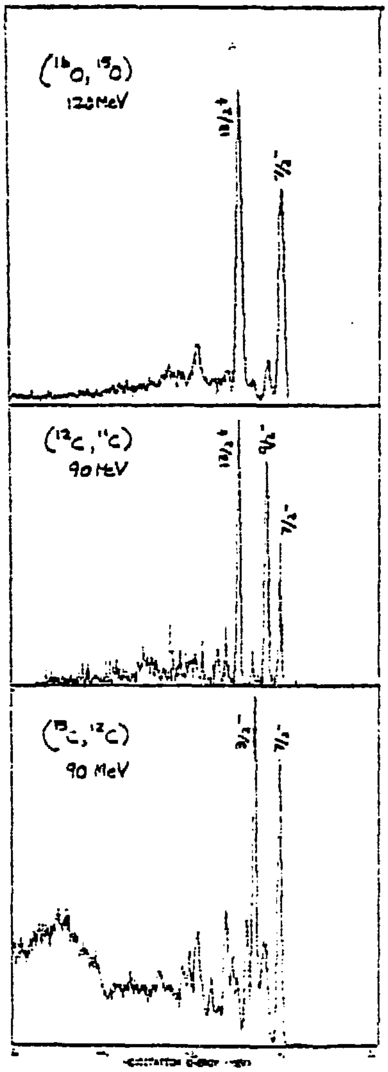


Figure 1. Single neutron transfer reactions from ^{148}Sm → ^{149}Sm. Spectra were taken at the peak of the angular distribution. Note that the strongest state with the (^{13}C,^{12}C) reaction (bottom) is spin $3/2^-$. With the (^{12}C,^{11}C) reaction (middle) the high spin levels are strongly favored and the $p_{3/2}$ is suppressed. The (^{16}O,^{15}O) reaction (top) additionally suppresses the high spin states with $j_f = \ell_f - \frac{1}{2}$.

reaction. In contrast, the ($^{12}C,^{11}C$) reaction has a very large negative Q value and strongly emphasizes the higher spin single particle states. This spectrum is similar to that one might obtain with ($\alpha,^{3}He$) 5). An added selectivity is obtained, however, with the ($^{16}O,^{15}O$) reaction which also has a very large negative Q value. Note that there is a very strong suppression of the $h_{9/2}$ state and, in general, $j_f = \ell_f - 1/2$ states are strongly suppressed with this reaction. Thus a comparison of the ($^{16}O,^{15}O$) and ($^{12}C,^{11}C$) reactions can be used to distinguish between high spin $j_f = \ell_f + 1/2$ and $j_f = \ell_f - 1/2$ final states and to provide complementary information to light ion reactions.

The observed selectivity in fig. 1 is reproduced very well by DWBA calculations and is similar to, but more pronounced than, that observed for proton transfer6). This selectivity has a simple semiclassical explanation which results from the large angular momentum mismatch, the observation that the intrinsic spin of the transferred neutron does not flip and the fact that the transferred neutron starts as $p_{1/2}$ in ^{16}O and $p_{3/2}$ in ^{12}C.

The strong selectivity for high spin states observed in fig. 1 is obtained at the price of a reduced cross section, thus high quality beams of high bombarding energy and a large solid angle spectrometer are crucial to these studies. The data in this paper have been taken at the Brookhaven National Laboratory Double Tandem Van de Graaff Facility, using the QDDD spectrometer.

Before discussing even-even nuclei, the location of the $\nu 13/2$ level in odd mass nuclei should be addressed. The structure of the $\nu 13/2^{+}$ states in the region of ^{146}Gd is thought to be complicated by mixing with the "low-lying" 3^{-} octupole vibration coupled to the $f_{7/2}$ neutron7). In fact, in several nuclei it has been proposed that this is the predominant configuration for the lowest lying $13/2^{+}$ state8). Until about 1974 the low-lying $13/2^+$ states were unknown in this mass region, having been incorrectly identified as $9/2^-$ states. However, a 19-MeV (d,p) experiment$^{9)}$ discovered two $13/2^+$ states in several N = 83 nuclei with most of the strength lying in the lower state, which implies that the lower state has a larger component of $\nu i_{13/2}$.

The spectra for the N = 83 nucleus ^{143}Nd from the ^{142}Nd(^{16}O,^{15}O) and (^{12}C,^{11}C) reactions are shown in fig. 2. The enormous difference in population of $13/2^+$ and $9/2^-$ states with these heavy-ion reactions make it clear which states are $9/2^-$ and confirms that the 1.22- and 2.81-MeV states are $13/2^+$. The $p_{3/2}$ state at 0.74 MeV, strongly populated in the (d,p) spectrum, is nearly invisible here.

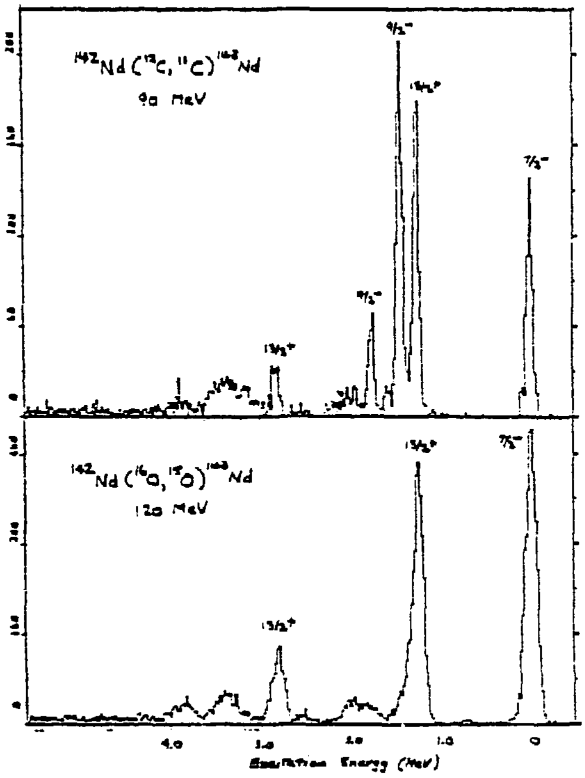


Figure 2. Spectra of ^{142}Nd(^{16}O,^{15}O) and ^{142}Nd(^{12}C,^{11}C) reactions. Note the very strong difference in the population of $9/2^-$ states and that the $13/2^+$ states are strongly populated in both reactions.

We now turn to the even-even nucleus ^{144}Nd where previous single neutron transfer from ^{143}Nd($J^\pi = 7/2^-$) identified only the low-lying 3^-

state as containing any $i_{13/2}$ strength[3]. This nucleus has also been studied by (α,2n) [10,11] and (^{18}O,4n) [12] reactions where spins up to 17^- have been assigned[12]. It has been common in (HI,xn) work to assign the lowest 3^-, 5^-, 7^-, 9^- states to a configuration of $3^- * (f_{7/2})^2$ because the energy spacings are nearly the same as the "$f^2_{7/2}$" multiplet. However, a nearly identical spectrum for these "natural parity" states is obtained by coupling $f_{7/2} * i_{13/2}$ with a delta function interaction. This latter configuration will also have "non-natural" parity states of 4^-, 6^-, 8^-, 10^- at an energy higher than the 9^- state. These even spin negative parity states would not be easily seen in the (HI,xn) experiments as they are non-yrast states. Thus configuration assignments from observed level spacings alone are not reliable.

We see in fig. 2 that with the (^{16}O,^{15}O) reaction only $f_{7/2}$ and $i_{13/2}$ neutrons should be transferred with appreciable cross section so the final states populated in ^{144}Nd with this reaction should have configurations $f^2_{7/2}$ (0^+, 2^+, 4^+ and 6^+) or $f_{7/2} * i_{13/2}$ (3^-....10^-). The relative population of states within these configurations will be modified from the pure shell model expectation of $(2J_f + 1)$ by the reaction mechanism Q value dependence and nuclear structure effects. States with other configurations, such as $3^- * (f_{7/2})^2$, will not be populated strongly. The 10^- state should be particularly strong in transfer since there will be no mixing with the $3^- * (f_{7/2})^2$ configuration (its maximum spin is 9^-).

The spectrum for ^{143}Nd(^{16}O,^{15}O)^{144}Nd is shown in fig. 3. The first point to notice is the few number of levels which are strongly populated up to 4 MeV in excitation energy. Note in particular the very strong state in the spectrum at 3.8 MeV which does not correspond to a known state. The positions of the known lowest 0^+, 2^+, 4^+, 6^+, 3^-, 5^-, 7^-, and 9^- states in ^{144}Nd are indicated on the figure, and it is tempting to make state assignments. However, there are close-lying states which would not be resolved for many of the positive parity states and all of the negative parity states so that these assignments cannot be made from the particle spectrum alone.

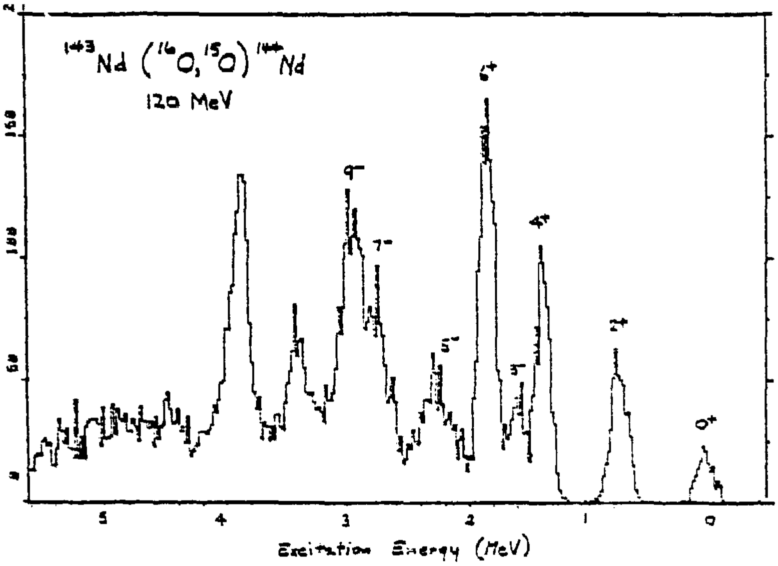


Figure 3. Spectrum of $^{143}Nd(^{16}O,^{15}O)^{144}Nd$ taken at the grazing angle. The energy resolution is about 150 keV.

In order to better determine the states in the particle spectrum, coincidence studies of ^{15}O particles detected in the QDDD and gamma rays in a Ge detector were performed. Two of these gamma-ray spectra are shown in fig. 4; one in coincidence with the peak labeled 9^- and the other with the peak at 3.8 MeV of fig. 3. The only strong gamma rays in coincidence with the peak at 2.9 MeV arise from the known 9^- state at 2.906 MeV established in the $(\alpha,2n)$ work[10,11]. It is interesting to note that there are several 9^- states in the region 2.9–3.5 MeV, but the lowest one gets most of the $i_{13/2}$ strength.

The spectrum in coincidence with the 3.8-MeV peak (fig. 4) shows the same gamma rays with the addition of only one other, at 900keV. Thus this state decays only through the 9^- state. Interestingly, one of the $(\alpha,2n)$ results[10]) did see a weak gamma ray of L = 1 multipolarity of this energy and tentatively assigned a state at 3.806 MeV. An M1 decay of states within

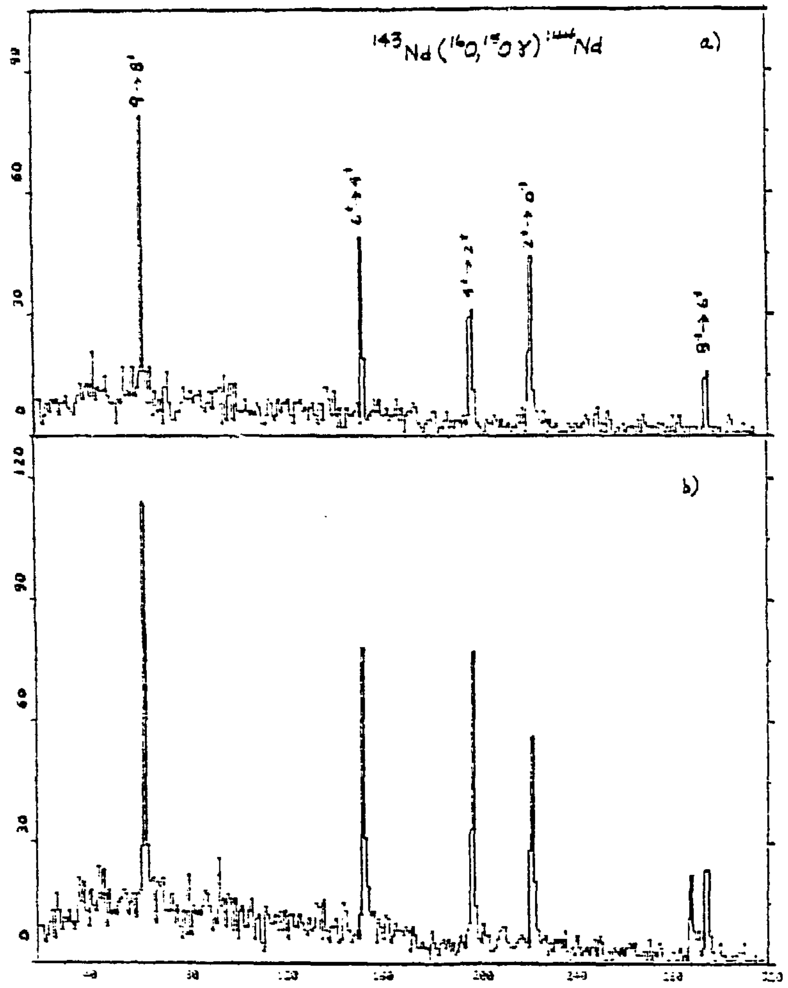


Figure 4. a) Gamma-ray spectrum following the ^{143}Nd(^{16}O,^{15}O)^{144}Nd reaction in coincidence with the ^{15}O peak labeled as 9⁻ in fig. 3

b) Gamma-ray spectrum in coincidence with the ^{15}O peak at an excitation energy of about 3.8 MeV in fig. 3.

the $\nu f_{7/2} * \nu i_{13/2}$ multiplet is expected, and because this state is so strongly populated in transfer, the assignment is most likely to be the $(f_{7/2} * i_{13/2})$ J = 10⁻ state. If this state had spin less than 9⁻, it would be expected to decay via a high-energy gamma ray to the 7⁻ or lower spin state.

Coincidence measurements with lower-lying states indicate the 3⁻ and 5⁻ states are populated very weakly, which indicate they are states of more complicated configuration than $f_{7/2} * i_{13/2}$. The 7⁻, 9⁻, and 10⁻ states, however, have very nearly the same spectroscopic factor as the lowest $i_{13/2}$ state has in ^{142}Nd.

The question arises as to why there is no hard evidence for the 4^-, 6^- and 8^- states. Several factors can hamper the observation of these states. The lower spin states will not be populated as strongly in transfer, but more importantly, there are numerous configurations ($\nu p_{3/2} * \nu i_{13/2}$, $\pi d_{5/2} * \pi h_{11/2}, \ldots$) which can form negative parity states of these spins at approximately the same energy as the even spin $\nu f_{7/2} * \nu i_{13/2}$ states. This configuration mixing does not readily occur for the 10^- state which should be nearly pure.

The coincidence results for with the states labeled with positive parity in fig. 3 confirm that they are the lowest 0^+, 2^+, 4^+, and 6^+ states. An analysis of their cross sectons indicate that all have very nearly the same spectroscopic factor. The relative population of these states is the same with the (^{12}C,^{11}C) reaction, which has strong $h_{9/2}$ transfer (fig. 2). Thus both reactions are consistent with a predominantly ($f_{7/2})^2$ configuration for these states. Note that because of the extreme selectivity of the (^{16}O,^{15}O) reaction, single components of both the positive and negative parity state wave functions are being determined in contrast, for example, to (d,p) studies.

Let me briefly turn to the 4-neutron nucleus $^{148}_{62}Sm_{86}$. The (^{16}O,^{15}O) spectrum is shown in fig. 5 and is seen to be very selective. The spectrum demonstrates that the lowest 0^+, 2^+, 4^+, and 6^+ are not populated as one would expect for an $(f_{7/2})^4$ configuration. Added emphasis is given to this when one compares the (^{12}C,^{11}C) spectrum to these same states (fig. 5). In ^{144}Nd the relative population of these states did not change with inclusion of $h_{9/2}$ transfer. However, in ^{148}Sm the relative population of these states changes so dramatically, it is clear that there is $h_{9/2}$ strength in several of them. The state at 3.534 MeV, however, has the same characteristics as the 3.806-MeV state in ^{144}Nd in that it is strongly populated in (^{16}O,^{15}O)

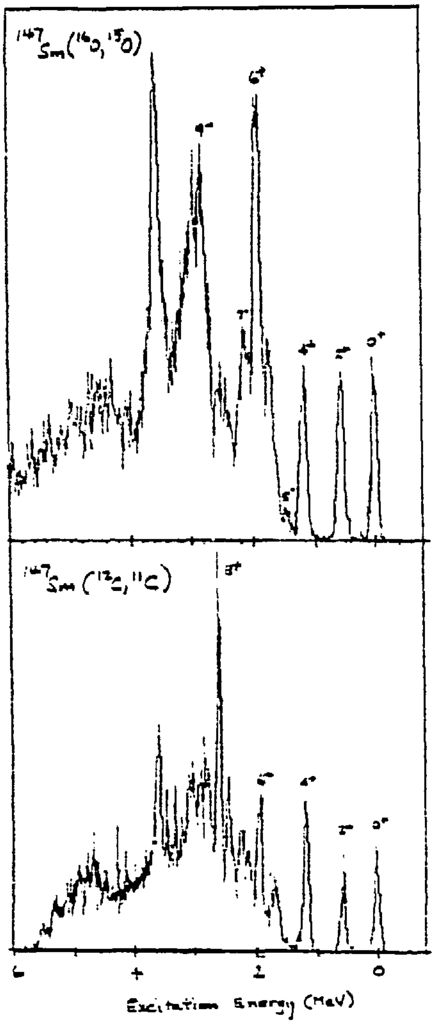


Figure 5. (upper) Spectrum of $^{147}Sm(^{16}O,^{15}O)^{148}Sm$ for 120 MeV bombarding energy and (lower) $^{147}Sm(^{12}C,^{11}C)^{148}Sm$ at 90 MeV bombarding energy. Spectra were taken at the peak of the cross section. The positive parity states in the upper figure result from only $f_{7/2}$ transfer while those in the lower figure from both $f_{7/2}$ and $h_{9/2}$ transfer.

transfer and decays to the 9^- state. Thus it is most likely to be the 10^- state. It should be pointed out that in $(\alpha,2n)$ and $(^3He,3n)$ experiments[14]) a 10^- state was assigned at 3.253 MeV. We see no evidence for that state. One other remarkable state to notice is the 8^+ state at 2.544 MeV which is absent in the $(^{16}O,^{15}O)$ reaction but is the strongest state in the spectrum for $(^{12}C,^{11}C)$. This spectrum determines that it is nearly a pure $(\nu f_{7/2} * \nu h_{9/2})$ configuration.

These heavy-ion-induced transfer reactions have been shown to be very useful in identifying high spin states in spherical nuclei, but one might wonder about their effectiveness in deformed nuclei where the level spacing is much closer and the transfer strength weaker. It has been shown[14]) that strong selectivity is also present in transfer to odd mass deformed Er nuclei, and several previously unknown high-spin orbitals have been identified (fig. 6). A particularly intriguing case to study was in ^{171}Er where the previously unknown $13/2^+$ level belonging to the $9/2^+[624]$ band and the $13/2^+$ member of the $7/2^+[633]$ band were shown to be nearly degenerate (fig. 6). As a result they are highly mixed by the Coriolis interaction.

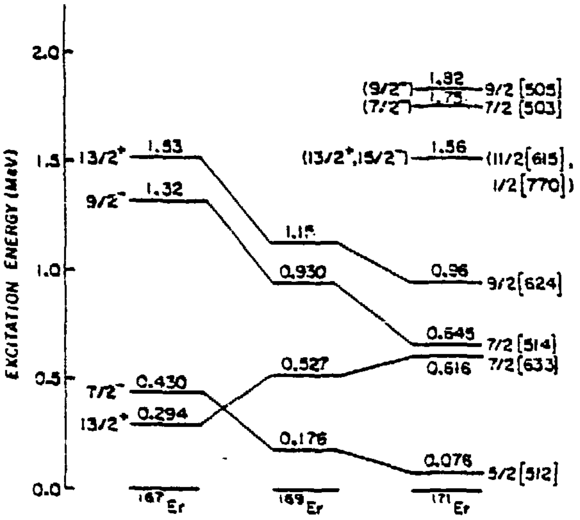
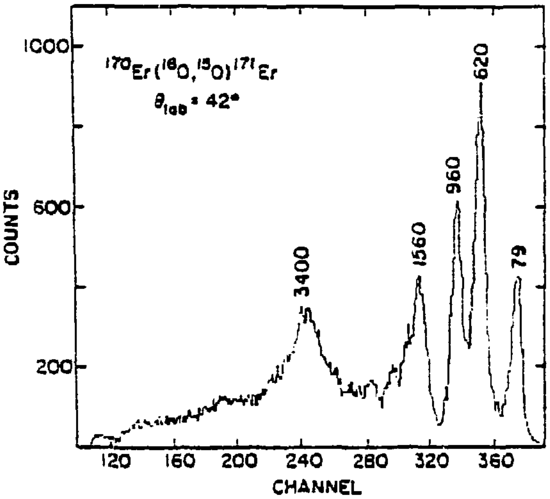


Figure 6. Levels deduced from a comparison of (^{16}O,^{15}O) and (^{12}C,^{11}C) reactions on ^{166,168,170}Er nuclei. Spins of the levels are to the left and Nilsson orbital to the right. Levels quoted to the nearest keV were previously known.

Shown in fig. 7 is the particle spectrum following the (^{16}O,^{15}O) reaction on ^{170}Er. The states at 620 ± 20 and 960 ± 20 keV were assigned as $13/2^+$ states[14]). The lower of these states was seen with the (d,p)

Figure 7. Spectrum of outgoing ^{15}O particles following the ^{170}Er(^{16}O,^{15}O)^{171}Er reaction. Excitation energies in keV are given above the peaks.



reaction15) and assigned as a member of the $9/2^+[624]$ band because the $7/2^+[633]$ band should be nearly filled, and, indeed, the lower $13/2^+$ state is more strongly populated. The systematics shown in fig. 6 make it possible to perform a quasiparticle plus rotor calculation which indicates that the states are strongly mixed, but the lower one has a larger amplitude of $7/2^+[633]$. Using the calculated amplitudes and emptiness factors, the expected ratio of $13/2_1 / 13/2_2$ is calculated to be 1.2, very close to the experimental ratio of 1.4. Despite the fact that the $7/2^+[633]$ is nearly filled, the lower state is more strongly populated because of the strong Coriolis mixing. Without Coriolis mixing the ratio of the transfer strength would be 0.14 or 7.0 depending upon which of the two levels were lower. A clear signature of the relative position of the 7/2[633] and 9/2[624] quasiparticles is the position of the $7/2^+$ state which is unique to the 7/2[633] band, but is not determined by the particle experiment.

In an effort to better determine the structure of these levels, gamma-ray coincidence measurements have been made16). The gamma-ray spectra in coincidence with the two $13/2^+$ states are shown in fig. 8.

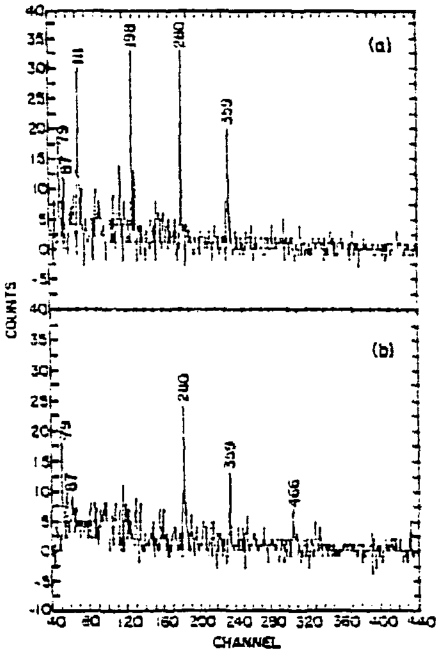


Figure 8. Gamma-ray spectra in coincidence with a) the lower $13/2^+$ state near 620 keV and b) the upper $13/2^+$ state near 960 keV in ^{171}Er. Note that more gamma rays appear in coincidence with the level whose excitation energy is lower and that the 280 and 359 keV transitions are common to both spectra.

The resulting level scheme, based upon the assumption that this is a good rotational nucleus, is shown in fig. 9. Not only is spacing of the two 13/2$^+$ levels determined more precisely, but the lower band members are determined. There is only weak evidence for the dashed transitions in fig. 9. Both the 11/2 → 9/2 and 9/2 → 7/2 transitions are expected to be highly converted, but the 11/2 → 7/2 transition should be observed if it were strong. The presence of the low-lying 7/2$^+$ state unequivocally demonstrates that the 7/2$^+$[633] quasiparticle level is lower lying than the 9/2$^+$[624] level. The same quasiparticle plus rotor calculations described above also reproduce the decay scheme rather well and in particular, the observation that the upper 13/2$^+$ state decays primarily to the lower 11/2$^+$ state. It also reproduces the observed lack of a 11/2 → 7/2 transition. The one remaining major discrepancy is the observed intensity of the 466-keV line out of the 971-keV level which appears to be only about 35% of the decay instead of the calculated intensity of about 74%.

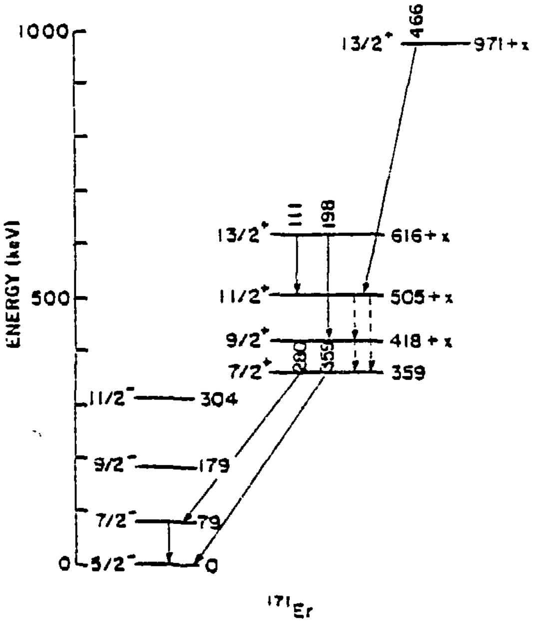


Figure 9. Level scheme derived from particle gamma coincidence measurements in the ^{170}Er(^{16}O,^{15}Oγ)^{171}Er reaction. The value of x is a common uncertainty of about 10 keV which is due to the fact that no gamma ray has been identified which connects the 359 keV level with levels above it. The dashed lines are expected transitions for which there is only weak evidence.

In conclusion, the use of heavy-ion-induced transfer reactions can be extremely useful for spectroscopic studies of high spin states in both near-spherical and deformed nuclei. While the present work has concentrated on single neutron transfer, the field is certainly not limited to that reaction. In the next few years the variety of reactions which are used should expand greatly with the increased energy of accelerators.

I wish to acknowledge my collaborators in various portions of this work, Jean Barrette, Craig Thorn, Andres Kreiner, Cyrus Baktash, Michael Collins, and Ole Hansen. This research was supported by the U. S. Department of Energy, Contract No. DE-AC02-76CH00016.

REFERENCES

1. N. Anyas-Weiss, et al., Phys. Rep. 12C (1974) 201
2. M. Ogawa, R. Broda, K. Zell, P. J. Daly, and P. Kleinheinz, Phys. Rev. Lett. 41 (1978) 289
3. S. Raman, R. I. Auble, J. B. Ball, E. Newman, J. C. Well, Jr., and J. Lin, Phys. Rev. C 14 (1976) 1381
4. W. Oelert, J. V. Maher, D. A. Sink, and M. J. Spisak, Phys. Rev. C 12 (1975) 417
5. For example, J. Rekstad, et al., Nucl. Phys. A369 (1981) 453
6. D. G. Kovar, F. D. Becchetti, B. G. Harvey, F. Puhlhöfer, J. Mahoney, D. W. Miller, and M. S. Zisman, Phys. Rev. Lett. 29 (1972) 1023
7. For example, P. Kleinheinz, Proc. Symp. on High Spin Phenomena, Argonne National Laboratory, ANL/PHY-79-4, 1979, p. 125
8. P. J.Daly, et al., Z. Phys. A 299 (1980) 173
9. W. Booth, S. Wilson, and S. S. Ipson, Nucl. Phys. A229 (1974) 61
10. Ya. Ya. Berzin, et al., Bull. Acad. Sci. USSR, Phys. Ser. 40 (1976) 80
11. L. E. de Geer, A. Kerek, Z. Haratym, J. Kownacki, and J. Ludziejewski, Nucl. Phys. A259 (1976) 399
12. M. A. Quader, T. E. Chapuran, K. Dybdal, W. F. Piel, Jr., D. B. Fossan, and L. K. Peker, Bull. Am. Phys. Soc. 27 (1982) 519; and private communication
13. E. Hammeren, E. Liukkonen, M Piiparinen, J. Kownacki, Z. Sujkowski, Th. Lindblad, and K. Ryde, Nucl. Phys. A321 (1979) 71
14. P. D. Bond, J. Barrette, C. Baktash, C. E. Thorn,
15. P. O. Tjoem and B. Elbek, K. Dan. Vidensk, Selsk. Mat-Fys. Medd. 37 (1967) 7
16. A. J. Kreiner, P. D. Bond, C. Baktash, J. Barrette, C. E. Thorn, and M. T. Collins, Phys. Rev. C 25 (1982) 866 and A. J. Kreiner, Phys. Rev. Lett. 46 (1981) 1565