RECEIVED
CONF-

BNL--37078

DE86 001739

HEAVY ION INDUCED TRANSFER REACTIONS - A SPECTROSCOPIC TOOL FOR HIGH SPIN STATES

P. D. Bond
Brookhaven National Laboratory, Upton, NY 11973

One of the early hopes of heavy ion induced transfer reactions was that new states in nuclei would be preferentially populated. The fact that this hope diminished was due primarily to insufficient understanding of the reaction mechanism, but also to the generally poorer energy resolution obtained with heavy ions as compared to light ions. In this paper, I hope to demonstrate that with the proper kinematical conditions there is a remarkable selectivity which can be obtained with a proper choice of the reaction and that these reactions can be valuable spectroscopic tools. The data in this talk have been taken using beams from the Brookhaven National Laboratory double MP tandem facility with particles identified in the focal plane of a QDDD spectrometer.

Shown in Fig. 1 are spectra for three single neutron transfer reactions leading to known states in the same final nucleus ^{149}Sm. The (^{13}C, ^{12}C) in reaction in Fig. 1 populates final states much as the (d,p) reaction and because of the worse energy resolution this heavy ion reaction is thus not very useful for spectroscopic purposes. The (^{12}C, ^{11}C) and (^{16}O, ^{15}O) reactions on the other hand show a very strong selectivity for high spin states with the latter reaction also showing a strong preference for $j=\ell+1/2$ final states. The reasons for this selectivity are discussed elsewhere [BON83], the purpose here is to use this selectivity for spectroscopic studies.

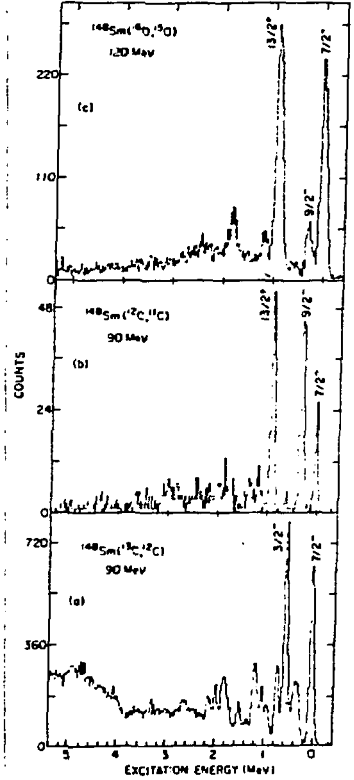

Fig. 1. Single neutron transfer reaction for ^{148}Sm → ^{149}Sm for three different projectiles.

Shown in Fig. 2 is a schematic representation of the shell model states for the region near ^{146}Gd. There has been a great deal of interest in this mass region since it was proposed [OGA78] that a shell closure occurs for Z=64. As in the ^{208}Pb region high spin single particle states are available so that simple configurations are likely to contribute to the structure of high spin states. In particular, near ^{146}Gd the proton $h_{11/2}$ orbital and the neutron $i_{13/2}$ orbital should play an important role, however, there is little direct evidence about the states based on these orbitals. For the Nd isotopes considered here the protons have partially filled the $g_{7/2}$-$d_{5/2}$ levels and the neutrons are beginning to fill orbitals above N=82.

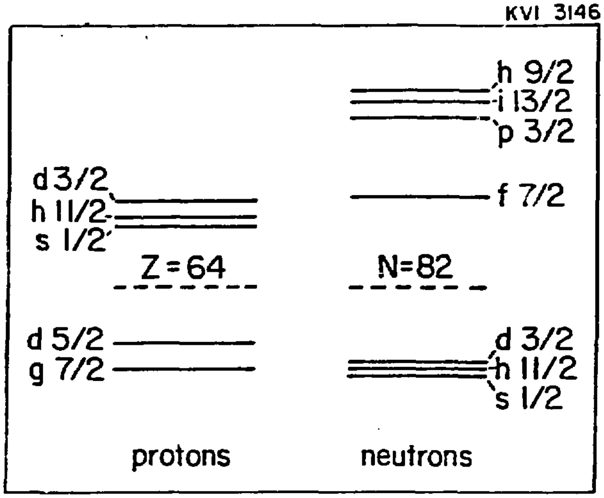

Fig. 2. Schematic representation of shell model orbitals near ^{146}Gd.

We first focus on the previously unknown $i_{13/2}$ neutron strength in the N=84 nucleus ^{144}Nd. An earlier (d,p) study [RAM76] observed no $i_{13/2}$ strength except in the low lying 3^- state. Gamma ray experiments following compound nucleus formation [BER76, GEE76, QUA82] found several negative parity states but all with odd spin (natural parity). The findings are consistent with the supposition that the negative parity states are formed by a 3^- core excitation coupled to two $f_{7/2}$ neutrons producing spins of 3^-, 5^-, 7^-, 9^-. Single nucleon transfer would only weakly populate these states through multistep processes. If, on the other hand, these negative parity states were due primarily to $\nu f_{7/2} * \nu i_{13/2}$ configurations the ordering of the natural parity states would be the same but transfer to these states should be strong. In addition, the unnatural parity states ($J^\pi = 4^-, 6^-, 8^-, 10^-$) of this multiplet should also be seen with the strongest state in the transfer spectrum being the unnatural parity state J^π=10^-. This state would not be easily seen in the xn experiments because it is not yrast.

The selectivity shown in Fig. 1 demonstrates the (^{16}O, ^{15}O) transfer strongly favors transfer to states of $f_{7/2}$ or $i_{13/2}$ character. In bombardment of a ^{143}Nd target, which has J^π=$7/2^-$, the states in ^{144}Nd which should be populated are therefore $(\nu f_{7/2})^2 = 0^+, 2^+, 4^+, 6^+$ and $\nu f_{7/2} * \nu i_{13/2}$ = $3^-, \ldots, 10^-$. In Fig. 3 the spectrum of the ^{143}Nd(^{16}O, ^{15}O)^{144}Nd reaction [COL85] is shown with the location of known states indicated on the figure. For excitation energies up to about 1.5 MeV there is no ambiguity in assignments since other states are not present. However, above that excitation energy the resolution of roughly 100 keV is not sufficient to uniquely identify the states. In order to help determine the spin and excitation of the levels, gamma rays in coincidence with the particle peaks have been measured with an intrinsic Ge detector.

Shown in Fig. 4 are two gamma ray spectra [COL85] one for the peak labeled 9^- in Fig. 3 and one for the particle peak at about 3.8 MeV, which was previously unknown. The upper gamma ray spectrum in Fig. 4 confirms that the peak at 2.902 MeV is indeed the 9^- state seen in previous work [BER76, GEE76, QUA82]. The particle peak at 3.8 MeV shows a nearly identical gamma ray spectrum with the addition of one gamma ray of 900 keV, just the difference in energy between the 9^- state and this state. Since this peak is so

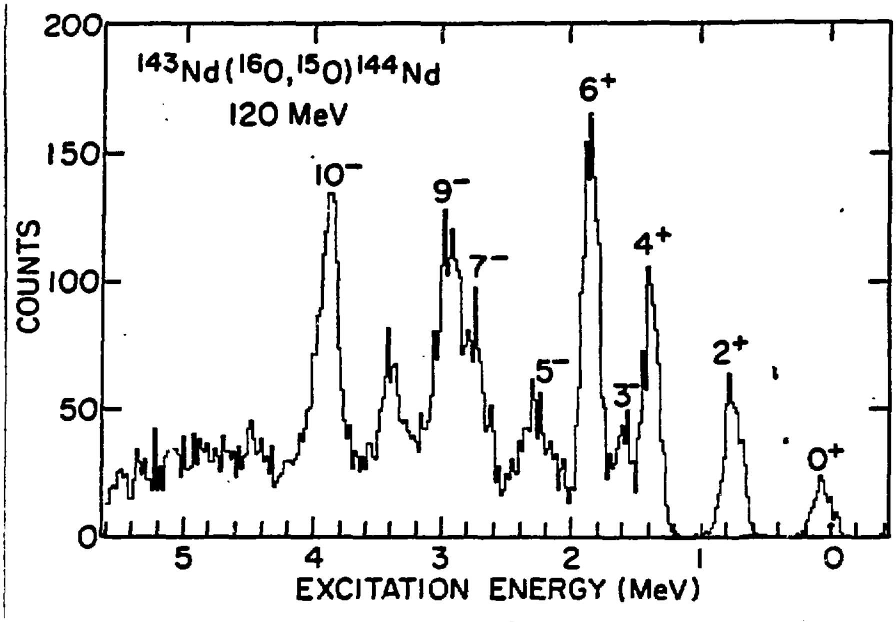

Fig. 3. Spectrum of the ^{143}Nd(^{16}O, ^{15}O)^{144}Nd reaction.

strongly populated in particle transfer and decays primarily to the 9⁻ state it is almost certainly the previously unobserved 10⁻ state. Gamma rays in coincidence with the other labeled peaks in the spectrum confirm they are indeed the states indicated on Fig. 3.

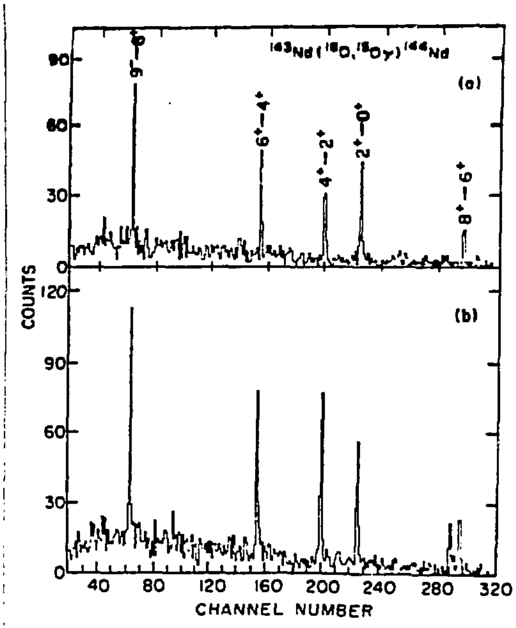

Fig. 4. Gamma rays in coincidence with a) the state at 2.9 MeV and b) the state at 3.8 MeV.

The level scheme of states in ^{144}Nd seen in this experiment are shown in Fig. 5. The structure of the negative parity states are as follows. The low lying 3^- and 5^- state appear to be rather complicated as their population does not follow the (2J+1) population expected for a simple multiplet. In contrast, the 7^-, 9^- and 10^- appear to have equivalent $f_{7/2} * i_{13/2}$ strength and thus have rather simple structure. On the other hand, no evidence is found for the 4^- or 8^- states and only weak evidence that the state at 3.3 MeV is a 6^- state. Configuration mixing is a possible, though not a certain, reason for the absence of these states. In any case, there does not appear to be a simple $\nu f_{7/2} * \nu_{13/2}$ multiplet.

For the positive parity states, the population of the $0^+ \rightarrow 6^+$ states follows (2J+1) which indicates that these states are consistent with being an $(f_{7/2})^2$ multiplet. As can be seen in Fig. 1, the spectrum of the (^{12}C, ^{11}C) reaction leading to ^{144}Nd enhances $h_{9/2}$ transfer. Comparison of the (^{16}O, ^{15}O) and (^{12}C, ^{11}C) spectra clearly shows that the 8^+ state at 2.709 MeV is primarily an $f_{7/2} * h_{9/2}$ configuration. Unfortunately, there are no extensive shell model calculations with which to compare these results.

We turn now to the proton levels in the N=82 nucleus ^{142}Nd. Similar spectra to those of Fig. 1 for proton transfer demonstrate that the (^{18}O, ^{17}N) reaction strongly enhances transfer to $d_{5/2}$ and $h_{11/2}$ proton orbitals. Since the ground state of ^{141}Pr is $5/2^+$ the (^{18}O, ^{17}N) reaction on that nucleus strongly enhances final states in ^{142}Nd of $(\pi d_{5/2})^2 = 0^+$, 2^+, 4^+ and $\pi d_{5/2} * \pi h_{11/2} = 3^- \ldots . 8^-$. The single proton transfer spectrum [BON85] to ^{142}Nd is shown in Fig. 6. Gamma rays in coincidence with these particle peaks have been measured and lead to the level scheme shown in Fig. 5.

The gamma decay of the level at 3.24 MeV is the same as was seen in (α,xn) [GEE75]. The parity of this level, previously assigned a spin of 7 [GEE75], can be assigned as negative since positive parity states up to only spin 4 can be populated. This conclusion is consistent with the results of the (^{3}He,d) [JON71] stripping reaction which saw a strong L=5 peak in this region of excitation energy. The previously unassigned fully aligned 8^- state from the $\pi d_{5/2} * \pi h_{11/2}$ configuration is identified by the strong population in the particle spectrum together with the observed gamma decay to the 7^- state. The assignment of the 8^- state is also consistent with an L=5 stripping peak seen in the (^{3}He,d) reaction [JON71]. The assignment of the 6^- state is more uncertain. A gamma decay to the presumed 5^- state is observed but another unobserved high energy transition must also depopulate this level. A spin 6 level at about the same excitation energy was seen in the (α,xn) experiment and decayed via a 1.245 MeV gamma ray to the 6^+ state but other proposed branches are not seen here. The 6^- assignment is consistent with an L=5 peak seen in (^{3}He,d) [JON71] and further indications that the 3.44 MeV peak is a 6^- peak comes from the expected 2J+1 population of the $d_{5/2} * h_{11/2}$ multiplet. The previously unassigned 5^- state is tentatively assigned at 2.96 MeV but shows no clear cut coincident gamma rays which would be expected to be of rather high energy. The peak at 2.96 MeV does coincide with an L=5 peak seen in (^{3}He,d). Only very tentative evidence is found for the 4^- state which is expected to be weakly populated. The 3^- state, which is nearly degenerate with the first 4^+ state, involves several configurations.

The positive parity states are interesting because two 4^+ states are seen with about equal strength and the previously unobserved decay of the higher one at 2.436 MeV is almost exclusively via a transition to the lower 4^+ state. The positive parity of the higher 4^+ state is determined from the L=2 character of the (^{3}He,d) stripping reaction.

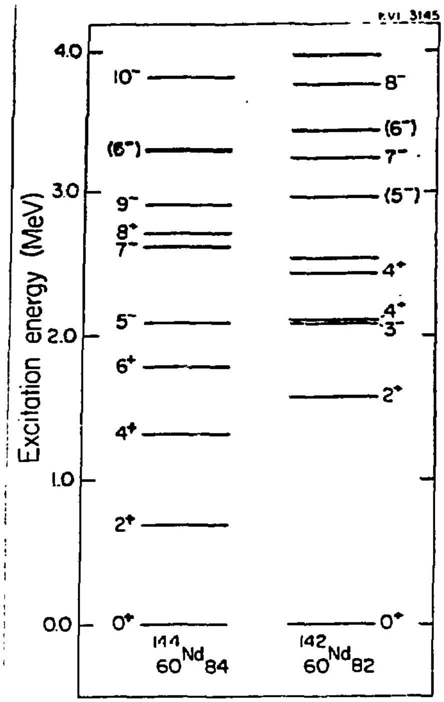

Fig. 5. Deduced levels schemes for ^{144}Nd and ^{142}Nd from the reaction studied here.

Recent shell model calculations [KRU85] for the nucleus ^{142}Nd reproduce both the relative transfer strength to these 4^+ states and gamma ray branching of the upper state very well. In addition, the $d_{5/2}* h_{11/2}$ negative parity multiplet is predicted to be rather pure and the positions of the levels are reproduced to within roughly 100 keV. Thus the understanding of the levels based on these proton orbitals appears to be in rather good shape, in contrast to the neutron levels.

In summary, the selectivity of certain heavy ion reactions have been used to identify two proton and two neutron states of high spin (both yrast and non-yrast) in Nd nuclei. The first direct information about the configurations of some of these states has been obtained and the results suggest simple configurations for some but not all of them. At the same time certain members of the neutron $f_{7/2} * i_{13/2}$ multiplet are not seen and comprehensive shell model calculations would be very useful to determine the reason. Heavy ion induced transfer reactions, if chosen carefully, are valuable spectroscopic tools,

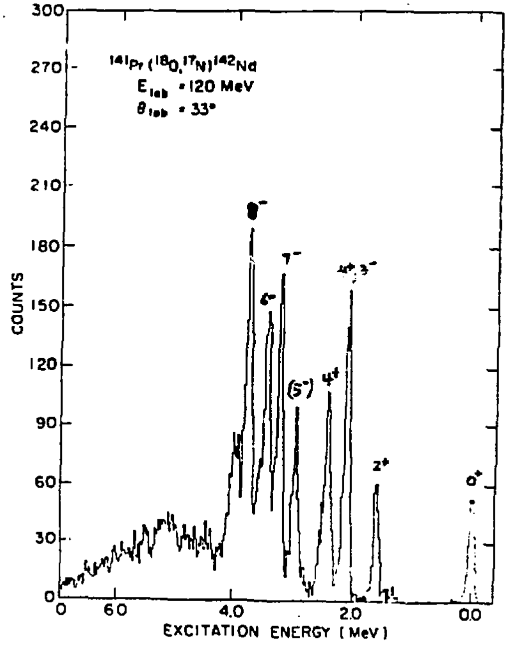

Fig. 6. Spectrum of the ^{141}Pr(^{18}O, ^{17}N)^{142}Nd reaction.

and the unique possibilities available with heavy ions to transfer more massive clusters will assure their continued importance to the field.

This work was supported by the U. S. Department of Energy, Division of Basic Energy Sciences under Contract No. DE-AC02-76CH00016.

References

[BER76]Ya Ya Berzin *et al.* Bull. Acad. Sci. USSR Phys. Ser. 40 80 (1976).
[BON83]P.D. Bond, Comments on Nuclear and Particle Physics 11 231 (1983).
[BON85]P.D. Bond, C.E. Thorn, J. Cizewski and M. Drigert, to be published.
[COL85]M.T. Collins, P.D. Bond, Ole Hansen, C.E. Thorn and J. Barrette, to be published.
[GEE75]L.E. de Geer *et al.*, Nucl. Phys. A246 104 (1975).
[GEE76]L.E. de Geer *et al.*, Nucl. Phys. A259 399 (1976).
[JON71]W.P. Jones *et al.*, Phys. Rev. C 4 580 (1971).
[KRU85]H. Kruse, private communication.
[OGA78]M. Ogawa *et al.*, Phys. Rev. Lett. 41 289 (1978).
[RAM76]S. Raman *et al.*, Phys. Rev. C 14 1381 (1976).
[QUA82]M.A. Quader *et al.*, Bull. Am. Phys. Soc. 27 519 (1982) and private communication.