Selective excitations of α-cluster states in ^{150}Nd

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The α-cluster pickup reaction ^{154}Sm(d,^{6}Li)^{150}Nd has been investigated at $E_d=33$ MeV. The observed spectra are dominated by transitions to the 0^+, 2^+, and 4^+ members of the ground state rotational band in ^{150}Nd and by transitions to newly observed states at $E_x=2050\pm25$, 2225 ± 25, and 2460 ± 25 keV. Spin-parity assignments for the latter group of states are compatible with 0^+, 2^+, and 4^+. The summed reduced α width for this group of excited states, presumably a rotational band, is approximately equal to that for the ground state rotational band. The presence of strongly excited α-cluster states at low excitation energy in the deformed nucleus ^{150}Nd, while not understood, is similar to the situation observed in the deformed actinide nuclei ^{228}Ra and ^{234}Th.

[NUCLEAR REACTIONS ^{154}Sm(d,^{6}Li)^{150}Nd, $E_d=33$ MeV; measured $\sigma(\theta,E_x)$; ^{150}Nd deduced levels, S_α, γ_α^2, rotational bands.]

I. INTRODUCTION

Alpha decay and alpha transfer can independently be used to infer reduced α widths γ_α^2 at large radii, and hence information about α clustering in the nuclear surface. Alpha-transfer reactions such as (^{6}Li,d) and (d,^{6}Li) have extended the range of nuclei which can be investigated from the α unstable to all stable nuclei.[1,2] Moreover, α-spectroscopic information for excited states is easier to obtain in such reactions, since α-pickup cross sections are approximately proportional to the reduced α width in the nuclear surface, whereas α-decay data are often limited to low excited states due to α penetrabilities. Investigations of α-transfer reactions in heavy nuclei are strongly affected, though, by the rapid decrease in cross section with increasing target mass.[3] Despite this difficulty, recent results for actinide nuclei[4] have revealed unusually strong selective excitations of α-cluster states which have become the object of a new theoretical approach.[5] The purpose of the present paper is to report on similar excited α-cluster states observed in the deformed rare-earth nucleus ^{150}Nd.

II. EXPERIMENTAL PROCEDURES

Targets of enriched ^{154}Sm, about 200 μg/cm^2 thick, were bombarded with 33 MeV deuterons from the Brookhaven National Laboratory double tandem Van de Graaff facility. The ^{6}Li particles from the (d,^{6}Li) reaction were detected and identified in the focal plane of the BNL quadrupole-dipole-dipole-dipole (QDDD) magnetic spectrometer[6] with a position-sensitive gas proportional counter system. The investigation reported here is part of a more comprehensive study[7,8] of (d,^{6}Li) α pickup on targets of Ce, Nd, Sm, and Gd with $N\geq82$. The target ^{154}Sm is the most neutron rich and most deformed target included in the more recent work.[7]

III. EXPERIMENTAL RESULTS

Figures 1 and 2 display the spectra obtained at angles of $\theta=16°$ and 22°, respectively. They cover a range of about 3 MeV. The energy resolution of about 80 keV was sufficient to resolve most states. The small cross sections, typically 0.1 μb/sr, required long exposure times ($\sim$14 h or $\sim$10 000 μC at 16°). Known and newly identified energy levels are indicated in the figures. Excitation energies, spin-parity assignments, and cross sections at $\theta=16°$ are included in Table I. Excitation energies for new states are given with uncertainties. The excitation energy for the (3^-) state at 940 ± 20 keV is a revised value. The spectra are characterized by

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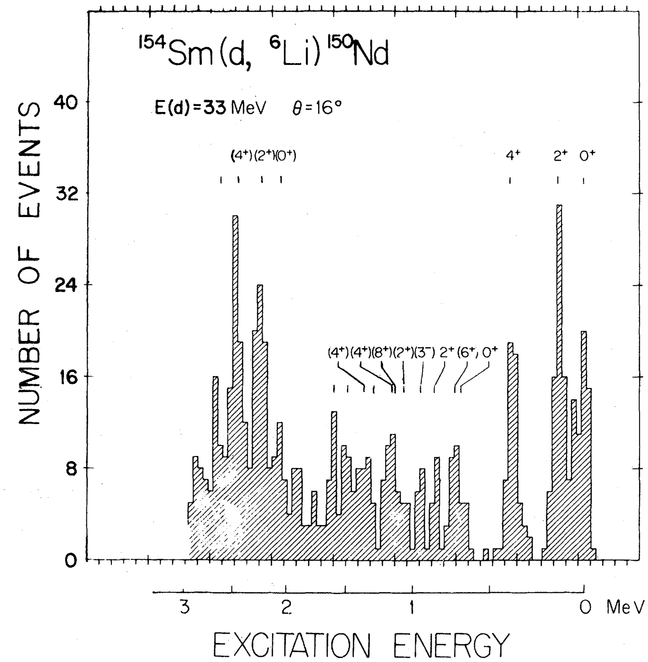

FIG. 1. Energy spectrum of ^{6}Li particles at $\theta=16°$ from the reaction ^{154}Sm(d,^{6}Li)^{150}Nd.

strong transitions to the low-spin members of the ground state (g.s.) rotational band and, with essentially the same cross section, to several states in the range $E_x=2.0-2.5$ MeV.

The signature of the spectra observed in ^{150}Nd is very different from that obtained for the less neutron-rich transitional rare-earth target nuclei.[7,8] The α-spectroscopic strengths for the lighter targets

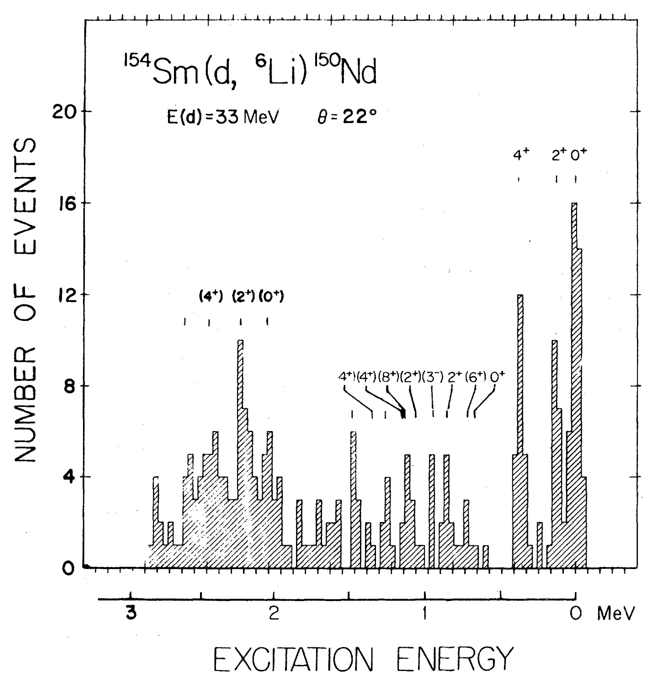

FIG. 2. Energy spectrum of ^{6}Li particles at $\theta=22°$ from the reaction ^{154}Sm(d,^{6}Li)^{150}Nd.

TABLE I. Data from ^{154}Sm$(d,{}^6$Li$)^{150}$Nd.

E_x[a] (keV)	J^π	$\frac{d\sigma}{d\Omega}$[d] (nb/sr)	$S_\alpha^{\rm rel}$[e]	$\gamma_\alpha^2(s)$[f] (eV)
0	0^+	143±18	1.00	62
130	2^+	180±21	1.77	101
383	4^+	126±17	2.17	100
677	0^+	23±7	0.14	8
721	(6^+)	54±11	2.84	93
851	2^+	35±9	0.42	22
940±20	(3^-)	37±9	0.44	17
1062	(2^+)	26±8	0.30	15
1131	(8^+)	80±14 (1131 and 1139)		
1139	(4^+)			
1265±20		14±6		
1354[b]	(4^+)	70±13		
1485±25		42±10		
1600±25		63±12		
2050±25	(0^+)[c]	77±13	1.01	48
2225±25	(2^+)[c]	182±21	2.70	116
2460±25[b]	(4^+)[c]	208±22	(2.58)	(90)
2620±25		75±13		

[a]Excitation energies with uncertainties from this work; other energies from C. M. Baglin, Nucl. Data Sheets 18, 223 (1976).
[b]Possibly unresolved doublet.
[c]Tentative assignments from this work.
[d]Differential c.m. cross sections obtained at $\theta=16°$.
[e]Relative α-spectroscopic factor normalized to the ground state. [Absolute S_α (g.s.)$=0.007$ to 0.2 depending on formfactor geometry.]
[f]Reduced α width at channel radius $s=1.7A^{1/3}$ fm normalized (factor 0.48) to the α decays of ^{144}Nd, ^{148}Sm, and ^{152}Gd (see Ref. 9). The relative and absolute uncertainties are estimated at $\pm25\%$ and $\pm50\%$, respectively.

are strongly concentrated in the ground state transitions, and the cross sections are larger. Neutron pairing vibration states at $E_x \gtrsim 3$ MeV are observed[7] for the residual nuclei with $N=82$, but these states seem to be fragmented for $N>82$ (see also the discussion below).

IV. DWBA ANALYSIS, α-SPECTROSCOPIC FACTORS, AND REDUCED α WIDTHS

The cross sections for the various states measured at the two selected angles were used to deduce spectroscopic factors S_α and reduced α widths $\gamma_\alpha^2(s)$. The three strong states in the range $E_x=2.0-2.5$ MeV are given tentative assignments of $J^\pi=0^+$, 2^+, and 4^+. This is based on the comparison of the $22°/16°$ cross sections with those for the known g.s. rotational band, on the relative strengths within the bands, and on the energy spacing. The finite-range DWBA analysis utilizes procedures and parameters identical to those used earlier[9] in the analysis of the ground state transitions of ^{144}Nd$(d,{}^6$Li$)^{140}$Ce, ^{148}Sm$(d,{}^6$Li$)^{144}$Nd, and ^{152}Gd$(d,{}^6$Li$)^{148}$Sm. These three target nuclei are long-lived α emitters, and absolute reduced α widths $\gamma_\alpha^2(s)$ can therefore be obtained for this mass region.

Macroscopic α-cluster wave functions used to construct form factors were generated in a Woods-Saxon plus Coulomb potential well ($r_0=r_{0C}=1.4$ fm; $a=0.65$ fm). Harmonic oscillator quantum numbers $2N+L=18$ ($=17$ for negative parity states) determine the number of radial nodes. The relative motion wave function for $^6\text{Li}=\alpha+d$ was generated by a hard-core potential, as discussed elsewhere.[9] The reduced α widths $\gamma_\alpha^2(s)$ of Table I are normalized to the α decays of ^{144}Nd, ^{148}Sm, and ^{152}Gd ($\mathcal{N}=0.48$) and are therefore absolute. The channel radius was taken as $s=1.7A^{1/3}$ fm. Spectroscopic factors S_α are strongly model dependent, and only relative values are therefore given in Table I.

V. DISCUSSION

The cross sections for α pickup to states in ^{150}Nd are about equal to those observed earlier[4] for deformed actinide nuclei ($A\approx230$). However, the excitation energies for members of rotational bands in ^{150}Nd are increased by a factor of about 2 due to the reduced moment of inertia, and the states are well resolved.

Only the low-spin members of the ground state rotational band and a group of states in the range $E_x=2.0-2.5$ MeV, presumably also a rotational band, are excited strongly in ^{150}Nd. The level at 2460 keV may be a doublet (see Fig. 2). Many additional states in the range $0.5-2.0$ MeV are excited weakly. This includes the 0^+, 677 keV state and the (3^-), 940 keV negative parity state.

The combined reduced widths γ_α^2 for the excited group of states (only 50% of the cross section is included for the 2460 keV level) is essentially equal to that for the low-spin members of the ground state band. This result is practically independent of the assumed spins and parities for the excited states. The ratio of the respective cross sections at $\theta=16°$ is also nearly unity, which reflects the fact that α-pickup cross sections are approximately proportional to the square of the α-cluster wave function in the nuclear surface and therefore to the probability of finding an α particle at a given radius.

This unusually strong population of excited α-cluster states is very similar to results obtained earlier[4] for the reactions ^{232}Th(d,^{6}Li)^{228}Ra and ^{238}U(d,^{6}Li)^{234}Th. Here, *three* groups of excited states in both ^{228}Ra and ^{234}Th are populated strongly in addition to the low-spin members of the ground state rotational bands. It was concluded that at least the first group of excited states, if not all, are rotational bands based on $J^\pi=0^+$. Another similarity is the fact that negative-parity states are populated much more weakly. The presence of excited α-cluster states in actinide nuclei and the observation of small reduced α-decay hindrance factors (typically ~ 7) for several 0_2^+ states is not understood even though much more experimental information is available than for ^{150}Nd.

Excited 0^+ states in the actinide nuclei and the rotational bands based on them have additional unusual properties (see discussion and references quoted in Ref. 4). The excitation energies of the 0_2^+ states are quite low with local minima of $E_x \approx 650$ keV at $A=230$ and $E_x \approx 900$ keV at $A=240$. Intruder bands with $K^\pi=0^+$ are observed, particularly at $A=236-238$, characterized by strong electromagnetic transitions between the bands. Strong (p,t) two-neutron pickup to the 0_2^+ states has been observed over the entire range of actinide nuclei,[10] which contradicts the interpretation of these levels as bandheads of β-vibrational bands, despite the fact that strong $E0$ transitions between corresponding levels of the (quasi) β band and the ground state band are often observed.[11,12] As pointed out by Sheline,[13] a strong correspondence exists between the excited bands based on $K^\pi=0^+$ and $K^\pi=0^-$ ($J^\pi=1^-, 3^-, \ldots$) as is evidenced by the A dependence of the moments of inertia and of the excitation energies (local minima of $E_x \approx 300$ keV at $A=224$ and $E_x \approx 77$ keV at $A=238-240$). This suggests a generic structural relationship based on a coexistence between quadrupole and octupole shapes, particularly in the lower part of the region of deformed nuclei.

Various theoretical models have been applied with some degree of success, most prominently the concept of pairing isomers.[14,15] Very recently, a new phenomenological approach based on the interacting boson model (IBA) has been introduced[5] to describe α clustering in heavy nuclei and the observed electromagnetic, two nucleon, and α-transfer amplitudes. Here, additional s^* and p^* bosons are assumed to represent α-particle condensates, whereas the s and d bosons used in standard IBA account for the normal collective features of nuclei. The model generates low-lying negative parity states, one of the salient features of these nuclei.

The nucleus ^{150}Nd belongs to the transitional Nd, Sm, and Gd isotopes, which exhibit shape transitions at $N=88$ and 90 between spherical and deformed shapes. They have been investigated by means of the (p,t) (Refs. 16–20) and (t,p) (Refs. 21 and 22) reactions, particularly between 0^+ states. The coexistence is manifest by strong $2n$ stripping from the spherical ground states with $N=88$ to spherical excited states with $N=90$ and by strong $2n$ pickup from the deformed ground states with $N=90$ to deformed excited states with $N=88$. This behavior is very well described[23] by IBA on the basis of s and d bosons.

The 0^+, 677 keV state in ^{150}Nd is indeed excited very strongly[22] in (t,p), suggesting spherical shape. The (p,t) reaction to this state cannot be observed, but the strength relative to the ground state for the transitions to the corresponding states in ^{152}Sm (688 keV) and ^{154}Gd (681 keV) is about 10–15%. The relative strength from Table I of $\gtrsim 10\%$ observed in (d,^{6}Li) is compatible with this and explains the weak population. Additional 0^+ states in ^{152}Sm at 1091 and 1662 keV and in ^{154}Gd at 1293 keV are practically not populated at all in the (p,t) reaction. Corresponding states may well exist in ^{150}Nd but are, of course, also not populated in the (d,^{6}Li) reaction.

Whereas in ^{228}Ra and ^{234}Th the excited α-cluster states are based on the *lowest* excited 0^+ state, this is not the case in ^{150}Nd. Also, the excitation energy of 2050 keV for the observed band in ^{150}Nd is not substantially below the pairing gap. A 0^+ neutron pairing vibration state is observed[16] in the $N=82$ nucleus ^{142}Nd at 2900 keV, but no strong transitions to such states are seen[16–20] with (p,t) in any Nd, Sm, or Gd nucleus with $N>82$. It is concluded[24] that the pairing vibrational strength is strongly fragmented and not readily detectable. It thus follows that the strong and selective excitation via (d,^{6}Li) in ^{150}Nd of a group of states in the range $E_x=2.0-2.5$ MeV, presumably a rotational band, involves a new type of α-cluster state.

Only two heavier rare-earth nuclei, ^{156}Gd and ^{162}Dy, have so far been investigated[3,8] via (d,^{6}Li) but only for the ground states and up to $E_x \approx 1400$ keV, respectively. No strong transitions to excited states were observed. The experiments are difficult because of small cross sections and the need for good particle identification in the presence of an α-particle background which is many orders of magnitude stronger.

The nucleus ^{156}Gd is of considerable interest in the above context. An extraordinary amount of experimental information is now available[12] for this nucleus, and seven rotational bands up to $J=10$ and beyond are well established. The most striking fact is the presence of *two* rotational bands based on $K^\pi=0^+$ with bandheads of 1049.4 and 1168.1 keV. The former is generally referred to as a β band, partly because of observed strong $E0$ transitions between corresponding states in this band and the ground state band.[12] The latter is generally referred to as an intruder band. It is not clear whether the presence of such intruder bands is a more general phenomenon or is due to the sudden transition with increasing neutron number N for $Z=64$ from shell closure to strong deformation due to the n-p force between spin-orbit partners.[25]

Preliminary attempts[26] to describe both of these bands have been made using IBA by introducing two additional bosons, s' and d'. Energy levels are described well. The physical contents of these additional bosons is not quite clear.

A detailed IBA calculation[12] based on s, d, and f bosons describes the excitation energies of both positive and negative parity states in ^{156}Gd very well. The intruder band, as expected, is not reproduced. This nucleus appears to be a good example of the SU(3) rotational limit of IBA, thus identifying the $K^\pi=0^+$ band with the bandhead at 1049.4 keV as a β-vibration band. This result appears to be at variance with the strong transition[18,19] (approximately 15% of g.s.) in (p,t) two-neutron pickup to this state. The transition to the intruder bandhead is also relatively strong (approximately 2.4% of g.s.). Data for this region of rare-earth nuclei ($N=86$ to 96) including the deformed Gd isotopes show a relatively strong and stable population in (p,t) of usually a single excited 0^+ state with about 15% of the ground state strength. While not nearly as stable and covering a smaller range, the situation is quite similar to that observed in the actinide nuclei.[10] Indeed, it is for this reason that Fleming *et al.*[18] discussed their observations in terms of the same theoretical models which were invoked in the actinide nuclei.

A simple IBA calculation[4] over the entire range of actinide nuclei reproduces energy spectra including the 0_2^+ states quite well but is in complete disagreement with the observed (p,t) and $(d,{}^6\text{Li})$ spectroscopic strengths. The same disagreement for the two-nucleon pickup strength follows from the comparison with analytical theoretical expressions[27] derived in the extreme SU(3) limit of IBA. Similar results probably apply to ^{156}Gd, and the lower (p,t) strength makes the 0^+ state at 1168.1 keV the more likely candidate for the bandhead of a possible β-vibrational band.

It is concluded that in addition to the "actinide puzzle"[1] there appears to exist a "rare-earth puzzle" which seems to require an extension or modification of the concept of β vibrations to include possible α condensation.

VI. SUMMARY

Unusually strong excitations of α-cluster states are observed in the deformed nucleus ^{150}Nd. The combined reduced α widths for this group of excited states, presumably a rotational band based on $K^\pi=0^+$, observed in $^{154}\text{Sm}(d,{}^6\text{Li})^{150}\text{Nd}$ is about equal to that for the low-spin members of the ground state rotational band. This result appears similar to the situation observed in deformed actinide nuclei. Present theoretical models including IBA do not adequately describe the data.

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