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Coulomb excitation of ^{144,146,148,150}Nd

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Coulomb excitation of $^{144,146,148,150}_{60}$Nd by 10.5 and 11 MeV alpha particles was studied by magnetic analysis of particles scattered into 150°. Values of $B(E2;0^+\to2^+)$ for the 2^+ states at 696, 454, 302, and 130 keV are 0.58(1), 0.78(1), 1.390(20), and 2.816(35) e^2b^2, respectively. For ^{148,150}Nd, values of $B(E3;0^+\to3^-)$ for 3^- states at 999 and 932 keV are 0.40(8) and 0.18(3) e^2b^3, respectively. For ^{148,150}Nd the hexadecapole transition matrix elements were deduced to be 0.36^{+10}_{-12} and 0.25(12) e b^2, respectively. Our measurements are compared to others and to interacting boson model predictions.

I. INTRODUCTION

Nuclei whose isotopes have a wide range of deformation in their ground states are particularly useful for testing nuclear structure models as well as for understanding the role of deformation in reactions between complex nuclei. The neodymium isotopes are such nuclei, as the lightest stable ones are spherical (^{142}Nd is neutron magic with $N=82$) and the heaviest stable one is deformed (^{150}Nd with $N=90$).

We have studied ^{144,146,148,150}Nd using Coulomb excitation by alpha particles. We deduced values of $B(E2;0^+\to2^+)$ for $I^\pi=2^+$ states in all of these nuclei, $B(E3)$ values for the lowest lying 3^- states in ^{148,150}Nd, and the hexadecapole transition matrix elements $\langle 0^+\|M(E4)\|4^+\rangle$ in ^{148,150}Nd. (A preliminary report of our ^{150}Nd studies has already appeared.[1]) Such experimental quantities provide stringent tests of nuclear structure models. For example, the interacting boson approximation model[2,3] has been used to explain systematic trends of nuclear properties over mass regions which vary widely in numbers of nucleons and in structural behavior. Indeed, already the data reported here were used recently[4] to clear up a problem in interacting boson approximation (IBA) calculations where the effective charge for neutrons was reported[5] to be larger than for protons, in contrast to shell model calculations. There we showed that when the mass dependence originating from g-boson renormalization effects is taken into account, the proton effective charge is larger than the neutron effective charge.[4] These data also facilitate interpretations of other kinds of experiments, such as gamma ray yields in heavy-ion Coulomb excitation studies, and help test reaction mechanism theories, such as for (p,p′), (n,n′), and (α,α'). The experimental details of our work are reported here.

II. THE EXPERIMENT

The Coulomb excitation of ^{144,146,148,150}Nd was accomplished by using 10.5 and 11 (in the case of ^{150}Nd only) MeV ^{4}He ions from the Oak Ridge National Laboratory (ORNL) EN tandem Van de Graaff accelerator. These beam energy choices were governed by Coulomb-nuclear interference studies[6,7] of some neighboring nuclei, as well as to achieve the same distance of closest approach as in our previous experiments.[8] The scattered particles were detected at a laboratory angle of 150° after being momentum analyzed by the ORNL Enge split-pole magnetic spectrometer. The detection system consisted of a position-sensitive gas-flow proportional counter mounted in the spectrometer focal plane. Efficiency and linearity calibrations of the system were made by measuring the yields and positions of the two most intense α groups in the decay of ^{244}Cm as functions of the magnetic field strength.

The targets were thin, $\sim50\ \mu$g/cm^2, and of high purity, $>99\%$ in isotopic purity. These were prepared at the ORNL 180° isotope separator. The backings were ~80 μg/cm^2 carbon foils.

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III. ANALYSIS AND RESULTS

Figure 1 shows the typical spectrum of α particles scattered from ^{144}Nd. Initially, one goal of this experiment was to measure $B(E2)$ and $B(E3)$ values for other states than those given in the Introduction. However, as evident in the spectra, target contaminants were present. These masked such states in most cases. Just prior to making the targets, some Sn targets were produced. We believe that complex ions of Sn and Ta with carbon or oxygen passed through the isotope separator onto our targets.

After obtaining peak areas the experimental ratios of inelastic-to-elastic scattering differential cross sections were obtained and compared to those calculated using the semiclassical coupled channels Coulomb excitation code of Winther and de Boer,[9] modified for $E3$ and $E4$ excitations as well as for thick targets.[10] In the case of ^{150}Nd, however, the quantum mechanical code AROSA (Ref. 11) was used because of the significant differences between the two approaches for 4^+ excitations. In the case of ^{148}Nd, corrections for the quantum mechanical effects were incorporated by adjusting the experimental 4^+ state yield by the size of the corrections ($\sim 8\%$) and comparing the adjusted cross section to the cross sections semiclassically calculated as a function of $M(E4)$.

These Coulomb excitation calculations are model independent in that relative matrix elements which connect

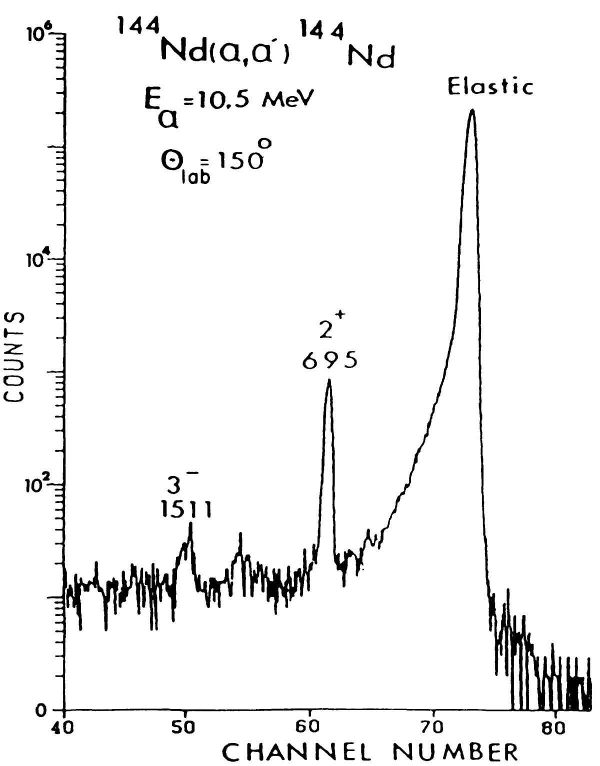

FIG. 1. The energy spectrum of alpha particles elastically and inelastically scattered from ^{144}Nd. The energies of the 2^+ and 3^- states are in units of keV and are given in the figure above the peaks corresponding to those excitations.

the states of interest are input parameters. Using AROSA to deduce $B(E2;0^+\to2^+)$ and $M(E4;0^+\to4^+)$ in ^{150}Nd, we first coupled the ground band 0^+, 2^+, and 4^+ states by using relative values of $M(E2;2^+\to4^+)$ and $M(E2;0^+\to2^+)$ derived from the lifetime measurements of Yates *et al.*[12] The nucleus ^{150}Nd is softly deformed and its ground band level energies and lifetimes deviate[12] somewhat from rigid rotor predictions. The relative $E4$ matrix elements as well as $M(E2;2^+\to2^+)$ and $M(E2;4^+\to4^+)$ were from rigid rotor relations. The matrix elements

$$M(E2;0^+\to2^+)=\langle 0^+\|M(E2)\|2^+\rangle$$

and

$$M(E4;0^+\to4^+)=\langle 0^+\|M(E4)\|4^+\rangle ,$$

to which the other $E2$ and $E4$ matrix elements are relative, are then taken as free parameters. To correct the calculated cross sections for neglected couplings to the 6^+ and vibrational states (and to calculate excitation cross sections for the latter), large-basis semiclassical calculations were performed and the two approaches compared. Rigid rotor relations were also assumed for those additional couplings except for $M(E2;4^+\to6^+)$, which was deduced from the 6^+ lifetime.[12]

For the 2^+ and 3^- states in ^{146,148}Nd the semiclassical code was used, coupling the levels 0_1^+, 2_1^+, 4_1^+, 0_2^+, 2_2^+, and 2_3^+ using relative $E2$ matrix elements and signs taken from the IBA model. The 3^- level was included by direct $E3$ excitation only. For ^{144}Nd, the 0_1^+, 2_1^+, 4_1^+, 3^-, and 2_2^+ levels were coupled. Here we used matrix elements from the study of Crowley, Kerns, and Saladin.[13]

The value of $M(E4)$ in ^{148}Nd was extracted by using $E2$ and $E4$ matrix elements of the IBA model. If one does not distinguish between neutron and proton bosons, then the $E4$ operator has only a single term

$$T(E4)=e_4(d^\dagger\tilde{d})^{(4)}$$

where e_4, the boson $E4$ effective charge, can be adjusted to reproduce $B(E4;0^+\to4^+)$. If one allows for neutron and proton bosons a similar picture holds, since the low-lying states are, to a large extent, symmetric in neutron and proton degrees of freedom. Then, for these states, only the sum of neutron and proton effective charges is important.

Our results along with those from other electromagnetic experimental studies are shown in Table I. The values of $M(E4)$ for ^{148,150}Nd shown in Table I are the positive ones that result from the quadratic relationship between the 4^+ cross section and $M(E4)$ where there is an interference between the direct $E4$ excitation and two-step $E2$ excitation. The positive values of $M(E4)$ are the theoretically expected ones in the light rare-earth region.

IV. DISCUSSION

As seen in Table I, other results where available are in good agreement with our generally more accurate measurements. Although the uncertainties are large, the value of $M(E4)$ for ^{148}Nd may be slightly larger than for

TABLE I. $B(E\lambda;0^+\rightarrow\lambda^\pi)$ values for $I^\pi=2^+$, 4^+, and 3^- states in ^{144,146,148,150}Nd from the present study and from other studies. Here, $\lambda^\pi=I^\pi$.

Nucleus	E (keV)	$I^\pi K$	$B(E\lambda:0^+\rightarrow\lambda^\pi)$ (e^2b^λ) Present study	Other studies		
^{150}Nd	130	2_0^+	2.816(35)	2.80(15)[a]	2.75(8)[b]	2.72(4)[c]
	381	4_0^+	0.25(12)[d]		$0.30(^{+7}_{-6})$[c,d]	
	851	2_0^+	0.015(3)	0.0121(22)[e]		
	932	3^-	0.18(3)	0.175(20)[f]		
	1062	2_2^+	0.076(5)	0.078(12)[e]	$0.064(^{+3}_{-4})$[f]	
^{148}Nd	302	2_0^+	1.390(20)	1.416(48)[e]	1.36(3)[g]	
	753	4_0^+	$0.36(^{+10}_{-12})$[d]			
	999	3^-	0.40(8)			
^{146}Nd	454	2_0^+	0.78(1)	0.81(7)[e]	0.760(22)[g]	
^{144}Nd	696	2_0^+	0.58(1)	0.56(6)[e]	0.510(16)[g]	

[a]Reference 12.
[b]Reference 16.
[c]Reference 17.
[d]The value of $M(E4)=[B(E4)]^{1/2}$ is given.
[e]Reference 15.
[f]Reference 18.
[g]Reference 13.

^{150}Nd. This is somewhat surprising because in the SU(3) limit of the IBA model,[2] corresponding to axially symmetric deformed nuclei, $M(E4)$ increases linearly with the number of bosons, while in the SU(5) spherical limit,[3] this matrix element is forbidden. One therefore expects to see a rapid increase in $M(E4)$ going from lighter to heavier Nd isotopes.

To compare to IBA predictions and to results from nucleon scattering the $B(E2)$ values from the different studies for the first 2^+ states were error-weight averaged. These are presented in Table II along with the IBA predictions of Scholten *et al.*[4] and with the results deduced from the neutron scattering experiments of Haoaut *et al.*[14] Those IBA predictions[4] considered both proton and neutron degrees of freedom. While not important in the calculations of Coulomb excitation where relative matrix elements were used, these IBA calculations were performed with an $E2$ operator generalized to include an additional term which accounts for strong coupling between the *s-d* boson space and *g* bosons ($J=4$ collective pairs), via the neutron-proton quadrupole-quadrupole interaction. The neutron and proton boson effective charges are thus mass independent. This treatment[4] leads to better agreement with experiment than previously found by Fahlander *et al.*[15] It should be realized that the experimental values $M(E2)$ quoted by us (Ref. 4, Table I) are the $|\sqrt{B(E2;0^+\rightarrow2^+)}|$ values. The calculated matrix elements $M(E2)$ are the reduced matrix elements and are the same whether it is $0^+\rightarrow2^+$ or $2^+\rightarrow0^+$ transition. The IBA predictions are in good agreement with the Coulomb excitation results. We deduced $B(E2)$ values from the neutron scattering results[14] by squaring the quadrupole moments of the real part of the optical model potential used in the analysis of the scattering. This invokes Satchler's theorem[19,20] which relates the multipole moments of the real part of the optical model potential to the moments of the matter distribution, assuming a density-independent interaction and equal neutron and proton distributions. The neutron scattering results are systematically larger than the Coulomb excitation results but have large uncertainties.

In summary, we have measured $B(E2)$ values for the first excited 2^+ states in ^{144,146,148,150}Nd, the second and third excited 2^+ states in ^{150}Nd, the lowest lying 3^- states in ^{148,150}Nd, and $\langle 0^+\|M(E4)\|4^+\rangle$ in ^{148,150}Nd. Other measurements, where available for comparison, are in good agreement with our generally more accurate results. The IBA model nicely reproduces these results for the $E2$ matrix elements but predicts the trend opposite to that observed for the $E4$ matrix elements in ^{148,150}Nd. The comparison between $B(E2)$ values for first 2^+ states obtained in electromagnetic studies and those deduced from neutron inelastic scattering suggests that more hadronic scattering experiments on the Nd isotopes would be useful.

TABLE II. $B(E2)$ values of the first 2^+ states in ^{144,146,148,150}Nd from averaging the electromagnetic measurements (EM) given in Table I are compared to predictions (Ref. 4) of the IBA model and to values deduced from inelastic neutron scattering (Ref. 14). The errors in the (nn′) results reflect quoted (Ref. 14) 5% uncertainties in deformation parameters.

Nucleus	$B(E2;0^+\rightarrow2_1^+)$ (e^2b^2) EM	IBA	(n,n′)
^{150}Nd	2.773(35)	2.75	2.41(25)
^{148}Nd	1.385(16)	1.20	1.70(17)
^{146}Nd	0.777(10)	0.78	1.14(12)
^{144}Nd	0.560(9)	0.43	0.70(7)

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