Test of octupole coupled 5^- state in ^{146}Nd using proton inelastic scattering

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(Received 14 June 1991)

The inelastic scattering of 35 MeV protons has been used to excite seven states below 2.1 MeV in ^{146}Nd. A comparison between a coupled-channels calculation that assumes an octupole coupled structure for the 5^- state at 1.517 MeV and the observed cross section suggests that the wave function of this state includes only a small two-quasiparticle component. In addition, the present results indicate that the level at 2.073 MeV, previously assigned $J^\pi=4^-$, actually has $J^\pi=3^-$.

For some time, sequences of negative parity states (3^-, 5^-, 7^-, etc.) observed in spectra of even-even lanthanide nuclei have been interpreted in terms of the coupling of an octupole phonon to the sequence of states (2_1^+, 4_1^+, 6_1^+, etc.) built on the ground state [1]. In vibrational and rotational nuclei, these negative-parity sequences can be called "octupole bands." The octupole band interpretation is motivated by the similarity of the spacings between the states in the negative-parity band to corresponding spacings in the ground-state band. However, an octupole band interpretation can be tested via the collection of several different kinds of spectroscopic information. For example, the transition quadrupole moments for $E2$ transitions in an octupole band should be equal to those for the corresponding transitions in the ground-state band. One example of such a test is given in a recent study [2] of high-spin states in ^{74}Se.

In another test [3] of the octupole band interpretation of negative-parity states, the inelastic scattering of protons by ^{144}Nd was used to probe the 5^- member of the negative-parity band. If a 5^- state is indeed a member of an octupole band, then it should be populated in a (p,p') reaction via a two-step process involving successive $E2$ and $E3$ excitations. The cross section for such a process can be computed by performing a coupled-channels calculation using β_2 and β_3 parameters extracted from an analysis of the differential cross sections of the 2_1^+ and 3_1^- states in the nucleus. In the ^{144}Nd(p,p') experiment reported in Ref. [3], it was found that such a calculation underpredicted the observed cross section for the 5^- state by an order of magnitude, implying that a simple octupole coupled interpretation for this 5^- state is inappropriate.

Predictions of strong octupole correlations and even static octupole deformation have been made in the N=86–90 region (for example, see Ref. [4]). Therefore, tests similar to the ones described above are necessary to provide a more detailed understanding of the negative-parity states of nuclei in this region. In the present work, we report on a study of ^{146}Nd using proton inelastic scattering. Results for seven states having J = 2–5 are reported. In this nucleus, a negative-parity band of states was observed previously in a γ-ray study and was interpreted as an octupole band [4].

The data reported here were obtained using 35 MeV protons accelerated by the Princeton University AVF Cyclotron. The targets used for this experiment consisted of Nd_2O_3 (enriched to 97.5% in ^{146}Nd) evaporated onto 20-μg/cm^2 carbon foils. The evaporated material had a thickness of 200$\pm$10 μg/cm^2. The scattered protons were analyzed using a quadrupole-dipole-dipole-dipole (QDDD) magnetic spectrograph, and detected in a position-sensitive gas counter and scintillator focal plane detectors. Details of the experimental apparatus may be found in Ref. [5]. The best energy resolution achieved was 35 keV.

Spectra were obtained at laboratory angles between 21° and 50°. The spectrum taken at a laboratory angle of 35° is shown in Fig. 1. The Gaussian peak-fitting program GELIFT [6] was used for integrating the observed peaks in the spectrum. Normalization factors for converting inelastic-scattering yields to absolute differential cross sections were determined by comparing elastic-scattering yields at each angle to the differential cross sections for elastic scattering predicted by using Becchetti-Greenlees optical model parameters [7].

Individual states in ^{146}Nd were obscured at particular angles by peaks corresponding to elastic scattering from the carbon backing, oxygen from the Nd_2O_3 target material, and silicon contaminants in the target. In a previous study of the ^{144}Nd(p,p') reaction, self-supporting foils of enriched Nd were used, minimizing the oxygen and carbon contaminants. However, an enriched ^{146}Nd foil could not be acquired for the present experiment, and as a result the contaminant peaks were much larger.

Angular distribution data were obtained for seven excited states in ^{146}Nd with excitation energies up to 2.1 MeV. The observed states were identified via a compar-

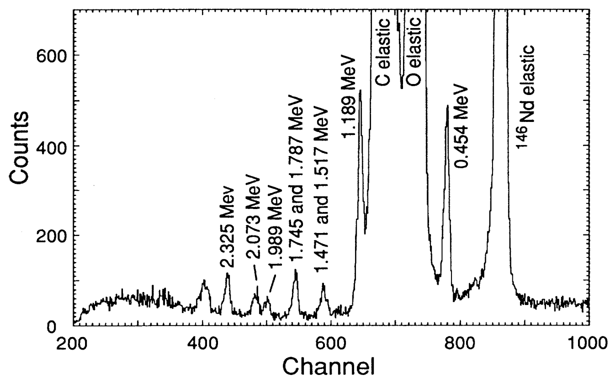

FIG. 1. Spectrum of scattered protons taken at a laboratory angle of 35°. Peaks corresponding to states in ^{146}Nd are labeled with their excitation energies. The large peaks corresponding to elastic scattering from carbon and oxygen nuclei are clearly evident.

ison with data from earlier studies of this nucleus compiled in Ref. [8]. The states observed in the present study were also seen in the ^{146}Nd(d,d') study of Christensen *et al.* [9], which utilized 12 MeV deuterons. The high resolution of the (d,d') study (7 keV) and the low density of states below 2 MeV in this nucleus allowed the compiler of Ref. [8] to identify states seen in the (d,d') data with those measured in γ-ray experiments. Consequently, we are able to assign our peaks to known states in ^{146}Nd despite the modest resolution in our experiment.

The ^{146}Nd states for which differential cross sections were measured in the present experiment are listed in Table I, and their angular distributions are shown in Figs. 2 and 3. Error bars shown in Figs. 2 and 3 result from uncertainties in the yields of peaks in the individual spectra. Uncertainties resulting from the normalization procedure and the target thickness were relatively small. Figure 1 shows that peaks appeared in the 35° spectrum between 2.3 and 2.5 MeV excitation energy; however, yield information could not be extracted at angles other than 35° for these peaks, and they are not listed in Table I. No peaks were observed in the present experiment above an energy of 2.5 MeV.

The angular distribution data reported here are consistent with all of the corresponding spin and parity assignments reported in Ref. [8], with the exception of the

TABLE I. Results of ^{146}Nd(p,p′) study.

E (MeV)[a]	J^π	β_L	$B(EL)$ (W.u.)[b]	EWSR[c] (%)
0.454	2^+	0.14(1)	28.1	6.0
1.189	3^-	0.12(1)	21.2	5.5
1.471	2^+	0.043(3)	2.6	1.8
1.517	5^-	0.054(3)	4.9	0.5
1.745	4^+	0.061(3)	5.8	1.2
1.989	4^+	0.048(3)	3.6	0.8
2.073	3^-	0.045(3)	3.0	1.3

[a]Energies are taken from [8].
[b]Calculated with the prescription of [12].
[c]Calculated with the prescription of [13].

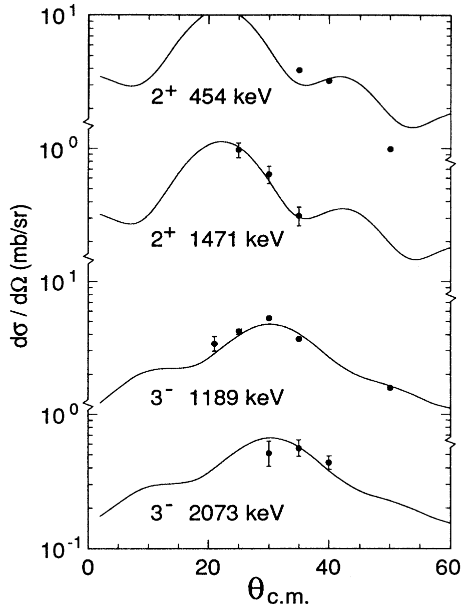

FIG. 2. Observed and calculated angular distributions of the differential cross sections of the 2^+ and 3^- states. Details of the calculations are described in the text.

state at 2.073 MeV. For this state, a spin and parity of 4^- were assigned in Ref. [8] on the basis of γ-ray transition data. However, because unnatural parity states are only weakly excited in (p,p') reactions at energies similar to the one used here [10], the $J^\pi=4^-$ assignment for the 2.073 MeV state is very doubtful. According to Ref. [8], the 2.073 MeV state is connected to the 1.189 MeV 3^- state by a mixed $M1/E2$ electromagnetic transition.

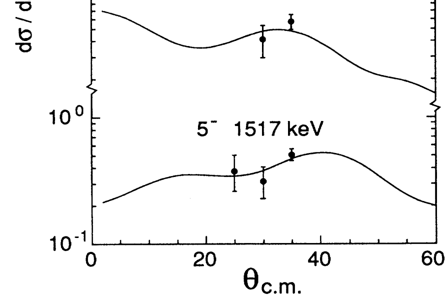

FIG. 3. Observed and calculated angular distributions of the differential cross sections of the 4^+ states and the 5^- state. Details of the calculations are described in the text.

The 3^- assignment we propose for the 2.073 MeV state is consistent both with the requirement of natural parity and the mixed $M1/E2$ multipolarity of the transition to the 1.189 MeV state.

The deformation parameters β_L listed in Table I were obtained by comparing the magnitudes of the present data to differential cross-section angular distributions that were calculated with the computer code CHUCK [11] using the Becchetti-Greenlees optical model parameters for single-step excitations. Standard collective form factors for vibrational excitations were used, and Coulomb excitation was included. The β_L values were then used to calculate the isoscalar strengths $B(EL;0^+_{\rm g.s.}\rightarrow L)$ listed in Table I via the prescription of Ref. [12] which assumes a sharp edge nuclear matter distribution and a nuclear radius of (1.2 fm)$A^{1/3}$. The energy-weighted sum rule (EWSR) fraction for each state is also listed in Table I. The sum rule used here is that given by Halbert *et al.* [13].

In the 12 MeV (d,d') study of ^{146}Nd described in Ref. [9], β_L values were reported for only the 2^+_1 and 3^-_1 states. The analysis of the 35 MeV (p,p') data reported here enables us to provide β_L values (see Table I) not only for these two states but also for five additional states with excitation energies above 1.2 MeV. It is encouraging to note that despite the differences in the roles of Coulomb excitation in the (d,d') experiment [9] and the present (p,p') work, the β_L values deduced from the two experiments for the 2^+_1 and 3^-_1 states agree within errors (β_2=0.137 in Ref. [9] and 0.14 in the present work, β_3=0.126 in Ref. [9] and 0.12 in the present work). In addition, a study of (p,p') experiments on a variety of targets, including a ^{146}Nd experiment with 30.7 MeV protons, was recently reported [14]; however, a result was given in Ref. [14] for only one of the states reported here (the 3^- state at 1.189 MeV, for which a β_3 value of 0.144 was given in Ref. [14]).

A comparison between the present data on ^{146}Nd and (p,p') data on ^{144}Nd from Ref. [3] reveals several similarities between the two isotopes. First, the $B(E2;0^+_{\rm g.s.}\rightarrow 2^+_1)$ values for the two nuclei (24 and 28 W.u. for ^{144}Nd and ^{146}Nd, respectively) are not very different, illustrating the gradual nature of the transition toward collectivity taking place between $N=82$ and 86. Second, the $B(E3;0^+_{\rm g.s.}\rightarrow 3^-_1)$ values of the two nuclei (23 and 21 W.u. for ^{144}Nd and ^{146}Nd, respectively) are quite similar despite the significant change in the energy of the 3^-_1 state, from 1.511 MeV in ^{144}Nd to 1.189 MeV in ^{146}Nd. Third, strong concentrations of $E4$ strength are found below 2.0 MeV in both nuclei. In ^{144}Nd, 13 W.u. of $E4$ strength are located in the 4^+_1 state at 1.315 MeV. In ^{146}Nd, a similar amount of $E4$ strength (a total of 9 W.u.) is found divided between two states at 1.745 and 1.987 MeV. The strong population of the 4^+_1 state in ^{144}Nd indicates that it is excited in (p,p') via a one-step process, suggesting either strong two-quasiparticle or hexadecapole vibration components. In contrast, the 4^+_1 state in ^{146}Nd is at an energy (1.044 MeV) slightly greater than twice the energy of the 2^+_1 state, suggesting a two-quadrupole phonon structure. With this structure, the 4^+_1 state would be populated by a two-step process, and would be only weakly excited in a (p,p') experiment. Indeed, the 4^+_1 state is not seen at all in the present experiment. Instead, the $E4$ strength located in the 4^+_1 state in ^{144}Nd is found in the higher-lying 4^+ states in ^{146}Nd. The differences in the properties between the 4^+_1 states in the $N=84$ nucleus ^{144}Nd and the $N=86$ isotope ^{146}Nd are indeed consistent with the trend expected in changing from the spherical $N=82$ nuclei to the well-deformed species at $N=90$.

The cross section for an octupole coupled 5^- state can be estimated by means of a coupled-channels calculation using the coupling scheme shown in Fig. 4(a). This scheme represents the fact that an octupole coupled 5^- state would be populated via a two-step process involving successive $E2$ and $E3$ excitations, instead of by a direct $E5$ excitation. The β_2 and β_3 values used in the calculation are those extracted for the 2^+_1 and 3^-_1 states. In ^{144}Nd, such a calculation underpredicted the observed cross section for the 5^-_1 state by an order of magnitude, strongly indicating that the octupole coupled interpretation could not be applied there [3]. Instead, the ^{144}Nd 5^- state is connected to the ground state via a large $E5$ matrix element, indicating two-quasiparticle structure. However, the disparity between the corresponding octupole-coupling calculation and data in ^{146}Nd [Fig. 4(b)] is not so apparent; the calculation underpredicts the magnitude of the data by only a factor of 2. In this case, it is possible that the inclusion of a small two-quasiparticle component in the octupole-coupled wave function could account for the magnitude of the observed cross section.

The results of the present study of ^{146}Nd and the previous study of ^{144}Nd suggest that a transition toward an octupole coupled nature in the 5^-_1 state is occurring in the Nd isotopes as the neutron number increases. A fur-

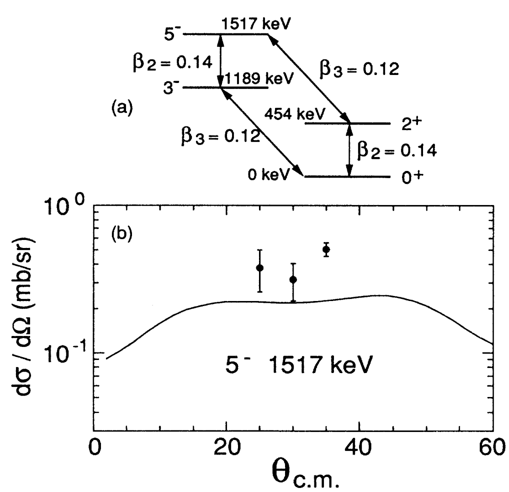

FIG. 4. (a) The coupled-channels scheme used to model the two-step excitation mechanism for the 1.517 MeV 5^- state. (b) Comparison of the data for the differential cross-section angular distribution for the 1.517 MeV 5^- state to the result of the coupled-channels calculation shown in (a).

ther study of this trend in heavier Nd isotopes (^{148,150}Nd) via proton scattering is clearly warranted. One additional way to probe the nature of the 5_1^- state is to determine the reduced matrix element of the γ-ray transition from the 5_1^- state to the 3_1^- state. In order to find this matrix element, measurements of both the lifetime of the 5_1^- state and the branching ratio for the deexcitation to the 3_1^- would be required. At present, neither of these values are known [8] for ^{146}Nd. In fact, the γ ray connecting the 5_1^- and 3_1^- states has not been observed at all because of the strength of the $E1$ transition deexciting the 5_1^- state to the 4_1^+ state.

In conclusion, seven excited states in ^{146}Nd have been measured by means of the inelastic scattering of 35 MeV protons. The strength of the state observed at 2.073 MeV suggests a 3^- assignment rather than 4^- as previously assigned. A comparison of the present results for ^{146}Nd and previous results for ^{144}Nd suggests that a predominantly octupole coupled description for this state becomes more appropriate as the neutron number is increased. This possibility can be explored further with proton scattering experiments on the heavier Nd isotopes.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation, the State of Florida, and Stockton State College.

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