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5^- "octupole" states in ^{146,148}Nd and ^{148}Sm via proton scattering

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The cross sections for populating the 2_1^+, 3_1^-, and 5_1^- states of ^{146,148}Nd and ^{148}Sm have been determined by inelastic scattering of 26 MeV protons and analyzed using coupled-channels calculations. In these nuclei, the 5_1^- states are usually considered to be "octupole coupled" states arising from the coupling of the 2_1^+ and 3_1^- states. It is found that the differential cross sections for excitation of the 5_1^- states are somewhat larger than would be expected for octupole coupled structure. This excess strength can be explained in terms of small admixtures of two quasiparticle excitations in the 5_1^- states.

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It has long been known that octupole collectivity plays a prominent role in N=84–88 nuclei, but the precise roles of octupole vibrations and static octupole deformation in this region are still in doubt. When bands of negative parity states were observed in the even-even nuclei of this region during the 1970s, they were interpreted as octupole bands arising from the coupling of an octupole phonon to the ground state band (for example, see [1]). The possibility that nuclei in this region may attain static octupole deformation was suggested by Leander *et al.* [2]. More recently, the possibility that both octupole vibrational behavior and static octupole deformation may play roles in a single nucleus at different angular momenta has been discussed by Nazarewicz and Tabor [3]. They predicted that particular even-even nuclei, including ^{146}Xe, ^{148}Ba, ^{146,148}Nd, ^{148,150}Sm, and ^{150,152}Gd, have reflection-symmetric ground states, but develop static octupole deformations at medium spins. In the context of this interpretation, the low-lying negative parity states, such as the 1_1^- and 5_1^- states, would arise from coupling of an octupole phonon to the ground state band, while higher-lying negative parity states would represent rotations of a statically octupole deformed rotor.

One way to examine the role of octupole vibrational behavior in the low-lying negative parity states of an even-even nucleus is to use proton inelastic scattering. Cottle *et al.* [4, 5] have used (p,p') reactions to examine the 5_1^- states in ^{144,146}Nd. If a 5^- state arises from the coupling of an octupole phonon to the 2_1^+ member of the ground state band, then it is populated in a (p,p') reaction via a two-step process involving successive $E2$ and $E3$ excitations. However, if the 5^- state possesses two-quasiparticle (2qp) structure, then it would be directly populated via an $E5$ excitation, which yields a much larger cross section than the octupole coupled two-step process. In this way, proton scattering can be used to test the purity of the wave function of a 5^- member of an octupole band.

In the present article, we report on a study of three nuclei, ^{146,148}Nd and ^{148}Sm, which Nazarewicz and Tabor [3] predict to be reflection symmetric in their ground states, but octupole deformed at medium spins. We find that the cross sections for the 5_1^- states of these nuclei are somewhat larger than would be expected for pure octupole band states. The observed cross sections can be understood if the 5_1^- states are dominated by octupole band structure but contain small admixtures of 2qp states.

Data on the ^{146}Nd(p,p'), ^{148}Nd(p,p'), and ^{148}Sm(p,p') reactions were obtained with a 26 MeV proton beam produced by the Australian National University 14UD Pelletron Accelerator. The protons were scattered from self-supporting foils of approximately 1 mg/cm^2 which were isotopically enriched to 97.8%, 98.2%, and 96.9% for ^{146}Nd, ^{148}Nd, and ^{148}Sm, respectively. Ejectiles were momentum analyzed using an Enge split-pole spectrograph and detected in a position sensitive gas counter. The energy resolution for the experiments was approximately 50 keV full width at half maximum.

Spectra were obtained at laboratory angles between 25° and 55°. Portions of the spectra obtained for the three targets at laboratory angles of 40° are shown in Fig. 1. Individual states in each of the three nuclei studied were obscured at particular angles by peaks corresponding to elastic scattering from carbon and oxygen contaminants. In addition, strong fluorine contaminants were present in the ^{148}Nd and ^{148}Sm targets.

The Gaussian peak-fitting program GELIFT [6] was used for integrating the observed peaks in the spectra. 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]. Only a single normalization factor was needed at each angle since a single magnetic field setting of the spectrograph allowed all states of interest, including the elastic peak, to be observed.

To allow coupled-channels analyses of the 5_1^- states, angular distributions were obtained for the 2_1^+, 3_1^-, and 5_1^- states in each of the target nuclei. Deformation parameters β_L were obtained for the 2_1^+ and 3_1^- states in each nucleus by comparing the data to differential cross-section angular distributions calculated for single-step excitations with the coupled-channels computer code CHUCK [8]. The data and calculated angular distributions for the 2_1^+ states are shown in Fig. 2; 3_1^- states are shown in Fig. 3. Becchetti-Greenlees optical model parameters [7] and standard collective form factors for vibrational excitations were used, and Coulomb excitation was included in the calculations. The calculated angular distributions for the 3_1^- states reproduced the shapes of the observed distributions reasonably well. Contaminant peaks obscured the 2_1^+ states for angles of less than 35° for all three nuclei (the only such data point available is the 25° point for ^{148}Sm); consequently, a careful comparison to the calculated angular distribution shapes for these states is not possible. The β_2 and β_3 values obtained for the 2_1^+ and 3_1^- states are listed in Table I. Table I also includes the isoscalar strengths G_2 and G_3 calculated using the prescription of Ref. [9], which assumes a sharp edge nuclear matter distribution and a nuclear radius of $(1.2\ \text{fm})A^{1/3}$. The G_L results are given in single-particle units (spu). The energies of the 2_1^+ and 3_1^- states listed in Table I are taken from [10, 11].

The values of β_2 and β_3 obtained here for ^{148}Sm can be compared with results from two other proton scattering experiments in the same energy range reported by Palla *et al.* [12] and Obiajunwa *et al.* [13]. Palla *et al.* [12] measured the $^{148}\text{Sm}(p,p')$ reaction at an energy of 25.6 MeV and obtained results of β_2=0.143 and β_3=0.166 using a coupled-channels analysis involving the 2_1^+ and 3_1^- states. Obiajunwa *et al.* [13] reported results of β_2=0.132 and β_3=0.120 from a similar coupled-channels analysis of their data, which was taken with 24 MeV protons. Our results are in good agreement with those of Obiajunwa

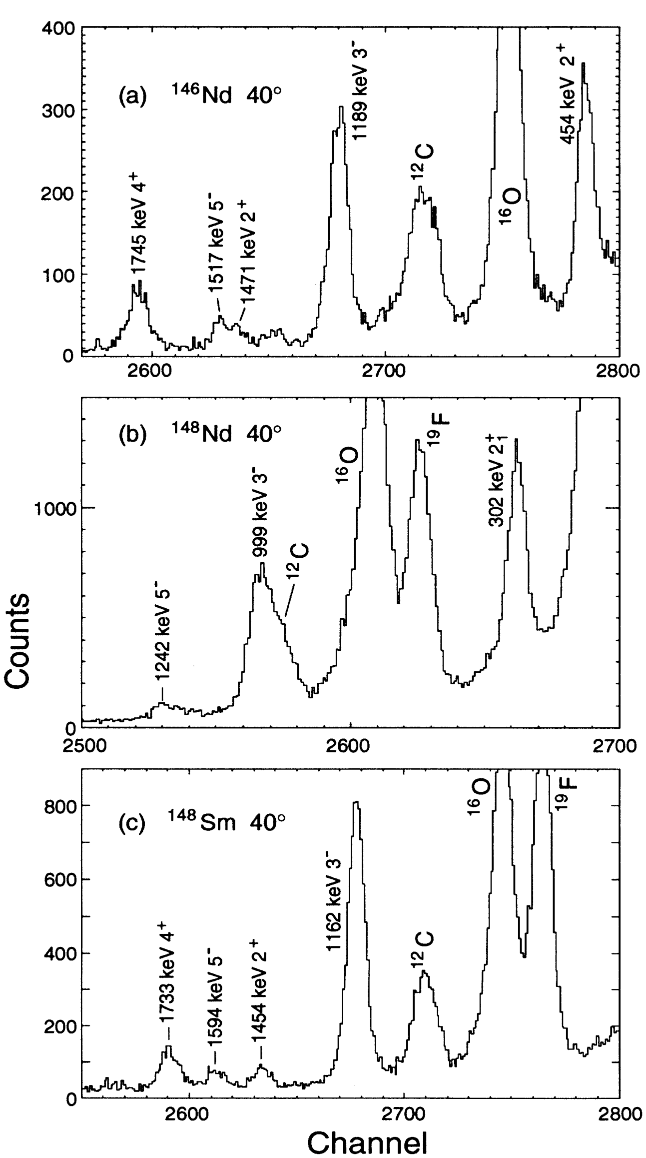

FIG. 1. Portions of the spectra taken at 40° on (a) ^{146}Nd, (b) ^{148}Nd, and (c) ^{148}Sm.

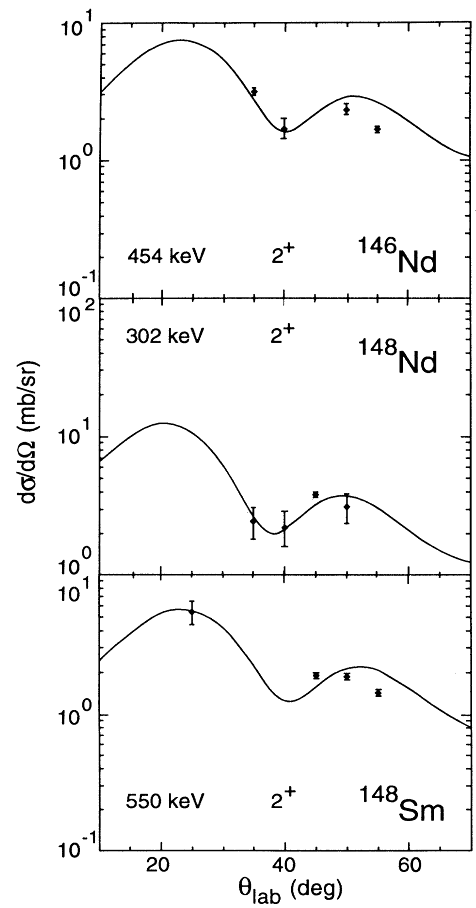

FIG. 2. Calculated angular distributions and data for the 2_1^+ states of (a) ^{146}Nd, (b) ^{148}Nd, and (c) ^{148}Sm.

TABLE I. Results for 2_1^+ and 3_1^- states.

Nucleus	J^π	Energy (keV)[a]	β_L	G_L (spu)[b]
^{146}Nd	2^+	454	0.140(10)	28(4)
	3^-	1189	0.113(6)	19(2)
^{148}Nd	2^+	302	0.160(10)	37(5)
	3^-	999	0.103(3)	16(1)
^{148}Sm	2^+	550	0.120(10)	22(4)
	3^-	1162	0.130(10)	27(4)

[a]Energies are taken from [10, 11].
[b]Calculated as described in the text.

et al. [13], but are somewhat below those of Palla *et al.* [12].

The present results of β_2=0.140(10) and β_3=0.113(6) for ^{146}Nd are in agreement with the results of a previous study [5] performed with 35 MeV protons [β_2=0.14(1) and β_3=0.12(1)]. No comparable proton scattering results are available for ^{148}Nd.

Two sets of coupled-channels calculations were performed (using CHUCK [8]) for the analysis of the 5_1^- state in each nucleus. The first set of calculations was used to predict the differential cross sections for a pure octupole band 5_1^- state which arises from the coupling of the 2_1^+ and 3_1^- states. We refer to such a structure as "octupole coupled," or OC. The primary population modes for an octupole coupled 5^- state would be the two-step excitation paths shown in Fig. 4(a). To obtain a prediction for an octupole coupled state, a coupled-channels calculation corresponding to the coupling scheme of Fig. 4(a) was performed with β_2 and β_3 coupling strengths extracted from the 2_1^+ and 3_1^- states.

In the second set of coupled channels calculations, a direct $E5$ excitation mechanism was added to the two-step excitation paths. The resulting "direct + OC" coupling scheme is shown in Fig. 4(b). For these calculations, the calculated angular distributions were fitted to the data by varying β_5. In this way, the $E5$ strength present in each of the 5_1^- states was determined.

The data on 5_1^- states in each of the nuclei studied here are compared to the octupole coupled and direct + OC coupled channels calculations in Fig. 5. The shaded bands around the octupole coupled curves correspond to the range of magnitudes of the calculated cross sections arising from the uncertainties in the values of β_2 and β_3. For all three nuclei, the octupole coupled calculations somewhat underpredict the data. The addition of a direct $E5$ excitation mechanism using the direct + OC coupling scheme allows a better fit to the data. The β_5 values obtained through a fitting procedure with the direct + OC scheme are listed in Table II, along with the corresponding G_5 results (calculated in the same way as G_2 and G_3). In all three cases, the extracted $E5$ strengths correspond to approximately 3 spu.

Proton scattering experiments on other even-even $N >$ 82 nuclei have also identified $E5$ strength in 5_1^- states. In the N=86 nucleus ^{150}Sm, Pignanelli *et al.* [14] found

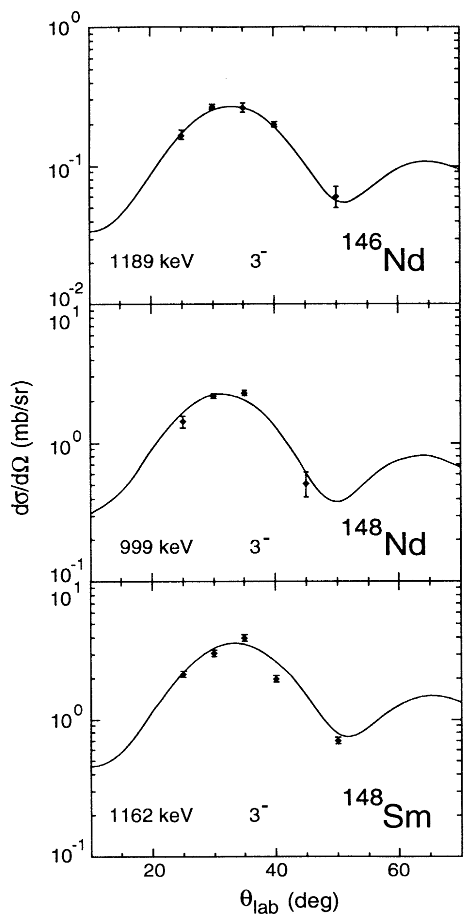

FIG. 3. Calculated angular distributions and data for the 3_1^- states of (a) ^{146}Nd, (b) ^{148}Nd, and (c) ^{148}Sm.

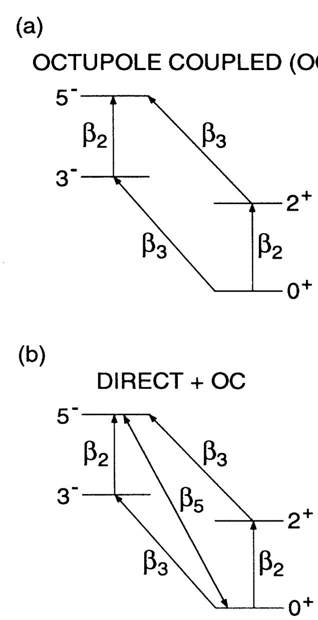

FIG. 4. Coupling schemes used in the multistep coupled-channels calculations: (a) octupole coupled, (b) octupole coupled with a direct $E5$ excitation route.

TABLE II. $E5$ excitation strengths.

Nucleus	$E(5_1^-)$ (keV)[a]	β_5	G_5 (spu)[b]
^{146}Nd	1517	0.044(3)	3.2(4)
^{148}Nd	1242	0.046(3)	3.5(5)
^{148}Sm	1594	0.040(3)	2.8(4)

[a]Energies are taken from [10, 11].
[b]Calculated as described in the text.

3.6 spu of $E5$ strength in the 1357 keV 5_1^- state. In their study with a radioactive ^{148}Gd (N=84) target, de Angelis *et al.* [15] observed 2.5 spu of strength in the 5_1^- state at 2082 keV. Cottle *et al.* [4] also identified a large concentration of $E5$ strength in the 2093 keV 5_1^- state of ^{144}Nd. The $E5$ strength in this state was originally reported [4] as 8.2(23) spu. However, we have found that their calculation is in error, and that the correct result is 10.1(8) spu. The largest G_5 among the 5_1^- states of $N > 82$ nuclei is in ^{144}Nd, while the rest of the nuclei in the region have G_5 values near 3 spu. These results are compiled in Fig. 6.

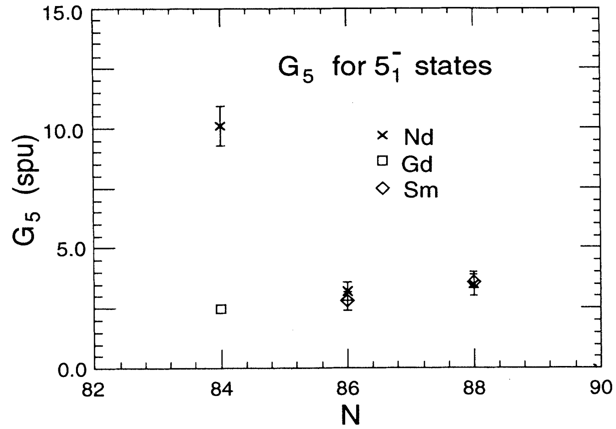

FIG. 6. G_5 values for the 5_1^- states of even-even N=84–88 nuclei. The values shown are taken from [4, 14, 15] and the present work.

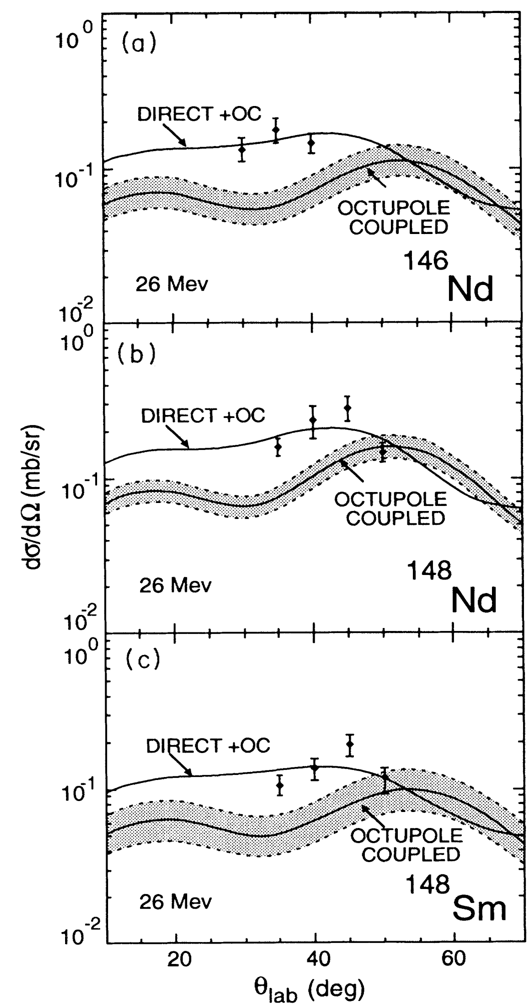

FIG. 5. Data for the 5_1^- states and the coupled-channels calculations for each nucleus: (a) ^{146}Nd, (b) ^{148}Nd, and (c) ^{148}Sm.

It seems likely that the $E5$ strength present in ^{146,148}Nd and ^{148}Sm, as well as other nuclei in the region, indicates the presence of a 2qp component in these states. In ^{148}Gd, de Angelis *et al.* [15] observed a strong (17 spu) 5^- state at 2632 keV, which they attributed to a 2qp excitation of a proton from the $d_{5/2}$ or $g_{7/2}$ orbits, which are below the Z=64 subshell energy gap, to the $h_{11/2}$ orbit, which is above the subshell gap. They concluded that the 2.5 spu of $E5$ strength present in the 2082 keV 5_1^- state of ^{148}Gd results from the admixture of a small component of the two-quasiproton excitation into the octupole coupled 5^- state. This particular two-quasiproton excitation may be responsible for the $E5$ strength observed in the $N > 82$ Nd and Sm isotopes; however, the $f_{7/2}i_{13/2}$ two-quasineutron excitation is also available.

The situation in ^{148}Gd suggests a straightforward approach to estimating the size of the 2qp component in a 5_1^- state. If an octupole coupled state with no $E5$ strength mixes with a 2qp state which has finite $E5$ strength, then most of the strength remains with the perturbed 2qp state, and a small amount of the 2qp $E5$ strength is imparted to the perturbed octupole coupled state. In the context of this two-level mixing scenario, the wave function of the 5_1^- state can be written as

$$\Omega = A \mid 3_1^- \times 2_1^+\rangle + B \mid 2\mathrm{qp}\rangle,$$

where $\mid 3_1^- \times 2_1^+\rangle$ is the octupole coupled component and $\mid 2\mathrm{qp}\rangle$ is the two-quasiparticle component. The quantity B^2 is given by the equation

$$B^2 = G_5(\mathrm{OC})/[G_5(\mathrm{OC}) + G_5(2\mathrm{qp})], \tag{1}$$

where $G_5(\mathrm{OC})$ is the $E5$ strength located in the perturbed octupole coupled state, and $G_5(2\mathrm{qp})$ is the strength found in the perturbed 2qp state. In ^{148}Gd, we are fortunate enough to know both $G_5(\mathrm{OC})$ and $G_5(2\mathrm{qp})$. For this case, B^2 can be estimated as

$$B^2 = (2.5 \text{ spu})/(2.5 \text{ spu} + 17 \text{ spu}) = 0.13.$$

In a case where the $E5$ strength is fragmented among more than two states, B^2 would simply be

$$B^2 = G_5(\mathrm{OC}) \Big/ \left(\sum G_5\right), \qquad (2)$$

where the sum is over all 5^- states. Equation (2) can be applied to ^{146}Nd, in which nine 5^- states above 2 MeV were measured by Pignanelli *et al.* [14]. The total of the G_5 values given by Pignanelli *et al.* for the higher-lying 5^- states is 11.1 spu. Therefore, for ^{146}Nd

$$B^2 = (3.2\ \mathrm{spu})/(3.2\ \mathrm{spu} + 11.1\ \mathrm{spu}) = 0.22.$$

We do not have data on higher-lying 5^- states in either ^{148}Sm or ^{148}Nd. However, the G_5 values for the 5_1^- states in ^{148}Sm and ^{148}Nd are about the same magnitude as in ^{146}Nd and ^{148}Gd. Therefore, it seems likely that the 2qp components of the perturbed octupole coupled wave functions in ^{148}Sm and ^{148}Nd are small, just as in ^{146}Nd and ^{148}Gd.

The situation is quite different in ^{144}Nd, where the G_5=10 spu value for the 5_1^- state is three times larger than in any of the other nuclei discussed here. While there are no data available on higher-lying 5^- states in ^{144}Nd, it is likely that more than 50% of the $E5$ strength in this nucleus is located in the 5_1^- state since the total observed $E5$ strength is less than 20 spu in both ^{146}Nd and ^{148}Gd.

It is not obvious why such a concentration of $E5$ strength occurs in ^{144}Nd. However, a study of ^{144}Nd using the neutron stripping reactions ^{143}Nd(d,p) or ^{143}Nd$(\alpha,{}^3\mathrm{He})$ would provide new information on the origin of the $E5$ strength in the 5_1^- state. If the 5_1^- state possesses a large $f_{\frac{7}{2}} i_{\frac{13}{2}}$ two-quasineutron component, then the state would be strongly populated in a neutron stripping reaction. The 5_1^- state would be populated weakly in such a reaction if the state has $d_{\frac{5}{2}} h_{\frac{11}{2}}$ two-quasiproton structure. A study of the ^{143}Nd(d,p) reaction has been performed by Raman *et al.* [16], but the resolution was not sufficient to separate the 5_1^- state from neighboring states.

In summary, the present results on ^{146,148}Nd and ^{148}Sm confirm that the 5_1^- states of these nuclei are octupole coupled states, as predicted by Nazarewicz and Tabor [3]. Only a small admixture of a 2qp "contaminant" is required to explain the present (p,p') data. This contrasts with the situation in ^{144}Nd, in which the 5_1^- state has G_5=10 spu, implying a large 2qp component. A simple octupole coupled interpretation is clearly inadequate for ^{144}Nd.

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