Negative-parity excitations in ^{144}Nd

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High angular momentum states in ^{144}Nd are studied via the γ rays produced in the ^{130}Te(^{18}O, 4n)^{144}Nd reaction. In addition to the previously known sequence of states built on the 3_1^- state, we have observed another negative-parity sequence built on the 3395 keV 9^- state, which is apparently of a two quasiparticle nature. These two negative-parity sequences probably interact and mix significantly. The present ^{144}Nd results raise questions regarding the interpretation of medium spin states of ^{146}Nd in terms of strong octupole correlations.

I. INTRODUCTION

In the $N=86$ isotones ^{146}Nd and ^{148}Sm sequences of alternating parity states ($J^\pi=4^+$, 5^-, 6^+, 7^-, etc.) have been observed.[1,2] Such sequences often signal the presence of strong octupole correlations or static octupole deformation. However, high angular momentum negative-parity states can also arise from two-quasiparticle (2qp) excitations involving the unique parity orbits of the valence shells. These 2qp states may interact and mix with states of octupole origin, making it difficult to determine whether the alternating parity structure does indeed indicate the presence of static octupole deformation. The $N=84$ isotones ^{144}Nd and ^{146}Sm are located just outside the region of possible static octupole deformation. Although these nuclei are not octupole deformed, they possess sequences of negative-parity states of angular momentum $4\hbar$ and above which have been interpreted to arise from the coupling of low-lying positive-parity states to 3_1^- states.[3,4] We will call these structures octupole-coupled sequences. Studies of the interaction of 2qp excitations with octupole-coupled sequences extracted from measurements of $N=84$ nuclei may cast new light on the nature of negative-parity states in the $N=86$ isotones.

In this work, a search was conducted for high angular momentum members of the octupole sequence and other negative-parity states which may interact and mix with the ocutpole-coupled sequence in the $N=84$ nucleus ^{144}Nd. We also analyze the octupole-coupled sequences of $N=84$ isotones in terms of a weak coupling picture in order to search for evidence of mixing with 2qp modes.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The isotope ^{144}Nd was produced via the ^{130}Te(^{18}O,4n) reaction at a beam energy of 70 MeV with a target of thickness 500 mg/cm^2 enriched to 98.96% in ^{130}Te. Both γ-γ coincidence and γ-ray angular distribution measurements were performed with beams produced using the Florida State University Super FN Tandem Van de Graaff accelerator. For the coincidence measurement four hyperpure germanium detectors with resolutions (full width half maximum) of 2.1 keV or better at 1.33 MeV and efficiencies of 23% [relative to a 7.5×7.5 cm NaI(Tl) detector] were used. Each detector was surrounded with a bismuth germanate (BGO) shield for suppression of the Compton scattering background. Approximately 75% of the Compton background produced by a ^{60}Co source was suppressed by this arrangement.

For the coincidence measurement the γ-ray detectors were located at 90 deg to the beam direction; forward angles were avoided because of the strong neutron flux produced by the ^{18}O beam. A total of 2.1×10^7 coincidence events was collected. Figure 1 displays γ-ray spectra gated on the 696 keV ($2_1^+\rightarrow0_{\text{g.s.}}^+$ transition of ^{144}Nd) and 162 keV [$13_1^-\rightarrow(12_1^+)$] γ rays.

The angular distribution measurement was performed with one Compton-suppressed germanium detector located 20 cm from the target at angles of 90, 120, 135, 150 and 155 deg. To normalize the data from the different angles a germanium detector positioned at an angle of 90 deg to the target was used.

The angular distribution of each γ ray was fitted with the expression

$$W(\theta)=A_0[1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)] ,$$

where P_i are Legendre polynomials. The coefficients determined from this procedure are tabulated, along with efficiency-corrected γ-ray intensities, in Table I.

The level spectrum deduced from the present measurement is given in Fig. 2. Precise energies for the levels are tabulated in Table II. All level placements are supported by coincidence data. Many of the γ rays have a_2 values in the range $-0.2\geq a_2\geq-0.3$ and a_4 values of approximately zero; these characteristics are consistent with stretched dipole nature. Others have a_2 values greater than $+0.2$, which is consistent with stretched quadrupole character. The spin assignments made here are deduced primarily using these stretched transitions. Parity assignments for levels below 3 MeV come from conversion electron measurements performed in a previous study of ^{144}Nd by Berzin *et al.*[5] It was also assumed that the transitions found to be quadrupole in character in the angular distribution experiment were $E2$; $M2$ transitions are generally quite slow.[6]

The spin assignment of the 3395 keV 9^- level is particularly important to the conclusions of this work. Three γ

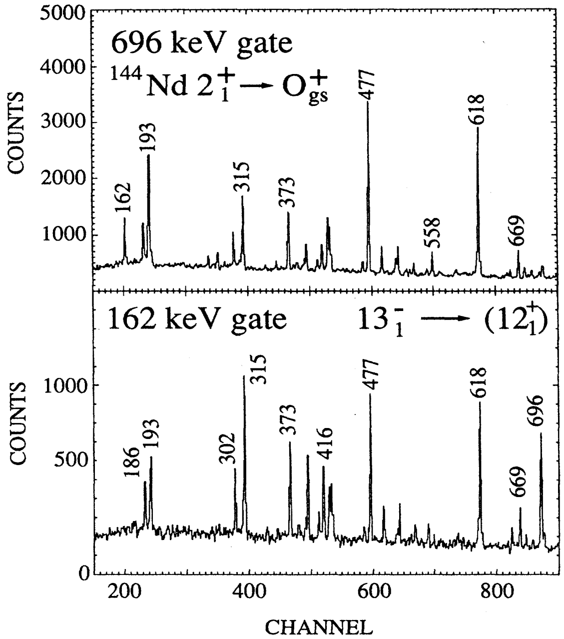

FIG. 1. Spectra from the γ-γ coincidence experiment gated on the (a) 696 keV ($2_1^+ \rightarrow 0_{g.s.}^+$) and (b) 162 keV [$13_1^- \rightarrow (12_1^+)$] transitions.

rays (423.7, 494.2, and 686.0 keV) deexcite this state; the angular distributions of the 423.7 and 494.2 keV γ rays are shown in Fig. 3. The angular distribution of the 423.7 keV γ ray which deexcites to the 2972 keV 8^+ state [$a_2 = -0.28(1)$, $a_4 = +0.02(2)$] is consistent with stretched $E1$ nature; this suggests a 9^- assignment for the 3395 keV state. The 494.2 keV γ ray deexcites to the 2902 keV 9^- level. The angular distribution results for this γ ray [$a_2 = +0.40(5)$, $a_4 = -0.17(8)$] are consistent[7] with an $E2/M1$ mixed transition of mixing ratio $+0.4 \leq \delta \leq +0.8$ between two states with $J = 9$. Finally, the angular distribution results for the 686.0 keV deexcitation to the 2709 keV 8^+ state [$a_2 = -0.16(13)$, $a_4 = -0.04(22)$] are imprecise, but consistent with a stretched $E1$ character. We conclude that the 3395 keV state has $J^\pi = 9^-$.

Two previous studies[3,5] of high-spin states of ^{144}Nd have been performed, both via the ^{142}Ce(α,2n) reaction. The results of those two studies agree with each other and with the present study up to an excitation energy of 3 MeV. Beyond that point the level spectra deduced from those studies diverge dramatically from each other and from the present results. In both Refs. 3 and 5, level spectra are proposed up to nearly 5 MeV, corresponding to angular momenta of 13$\hbar$. However, our coincidence data directly contradict placements of several γ rays in each of the other studies. For example, we find that the

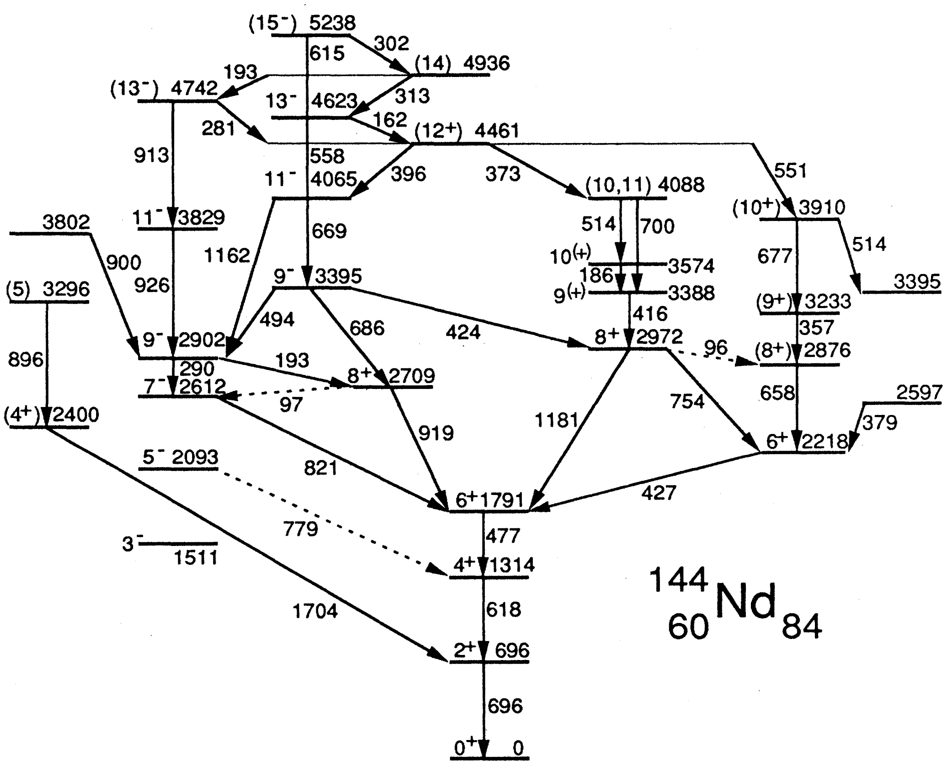

FIG. 2. Level spectrum for ^{144}Nd deduced in this work. The 1511 keV 3^- state, which was not observed here, is included for reference. Dotted transitions are not observed in this work but are placed on the basis of previous experiments.[3,5]

669.3, 558.1, and 615.1 keV γ rays are strongly in coincidence with one another, and we have proposed that they form a cascade which deexcites the 5238 keV (15^-) state and falls to the 3395 keV 9^- state. In both Refs. 3 and 5, the 669 and 558 keV γ rays are placed in such a way that they would not be in coincidence with one another.

III. OCTUPOLE-COUPLED SEQUENCE IN ^{144}Nd

The interpretation of negative-parity sequences of states in the lanthanide and light actinide regions as octupole-coupled sequences is suggested most strongly by the similarity of the spacings of states in the sequence $0^+_{\rm g.s.}$, 2^+_1, 4^+_1, 6^+_1 with those of the negative-parity sequence 3^-_1, 5^-_1, 7^-_1, 9^-_1 as well as the strong $E2$ transitions connecting the negative-parity states. In the transitional nucleus ^{144}Nd, the 2093 keV 5^- state, 2612 keV 7^- state, and 2902 keV 9^- state are most readily interpreted[3] as members of an octupole-coupled sequence built on the 1511 keV 3^-_1 state. The $E2$ transitions connecting the 3^-, 5^-, and 7^- members of this sequence are not apparent in this experiment, probably because of competition from high-energy $E1$ transitions deexciting the same states. States having $J^\pi=11^-$ (3829 keV) and $J^\pi=(13^-)$ (4742 keV) also deexcite to this sequence; however, the

TABLE I. Properties of γ rays observed in ^{144}Nd.

E_γ[a] (keV)	a_2	a_4	I_γ	$E_i \rightarrow E_f$
162.3	−0.25(1)	−0.02(2)	10(1)	4623→4461
185.9	−0.26(1)	−0.06(2)	6(1)	3574→3388
193[b]				4935→4742
193.2	−0.29(1)	−0.01(1)	25(2)	2902→2709
281.1	−0.26(3)	−0.08(4)	4(1)	4742→4461
290.2	+0.11(8)	+0.22(13)	2(1)	2902→2612
302.3	−0.11(2)	−0.10(3)	12(3)	5238→4936
312.6	+0.04(8)	−0.04(13)	5(2)	4936→4624
356.7	−0.22(8)	−0.26(13)	2(1)	3233→2876
372.9[c]			16(4)	4461→4088
379.0[c]			3(1)	2597→2218
396.1	+0.06(2)	+0.07(3)	9(4)	4461→4065
415.8	−0.26(2)	+0.01(3)	9(2)	3388→2972
423.7	−0.28(1)	+0.02(2)	16(3)	3395→2972
426.8	+0.30(1)	+0.01(2)	23(3)	2218→1791
476.8	+0.27(1)	−0.05(1)	76(7)	1791→1314
494.2[d]	+0.40(5)	−0.17(8)	11(5)	3395→2902
514.3[b]			7(2)	4088→3574
514.4[b]			3(1)	3910→3395
551.0	+0.04(4)	+0.01(6)	4(1)	4461→3910
558.1	+0.20(3)	−0.17(5)	17(4)	4623→4065
615.1[b]			7(3)	5238→4623
618.1	+0.26(1)	−0.07(1)	85(8)	1314→696
658.4	+0.44(4)	−0.08(6)	6(2)	2876→2218
669.3	+0.19(1)	+0.04(2)	25(3)	4065→3395
677.1[b]			2(1)	3910→3233
686.0	−0.16(13)	−0.04(22)	3(1)	3395→2709
695.8	+0.17(1)	−0.04(1)	100	696→0
700.3	+0.20(4)	−0.03(6)	5(2)	4088→3388
754.4	+0.14(2)	+0.01(3)	20(2)	2972→2218
779.2			2(1)	2093→1315
821.2	−0.30(9)	+0.28(14)	7(2)	2612→1791
895.8	−0.34(4)	+0.11(7)	9(3)	3296→2400
899.6	−0.01(12)	+0.12(19)	2(1)	3802→2902
913.5	+0.47(7)	−0.25(11)	2(1)	4742→3829
918.6	+0.36(5)	−0.05(8)	32(4)	2709→1791
926.4	+0.26(11)	+0.10(17)	11(2)	3829→2902
1162.4	+0.05(2)	−0.07(3)	6(2)	4065→2902
1181.0	+0.31(3)	−0.08(4)	14(3)	2972→1791
1703.6			7(3)	2399→696

[a]Errors in energies are ±0.2 keV.
[b]Doublet with γ ray from ^{144}Nd.
[c]Doublet with γ ray from ^{143}Nd.
[d]Doublet with unassigned γ ray.

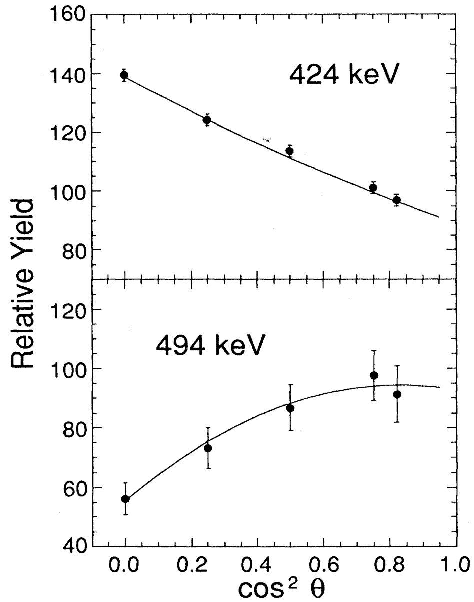

FIG. 3. Angular distributions for 423.7 and 494.2 keV γ rays. The curves are the Legendre polynomial fits described in the text.

TABLE II. States in ^{144}Nd observed in this work.

E (keV)	J^{π}
695.8	2^+
1313.9	4^+
1790.7	6^+
2093.1	5^-
2217.5	6^+
2399.4	(4^+)
2596.5	
2611.9	7^-
2709.3	8^+
2875.9	(8^+)
2902.3	9^-
2971.8	8^+
3232.6	(9^+)
3295.2	(5)
3387.6	$9^{(+)}$
3395.4	9^-
3573.5	$10^{(+)}$
3801.9	
3828.7	11^-
3909.7	(10^+)
4064.7	11^-
4087.8	(10,11)
4460.8	(12^+)
4622.9	13^-
4742.2	(13^-)
4935.5	(14)
5237.9	(15^-)

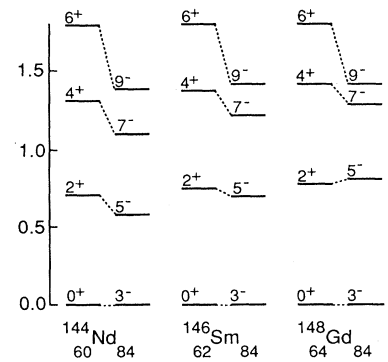

FIG. 4. A comparison of ground-state and octupole sequences in the $N=84$ isotones. Data are taken from this work and Refs. 4 and 11.

ground-state positive-parity sequence forks above the 6^+ member, making the interpretation of an octupole sequence difficult above $9\hbar$.

Figure 4 compares the ground state and assumed octupole sequences for the $N=84$ isotones, including ^{144}Nd. In this figure, the ground and 3_1^- states are drawn together so that the relative energies of high-spin members of the sequences can be compared. It is seen that deviation from the weak coupling picture is less than 150 keV for the 5^- states, somewhat greater for the 7^- states, and quite large for the 9^- states. It would therefore seem that the octupole sequence interpretation is appropriate for the 5^- states, and possibly for the 7^- states as well. However, such an interpretation for the 9^- states is questionable.

We can expand and systematize this analysis by comparing octupole sequences from the $N=84-92$ region with the simple weak coupling picture. In such a picture, the relation

$$E(J,\pi=-)=E(3_1^-)+E(J-3,\pi=+) \qquad (1)$$

approximately holds for each member J of the octupole

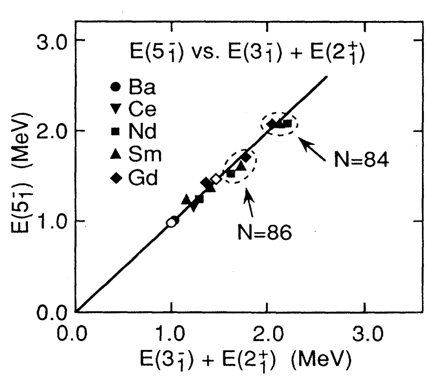

FIG. 5. $E(5^-)$ vs $E(3_1^-)+E(2_1^+)$ for octupole sequences of $Z=56-64$, $N=84-92$ nuclei. Open shapes denote tentative spin or parity assignments. Data are taken from Refs. 1, 2, 9–16, and this work.

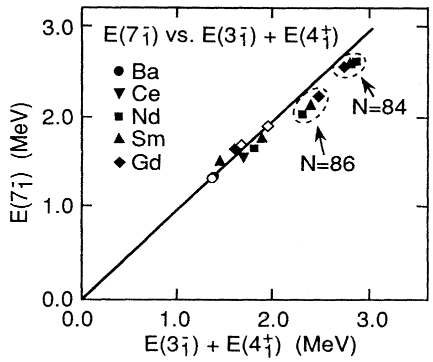

FIG. 6. $E(7^-)$ vs $E(3_1^-)+E(4_1^+)$ for octupole sequences of $Z=56-64$, $N=84-92$ nuclei. Open shapes denote tentative spin or parity assignments. Data are taken from Refs. 1, 2, 9–16, and this work.

sequence. For transitional lanthanide ($Z=56-66$, $N=84-92$) and light actinide ($Z=88-90$, $N=130-142$) nuclei this relation holds to within 150 keV for $J^\pi=5^-$ members of octupole sequences, and 250 keV for 7^- members.[8] It should be kept in mind, however, that octupole sequence states can mix with other states, such as negative-parity 2qp states and members of sequences built upon them. Consequently, the deviation of octupole sequence states from the simple weak coupling picture described in Eq. (1) arises in part from the impurity of the wave functions of the states. The interaction of the quadrupole and octupole excitations also plays an important role.

Deviations from the simple weak coupling picture are illustrated in Figs. 5–7, in which $E(J,\pi=-)$ is compared to

$$E(J-3,\pi=+)+E(3_1^-)$$

for members of octupole sequences in even-even nuclei of the $Z=56-62$, $N=84-92$ region.[1,2,9–16] It can be seen that 5^- states conform to Eq. (1) quite well; however, deviations become larger for 7^- and, more clearly, 9^- states of octupole sequences of $N=84-86$ nuclei. The trends of the deviations with increasing spin are illustrated in Fig. 8, in which the difference of the two sides of Eq. (1) is graphed against J. The trends are most dramatic for $N=84$ nuclei, for which the deviations are quite pronounced for $J=9$. The deviations may arise from interactions of the octupole phonon with the ground-state sequence states; however, the octupole sequence 9^- states in $N=84$ nuclei are located relatively close to the pairing gap energy, where 2qp states would be expected to occur. It seems more probable that considerable mixing with states of nonoctupole origin, especially 2qp states such as

$$\nu(f_{7/2}^{-1}i_{13/2})^{9-} ,$$

cause these deviations. In more deformed nuclei, the 7^-

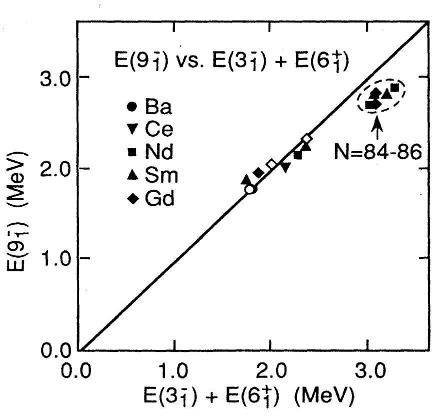

FIG. 7. $E(9^-)$ vs $E(3_1^-)+E(6_1^+)$ for octupole sequences of $Z=56-64$, $N=84-92$ nuclei. Open shapes denote tentative spin or parity assignments. Data are taken from Refs. 1, 2, 9–16, and this work.

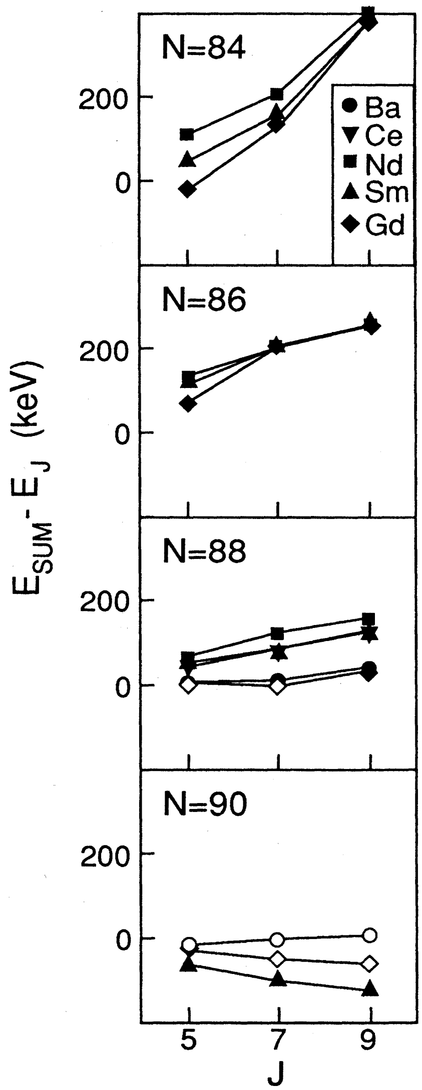

FIG. 8. E_J-E_{sum} vs J for octupole sequences in $Z=56-64$, $N=84-90$ nuclei, where $E_{\mathrm{sum}}=E(J,\pi=+)+E(3_1^-)$. Open shapes denote tentative spin or parity assignments. Data are taken from Refs. 1, 2, 9–15, and this work.

and 9^- octupole band states would occur at lower energies and would have less interaction with 2qp states. This is consistent with the information in Fig. 8. We may infer, therefore, that the 9^- members of octupole sequences in $N=84$ nuclei are quite impure.

Several experimental results have been used to support the octupole origin of the 9^- members of the octupole sequences in the $N=84$ isotones ^{146}Sm and ^{148}Gd. A recoil distance measurement of the lifetimes of low and medium spin levels in ^{146}Sm demonstrated[17] that the $B(E2)$ values for transitions connecting members of the octupole sequence up to $9\hbar$ were similar to those connecting ground-state sequence members. In addition, a measurement of the g factor of the corresponding 9^- state in ^{148}Gd yielded[18] a result which was consistent with an octupole coupled origin. However, experimental uncertainties prevented the exclusion of other components of the 9^- state wave function, such as $\nu(f_{7/2}^{-1}i_{13/2})$. The hypothesis of impurity in the 2902 keV 9^- state of ^{144}Nd may be further tested via direct reactions. For example, proton inelastic scattering experiments would probe for 2qp components.

IV. STRUCTURE OF THE 3395 keV 9^- STATE

The perturbation of the energy of the 9_1^- state discussed in the previous section may be partially attributable to interaction with the 3395 keV 9_2^- state. For ^{144}Nd, the neutrons occupy the $f_{7/2}$ orbit in the ground state. A 9^- 2qp excitation would result from the promotion of one neutron to the $i_{13/2}$ orbit. Protons primarily occupy the $g_{7/2}$ orbit; a stretched excitation to the $h_{11/2}$ orbit would again form a $J^{\pi}=9^-$ 2 qp state.

Information on the 2qp composition of the 3395 keV 9^- state can be extracted in two ways. The 9_2^- states[4,11] in the isotones ^{144}Nd, ^{146}Sm, and ^{148}Gd are located at energies of 3395, 3355, and 3367 keV, respectively. There is no apparent trend in these energies with proton number; consequently, a neutron excitation is indicated.

We may also estimate excitation energies for the candidate proton and neutron 2qp states by performing a simple Bardeen-Cooper-Schreiffer (BCS) calculation involving the neutron $f_{7/2}$, $i_{13/2}$, $p_{3/2}$, and $h_{9/2}$ orbits and the proton $g_{7/2}$, $d_{5/2}$, $s_{1/2}$, $h_{11/2}$, and $d_{3/2}$ orbits. For this calculation, the gap parameters Δ_n and Δ_p for protons and neutrons were determined using the binding energies of adjacent nuclei.[19] The gap parameters were calculated to be $\Delta_n=0.94$ MeV and $\Delta_p=1.33$ MeV. Single-particle energies were taken to be those determined for ^{146}Gd by Kleinheinz *et al.*[20] The number of valence particles N was fixed (to 2 for neutrons and 10 for protons) and the equations

$$V_i^2=\tfrac{1}{2}[1-(\epsilon_i-\lambda)/E_i] \ ,$$

$$E_i=[(\epsilon_i-\lambda)^2+\Delta^2]^{1/2} \ ,$$

$$N=2\sum_i V_i^2 \ ,$$

were solved iteratively. In these equations, λ is the chemical potential, ϵ_i are the single-particle energies, V_i^2 are the occupation numbers, and E_i are the one-quasiparticle energies. In order to calculate the 2qp energies, the one-quasiparticle energies for the particle and hole orbits are added. For the $\nu(f_{7/2}^{-1}i_{13/2})$ configuration, the calculated 2qp energy is 3.79 MeV, for the $\pi(g_{7/2}^{-1}h_{11/2})$ state, 4.86 MeV. A comparison with the observed energy, 3.395 MeV, clearly favors a neutron interpretation.

The 2qp interpretation of the 3395 keV 9^- state could also be experimentally tested with a proton inelastic scattering study. If this state indeed has a $\nu(f_{7/2}^{-1}i_{13/2})$ origin, it might also be observable in the ^{143}Nd$(\alpha,{}^3$He$)^{144}$Nd reaction.

As discussed in the previous section, the systematic behavior of octupole-coupled sequence states provides evidence that the 2902 keV 9_1^- state is substantially mixed with other 9^- states. It is likely that the 3395 keV 9^- state is among those which interact strongly with the 2902 keV state. In a similar way, a corresponding 2qp 9^- excitation may play an important role in the behavior[1] of ^{146}Nd at equivalent angular momentum values. The 2707 keV 9^- state of ^{146}Nd is fed strongly by two 11^- states, one at 3406 keV, the other at 3502 keV. The authors of Ref. 1 suggest that this forking may be attributed to the onset of strong octupole correlations bordering on static octupole deformation; however, this phenomenon may also be explained as arising from the interaction of the $\nu(f_{7/2}^{-1}i_{13/2})^{9^-}$ 2qp excitation with the octupole band which is evident at lower angular momenta.

The sequence of states built on the 3395 keV 9^- level in ^{144}Nd may be interpreted as a sequence of vibrational excitations. The three γ rays connecting these states, 669, 558, and 615 keV, appear strongly in coincidence with one another, and the first two of these transitions are quite clearly $E2$ (the multipolarity of the 615 keV transition cannot be determined because its peak sits on the tail of the 618 keV $4_1^+\rightarrow 2_1^+$ peak).

V. CONCLUSIONS

A study of high angular momentum states in ^{144}Nd has revealed a sequence of states built on the 9_2^- state. Evidence that the 9^- member of the octupole-coupled sequence does indeed strongly interact with other 9^- states in ^{144}Nd, including the 9_2^- state, has been presented. Furthermore, the implications of the present results for the interpretation of high-spin behavior of ^{146}Nd in terms of strong octupole correlations have been discussed. In particular, the presence of the sequence built on the 9_2^- state in ^{144}Nd suggests that a corresponding one may exist in ^{146}Nd. The interaction of the 9_2^- state and corresponding higher angular momentum states with octupole band states would offer an alternative explanation for behavior in ^{146}Nd which has previously been attributed to the onset of strong octupole correlations.

ACKNOWLEDGMENTS

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