Proton inelastic scattering on the transitional nucleus ^{144}Nd

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The nucleus ^{144}Nd is studied via the ^{144}Nd(p,p') reaction with 35 MeV protons. Angular distributions are measured for 13 states; 12 are assigned $J^{\pi}=2^+$, 3^-, 4^+, or 5^-. The present results are useful in understanding the nuclear shape transition taking place in the range $N=82-90$ and in the investigation of a proposed mixed symmetry mode in ^{144}Nd.

I. INTRODUCTION

The $N=84$ isotones provide a particularly interesting case for studying the competition between collective and single-particle degrees of freedom. Collectivity is present at low angular momenta; however, higher spin states are better described in a single-particle picture. A previous article[1] reported on a study of high spin states in the $N=84$ nucleus ^{144}Nd by means of a heavy-ion-induced fusion-evaporation reaction. In the present work we report on a study using proton inelastic scattering of collectivity in the low spin states of ^{144}Nd and the transition toward single-particle structure at the $J=4$ and 5 states.

One example of collectivity in ^{144}Nd is the mixed symmetry vibrational mode,[2] which has been studied extensively in several deformed rare-earth nuclei (see Refs. 3 and 4, and references contained therein). It has been proposed[5] that the mixed symmetry strength in the even-A $N=84$ isotones is concentrated in the 2_3^+ states which have been observed near 2 MeV; however, only limited information has been available on these states.

In addition to the transition from collective to single-particle nature which occurs with increasing spin, ^{144}Nd is located in a region in which a similar transition is taking place as a function of decreasing neutron number N. For example, the 4_1^+ states of the even-A $N=82$ isotones are formed from two-quasiparticle (2qp) couplings of protons in the $d_{5/2}$ and $g_{7/2}$ orbits, while the 4_1^+ states are rotational at $N=90$. The 4_1^+ states in the $N=84-88$ transitional region are not so well understood. Consequently, information on the nature of the 4_1^+ state of ^{144}Nd provides additional understanding of shape transitions which occur as functions of both J and N.

The measurement of isoscalar multipole strengths with inelastic proton scattering can be used as a tool in characterizing known states. It also allows the observation of previously unknown states in which multipole strength is concentrated. The present article reports on a study of the ^{144}Nd(p,p') reaction with 35-MeV protons. Results are extracted for 13 states including the 4_1^+ and 2_3^+ states. The implications of these results for our understanding of the evolution of 4_1^+ states in $N=82-90$ nuclei and for the identification of mixed symmetry modes in ^{144}Nd are discussed.

A brief report which concentrated on the excitation mechanism of the 5^- state at 2.093 MeV has been published previously.[6]

II. EXPERIMENTAL PROCEDURE

Data on the ^{144}Nd(p,p') reaction were obtained with a 35-MeV proton beam produced by the Princeton University AVF Cyclotron. The protons were scattered from a 1-mg/cm^2 target of self-supporting ^{144}Nd metal isotopically enriched to 99.8%. Ejectiles were momentum analyzed using a quadrupole-dipole-dipole-dipole (QDDD) spectrograph and detected in a position-sensitive gas counter. The spectrograph and counter system are described in detail in Ref. 7. For the present experiment, the gas counter was capable of detecting proton energies corresponding to an excitation energy range of approximately 2.0 MeV in the target nucleus. Spectra were taken with the spectrograph tuned to four energy bites of approximately 2 MeV each, centered on 0.7-, 1.5-, 2.2-, and 3.3-MeV excitation, with a resolution of 20 keV.

Differential cross sections were measured at laboratory angles between 15° and 65°. Spectra of proton groups corresponding to the 1.5- and 2.2-MeV energy bites, each at a laboratory angle of 21°, and to the 3.3-MeV bite at 25°, are shown in Fig. 1. Individual states were obscured at particular angles by peaks corresponding to elastic scattering from carbon, oxygen, and silicon contaminants and inelastic scattering from the 1.78-MeV 2^+ state of ^{28}Si.

III. EXPERIMENTAL RESULTS

Peak centroids and intensities were obtained at each angle where contaminants did not obscure the peaks. Where necessary, the Gaussian peak-fitting program[8] GELIFT was used. The elastic-scattering cross sections were compared to those calculated using the Becchetti-Greenless optical-model parameters.[9] As shown in Fig. 2, these parameters reproduce the elastic-scattering data reasonably well. Therefore, they were used in the subse-

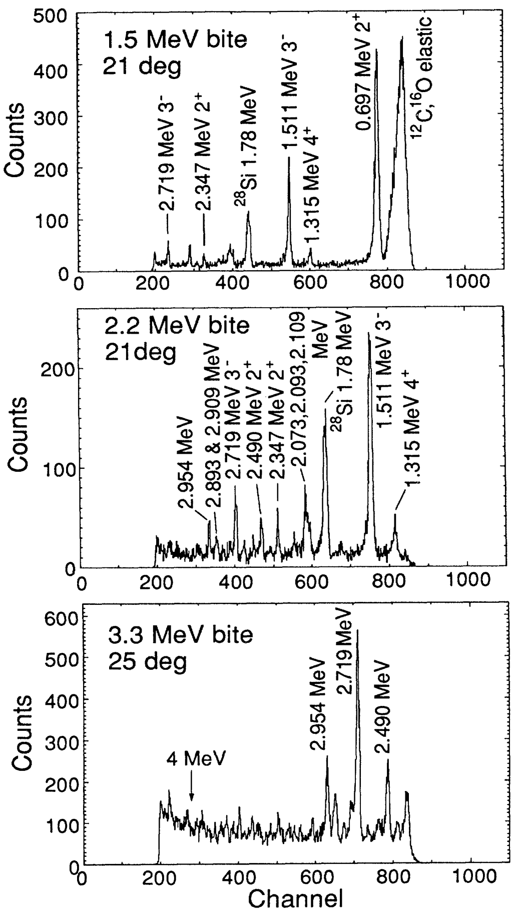

FIG. 1. Spectra of scattered protons taken at 21° with energy bites centered at (a) 1.5 MeV and (b) 2.2 MeV excitation energies, and (c) a spectrum taken at 25° with a bite centered at 3.3 MeV.

quent analysis of the inelastic-scattering data. The comparison between the observed differential cross sections and those calculated with the Becchetti-Greenless parameters also allows an estimate of 10% for the minimum error in the measured cross sections. The errors shown in angular distributions here also reflect uncertainties in integration of peaks in the spectra.

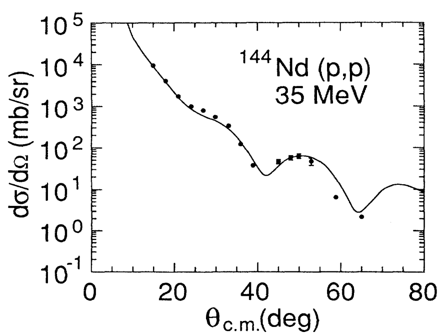

FIG. 2. Experimental angular distribution for elastic scattering and a theoretical curve calculated with Becchetti-Greenlees optical-model parameters (Ref. 9).

We were able to recognize all of the states in the 1.5-MeV energy bite [Fig. 1(a)] from previous studies[10] of this nucleus with other probes. Our level energies, determined from a linear energy calibration, agree with previous results to within 15 keV for each state. The 2.2-MeV bite [Fig. 1(b)] contained some peaks for which immediate assignments to known states could not be made. A calibration for this spectrum was calculated on the basis of the locations of the peaks corresponding to the 1.315-, 1.511-, and 2.093-MeV states. The calibration yields energies correct to within 7 keV for the known states; we quote an error of 25 keV for other states seen in this bite. Several states appeared in both the 1.5- and 2.2-MeV bites. Energies of these states obtained via calibrations of each of these bites were equal to within 7 keV. The 3.3-MeV bite [Fig. 1(c)], which extends up to an energy of 4.2 MeV, shows several of the higher-energy states from the 2.2-MeV bite, but no other states which were strong enough for angular distribution analysis. No distinct states were observed above 3 MeV excitation energy at any angle.

Table I lists the compiled values[10] for the energies of states observed at 2.1 MeV and below, as well as the energies of all the states observed in our present experiment. Above 2.1 MeV, the correspondence between states observed here and those known from previous experiments is not clear. Therefore, only the energies determined in the present experiment are listed in Table I for states above 2.1 MeV.

Angular distributions were obtained for 13 excited states with energies up to 3.0 MeV. Unique spins were obtained for 11 of these states by comparing their observed angular distributions to curves calculated[11] with CHUCK for $L=2$, 3, 4, and 5 single-step excitations. Parities were inferred by exploiting the fact that unnatural parity states are weakly excited in (p,p') reactions at energies similar to the one used here.[12] Deformation parameters β_L were obtained using the usual collective transition potential $\beta_L \partial U_{\text{opt}}/\partial r$. These β_L values were then used to calculate the isoscalar strengths $B(EL;0^+_{\text{g.s.}}\to L)$ via the prescription of Ref. 13, which assumes a sharp edge nuclear matter distribution and a nuclear radius of $(1.2\ \text{fm})A^{1/3}$. The β_L and $B(EL)$ values obtained in this way are tabulated in Table I (except for the 1.315- and 2.093-MeV states, as discussed below). Experimental and calculated angular distributions for states assigned L values of 2, 3, 4, and 5 are shown in Figs. 3–7. We were unable to reproduce the angular distribution of the 2.954-MeV state (see in Fig. 7) in our calculations for any reasonable L values. No states having $L=6$ or 7 were observed in this experiment, demonstrating that no large concentrations of $E6$ or $E7$ strength occur in any single state below 4.2 MeV.

The energy-weighted sum rule (EWSR) fraction for each state is also listed in Table I. The particular sum rule used here is that given by Halbert et al.[14]

Figure 6 includes data for the previously known 1.315-MeV 4^+ state and a best-fit $L=4$ curve. The fit is clearly unsatisfactory and no β_4 value was extracted from this single-step analysis. A further discussion of this state can be found in Sec. IV C. In addition, the β_5 value listed in

TABLE I. Results of ^{144}Nd(p,p') study.

E (MeV)[a] (Previous work)	E (MeV)[b,c] (Present work)	J^π (Present work)	β_L	$B(EL)$ (W.u.)[d]	EWSR[d] (%)
0.697		2^+	0.130(3)	24.2	7.7
1.315	1.311	4^+	0.09(1)	12.6	1.9
1.511	1.517	3^-	0.126(3)	23.4	7.5
2.073	2.066	2^+	0.027(3)	1.0	1.0
2.093	2.091	5^-	0.07(1)	8.2	1.2
2.109	2.107	2^+	0.032(3)	1.5	1.4
	2.347	2^+	0.028(3)	1.1	1.2
	2.490	2^+	0.030(3)	1.3	1.5
	2.719	3^-	0.065(3)	6.2	3.6
	2.771	4^+	0.033(3)	1.7	0.6
	2.893	4^+	0.030(3)	1.4	0.5
	2.909	2^+	0.021(3)	0.6	0.9
	2.954				

[a]Energies taken from Ref. 10. Energies above 2.1 MeV are not listed for reasons described in the text.
[b]Errors are ± 25 keV.
[c]Energies obtained using calibration described in the text.
[d]Calculated as described in the text.

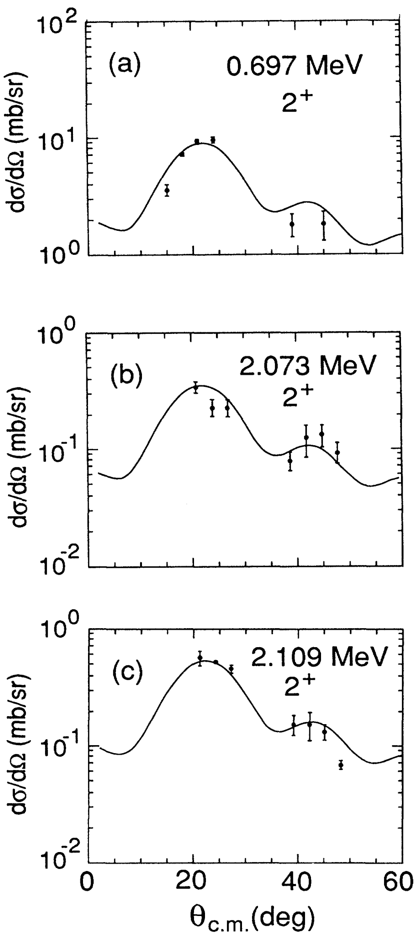

FIG. 3. Observed and calculated angular distributions for the 2^+ states at 0.697, 2.073, and 2.109 MeV. Details of the calculations are described in the text.

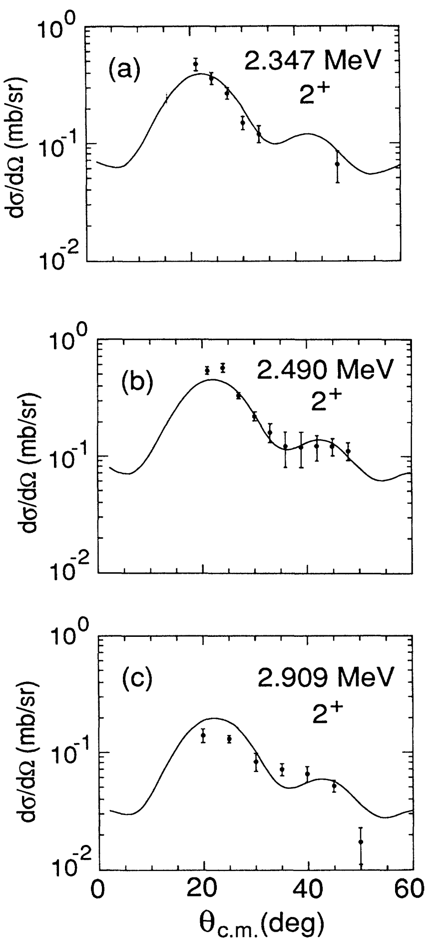

FIG. 4. Observed and calculated angular distributions for the 2^+ states at 2.347, 2.490, and 2.909 MeV. Details of the calculations are described in the text.

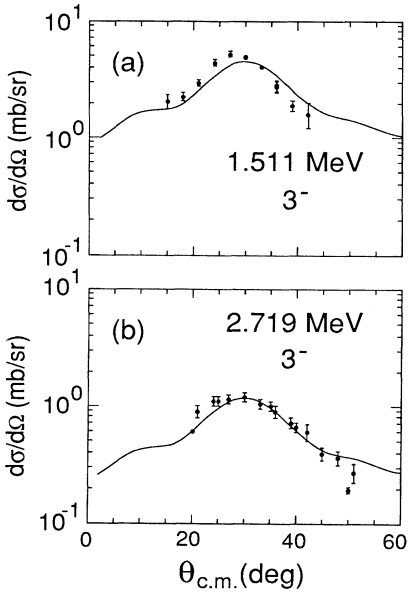

FIG. 5. Observed and calculated angular distributions for the 3^- states at 1.511 and 2.719 MeV. Details of the calculations are described in the text.

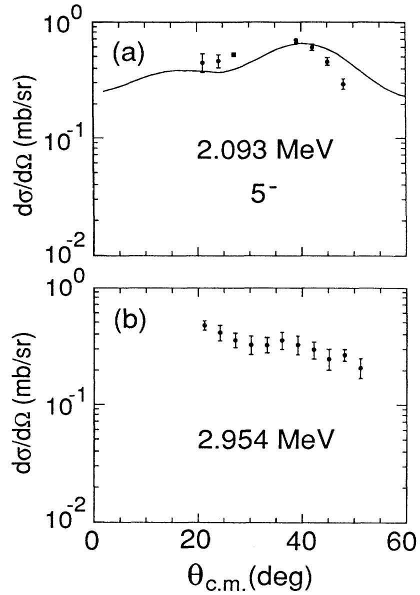

FIG. 7. Observed and calculated angular distributions for the 5^- state at 2.093 MeV and the state of unknown spin at 2.954 MeV. Details of the calculations are described in the text.

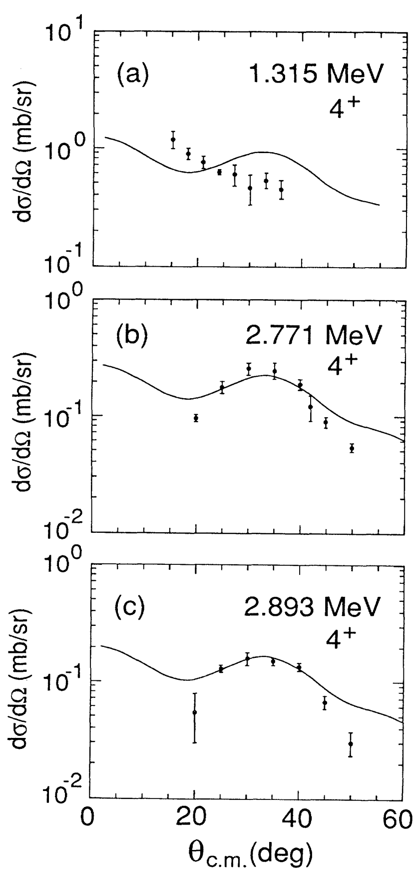

FIG. 6. Observed and calculated angular distributions for the 4^+ states at 1.315, 2.771, and 2.893 MeV. Details of the calculations are described in the text.

Table I for the 2.093-MeV state does not correspond to the single-step analysis (Fig. 7). The β_L values listed in Table I for both the 1.315- and 2.093-MeV states are obtained in Sec. IV.

While we were able to associate peaks in our spectrum with known states in ^{144}Nd at an excitation energy of 2.1 MeV and below, the increasing density of states made this task more difficult above 2.1 MeV. However, a comparison of the present data with $(n,n'\gamma)$ results[10] allowed a *tentative* identification of states observed in the present work above 2.1 MeV with those complied in Ref. 10. It is likely that the strong states in our experiment were populated in direct one-step excitation processes. Therefore, we would expect that the strong 2^+ states seen in this study would be seen to γ decay directly to the ground state in a $(n,n'\gamma)$ experiment. We exploited this approach to tentatively identify in our spectrum two 2^+ states which also appeared in the $(n,n'\gamma)$ results. The first of these states, measured to have an energy of 2.368 MeV in the $(n,n'\gamma)$ experiment, is separated by 50 keV from any other state in that experiment and may correspond to the state observed here, to which we assign an energy of 2.347 MeV. The second of these states, placed at 2.527 MeV in the $(n,n'\gamma)$ experiment, is separated by 60 keV from any other state that was seen to γ decay to the ground state; it may correspond to the 2^+ state, to which we assign an energy of 2.490 MeV here.

IV. DISCUSSION OF STATES IN ^{144}Nd

A. 2^+ states

Six 2^+ states were identified. The 2_1^+ state at 0.697 MeV was determined to have $\beta_2=0.130$ [$B(E2)=24.2$

W.u.]; this compares quite well with the value of $\beta_2=0.1309\pm0.0036$ [$B(E2)=24.4\pm0.3$ W.u.] adopted by Raman *et al.*[15] from a number of Coulomb excitation studies. The 2_2^+ state at 1.561 MeV was very weakly populated in this experiment, and an angular distribution could not be determined.

Our result for the 2_3^+ state at 2.073 MeV [$\beta_2=0.027$, $B(E2)=1.0$ W.u.] is of particular interest because of the proposal by Hamilton, Irback, and Elliot[5] that this state belongs to a class of states described by Iachello[2] as mixed symmetry states. These are collective states which have an isovector character; that is, the proton and neutron "fluids" oscillate out of phase. This suggestion was based on measurements of γ-ray branching ratios from these states in the $N=84$ isotones ^{140}Ba, ^{142}Ce, and ^{144}Nd. A number of studies of mixed symmetry states have been performed in deformed even-even rare-earth nuclei, in which the lowest-lying states of this type are located near 2.5 MeV and have $J^\pi=1^+$. The most commonly used probes for these studies have been inelastic electron scattering[3] and nuclear resonance fluorescence.[4]

For vibrational nuclei such as ^{144}Nd, the lowest mixed symmetry state has $J^\pi=2^+$; Iachello estimated[2] that the electromagnetic matrix element for this state, $B(E2;0^+_{\mathrm{g.s.}}\rightarrow 2^+)$, would be near 3 W.u. Recently, a study of a possible mixed symmetry state 2^+ at 2.004 MeV in ^{142}Ce has been performed using Coulomb excitation.[16,17] In that study, a result of $B(E2;0^+_{\mathrm{g.s.}}\rightarrow 2_3^+)=3.2(5)$ W.u. was obtained for this state in ^{142}Ce. This strength is in rough agreement with the general estimate of 3 W.u. given by Iachello.

The $B(E2;0^+_{\mathrm{g.s.}}\rightarrow 2_3^+)$ result for ^{144}Nd from the present work, 1.0 W.u., is quite different from the general 3 W.u. estimate. Furthermore, all of the 2^+ states observed here (except for the 2_1^+ state) have $B(E2;0^+_{\mathrm{g.s.}}\rightarrow 2^+)$ matrix elements of 1.5 W.u. or less, significantly less than the 3 W.u. value. This disagreement suggests that the mixed symmetry mode may be fragmented among several 2^+ states. In fact, Meyer *et al.*[18] have recently proposed that in ^{144}Nd large components of the mixed symmetry mode may be present in both the 2_3^+ state (at 2.073 MeV) and the 2_4^+ state (at 2.109 MeV), which are in close proximity to one another. The sum of the $B(E2;0^+_{\mathrm{g.s.}}\rightarrow 2^+)$ strengths in these two states, 2.4 W.u., is reasonably close to Iachello's 3 W.u. estimate, suggesting that most of the mixed symmetry strength might indeed be divided between these two states. In this way, the data presented here support the proposal of Meyer *et al.*[18]

Three other 2^+ states are observed. All three of these states have $B(E2;0^+_{\mathrm{g.s.}}\rightarrow 2^+)$ values near 1 W.u. These states are at least 300 keV away from the 2_3^+ and 2_4^+ states; consequently, it is less likely that the higher-lying states contain significant mixed symmetry strength.

B. 3^- states

Two 3^- states are observed in the present work. The first is the well-known 3_1^- state at 1.511 MeV. We measure a $B(E3;0^+_{\mathrm{g.s.}}\rightarrow 3_1^-)$ value of 23.4 ± 1.2 W.u., which differs from the result obtained via Coulomb excitation[17] (30.5 ± 1.2 W.u.). However, Spear[19] found that $B(E3)$ values obtained via (p,p') for $A>20$ nuclei deviate as much as 33% (both above and below) from values measured via Coulomb excitation. Consequently, the 23% deviation seen between the two measurements is not surprising.

A second 3^- state is observed at 2.719 MeV and has a considerable amount of $B(E3;0^+_{\mathrm{g.s.}}\rightarrow 3^-)$ strength (6.2 W.u.). The occurrence of two octupole states separated by 1.2 MeV is somewhat similar to the observation of two octupole states in a recent study[20] of the ^{142}Nd(p,p') reaction at 25 MeV. In ^{142}Nd, the 3_1^- state occurs at 2.084 MeV and has a strength of 26 W.u. A second 3^- state is observed at an energy of 3.563 MeV (1.5 MeV higher than the 3_1^-) state and has a strength of 2.6 W.u. The 3_1^- states in ^{142,144}Nd arise primarily from *intrashell* two-quasiparticle (2qp) excitations. It is possible that the 3_2^- states in these Nd isotopes are composed primarily of excitations of neutrons *across* the $N=82$ shell gap.

C. 4^+ states

The transition of 4_1^+ states from their 2qp character in the $N=82$ nuclei to their rotational nature in the $N=90$ nuclei was discussed in Sec. I. Here we propose that excitation mechanisms characteristic of both 2qp and collective structure must be utilized in order to achieve the best fit to the present data for the 4_1^+ state in ^{144}Nd.

The analysis described in Sec. III involves a direct one-step excitation mechanism. This mechanism is applicable if the 4^+ state possesses either a 2qp or else a hexadecapole vibrational structure which endows the state with $B(E4;0^+_{\mathrm{g.s.}}\rightarrow 4_1^+)$ strength. The success of the direct one-step approach with the higher-energy 4^+ states at 2.771 and 2.893 MeV [see Figs. 6(b) and 6(c)] serves to emphasize its inadequacy for the 4_1^+ state at 1.315 MeV [Fig. 6(a)].

Although the energy spacing of the $0^+_{\mathrm{g.s.}}$-2_1^+-4_1^+ sequence (0, 0.697, and 1.315 MeV) clearly rules out a rotational origin, the nearly equal spacing of these states does suggest that the 4_1^+ state may arise from the coupling of two quadrupole phonons. However, it is straightforward to demonstrate that the differential cross section observed in the present experiment excludes a simple two-quadrupole-phonon origin for this state. If the 4_1^+ state had such an origin, it would be populated via the two-step excitation mechanism illustrated in Fig. 8(a). A coupled-channel calculation (with CHUCK) for such a coupling scheme and utilizing for both steps the β_2 value of 0.130 obtained for the 2_1^+ state underpredicts the differential cross section by an order of magnitude [Fig. 8(c)].

A coupled-channel calculation using the scheme shown in Fig. 8(b) demonstrates that the most successful fit is obtained when *both* direct and two-step mechanisms are included. A fit using this scheme is illustrated in Fig. 8(c); a β_4 value of 0.09 is used to achieve this fit and is listed in Table I. Our result supports the conclusion that significant 2qp and two-phonon components are *both* present in the 4_1^+ state. Coulomb excitation data also support this view for the following reason. For harmonic quadrupole phonons,[21] $B(E2;4_1^+\rightarrow 2_1^+)$ would be twice

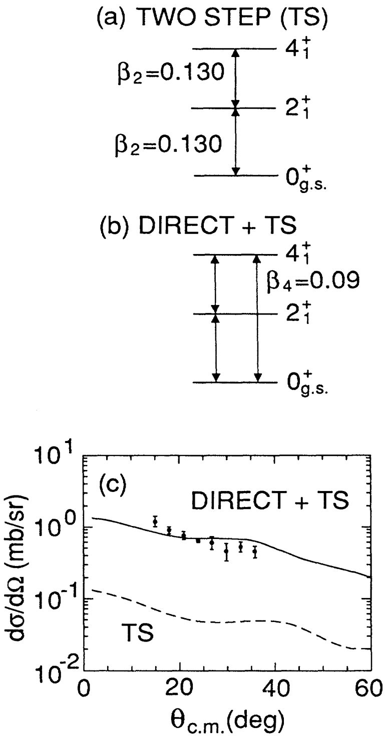

FIG. 8. (a) Coupled-channel scheme used to model the two-step excitation mechanism for the 1.315-MeV 4^+ state. (b) Coupled-channel scheme including direct excitation mechanism. (c) A comparison of the observed angular distribution for the 1.315-MeV state to the result of the coupled-channel calculations shown in (a) and (b).

the value of $B(E2;2_1^+ \rightarrow 0_{g.s.}^+)$. However, Spear *et al.*[17] have found via Coulomb excitation that $B(E2;2_1^+ \rightarrow 4_1^+)$ is 0.100 ± 0.009 e^2b^2, much smaller in magnitude than their $B(E2;0_{g.s.}^+ \rightarrow 2_1^+)$ value of 0.491 ± 0.004 e^2b^2, and contrary to what would be expected for a pure two-quadrupole-phonon state.

The result for the 4_1^+ state demonstrates that rapid changes in the nature of the states are taking place in ^{144}Nd as the spin increases. Both the 2_1^+ and 3_1^- states possess $B(EL)$ values greater than 20 W.u., signaling their collective origins. If the relatively large $B(E4;0_{g.s.}^+ \rightarrow 4_1^+)$ strength of 12 W.u. in the 4_1^+ state is indeed caused largely by the presence of 2qp components, then this state is clearly less collective than either the 2_1^+ or 3_1^- state. Furthermore, the presence of both collective and 2qp components in the 4_1^+ state is an excellent demonstration of the nuclear shape transition taking place between the spherical $N=82$ isotones and the substantially deformed rotors at $N=90$.

D. 5^- states

Only one 5^- state was observed here, at 2.093 MeV, but it contained a significant amount of strength, 8.2 W.u. This state had been previously interpreted[1,22] as arising from the coupling of the 0.697-MeV 2_1^+ and 1.511-MeV 3_1^- states. If this were indeed the case, then the 5^- state would be populated via a two-step process involving successive $E2$ and $E3$ excitations, as shown in Fig. 9(a). A coupled-channel calculation performed using the code CHUCK and the β_2 and β_3 values obtained for the 2_1^+ and 3_1^- states (0.130 and 0.126, respectively) underpredicted the differential cross-section data by an order of magnitude [see Fig. 9(c)]. Clearly, the cross section observed in this experiment cannot be explained in the context of such a model, and an additional direct $E5$ excitation mechanism from the ground state is required. A coupling scheme including both single- and two-step excitation mechanisms [Fig. 9(b)] provides a good fit [Fig. 9(c)] with a value of $\beta_5=0.07$, which is listed in Table I.

The fit in Fig. 9(c) is not obviously better than that resulting from the simple one-step calculation (Fig. 7). Consequently, we cannot use our result as evidence for the presence of a large quadrupole-octupole component in the wave function of the 5_1^- state. In order to test the 5_1^- more sensitively for the magnitude of its quadrupole-

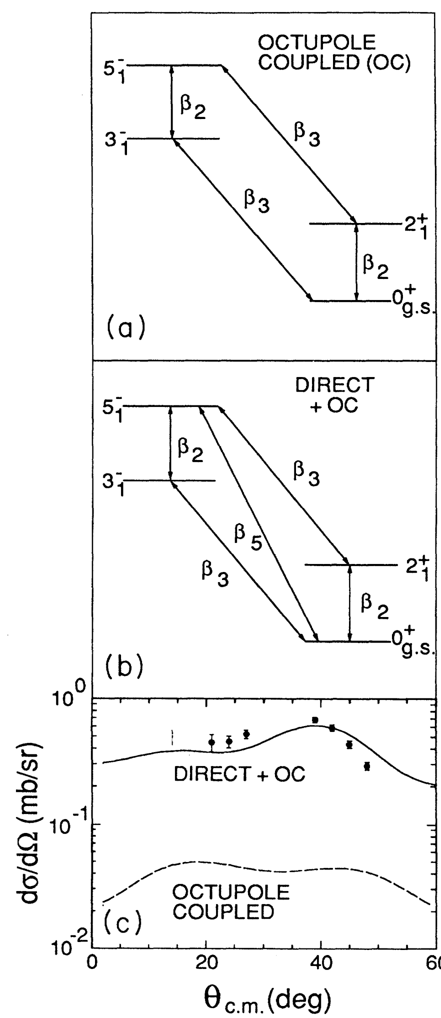

FIG. 9. (a) Coupled-channel scheme used to model the two-step excitations mechanism for the 2.093-MeV 5^- state. (b) Coupled-channel scheme including direct excitation mechanism. (c) A comparison of the observed angular distribution for the 2.093-MeV state to the result of the coupled-channel calculations shown in (a) and (b).

octupole component, it would be necessary to measure the strength of the $E2$ transition connecting the 5_1^- state with the 3_1^- state. Such a measurement might be performed using a technique to measure the Doppler shift of γ rays emitted by the 5^- (both the $5^- \rightarrow 3^-$ $E2$ and the $5^- \rightarrow 4^+$ $E1$ transitions) after it has been excited via a scattering reaction involving neutrons, protons, or heavy ions.

V. CONCLUSION

The scattering of 35-MeV protons from ^{144}Nd has been experimentally studied, and angular distributions for 13 states have been measured. Our results support the fragmentation of the mixed symmetry strength between the 2_3^+ and 2_4^+ states as proposed by Meyer *et al.*[18] In addition, our analysis suggests that the 4_1^+ state of ^{144}Nd contains both 2qp and two-quadrupole-phonon components. This result demonstrates that a transition from collective to single-particle nature is occurring with increasing spin in ^{144}Nd. Furthermore, our work casts new light on the transition from spherical to deformed shapes taking place in the Nd isotopes between $N = 82$ and 90. Finally, we have demonstrated that the 5^- state at 2.093 MeV is not a pure quadrupole-octupole coupled state. It is clear that further investigations of the other even-even Nd isotopes using proton inelastic scattering, as well as other probes such as $(n,n'\gamma)$ experiments, would yield additional information on each of the topics discussed here.

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[1] P. D. Cottle, S. M. Aziz, J. D. Fox, K. W. Kemper, and S. L. Tabor, Phys. Rev. C **40**, 2028 (1989).

[2] F. Iachello, Phys. Rev. Lett. **53**, 1427 (1984).

[3] U. Hartmann, D. Bohle, T. Guhr, K. D. Hummel, G. Kilgus, U. Milkau, and A. Richter, Nucl. Phys. **A465**, 25 (1987).

[4] B. Kasten, R. D. Heil, P. v. Brentano, P. A. Butler, S. D. Hoblit, U. Kneissl, S. Lindenstruth, G. Muller, H. H. Pitz, K. W. Rose, W. Scharfe, M. Schumacher, U. Seeman, Th. Weber, C. Wesselborg, and A. Zilges, Phys. Rev. Lett. **63**, 609 (1989).

[5] W. D. Hamilton, A. Irback, and J. P. Elliot, Phys. Rev. Lett. **53**, 2469 (1984).

[6] P. D. Cottle, S. M. Aziz, K. W. Kemper, M. L. Owens, E. L. Reber, J. D. Brown, E. R. Jacobsen, and Y. Y. Sharon, Phys. Rev. C **42**, 762 (1990).

[7] R. T. Kouzes, Ph.D. thesis, Princeton University, 1974 (unpublished).

[8] D. C. Radford, A. W. Wright Nuclear Structure Laboratory (Yale University) Internal Report No. 69, 1979 (unpublished).

[9] F. D. Becchetti and G. W. Greenless, Phys. Rev. **182**, 1190 (1969).

[10] J. K. Tuli, Nucl. Data Sheets **56**, 607 (1989).

[11] P. D. Kunz, University of Colorado report (unpublished).

[12] D. Larson, S. M. Austin, and G. H. Wildenthal, Phys. Rev. C **9**, 1574 (1974).

[13] A. M. Bernstein, in *Advances in Nuclear Physics,* edited by M. Baranger and E. Vogt (Plenum, New York, 1969), Vol. 3, p. 321.

[14] E. C. Halbert J. B. McGrory, G. R. Satchler, and J. Speth, Nucl. Phys. **A245**, 189 (1975), Eq. (8).

[15] S. Raman, C. H. Malarkey, W. T. Milner, C. W. Nestor, Jr., and P. H. Stelson, At. Data Nucl. Data Tables **36**, 1 (1987).

[16] W. J. Vermeer, C. S. Lim, and R. H. Spear, Phys. Rev. C **38**, 2982 (1988).

[17] R. H. Spear, W. J. Vermeer, S. M. Burnett, G. J. Gyapong, and C. S. Lim, Aust. J. Phys. **42**, 345 (1989).

[18] R. A. Meyer, O. Scholten, S. Brant, and V. Paar, Phys. Rev. C **41**, 2386 (1990).

[19] R. H. Spear, At. Data Nucl. Data Tables **42**, 55 (1989).

[20] L. Trache, J. Wrzesinski, C. Wesselborg, A. Clauberg, K. O. Zell, R. Reinhardt, P. von Brentano, D. Bazzacco, G. P. A. Berg, W. Hurlimann, J. Meissburger, and J. L. Tain, Nucl. Phys. **A492**, 23 (1989).

[21] A. Bohr and B. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. II, p. 349.

[22] D. F. Kusnezov, Ph.D. dissertation, Princeton University, 1988 (unpublished).