Octupole Collectivity in the Ground Band of ^{148}Nd

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$E3$ matrix elements have been determined for transitions between states up to $I^\pi=13^-$ in ^{148}Nd, providing direct evidence for strong octupole collectivity in a rotational band. These values, as well as the corresponding $E1$ and $E2$ matrix elements, were obtained from Coulomb excitation data using ^{58}Ni and ^{92}Mo ions, projectile excitation using a ^{208}Pb target, and from recoil distance lifetime measurements. The results are consistent with collective model predictions for ^{148}Nd assuming intrinsic quadrupole and octupole moments of $Q_{20} \approx 400\ e\,\mathrm{fm}^2$ and $Q_{30} \approx 1500\ e\,\mathrm{fm}^3$. The $E3$ strength coupling the negative-parity states to the β band is found to be appreciable.

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The experimental study of nuclei with $Z = 54$–60 and $N \approx 88$ populated by α-induced reactions [1] and fission [2] has revealed the presence of interleaved negative- and positive-parity yrast bands that are coupled by enhanced $E1$ transitions. This behavior, which is characteristic of reflection-asymmetric shapes, has been interpreted within the mean-field approach as arising from the presence of an octupole deformation, i.e., $\beta_3 \neq 0$ [3,4]. Measurement of enhanced $E3$ matrix elements connecting these states would provide unambiguous and direct evidence for collective octupole correlations. Although the $E3$ matrix element between the ground state and lowest 3^- state has been measured for many nuclei [5] including ^{148}Nd [6], no measurement has yet been made of the $E3$ matrix elements as a function of spin for an octupole band. This is because real photon $E3$ emission typically is about 10^4 times weaker than competing $E1$ and $E2$ decay. The observed $E1$ transition strengths are known to be an unreliable indicator of octupole correlations because they are strongly affected by large single particle contributions [7,8]. Heavy-ion Coulomb excitation provides a sensitive means of measuring $E3$ matrix elements since $E3$ excitation can be an order of magnitude stronger than competing $E1$ excitation. This has been exploited in this work to carry out the first measurements of $E3$, as well as $E1$ and $E2$, matrix elements for a possible octupole collective band in ^{148}Nd. During the progress of this work, similar studies of ^{226}Ra [9] and ^{150}Nd [10] were undertaken.

Presented here are the results of such measurements on ^{148}Nd following Coulomb excitation with ^{58}Ni ions, ^{92}Mo ions, and a ^{208}Pb target in which both γ-ray yields and lifetimes were determined. A summary of the experiments performed is as follows:

(i) A beam of 200 MeV ^{58}Ni, provided by the Rochester tandem Van de Graaff accelerator, bombarded a self-supporting 1 mg/cm^2 Nd target enriched to 93% ^{148}Nd. The scattered Nd and Ni ions were detected in kinematic coincidence using a parallel plate avalanche counter (PPAC) covering the angular range $14^\circ \le \theta \le 76^\circ$, and ^{58}Ni ions were detected in a PPAC covering $110^\circ \le \theta \le 150^\circ$. This detector system is described elsewhere [11,12]. The γ rays were detected in coincidence with scattered ^{58}Ni and recoiling ^{148}Nd ions using five Compton-suppressed Ge spectrometers, positioned 15 cm from the target. Measurements of the coincidence γ-ray yields were binned into four ranges of scattering angle, so that the dependence of the Coulomb excitation on impact parameter could be exploited.

(ii) Particle-γ and particle-γ-γ coincidences were measured following the bombardment of the previously described target with 330 MeV ^{92}Mo ions, provided by the Nuclear Structure Facility, Daresbury. The γ rays were detected by POLYTESSA [13] consisting of twenty Compton-suppressed Ge detectors, and the scattered ions were detected in PPACs subtending an angular range of 104°–154° [8]. In this experiment, transitions from both the positive- and negative-parity states in the octupole band were observed up to spins 10^+ and 9^-, respectively (see Fig. 1). Gamma-ray intensities were determined, in coincidence with all backscattered Mo ions, at four selected Ge detector angles.

(iii) An isotopically pure beam of 700 MeV ^{148}Nd, provided by HHIRF, at the Oak Ridge National Laboratory, was excited by a 0.2 mg/cm^2 self-supporting ^{208}Pb target. Nd and Pb ions were detected in kinematic coincidence using a PPAC covering $14^\circ \le \theta \le 76^\circ$ [11]. The γ rays were detected (in coincidence with both ions) by sixteen Compton-suppressed Ge detectors in the Spin Spectrometer, which measured the total energy of the entrance states and the multiplicity of the γ-ray decay. The γ-ray yields were binned into five ranges of θ_{Nd}.

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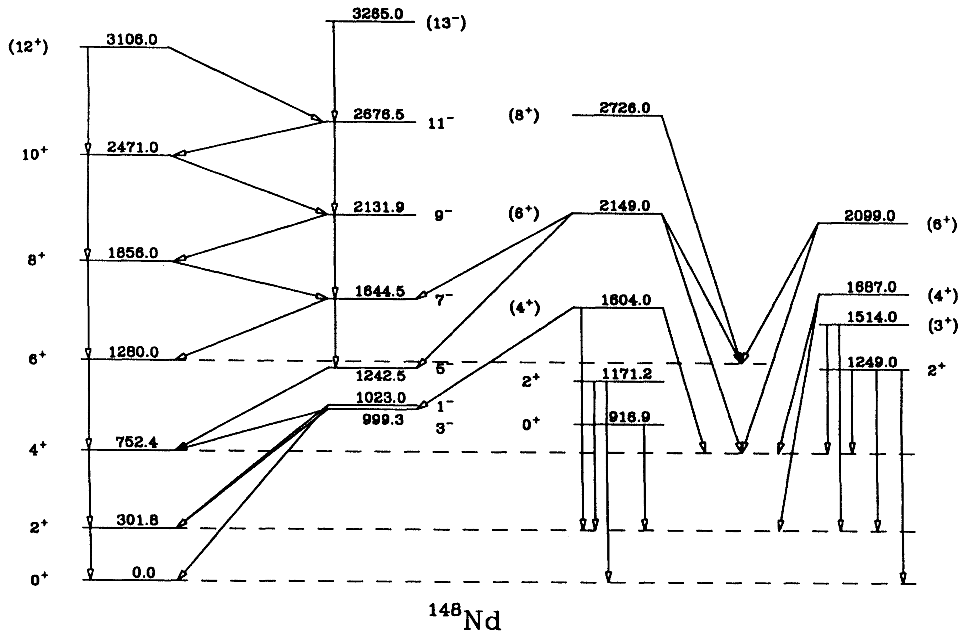

FIG. 1. Partial level scheme for ^{148}Nd.

(iv) Lifetimes of nine excited states in ^{148}Nd were measured using the recoil distance method, following inelastic scattering of ^{58}Ni ions at a bombarding energy of 210 MeV. This experiment has been described in more detail elsewhere [14].

Previously identified levels [1,15,16] and the levels identified in this work are shown in Fig. 1. For the ^{58}Ni and ^{92}Mo work the $3^- \rightarrow 2^+$ transition was obscured by the lowest $(2^+ \rightarrow 0^+)$ transition in ^{144}Nd, the 338 keV transition $(10^+ \rightarrow 9^-)$ is contaminated by the $6^+ \rightarrow 4^+$ transition in ^{150}Nd, and no transitions from states above the 10^+ state were observed. In all these experiments, the 615 keV γ ray $(10^+ \rightarrow 8^+)$ is a doublet with the $0_2^+ \rightarrow 2_1^+$ transition. $E2$ transitions within the negative-parity band were not observed in these two experiments, but transitions deexciting the quasi-β and -γ vibrational bands [16] were observed.

The Pb experiment was free of the isotopic contamination problems present in the first two experiments. The 13^- state was the highest spin observed in the Pb experiment with sufficient transition strength to be analyzed, and several $E2$ transitions within the negative-parity band were observed. Particle-particle-γ-γ events were used in conjunction with the γ-ray multiplicity to make assignments of unknown γ transitions. Assignments based on the present work were made using the Mo and Pb particle-γ-γ data for the 13^-, 12^+, 4_β^+, 6_β^+, 8_β^+, 3_γ^+, 4_γ^+, and 6_γ^+ levels. The levels shown in Fig. 1 comprise all but 8 of those known to lie within 2 MeV of the yrast line up to spin 13^-.

A total of 2158 independent data points (2148 γ-ray yields, 9 lifetimes, and a previous measurement of the decay width $\Gamma_{1^- \rightarrow 0^+}$ [17]) were used with the semiclassical Coulomb-excitation least-squares search code, GOSIA [18], to fit 227 $E1$, $E2$, $E3$, and $M1$ matrix elements for ^{148}Nd. A total of 140 of these matrix elements were determined with moderate error limits. The relative phases of the wave functions were chosen by fixing the sign of one in-band $E2$ transition matrix element leading to each state, and one $E3$ matrix element between the positive- and negative-parity bands. The other signs are observables. In order to take into account effects due to virtual excitation, the rigid-rotor model was used to constrain the possible values of matrix elements with λ=1, 2, 3 for unobserved transitions involving states with $I > 13^-$. In these calculations the $E4$ matrix elements were constrained to lie within a range of values determined by a previous measurement of $\langle 4^+ || E4 || 0^+ \rangle = 3600\ e\,\text{fm}^4$ [6] and the predictions of the axial rigid-rotor model. The effect of varying the $E4$ values was tested; the resulting changes in the $E1$, $E2$, and $E3$ matrix elements were less than $10^{-6}\ e\,\text{fm}$, $5\ e\,\text{fm}^2$, and $70\ e\,\text{fm}^3$, respectively, which are much smaller than the assigned errors. Matrix elements connecting states in the quasi-β and -γ bands also were included in the fit. The overall value of the χ^2, normalized to the number of data points in the fit, was 1.01. The extracted values of the $E1$, $E2$, and $E3$ matrix elements for the yrast states are shown in Figs. 2, 3, and 4, respectively. The errors shown take into account cross-correlation effects.

The enhanced $E2$ matrix elements [e.g., $B(E2; 2^+ \rightarrow 0^+) = 55$ Weisskopf units (W.u.)] for the positive-parity states follow the predictions of the rotational model, i.e.,

$$\langle J_f || E\lambda || J_i \rangle = a_\lambda Q_{\lambda 0} (2J_i + 1)^{1/2} \langle J_i 0 \lambda 0 | J_f 0 \rangle,$$

with an approximately constant intrinsic moment $Q_{\lambda 0}$. The negative-parity states show a systematically smaller intrinsic-frame quadrupole moment for lower spins. The

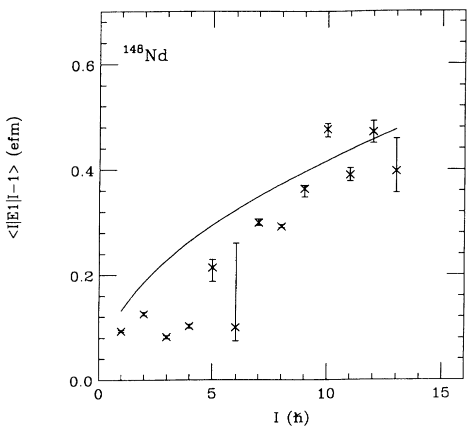

FIG. 2. Ground-band $E1$ matrix elements. Curve corresponds to rotor predictions assuming $Q_{10} = 0.25\ e\,\text{fm}$.

measured static $E2$ moments are consistent with the assignment of a prolate intrinsic shape for this nucleus except that the static $E2$ moment for the 1^- state is considerably smaller than the rotor prediction. The $E2$ systematics are illustrated by the summed $B(E2)$ strengths involving each state. These summed strengths ($\langle[E2 \times E2]^{\Delta J=0}\rangle$) can be related directly to the intrinsic-frame quadrupole moment [19]. The summed $E2$ strengths for the ground-state band are fairly constant for spins >5, with a value of $\approx$+20 000 $e^2\,\text{fm}^4$. The measured intrinsic collective moments, $Q_{\lambda 0}$, can be related to the deformation coordinates β_λ using the formalism of Leander and Chen [20]. The summed strength involving the ground-, β-, and γ-band states corresponds to a β_2^{rms} =+0.20. Summations involving only ground-band states correspond to 90% of the $E2$ strength.

The ground-band $E3$ matrix elements follow the trend of the rotational model predictions for a $K = 0$ band, assuming a $|Q_{30}| \approx 1500\ e\,\text{fm}^3$ ($|\beta_3| \approx 0.12$), but for lower spins the $E3$ matrix elements exhibit a stagger (positive- and negative-parity states are shown with different symbols in Fig. 4). This stagger could be indicative of mixing with higher $K \neq 0$ states, although a survey of rare-earth nuclei with $Z \geq 50$ [21] has revealed little evidence for this. Nevertheless, such K mixing also could explain the anomalously small value of the static quadrupole moment of the 1^- state. The measured value of $B(E3; 3^- \to 0^+) = 36$ W.u. is in good agreement with the previous measurement [6]. The $E3$ matrix elements connecting the negative-parity states to the β band are unexpectedly large, being about half of those to the ground band. This is reflected in the summed $B(E3)$ strengths for the negative-parity band which are fairly constant, with $\approx$30% of the $B(E3)$ strength coupling to the β band, while the B($E3$) strength involving the gamma band accounts for <10%. This shows a considerable fractionation of the $E3$ strength among the $K = 0$ bands.

The $E1$ matrix elements are fairly constant for $I < 5$

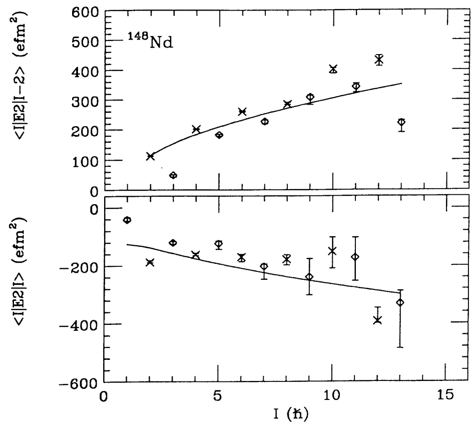

FIG. 3. Ground-band $E2$ matrix elements. Curve corresponds to rotor predictions assuming $Q_{20} = +400\ e\,\text{fm}^2$. Matrix elements connecting positive-parity states are plotted with crosses; matrix elements connecting negative-parity states are plotted with diamonds.

[$B(E1; 1^- \to 0^+) = 0.0016$ W.u.]. Above $I \approx 7$, the $\langle I||E1||I-1\rangle$ are consistent with the value of $Q_{10} = 0.23\ e\,\text{fm}$ given by recent experiments [1,22], and agree reasonably well with estimates [1,23], but are lower than calculations [24] using more appropriate shape parameters, which predict $Q_{10} = 0.34\ e\,\text{fm}$. The relative signs of the $E1$ and $E3$ matrix elements have been fixed in the present analysis so that Q_{10} and Q_{30} have the same sign. This relative phase is taken from Ref. [24] and is the same as that expected for a deformed liquid drop [25] alone using Strutinski's method to calculate the dipole moment. This phase of the product $E1 \times E3$ could not be measured uniquely, since comparable fits were obtained with either choice of this phase, resulting in similar magnitudes for the $E1$ and $E3$ matrix elements.

Mean-field calculations which allow octupole deformation have been made for ^{148}Nd [1]. These give

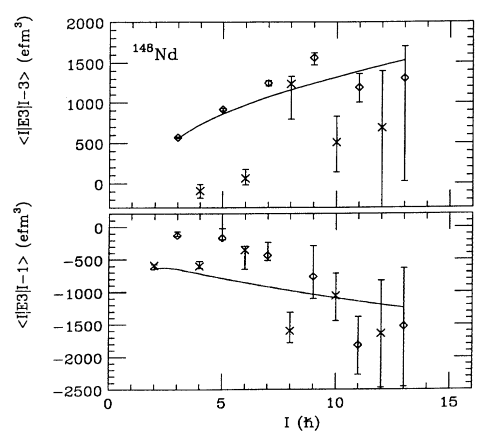

FIG. 4. Ground-band $E3$ matrix elements. Curve corresponds to rotor predictions assuming $|Q_{30}| = 1500\ e\,\text{fm}^3$. Matrix elements for even I are plotted with crosses; matrix elements for odd I are plotted with diamonds.

an octupole-deformed configuration at spin 7-8 with mean values of the deformation parameters of $\overline{\beta}_2$=+0.20, $\overline{\beta}_3$=0.075 lying close in energy to the reflection symmetric minimum with $\overline{\beta}_2$=+0.22 and $\overline{\beta}_3$=0. The value of $|\beta_3^{\rm rms}|$ extracted from the centroid of Q_{30}^2 depends on the magnitude of the octupole moment at the minimum, and the softness of the nucleus to octupole deformation. Nazarewicz and Tabor [23] have investigated the effect of varying the barrier height between the octupole minima upon the $K^\pi = 0^+$ - $K^\pi = 0^-$ energy level splitting and the $B(E3)$ transition rate between the bands. They find that although the energy levels are very sensitive to the barrier height, the $B(E3)$ remains almost constant for large barrier height (octupole deformed) and almost zero barrier (octupole vibrator). It therefore appears that while the existence of strong octupole collectivity can be demonstrated in ^{148}Nd, the present data are insufficient to determine the degree of octupole softness.

In summary, a comprehensive set of $E1$, $E2$, and $E3$ matrix elements are presented for ^{148}Nd. The yrast band $E2$ and $E3$ matrix elements are consistent with predictions of a model which assumes a rotating shape having, on average, $Q_{20} \approx +400$ $e\,$fm^2 ($\beta_2 \approx +0.18$), and $|Q_{30}| \approx 1500$ $e\,$fm^3 ($|\beta_3| \approx 0.12$), with a considerable stagger for low spins. These results are sensitive only to the centroid of Q_{30}, not the distribution width. The $B(E3)$ values coupling the negative-parity states to the β band are roughly half the magnitude of the $B(E3)$ values in the ground band. This measurement of the $E3$ matrix elements up a collective band provides unambiguous evidence for strong octupole collectivity in the ground band of ^{148}Nd.

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