EVOLUTION OF THE DECAY MODES OF ^{158}Yb WITH SPIN

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The decay of the entry states in ^{158}Yb populated in the reactions of 149 MeV ^{20}Ne with ^{144,146}Nd has been investigated with the Spin Spectrometer gated by a Ge counter. The average excitation energy, the γ-ray spectra and the angular distributions as a function of multiplicity suggest a region of non-collective behavior at low spin. At higher spin collective characteristics are apparent, but between $I \approx 40$ and 49 a strong stretched dipole component is seen. Above $I \approx 49$ no additional dipole transitions are observed. These characteristics are discussed in terms of recent calculations.

The evolution of nuclear shapes as a result of the interplay of the single-particle and collective degrees of freedom has been the subject of intensive theoretical and experimental investigation in the past few years [1–3]. Many nuclei with N = 82–86 are slightly oblate [4] and generate their angular momentum, at least up to spin $I \approx 38$, by aligning quasiparticle spins. Rare earth nuclei with $N \geqslant 92$ are prolate and have rotational spectra at least up to $I = 26$ [5]. Transitions from one type of behavior to another may be observable in a single nucleus as a function of I. For example, recent evidence suggests that collectivity in ^{152}Dy may set in above $I = 30$ [6], that a change may occur in ^{154}Dy at $I \approx 30$ from prolate to oblate via triaxial shapes [7], and that a transition from prolate to a collectively rotating oblate shape appears to take place in ^{160}Yb at $I \approx 45$ [8]. In view of this evidence and the prediction of super-deformed configurations ($\epsilon \approx 0.6$) in $N \approx 86$ nuclei [9], it seemed that ^{158}Yb (N = 88) would be a good candidate for studying the evolution of nuclear shape as a function of spin.

We have investigated the γ-decay properties of the entry states in ^{158}Yb populated in reactions of 149 MeV ^{20}Ne from ORIC with ^{144}Nd and ^{146}Nd. Population distributions of the entry states, γ-ray energy spectra, and angular distributions were measured with the Spin Spectrometer at the Holifield Heavy-Ion Research Facility. The spectrometer is a 4π arrangement of 72 NaI detectors allowing the efficient measurement of γ-ray spectra simultaneously with the multiplicity M_γ excitation energy E^*, and γ-ray angular correlations. The exit channel was identified by gating on known low-lying transitions in ^{158}Yb with a Ge detector at 117°. The electronics of the Spin Spectrometer were triggered by the Ge signals. Sixty-nine detectors in the spectrometer were used, covering 92.3% of 4π. Data collection and analysis to obtain population distributions of the entry states in ^{158}Yb as a function of I and E^* were carried out as described in refs. [10] and [11].

For each coincidence fold, k, NaI pulse-height spectra were constructed for events from all the detectors and for four groups of detectors at angles of 24.4°, 45.6°, 65.7°, and 82.4° (and their supplements) with respect to the beam, in coincidence with

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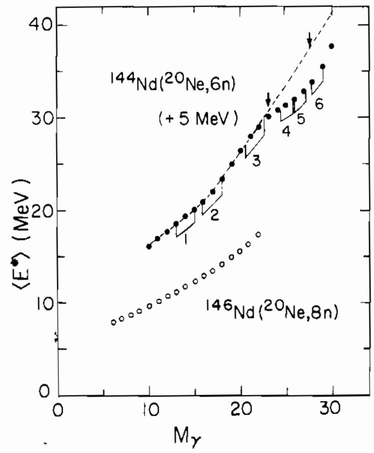

Fig. 1. Entry lines, $\langle E^* \rangle$ versus M_γ. The points are from the reactions indicated. The dashed line was used to derive the M_γ to I mapping (see text). The data and calculation for the ^{144}Nd target are offset by +5 MeV. The bracketed regions marked 1 to 6 give the M_γ gates used for the spectra shown in fig. 2b. The vertical arrows mark the start of the downbend of the entry line with M_γ.

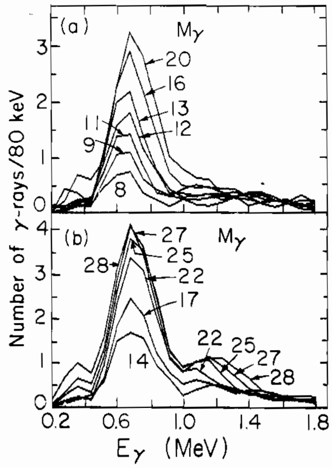

Fig. 2. (a) Unfolded γ-ray continuum spectra for single-k bins normalized to M_γ from the ^{146}Nd(^{20}Ne, 8n) data. (b) Unfolded γ-ray spectra from k-bins of three consecutive k values normalized to M_γ. The labels for both (a) and (b) are round values of the centroid of the M_γ region for each k bin.

the 358.4 keV $2^+ \to 0^+$ transition in ^{158}Yb. The contribution of the Compton background in the Ge gate was subtracted. The γ-ray energy spectra were then obtained from the NaI pulse-height spectra by an iterative unfolding procedure taking into account the detector responses. The response functions were obtained by measurements with radioactive sources for γ-ray energies between 0.136 and 4.439 MeV and by extrapolation for higher energies. They include corrections for coincidence summing [10].

The experimental entry lines, $\langle E^* \rangle$ versus M_γ, for ^{158}Yb from both reactions are shown in fig. 1. Calculated entry lines were obtained from the statistical model code JULIAN-PACE [12] modified to give a more realistic treatment of γ-emission [11]. The calculations reproduce the slopes of the entry lines from both reactions up to $M_\gamma \approx 22$. At this value the experimental entry lines for the ^{144}Nd(^{20}Ne, 6n) reaction shows a downward bend of $\langle E^* \rangle$ with M_γ, and a subsequent upbend at $M_\gamma \sim 27$.

The γ-decay of the entry states was investigated for M_γ = 7 to 22 for ^{146}Nd(^{20}Ne, 8n) and 12 to 30 for ^{144}Nd(^{20}Ne, 6n). Selected energy spectra from the 8n reaction, obtained from all the NaI detectors in the spectrometer and normalized to their respective multiplicities are shown in fig. 2a. They correspond to selected single k values. Spectra from the 6n reaction corresponding to bins of three consecutive k values are shown in fig. 2b. The labels in fig. 2 are the mean values of M_γ corresponding to each k-bin. The six k gates for the 6n reaction correspond to the M_γ regions shown in fig. 1. The sharp edges may be deceptive, as the M_γ gates actually extend about 2 units above and below the indicated ranges due to the finite M_γ resolution of the spectrometer.

Two prominent features are apparent in the spectra of fig. 2. One is a bump at $E_\gamma \approx 600$ to 800 keV which evolves smoothly up to $M_\gamma \approx 20$. Above $M_\gamma \approx 22$ a second bump appears at higher energy with its upper edge reaching ≈1.4 MeV at $M_\gamma \approx 28$. The behavior of these structures with increasing M_γ will be correlated with the angular distribution data and the shape of the entry line (fig. 1), to provide a consistent picture of the γ de-excitation in ^{158}Yb. The yrast decay scheme of ^{158}Yb is known up to $I = 12$ and consists of a cascade of stretched E2 transitions, with E_γ from 358 to 683 keV [13]. The behavior of the lower bump, particularly the motion of its upper edge, is consistent with a continuation of a predominantly quadrupole cascade up to $M_\gamma \approx 20$. However, angular distributions of the continuum γ-rays for M_γ between 12 and 20 are less anisotropic than would be expected for pure stretched quadrupole radiation, indicating that some dipoles are present. Moreover, below $M_\gamma \approx 20$ the additional contributions to the bump with increasing M_γ occur not only at the high E_γ edge as generally observed in the yrast cascade of a good rotor [3], but also in the region of the peak. These observations suggest a tendency toward non-collective cascades, which in the light rare earths have been associated with aligned quasiparticle structure and small oblate deformations [1].

A different behavior is seen at higher M_γ. Above $M_\gamma \approx 22$ the upper edge of the low energy bump ceases to move to higher E_γ as M_γ increases. Related effects are observed in the entry line and in the angular distributions. At $M_\gamma \approx 22$ the entry line (fig. 1) begins to bend down significantly relative to the behavior expected from the statistical-model calculations. In the same M_γ region the lower half ($E_\gamma < 700$ keV) of the intense bump develops an angular distribution characteristic of stretched dipole radiation. All three observations are consistent with the onset at $M_\gamma \approx 22$ of a strong dipole component which is well localized in E_γ. From the spectra at various angles, we estimate that the dipole energies are confined to a narrow energy region at ~650 keV with a full width half maximum of ~200 keV.

For $M_\gamma > 22$ the high energy bump becomes increasingly prominent. This bump evolves up to the highest M_γ in just the way expected for a rotational quadrupole cascade with approximately constant moment of inertia. The angular distribution data show clearly that the transitions in this energy region are stretched E2 (see fig. 3a). If we assume that the spectrum is in fact rotational, an effective moment of inertia $2\mathcal{I}_{eff}/\hbar^2$ can be deduced from the energies of the upper edge of the quadrupole spectrum. Results obtained in this way are shown in fig. 3b.

Another change in decay mode at high M_γ is apparent in fig. 2b. The dipole component at $E_\gamma \sim 650$ keV stops increasing at $M_\gamma \approx 27$. This is entirely consistent with the behavior of the entry line (fig. 1) which shows an upbend at this M_γ. Above $M_\gamma = 28$ the entry line has resumed the slope expected for predominantly quadrupole cascades.

In order to connect M_γ to spin, the statistical-model calculations were used. The rotational picture employed in the calculation reproduces the slope of the entry lines from both reactions up to $M_\gamma \approx 22$. Hence the mapping from M_γ to I in this region can be obtained from the entry line calculated as a function of M_γ and of I. At higher M_γ the mapping must be corrected for the additional $\Delta I = 1$ transitions. The dashed line in fig. 1 was derived by taking these transitions to be ~650 keV each. The shape of the experimental entry line suggests that 3 to 4 of the 6 transitions between $M_\gamma = 22$ and $M_\gamma = 28$ are dipole, while there are essentially no dipoles among the additional transitions above $M_\gamma \approx 28$.

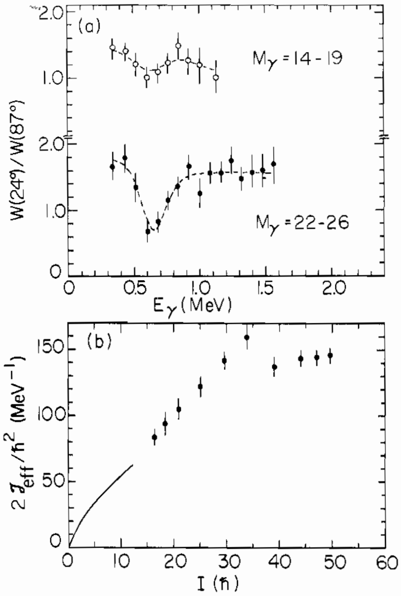

Fig. 3. (a) Anisotropies of the γ-ray continuum in ^{158}Yb as a function of E_γ. The M_γ values give the half maximum limits of the corresponding k gates. The dashed lines guide the eye. (b) Effective moments of inertia $\mathcal{I}_{eff}$ as a function of spin I in ^{158}Yb. The discontinuity at $I \approx 37$ is associated with the onset of the localized dipole radiation.

To summarize our experimental observations, the continuum spectroscopy of ^{158}Yb can be divided into three, or perhaps four, angular momentum regions with distinctive characteristics. At low spin ($I < 12$) ^{158}Yb is known to be a prolate rotor. At moderate spins ($I \approx 16$) there is evidence for non-collective effects in the continuum, but the smooth evolution of the moment of inertia (fig. 3b) perhaps contradicts this. At $I \approx 40$ ($M_\gamma \approx 22$) a dramatic change occurs. A strong stretched dipole component appears at an energy ($E_\gamma \approx 650$ keV) one half the quadrupole edge at the same spin. These dipoles account for 50–60% of the additional transitions between $I = 40$ and 49. Nevertheless a stretched quadrupole component continues to evolve over this spin range in the way expected of a rotational spectrum. $I \approx 49$ is another transition point. Above this spin no additional stretched dipole transitions were seen.

It is interesting to relate these observations to the evolution in nuclear structure predicted for the yrast state of the even-mass Yb isotopes by Bengtsson et al. [2]. These cranked modified oscillator calculations predict prolate ground states for ^{160,162}Yb. These nuclei are predicted to become oblate at $I \approx 40$ ($A = 160$) and $I \gtrapprox 50$ ($A = 162$). ^{158}Yb is predicted to be oblate even in its ground state, but this is an artifact of the neglect of pairing in the calculation. Above $I \approx 30$ and $I \approx 40$, respectively, ^{158}Yb and ^{160}Yb are predicted to evolve toward increasing oblate deformation with increasing spin until triaxial shapes with rapidly increasing deformations become favored at spin 60 and 70 $\hbar$ respectively. The hint of non-collective behavior observed in our data above $I \approx 16$ is consistent with the predicted transition to oblate shape at fairly low spin in ^{158}Yb. An oblate nucleus with not too large a deformation should have a non-collective, aligned quasiparticle spectrum [1,2,4]. It is possible that the region of strong dipole transitions is also associated with an oblate shape. The yrast states in an oblate nucleus are expected to be aligned ($K \approx I$) quasiparticle states. If the deformation is sufficiently large the states should have rotational states built upon them [14]. Such high K bands are good candidates for producing M1 radiation since for intra-band transitions in the rotational model [14,15], $B(\mathrm{M1}) \propto K^2$, while $B(\mathrm{E2}) \propto 1/K$. The remarkable localization of dipole radiation at half the quadrupole energies (fig. 3a) supports the intra-band M1 speculation. The M1 peak should move to higher energy with increasing spin as the E2 transitions do, but the total movement from $I = 40$ to 49 should be only about 100 keV. Furthermore, the extent in energy over this spin region is comparable to the multiplicity resolution of the spectrometer [10]. Although we see no such systematic movement of the dipole peak, it cannot be ruled out. It is tempting to associate the disappearance of the dipole radiation above $I \approx 49$ with the predicted tendency of ^{158}Yb to move away from oblate shapes toward triaxiality near this spin. However, neither the experimental data nor the theoretical expectations are yet sufficiently well developed to support such a suggestion. Certainly the moments of inertia in fig. 3b do not suggest a rapid increase in deformation at the highest spins.

Similar data also exist on ^{160}Yb [8]. The difference between ^{158}Yb and ^{160}Yb are in qualitative agreement with the calculation by Bengtsson et al. [2]. A similar stretched dipole component appears at somewhat higher spins, but additional stretched dipole transitions are seen up to the highest spin observed. There is no evidence for a non-collective region in ^{160}Yb.

In summary we have isolated three – and perhaps four – distinct spin regions in ^{158}Yb in which the continuum spectra, the entry line and the angular distributions show distinct behaviors. These characteristics are qualitatively consistent with the evolution of nuclear shape with spin predicted for the yrast states by Bengtsson et al. [2].

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