Anomalous γ-Band Intraband Transition Rates in Er^{166}†

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The 7+→6+, 6+→5+, and 5+→4+ intraband transitions within the γ vibrational band of Er^{166} have been observed. The intensities of these transitions have been measured relative to the $E2$ crossover transitions which originate from the same states. The $\Delta I=-1$ "stopover" transitions have intensities which exceed the Alaga-rule predictions for pure $E2$ $\Delta I=-1$ transitions. The excess intensity is indicative of an $M1$ admixture into these transitions, in contrast to a vanishing $M1$ rate which would be anticipated if rotational states correspond to the rotation of a uniform nuclear fluid. The square of the $M1$ matrix element, which is deduced from these data, increases with the spin of the initial state approximately as $I^2(I+1)^2$.

THE strongly deformed nucleus Er^{166} has an interesting level structure. In addition to exhibiting a well-developed rotational band built on the 0+ ground state, a well-developed rotational band built on the γ vibrational state at 787 keV is known to spin 8. Most of the level-structure information about this nucleus has come from many detailed studies[1–3] of electron and γ-ray spectra following the β decay of Ho^{166m}. Although several crossover $E2$ transitions within the γ band are known, only fragmentary evidence exists concerning the competing $I\to I-1$ intraband transitions. These transitions are expected to be of the $E2$ type with intensities relative to the crossover $E2$ originating from the same level given in terms of the Clebsch-Gordon coefficients by an expression of the form

$$\frac{I_\gamma(E2;\,\text{stopover})}{I_\gamma(E2;\,\text{crossover})}=\left(\frac{E_{\text{s.o.}}}{E_{\text{c.o.}}}\right)^5 \times\frac{\langle I_i\,2\,2\,0\,|\,I_i\,2\,I_i\!-\!1\,2\rangle^2}{\langle I_i\,2\,2\,0\,|\,I_i\,2\,I_i\!-\!2\,2\rangle^2}. \quad (1)$$

In their study of the conversion electron spectrum of Er^{166} following the electron capture of Tm^{166}, Harmatz *et al.*[4] reported the observation of the 4+→3+, 4+→2+, and 3+→2+ transitions within the γ band with a suggestion of an $M1$ component of unspecified intensity in the $\Delta I=-1$ transitions (see Table XII of Ref. 4). Similarly, Emery *et al.*[5] reported a possible $M1$ component in the 3+→2+ transition in the γ band of the transitional nucleus Os^{186} (see Table V and discussion of transition GF in footnote 37 of Ref. 5).

To the extent that rotational states correspond to the rotation of a uniform nuclear fluid, $M1$ intraband transition rates are zero. A departure from such a behavior should manifest itself by the introduction of an $M1$ admixture into the intraband $\Delta I=-1$ transitions. Although this $M1$ rate can be expected to be small, its measurement may provide an additional way to determine departures from pure rotation within the band and may suggest the mechanism responsible for the departure.

The γ-ray spectrum following β decay of Ho^{166m} is very complex. The observation of the $\Delta I=-1$ transitions requires a γ ray detector of excellent resolution, particularly since the energies of some of these transitions are within about 2 keV of the energies of other unrelated lines in the spectrum. We have searched for these transitions with a coaxial Ge(Li) detector of about 20-cm^3 volume. The system resolution is about 1.0 keV near 120 keV. The 7+→6+, 6+→5+, and 5+→4+ γ-ray transitions have been observed and their intensities measured relative to the $E2$ crossover transitions which originate from the same state.

A portion of the γ-ray spectrum containing the $I\to I-1$ transitions is shown in Fig. 1. The intensities of the $I\to I-1$ transitions exceed the prediction derived from Eq. (1). The excess intensity is attributed to an $M1$ admixture into the transition and allows a determination of $\delta^2\equiv E2/M1$ for each transition.

The assumption that the $(I\to I-1)$ $E2$ rates are determinable from the Alaga rules[6] may be justified by the fact that, so far as is known, the $B(E2,\,4+\to2+)/B(E2,\,2+\to0+)$ ratio for well-deformed, even-even rotational nuclei obeys[7] the rotational model prediction to within a few ($\approx$10) percent. The prediction has a less secure experimental verification for the higher rotational spin states. Recent $B(E2)$ determinations[8] for higher

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[1] References to the extensive earlier literature may be found in *Nuclear Data Sheets*, compiled by K. Way *et al.* (U.S. Government Printing Office, National Academy of Sciences, National Research Council, Washington, D.C. 20025), Vol. 6, Set 4, p. 36; Nucl. Data **B2**, 57 (1966); in C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), 6th ed.

[2] C. Gunther and D. R. Parsignault, Phys. Rev. **153**, 1297 (1967).

[3] S. B. Burson, P. F. A. Goudsmit, and K. Konijn, Phys. Rev. **158**, 1161 (1967).

[4] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. **123**, 1758 (1961).

[5] G. T. Emery, W. R. Kane, M. McKeown, M. L. Perlman, and G. Scharff-Goldhaber, Phys. Rev. **129**, 2597 (1963).

[6] G. Alaga, K. Alder, A. Bohr, and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **29**, No. 9 (1955).

[7] A. C. Li and A. Schwarzschild, Phys. Rev. **129**, 2664 (1963).

[8] David Ward, Bull. Am. Phys. Soc. **13**, 1400 (1968); R. M. Diamond, F. S. Stephens, W. H. Kelly, and D. Ward, Phys. Rev. Letters **22**, 546 (1969).

TABLE I. Summary of branching-ratio data, calculated stopover γ-ray mixing ratios, reduced mixing ratios (see text), and reduced mixing ratios multiplied by $I_i^2(I_i+1)^2$. I_i is the initial spin, $\lambda_{\mathrm{expt}}=I_\gamma(I_i\rightarrow I_i-1)/I_\gamma(I_i\rightarrow I_i-2)$, $I_\gamma(E2)$ is the calculated $E2$ γ-ray intensity for stopover [from Eq. (1)], $I_\gamma(M1)=I_\gamma(I_i\rightarrow I_i-1)-I_\gamma(E2)$, $\delta^2=I_\gamma(E2)/I_\gamma(M1)$, $\delta'^2=|M_{E2}|^2/|M_{M1}|^2$ [see Eq. (2)], and $f=10^{-3}\delta'^2 I_i^2(I_i+1)^2$.

I_i	λ_{expt}	$I_\gamma(E2)$	$I_\gamma(M1)$	δ^2	δ'^2	f
7	0.032 ± 0.004	0.0176	0.0144 ± 0.0040	$1.22^{+0.47}_{-0.27}$	$2.7^{+1}_{-0.6}$	$8^{+3.1}_{-1.9}$
6	0.0372 ± 0.0084	0.0281	0.0091 ± 0.0084	≥1.6	≥3.3	≥5.8
5	0.063 ± 0.005	0.0514	0.0116 ± 0.0050	$4.43^{+3.36}_{-1.33}$	$8.9^{+6.7}_{-2.7}$	$8.0^{+6.0}_{-2.4}$

spin states in the ground-state bands of Er^{160}, Er^{158}, and Er^{156} indicate that for Er^{160}, the best rotator of this group as indicated by the energy spectrum, the $B(E2)$ values out of the higher spin states tend to fall below the rotational prediction, although the opposite trend is observed for Er^{158} and Er^{156}. Since, however, as can be seen from the data in Table I, the intensity of the $7+\rightarrow6+$ transition deviates from the prediction of the rotational model by more than 50% and perhaps by as much as a factor of 2, we tentatively regard the deviations as mainly due to an $M1$ admixture into the transitions.

In order to provide a comparison of the ratio of the $E2/M1$ matrix elements, the δ^2 values have been manipulated in the following manner:

$$\frac{I(E_2,\mathrm{s.o.})}{I(M1,\mathrm{s.o.})}\equiv\delta^2\propto\frac{|M_{E2}|^2}{|M_{M1}|^2}\frac{E_{\mathrm{s.o.}}{}^5}{E_{\mathrm{s.o.}}{}^3}\times\frac{\langle I_i\,2\,2\,0\,|\,I_i\,2\,I_i{-}1\,2\rangle^2}{\langle I_i\,1\,2\,0\,|\,I_i\,1\,I_i{-}1\,2\rangle^2}=\delta'^2E_{\mathrm{s.o.}}{}^2\frac{\langle I_i\,2\,2\,0\,|\,I_i\,2\,I_i{-}1\,2\rangle^2}{\langle I_i\,1\,2\,0\,|\,I_i\,1\,I_i{-}1\,2\rangle^2}. \quad (2)$$

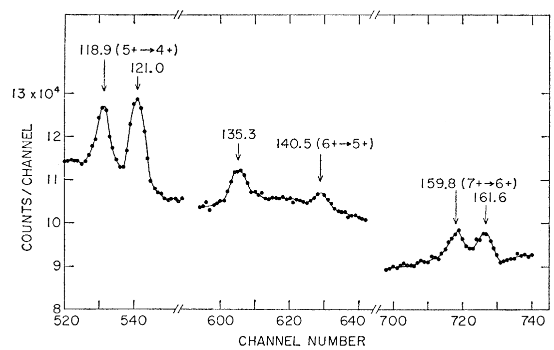

FIG. 1. Portion of γ-ray spectrum in the region of the $\Delta I=-1$ intraband transitions within the Er^{166} γ band.

The reduced mixing ratio $\delta'^2\equiv|M_{E2}|^2/|M_{M1}|^2$ is the quantity of interest to us. The experimentally observed branching ratios, mixing ratios δ^2, and reduced mixing ratios δ'^2 are listed in Table I, where the E^2 correction has been made by normalizing to unity for the 118.9-keV $5+\rightarrow4+$ transition. The branching-ratio data are summarized in Fig. 2. It is interesting to note that although the precision available is not high, the values of δ'^2 decrease as one goes up the band. The δ'^2 values are most consistent with an $I^2(I+1)^2$ dependence of $|M_{M1}|^2$, as illustrated in Table I, although neither a dependence proportional to $I(I+1)$ or $I^3(I+1)^3$ can be ruled out by these data. It would be interesting to see whether a correlation exists between the magnitude of the $I^2(I+1)^2$ term in the energy spectrum and the absolute $M1$ rates within the γ bands of well-deformed nuclei. These data, unfortunately, are not yet available.

The absolute $M1$ transition probabilities for these intraband transitions, although comparable to the enhanced $E2$ rates, are nevertheless still small. In particular, for the 159.8-keV transition, the observed branching ratio corresponds to an $M1$ transition probability of the order of 0.01 Weisskopf units. If, *for purposes of illustration only*, we treat the $B(M1)$ formula appropriate for odd-A nuclei as applicable to these $\Delta I=-1$

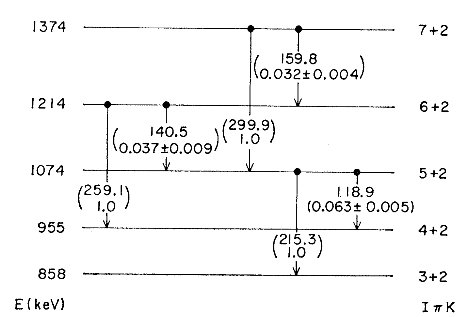

FIG. 2. Summary of measured $\Delta I=-2$ and $\Delta I=-1$ intraband γ-ray branching intensities within the γ band of Er^{166}. Interband transitions into the ground-state band are not shown.

transitions, the $7+\rightarrow 6+$ $M1$ rate (with $K=\Omega=2$), based on the assumption that the intrinsic quadrupole moment Q_0 for the γ band is 1.38 times larger[2,9] than that for the ground-state band, leads to a value $|\Delta g|^2 \simeq 5.3\times 10^{-2}$. This value corresponds to about $\frac{1}{3}(Z/A)^2$. Similarly, the limit on the $6+\rightarrow 5+$ $M1$ rate implies $|\Delta g|^2<0.46$, while the $5+\rightarrow 4+$ $M1$ rate leads to $|\Delta g|^2\simeq 2\times 10^{-2}$, a value which is about $\frac{1}{8}(Z/A)^2$. A somewhat smaller value of Q_0 for the γ band would slightly reduce these $|\Delta g|^2$ values.

The expansion of the γ-band energy spectrum in the usual way in powers of $I(I+1)$, i.e., $E\sim A(I)(I+1)+B(I)^2(I+1)^2+\cdots$, requires $B/A=1.5\times 10^{-3}$. It is difficult to understand how any mechanisms which perturb the energy spectrum by such a small amount can alter the $M1$ rates so significantly. It is possible, of course, that the assumption underlying the analysis, namely, that the intraband $E2$ rates are accurately predicted by the Alaga rules, may not be justified.

The possibility of independently verifying the $M1$ admixture into the 159.8-keV $7+\rightarrow 6+$ transition by a measurement of the

$$7+\xrightarrow{L=1,2}6+\xrightarrow{L=2}4+$$

γ-γ correlations exists, although these measurements will be difficult because of the small $7+\rightarrow 6+$ γ-ray intensity and because of the need for extremely good energy resolution in both channels of the measurement. However, the results of such measurements could provide an unambiguous verification of the $M1$ admixture.

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[9] C. J. Gallagher, O. B. Nielsen, and A. W. Sunyar, Phys. Letters **16**, 298 (1965).

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Neutron Decay of Isobaric Analog Resonances in ^{90}Zr†

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Excitation functions and angular distributions of the γ radiation from ^{89}Zr following the reaction ^{89}Y(p, n) have been measured with a 56-cm^3 Ge(Li) detector in the range from 5.4- to 7.8-MeV bombarding energy. At 6.00-, 6.16-, 7.28-, and 7.45-MeV bombarding energy, resonances in several neutron channels were observed which were attributed to isobaric analog states in the compound system ^{90}Zr. From an analysis of the 6.16-MeV 1^- resonance in terms of Robson's theory, the level shift $\Delta=86$ keV was obtained which was compared with an estimate derived from the spreading width of this resonance. New states in ^{89}Zr were identified at 1834-, 2081-, 2130-, 2220-, 2298-, 2389-, 2570-, and 2610-keV excitation energy. From a Hauser-Feshbach analysis of the γ-ray excitation functions and angular distributions, the spins of a number of these states and mixing ratios of γ-ray transitions were found. Evidence is given for a weak coupling multiplet of a $g_{9/2}$ neutron hole coupled to the 2.18-MeV 2^+ state in ^{90}Zr.

1. INTRODUCTION

Since their discovery by Fox *et al.*,[1] isobaric analog resonances (IAR) in the compound system ^{90}Zr have been thoroughly investigated. The large spectroscopic factors $S_n=0.7$–1.0 of their parent states in ^{90}Y measured in the ^{89}Y(d, p) reaction[2] favor a simple shell-model description of one particle and one hole outside a ^{90}Zr core giving rise to the four doublets $[(p_{1/2})^{-1}(l_j)]_{J=j\pm 1/2}$, with $l_j=d_{5/2}, s_{1/2}, d_{3/2}$, and $g_{7/2}$. This simplicity of the structure was used as a guide in studying other isospin-allowed decay modes of the IAR (inelastic protons,[3] γ ray) and more complex phenomena like the interaction of the $J^\pi=1^-$ analog states with the giant dipole resonance.[4]

The isospin-forbidden decay into the (^{89}Zr$+n$) channels has been investigated with the ^{89}Y(p, n) reaction between 3.6- and 6.4-MeV bombarding energy. Excitation functions of the total neutron cross section were measured over the strong 2^- and 3^- $[(p_{1/2})^{-1}(d_{5/2})]$ resonances at 4.82 and 5.02 MeV[1,5,6] as well as dif-

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[1] J. D. Fox, C. F. Moore, and D. Robson, Phys. Rev. Letters **12**, 198 (1964).

[2] N. Mishra, C. F. Moore, and C. E. Watson, Nucl. Phys. **A110**, 353 (1968), and references herein.

[3] D. D. Long and J. D. Fox, Phys. Rev. **167**, 1131 (1968).

[4] E. Obst, F. Rauch, and H. G. Wahs-weiler, Nucl. Phys. **A103**, 17 (1967); D. Drechsel, J. B. Seaborn, and W. Greiner, *ibid.* **A94**, 698 (1967); P. Axel, D. M. Drake, S. Whetstone, and S. S. Hanna, Phys. Rev. Letters **19**, 1343 (1967); B. Goulard and S. Fallieros, Can. J. Phys. **45**, 3221 (1967).

[5] J. Black, M. M. Islam, G. A. Jones, G. C. Morrison, and R. B. Taylor, in *Proceedings of the Conference on Isobaric Spin in Nuclear Physics*, edited by J. D. Fox and D. Robson (Academic Press Inc., New York, 1966), p. 863.

[6] C. H. Johnson, R. L. Kernell, and S. Ramavataram, Nucl. Phys. **A107**, 21 (1968).