The states (E) $\Psi^{nlj}(000)$ are easily formed by coupling $\psi_{\rm I}(000)$ to the state $\Psi_{\rm II}(100)$ given by the equation

$$\Psi_{\rm II}(000)=\tfrac{1}{2}[\{\varphi_{1p\frac{1}{2}}{}^{-\frac{1}{2},0}\psi_{1p\frac{1}{2}}{}^{\frac{1}{2},1}\}-\{\varphi_{1p\frac{1}{2}}{}^{-\frac{1}{2},1}\psi_{1p\frac{1}{2}}{}^{\frac{1}{2},0}\} -\{\varphi_{1p\frac{1}{2}}{}^{\frac{1}{2},0}\psi_{1p\frac{1}{2}}{}^{-\frac{1}{2},1}\}+\{\varphi_{1p\frac{1}{2}}{}^{\frac{1}{2},1}\psi_{1p\frac{1}{2}}{}^{-\frac{1}{2},0}\}]. \quad (38)$$

To calculate the states for $A=34$ we follow the same procedure as above. The states $\psi_{\rm II}(011)$ and $\psi_{\rm II}(000)$ have a different form for a $(1d_{\frac{3}{2}})^2$ configuration.

$$\Psi_{\rm II}(011)=\tfrac{1}{2}[\{\varphi_{1d\frac{3}{2}}{}^{-\frac{1}{2},1}\varphi_{1d\frac{3}{2}}{}^{\frac{1}{2},1}\}-\{\varphi_{1d\frac{3}{2}}{}^{-\frac{3}{2},1}\varphi_{1d\frac{3}{2}}{}^{\frac{3}{2},1}\}], \quad (39)$$

$$\Psi_{\rm II}(000)=8^{-\frac{1}{2}}[\{\varphi^{-\frac{1}{2},0}\psi^{\frac{1}{2},1}\}-\{\varphi^{-\frac{1}{2},1}\psi^{\frac{1}{2},0}\}-\{\varphi^{\frac{1}{2},0}\psi^{-\frac{1}{2},1}\} +\{\varphi^{\frac{1}{2},1}\psi^{-\frac{1}{2},0}\}-\{\varphi^{-\frac{3}{2},0}\psi^{\frac{3}{2},1}\}+\{\varphi^{-\frac{3}{2}}\psi^{\frac{3}{2},0}\} +\{\varphi^{\frac{3}{2},0}\psi^{-\frac{3}{2},1}\}-\{\varphi^{\frac{3}{2},1}\psi^{-\frac{3}{2},0}\}]. \quad (40)$$

The subscript $1d_{\frac{3}{2}}$ has been omitted from the single-particle wave functions in writing this equation.

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Decay of Er^{171}†

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The decay of Er^{171} (7.52 hours) has been studied with beta- and gamma-scintillation spectrometers, a magnetic lens spectrometer, and a 180° permanent-magnet spectrograph. A number of previously unobserved beta-ray and gamma-ray transitions were found. On the basis of coincidence studies, intensity data, internal conversion coefficients, and the measured transition energies, a consistent level scheme for Tm^{171} is proposed which has excited states at energies of 0.0051, 0.1167, 0.1291, 0.4251, 0.636, 0.688, 0.744, 0.921, and 1.008 Mev. The observed states are identified with appropriate orbitals of the Nilsson energy level diagram, and the experimental transition probabilities are examined in terms of the asymptotic selection rules for strongly deformed nuclei.

I. INTRODUCTION

ERBIUM-171 decays by negatron emission to energy levels of the odd-proton nuclide Tm^{171}. The ground state of Tm^{171} is beta unstable ($T_{\frac{1}{2}}=1.9$ yr), and there is at present no practical way of studying the excited states of this nucleus except by examining the radiations of Er^{171}. Several such studies have been reported, the most recent being that of Hatch and Boehm.[1] Their precision measurements confirmed, among other things, that the four lowest states of Tm^{171} form a $K=\frac{1}{2}$ anomalous rotational band, a conclusion which had been reached by earlier investigators[2,3] on the basis of less complete data. In all of the above studies, however, information was obtained only on the relatively low-energy (<0.5-Mev) transitions in Tm^{171}. From the estimated Er^{171} decay energy of ~1.5 Mev, it was evident that a further search for higher energy γ-ray transitions should be made.

In the present investigation, it has been established that the decay scheme of Er^{171} is much more complicated than previously proposed and involves a number of γ-ray transitions with energies >0.5 Mev. Although the observed energy levels of Tm^{171} above 0.5 Mev are quite weakly populated, sufficient data on these states have been obtained to make possible various tests of the predictions of current nuclear theory. In particular, certain features of the decay scheme can best be explained as resulting from operation of selection rules involving the asymptotic quantum numbers[4] used in describing the states of strongly deformed nuclei.

II. SOURCE PREPARATION

The Er^{171} source material was produced by thermal neutron bombardment of Er_2O_3 of natural isotopic abundance.[5] The only observed radiation from isotopes of erbium other than Er^{171} was the 0.33-Mev beta group of Er^{169} (9.4 day). A slight Dy^{165} contamination was detectable immediately after irradiation, but this activity did not interfere with the Er^{171} measurements because of its very different half-life (2.36 hr). Further chemical purification of the irradiated source material in an ion-exchange column failed to reveal the presence of any other contaminants; consequently, in most of the measurements described below, the Er_2O_3 was not purified after irradiation.

Sources for the lens spectrometer were mounted on Mylar backing 0.00025 inch thick. The source material was deposited on this backing by evaporating to dryness a drop of Zapon which had a small amount of irradiated Er_2O_3 in suspension.

† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] E. N. Hatch and F. Boehm, Phys. Rev. **108**, 113 (1957).

[2] S. D. Koički and A. M. Koički, Bull. Inst. Nuclear Sci., "Boris Kidrich" (Belgrade) **6**, 1 (1956).

[3] S. A. E. Johansson, Phys. Rev. **105**, 189 (1957).

[4] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 16 (1955).

[5] The Er_2O_3, of specified purity 99.9%, was obtained from F. H. Spedding, Iowa State College, Ames, Iowa.

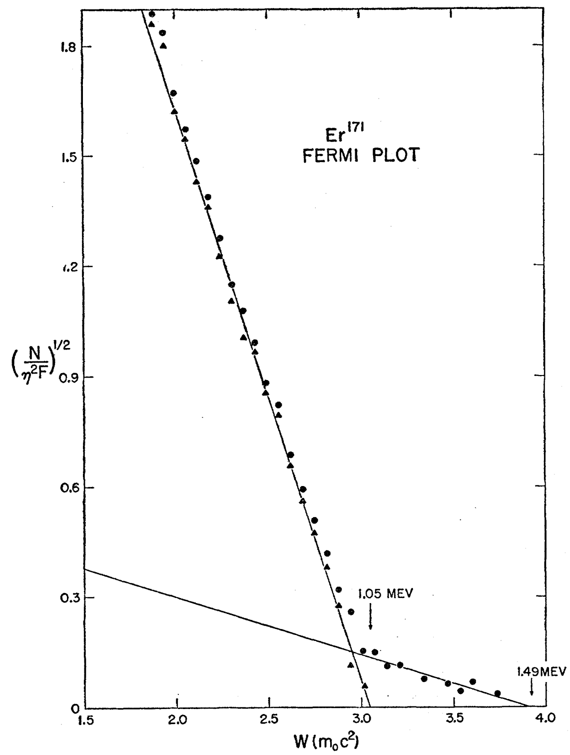

FIG. 1. Fermi-Kurie analysis of the beta-ray spectrum of Er^{171}.

Sources for the permanent-magnet spectrograph were prepared by electrophoretic deposition[6] of irradiated Er_2O_3 onto a 0.012-inch nickel wire.

III. HALF-LIFE

The half-life of Er^{171} previously reported by us (7.80 ± 0.18 hr),[7] determined by following the decay of the gross beta activity, was found to be in error. We have remeasured the half-life by observing the decay of the 0.307-Mev photopeak (see Fig. 2) with a scintillation spectrometer. These data indicate that the half-life of Er^{171} is 7.52 ± 0.03 hr.

IV. INTERNAL CONVERSION MEASUREMENTS

The internal conversion spectrum was studied with a 141-gauss, 180° permanent-magnet spectrograph of $\sim$0.2% resolution. The data obtained are given in Table I. Five successive sources were required in order to obtain sufficient exposure of the spectrograph plate from which these data were taken.

Each of the observed conversion lines is attributable to one of the following known[1] transitions in Tm^{171}: 111.6, 116.7, 124.0, 296.0, and 308.4 kev. Keller and Cork[8] observed conversion electron lines which indicated the existence of two additional transitions with energies of 176.4 and 419.7 kev. We found no evidence for these conversion lines. However, the proposed 176.4-kev transition may be identifiable with the 177-kev transition observed in our scintillation experiments (see Sec. VII.B). Further remarks concerning the hypothetical 419.7-kev transition are given in Sec. VI.

The multipolarity assignments (see Table I) for the 111.6-, 116.7-, and 124.0-kev transitions are based primarily on a comparison of the observed L subshell ratios with the theoretical ratios of Rose *et al.*[9] This analysis was simplified by the fact that these three transitions depopulate levels whose half-lives are known to be $<10^{-8}$ sec (see Sec. VII.B); consequently, only the $E1$, $E2$, and $M1$ possibilities needed to be considered.

The K and $L+M$ internal conversion lines of the 296.0- and 308.4-kev transitions were observed with the lens spectrometer. Both transitions were found to have $K/(L+M)$ ratios of ~5. The K-conversion coefficients (ϵ_K) of these transitions were calculated by making use of the following information: (1) the areas of the K-conversion lines relative to the area of the 1.05-Mev β-ray group, from the magnetic lens spectrum (see Sec. V); (2) the relative intensities of the 296.0- and 308.4-kev γ rays, as reported by Hatch and Boehm[1]; and (3) the fact that the ratio of the intensity of the 1.05-Mev β-ray group to the sum of the intensities of the 296.0- and 308.4-kev transitions is ~0.99 (see Fig. 8). The results obtained were $\epsilon_K(296.0)=0.035\pm0.011$ and $\epsilon_K(308.4)=0.017\pm0.005$. Comparison of these values with the theoretical values of Sliv and Band[10] [$\alpha_1(296.0)=0.0174$, $\beta_2(296.0)=0.555$; $\alpha_1(308.4)=0.0157$, $\beta_2(308.4)=0.472$] indicates that the multipolarity of the 296.0-kev transition is probably $E1$

TABLE I. Conversion electron data for Er^{171}.

Electron energy (kev)	Proposed interpretation	Transition energy (kev)	Estimated relative intensity	Multi-polarity
52.1	K	111.5	600	
101.4	L_I	111.5	102	$M1$
109.1	M_I	111.4	20	
57.1	K	116.5	20	
106.8	L_{II}	116.4}	24	$E2$
107.8	L_{III}	116.5}		
64.4	K	123.8	69	
114.2	L_{II}	123.8	46	$E2$
115.2	L_{III}	123.9	31	
121.9	$M_{II,\ III}$	123.9	16	
236.7	K	296.1	10	$E1$[a]
248.8	K	308.2	20	$E1$[a]

[a] Assigned from lens spectrometer data.

[6] F. P. Cranston and W. J. McCreary, Rev. Sci. Instr. **27**, 973 (1956).
[7] Cranston, Bunker, Mize, and Starner, Bull. Am. Phys. Soc. Ser. II, **1**, 389 (1956).
[8] H. B. Keller and J. M. Cork, Phys. Rev. **84**, 1079 (1951).
[9] Rose, Goertzel, and Swift (privately circulated tables).
[10] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Report 57 ICC K1, issued by the University of Illinois, Urbana, Illinois (unpublished)], Part I.

$+M2(M2/E1=0.034\pm0.020)$, whereas the 308.4-kev transition is nearly pure $E1$.

V. BETA-RAY SPECTRA

The β-ray spectrum was examined with a magnetic lens spectrometer which was operated at $\sim 2\%$ resolution. A Fermi-Kurie analysis of the data (Fig. 1) revealed two β-ray groups with end-point energies of 1.49 ± 0.02 and 1.05 ± 0.01 Mev. From a reconstruction of the separate β-ray spectra, based on the Fermi-Kurie plot, the ratio of the intensity of the higher-energy group to that of the 1.05-Mev group was measured to be 0.037 ± 0.002. However, our β-γ coincidence experiments indicate the existence of several other weak β-ray groups (see Sec. VII.C and Fig. 8) which could not be resolved in the above analysis. One of these weak groups, of end-point energy 1.36 Mev, contributes significantly to the observed portion of the spectrum beyond 1.05 Mev. The other weak groups have end-point energies $\leqslant 0.89$ Mev, and their presence has a negligible effect on the intensity of the 1.05-Mev group, as calculated from our reconstruction. The above intensity ratio is therefore interpreted as representing the sum of the intensities of the 1.36- and 1.49-Mev groups, normalized to the intensity of the 1.05-Mev group.

VI. GAMMA-RAY SPECTRA

The observed γ-ray spectra are shown in Figs. 2 and 3. These data were obtained with a 2×2-inch NaI(Tl) crystal mounted on an RCA-6342 photomultiplier tube. The spectra were recorded with a fast 100-channel pulse-height analyzer (average dead-time ≈ 72 μsec).

It can be seen in Fig. 2 that the photopeaks of the 111.6-, 116.7-, and 124.0-kev transitions merge into a single peak at ~ 113 kev. Similarly, the peak at 307 kev is a composite of the 296.0- and 308.4-kev photopeaks. The very weak 210-kev photopeak, which has also been observed by Johansson,[3] undoubtedly receives most of its intensity from the 210.6-kev γ ray reported by Hatch and Boehm.[1] The prominent thulium

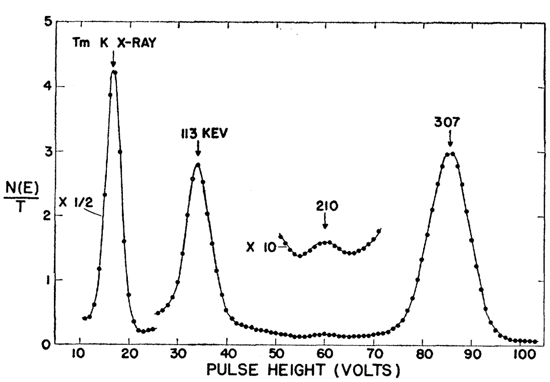

FIG. 2. Pulse-height spectrum of Er^{171} low-energy gamma rays, obtained with a 2×2-inch NaI(Tl) crystal.

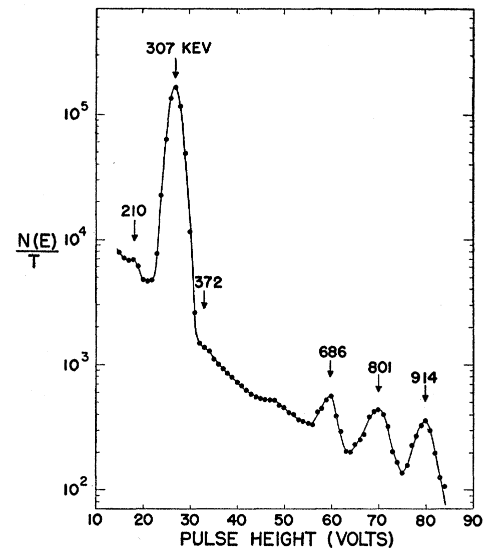

FIG. 3. Pulse-height spectrum of Er^{171} high-energy gamma rays, obtained with a 2×2-inch NaI(Tl) crystal.

K x-ray peak results primarily from K conversion of the transitions which contribute to the 113-kev photopeak.

The high-energy portion of the γ-ray spectrum, shown in Fig. 3, exhibits well resolved photopeaks at 0.686, 0.801, and 0.914 Mev. Furthermore, a careful "unfolding" of this spectrum, involving the use of the measured pulse-height distributions associated with monoenergetic γ rays of appropriate energies, revealed the presence of additional photopeaks at energies of approximately 0.372, 0.57, 0.62, and 0.74 Mev. Further verification of the existence of these four transitions was obtained from coincidence experiments (see Sec. VII).

A very careful search was made for evidence of a γ ray of ~ 420 kev, since Keller and Cork[8] and Johansson[3] have reported the existence of such a transition. Our data indicate that if a γ ray of this energy does exist, its intensity must be $<10^{-3}$ per disintegration. It seems likely that the 425-kev peak observed by Johansson[3] was the result of coincidence summing of the 113- and 307-kev γ-ray groups. We are unable to account for the 360.2-kev electron line (assigned as the K-conversion line of a 419.7-kev transition) observed by Keller and Cork.[8]

VII. COINCIDENCE EXPERIMENTS

A. Equipment

Most of the coincidence scintillation experiments were carried out with a "slow" coincidence spectrometer having a resolving time of $2\tau\simeq 4\times10^{-7}$ sec. In some cases, this equipment was used in conjunction with a "fast" coincidence circuit ($2\tau\simeq 1.5\times10^{-8}$ sec) similar to the one described by Bell *et al.*[11] In all cases, the

[11] Bell, Graham, and Petch, Can. J. Phys. **30**, 35 (1952).

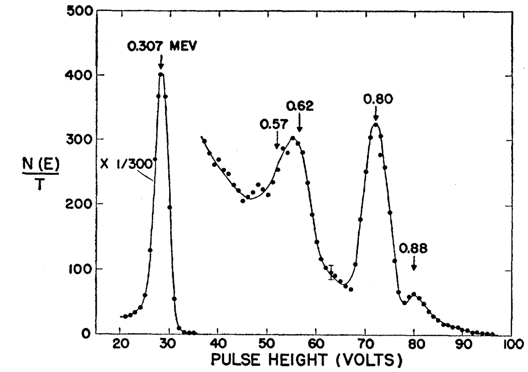

FIG. 4. Gamma-gamma coincidence spectrum of Er^{171}. Gate interval 95 to 135 kev.

pulse-height spectrum in coincidence with pulses in the selected "gate" region was analyzed with the 100-channel analyzer.

In cases where there was reason to believe that Compton-backscattered quanta could contribute serious coincidence background effects, the two detector crystals were shielded from one another with appropriate lead absorbers in such a way that the "Compton coincidences" were greatly reduced relative to true γ-γ (or β-γ) coincidences.

B. Gamma-Gamma Coincidences

The detectors used in most of the γ-γ coincidence experiments were 2×2-inch NaI(Tl) crystals mounted on RCA-6342 photomultiplier tubes. The resolution of these detectors at 0.662 Mev was $\sim$8%.

The main results of our γ-γ coincidence measurements are shown in Table II. It had been previously determined[2,3] that the 0.1116- and 0.3084-Mev transitions are in coincidence and that the 0.1240-Mev transition is in coincidence with the 0.2960-Mev transition. We have verified these coincidence relationships and have shown that in both cascades, the half-life of the intermediate state is $<10^{-8}$ sec.

In contradiction to the observations of Johansson,[3] we find no evidence of the 0.210-Mev photopeak in the spectrum coincident with pulses which contribute to the 0.113-Mev photopeak. Specifically, our data indicate that not more than 20% of the quanta which contribute to the 0.210-Mev photopeak are in prompt coincidence with the 0.113-Mev group. This conclusion is strongly supported by other experiments described below.

The high-energy portion of the γ-ray spectrum in coincidence with the 0.113-Mev group is shown in Fig. 4. Photopeaks are observed at 0.88, 0.80, 0.61, and 0.307 Mev. The relatively strong 0.686- and 0.914-Mev peaks (see Fig. 3) are conspicuously absent. This is the only experiment in which the 0.88-Mev photopeak was resolved. The relatively broad peak at $\sim$0.61 Mev has a shape which suggests that it is a composite of two peaks with approximate energies of 0.57 and 0.62 Mev. Coincidence experiments were also conducted in which the gate region included only the lower or upper half of the 0.113-Mev peak, thus accentuating, respectively, those coincidences involving the 0.1116-Mev γ ray and the 0.1240-Mev γ ray. Comparison of the two observed coincidence spectra revealed a definite shift in the position of the $\sim$0.80-Mev peak. The data strongly suggest the existence of 0.80-, 0.1116-Mev and 0.79-, 0.1240-Mev cascades, i.e., the 0.80-Mev photopeak of Fig. 4 is really a doublet. As will be mentioned later, there is reason to believe that the 0.57-, 0.62-, and 0.88-Mev photopeaks are doublets of the same type; however, since these photopeaks are so poorly resolved, we were unable to establish their complexity by the above technique.

The coincidence spectrum obtained when the gate interval was centered on the 0.210-Mev photopeak is shown in Fig. 5. The photopeaks of principal interest are those at 0.285 and 0.372 Mev. It was found that the spectra in coincidence with either the 0.285- or 0.372-Mev regions exhibited a strong photopeak at 0.210 Mev. Therefore, the existence of 0.285-, 0.210-Mev and 0.372-, 0.210-Mev γ-γ coincidences seems firmly established. The peak at 0.113 Mev in Fig. 5 was found to be caused almost entirely by the unavoidable presence in the "gate" spectrum of part of the Compton distribution induced by the 0.2960- and 0.3084-Mev γ rays. Similarly, it was demonstrated that the peak at 0.210 Mev results from coincidences between the 0.210-Mev γ ray and "Compton" pulses associated with the 0.285- and 0.372-Mev γ rays. The 0.285-Mev γ ray is undoubtedly identifiable with the 0.2849-Mev transition reported by Hatch and Boehm.[1] The 0.372-Mev γ ray, detected also in our ungated spectra, has not been previously observed.

TABLE II. Gamma-gamma coincidence results.

Dominant γ-ray photopeak included in gate interval (Mev)	Experimentally verified coincident γ rays (Mev)
0.113[a]	0.296, 0.308, 0.57, 0.62, 0.80, 0.88
0.111[b]	0.308, 0.80
0.124[c]	0.296, 0.79
0.177	0.62, 0.74
0.210	0.285, 0.372
0.233	0.57, 0.686
0.307[d]	0.111, 0.124, 0.210,[e] 0.285,[e] 0.372[e]
0.296[f]	0.124
0.308[g]	0.111
0.686	0.233
0.801	0.111, 0.124
0.88	0.111, 0.124
0.914	0.087

[a] Gate interval included entire 0.113-Mev photopeak (see Fig. 2).
[b] Gate interval included only the lower half of the 0.113-Mev photopeak (see Fig. 2).
[c] Gate interval included only the upper half of the 0.113-Mev photopeak (see Fig. 2).
[d] Gate interval included entire 0.307-Mev photopeak (see Fig. 2).
[e] Delayed coincidence. See text, Sec. VII. B.
[f] Gate interval included only the lower half of the 0.307-Mev photopeak (see Fig. 2).
[g] Gate interval included only the upper half of the 0.307-Mev photopeak (see Fig. 2).

It seems very definite, on the basis of our measurements and those of other investigators,[1–3] that the 0.2960- and 0.3084-Mev transitions originate at a delayed level ($T_{\frac{1}{2}} \approx 2.5$ μsec)[12] of energy 0.4251 Mev. In an effort to determine what γ rays populate the 0.4251-Mev level, a delayed-coincidence experiment was performed in which the gate interval covered the 0.307-Mev photopeak. A time delay was introduced such that a pulse from the "analyzer" detector would arrive at the coincidence circuit ∼1 μsec later than a simultaneous pulse from the "gate" detector. The coincidence counting rate was very low, but the observed spectrum showed well resolved peaks at 0.210 and 0.285 Mev and evidence of a much weaker peak at ∼0.37 Mev. We therefore conclude that the 0.4251-Mev level is populated by a 0.2849-, 0.2106-Mev cascade and probably also by a 0.372-, 0.2106-Mev cascade.

The solid curve of Fig. 6 is the coincidence spectrum obtained when the gate interval was approximately centered on the 0.686-Mev photopeak. Two previously unobserved photopeaks at 0.177 and 0.233 Mev are clearly evident. By the introduction of various thicknesses of lead between the source and the "gate" detector, it was established that neither peak was the result of Compton backscattering of γ rays with energies >0.686 Mev. We therefore conclude that the 0.177- and 0.233-Mev peaks are photopeaks caused by γ rays of these two energies. The coincidence spectra obtained by gating respectively with pulses in the 0.177- and 0.233-Mev regions revealed the coincidence relationships indicated in Table II. We found no positive evidence of 0.177-, 0.686-Mev coincidences. The occurrence of the 0.177-Mev photopeak in the solid-curve spectrum of Fig. 6 was found to be due to gate pulses associated with the ∼0.62- and ∼0.74-Mev γ rays. Similarly, the peak at 0.113 Mev is not the consequence of 0.686-, 0.113-Mev coincidences but is induced by gate pulses associated with the ∼0.62- and ∼0.80-Mev γ rays.

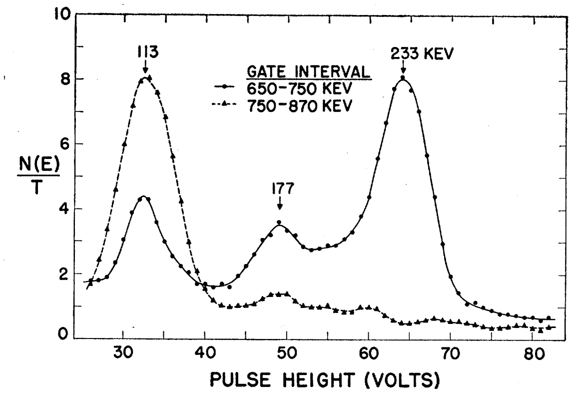

Fig. 6. Gamma-gamma coincidence spectra of Er^{171}. Solid curve, gate interval 650 to 750 kev. Dashed curve, gate interval 750 to 870 kev.

The spectrum in coincidence with pulses in the 0.80-Mev region is shown as the dotted curve of Fig. 6. The dominant feature of the spectrum is the 0.113-Mev photopeak, attributable primarily to the ∼0.80-, ∼0.113-Mev coincidences discussed earlier in this section. One would expect a weak photopeak to occur at 0.177 Mev because part of the 0.74-Mev photopeak lies within the bounds of the gate region. Although the statistics are not very good above 0.15 Mev, it can be seen that there is some evidence for the 0.177-Mev photopeak.

The coincidence spectrum obtained when the gate region included only the upper half of the 0.914-Mev photopeak is shown in Fig. 7. From a series of similar experiments in which the gate width was held constant at 50 kev and the lower bound of the gate interval was

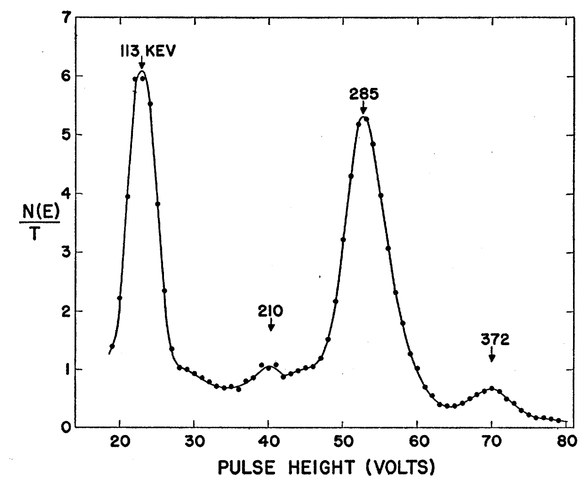

Fig. 5. Gamma-gamma coincidence spectrum of Er^{171}. Gate interval 193 to 223 kev.

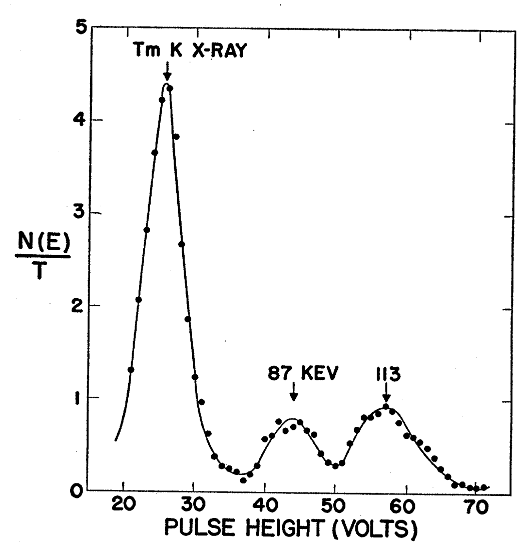

Fig. 7. Gamma-gamma coincidence spectrum of Er^{171}. Gate interval 914 to 1000 kev.

[12] S. DeBenedetti and F. K. McGowan, Phys. Rev. 74, 728 (1948).

set at various positions between 0.80 and 1.0 Mev, we conclude that the 0.087-Mev photopeak of Fig. 7 is the result of ~0.92-, 0.087-Mev γ-γ coincidences, and that the 0.113-Mev photopeak is the result of ~0.88-, 0.113-Mev coincidences. Quantitative study of the above coincidence data yields an intensity for the 0.087-Mev γ ray of only 0.0005 ± 0.0001 (per disintegration). Since this transition is much too weak to be detected in ungated scintillation spectra, it is clearly not identifiable with the 0.088-Mev γ ray reported previously.[3] It seems likely that the peak observed by Johansson[3] at this energy was the escape peak associated with the ~0.113-Mev γ-ray group. It is noted that Hatch and Boehm[1] found no evidence for 0.088-Mev quanta.

An estimate of the K-conversion coefficient of the 0.087-Mev transition can be obtained from the data of Fig. 7 if one makes the reasonable assumption that the K x-ray photopeak of that spectrum is engendered entirely by K conversion of the observed 0.087- and ~0.113-Mev transitions. The K x-ray contribution associated with the ~0.113-Mev γ-ray group is determinable from the coincidence spectrum observed when the gate interval was centered on 0.88 Mev. If the remainder of the K x-ray photopeak is assigned to the 0.087-Mev transition and the obvious efficiency corrections (including fluorescence yield) are made, one obtains $\epsilon_K(0.087)=3.7\pm0.5$. This value indicates a multipolarity assignment of either $M1+E2$ or $E1+M2$. The latter possibility can be excluded, however, since the β-decay data indicate that the two states connected by the 0.087-Mev transition have the same parity. On the basis of the theoretical conversion coefficients[9] [$\alpha_2(0.087)=1.3$, $\beta_1(0.087)=3.9$], it is evident that the transition is predominantly $M1$.

C. Beta-Gamma Coincidence Measurements

On the basis of the observed energies and relative intensities of the γ rays plus the established γ-γ coincidence relationships, it seemed probable that the decay scheme of Er^{171} involved levels in Tm^{171} at 0.0051, 0.1167, 0.1291, 0.4251, 0.636, 0.688, 0.744, 0.921, and 1.008 Mev. Numerous β-γ coincidence experiments were performed in order to verify this level scheme and to obtain the intensities of the β-ray groups which were too weak to be resolved with the magnetic lens spectrometer. In these experiments, a Pilot Plastic Scintillator-B phosphor, $1\frac{3}{4}$ inches in diameter and $\frac{3}{4}$ inch thick, served as the β-ray detector, and a 2×2-inch NaI(Tl) crystal was used as the γ-ray detector. In most cases, the fast-slow coincidence circuit was employed.

We have confirmed the previous observations[2,3] that there are very few prompt β-γ coincidences and that the strong 1.05-Mev β-ray group is in delayed coincidence with the γ rays which contribute to the 0.113- and 0.307-Mev photopeaks. Our delayed-coincidence data indicate a half-life for the intermediate state of ~2.5 μsec,* in agreement with the results of DeBenedetti and McGowan.[12] Consideration of the observed γ-ray intensities, the established γ-γ coincidence relationships, and the above β-γ coincidence data fixes the energy of the metastable state at 0.4251 Mev.

A comparison of the γ-ray spectra in prompt and delayed coincidence with pulses which contribute to the portion of the β-ray spectrum >0.80 Mev revealed that the 0.113-Mev photopeak was much stronger relative to the 0.307-Mev photopeak in the "prompt" spectrum than in the "delayed" spectrum. This is interpreted as positive evidence that there are direct β-ray transitions (calculated end-point energy ≈1.36 Mev) to one or both of the levels at 0.1167 and 0.1240 Mev, a conclusion reached earlier by Johansson.[3] The ratio of the intensity of the 1.36-Mev β-ray group to that of the 1.05-Mev group can be estimated by analyzing the spectra described above, and was found to be 0.016 ± 0.002.

It has been previously proposed[3] that a 0.21-Mev γ ray is associated with the decay of the 0.425-Mev delayed level. However, we could find no evidence for delayed (or prompt) β-γ coincidences between β rays of energy >0.60 Mev and γ rays of energy ~0.21 Mev. On the other hand, the γ-ray spectrum in prompt $(2\tau=1.5\times10^{-8})$ coincidence with that portion of the β-ray spectrum between 0.25 and 0.60 Mev exhibited photopeaks at 0.113, 0.177, 0.210, 0.233, 0.285, 0.69, 0.80, and 0.91 Mev. These data suggest that each of the indicated γ rays is somehow involved in the depopulation of one or more of the energy levels above 0.8 Mev.

Fermi-Kurie analysis of the "prompt" β-ray coincidence spectra obtained by gating, respectively, with pulses in the 0.210-, 0.233-, 0.285-, 0.372, 0.686-, 0.801-, and 0.914-Mev γ-ray photopeak regions revealed, in every case, the presence of a relatively strong β-ray group of end-point energy 0.55 ± 0.05 Mev. This value is consistent with the energy difference of ~0.56 Mev between the total decay energy of 1.48 Mev (see Sec. VIII) and the energy of the proposed level at 0.921 Mev. A very weak β-ray group of end-point energy ~0.90 Mev was observed in the spectrum obtained by gating with the 0.686-Mev photopeak. This is interpreted as direct evidence of β-ray transitions (calculated end-point energy=0.89 Mev) to the proposed level at 0.688 Mev. From the above data and the measured γ-ray intensities, we estimate the intensity (per disintegration) of the 0.89-Mev β-ray group to be ~0.1%. This same intensity value is indicated by a comparison of the observed 0.686-, 0.233-Mev and 0.80-, 0.113-Mev γ-γ coincidence rates.

* *Note added in proof.*—In a subsequent experiment employing a time-to-pulse-height converter in conjunction with the 100-channel analyzer, we obtained the value 2.59 ± 0.03 μsec.

VIII. CONSTRUCTION OF THE DECAY SCHEME

A summary of the measured γ-ray intensities, indicated (or assumed) multipolarities, and estimated transition intensities for the transitions in Tm^{171} is shown in Table III. The β-ray data are summarized in Table IV. A decay scheme consistent with these data and with the β-γ and γ-γ coincidence measurements is shown in Fig. 8. The main arguments which support this scheme are discussed below.

The β-γ delayed-coincidence results indicate that both the 0.3084-, 0.1116-Mev cascade and the 0.2960-, 0.1240-Mev cascade depopulate the 2.5-μsec delayed level. In both cascades, the higher-energy transition must precede the other transition in order to be consistent with the observation of 0.80-, 0.1116-Mev and 0.79-, 0.1240-Mev prompt γ-γ coincidences. This conclusion is confirmed by the existence of prompt coincidences between β rays of energy >0.8 Mev and the $\sim$0.113-Mev γ-ray group. Consideration of these facts and the numerous coincidence relationships implied by the precise energy measurements of Hatch and Boehm[1] leads to the postulation of levels B, C, D, and E in the positions shown.

The positions of levels I and J will now be considered. The existence of a level at 0.921 Mev is indicated by the following facts: (1) the β-γ coincidence data suggest the existence of a level at $\sim$0.92 Mev (see Sec. VII. C); (2) level E is populated by a 0.2849-, 0.2106-Mev cascade; (3) the summation of energies in several other of the established γ-ray decay chains equals $\sim$0.92 Mev (see Table II). The observed 0.914-Mev photopeak is thought to be engendered primarily by transition IB (0.916 Mev), although a small contribution from transition IA (0.921 Mev) would not be detected. The reason the photopeak in question occurs at an energy slightly lower than 0.916 Mev is attributed to the known presence of the 0.88-Mev photopeak.

TABLE III. Transitions in Tm^{171}.

Energy (Mev)	Transition[b]	γ-ray intensity[c]	Multipolarity	Estimated total conv. coeff.[d]	Transition intensity[c]
0.0051[a]	BA	...	$M1+E2$[a]	...	...
0.0124[a]	DC	...	$M1+E2$[a]	...	...
0.087	JI	0.05±0.01	$M1+E2$	4.75	0.29
0.1116	CB	22 ±3	$M1$	2.24	71
0.1167	CA	1.8 ±0.3	$E2$	1.86	5.2
0.1240	DB	8.5 ±0.8	$E2$	1.46	21
0.177	IH	0.12±0.04	$(M1+E2)$	~0.7	0.20
0.2106	FE	0.95±0.20	$(E1)$	0.05	1.0
0.233	IG	0.35±0.09	$(M1+E2)$	~0.3	0.46
0.2849	IF	0.73±0.14	$(M1+E2)$	~0.2	0.88
0.2960	ED	23 ±2	$E1+M2$	0.04	24
0.3084	EC	69 ±7	$E1$	0.02	70
0.372	JF	0.12±0.03	$(M1+E2)$	~0.1	0.13
~0.57	GD, GC	0.08±0.03	$(E2)$, $(M1+E2)$	~0.02	0.08
~0.62	HD, HC	0.12±0.04	$(M1+E2)$	~0.02	0.12
~0.69	GB, GA	0.47±0.09	$(M1+E2)$	~0.02	0.48
~0.74	HB, HA	0.07±0.03	$(M1+E2)$, $(E2)$	~0.01	0.07
~0.80	ID, IC	0.80±0.10	$(M1+E2)$	~0.01	0.80
~0.88	JD, JC	0.16±0.04	$(M1+E2)$	~0.01	0.16
~0.92	IB, IA	0.56±0.06	$(M1+E2)$, $(E2)$	~0.01	0.57

[a] See reference 1.
[b] See Fig. 8.
[c] Per 100 Er^{171} disintegrations.
[d] Based on experimental results, if available. Otherwise, based on theoretical conversion coefficients of Sliv (reference 10) and Rose (reference 9).

TABLE IV. Er^{171} β-ray transitions.

E_β (Mev)	Intensity (percent)	Logft[b]
(0.47)[a]	0.6±0.2	7.4
0.55	2.6±0.5	6.9
(0.73)[a]	<0.1	>8.7
0.89	0.1±0.05	9.0
1.05	93 ±2	6.3
(1.36)[a]	1.5±0.2	8.6
1.49	2.1±0.2	8.6

[a] Not observed as a resolved group.
[b] Determined from the curves given by S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).

The observation of $\sim$0.88-, $\sim$0.113-Mev γ-γ coincidences suggests that there is a level at $\sim$1.0 Mev. The added observation of $\sim$0.92-, 0.087-Mev γ-γ coincidences confirms this hypothesis and fixes the energy of level J at $0.921+0.087=1.008$ Mev.

Since both the 0.372- and 0.2849-Mev transitions are coincident with the 0.2106-Mev transition, and since $0.372-0.285=0.087$ Mev, one is led to the conclusion that the 0.372- and 0.2849-Mev transitions *precede* the 0.2106-Mev transition. There is therefore a level (F) at $0.4251+0.2106=0.6357$ Mev.

The existence of $\sim$0.57-, $\sim$0.113-Mev γ-γ coincidences plus the fact that the 0.233-Mev γ ray is in coincidence with γ rays of approximate energy 0.57 and 0.69 Mev indicates that there is a level at $0.921-0.233=0.688$ Mev, designated as level G. Similarly, the evidence for level H, at 0.744 Mev, is the observation of the following γ-γ coincidences: $\sim$0.113 Mev coincident with $\sim$0.62 Mev, and 0.177 Mev coincident with $\sim$0.62 and $\sim$0.74 Mev.

It is clear, from the state assignments of the next section, that each of the observed high-energy photopeaks is probably a "doublet" caused by γ-ray transitions from a given level to a pair of close-lying levels, either A and B or C and D. Consequently, all transitions which were found to proceed from levels G, H, I, and J to levels A (and/or B) and C (and/or D) are shown as "double" transitions, whether or not this fact was established experimentally.

From the summation of beta and gamma energy in the various decay chains which connect the two ground states, we conclude that the total decay energy of Er^{171} is 1.48 ± 0.01 Mev.

IX. STATE ASSIGNMENTS

The experimental and theoretical arguments which lead to the state assignments of Fig. 8 will now be presented. In view of the success of the Nilsson calculations[4,13,14] in explaining the properties of the low-lying

[13] B. R. Mottelson and S. G. Nilsson, Phys. Rev. **99**, 1615 (1955).
[14] Recent results communicated by Dr. S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. (to be published).

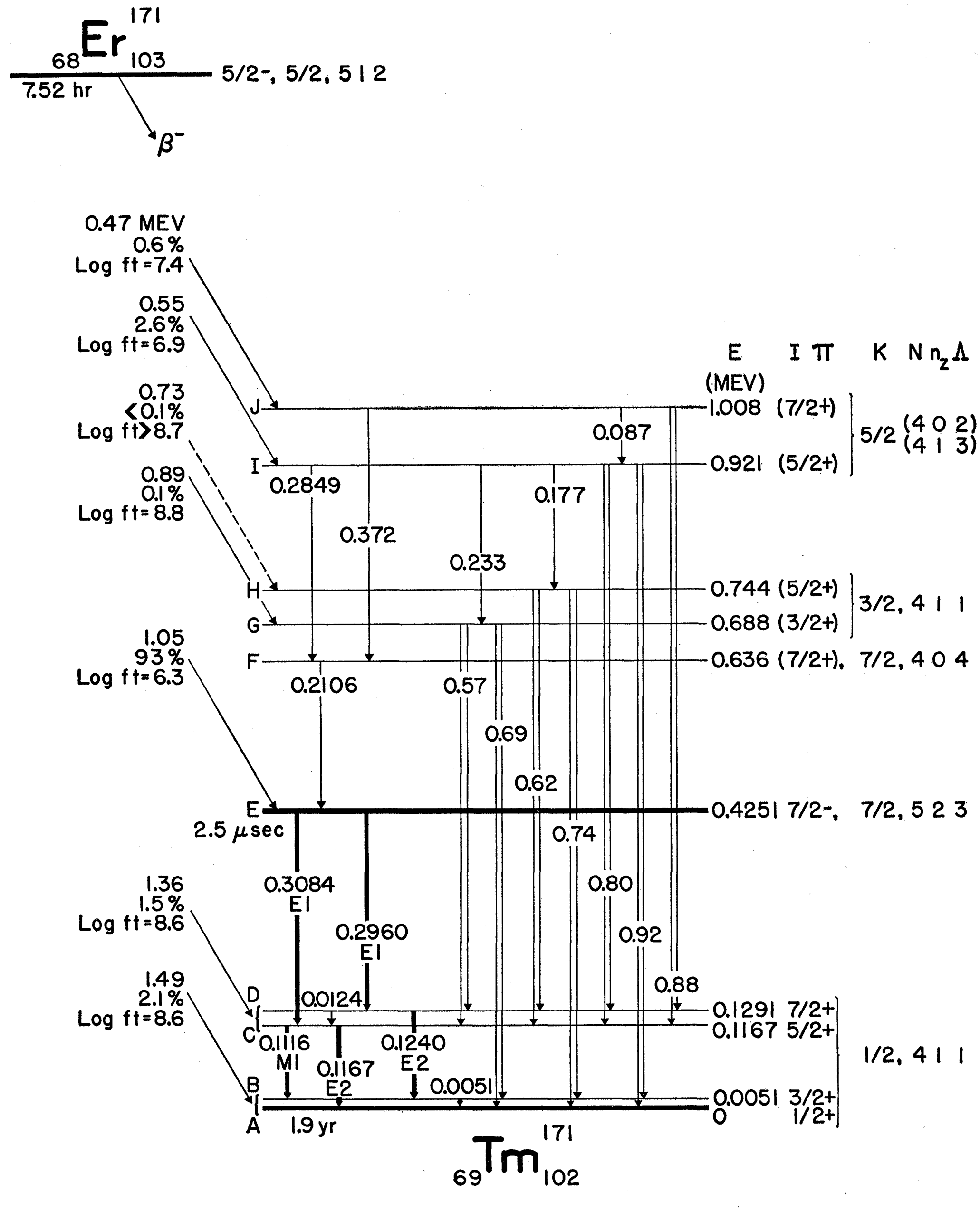

FIG. 8. Proposed decay scheme of Er^{171}.

states of strongly deformed nuclei, we have attempted to correlate the observed intrinsic states of Tm^{171} with appropriate Nilsson orbitals. The applicable portion of the Nilsson diagram[14] is shown in Fig. 9. Calculations based on experimental quadrupole moments indicate that a reasonable value to assume for the deformation parameter, δ, is 0.28.[13] In the interpretation of rotational-level spacings, use is made of the formula[15]

$$E_I = (\hbar^2/2\mathfrak{J})[I(I+1)+\delta_{K,\frac{1}{2}}a(-1)^{I+\frac{1}{2}}(I+\tfrac{1}{2})]. \quad (1)$$

[15] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. 27, No. 16 (1953).

As has been previously pointed out,[1–3,7] the energy spacings of levels A, B, C, and D and the multipolarities of the interconnecting transitions are consistent with the assumption that these four levels are members of a $K=\frac{1}{2}$ anomalous rotational band, with a spin sequence of $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$, respectively. The only reasonable spin $\frac{1}{2}$ Nilsson state available for assignment to the ground state of Tm^{171} is the $\frac{1}{2}+$ [4, 1, 1][16,17] orbital which, in fact, is the predicted assignment for an odd-A nucleus with 69 protons.

[16] The symbolism used here is $\Omega\pi$ $[N,n_z,\Lambda]$. See reference 17.
[17] J. M. Hollander, Phys. Rev. **105**, 1518 (1957).

The calculated position of the 9/2+ level of the ground-state rotational band is 0.3439 Mev.[1] We have no experimental evidence that this level is populated in the decay of Er^{171}. The fact that there are virtually no β-ray or γ-ray transitions to this level is explainable in terms of the state assignments of Fig. 8 and the intensity rules outlined by Alaga *et al.*[18]

Since transitions *EC* and *ED* are of *E*1 multipolarity and terminate at $\frac{5}{2}+$ and $\frac{7}{2}+$ states, respectively, level *E* must have spin and parity $\frac{5}{2}-$ or $\frac{7}{2}-$. The $\frac{5}{2}-$ choice seems improbable from the fact that no transitions are observed to proceed from level *E* to level *B*. Examination of the Nilsson curves reveals that the only $\frac{7}{2}-$ state which is near the $\frac{1}{2}+$ [4, 1, 1] state is the $\frac{7}{2}-$ [5, 2, 3] state. This state is therefore assigned to level *E*. A $\frac{7}{2}-$ level, presumably identifiable with this same orbital, occurs in Tm^{169} at an energy of 379.3 kev.[19] In both of these nuclei, the $\frac{7}{2}-$ state is presumably a hole state, corresponding to the configuration $\{\frac{7}{2}-[5,2,3]\}^1 \{\frac{1}{2}+[4,1,1]\}^2$ for the last three protons.

We shall next consider the state assignment for Er^{171}. The log*ft* values of the β transitions to the ground-state rotational band are characteristic of first forbidden transitions, with $\Delta K \leq 2$. Since levels *A* and *E* are of opposite parity, it follows that the β transition to level *E* ($\frac{7}{2}-$) must be an allowed transition, even though the log*ft* value (6.3) is somewhat higher than that of a normal allowed transition. The only spin and parity assignment for Er^{171} consistent with these restrictions is $\frac{5}{2}-$. The ground state of Er^{171} is identified with the Nilsson state $\frac{5}{2}-$ [5, 1, 2] since there is no other state with $\Omega=\frac{5}{2}$ in the region of 105 nucleons.

The remaining state assignments are less certain since we have essentially no multipolarity data on the transitions which depopulate levels *F*, *G*, *H*, *I*, and *J*. In view of the energy systematics of Nilsson states in this region,[19] one expects the $\frac{7}{2}+$ [4, 0, 4] state to occur as a low-lying excited state of Tm^{171}. If the $\frac{7}{2}+$ [4, 0, 4] state lies above level *E*, then, because of *K*-selection rules, one would expect this state to decay to level *E* rather than to the ground-state rotational band. Of the levels *F* through *J*, only level *F* decays in this manner; consequently, it is given the assignment $\frac{7}{2}+$ [4, 0, 4]. On the sole basis of its decay properties, level *F* could also be the Nilsson state 9/2− [5, 1, 4], which has been observed as an excited state in both Lu^{175} [19] and Lu^{177}.[20] However, the γ-ray branching to this level from higher levels appears to be inconsistent with the 9/2− possibility.

There are several convincing arguments which indicate that levels *I* and *J* are the first two members of a $K=\frac{5}{2}$ rotational band:

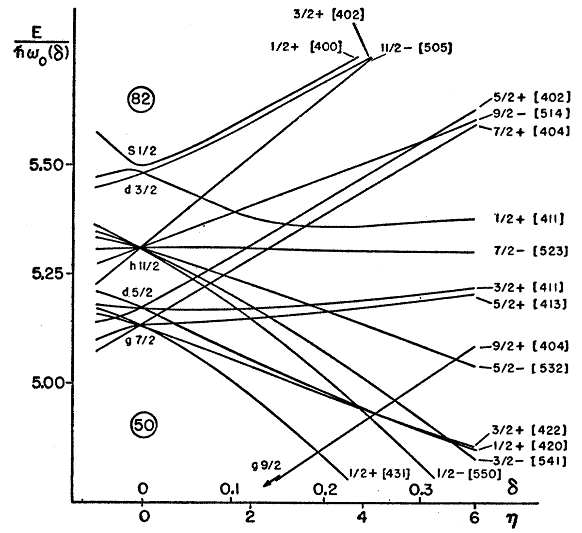

FIG. 9. Nilsson energy-level diagram for prolate deformation.

(a) Consideration of the log*ft* values of the β-ray transitions to levels *I* and *J* and examination of the γ decay of these two levels to the $K=\frac{1}{2}$ band and to level *F* lead to the conclusion that the most probable spin and parity assignments for levels *I* and *J* are $\frac{5}{2}+$ and $\frac{7}{2}+$, respectively. The *M*1(+*E*2) multipolarity of transition *JI* is consistent with these state assignments. An explanation of why neither level decays to level *E* is presented in Sec. X.

(b) According to Eq. (1), the energy difference between the $\frac{5}{2}$ and $\frac{7}{2}$ states of a normal rotational band should be $\Delta E(\frac{7}{2}-\frac{5}{2})=7\hbar^2/2\mathfrak{J}$. If the value of $\hbar^2/2\mathfrak{J}$ is assumed to be the same as that calculated for the $K=\frac{1}{2}$ band (11.63 kev),[1] then one obtains $\Delta E(\frac{7}{2}-\frac{5}{2})=81.4$ kev, in reasonable agreement with the observed *J*-*I* difference of 87 kev. It is noted that the observed $\frac{7}{2}-\frac{5}{2}$ spacing of the $K=\frac{5}{2}$ band in Tm^{169} is 89.4 kev,[19] whereas the spacing calculated on the basis of the rotational splitting term of the $K=\frac{1}{2}$ band is 83.8 kev.

(c) Although transition *JI* is of much lower energy than the other transitions which depopulate level *J*, it has a γ-ray intensity comparable to the intensities of the competing transitions. The most plausible explanation of this fact is the hypothesis that transition *JI* is a rotational transition.

In view of the preceding arguments, level *I* is assumed to be a $\frac{5}{2}+$ intrinsic state, with level *J* being the associated first rotational state. Examination of the Nilsson diagram reveals that a $\frac{5}{2}+$ [4, 0, 2] state lies slightly above the $\frac{7}{2}+$ [4, 0, 4] state. However, it is also evident that the energy required to excite the $\frac{5}{2}+$ [4, 1, 3] hole state could reasonably be ~1 Mev. It seems probable, on the basis of the observed features of the population and depopulation of levels *I* and *J*, that the state function associated with level *I* contains components of both of the above-mentioned $\frac{5}{2}+$ states. The detailed

[18] Alaga, Alder, Bohr, and Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 9 (1955).
[19] Hatch, Boehm, Marmier, and DuMond, Phys. Rev. **104**, 745 (1956).
[20] Mize, Bunker, and Starner, Phys. Rev. **103**, 182 (1956).

reasons for this assumption are presented in a subsequent section.

It is evident from the radically different decay properties of levels G and F that level G is not a rotational state associated with level F; consequently, it is assumed to be another intrinsic state. The logft value (8.8) of the β-ray transition to level G suggests that this state is of positive parity. The fact that this level appears to decay only to the $K=\frac{1}{2}$ band and not to levels E and F (both $K=\frac{7}{2}$ states) is indicative, on the basis of K-selection rules, that the spin of level G is $\leq\frac{5}{2}$. It then follows, in view of the relative strength of transition IG, that there should be a detectable transition from level I to the first rotational state associated with level G. Since there is indeed a transition from level I to level H, one is led to examine whether level H exhibits other properties consistent with it being the rotational state in question. It is noted that the H-G spacing is 56 kev, which is close to the theoretical value of ~58 kev for the $\frac{5}{2}-\frac{3}{2}$ spacing in a normal rotational band (calculated on the assumption that the value of $\hbar^2/2\mathfrak{J}$ is approximately the same as for the $K=\frac{1}{2}$ band). Since all aspects of the population and depopulation of levels G and H appear to be consistent with the spin assignments suggested above and with the assumption that both levels belong to the same rotational band, level G is believed to be a $\frac{3}{2}+$ intrinsic state, with level H being the associated $\frac{5}{2}+$ first rotational state. Unfortunately, all attempts to observe the 56-kev transition HG were unsuccessful. Intensity balance considerations suggest that transition HG is weaker than any of the observed transitions from level H to the $K=\frac{1}{2}$ band. Such a weak transition would be extremely difficult to observe in view of the fact that the total conversion coefficient could be as high as 20 and the fact that the 56-kev region is masked by the thulium K x-ray.

There are two $\frac{3}{2}+$ Nilsson states available for assignment to level G: the $\frac{3}{2}+$ [4, 0, 2] particle state and the $\frac{3}{2}+$ [4, 1, 1] hole state. If pairing-energy effects are neglected and the relative level spacings of the Nilsson diagram are assumed to be semiquantitative, it would seem that the $\frac{3}{2}+$ hole state should lie fairly close to the $\frac{7}{2}+$ [4, 0, 4] state, whereas the $\frac{3}{2}+$ particle state should be at least 1 Mev higher. Consequently, level G is identified with the Nilsson orbital $\frac{3}{2}+$ [4, 1, 1].

TABLE V. Classification of Er^{171} β-ray transitions.

Final state	ΔI, $\Delta\pi$ type	ΔK, ΔN Δn_z, $\Delta\Lambda$	Asymptotic classification	Exptl. logft
A	2, yes, 1st forb.	$\Delta K=2$	K-forb.	≥ 8.6
B	1, yes, 1st forb.	$\Delta K=2$	K-forb.	≥ 8.6
C	0, yes, 1st forb.	$\Delta K=2$	K-forb.	≥ 8.6
D	1, yes, 1st forb.	$\Delta K=2$	K-forb.	≥ 8.6
E	1, no, allowed	1, 0, 1, 1	hindered	6.3
F	1, yes, 1st forb.	1, 1, 1, 2	hindered	>9.0
G	1, yes, 1st forb.	1, 1, 0, 1	unhindered	8.8
H	0, yes, 1st forb.	1, 1, 0, 1	unhindered	>8.7
I	0, yes, 1st forb.	(0, 1, 1, 0)[a]	unhindered	6.9
		(0, 1, 0, 1)[b]	unhindered	
J	1, yes, 1st forb.	(0, 1, 1, 0)[a]	unhindered	7.4
		(0, 1, 0, 1)[b]	unhindered	

[a] Associated with the 5/2+ [4, 0, 2] component of I, J.
[b] Associated with the 5/2+ [4, 1, 3] component of I, J.

X. FURTHER REMARKS ON TRANSITION PROBABILITIES

As indicated in Sec. IX, the only selection rules used as guides in assigning appropriate Nilsson states to the observed levels were those concerning ΔI, $\Delta\pi$, and ΔK. Since it appears well established that violation of the asymptotic selection rules on ΔN, Δn_z, and $\Delta\Lambda$, given by Alaga[21,22] and others,[23–25] can cause transitions to be retarded,[17,21,25,26] it is of obvious interest to determine the extent to which the beta and gamma transitions of the present decay scheme reflect the influence of these rules.

The classification of the β-ray transitions of Er^{171}, based on the proposed state assignments, is given in Table V. The transitions are classified as unhindered or hindered according to whether they obey or violate the appropriate asymptotic selection rules. A brief discussion of the β-ray transitions follows:

The logft value (≥ 8.6) of the β transition to the ground state is reasonable for a $\Delta I=2$ (yes) transition.

The first forbidden transitions to states B, C, and D are each expected to exhibit considerable $\Delta I=2$ admixture because of operation of the K-selection rule, $\Delta K\leq L$,[18] where L is the multipole order of the transition. The experimental logft values (each ≥ 8.6) are consistent with this hypothesis.

The allowed transition to level E violates the Δn_z and $\Delta\Lambda$ rules, thus providing an explanation for the relatively high logft value of 6.3. The hindrance factor (~10) is similar to that of other known hindered allowed transitions.[21] However, part of the retardation may be related to the hole character of the final state.

The transition to level F, classified as hindered first forbidden, with $\Delta K=1$, was not observed. The logft value is estimated to be >9, indicative of a large hindrance factor.

The transitions to states G and H, presumably of the unhindered first forbidden class, have anomalously high logft values. This anomaly tends to confirm the classification of level G as a relatively pure $\frac{3}{2}+$ [4, 1, 1] hole state.

The transitions to states I and J have logft values consistent with their classification as unhindered first

[21] G. Alaga, Phys. Rev. **100**, 432 (1955).
[22] G. Alaga, Nuclear Phys. **4**, 625 (1957).
[23] S. G. Nilsson, dissertation, Berlingska Boktr., Lund, 1955 (unpublished).
[24] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. (to be published).
[25] Rasmussen, Canavan, and Hollander, Phys. Rev. **107**, 141 (1957).
[26] D. Strominger and J. O. Rasmussen, Nuclear Phys. **3**, 197 (1957).

forbidden. This is interpreted as a strong indication that one of the admixed components of state I is a *particle* state, presumably $\frac{5}{2}+$ [4, 0, 2].

It is also of interest to compare the observed β-ray branching ratios for each rotational band with the theoretical ratios calculated according to the intensity rules of Alaga *et al.*[18] However, these rules are not strictly applicable to K-forbidden transitions, and the extent of their applicability to hindered transitions is not clear. The only transitions in the present scheme which are neither K-forbidden nor hindered are those which populate the $K=\frac{3}{2}$ and $K=\frac{5}{2}$ bands. The fact that we have such limited experimental information on the β branching to the $K=\frac{3}{2}$ band does not seem to justify further analysis of these data. The theoretical value for the ratio of the ft values of the β transitions to the $\frac{5}{2}+$ intrinsic state and to the associated $\frac{7}{2}+$ first rotational state is 0.40, which is in fair agreement with the observed ratio of 0.30 ± 0.08.

We will now consider the γ-ray transitions, in particular those transitions which proceed from one rotational band to another. The values of ΔK, ΔN, Δn_z, and $\Delta\Lambda$ for all possible combinations of assigned orbitals is given in Table VI. Since all of the observed levels except level E (known to be depopulated by two $E1$ transitions) were found to have half-lives of $<4\times10^{-8}$ sec, it is assumed that the only significant multipolarities involved in the entire decay scheme are $E1$, $E2$, $M1$, and $M2$. On this basis, all of the transition types which might contribute measurably to the depopulation of levels E, F, G, H, I, and J are listed in Table VI.

The two $E1$ transitions which depopulate level E are each retarded compared to the theoretical single-particle rate[27] by a factor of $\sim10^9$. These large retardations are the result of violation of the strong K-selection rule, $\Delta K\leq L$.[18] Most of the known $E1$ transitions which involve $\Delta K=3$ exhibit similar retardation factors.

In regard to the measured value of the K-internal conversion coefficient of transition ED, it was at first considered possible that the deviation of this value from the theoretical $E1$ value did not necessarily indicate $M2$ admixture since it is well known that several highly-retarded $E1$ transitions exhibit anomalous conversion coefficients. However, it has been recently pointed out[28] that *K-forbidden* $E1$ transitions can be expected to have normal conversion coefficients; therefore, the observed ϵ_K value for transition ED is interpreted as an indication of $M2$ admixture. On the basis of the calculated mixing ratio, $M2/E1=0.034$ (see Sec. IV), one finds that the comparative lifetime of the $M2$ component of the 0.2960-Mev transition is $\sim2.5\times10^3$ greater than the single-particle estimate.[27] Similarly, the retardation of the $M2$ component of the 0.3084-Mev transition is estimated to be $\geq10^4$. These retardation factors presumably result from the fact that, in both cases, $M2$ radiation is first-order K-forbidden.

The only transiton observed to depopulate level F is FE (0.2106 Mev), classified as a hindered (n_z-forbidden) $E1$ transition. The half-life of level F was found to be shorter than we could measure with our coincidence apparatus; consequently, we have no way of estimating the retardation factor of transition FE. The theoretical ratio of the intensity of transition FE to that of the hypothetical $E1$ transition from level F to the $9/2-$ first rotational state associated with level E (expected to lie $\sim$0.105 Mev above level E), calculated according to the rules given by Alaga *et al.*,[18] is 28:1. Even if this estimate is in error by a factor of 2 because of the fact that these transitions are hindered, it is evident that the transition from level F to the $9/2-$ state in question would be extremely difficult to observe.

Both $M1$ and $E2$ transitions can proceed "unhindered" from the $\frac{3}{2}+$ [4, 1, 1] band to the $K=\frac{1}{2}$ band. Therefore, each of the transitions GA, GB, GC, HB, HC, and HD may be of $M1+E2$ multipolarity. Since we have no way of estimating the mixing ratios, no further theoretical interpretation of the observed γ-ray branching from levels G and H will be attempted.

TABLE VI. Classification of transitions in Tm^{171}.

Initial state	Final state	ΔK, ΔN Δn_z, $\Delta\Lambda$	Assumed multipolarity	Asymptotic classification
E	B, C, D	3, 1, 1, 2	$E1$	K-forbidden
			$M2$	K-forbidden
F	B, C, D	3, 0, 1, 3	$M1$	K-forbidden
			$E2$	K-forbidden
F	E	1, 1, 2, 1	$E1$	hindered
G, H	A, B, C, D	1, 0, 0, 0	$M1$	unhindered
			$E2$	unhindered
G, H	E	2, 1, 1, 2	$E1$	K-forbidden
G, H	F	2, 0, 1, 3	$M1$	K-forbidden
			$E2$	hindered
I, J	A, B, C, D	(2, 0, 1, 1)[a]	$M1$	K-forbidden
			$E2$	hindered
		(2, 0, 0, 2)[b]	$M1$	K-forbidden
			$E2$	unhindered
I, J	E	(1, 1, 2, 1)[a]	$E1$	hindered
		(1, 1, 1, 0)[b]	$E1$	hindered
I, J	F	(1, 0, 0, 2)[a]	$M1$	hindered
			$E2$	hindered
		(1, 0, 1, 1)[b]	$M1$	unhindered
			$E2$	unhindered
I, J	G, H	(1, 0, 1, 1)[a]	$M1$	unhindered
			$E2$	unhindered
		(1, 0, 0, 2)[b]	$M1$	hindered
			$E2$	hindered

[a] Associated with the $5/2+$ [4, 0, 2] component of I, J.
[b] Associated with the $5/2+$ [4, 1, 3] component of I, J.

[27] M. Goldhaber and A. W. Sunyar, in *Beta and Gamma Ray Spectroscopy*, edited by Kai Siegbahn (North Holland Publishing Company, Amsterdam, 1955), Chap. XVI (II), p. 463.
[28] S. G. Nilsson and J. O. Rasmussen, Nuclear Phys. **5**, 617 (1958).

The following comments are directed toward explaining certain features of the γ decay of levels I and J:

(*a*) The fact that level I decays observably to level G, believed to be predominantly a hole state, forms the principle argument for postulating that state I contains an admixture of the hole state $\frac{5}{2}+$ [4, 1, 3]. Thus, IG and IH are interpreted as unhindered hole-hole transitions.

(*b*) The ($M1+E2$) transitions to level F have the possible alternative classifications: hole-particle unhindered or particle-particle hindered. Either possibility would be expected to have an abnormally low transition probability. The dominant contribution to the transition probabilities of IF and JF may come from a coupling between states J and F, as has been proposed in the case of Ta^{181}.[29]

(*c*) The large retardations of the unobserved $E1$ transitions to level E from the $K=\frac{5}{2}$ band are presumed to result mainly from violation of the asymptotic rules.

(*d*) There seems to be no obvious selection-rule explanation for the observed γ-ray branching from the $K=\frac{5}{2}$ band to the various levels of the $K=\frac{1}{2}$ band. Here again, the transition probabilities may strongly reflect a coupling between the rotational bands.

XI. CONCLUSIONS

Most of the features of the decay scheme of Er^{171} appear to be explainable in terms of the Nilsson model. The recent calculations of Rassey[30] yield a theoretical level diagram similar to that of Nilsson. The present data do not give any clear indication as to whether the Rassey diagram is an improvement over that of Nilsson. In both the Rassey and Nilsson schemes, there are several levels which come down into the region $60<Z<82$ from the shell-model states above $Z=82$ (these levels are not shown in Fig. 9). None of these levels appear to be involved in the present decay scheme. However, the population of these states, if energetically possible, would be inhibited by selection-rule violations in almost every case. Consequently, the present data do not exclude the possibility that several of these levels lie within 1 Mev of the Tm^{171} ground state. On the other hand, the sequence of known ground-state spins of the odd-Z nuclei from $Z=61$ to $Z=79$ gives no indication that levels other than those shown in Fig. 9 occur in this region.

We have attempted to present a consistent interpretation of the β- and γ-ray transition intensities. This analysis has revealed that the inhibition of a number of the transitions can be explained as being due to violation of the asymptotic selection rules. However, it is evident that the use of these rules as a guide in interpreting transition probabilities is limited by the effect of admixed states (which usually tends to enhance transition rates) and dissimilar core configurations in the initial and final states (which tends to inhibit transition rates).

XII. ACKNOWLEDGMENTS

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[29] See reference 4, p. 13.
[30] A. J. Rassey, Phys. Rev. **109**, 949 (1958).