Study of Low-Lying 1^- States in ^{166,168,170}Er Using the Resonant Scattering of Bremsstrahlung*

F. R. Metzger and V. K. Rasmussen
Bartol Research Foundation of the Franklin Institute, Swarthmore, Pennsylvania 19081
(Received 7 June 1973)

In addition to the previously known 1^- states of ^{166}Er at 1663 and 1830 keV, levels at 1812 ± 1 keV (^{166}Er), 1786 ± 1 keV (^{168}Er), and 1824 ± 1 keV (^{170}Er) have been excited using electron bremsstrahlung. Based on the observed angular distributions of the scattered photons, all three previously unknown levels were found to have spin 1. Linear polarization measurements using a two-slab Ge(Li) polarimeter led to negative parity assignments for the 1786- and 1824-keV levels but were inconclusive with respect to the less strongly excited 1812-keV level. Below 1.9 MeV, the 1663-, 1786-, and 1824-keV levels are the dominant $E1$ excitations in their respective isotopes, the partial widths of their ground-state transitions being $\Gamma_0 = 32 \pm 5$, 46 ± 5, and 30 ± 3 meV. The $B(E1;1^- \rightarrow \text{g.s.})/B(E1;1^- \rightarrow 2_1^+)$ ratios of 0.52 ± 0.02, 0.51 ± 0.02, and 0.53 ± 0.02 differ considerably from the ratio 1.31 ± 0.11 for the 1812-keV level and the reported ratio 0.22 for the 1830-keV 1^- state and are very close to the Alaga value of 0.50 for $K = 0^-$ levels.

I. INTRODUCTION

The experimental information concerning the low-lying 1^- states in $^{166, 168, 170}$Er is rather limited. Only the 1663- and 1830-keV states of ^{166}Er, which are populated in the decay of ^{166}Ho, are clearly established[1,2] as 1^- states. In ^{168}Er, a 1357-[3] (1354-[4]) keV level, seen in the (d,p)[3] and (n,γ)[4] reactions, has been tentatively identified as the 1^- member of the $K^\pi = 1^-$ band. Furthermore, it has been suggested[4] that the 3^- level at 1914 keV is a member of the $K^\pi = 0^-$ octupole vibrational band, with the band head expected between 1.7 and 1.8 MeV. In ^{170}Er, inelastic deuteron scattering[5] strongly excited a 3^- state at 1575 keV, and the authors suggested that levels observed at 1539 and 1709 keV were probably the 1^- and 5^- members of the associated rotational band.

Since the resonant scattering of photons is proportional to Γ_0^2/Γ, where Γ_0 is the radiative width of the ground-state transition and Γ the total width of the level, and since for a given transition energy the widths decrease, in general, rapidly with increasing multipole order, only dipole and quadrupole excitations are observed in nuclear resonance fluorescence (NRF) experiments. In the heavier nuclei ($Z > 30$) where the advent of sizable (Ge(Li) detectors has rendered NRF experiments utilizing bremsstrahlung feasible,[6,7] the emphasis is even more strongly on dipole transitions. In the past, when radioisotopes or nuclear reactions served as the photon sources, most of the levels studied with the resonance fluorescence method were already known and had had their properties (spins, parities) determined by other studies. The purpose of the photon scattering experiments was then the measurement of the radiative widths of these levels. The possibility of utilizing bremsstrahlung has provided the NRF experimentalist with utter flexibility with respect to excitation energy, the only limitation being the available machine energy. As a consequence many hitherto unknown or very poorly known levels are being excited, and it has become necessary to determine the main characteristics of these levels in addition to their radiative properties. For even nuclei the spin determination is straightforward since the angular distributions for the possible spin sequences 0-1-0 and 0-2-0 are very different. Clearly, a study of the linear polarization of the resonance radiation can lead to a parity determination, a fact used in the past in resonance fluorescence experiments with more favorable photon sources.[8,9] Because of the low counting rate character of most NRF experiments, NaI(Tl) detectors were used in those studies. As has been pointed out before, NaI(Tl) detectors cannot be used in NRF experiments using bremsstrahlung, at least not for nuclei with $Z \gtrsim 30$. On the other hand, a Ge(Li) slab combines high-energy resolution with sensitivity to linear polarization.[10] Estimates indicated that, with an array of several slabs, the counting rates would be sufficient, at least for some of the stronger levels, to render possible parity determinations using the bremsstrahlung NRF technique. A two-slab polarimeter was found to be technically and economically feasible and such a device was consequently acquired.[11] As a test case for the performance of this polarimeter, the 1663-keV 1^-

state in ^{166}Er looked promising since its parity was well established.[1] A survey with natural Er showed fairly strong resonant scattering from the 1663-keV level, but revealed several other levels of comparable strengths and with rather similar "signatures", i.e., rather similar intensity ratios of the transitions to the ground states and the first excited states. To assign these levels to the proper isotopes, experiments were carried out with scatterers enriched in ^{166}Er, ^{168}Er, and ^{170}Er, respectively. In this paper the results for the levels seen below 1.9-MeV excitation energy are reported.

2. EXPERIMENTAL PROCEDURES

A. Scatterers

Three scatterers were used. Each contained approximately 115 g of enriched isotope[12] in the form of Er_2O_3 in a cylindrical volume 5.71 cm in diameter and 1.63 cm long. The containers were fabricated from Plexiglas. The isotopic compositions of the scatterers are listed in Table I.

B. Yield Measurements

The scatterer was placed on the electron beam axis with its center 44 cm from the 37 mg/cm^2 gold foil in which the bremsstrahlung was produced. For typical geometries and other details, see Refs. 6 and 7. The scattered γ radiation was detected with a 45-cm^3 Ge(Li) detector. The distance from the center of the scatterer to the effective center of the detector was 19.5 cm. Typically, 1.9 cm of Pb were placed between scatterer and detector to remove the Compton-scattered radiation and most of the annihilation radiation and thus keep the counting rate in the detection system within manageable limits ($\lesssim$20 000 counts/sec). A gated integrator[14] was used to keep the losses below 10%.

Typical spectra, obtained at an electron bombarding energy of 1.93 MeV, are shown in Fig. 1.

C. Linear Polarization Measurements

For the polarization measurements, the 45-cm^3 Ge(Li) detector was replaced by a two-slab Ge(Li) detector. The two rectangular slabs measured $5.8\times3.8\times0.8$ cm^3 and were separated by 2 cm. The centers of the slabs were placed at a distance of approximately 18 cm from the center of the scatterer. A mean scattering angle of 98° rather than the optimum of 90° was chosen because of the steep increase in background counting rate with decreasing scattering angle.

Since, at the time of these measurements, only one gated integrator was available, the outputs from the two preamplifiers were fed into this gated integrator and from there into a multichannel analyzer. Measurements were carried out with the plane of the slabs in the plane of the resonant scattering and perpendicular to that plane, with the polarimeter position being changed approximately every half hour. For each transition between 10 and 35 h of running were needed to obtain sufficient statistics for a parity determination. The ^{170}Er and ^{168}Er measurements and some of the ^{166}Er measurements were carried out with an electron energy of 2.1 MeV. The rest

TABLE I. Isotopic analysis (Ref. 13) of Er scatterer materials (atomic percent).

Scatterer \ Isotope	^{162}Er	^{164}Er	^{166}Er	^{167}Er	^{168}Er	^{170}Er
^{166}Er	<0.05	<0.1	94.85	3.76	1.16	0.24
^{168}Er	<0.02	0.04	1.44	2.44	95.47	0.61
^{170}Er	0.02	0.04	0.87	0.72	1.46	96.89

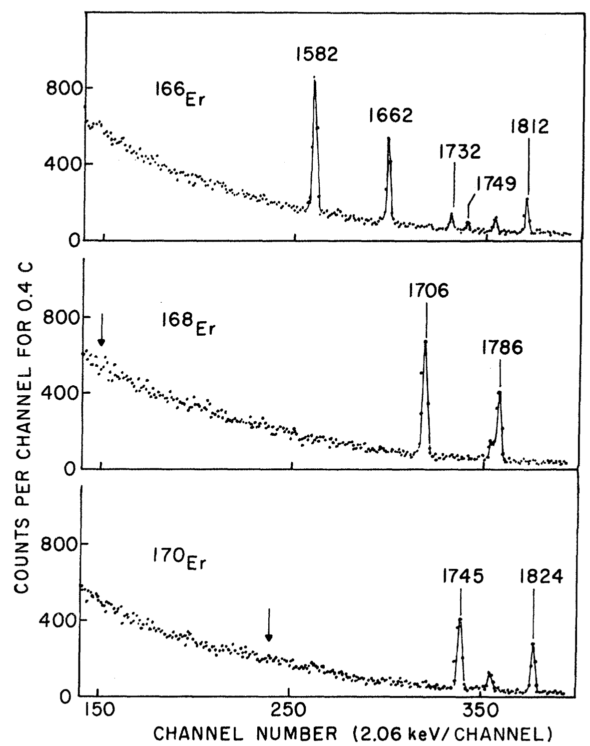

FIG. 1. Pulse-height distributions observed with enriched scatterers of ^{166}Er, ^{168}Er, and ^{170}Er for a mean scattering angle of 127°. The bombarding energy was 1.93 MeV. γ-ray energies are given in keV. The peak in channel 354 represents resonant scattering from the 1779-keV level of ^{28}Si contained in the building materials of the laboratory. The arrows in the ^{168}Er and ^{170}Er spectra indicate where the ground-state transitions from suggested (Refs. 3–5) 1^- levels (1355 keV in ^{168}Er and 1539 keV in ^{170}Er) are expected.

of the ^{166}Er measurements used $E_e = 1.9$ MeV. In a separate experiment the unpolarized radiation from the 2.125-MeV $\frac{1}{2}^-$ state in ^{11}B was used to ascertain that there was no significant asymmetry in the apparatus.

3. RESULTS

In addition to the strong excitations at 1663 keV in ^{166}Er, at 1786 ± 1 keV in ^{168}Er, and at 1824 ±1 keV in ^{170}Er, levels in ^{166}Er at 1812 ± 1 and 1830 ± 2 keV were observed. There is no evidence for the excitation of the levels at 1354 keV in ^{168}Er and at 1539 keV in ^{170}Er which had been suggested[3-5] as possible 1$^-$ states. Of course this does not mean that these levels do not exist, but it places limitations on their Γ_0^2/Γ values. Either the branches from these levels to the ground states are weak compared with other branches or the partial $E1$ widths for the ground-state transitions are small, or both.

A. Spins

In Table II, the yields at a scattering angle of 127° are compared with the 98° yields and with the relative yields expected for spin-1 levels and spin-2 levels and the actual geometries.

The comparison of theory and experiment in Table II shows that all the listed levels have a spin of 1. For the 1830-keV level of ^{166}Er, for which the NRF experiments did not provide sufficient statistics for a spin determination, spin 1 had already been established in other studies.[1,2]

The angular distributions for the $1 \rightarrow 2_1^+$ branches were all found to be consistent with the ratio $N(127°)/N(98°) = 1.05$ expected if the $1 \rightarrow 2^+$ transition is pure dipole.

B. Parities

The results of the measurements using the two-slab Ge(Li) polarimeter are summarized in Table III. The counting rates registered in the full energy peaks with the slabs parallel to the scattering plane and perpendicular to that plane are denoted by $N_\parallel$ and $N_\perp$. On the basis of the experiences of other authors[10,15] it was expected that the ratio

$$R = \frac{N_\parallel - N_\perp}{N_\parallel + N_\perp}$$

would be approximately +10% if the ground-state transitions were electric dipoles, and −10% if they were magnetic dipoles. For the transitions to the 2_1^+ states the corresponding expected ratios would be +1 and −1%.

From the results given in the last column of Table III it is concluded that the three strong transitions are electric dipoles, i.e., that the parities of these spin-1 states are negative. For the 1812-keV level in ^{166}Er the statistics were not sufficient for a parity determination. The available data favor a positive parity assignment. It is expected that, once the second gated integrator becomes available, the parity of the 1812-keV state will be determined unambiguously. The fact that the 1812-keV level does not appear to be populated in the decay of ^{166}Ho favors a 1$^+$ assignment, but does not rule out negative parity.

For the 1830-keV level in ^{166}Er, which is very weakly excited in the NRF experiments, one has to rely on its identification with the 1$^-$ state populated in the ^{166}Ho decay.

C. Branching

The spectra of Fig. 1 show that there is considerable branching to the first 2$^+$ state at ~80-keV excitation energy for all the observed levels. There is no evidence for branching to more highly excited states. However, it is clear from the rising background of Fig. 1 that decays to higher states are increasingly difficult to observe as one moves from the region of the ground-state transition to the region where one would expect to find the cascade transitions to these more

TABLE II. Comparison of the experimental ratios of the counting rates in the 98 and 127° scattering geometries with the ratios expected for different values of the spins of the excited states.

		$N(127°)/N(98°)$		
			Theory	
Isotope	E_{level} (keV)	Experiment	Spin 1	Spin 2
^{166}Er	1663	1.39 ± 0.11	1.36	0.49
^{166}Er	1812	1.40 ± 0.17		
^{168}Er	1786	1.38 ± 0.07		
^{170}Er	1824	1.33 ± 0.09		

TABLE III. Results of the measurements using the two-slab Ge(Li) polarimeter. $N_\parallel$ and $N_\perp$ represent the counting rates in the full energy peaks with the slabs parallel and perpendicular to the scattering plane, respectively.

Isotope	E_{level} (keV)	Transition $I_i \rightarrow I_f^\pi$	E_γ (keV)	$(N_\parallel - N_\perp)/(N_\parallel + N_\perp)$ (%)
^{166}Er	1662	$1^- \rightarrow 0^+$	1662	+7.4 ± 4.9
		$1^- \rightarrow 2^+$	1582	+3.7 ± 3.4
	1812	$1 \rightarrow 0^+$	1812	−5.6 ± 10.0
^{168}Er	1786	$1 \rightarrow 0^+$	1786	+16.7 ± 7.4
		$1 \rightarrow 2^+$	1706	−1.4 ± 4.3
^{170}Er	1824	$1 \rightarrow 0^+$	1824	+9.8 ± 4.8
		$1 \rightarrow 2^+$	1745	0.0 ± 3.1

highly excited states as, e.g., the γ vibrational band.

For the two levels which had been known prior to this NRF experiment, the 1663- and 1830-keV 1^- states in ^{166}Er, studies[1,2,16,17] of the decay of ^{166}Ho had not revealed any additional branching.

Since the NRF scattering yield is proportional to Γ_0^2/Γ while the self-absorption is proportional to Γ_0, branching information may also be derived from a comparison of the results of these two types of experiments. Unfortunately, the statistical accuracy of the self-absorption data usually limits the usefulness of such information. Since Γ_0 is biggest for ^{168}Er, a self-absorption experiment was carried out for the 1786-keV level of that isotope. A natural Er metal absorber of 1-cm thickness was placed in the incident beam and the resultant resonant reduction in the scattering yield was observed. The branching ratio determined in this manner, $\Gamma_0/\Gamma = 0.37 \pm 0.07$, agrees with the ratio $\Gamma_0/(\Gamma_0 + \Gamma_1) = 0.37 \pm 0.01$ obtained from a comparison of the areas of the 1786- and 1706-keV peaks. Here Γ_1 is the partial width of the 1706-keV cascade transition to the 2_1^+ state. All that may be concluded on the basis of this additional experiment is that $\Gamma \approx \Gamma_0 + \Gamma_1$, i.e., that no major branching to higher levels was missed.

The branching information is collected in columns 3 and 6 of Table IV.

For the 1830-keV level in ^{166}Er, the NRF experiments gave only a weak indication of a ground-state transition while the 1749-keV branch to the 2_1^+ state showed up clearly (Fig. 1). This observation is consistent with the best estimate $I(1749)/I(1830) = 3$ obtained[18] from studies of the ^{166}Ho decay.

D. Radiative Widths

If N_{sc} denotes the yield of scattered quanta representing decays directly to the ground state, the partial radiative width Γ_0 for the ground-state transition is connected to N_{sc} through

$$N_{sc} = N(E_r) G g \Gamma_0^2/\Gamma, \qquad (1)$$

where $N(E_r)$ is a measure of the incident γ intensity at the resonant energy E_r, g the ratio $(2I_{exc}+1)/(2I_{g.s.}+1)$ which assumes the value 3 for all the erbium levels reported on in this paper, and G is a factor taking into account the geometry, the scatterer composition, etc. In general, G depends slightly on Γ_0 through the resonant attenuation of the incoming beam on its path through the scatterer. The evaluation of Eq. (1) in terms of Γ_0 thus proceeds by iteration. When this was done using the exact form[19] for the absorption cross section and $N(E_r)$ was interpolated from a set of $N(E_r)$ data for "standard" levels of known widths,[6] the widths listed in columns 5 and 7 of Table IV were obtained. For the 1830-keV level, the 1749-keV branch to the 2_1^+ state, rather than the weak ground-state transition, was used in determining Γ_0. If N_{sc} in Eq. (1) refers to the 1749-keV branch to the first excited state rather than to the ground-state transition, the factor Γ_0^2/Γ has to be replaced by $\Gamma_0\Gamma_1/\Gamma$. With $\Gamma_1/\Gamma = 0.75$,[18] the NRF experiment yielded $\Gamma_0 = (2.4 \pm 0.4)$ meV. The error in Γ_0 does not include the (unknown) uncertainty in the ratio Γ_1/Γ.

In the Introduction it was mentioned that a 1355-keV level in ^{168}Er and a 1539-keV level in ^{170}Er had been tentatively identified[3,5] as 1^- states. In the NRF spectra no indication for the excitation of either of these levels was found. Upper limits of 1 meV can be placed on the Γ_0^2/Γ values for these levels.

4. DISCUSSION

The most striking feature of Fig. 1 is probably that the two strong lines in the ^{166}Er spectrum, representing the decay of the 1663-keV 1^- level, carry over to the ^{168}Er and ^{170}Er spectra with 1^-

TABLE IV. Widths and branching ratios of the ^{166,168,170}Er levels. The direct results of the NRF scattering experiments are listed in column 5.

Isotope	Level (keV)	Γ_0/Γ_1	$B(E1; 1^- \to \text{g.s.})/B(E1; 1^- \to 2_1^+)$	Γ_0^2/Γ (meV)	Γ_0/Γ [a]	Γ_0 (meV)
^{166}Er	1663	0.60 ± 0.02 [b]	0.52 ± 0.02	12.0 ± 1.8	0.38 ± 0.01	32 ± 5
	1812	1.50 ± 0.12	1.31 ± 0.11 [c]	4.8 ± 0.6	0.60 ± 0.02	8 ± 1
	1830	≈ 0.33 [d]	≈ 0.22	...	≈ 0.25	2.4
^{168}Er	1786	0.59 ± 0.02	0.51 ± 0.02	17.0 ± 1.7	0.37 ± 0.01	46 ± 5
^{170}Er	1824	0.61 ± 0.02	0.53 ± 0.02	11.4 ± 1.1	0.38 ± 0.01	30 ± 3

[a] Assuming the absence of branching to levels above the 2_1^+ state.
[b] In good agreement with the value of 0.61 adopted in Ref. 18.
[c] This might be the ratio of $B(M1)$'s rather than $B(E1)$'s since the polarization experiment was not conclusive.
[d] From the decay of ^{166}Ho; see Ref. 18.

states at 1786 and 1824 keV. The experimental ratios $B(E1; 1^- \to 0^+)/B(E1; 1^- \to 2^+)$ are very close to the value 0.5 expected[20] for $K=0$ 1^- states in the absence of K mixing due to the Coriolis interaction. Kocbach and Vogel,[21,22] in fitting various observed branching ratios, find that such mixing is required. They also find that the $E1$ amplitudes for $|\Delta K|=1$ transitions are approximately an order of magnitude smaller than for $\Delta K=0$ transitions, and point out that this is in qualitative agreement with the observed behavior[23] of $E1$ transitions in odd-A deformed nuclei. For a predominantly $K=0$ 1^- state, then, small admixtures of a $K=1$ component will hardly affect the $E1$ transitions to the ground-state band, but for a predominantly $K=1$ 1^- state, small admixtures of $K=0$ may have a large effect because of the possibility of interference. We suggest, then, that the 1663-, 1786-, and 1824-keV 1^- states in ^{166}Er, ^{168}Er, and ^{170}Er are predominantly $K=0$. A $K=0$ assignment had previously been made by Gallagher and Soloviev[24] for the 1663-keV level in ^{166}Er. On the other hand, Neergård and Vogel,[25] who predicted the $K=1$ 1^- states in the erbium isotopes to lie below the $K=0$ 1^- states, assigned $K=1$ to the 1663-keV and $K=0$ to the 1830-keV level.

In addition to the 1663-keV 1^- level, the $K^\pi=0^-$ band in ^{166}Er may also include the 3^- 1719-keV level and the 5^- 1901-keV level.[5] In ^{168}Er and ^{170}Er, possible 3^- members of the $K^\pi=0^-$ bands were observed at 1914 keV [4] in ^{168}Er and at 1931 keV [5] in ^{170}Er.

The $E1$ strengths of the ground-state transitions from the 1663-, 1786-, and 1824-keV levels range from 2.4×10^{-3} single-particle units (s.p.u.) for ^{170}Er to 3.9×10^{-3} s.p.u. for ^{168}Er. These strengths are very similar to the strength measured[26] for the 963-keV $K=0$ 1^- state in ^{152}Sm and agree to within a factor of 2 with theoretical estimates[25,27] obtained using an effective charge $-(Z/A)e$.

We postpone discussion of the 1812-keV level in ^{166}Er until there is more solid evidence concerning its parity.

From the previous discussion of $E1$ strengths and branchings, $K=1$ may be tentatively assigned to the 1830-keV 1^- level of ^{166}Er, noting that in the cases of ^{152}Sm, ^{154}Gd, and ^{234}U even smaller branching ratios for $K=1$ 1^- levels were accommodated[22] using reasonable values of the parameters.

Calculations using the surface δ interaction[28] reproduce fairly well the trend of the $K=0$ 1^- states in ^{166,168,170}Er. They place the $K=1$ 1^- states in ^{168}Er and ^{170}Er below the $K=0$ states in accord with Ref. 25, but in ^{166}Er they place the $K=1$ 1^- state several hundred keV above the $K=0$ 1^- state.

Since the $E1$ transitions with $|\Delta K|=1$ may be very weak, our failure to observe the tentatively identified 1^- states at 1355 keV [3,4] in ^{168}Er and 1539 keV[5] in ^{170}Er is not surprising.

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*Work supported in part by the National Science Foundation.

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