Decay of $_{68}Er^{161}$ (3.1 hr)*

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Sources of $_{68}Er^{161}$(3.1 hr) were produced by the $(n,2n)$ and (γ,n) reactions. A study of the gamma-ray spectrum by means of scintillation coincidence spectrometry indicated 32 gamma rays. All but three of these are fitted into a tentative decay scheme with levels at 0, 211, 585, 826, 945, 1165, 1253, 1315, 1395, 1450, (1604), 1700, and 1830 kev. The data are consistent with a $\frac{3}{2}^-$ spin assignment to the Er ground state and $\frac{7}{2}^-$ and $\frac{1}{2}^+$ assignments to the ground state and 211-kev state of Ho, respectively. The 826-kev level in Ho probably has $\frac{5}{2}^-$ character.

INTRODUCTION

An erbium isotope of 3.6-hour half-life was produced by Handley and Olson[1] by bombarding Er_2O_3 with 24-Mev protons. They assigned it the mass number 161. These investigators found gamma rays of 0.824 and 1.12 Mev and possible gamma rays of 0.065 and 0.195 Mev. They determined that the daughter is Ho and, from the absence of annihilation radiation, inferred that the nuclide decays predominantly by K capture.

The mass assignment was confirmed by Michel and Templeton[2] by the use of a time-of-flight isotope separator. They obtained the nuclide by proton spallation of tantalum and reported a half-life of 3.5 hr. Nervik and Seaborg,[3] using these same techniques of production and identification, found positrons of 1.2 ± 0.1 Mev which they said belonged either to Er^{161} or its Ho daughter. They believed that their value of 3.05 hr for the erbium lifetime was to be preferred over the above value of 3.5 hr.

Dneprovskii and Kolesov[4] also produced neutron-deficient isotopes of Er and Ho by the proton spallation of tantalum. They used a β-ray spectrometer to study the internal-conversion-electron spectrum and found four groups of lines with approximate half-lives of 30, 3.5, 2.5, and 1 hr. In the 3.5-hr group they found lines which they assigned to Er^{161}. These lines corresponded to gamma rays with energies of 67.0 ± 0.1, 210.6 ± 0.2, and 826.5 ± 0.5 kev. They also found electrons with energies of 62.0, 69.2, and 164.2 kev which they were not able to identify.

Harmatz *et al.*[5] bombarded a target of Er_2O_3 enriched in Er^{162} with protons to produce Er^{161}. Using magnetic spectrographs they found internal-conversion-electron lines corresponding to a transition with an energy of 211.4 ± 0.3 kev. They assigned it the character $E3$, which is in agreement with Dneprovskii and Kolesov.

The investigation reported here was undertaken to determine the decay scheme of Er^{161}, principally by means of scintillation coincidence spectrometry.

SOURCE PREPARATION AND EXPERIMENTAL APPARATUS

Sources of Er^{161} were produced by the $Er^{162}(n,2n)Er^{161}$ reaction in a target of Er_2O_3 enriched to 6.1%[6] in Er^{162}. A Cockcroft-Walton accelerator was used to provide fast neutrons for most of the irradiations.[7] An average flux of 10^9 14-Mev neutrons/cm²/sec was obtained via the $H^3(d,n)He^3$ reaction. For a few irradiations the Argonne 60-in. cyclotron was used as an irradiation facility. A flux of approximately 10^{10} neutrons/cm²/sec at about 23-Mev maximum energy was obtained by means of the $Be^9(d,n)B^{10}$ reaction. The samples were wrapped in 1-mil Al foil for irradiation and transferred to new packets afterwards. For the cyclotron irradiations the packets were encased in about $\frac{3}{32}$ in. of BN in order to diminish the number of slow neutrons reaching the Er_2O_3. The amounts of Er_2O_3 irradiated varied from 1 to 60 mg; the latter amount was used in most irradiations employing the Cockcroft-Walton accelerator. Near the conclusion of this work the Argonne 20-Mev linear accelerator was put into operation. Three sources were activated by the (γ,n) reaction. This facility provided the most intense sources as well as those most free of spurious activities produced by neutron capture in other isotopes and contaminants. Other activities were quite weak as found by following the rate of decay of the counting rate in the "singles" and coincidence experiments.

The gamma-ray spectra were studied by means of cubic NaI(Tl) crystals, about $2\frac{1}{4}$ in. on an edge, coupled to Dumont Type 6292 photomultipliers. The pulse-height analysis was accomplished by means of the

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[1] T. H. Handley and E. L. Olson, Phys. Rev. **93**, 524 (1954).

[2] M. C. Michel and D. H. Templeton, Phys. Rev. **93**, 1442 (1954).

[3] W. E. Nervik and G. T. Seaborg, Phys. Rev. **97**, 1092 (1955).

[4] I. S. Dneprovskii and G. M. Kolesov, Izvest. Akad. Nauk S.S.S.R., Ser. Fiz. **22**, 935 (1958) [translation: Bull. Acad. Sciences U.S.S.R. **22**, 935 (1958)].

[5] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. **114**, 1082 (1959).

[6] Enriched oxide obtained from Isotopes Division, Oak Ridge National Laboratory.

[7] The authors wish to gratefully acknowledge the cooperation of Dr. L. A. Rayburn and Dr. H. Casson in making the accelerator available for the irradiations.

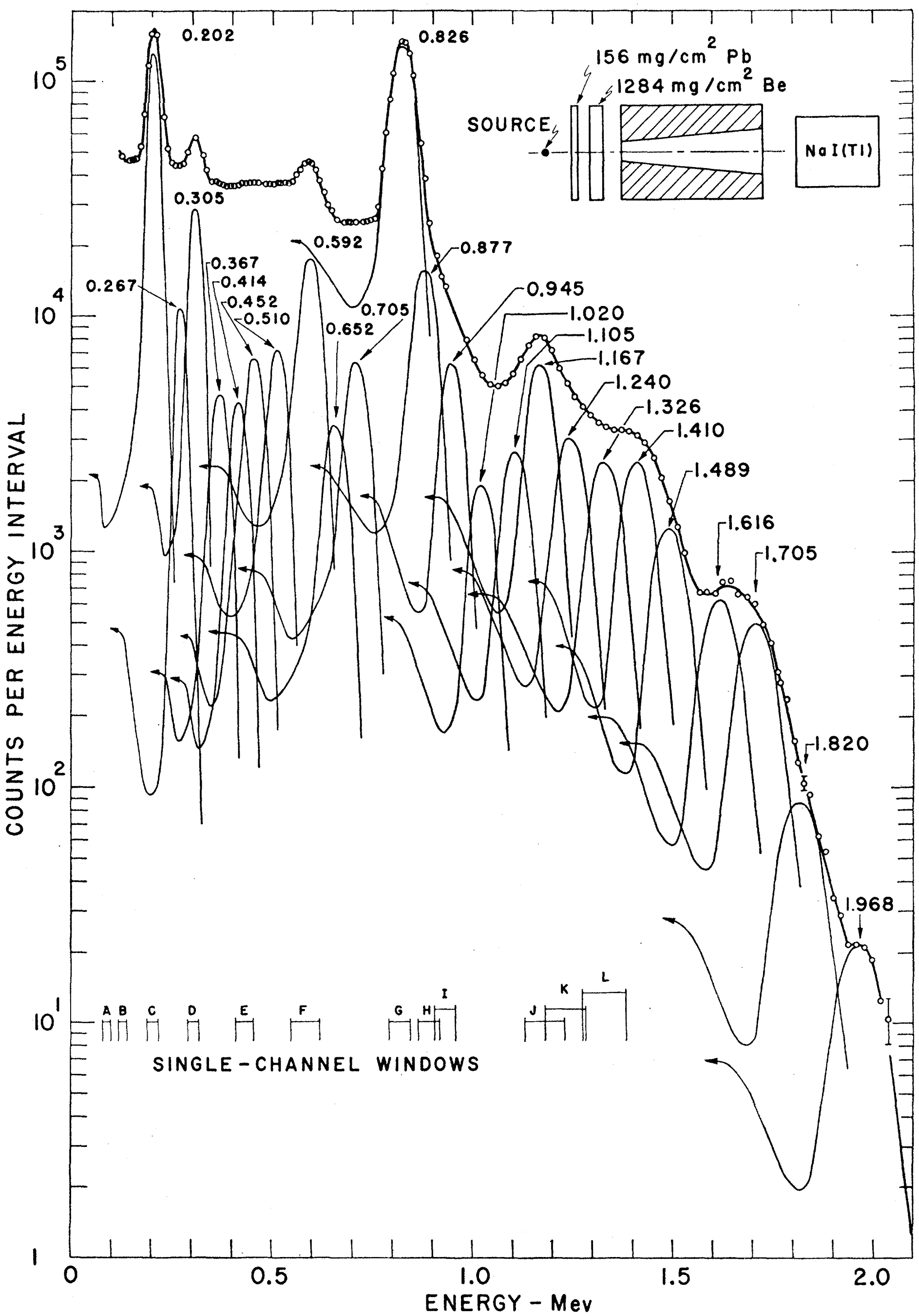

FIG. 1. Gamma-ray spectrum of Er^{161}.

Argonne 256-channel analyzer. For coincidence experiments a single-channel analyzer and conventional "fast-slow" coincidence circuit (resolving time $2\tau=40\times10^{-9}$ sec) were used in conjunction with the multichannel analyzer.

A 180° magnetic spectrograph was used in an attempt to study the internal-conversion-electron spectrum. With the source activities available from a single irradiation, no lines were observed. Iterated exposures were not attempted.

EXPERIMENTS

Gamma-Ray Spectrum

The scintillation spectrum of gamma rays from Er^{161} is shown in Fig. 1. A lead collimator[8] was used to confine the incident beam to the central region of the crystal. The collimator reduces the height of the Compton-

[8] S. B. Burson, H. A. Grench, and L. C. Schmid, Phys. Rev. **115**, 188 (1959).

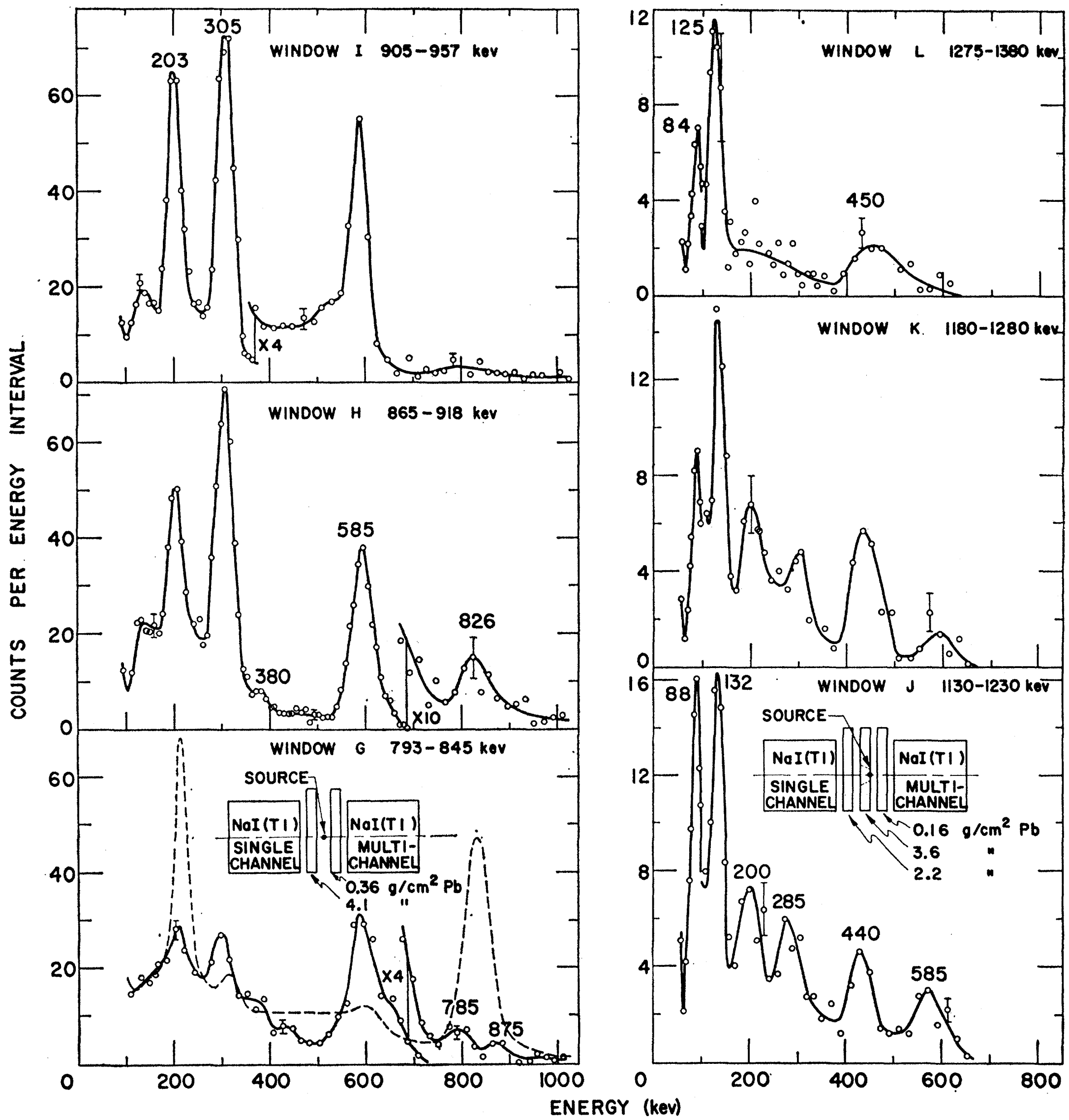

FIG. 2. Gamma rays in coincidence with the high-energy region of the spectrum. In windows *J*, *K*, and *L* the data below 100 kev were not obtained with the geometrical arrangement shown and are not normalized to the spectra above this energy. The dotted curve in window *G* shows the singles spectrum.

electron distribution relative to the photopeak. It also serves to prevent scattered radiation from reaching the crystal. The lead filter shown was used so that the intense x rays from the source would not cause excessive dead time in the analyzer. The beryllium absorbed secondary electrons from the lead.

As indicated in the figure, the total spectrum was decomposed in order to determine the energies and relative intensities of its components. The analysis started with the high-energy side of the most energetic photopeak. The spectrum of a single radiation of similar energy obtained in the same geometric arrangement was fitted. This spectrum was first adjusted to the correct energy and photopeak resolution. After the fitting, the spectrum of the monoenergetic gamma ray was subtracted and the process was repeated. The original spectral shape was rather ideal for such an analysis since the counting rate decreased sharply with increasing energy. Small errors in the spectral shape of a subtracted component did not significantly influence the shape below it.

The results of the analysis are shown in Table I. The gamma-ray intensities were derived from the areas under the photopeaks by correcting for the net photopeak efficiency of the crystal and for the lead and beryllium filters used. The energies shown in Fig. 1 are those obtained from the calibration in that particular experiment. Although the results of such a complex analysis must be accepted with great reservation, the fact that most of the components obtained were found

TABLE I. Gamma rays of Er^{161}.

Energy (kev)	Gamma-ray intensity	Energy (kev)	Gamma-ray intensity
Ho x ray	175±50	785±15	0.23±0.09[a]
84±5	1.7±1.0[a]	826±4	100
88±4	5.2±2.0[a]	865±8	12±5
125±5	3.0±2.0[a]	877±13	0.10±0.06[a]
132±5	3.4±2.0[a]	945±20	4.6±1.3
203±4	3.8±0.6[a]	1020±25	1.7±0.5
211±2	15.0±2.0	1105±10	1.8±0.3[a]
267±15	1.6±1.0	1115±20	0.9±0.3[a]
305±5	4.3±0.6	1167±10	7.1±0.4
367±20	1.2±0.5	1240±20	4.0±0.4
414±10	1.2±0.5	1326±20	3.6±0.8
429±10	0.02±0.01[a]	1410±20	3.8±0.8
452±10	2.2±0.4	1489±30	2.2±0.5
510±7	2.5±0.7	1616±20	1.4±0.2
592±5	7.6±0.8	1705±20	1.2±0.4
652±15	1.8±0.5	1820±30	0.25±0.05
705±15	3.8±2.0	1968±40	0.07±0.03

[a] Intensity found from coincidence measurements. The remaining values were found from decomposition of the "singles" spectrum.

in coincidence experiments adds credence to the results. In determining the uncertainty in the energy and intensity of a particular radiation found in the "singles" analysis, it was assumed that the decomposition of the spectrum was correct to that point. The possibility of cumulative errors as a result of this procedure is acknowledged. Of the 24 radiations found, only the 414-, 705-, and 1968-kev components find no place in the decay scheme proposed.

Coincidence Experiments

Introduction. Coincidence relationships between gamma rays were investigated by use of two NaI(Tl) crystals. The output of one went to the multichannel analyzer; that of the other went to a single-channel pulse-height analyzer whose window was used, in conjunction with the coincidence circuit, to gate the multichannel system.

Because of the large number of coincidence experiments carried out (over 100), only selected figures will be used to illustrate the main relationships. Because of the great complexity of the gamma-ray spectrum, a single experiment was rarely definitive in showing the coincidence of radiations. Instead, experiments using a series of adjacent windows had to be used for interpretation. The low activity and short half-life of the sources hampered such experiments. The various energy intervals accepted by the single-channel window, and for which the corresponding coincidence spectra are illustrated, are shown in Fig. 1.

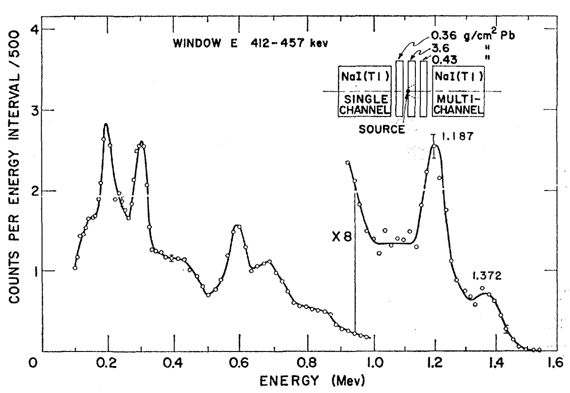

FIG. 3. Gamma rays in coincidence with the 440-kev region of the spectrum.

Coincidence of 450- and 1372-kev gamma rays. The principal features of the coincidence spectra obtained with the single-channel window ranging across the high-energy region of the spectrum are depicted in Fig. 2. Aside from the capture x rays, there were no radiations in coincidence with the gamma rays in the interval from 1685 to 1770 kev (not shown). Figure 2, window L, shows a gamma ray with an energy of 450±8 kev. The spectrum in coincidence with the 450-kev region is shown in Fig. 3. The highest energy radiation observed here is at 1372±20 kev. This establishes that the 450-kev gamma ray is in coincidence with a 1372±20 kev gamma ray rather than with counts in the Compton distribution of some higher energy radiation. The 1820-kev radiation in Fig. 1 is interpreted as the crossover transition.

Coincidences of 84- and 125-kev gamma rays with 1320-kev radiation. The high-energy tail on the 450-kev peak in Fig. 2, window L, is attributed to annihilation radiation from Na^{24} contamination as are some counts in the 200- and 300-kev regions. This conclusion is reached by following the rate of decay of the counting rate. The other main features of this figure are the radiations of 84±5 and 125±5 kev. Figure 4 shows the gamma rays in coincidence with the 84- and 125-kev sections of the spectrum. This indicates that gamma rays of about 1320 kev are in coincidence with these radiations.

Coincidence of 440- and 1187-kev gamma rays. Further comparison of Figs. 2 and 3 indicates that a gamma ray of about 440 kev is in coincidence with a radiation at 1187±20 kev. On the assumption that the 440- and 450-kev peaks are the same transition, it was concluded from the series of experiments from which Figs. 2, 3, and 4 were selected that the 1187- and 1372-kev peaks are the only features of the spectrum of Fig. 3 which can be definitely associated with the 440-kev transition.

Coincidence of 132- and 1230-kev gamma rays. As seen in Fig. 2, windows J and K, the peak at about 125 kev has a somewhat greater intensity than was observed in Fig. 2, window L. It has also shifted in energy to 132±5 kev. The energy difference between the 132- and 125-kev peaks is believed to be 7±4 kev. These are interpreted as two different gamma rays. After subtracting the 1320-kev component in Fig. 4, window B, one finds a gamma ray of 1230±25kev. Thus the 1230- and 132-kev gamma rays are in coincidence.

Coincidence of 88- and 1165-kev gamma rays. An 88±4-

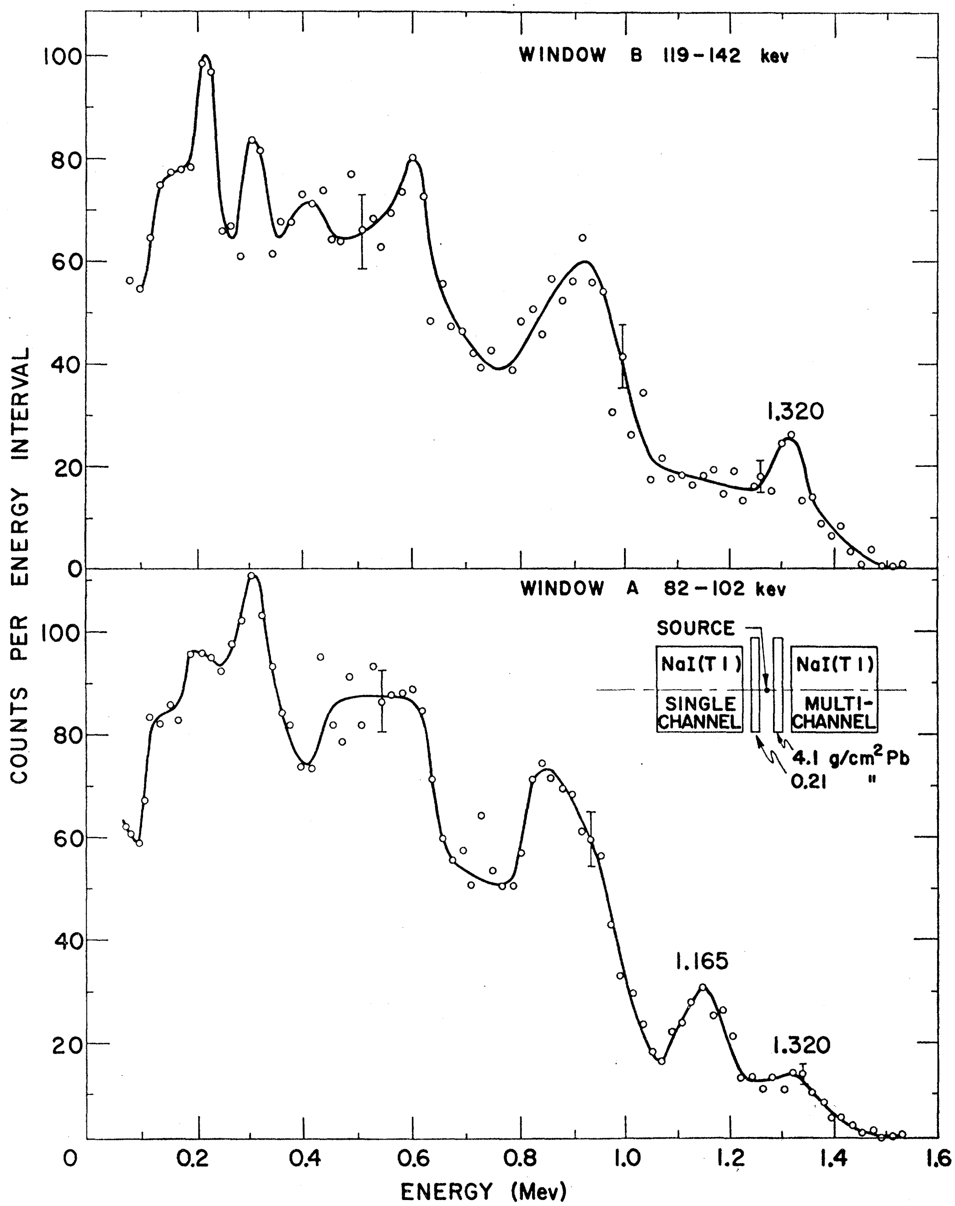

FIG. 4. Gamma rays in coincidence with the 90- and 125-kev regions of the spectrum.

kev gamma ray was also seen to be in coincidence with a radiation of 1165±15 kev. Although the data are not so certain as in the 125-kev case, it appears likely that this 88-kev gamma ray is not the same as that observed at 84 kev in coincidence with the 1320-kev transition. The gamma ray observed at 1240 kev in the singles spectrum is interpreted as the 1165–88 crossover transition. The features of Fig. 4 that are not discussed here can for the most part be understood in terms of other coincidence relationships which are shown to exist.

Coincidences involving 205-, 285-, 1040-, 1165-, and 1250-kev gamma rays. Figure 2, windows *J* and *K*, also contains peaks at 205±10 and 285±10 kev. Figure 5 shows the curves obtained with the window at 200 and 300 kev. In order to examine the differences in the high-energy regions of these spectra, the curves were normalized to equal peak heights at 940 kev. Then the difference curve was obtained and it was found that a gamma ray of 1250±20 kev was in coincidence with 200-kev gamma rays and not with those at 300 kev. Furthermore, a gamma ray at 1040±20 kev was found to be in coincidence with 200-kev radiation. A gamma ray at about 1165 kev was found to be in coincidence with radiations near 200 kev and near 300 kev but more strongly with the latter.

Coincidences of 1115-, 865-, and 365-kev radiations with 585-kev gamma rays. The peak remaining to be discussed in Fig. 2, windows *J* and *K*, is at 580±10 kev.

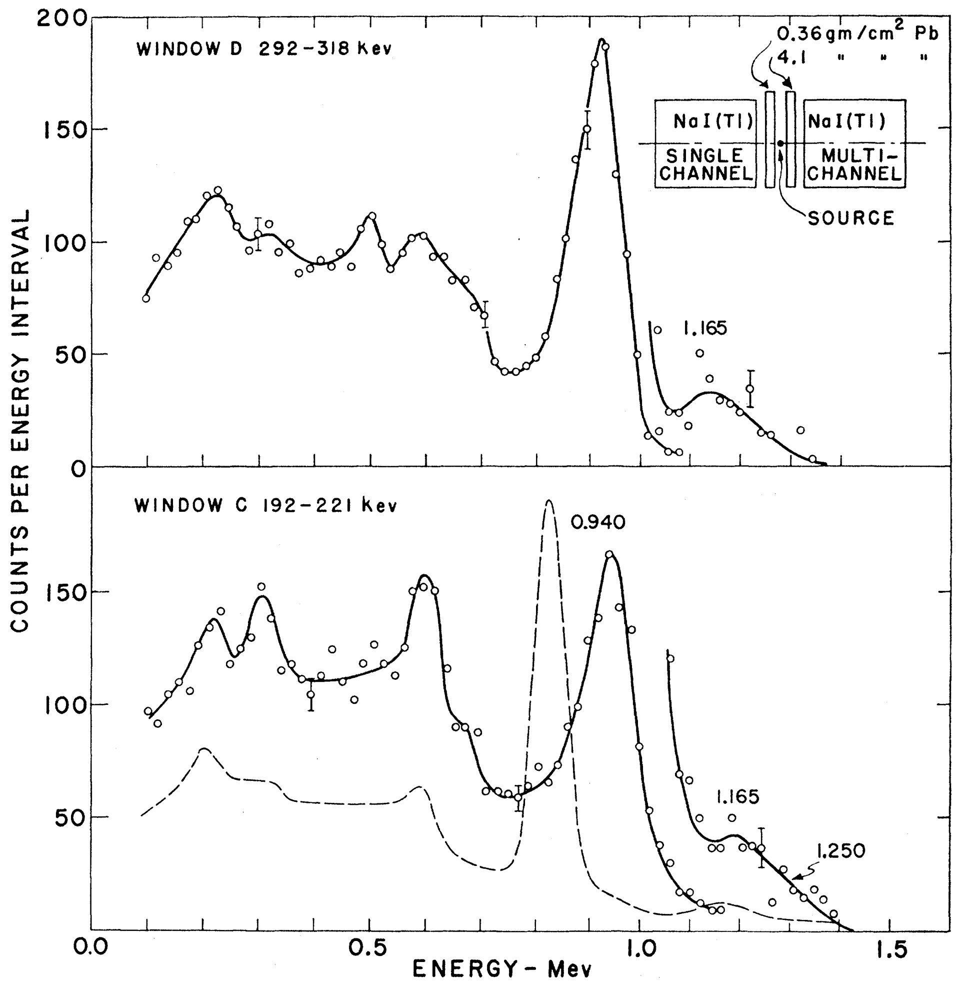

FIG. 5. Gamma rays in coincidence with the 200- and 300-kev regions of the spectrum. The dotted curve in window C is the singles spectrum.

As seen in Fig. 6, with the single-channel window accepting 580-kev gamma rays, the highest energy radiation observed is at 1115±20 kev. The most prominent feature of Fig. 6 is the transition with an energy of 865±7 kev. Examination of Fig. 2, window H, verifies that the gamma rays at 865 and 585±6 kev are in coincidence.

The radiation at 365±10 kev in Fig. 6 was also verified to be in coincidence with a 585-kev radiation. In summary, then, the 585-kev transition has been found to be in coincidence with 365-, 865-, and 1115-kev gamma rays. The 1705-kev transition found in the singles spectrum, Fig. 1, is interpreted as the 585-1115 crossover transition.

The high, broad peak at 200 kev in coincidence with the counts included in the 550–620 kev window is due mostly to backscattered quanta from the intense 826-kev transition. Although lead was used between crystals to minimize this effect, the backscattering was present to some extent in all experiments with the window set at 200 or 585 kev and with the crystals arranged as shown in the figures. In order to determine whether there were any real coincidences between the 200- and 585-kev transitions, experiments were done with an angle of about 18° between the lines from the source to the two crystals. A thick lead wedge was placed between the crystals. With this geometric arrangement no crystal-to-crystal scattering was possible. There was no 585-kev peak resolved with the window set at 200 kev. The peak in Fig. 6 at about 280 kev may be due to coincidences with pulses in the 940-kev Compton distribution (to be discussed later).

Coincidences involving 825-, 875-, 785-, 380-, 650-, and 430-kev gamma rays. As shown in Fig. 2, windows G and H, there is a weak coincidence between the pair at 825±15 and 875±20 kev. Also indicated and illustrated in Fig. 2, window G, is a coincidence between the radiations at 785±15 kev and about 826 kev. As is apparent in Fig. 2, window H, a gamma ray of 380±15 kev was found to be in coincidence with the radiation

TABLE II. Coincidence relationships of gamma rays. *x*—strong evidence of coincidence; 0—strong evidence of noncoincidence; ?—some, but inconclusive, evidence of coincidence; no mark—no evidence either way. Energies are in kev.

E \ E	1968	1820	1705	1616	1489	1410	1326	1240	1167	1115	1105	1020	945	877	865	826	785	705	652	592	510	452	429	414	367	305	267	211	203	132	125	88
84	0	0	0	0	0		x		0																							
88	0	0	0	0	0		0		x																							
125	0	0	0	0	0		x		0		?																		x			
132	0	0	0	0	0		0	x	x																							
203	0	0	0	0	0	0	0	x	x			x	x													x						
211	0	0	0	0	0	0	0																									
267	0	0	0	0	0	0	0		x																							
305	0	0	0	0	0	0	0	0	0				x																			
367	0	0	0	0	0	0	0	0	0						x					x												
414	0	0	0	0	0	0	0	0	0									?				?										
429	0	0	0	0	0	0	0	0	0							?																
452	0	0	0	0	0	x		x	x																							
510	0	0	0	0	0	0	0	0	0																							
592	0	0	0	0	0	0	0	0	0	x					x																	
652	0	0	0	0	0	0	0	0	0				?																			
705	0	0	0	0	0	0	0	0	0	0	0																					
785	0	0	0	0	0	0	0	0	0	0	0	0				x																
826	0	0	0	0	0	0	0	0	0	0	0	0		x																		
865	0	0	0	0	0	0	0	0	0	0	0	0	0																			
877	0	0	0	0	0	0	0	0	0	0	0	0	0																			
945	0	0	0	0	0	0	0	0	0	0	0	0																				
1020	0	0	0	0	0	0	0	0	0	0	0																					
1105	0	0	0	0	0	0	0	0	0	0																						
1115	0	0	0	0	0	0	0	0	0																							
1167	0	0	0	0	0	0	0	0																								
1240	0	0	0	0	0	0	0																									
1326	0	0	0	0	0	0																										
1410	0	0	0	0	0																											
1489	0	0	0	0																												
1616	0	0	0																													
1705	0	0																														
1820	0																															

at about 865 kev. Evidence for an approximately 650-kev gamma ray can be seen in Fig. 2, window *G*. A detailed analysis of this region of the spectrum in this and in a series of adjacent coincidence runs showed evidence that this radiation persists in the coincidence spectra with windows to about 1 Mev. It was not possible, however, to determine with which radiation this gamma ray was in coincidence. A 652-kev gamma ray is also found in the singles analysis, Fig. 1.

The gamma ray at about 430 kev in Fig. 2, window *G*, appears to be in coincidence with 826-kev radiation. However, it was not possible to verify this relationship.

Coincidences of 203- and 305-kev gamma rays with 940-kev radiation. In the series of experiments done with the single-channel window accepting 200- and 300-kev radiation, it was found that there exists a gamma ray at 940±15 kev in coincidence with radiation at 203±3 and 305±3 kev. The small peak at 500 kev, observed in coincidence with 940-kev radiation, is interpreted as a summing of 200- and 300-kev gamma rays in the crystal. The other peaks in Fig. 5 are consistent with the coincidence relationships noted except for the peak at about 490 kev which is unexplained.

The coincidence relationships discussed in the foregoing paragraphs are summarized in Table II.

Decay Scheme

The proposed decay scheme is shown in Fig. 7. The presence of a level at 826 kev is established primarily on the basis of the intensity of the transition. The intensity of the 826-kev gamma ray is approximately the same as all the other radiations in the spectrum combined. However, it shows no strong coincidences with any other radiations. The observation of coincidences between the 826-kev gamma ray and *K* x rays indicates that the gamma ray is not associated with a delayed state unless, however, there is an unobserved highly-converted low-energy gamma ray that also gives rise to Ho x rays. The possibility of this explanation is conceded, although the 826-kev transition is shown as going directly to the ground state.

The next most intense gamma ray, 211 kev, has been found to have *E*3 character.[4,5] On the assumption that the expected $\frac{7}{2}^-$ character[9] of the ground state is correct, it will be seen that the experimental evidence supports placement of a $\frac{1}{2}^+$ isometric state at 211 kev. It was

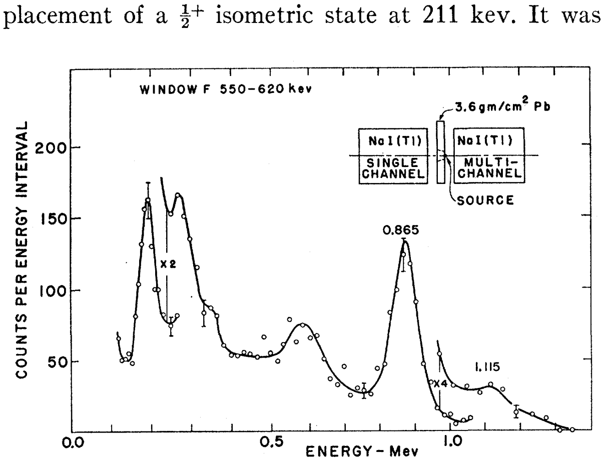

FIG. 6. Gamma-ray spectrum in coincidence with the 585-kev region of the spectrum.

[9] J. M. Baker and B. Bleaney, Proc. Phys. Soc. (London) **A68**, 1090 (1955).

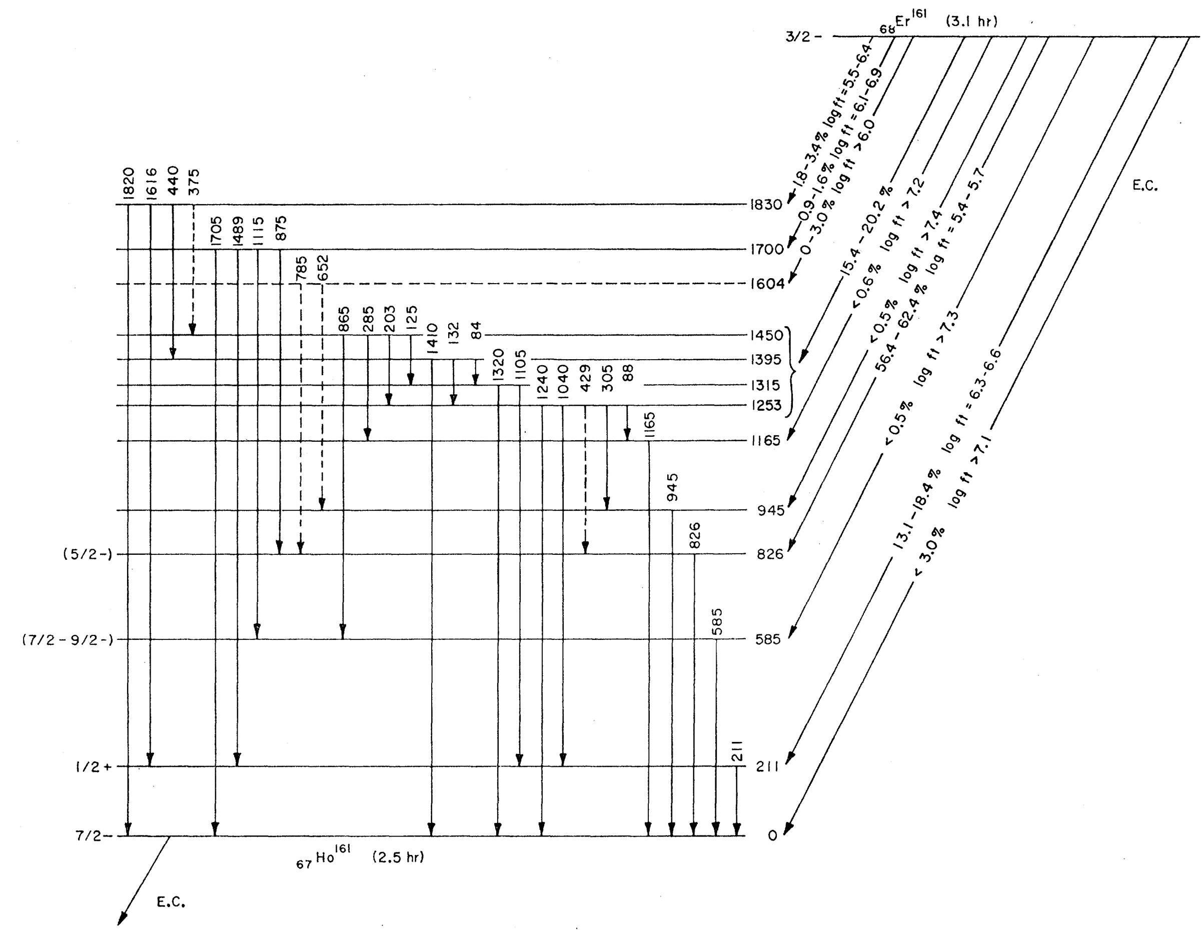

FIG. 7. Proposed decay scheme of Er^{161}.

seen in the coincidence spectrum, taken with the single-channel analyzer accepting only the x-ray peak, that the coincidence rate in the neighborhood of 211 kev was approximately 20% that observed for the 826-kev peak. Since no evidence was found which would indicate the presence of a converted low-energy transition in cascade with the 211-kev gamma ray, it was concluded that another transition of approximately 200 kev existed elsewhere in the decay scheme. This conclusion is supported by the fact that the peak at about 200 kev observed in coincidences between the x rays and the 211-kev gamma ray always appeared at a point slightly lower in energy than the corresponding 211-kev peak in the singles, and further that such a peak is found in coincidence with high-energy gamma rays. Lastly, other transitions were observed whose energies are consistent with a state at 211 kev.

Several experiments were done in order to try to determine the lifetime of the state from which this radiation arises. In order to determine a lower limit for the lifetime, coincidence experiments were done in which the single-channel analyzer accepted counts in the x-ray peak. Then the x-ray pulses were delayed up to about 10^{-7} sec relative to the fast pulses from the other crystal. Taking into account the resolving time of the coincidence circuit ($\tau = 2\times10^{-8}$ sec) it is believed that delayed coincidences would have been observed if the mean life of the state were less than 5×10^{-7} sec. To find an upper limit, an ion-exchange separation was done to separate Er^{161} from its Ho daughter. The Er enriched fraction was almost completely eluted in about 15 minutes. Both fractions were studied and no relative change in the intensities of the 211- and 826-kev radiations was found. An upper limit of 10 min is placed on the mean life of the 211-kev state. With improved ion-exchange-column techniques the range of these limits could be substantially reduced. However, the limits obtained are consistent with the $E3$ character assigned to the 211-kev transition.

The levels at 585, 1450, and 1700 kev are established from the 585–865 kev and 585–1115 kev cascade pairs. Since neither the 585 nor the 865-kev radiations are seen in coincidence with any other gamma rays of sufficient intensity to justify separating them from each other or from the ground state, a level at 1450 kev is suggested. As will be seen, other coincidence pairs also

sum to this energy. The existence of the 585–1115 kev pair indicates that the 585-kev transition lies on the bottom. The 1705-kev gamma ray is interpreted as a ground-state transition because of the excellent agreement with the 585–1115 sum and because of the absence of gamma rays in coincidence with 1705-kev radiation. The presence of the 1105-kev transition between the 1315- and 211-kev states was verified from consideration of the gamma-ray intensities. The intensity of the 1115-kev gamma ray found in coincidence with the 585-kev radiation accounts for only about $\frac{1}{3}$ of the intensity of the 1105-kev peak found in the singles analysis. The 1105-kev transition placed as shown explains this discrepancy in intensities. In addition, the weak coincidences observed between the 826- and 875-kev gamma rays can arise from a transition from the 1700- to the 826-kev level. The gamma ray of approximately 375 kev found in coincidence with 585- and 865-kev radiation is placed above the 1450-kev level. Radiation with an energy of $375+1450=1825$ kev is found in the singles spectrum. Furthermore, other pairs which sum to 1825 kev will be seen. Alternative positions for the 375-kev radiation will be discussed later.

The foregoing analysis is presented with some measure of conviction. The following interpretations embody a much greater degree of tentativeness since in many cases alternative possibilities exist.

The 440–1372 kev coincidence pair also sums to approximately 1830 kev. The intermediate state is placed at 1395 kev since another combination also sums to this energy and the intensity of the 440-kev transition is too low to account for the total radiations which span the 1395-kev energy difference. The 1410-kev gamma ray found in the singles analysis is interpreted as the ground-state transition. The 1250–132 kev coincidences are attributed to decay of the 1395-kev state through a level at 1253 kev to the ground state. A transition between the 1450- and 1253-kev levels fixes the sequences of the 132–1250 kev cascade and simultaneously explains the 1250–200 kev coincidences.

All the observed coincidence relationships involving the 1165-kev transition can be explained by fixing a level at that energy. The 285-kev gamma ray is the transition between the 1450- and 1165-kev levels. The 1165–88 kev pair add to 1253 kev and allow the 1165-kev radiation to be in coincidence with a 200-kev gamma ray via the 88-kev transition. This interpretation is consistent with the fact that coincidences exist between the 88- and 200-kev gamma rays.

A level is placed at 945 kev to explain the 305–945 kev coincidences. Coincidences between the same 945-kev gamma ray and 203-kev radiation may be due to decay from the 1450- to the 1250-kev level. It would be difficult to distinguish between this effect and some 220-kev radiation between the 1165 and 945-kev levels.

A number of the observed phenomena may be explained if a level at 1315 kev is postulated. The sums of the 1315–125 and 1315–84 kev coincidence pairs may be explained by transitions from the 1450- and 1395-kev levels, respectively. The 440–1187 kev coincidences observed are explained by the decay of the 1830-kev level via the 440–132–88 kev cascade to the level at 1165 kev. It cannot be said with certainty that a 447-kev transition does not exist between the 1700- and 1253-kev levels.

The 1616- and 1489-kev gamma rays are placed as transitions to the 211-kev level on the basis of their energies.

As mentioned earlier, the 375-kev transition has been placed between the 1830- and 1450-kev levels. An alternative hypothesis may equally well explain the observed coincidences. Instead of the transition indicated, or perhaps in addition to it, two other gamma rays of very nearly the same energy may exist. These would occur between the 945- and 585-kev levels and between the 585- and 211-kev levels. The choice presented was selected by virtue of its greater simplicity.

The 785–826 kev coincidences observed may be due to decay of a state of about 1600 kev. The 650-kev gamma ray, noted in Fig. 2, window G, may be explained as the transition from this level to the 945-kev state. Since there is no positive evidence of these relationships, the state at 1604 kev is dotted in as are the 785- and 652-kev radiations. It should also be mentioned here that the 1616-kev gamma ray, which has been placed as the transition between the 1830- and 211-kev levels, could be interpreted as the ground-state transition from the 1604-kev level. Both transitions may, in fact, be present.

Although considerable doubt is acknowledged, the 429-kev transition between the 1253- and 826-kev levels is dotted in to explain the possible 826–429 kev coincidences observed. No evidence of the 67-kev transition reported by Dneprovskii and Kolesov[4] was found.

The decay energy to the Ho ground state assumed for the determination of the log ft values is 2.2–2.6 Mev. The range of log ft values for a given branch incorporates this range of energy and the uncertainties in the intensities of the gamma transitions. Internal-conversion of gamma rays for reasonable multipolarities was also taken into consideration in associating the branching with the states. The upper limit of about 3% branching to the ground state was found by comparing the total x-ray intensity with the x-ray intensity necessary to feed the other levels. If the 1.2-Mev positron found by Nervik and Seaborg[3] corresponds to a transition to the 211-kev level, the indicated decay energy to the ground state is 2.4 Mev. Furthermore, the theoretical K/β^+ ratio[10] of about 13 to the 211-kev state is in rather good agreement with the ratio of about 9 one obtains by assuming that the 510-kev radiation found in the singles analysis is the annihila-

[10] M. L. Perlman and M. Wolfsberg, Brookhaven National Laboratory Report BNL-485, 1958 (unpublished).

tion radiation. Finally, the mass tables of Cameron[11] predict a ground-state decay energy of 2.0 Mev.

In the level diagram, the states at 211, 585, 826, 1450, 1700, and 1830 kev are considered to be established with substantial reliability. However, it should be emphasized that, although the remaining states and the transitions between them are consistent with the experimental data, the uncertainties in the energies and intensities are such that the interpretation is probably not unique. Therefore, the decay scheme in its entirety should be considered as tentative.

DISCUSSION

Since the nuclide $_{67}Ho^{161}$ has many particles outside of closed shells, its nuclear shape is expected not to be spherically symmetric. Its intrinsic states are expected to be governed by the 67th proton. Current theories[12] predict bands of rotational states based upon these levels.

On the basis of systematics and the Nilsson level diagram, the Er^{161} ground state would be predicted to have $\frac{3}{2}^-$ character. However, there is little experimental evidence to support this assignment.

The ground state of Ho^{161} is expected to have $\frac{7}{2}^-$ character in analogy with the measured spin[9] of Ho^{165}. The assignment of $\frac{1}{2}^+$ character to the 211-kev state is strengthened by the 305-kev $E3$ transition observed[13] in Ho^{163}.

The log ft values for the decays to the 211-kev and ground states of Ho are consistent with the $\frac{3}{2}^-$ assignment of the Er ground state. This $\frac{3}{2}^-$ assignment will be assumed in the following discussion.

Since the capture branch to the 826-kev level is an allowed transition, the spin of the 826-kev state must be $\frac{1}{2}^-$, $\frac{3}{2}^-$, or $\frac{5}{2}^-$. The first two possibilities are rejected since the transitions to the 211-kev state would be much more intense than the ground-state transition. The choice of $\frac{5}{2}^-$ implies that the ground-state transition has $M1$ or $M1+E2$ character. From the work of Dneprovskii and Kolesov[4] one obtains the ratio

$$e_K(211)/e_K(826) = 5.0 \pm 0.8.$$

From the tables of Rose[14] we find $\alpha_K(211) = 0.46$. With this information and the gamma-ray intensities of the 211- and 826-kev transitions reported here, one finds $\alpha_K(826) = 0.014 \pm 0.003$. The theoretical value of $\alpha_K(826)$ for an $M1$ transition is 0.007 and for an $E2$ transition is 0.004. Thus we do not have very good confirmation of the $\frac{5}{2}^-$ assignment. Since arguments concerning possible spins for the other levels must be based in part on the spin of the 826-kev state and since the latter is uncertain, further interpretation is not attempted.

None of the states identified in this work were shown to have rotational character. The theory predicts that the first excited state of a rotational band based upon the 211-kev level would be but a few kev higher. Population of this level would then appear merely as enhanced intensity of the 211-kev transition.

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[11] A. G. W. Cameron, Chalk River Laboratory Report CRP-690, 1957 (unpublished).

[12] For references on and summary of properties of odd-A nuclei, see B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **1**, No. 8 (1959).

[13] C. L. Hammer and M. G. Stewart, Phys. Rev. **106**, 1001 (1957).

[14] M. E. Rose, *Internal Conversion Coefficients* (North Holland Publishing Company, Amsterdam, 1958).