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Decay of Zn^{63}†*

J. B. CUMMING AND N. T. PORILE
Chemistry Department, Brookhaven National Laboratory, Upton, New York

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The decay of 38.4-min Zn^{63} has been investigated using scintillation and beta spectrometer techniques. 84% of the decays are to the Cu^{63} ground state. Gamma rays having energies of 0.67, 0.96, and 1.42 Mev are present with intensities of 9.0, 6.7, and 0.9% of the β^+ transitions. Low intensity gamma rays (<0.2%) were observed at energies of 1.55, 1.83, 2.04, 2.34, 2.55, 2.77, and 3.10 Mev. Coincidence measurements established positron feeding of the Cu^{63} levels at 0.67, 0.96, and 1.42 Mev but no γ-γ coincidences were observed. Internal conversion coefficients of the 0.67- and 0.96-Mev gamma rays are in agreement with predominantly $M1$ assignments to both transitions. A decay scheme is presented which differs significantly from that previously reported. It is inferred that the spin of Zn^{63} is $\frac{3}{2}-$. $M1$ and $E2$ transition probabilities between the various levels of Cu^{63} and Cu^{65} are discussed in terms of the "center-of-gravity" model for states in these nuclei. Both agreements and disagreements with the model predictions are observed.

I. INTRODUCTION

THE present investigation of the decay of Zn^{63} was prompted by the observation of a prominent 0.67-Mev γ ray in the spectrum of Zn^{63}. Although this γ ray had been observed in the Coulomb excitation of Cu^{63} [1] and the corresponding level observed in inelastic scattering experiments,[2–6] it was not reported in the previously published decay scheme study of Huber, Marcus, Preiswerk, and Steffen.[7] These authors resolved the Zn^{63} positron spectrum into three groups having end points of 2.36, 1.40, and 0.47 Mev, and observed conversion electrons from a 0.96-Mev gamma ray. From absorption studies of the gamma radiation and of secondary electrons they also inferred the presence of 1.89- and 2.60-Mev gamma rays. The γ-ray spectrum of Zn^{63} has been investigated more recently by Hayward, Farelly-Pessoa, Hoppes, and van Lieshout,[8] and by Ricci, Girgis, and van Lieshout.[9] In the more complete of these studies[9] these authors find a complex spectrum consisting of 19 γ rays, including the 0.67-Mev transition.

The levels of Cu^{63} have been investigated extensively in proton and neutron inelastic scattering experiments. The more detailed of these studies is that of Mazari, Buechner, and de Figueiredo,[2] who found a total of 46 levels ranging from 0.668 to 3.476 Mev. Levels at 0.67 and 0.96 Mev have been excited by Coulomb excitation.[1,10] Nuclear resonance fluorescence from the 0.96-Mev level has also been reported by Ilakovac.[11] As a part of the present investigation, further resonance fluorescence studies of the 0.67- and 0.96-Mev levels were undertaken and have been reported elsewhere.[12] The resonance fluorescence of these levels has also been observed by Rothem, Metzger, and Swann,[13] and by Booth.[14] From the various data now available, a spin and parity $\frac{5}{2}-$ may be assigned to the 0.96-Mev level and a spin and parity of $\frac{1}{2}-$ to the 0.67-Mev level of Cu^{63}. Since the Cu^{63} ground state has a spin and parity $\frac{3}{2}-$ [15] and since Zn^{63} decays directly to both excited states and the ground state, the Zn^{63} spin and parity must also be $\frac{3}{2}-$. These points will be considered in detail below.

The present report includes a study of the positron, conversion electron and γ-ray spectra of Zn^{63}. The γ-ray spectrum, as determined with the aid of coincidence measurements, differs in a number of important respects from that reported by Ricci *et al.*[9]

II. GAMMA-RAY SPECTRA

Zinc-63 was prepared by the $Cu^{63}(p,n)Zn^{63}$ reaction with 9-Mev protons from the Brookhaven 60-in. cyclotron. At this energy the only other activity observed was 245-day Zn^{65}. To prepare beta spectrometer sources and some sources for the gamma-ray studies, zinc was chemically separated from the copper foil targets by use of a Dowex 1 anion exchange column. Copper was first elluted with 1*N* HCl and zinc was then removed with water. Comparison of spectra of chemically separated zinc sources with unseparated

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1 G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956).
2 M. Mazari, W. W. Buechner, and R. P. deFigueiredo, Phys. Rev. **108**, 373 (1957).
3 P. M. Windham, C. R. Gossett, G. C. Phillips, and J. P. Schiffer, Phys. Rev. **103**, 1321 (1956).
4 R. M. Sinclair, Phys. Rev. **102**, 461 (1956).
5 V. E. Scherrer, B. A. Allison, and W. R. Faust, Phys. Rev. **96**, 386 (1954).
6 L. A. Rayburn, D. L. Lafferty, and T. M. Hahn, Phys. Rev. **94**, 1641 (1954).
7 O. Huber, H. Marcus, P. Preiswerk, and R. Steffen, Helv. Phys. Acta **20**, 495 (1947).
8 R. W. Hayward, E. Farrelly-Pessoa, D. D. Hoppes, and R. van Lieshout, Nuovo cimento **11**, 153 (1959).
9 R. A. Ricci, R. K. Girgis, and R. van Lieshout, Nuovo cimento **11**, 156 (1959).
10 L. K. McGowan and P. H. Stelson, (private communication).
11 K. Ilakovac, Proc. Phys. Soc. (London) **A67**, 601 (1954).
12 J. B. Cumming, A. Schwarzschild, A. W. Sunyar, and N. T. Portile, Phys. Rev. **120**, 2128 (1960), also Bull. Am. Phys. Soc. **4**, 57 (1959).
13 T. Rothem, F. R. Metzger, and C. P. Swann, Bull. Am. Phys. Soc. **5**, 266 (1960).
14 E. C. Booth, Bull. Am. Phys. Soc. **5**, 239 (1960).
15 R. Ritschl, Z. Phys. **79**, 1 (1932).

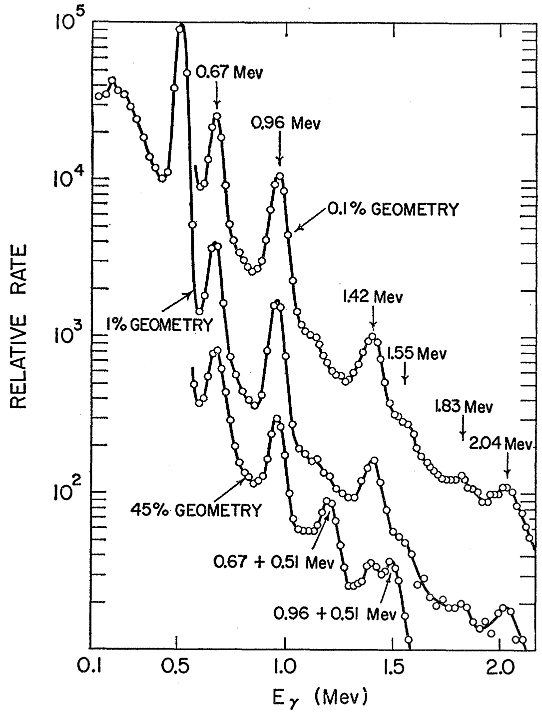

FIG. 1. Gamma-ray spectra of Zn^{63} obtained in several different geometries.

foils showed no differences; hence, the bulk of the gamma ray and coincidence data presented below was obtained with unseparated sources.

The half-life of Zn^{63} was obtained from decay measurements on a number of specific features of the gamma, positron, and conversion electron spectra, as well as from the gross beta activity. The best value of the half-life is (38.4±0.2) min in agreement with the value (38.1±0.3) min reported by Ricci *et al.*[9] and consistent with earlier values.[16]

The γ-ray spectrum of Zn^{63} was investigated with a 3×3 in. NaI(Tl) crystal in conjunction with a 100-channel pulse-height analyzer. The resolution of the system for the 662-kev line of Cs^{137} was 8%. Spectra were obtained for a wide range of source-to-crystal distances corresponding to geometries of from 0.1 to 45% of 4π steradians so that the effects of addition peaks (summing) could be evaluated. Sources were sandwiched between beryllium absorbers sufficiently thick to stop all positrons.

Spectra for 45, 1, and 0.1% geometries are presented in Fig. 1. The energy calibration for the various peaks was made by the use of standard sources of Na^{22}, Cs^{137}, Co^{60}, and Na^{24}. Peaks may be seen at gamma-ray energies of 0.67, 0.96, 1.42, and 2.04 Mev. In addition, the 45% geometry spectrum (lower curve in Fig. 1) shows pronounced peaks at 1.18 and 1.47 Mev corresponding to the addition of 0.67+0.51 Mev and 0.96+0.51 Mev. The high geometry also results in a filling-in of the valleys between the 0.51-, 0.67-, and 0.96-Mev peaks. The addition peaks were still present (but in lower intensity) in a 5% geometry spectrum (not shown) but appear to be absent in the 1% and 0.1% geometry spectra. It should be noted that the shoulder on the high-energy side of the 1.42-Mev peak remains essentially unchanged when the geometry is changed from 1% to 0.1%, indicating a true gamma ray at 1.55 Mev. Because of their low intensities, several higher energy gamma rays were observed in a separate experiment in which the detector was shielded with 1 cm of lead to reduce its response to annihilation radiation.

The quantitative analysis of the various 1 and 0.1% geometry spectra was performed by a successive subtraction procedure in which sources such as Na^{24}, K^{42}, Na^{22}, Zn^{65}, and Cs^{137} were used to give the detector response to monoenergetic gamma rays. A substantial continuous background, due to annihilation of positrons in flight[9,17] and bremsstrahlung, must be included in this analysis if errors in low intensity peaks are to be avoided. Furthermore, since the annihilation in flight produces γ rays having energies greater than 0.51 Mev, a correction to the 0.51-Mev peak is necessary if the correct fraction of decays via positron emission is to be obtained. Gerhart, Carlson, and Sherr[17] have calculated that there are 0.06 γ/β^+ at energies >0.51 Mev for Ne^{19} positrons (E_{max}=2.2 Mev) stopping in Lucite. The average effect for the 2.33-Mev ground state β^+ group and the inner groups of Zn^{63} is expected to be close to that of Ne^{19}. The beryllium absorbers used in the present experiment should lead to a smaller effect. Since Gerhart *et al.* observed higher yields than those predicted by theory for Lucite, we have assumed the correction for Zn^{63} positrons in beryllium is the same as that calculated for Ne^{19} positrons in Lucite and applied

TABLE I. Energies and intensities of gamma rays observed in the decay of Zn^{63}.

Energy (Mev)	Relative intensity This work	Relative intensity Ricci *et al.*[a]
0.511	200	200
0.669±0.002[b]	9.0 ±0.6	14.0 ±0.8
0.962±0.002[b]	6.7 ±0.7	10.0 ±0.9
1.33	<0.05	0.41±0.05
1.42 ±0.03	0.94±0.15	0.80±0.07
1.55 ±0.05	0.12±0.03	0.20±0.05
1.83 ±0.04	0.02±0.01	0.02±0.01
2.04 ±0.04	0.14±0.03	0.12±0.01
2.34 ±0.04	0.07±0.02	0.05±0.01
2.55 ±0.05	0.06±0.02	0.08±0.01
2.77 ±0.06	0.04±0.02	0.03±0.01
3.10 ±0.08	0.02±0.01	...

[a] See reference 9. These authors also reported gamma rays at energies of 0.810, 0.875, 1.10, 1.27, 1.67, 1.90, 2.14, and 2.69 Mev.
[b] These energies were determined from the conversion electron spectrum.

[16] *Nuclear Data Sheets*, edited by C. L. McGinnis (National Academy of Sciences-National Research Council, Washington, D. C.).

[17] J. B. Gerhart, B. C. Carlson, and R. Sherr, Phys. Rev. **94**, 917 (1954).

a 3% correction to the 0.51-Mev peak. To convert photopeak areas to relative intensities, standard sources of Na^{22}, Co^{60}, and Na^{24} were used to obtain a calibration curve of photopeak efficiency vs energy for the particular detector system used.

The energies and relative intensities of gamma rays obtained from the 1 and 0.1% geometry spectra are presented in Table I. Errors assigned to the intensities are based on reproducibility of the resolutions of the various spectra by both authors and on estimated systematic effects. The intensities of the corresponding γ-rays given by Ricci *et al.*[9] are listed in Table I for comparison. The energies of the lines in Table I are in good agreement with those reported by Ricci *et al.* and Mazari *et al.*[2] It is seen that the agreement in intensities is not very good. In particular, the intensities of the two most prominent γ rays, as determined in the present work, are some 40% lower than the values quoted by Ricci *et al.* These authors have also reported gamma rays at 0.810, 0.875, 1.10, and 1.35 Mev having intensities of 1.8, 1.2, 0.7, and 0.4% of the positrons as well as a number of lower-intensity gamma rays. These were not observed in the present measurements and a limit for the abundance of the 1.33-Mev gamma ray is included in Table I. Ricci *et al.* place the 0.810- and 0.875-Mev gamma rays in cascade with the 0.67-Mev level and the 1.10-Mev gamma in cascade with the 1.35-Mev level. The results of the coincidence measurements described below set upper limits for these gamma rays substantially lower than the abundances given by Ricci *et al.*

III. COINCIDENCE MEASUREMENTS

The spectrum of γ rays in coincidence with annihilation radiation was investigated in a 511-511-γ triple coincidence measurement similar to that previously described.[18] Detection of 511-kev γ rays by each of two 2×2-in. NaI(Tl) scintillators located at an angle of 180° with respect to the source was required in coincidence with a pulse from a 3×3-in. detector at 90° to the axis of the 2-in. detectors. The detector and source geometries were such that no straight line connected the volume in which the positrons annihilated, either of the 2-in. detectors, and the 3-in. detector. When these coincidence conditions were satisfied a 100-channel pulse-height analyzer was gated to analyze the pulse from the 3-in. detector. The concidence conditions were determined with a conventional fast-slow coincidence circuit which had a resolving time τ of 0.2 μsec. Circuit performance was checked with a Na^{22} source. The contribution of accidental coincidences was determined by delaying the pulse from the 3-in. detector relative to those from the 2-in. detectors by 0.5 μsec.

Coincidence spectra obtained for several sources all showed peaks at 0.67, 0.96, and 1.42 Mev indicating that these transitions are fed by positrons. The fractional feeding of these levels by positrons was calculated from the ratio of the photopeak area in the coincidence spectrum to the peak area in the singles spectrum, the same ratio for the 1.28-Mev gamma ray of a Na^{22} standard, and the known fraction of positrons, 0.90, feeding this level in Na^{22}.[19] The results of the present measurements are presented in Table II. The very limited statistical accuracy in the case of the 1.42-Mev transition did not allow resolution of the contribution of the 1.55-Mev line. Theoretical values for the fraction of positrons feeding these levels and the ground state are presented for comparison. These have been obtained from the K/β^+ ratios for allowed transitions[20] and from the L/K capture ratios.[21,22] The experimental values are in fair agreement with the theoretical ones. Since relatively intense sources of Zn^{63} were necessary to obtain a reasonable number of coincidences, it is possible that some gain shifting of the phototubes may have lowered the efficiency for detecting the 511-kev quanta relative to that for the Na^{22} standard, an effect which would lead to low results. Of the various sources used for the measurements, the lowest intensity source resulted in values of the fractional feeding of the 0.67- and 0.96-Mev levels of 0.87 ± 0.08 and 0.85 ± 0.08. In view of the limited precision and possible systematic effects, the theoretical values will be used in all subsequent calculations. The overall fraction of Zn^{63} which decays by positron emission is calculated to be 93.4%, in agreement with the 90–95% reported by Huber *et al.*[7]

Since the 0.51-Mev peak does not appear in the coincidence spectra described above (except as accidentals), these spectra may be examined for low-energy gamma rays which might have been obscured by the intense annihilation radiation peak in the singles spectra. No such gamma rays were observed and in the energy region 0.15–0.45 Mev could not be present in excess of 0.5% of the Zn^{63} decays. In the vicinity of annihilation radiation, a limit of 1% was set.

TABLE II. Positron feeding of Cu^{63} levels by the decay of Zn^{63}.

Level (Mev)	Fraction of transition fed by positrons: Measured	Fraction of transition fed by positrons: Calculated[a]
ground state	···	0.956
0.67	0.84 ± 0.04	0.884
0.96	0.77 ± 0.07	0.813
1.42	0.40 ± 0.15	0.552
1.55		0.415
all transitions	···	0.934

[a] See references 20–22.

[18] D. S. Harmer and M. L. Perlman, Phys. Rev. **114**, 1133 (1959).

[19] R. Sherr and R. H. Miller, Phys. Rev. **93**, 1076 (1954).

[20] M. L. Perlman and M. Wolfsberg, Brookhaven National Laboratory Report BNL-485 (T-110), 1958 (unpublished).

[21] H. Brysk and M. E. Rose, Revs. Modern Phys. **30**, 1169 (1958).

[22] B. L. Robinson and R. W. Fink, Revs. Modern Phys. **32**, 117 (1960).

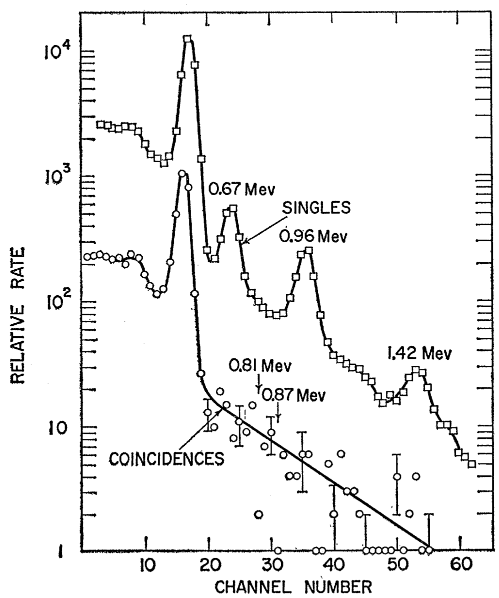

FIG. 2. Spectrum of gamma rays coincident with 0.67 Mev. The singles spectrum is included for comparison.

Ricci *et al.*[9] have reported that ~10% of the 0.67-Mev gamma rays are preceded by a cascade of 0.81- and 0.87-Mev γ rays. To search for this cascade, two 3×3 in. detectors set at ~60° angles to each other viewed a Zn^{63} source. The detectors were shielded from each other by more than 2 cm of lead to minimize scattering of γ rays from one detector to the other. A single-channel pulse height analyzer selected pulses in the region of the 0.67-Mev photopeak from one detector and a 100-channel pulse height analyzer displayed only those pulses from the other in coincidence with these. The spectrum of gamma rays in coincidence with 0.67 Mev is shown in Fig. 2. Included for comparison is the singles spectrum from the same detector. If Ricci *et al.* were correct, a peak $\sim\frac{1}{10}$ as intense as the annihilation peak should have been observed between 0.81 and 0.88 Mev. The observed counting rate in this vicinity is only ~1% of that at the 0.51-Mev peak. Furthermore, the tail on the high-energy side of the 0.51-Mev peak is consistent with annihilation of positrons in flight and shows no structure expected for single gamma rays. Hence the cascade reported by Ricci *et al.* can not be present. A similar experiment was performed with the single channel set at 0.96 Mev. The coincidence spectrum was very similar to that in Fig. 2 showing coincidence only with annihilation radiation. The channel was then set at 1.33 Mev to search for the 1.10–1.33-Mev cascade reported by Ricci *et al.* in ~0.5% of the decays. No such cascade was observed. To complete the coincidence measurements, a wide channel was set to include all gamma rays above 1 Mev. Again, the only peak in the coincidence spectrum was annihilation radiation.

The intensities reported by Ricci *et al.*[9] and the upper limits set by the coincidence measurements described above are listed in Table III. It is seen that the upper limits are nearly an order of magnitude lower than the previously reported intensities for these gamma rays. The conclusions of Ricci *et al.* were based completely on data obtained using a 1×1 in. NaI(Tl) crystal. Coincidences were identified by sum peaks. It is quite possible that the use of a small detector for analysis of a rather complex spectrum is the cause of the above discrepancies.

IV. POSITRON AND CONVERSION ELECTRON STUDIES

Positron and conversion electron spectra of Zn^{63} were obtained with an intermediate image beta ray spectrometer.[23] Sources were less than 100 $\mu g/cm^2$ thick and were mounted on 50 $\mu g/cm^2$ VYNS[24] films or on 0.9 mg/cm^2 Mylar foils. Examination of the low-energy region of the β^+ spectrum indicated that the use of the heavier backing had a negligible effect on the intensities reported below. The spectrometer, which was equipped with a set of spiral baffles to reject particles of sign opposite to those of interest,[25] was set for a nominal resolution of 1.5%. Due to the large differences in intensities of positrons and conversion electrons, it was not possible to obtain a β^+ spectrum of a given source until a considerable time (as much as seven half-lives) after the electrons were observed. To overcome the need for such long extrapolations, β^+ spectra were obtained from weaker sources whose relative strengths were assayed by gamma counting. A Kurie plot of a Zn^{63} position spectrum is presented in Fig. 3. It is seen that the ground state group has an allowed shape. A least squares fit gives an endpoint of 2.33±0.02 Mev which agrees with the average of other values reported for this end point.[16] After subtracting the ground-state group, the inner groups are also plotted in Fig. 3. The results are consistent with a mixture of transitions having endpoints of 1.37 and 1.66 Mev but the limited statistical accuracy does not permit a detailed analysis. It is possible however, to obtain the intensity of all inner group positrons as (12±2)% of all β^+ transitions. This value is compared in Table IV to that observed by Huber *et al.*[7] Agreement

TABLE III. Upper limits for the intensities of gamma rays.

Energy (Mev)	Intensity ($\gamma/100\beta^+$) This work	Ricci *et al.*[a]
0.29	<0.02	<0.5
0.81	<0.2	1.8
0.88	<0.2	1.2
1.10	<0.2	0.7
1.27+1.33	<0.05	0.7

[a] See reference 9.

[23] D. E. Alburger, Rev. Sci. Instr. **27**, 991 (1956).
[24] B. D. Pate and L. Yaffe, Can. J. Chem. **33**, 15 (1955).
[25] D. E. Alburger, S. Ofer, and M. Goldhaber, Phys. Rev. **112**, 1998 (1958).

is good although Huber *et al.* resolved the inner groups into components having endpoints of 1.37 and 0.47 Mev. From the intensities of the gamma rays in Table I and capture/positron ratios of Table II, the inner groups would be expected to have an intensity of $(14.0\pm1.0)\%$ in agreement with the above value. If the gamma-ray intensities of Ricci *et al.* were correct, over 19% of the positrons would be in inner groups.

Conversion electron spectra were obtained by reversing the spectrometer field. Lines were observed at 660 and 952 kev corresponding to the most intense gamma transitions in Zn^{63}. The L and M lines were not resolved from the K conversion line, but because of their low intensity the line position is not expected to shift appreciably. The energy scale for the e^- and β^+ measurements was calibrated using the K conversion line of the 1.06-Mev transition in the decay of Bi^{207}.[26] The intensities of the two Zn^{63} conversion lines are inincluded in Table IV. The intensity of the 952-kev line agrees with that reported by Huber *et al.*[7] They did not observe the 660-kev line. From the intensity of conversion lines relative to positrons in Table IV and from the intensity of gamma rays to positrons in Table I, the total conversion coefficients of the 669- and 961-kev transitions are calculated to be $(5.2\pm0.3)\times10^{-4}$ and $(2.3\pm0.3)\times10^{-4}$, respectively. These agree well with the theoretical values[27] for $M1$ transitions, 5.0×10^{-4} and 2.3×10^{-4}, but are lower than the values for $E2$ transitions, 7.5×10^{-4} and 2.8×10^{-4}. It is known that both transitions are predominantly $M1$.[12]

As an independent check on the conversion coefficients and the gamma ray intensities of Zn^{63}, the gamma-ray intensities of the zinc spectrometer sources were compared to the intensities of the 1.06- and 0.57-Mev gamma rays from the Bi^{207} calibration source. The scintillation detector response was calibrated on the assumption that the relative intensity of 1.06- to 0.57-Mev quanta was 74/100.[28] The theoretical K conversion coefficient[27] for the 1.06-Mev $M4$ transition, 0.097, was used. The resulting total conversion coefficients for the 0.67- and 0.96-Mev transitions were 5.7×10^{-4} and 2.5×10^{-4} in agreement with those values calculated above. The relative intensities were 200, 9.9, and 7.3

TABLE IV. Relative positron and conversion electron intensities.

	Relative intensities	
Particle	Present experiment	Huber *et al.*[a]
β^+ ground state	88 ± 2	87
β^+ excited states	12 ± 2	13
e^- 660 kev	$(4.8\pm0.2)\times10^{-3}$	not observed
e^- 952 kev	$(1.6\pm0.2)\times103^{3}$	$(1.6\pm0.8)\times10^{-3}$
e^- 283 kev	$<1.7\times10^{-4}$	not reported

[a] See reference 7.

[26] D. E. Alburger, Phys. Rev. **92**, 1257 (1953).
[27] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).
[28] R. A. Ricci, Physica **23**, 693 (1957), and A. H. Wapstra, Arkiv Fysik **7**, 279 (1954).

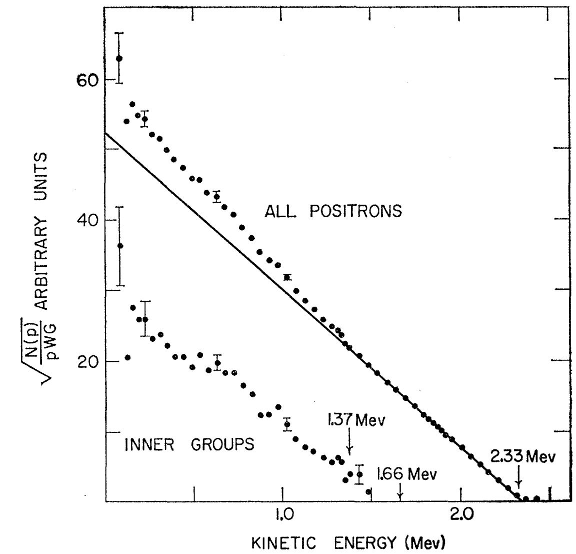

FIG. 3. Kurie analysis of the Zn^{63} positron spectrum.

for the 0.51, 0.67, and 0.96-Mev gamma rays, respectively, in reasonable agreement with the results in Table I.[29]

The beta spectrometer was also used to search for the conversion line of the $E2$ stopover transition from the 0.96- to the 0.67-Mev level. No line was observed, a limit being indicated in Table IV. By combining this value with the theoretical $E2$ conversion coefficient, an intensity limit of less than 2×10^{-4} per decay can be set for the corresponding gamma ray. However, even if this $E2$ transition were accelerated to the same extent as the $E2$ parts of the 0.96- and 0.67-Mev transitions, its intensity would be less than 2×10^{-5} per decay.

V. DISCUSSION

The conclusions of the present work are summarized in the decay scheme of Fig. 4. All of the observed gamma rays have been assigned as arising from levels at the corresponding energies since no gamma-gamma coincidences were observed. The levels shown here agree in energy with single levels (or in the case of the levels at 2.04 Mev and higher, groups of levels) in Cu^{63} observed in the proton inelastic scattering studies.[2] Direct positron and electron capture feeding of the ground state and 0.67-, 0.96-, 1.42-, and 1.55-Mev levels is shown. Direct positron feeding of the latter level, has not been experimentally confirmed but appears probable. It is not expected that positron feeding of the higher levels will be significant. This decay scheme is in agreement with the qualitative conclusions of Hayward *et al.*[8] but differs from that proposed by Ricci *et al.*[9] The present study finds lower intensities for the most prominent

[29] Due to the particular geometry of the spectrometer sources, it was not possible to stop all Zn^{63} positrons close to the source. This is believed to account for the slightly higher gamma ray intensities observed here.

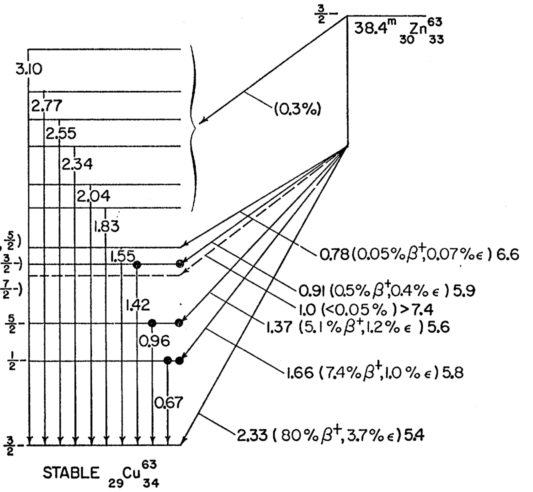

FIG. 4. Decay scheme of Zn^{63}. Positron energies, positron and electron capture intensities, and log *ft* values are indicated for the various transitions.

gamma rays and the absence of γ-γ cascades reported in their paper.

The spin and parity of the Cu^{63} ground state has been measured to be $\frac{3}{2}^-$.[15] This agrees with the shell model assignment of the 29th proton to a $p_{\frac{3}{2}}$ orbital. The $\frac{5}{2}^-$ assignment to the 0.96-Mev level is uniquely determined by the Coulomb excitation angular correlation[10] which is peaked at 90°, and is consistent with the resonance fluorescence correlation[13] and resonance yield attenuation measurements.[12] This level has been identified as the $f_{\frac{5}{2}}$ level by Nussbaum.[30] However, this assignment appears doubtful since the log *ft* for beta decay to this state is 5.6 and shows none of the hindrance expected for an *l*-forbidden transition. Transitions from $f_{\frac{5}{2}}$ ground states of Zn^{65} and Ni^{65} to the $p_{\frac{3}{2}}$ ground state of Cu^{65} have log *ft* values of 7.4 and 6.6.

Both Coulomb excitation[10] and resonance fluorescence[13] angular correlations have been found to be isotropic for the 0.67-Mev level. Unfortunately, because of the particular $E2/M1$ mixing ratio in this transition, an isotropic correlation would be the result if the spin were $\frac{1}{2}$, $\frac{3}{2}$, or $\frac{5}{2}$. It has been shown[12] that the resonance fluorescence attenuation due to recoil stopping in solid copper, when combined with the resonance cross section, is consistent only with a spin $\frac{1}{2}$ assignment for this state.

The allowed decay of Zn^{63} to the spin $\frac{3}{2}^-$ ground state of Cu^{63}, the spin $\frac{1}{2}^-$ level at 0.67 Mev, and the spin $\frac{5}{2}^-$ level at 0.96 Mev establishes that the spin and parity assignment of Zn^{63} is $\frac{3}{2}^-$. Since Zn^{63} has 33 neutrons, 5 in excess of the shell closed at 28, and since the $p_{\frac{3}{2}}$ levels can hold at most 4, at least one pair of neutrons must be in the $f_{\frac{5}{2}}$ level. This preferential filling by pairs of levels of high orbital momentum is well known in the case of protons in this mass region. For example, the ground states of arsenic isotopes (33 protons), bromine isotopes (35 protons), and some rubidium isotopes (37 protons) have $\frac{3}{2}^-$ ground states. In the case of the zinc isotopes, however, the next pair of neutrons added beyond Zn^{63} results in the filling of the $p_{\frac{3}{2}}$ level. Both Zn^{65} and Zn^{67} have $\frac{5}{2}^-$ ground states.[16]

The failure to observe beta decay to the level at 1.33 Mev (shown by the dotted lines of Fig. 4) requires that the log *ft* be greater than 7.4 for this transition. This implies that the spin of the level is $\frac{7}{2}$ or larger and that the decay is strictly forbidden, or possibly that the level might be $f_{\frac{7}{2}}$ in character and the decay would be *l*-forbidden as discussed above.[31] In Fig. 4 a spin of $\frac{7}{2}^-$ has been assigned to the 1.33-Mev level. This is consistent with angular correlation studies of the analogous states in Cu^{65},[32] and with the model of these states discussed below. This model also requires that the 1.42-Mev level have spin and parity $\frac{3}{2}^-$ as has been shown in the figure.

To facilitate discussion of the various transitions in Cu^{63} and Cu^{65}, simplified decay schemes of Ni^{65} and Zn^{65} are presented in Fig. 5. These data were obtained from the Nuclear Data Sheets[16] and from the recent work of Jambunathan *et al.*[32] The spins assigned to the various levels in this figure are consistent with the recent experimental data[32] but are not uniquely determined in all cases.

Lawson and Uretsky[33] have proposed a model for states in Cu^{63}, Cu^{65}, and a number of other nuclei having a single odd particle (or hole) in excess of a closed shell. In this model the ground state of the odd mass nucleus is obtained by coupling the odd particle to the

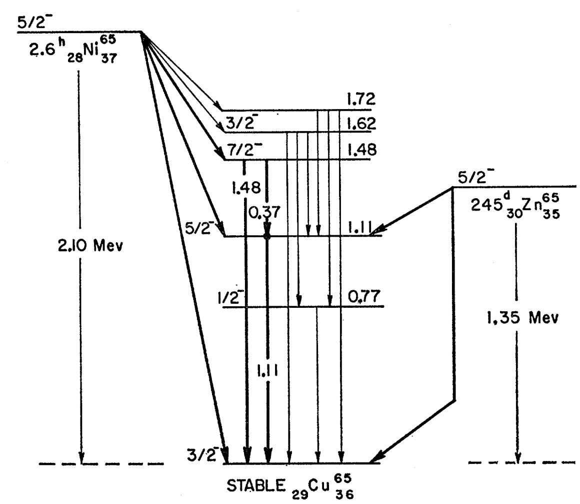

FIG. 5. Principal features of the decay schemes of Ni^{65} and Zn^{65}.

[30] R. H. Nussbaum, Revs. Modern Phys. **28**, 423 (1956).

[31] A log $ft \sim 7$ could arise from a positive-parity level having spin $\frac{1}{2}$, $\frac{3}{2}$, or $\frac{5}{2}$. This would be inconsistent with data for the analogous level in Cu^{65}.

[32] R. Jambunathan, M. R. Gunye, and B. Saraf, Phys. Rev. **120**, 1839 (1960).

[33] R. D. Lawson and J. L. Uretsky, Phys. Rev. **108**, 1300 (1957).

0^+ ground state of the even-even core and excited states are obtained by coupling the odd particle in the same state to the 2^+ first excited state of the core. In the case of the copper isotopes, the $p_{\frac{3}{2}}$ proton when coupled to the 2^+ state gives rise to a quartet of excited states having spins $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$. This model predicts that the "center of gravity" $[(2j+1)$ weighted average$]$ of the

TABLE V. Partial lifetimes and favored factors for $E2$ transitions in Cu and Ni isotopes.

Isotope	Transition	$E2$ partial lifetime (sec)	Favor d factor[a]
Cu^{63}	$0.67 \rightarrow 0$	3.0×10^{-11}[b]	13.2
Cu^{63}	$0.96 \rightarrow 0$	5.2×10^{-12}[b]	12.7
Cu^{65}	$0.77 \rightarrow 0$	1.7×10^{-11}[b]	11.1
Cu^{65}	$1.11 \rightarrow 0$	2.6×10^{-12}[b]	11.4
Cu^{65}	$1.48 \rightarrow 0$	6.5×10^{-13}[c]	11.2
Ni^{58}	$1.45 \rightarrow 0$	8.5×10^{-13}[d]	10.7
Ni^{60}	$1.33 \rightarrow 0$	1.15×10^{-12}[d]	12.1
Ni^{62}	$1.17 \rightarrow 0$	2.24×10^{-12}[d]	11.2
Ni^{64}	$1.34 \rightarrow 0$	...	...

[a] Favored factor calculated relative to the single-particle lifetime given by $\tau_{sp} = 1.35 A^{-4/3} E^{-5} \times 10^{-8}$ sec (E in Mev).
[b] Calculated from Coulomb excitation data of reference 1.
[c] Calculated assuming the same favored factor as observed for the other transitions in this isotope.
[d] Reference 10.

energies of these four states should equal the energy of the 2^+ level of the core nucleus. This conclusion is well satisfied in the case of Cu^{63} and Cu^{65}.

A further consequence of this model is that transitions from any one of the levels of the quartet to the ground state should be $E2$ and that the reduced transition probabilities (without any statistical factors removed) should be the same as that for the $2^+ \rightarrow 0^+$ transition in the core nucleus. The agreement in the case of the first two excited states of Cu^{63} has been discussed.[12] Reduced $E2$ lifetimes and favored factors are tabulated in Table V for Cu^{63}, Cu^{65} and the even-even Ni isotopes. These results have been obtained from Coulomb excitation data.[1,10] Although no data are available for Ni^{64}, the "core" of Cu^{65}, there appears to be little change between Ni^{58}, Ni^{60}, and Ni^{62}. The narrow range of the favored factors would support the model. It has been pointed out[12] that the $M1$ parts of these transitions should be strongly hindered by the spin change of the core. It might be expected that these transitions would be retarded by factors of the same order of magnitude as observed in the case of "l" forbidden $M1$ transitions. For example, the 93-kev isomeric state of Zn^{67} has a mean life $\sim 5 \times 10^5$ larger than the $M1$ single-particle estimate. Presumably this is a consequence of the $p_{\frac{3}{2}} \rightarrow f_{\frac{5}{2}}$ nature of the states involved. In the case of Cu^{63}, the $M1$ part of the 0.67-Mev transition proceeds with 0.2 of single-particle speed. This is also true for the analogous transition in Cu^{65}. The partial $M1$ lifetimes and favored factors for transitions in Cu^{63} and Cu^{65} are listed in Table VI. The relatively fast $M1$ de-excitation of the first excited states of both isotopes is in disagreement with the Lawson and Uretsky model.

A further comparison with the model may be made by examining transitions between two states of the quartet corresponding to the same core configuration. In this case, $M1$ transitions should not be hindered. Although the limits set on these transitions in Cu^{63} do not allow meaningful conclusions to be drawn, such a stopover transition is prominent in Cu^{65}.[16,32] The spin $\frac{7}{2}^-$ state at 1.48 Mev decays directly to the $\frac{3}{2}^-$ ground state and also by a stopover transition via the spin $\frac{5}{2}^-$ level at 1.11 Mev. The crossover de-excitation of the 1.48-Mev level is probably $E2$ and the model predicts it should have the same reduced $E2$ lifetime as the 1.11- and 0.77-Mev states listed in Table V. If this is true the partial lifetime for the crossover transition is 6.5×10^{-13} sec. Since the ratio of stopover to crossover is 0.21,[32] the partial lifetime for the stopover is 3.1×10^{-12} sec. This is 2400 times the single-particle $E2$ speed and hence the transition must be nearly pure $M1$ in nature. If it is assumed to be all $M1$, then it proceeds with 0.18 of single-particle speed, a rate in agreement with the model prediction.[34]

In concluding, the "center of gravity" model is successful in predicting the energies of levels in Cu^{63} and Cu^{65}, the $E2$ transition probabilities, and the rather rapid $M1$ transition between two levels corresponding to the same core configuration. Strict application of the model requires that $M1$ transitions between states having a 2^+ core configuration and those having a 0^+ core would be forbidden. Whether sufficient admixtures of other wave functions (say, for example, $p_{\frac{1}{2}}$ to the first excited state) can account for the observed $M1$ transitions and still not destroy the other conclusions of the model can only be determined by a more detailed calculation.

TABLE VI. Partial lifetimes and favored factors for $M1$ transitions in Cu^{63} and Cu^{65}.

Isotope	Transition	$M1$ partial lifetime (sec)	Favored factor[a]
Cu^{63}	$0.67 \rightarrow 0$	3.0×10^{-13}[b]	0.20
Cu^{63}	$0.96 \rightarrow 0$	8.4×10^{-13}[b]	0.04
Cu^{65}	$0.77 \rightarrow 0$	2.4×10^{-13}[c]	0.16
Cu^{65}	$1.11 \rightarrow 0$	...	...
Cu^{65}	$1.37 \rightarrow 1.11$	3.1×10^{-12}[d]	0.18

[a] Favored factor calculated relative to single-particle speed as given by S. A. Moszkowski (including proper statistical factor), in *Beta and Gamma Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955).
[b] See reference 12.
[c] See reference 14.
[d] See text for source of this value.

Further studies of Cu^{65} would be of considerable interest. In particular, a lifetime measurement of the

[34] We are indebted to Dr. B. J. Raz for supplying the results of a calculation which indicated that this transition should proceed with 0.12 of single-particle speed.

1.11-Mev state would establish an $E2/M1$ mixing ratio and aid in interpreting the 0.37-1.11-Mev angular correlation. Angular correlation studies of the low intensity 0.95-0.77-, 0.85-0.77-, 0.61-1.11-, and 0.51-1.11-Mev cascades which have been reported[32] in the decay of Ni^{65} would give additional data on transitions between various members of the excited quartet of states.

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Coulomb Excitation of the Second 2+ States in W, Os, and Pt Nuclei

F. K. McGowan and P. H. Stelson
Oak Ridge National Laboratory, Oak Ridge, Tennessee
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The location of a second 2+ state has been established for six even-even nuclei by means of Coulomb excitation produced by 4- to 5-Mev protons. The relatively weak excitation of these states is detected by a measurement of the gamma-ray yields from singles spectra and from coincident measurements of the cascade gamma rays. The $B(E2)$'s for decay of the second 2+ state to ground state by the crossover transition exhibit some uniformity for the even-even isotopes of W and Os, being about 6 times the single-particle value. The cascade/crossover ratio for the decay of the second 2+ state is known for these nuclei. The upper cascade $B(E2)$'s exhibit enhancements of 10 to 60 times the single-particle value. The ratios of the $B(E2)$'s for decay of the first and second 2+ states are compared to the predictions of several collective models. For five of these nuclei the $E2/M1$ ratio is known for the upper cascade transition. The $B(M1)$ values obtained are exceedingly small compared to the single-particle estimate. This result is in qualitative agreement with the collective models which predict that $M1$ radiation is forbidden in the decay of vibrational excitations.

I. INTRODUCTION

THE level structures of the nuclei of the neighboring elements wolfram, osmium, and platinum suggest that these nuclei mark a rather gradual boundary for the rare-earth group of spheroidal nuclei. The even-A nuclei of wolfram exhibit the characteristic rotational bands of spheroidal nuclei. On the other hand, the platinum nuclei have no recognizable rotational bands, but have, instead, spectra somewhat suggestive of the near-harmonic spectra observed for many medium-weight nuclei. The spectra of the osmium nuclei are particularly interesting because these nuclei link the wolfram and platinum nuclei.

In addition to the rotational band based on the ground state, the even-A rare-earth nuclei systematically exhibit rotational bands based on excited states at approximately 1-Mev excitation.[1] These excited states have properties expected for β- and γ-vibrational states. In particular, it has proved possible to observe the weak Coulomb excitation of the high-lying second 2+ γ-vibrational state in the even-A wolfram nuclei. Whereas the first 2+ state is observed to continuously increase in energy as one moves out of the spheroidal region, the second 2+ state systematically decreases in energy as the platinum nuclei are approached. It is therefore possible to also measure the Coulomb excitation of this state for osmium and platinum nuclei.

We wish to report the excitation energies and $B(E2)$ values obtained from the Coulomb excitation of 2+ states in W^{184}, W^{186}, Os^{188}, Os^{190}, Os^{192}, Pt^{194}, and Pt^{196}. Similar results have been obtained for nuclei in this region by Barloutaud *et al.*[2] and for W^{182}, W^{184}, and W^{186} by Alkhazov *et al.*[3]

In our experiments, the Coulomb excitation cross section for the second 2+ state is deduced from the yield of the de-excitation γ rays. A virtue of this method is that, in addition to obtaining the $B(E2)$ for decay of the second 2+ state directly to the ground state, one also obtains the $B(E2)$ for decay of the second 2+ state to the first 2+ state. In some cases the $M1$–$E2$ mixture for the $2'+ \rightarrow 2+$ transition is known. Having both the $M1$–$E2$ mixture and the $B(E2)$ for the $2'+ \rightarrow 2+$ transition, one can then obtain the value for $B(M1)$ for the $2'+ \rightarrow 2+$ transition.

[1] See, e.g., the review paper by R. K. Sheline, Revs. Modern Phys. **32**, 1 (1960).

[2] R. Barloutaud, A. Leveque, P. Lehmann, and J. Quidort, J. phys. radium **19**, 60 (1958).

[3] D. G. Alkhazov, A. P. Grinberg, G. M. Gusinskii, K. I. Erokhina, and I. Kh. Lemberg, J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 1325 (1958) [translation: Soviet Phys.—JETP **8**, 926 (1959)].