experiment may further improve if the p-n residual interaction is included in the pairing-plus-quadrupole model calculations.

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Decay Schemes of ^{60}Zn and ^{62}Zn†

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The decays of 2.4-min ^{60}Zn and 9.3-h ^{62}Zn have been investigated with the use of Ge(Li) and NaI(Tl) γ-ray detectors. Coincidence relationships among the γ rays were determined in γ-γ coincidence experiments. It was established that the decay of 2.4-min ^{60}Zn populates levels at 61.4, 334.4, 364.6, 572.4, and 669.7 keV in ^{60}Cu, and the decay of 9.3-h ^{62}Zn populates levels at 40.84, 243.43, 287.86, 548.25, and 637.20 keV in ^{62}Cu. Many spin assignments have been made from present logft values, previously reported conversion-electron data, and spectroscopic studies from nuclear reactions. The half-life of ^{60}Zn was measured to be 2.42±0.02 min. The fraction of β decay (positron plus electron capture) of ^{62}Zn to the ground state of ^{62}Cu was measured to be 0.43±0.05; the ratio of positron to K capture for the same decay was measured to be 0.22±0.01.

I. INTRODUCTION

The discovery of ^{60}Zn was reported in 1955 by Lindner and Brinkman[1] who reported a half-life of 2.1±0.1 min. No work could be found on the decay scheme of the 2.4-min ^{60}Zn up to the present time. However, levels in ^{60}Cu have been reported by Miller and Kavanagh[2] and by Young and Rapaport[3] from studies of the ^{58}Ni(^{3}He, p)^{60}Cu reaction. Finally, Birstein and co-workers[4] have reported levels in ^{60}Cu from studies of the ^{60}Ni(p, $n\gamma$)^{60}Cu reaction.

The decay scheme of the 9.3-h ^{62}Zn has been the subject of several recent works,[5–7] the most definitive being the Ge(Li) γ-ray work of Roulston *et al.*[6] and the conversion-electron and Ge(Li) γ-ray work of Antman *et al.*[7] The last named authors assigned levels at 40.88, 243.40, 287.89, 548.37, and 637.45 keV populated in the decay of the 9.3-h ^{62}Zn. The only coincidence work is that of Brun and co-workers[5] and involved NaI(Tl) scintillation spectroscopy. The definite coincidences seen were the 590-, 510-, and one of the 250-keV complex coincident with the 41-keV line and one of the 250-keV complex coincident with one of the 390-keV complex.

The investigation of the decay schemes of the 2.4-min ^{60}Zn and the 9.3-h ^{62}Zn was undertaken in order to obtain the levels, the γ-ray transitions, and their coincidence relationships. This information is essential to studies of γ rays from nuclear reactions induced on ^{58}Ni and ^{60}Ni that we are presently investigating. The scheme for the decay of the 2.4-min ^{60}Zn that we are proposing has not been previously reported. The scheme for the decay of the 9.3-h ^{62}Zn determined in this work is in good agreement with the previously reported one.[6,7]

II. EXPERIMENTAL PROCEDURES

A. Production of ^{60}Zn Samples

The ^{60}Zn samples were produced by the (^{3}He, n) reaction at the Washington University cyclotron on 10.5-mg/cm^2 natural nickel foils. The maximum ^{3}He-ion energy was kept below 10 MeV to minimize the ^{60}Ni(^{3}He, $2n$) reaction, which produces the 86-sec ^{61}Zn. The bombardment times were about 60 sec. The most prominent 476-keV γ ray from ^{61}Zn was not observed in any of the samples. The targets were mounted on carriers in a pneumatic tube which returned the sources to the counting area in less than 5 sec after the end of bombardment. In all cases, the following procedure was

† Work supported in part by the U.S. Atomic Energy Commission under Contract Nos. AT(11-1)-1530 and AT(11-1)-1760.
[1] L. Lindner and G. A. Brinkman, Physica **21**, 747 (1955).
[2] R. G. Miller and R. W. Kavanagh, Nucl. Phys. **A94**, 261 (1967).
[3] Helen J. Young and J. Rapaport, Phys. Letters **26B**, 143 (1968).
[4] L. Birstein, Ch. Drory, A. A. Yaffe, and Y. Zioni, Nucl. Phys. **A97**, 203 (1967).
[5] E. Brun, W. E. Meyerhof, J. J. Kraushaar, and D. J. Horen, Phys. Rev. **107**, 1324 (1957).
[6] K. I. Roulston, E. H. Becker, and R. A. Brown, Phys. Letters **24B**, 93 (1967).
[7] S. Antman, H. Petterson, and A. Suarez, Nucl. Phys. **A94**, 289 (1967).

employed in order to purify the Zn activities from the products of the (^3He, d) and (^3He, p) reactions that are produced in high yield. The target foils were dissolved in hot concentrated HNO_3, the HNO_3 was destroyed with concentrated HCl, and the solution was made $1M$ in HCl. To this solution, 0.05 mg of Zn^{++} and Cu^{++} carriers were added, and the solution was shaken with a few mg of Dowex-1 anion exchange resin. The resin bed was filtered, washed with $1.0M$ HCl solution, and mounted for counting. The decontamination factor from the Cu activities in these rapid separations was determined to be larger than 10^2. The only foreign activity that could be identified in the samples was that of 23-min ^{60}Cu daughter.

B. Production of ^{62}Zn Samples

The ^{62}Zn sources were produced by the (^3He, n) reaction on 10.5-mg/cm natural nickel foils. The ^3He-ion energies varied between 13 and 20 MeV. The irradiated foils were allowed to decay for at least 6 h before counting to eliminate the 38-min ^{63}Zn activity. The 245-day ^{65}Zn isotope is not produced in sufficient amounts to interfere. The purification procedure for the ^{62}Zn activity was essentially the same with the one described above. Spectra of the radiations from ^{62}Zn essentially free from the 9.8-min ^{62}Cu daughter radiations were obtained by counting the ^{62}Zn activities from an anion exchange column and periodically washing and discarding the growing daughter activities.

C. Detection Equipment and Methods of Counting

For γ-ray counting both Ge(Li) and NaI(Tl) detectors were employed. The Ge(Li) detectors had active volumes of 3.5, 20, and 30 cm^3 with full widths at half-maximum (FWHM) 2.8, 2.4, and 3.5 keV for the γ rays from a ^{137}Cs source, respectively. The NaI(Tl) detectors used were integrally mounted 7.6×7.6-cm crystals.

In the γ-γ coincidence measurements two NaI(Tl) detectors were employed for the decay of 2.4-min ^{60}Zn and two Ge(Li) detectors (in the combinations 20×3.5 or 20×30 cm^3) were used for the decay of 9.3-h ^{62}Zn. The coincidence resolving times employed were typically 50–100 nsec.

For pulse-height analysis, a 4096-channel pulse-height analyzer with two 4096-channel analog-to-digital converters were used. The analyzer was equipped with a buffer-tape and a read-search control unit coupled with a magnetic-tape drive. Two-parameter coincidence spectra were recorded for the NaI(Tl)×NaI(Tl) measurements in a 256×512 channel configuration. The second half of the channel capability of the two-parameter system consisting of another 256×512 channel configuration was used to record simultaneously the random coincidence events obtained by proper delay and routing.

For the Ge(Li)×Ge(Li) coincidence measurements,

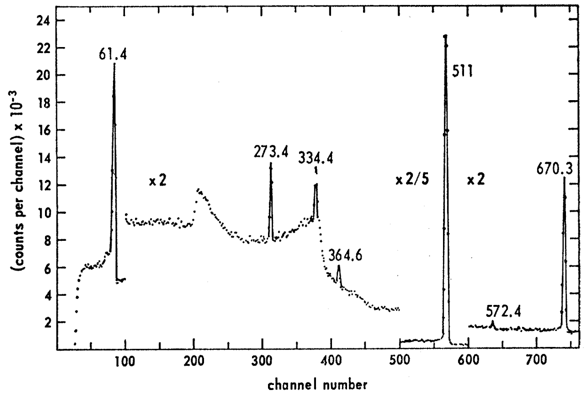

FIG. 1. Early γ-ray spectrum following 2.4-min ^{60}Zn decay, taken with the 20-cm^3 Ge(Li) detector. The energies are given in keV.

the full 512×512 channel configuration was employed. The rate of random coincidence events in these cases represented only ~5% of the total coincidence rate, and the random events were not determined separately. The coincidence spectra presented in this work were obtained by integrating to ~140 keV per channel window for the NaI(Tl) axis and ~4 keV on the Ge(Li) axis with the use of the read-search unit.

III. RESULTS

A. Decay of 2.4-min ^{60}Zn

To obtain singles γ-ray spectra with good statistics from the decay of the short-lived 2.4-min ^{60}Zn many sources were employed. The sources were counted for two fixed consecutive time intervals of 2.0 and 4.0 min and the corresponding spectra were added to increase statistics. Comparison of the relative intensities from the two timed spectra allowed clear identification of the γ-ray peaks with a half-life of 2.2–2.6 min. A typical singles spectrum of the 2.4-min ^{60}Zn, obtained during an early time interval of 2 min, is shown in Fig. 1. Only the γ rays associated with the decay of the 2.4-min ^{60}Zn are seen.

The energies of the γ rays were determined by using standard sources of ^{241}Am, ^{57}Co, ^{139}Ce, ^{203}Hg, ^{22}Na, ^{207}Bi, and ^{137}Cs for calibration.

The relative efficiencies of the γ rays were determined from photopeak areas using a detector efficiency curve which was obtained by means of standard sources of ^{109}Cd, ^{57}Co, ^{203}Hg, ^{137}Cs, ^{180m}Hf, and ^{56}Co. The values of the relative intensities used for these photons are given in Ref. 9, p. 563.

The energies and the relative intensities of the γ rays thus determined are summarized in Table I.

The half-life for the decay of ^{60}Zn was determined in a number of experiments. For this purpose, pulses from the 490–550- and 630–700-keV regions were multiscaled for several hours at 12 sec per interval. The decay curves

TABLE I. Energies and relative intensities of γ rays following 2.4-min ^{60}Zn decay from γ-ray singles data.

γ-ray energies (keV)[a]	Relative γ-ray intensities[b]
61.4±0.6	44.8±4.5
273.4±0.4	18.8±1.3
334.4±0.1	15.2±1.1
364.6±0.3	5.5±1.0
572.4±0.3	4.1±1.1
670.3±0.3	100.00

[a] Energies are averages from four measurements except for the 364.6- and 572.4-keV γ rays, which are averages from two measurements.
[b] Intensities are averages from two independent measurements.

were corrected for dead time and for growth of the underlying Compton background from the high-energy γ rays of the daughter ^{60}Cu. The decay curves thus obtained were annlyzed by the least-squares technique and the value of the half-life obtained is 2.42±0.02 min.

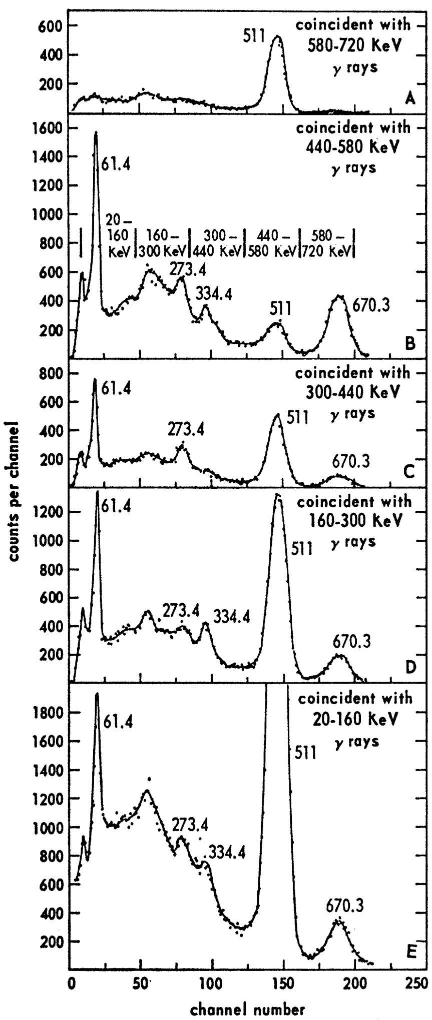

FIG. 2. Spectra of γ rays, taken with NaI(Tl) detector, in coincidence with the energy regions indicated. In (b) are shown the energy regions used for gates.

In another set of experiments, the total conversion coefficient for the 61.4-keV transition was measured. The multipolarity of this transition is expected to be $M1$ or $E2$, with theoretical α_K values of 0.23 and 3.0, respectively. This difference is sufficiently high to allow a determination of the α_K value by measuring the fraction of the total γ rays to the total decays represented by the intensity of the positron peak from the decay of the 2.4-min ^{60}Zn. γ-ray spectra showing the 511- and 670-keV peaks were recorded as a function of time, using sources of ^{60}Zn freed from the daughter activity. Care was taken to annihilate the positrons near the source and far from the detector. The growth-decay curves were analyzed by the least-squares method to obtain the 2.4-min component of the 511-keV peak and

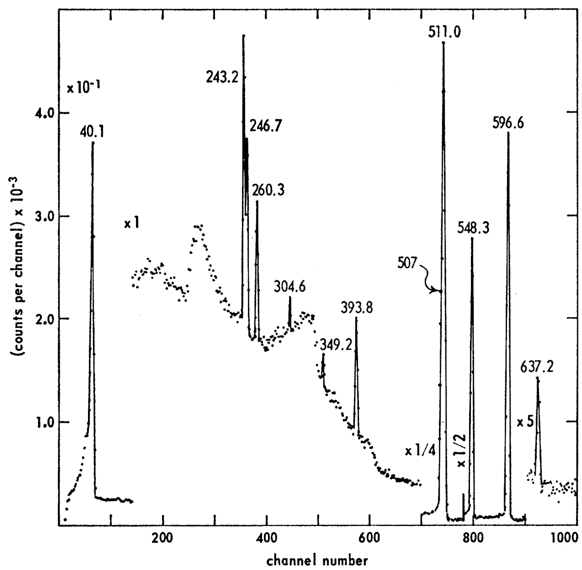

FIG. 3. γ-ray spectrum following 9.3-h ^{62}Zn decay, taken with the 20-cm^3 Ge(Li) detector. The energies are given in keV.

the 670-keV component at the time of separation. The total number of ^{60}Zn decays was obtained by correcting the positron activity for electron capture (EC), using theoretical estimates for β^+/EC. From this information the total feeding to the 61-keV level and the intensity of the 61-keV γ ray were calculated. The results of three independent measurements gave an upper limit for $\alpha_{K+L+\cdots}$ of 1.71±0.20.

In the study of the decay of 2.4-min ^{60}Zn, coincidence spectra were taken with the analyzer operated in a two-parameter NaI(Tl)–NaI(Tl) system with 512×256 channel configuration covering an energy range of 2.0×1.0 MeV. Consecutive spectra with one of the NaI(Tl) detectors for every 35 keV of the other NaI(Tl) axis were analyzed. The coincidence spectra presented here correspond to sufficiently large windows to minimize the number of illustrations needed to present the evidence necessary for the construction of the decay scheme. In Fig. 2 are shown the spectra taken in coincidence with the indicated energy regions. The random coincidence spectra were determined and found to be negligible.

B. Decay of 9.3-h ^{62}Zn

A typical singles spectrum of 9.3-h ^{62}Zn is shown in Fig. 3. This spectrum was obtained clean from the radiations from 9.8-min ^{62}Cu by removing chemically the Cu activities approximately every 5 min. The γ rays seen in Fig. 2 have been previously reported and no other γ rays associated with ^{62}Zn were observed. In a number of experiments the γ rays at 260.32, 393.84, 548.33, and 596.60 keV were used as internal standards for the weaker transitions. The energies were determined by the least-squares technique from the centroids of the peaks which were determined by fitting Gaussian curves to the data points by means of a digital computer.

The energies and the relative intensities of the γ rays determined are summarized in Table II. In Table II we also list the α_K values for the ^{62}Zn transitions determined by using the relative conversion-electron intensities from Ref. 7 and the γ-ray intensities from this work. These determinations have been based on the calculated[8,9] values of 0.59 and 0.0058 for the 40.84- and 596.6-keV transitions which are $M1$ in character.[7]

In two other experiments, the fraction of decay of ^{62}Zn to the ground state of ^{62}Cu was measured. In these experiments, γ-ray spectra were recorded as a function of time using sources of ^{62}Zn freed from the daughter activity. Spectra were obtained until transient equilibrium between 9.3-h ^{62}Zn and 9.8-min ^{62}Cu was established. Again, the positrons were annihilated near the source and far from the detector. The growth-decay curves were analyzed by the least-squares method to obtain the 9.8-min 511-keV component of the (507–511-keV) complex that grows in and the ^{62}Zn γ rays at the time of separation. The fact that ^{62}Cu decays 97% by positron emission[8] allows one to calculate the total ^{62}Zn activity at the time of separation by making use of the transient equilibrium expression

$$A^0(^{62}\mathrm{Zn}) = \frac{1}{2}\frac{0.98}{0.97}A_{511}{}^0(^{62}\mathrm{Cu}),$$

where $A_{511}{}^0(^{62}\mathrm{Cu})$ is the 9.8-min component of the 511-keV peak at the separation time.

This activity is then compared with the total γ-ray activity that feeds the ^{62}Cu ground state after correction for internal conversion. From this information the fraction of decay to the ground state of ^{62}Cu was calculated to be 0.434±0.008. From our data the fraction of the (507+511)-keV complex from ^{62}Zn was measured to be 0.158±0.008. After proper subtraction of the 507-keV line intensity, the fraction for total positron

[8] C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), 6th ed.

[9] L. A. Sliv and I. M. Band, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1965), p. 1639.

TABLE II. Energies and relative intensities of γ rays following 9.3-h ^{62}Zn decay from γ-ray singles and conversion-electron data.

γ-ray energy (keV) Ref. 6	Ref. 7	This work[a]	Adopted[b]	Relative K-conversion intensities[c]	Relative γ-ray intensities Ref. 6 (10%)	Ref. 7	This work[d]	α_K value	Multipolarity
41.5±0.2	40.88±0.09	40.84±0.13	40.84±0.15	60.2±8	192	102 (calc)	99.4±3.5	0.59±(2)	$M1$
243.7±0.5	243.40±0.05	243.18±0.15	243.43±0.20	0.0480±14	15.4	~7±9	10.3±0.5	0.0045±(3)	$M1$
247.2±0.5	247.02±0.09	246.70±0.10	247.02±0.20	0.0313±9	11.5	~4	8.2±0.3	0.0037±(1)	$M1$
260.7±0.5	260.44±0.10	260.32±0.06	260.39±0.08	0.0203±14	8.46	2.6±0.5	5.9±0.1	0.0034±(3)	$M1$
305.5±1.0	...	304.60±0.11	304.80±0.20	...	0.77	...	1.32±0.07	...	...
349.5±1.0	349.69±0.25	349.22±0.09	349.34±0.11	0.0068±10	1.54	~1	1.59±0.16	0.0042±(6)	$E2$
394.5±0.5	394.12±0.18	393.84±0.06	393.80±0.06	0.0217±24	10.8	6.2±1.0	9.16±0.12	0.0023±2	$M1+E2$
507.5±1.0	505.57±0.13	507.2±1.0	507.41±0.15	0.0693±20	77	60±15	65±15[e]	0.00076±(19)	$M1$
548.7±0.5	548.33±0.22	548.33±0.06	548.25±0.11	0.0528±12	65.4	54.5	62.2±0.9	0.00083±(5)	$M1$
597.0±0.5	596.68±0.20	596.60±0.06	596.60±0.11	0.0590±13	100	100±8	100	0.00058±(4)	$M1$
638.5±1.0	636.9±0.5	637.25±0.06	637.20±0.12	0.0015±7	1.54	≤1	3.45±0.25	0.00042±(20)	$M1$

[a] Energies are averages of nine independent determinations.
[b] Values obtained by minimizing the deviations to the energy sum rules between the various transition energies.
[c] Reference 7.
[d] These values are averages from nine independent determinations.
[e] From only one measurement.

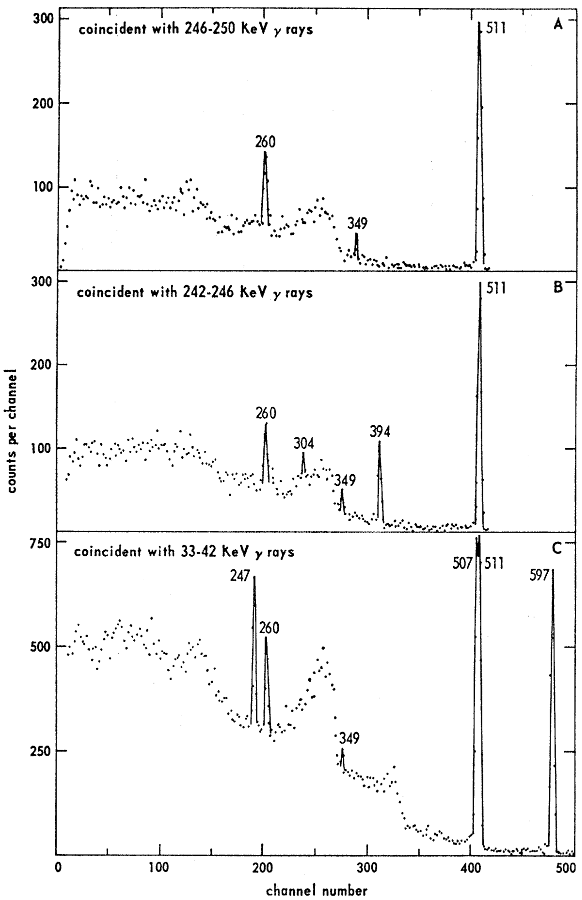

FIG. 4. Spectra of γ rays taken with a 3.5-cm^3 Ge(Li) in coincidence with the energy regions indicated. The gates correspond to selected planes of the two-parameter configuration. The gating detector was a 20-cm^3 Ge(Li) detector.

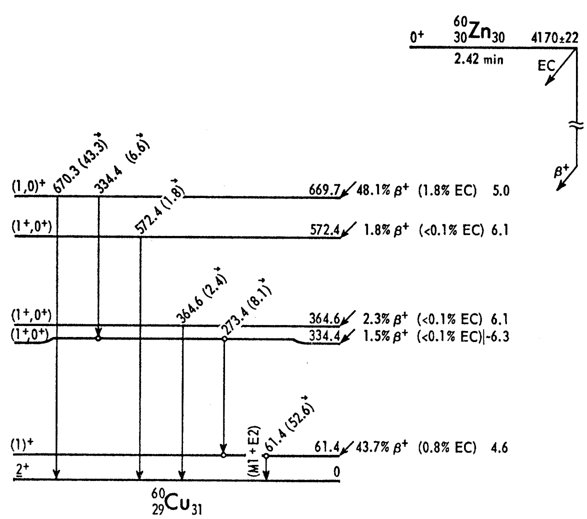

FIG. 5. Proposed decay scheme for the 2.4-min ^{60}Zn. The conventions used are those of Ref. 12, except that the energies are given in keV. The intensities of the transitions are given per 100 ^{60}Zn decays.

decay of ^{62}Zn was calculated to be 0.079±0.019. Since the first three excited states in ^{62}Cu have not been observed to be populated by β decay, it can be concluded that all positron decays feed the ground state, thus establishing the K-capture–to–positron ratio for decay to the ground state to be 4.4±0.9.

In the study of 9.3-h ^{62}Zn it was possible to exploit the two-parameter analyzer by taking coincidence spectra with two Ge(Li) detectors. In these measurements, a Ge(Li)–Ge(Li) configuration with 512×512 channels was employed, covering an energy range of 700×700 keV. In Fig. 4 are shown the spectra taken with a 3.5-cm^3 Ge(Li) in coincidence with the indicated narrow energy regions in a 20-cm^3 Ge(Li) detector.

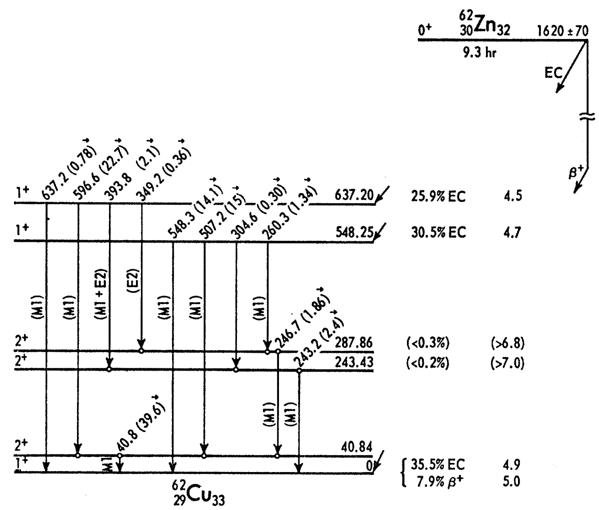

FIG. 6. Proposed decay scheme for the 9.3-h ^{62}Zn. The conventions used are those of Ref. 12, except that the energies are given in keV. The intensities are given per 100 ^{62}Zn decays.

IV. CONSTRUCTION OF DECAY SCHEMES

In Figs. 5 and 6 are shown the decay schemes for ^{60}Zn and ^{62}Zn, respectively, and below arguments are given for the proposed schemes.

A. Decay Scheme of 2.4-min ^{60}Zn

The 670-keV γ ray is only seen to be in coincidence with the annihilation radiation [Figs. 2(a) and 2(b)], and since it is the most intense γ ray, it must feed the ground state. This establishes a level at 669.7 keV. The 61-keV γ ray is in coincidence with the 273.4- and 334.4-keV γ rays [Figs. 2(c)–2(e)]. Furthermore, the 273.4- and 334.4-keV γ rays are in coincidence with each other [Figs. 2(c) and 2(d)]. The energies 61.4, 273.4, and 334.4 keV have a sum equal to 669.2 keV, which agrees with the 670.3-keV transition within the assigned experimental error. The relative intensities of the 61.4-, 273.4-, and 334.4-keV γ rays, in cascade, require that the 334.4-keV transition feed the level de-excited by the 273.4-keV transition. The 61.4-keV γ ray is the most intense of the three and must feed the ground state.

This establishes levels at 61.4 and 334.4 keV. Interestingly, the 334.4-keV level lies very close to one-half the energy of the 669.7-keV level. Coincidence information obtained does not support a 334.4-keV crossover transition to the ground state, because this would require the 334.4-keV γ ray to be in coincidence with the γ ray from a transition of equal energy between the 669.7- and 344.4-keV levels, and such a coincident γ ray was not observed [Fig. 2(c)]. An upper limit for this crossover transition can be set to be 3 relative to 100 for the 670.3-keV γ ray. The 364.6- and 572.4-keV γ rays were not seen in coincidence with any γ ray. We tentatively, therefore, place these γ rays to de-excite levels at 364.6 and 572.4 keV. The former of these assignments is supported by the $^{58}Ni(^{3}He, p)$ reaction data of Miller and Kavanagh[2] and of Young and Rapaport,[3] who reported a level at 376±7 and 361±10 keV, respectively. We have identified these levels as the same as the 364.6-keV level populated in the decay of ^{60}Zn. The 572.4-keV γ ray could possibly feed the 61.4-, 334.4-, or 364.6-keV level. However, the corresponding levels were not seen in the $^{58}Ni(^{3}He, p)$ reaction studies. The spin[10] of the ^{60}Cu ground state has been determined by atomic-beam experiments to be 2, and the parity is even.[11] The spin and parity of the ^{60}Zn ground state is 0^+, and β^+ decay to the ^{60}Cu ground state would be second forbidden and therefore insignificant. The percent of decays to each level was calculated after correction for internal conversion estimated using the values of Sliv and Band.[8,9] The logft values were calculated using Moszkowski's nomogram[12] with the value of 4.170±0.022 MeV for Q_{EC} for ^{60}Zn of Miller and Kavanagh[2] and estimated EC/β^+ ratios from Ref. 8, p. 575. The transition intensities given in Fig. 5 are expressed in terms of 100 decays of the parent.

B. Decay Scheme of 9.3-h ^{62}Zn

The 548.3- and 637.2-keV γ rays were not seen in coincidence with any γ ray. The 40.8-keV transition (γ rays plus conversion electrons) is the most intense and it must feed the ground state. This establishes a level at 40.84 keV. The 246.7-, 260.3-, 349.2-, 507.2-, and 596.6-keV γ rays are in coincidence with the 40.84-keV γ ray [Fig. 4(c)]. The 596.6-keV γ ray is only in coincidence with the 40.8-keV γ ray and it must feed the 40.8-keV level. This establishes a level at 637.20 keV with the 637.2-keV γ ray as a crossover transition to the ground state. The 507.2-keV γ ray is in coincidence with 40.8-keV γ ray only; therefore it must feed the 40.8-keV level. This establishes a level at 548.25 keV with the 548.3-keV γ ray for the crossover transition to the ground state. The 260.3-keV γ ray is in coincidence with the 246.7-keV γ ray [Figs. 4(a) and 4(b)], and since it is the weaker, it must feed the level de-excited by the 246.7-keV γ ray. This establishes a level at 287.86 keV and confirms the level at 548.25 keV. The 349.2-keV γ ray is also in coincidence with the 246.7-keV γ ray [Fig. 2(b)], thus confirming the 637.2-keV level. The 304.6- and 393.8-keV γ rays are in coincidence with the 243.2-keV γ ray, but not the 246.7-keV γ ray [Figs. 4(a) and 4(b)]. This further confirms the levels at 548.25 and 637.20 keV.

From the result of our measurements of the fraction of decay to the ground state of ^{62}Cu and the K-capture–to–positron ratio, it is possible to express all transition intensities in terms of 100 decays of the parent (Fig. 6). An upper limit for the end-point energy of the positron branch from ^{62}Zn to the ground state is reported by Hayward[13] to be 660±10 keV, while his estimate of the fraction of ^{62}Zn decays by positron emission is $\sim$10%, which is in agreement with our measurement. A second measurement is quoted in Ref. 12 to be 675±10 keV from the data of Nussbaum *et al.*[14] and private communication. These values give $Q_{EC}=1690$ keV for the ^{62}Zn decay. This value of Q_{EC} give a theoretical ratio EC/β^+ of 2.2 (Ref. 8, p. 575), in disagreement with the observed ratio of 4.4±0.9. We believe that this discrepancy is due to the value of Q_{EC}, which may be overestimated by about 70 keV. We therefore have chosen the value 1620±70 keV for Q_{EC} and thus calculate the logft values given in Fig. 6.

The proposed decay scheme for ^{62}Zn is in good agreement with the work of Roulston *et al.*[6] and of Antman *et al.*[7] Recently, however, Bakhru[15] reported on the decay of ^{62}Zn and assigned a level at 682 keV. A γ ray at 682 keV was not observed in any of our spectra (Fig. 3) and we find the 394-keV γ ray in coincidence with the 243- and not the 247-keV γ ray [Figs. 4(a) and 4(b)].

V. ASSIGNMENT OF SPINS AND PARITIES AND INTERPRETATION OF THE LEVELS

A. Levels in ^{60}Cu

The logft values calculated for the decay of 2.4-min ^{60}Zn suggest that the transitions to the 61.4- and 670.3-keV levels are allowed, while those to the 334.4-, 364.6-, and 572.4-keV levels may be either allowed or first forbidden. The measured total internal conversion coefficient for the 61.4-keV transition in ^{60}Cu, when

[10] I. Lindgren, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1965), p. 1623.

[11] *Nuclear Data Sheets*, edited by K. Way (Academic Press Inc., New York, 1967).

[12] S. A. Moszkowski, Phys. Rev. **82,** 35 (1951).

[13] R. W. Hayward, Phys. Rev. **79,** 541 (1950).

[14] R. H. Nussbaum, A. H. Wapstra, R. VanLieshout, G. J. Nijgh, and L. Th. M. Ornstein, Physica **20,** 571 (1954).

[15] H. Bakhru, Phys. Rev. **169,** 889 (1968).

TABLE III. Levels in ^{60}Cu and their spin and parity assignment.

This work		Ref. 2	Ref. 3			Ref. 4	Adopted values	
Level (keV)	J^π	Level (keV)	Level (keV)	L	J^π	Level (keV)	Level (keV)	J^π
0	2^+	0	0	2	2^+	0	0	2^+
61.4	$(1)^+$	72±7	58±10	0+2	1^+	62±2	61.4	1^+
...	...	...	163±20	...	...	...	163	...
...	...	298±7	287±10	2	$(2)^+$	287±2	287	$(2)^+$
334.4	$(1,0)^\pm$	...	...	...	...	332±2	334.4	$(1,0)^+$
364.6	$(1,0)^\pm$	371±7	361±10	0+2	1^+	364±2	364.6	1^+
...	...	465±7	452±10	(2+4)	$(3)^+$	455±2	455	$(3)^+$
		568±9	558±10	(4)	$(4)^+$	...	560	$(4)^+$
(572.4)	$(1,0)^\pm$	...	...	...	...	...	(572.4)	$(1,0)^+$
...	...	606±9	597±10	(2+4)	$(3)^+$	...	600	$(3)^+$
669.7	$(1,0)^+$	681±7	667±10	(0+2)	$(1)^+$	...	669.7	$(1)^+$
...	...	796	779	...	...	...	...	...
(906.8?)	...	...	900	...	...	...	...	...
(937.0?)	...	940	943	...	...	...	...	...

corrected for L conversion, indicates that this transition is a mixture of $E2$ and $M1$. This is consistent with an assignment of $(1, 0)^+$ for the 61.4-keV level.

From the presently available experimental evidence from β decay it is not possible to limit further the possible spin and parity values $(1^\pm, 0^\pm)$ for the levels of 334.4, 364.6, and 572.4 keV on the basis of relative transition probabilities.

Recently Young and Rapaport[3] have studied the levels of ^{60}Cu populated in the reaction ^{58}Ni(^{3}He, p) and from angular distributions of the outgoing protons have assigned spin values to a number of states in ^{60}Cu. In Table III we summarize the pertinent information up to 940-keV excitation energy. In columns 1 and 2 we give the levels and the spin and parity assignment consistent with the logft values measured in this work. In column 3 we give the results of Miller and Kavanagh,[2] in column 4 we give the level energies of Young and Rapaport,[3] in columns 5 and 6 we give the orbital angular momentum transferred and the assigned level spin from the analysis of their angular-distribution data, and in column 7 we give the results of Birstein and coworkers[4] from the ^{60}Ni(p, $n\gamma$)^{60}Cu reaction. Finally, in the last two columns we summarize the best energy values for the levels up to 669.7 keV and the corresponding spins. From Table III it can be seen that the energy values from Ref. 3 are on the average about 3 keV lower than our values, while those from Ref. 2 are about 10 keV higher. Finally, the values from Ref. 4 agree within 1 keV with our values. It is interesting to point out that Young and Rapaport indicate that in the ^{58}Ni(^{3}He, p) reaction the states for which l values could be assigned correspond to mixed 0 and 2 transfer, to pure 2, or to higher l transfer. The first pure 0 transfer occurs in the excitation of the analog state at 2536 keV. It is tempting, therefore, to assume that states with l zero transfer are only very weakly excited. This suggests that states of spin 0 are not significantly populated. The state at 334.4 keV was not observed in the ^{58}Ni(^{3}He, p) reaction but was seen in the ^{60}Ni(p, $n\gamma$) reaction. From logft values this state must be 1^+ or 0^+, but we favor the value 0^+ on the above basis. A similar argument can be made for the tentative level at 572.4 keV, thus favoring the spin to 0^+.

B. Levels in ^{62}Cu

The spin for the ground state in ^{62}Cu has been determined from atomic-beam measurements to be 1 (see, e.g., Ref. 16). The 40.84-keV level is not populated by β^+ decay of the 9.3-h ^{62}Zn, and therefore it must have a spin 2 or higher. From internal-conversion data the $L_{\rm I}/(L_{\rm II}+L_{\rm III})$ ratio supports an $M1$ assignment for this transition, and this limits the spin and parity of this level to 2^+.

The levels at 243.43 and 287.86 keV are not populated by β decay. Lower limits for the logft values to these levels were calculated to be 7.0 and 6.8, respectively. We may therefore eliminate the 0^+ or 1^+ spin and parity assignments for these levels. The 243.2-keV transition is $M1$ in character, and this is consistent with the assignment of 2^+ for the 243.43-keV level. The 260.3-keV transition is $M1$ in character and the 548-keV level cannot have spin greater than 1^+, since it is populated by an allowed β transition. This excludes the value of 3^+ for the 287.86-keV level as a possibility and limits the spin and parity of this level to 2^+.

The 548.25- and 637.20-keV levels are populated in β decay with logft values of 4.7 and 4.5, respectively. This indicates that these transitions are allowed, and since ^{62}Zn has a spin and parity 0^+, this limits the assignment to these levels to 0^+ or 1^+. The internal conver-

[16] I. Lindgren, in *Perturbed Angular Correlations*, edited by E. Karlson, E. Matthias, and K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1964), Appendix 1.

sion coefficients calculated for the 260.3-, 507.2-, and 548.3-keV transitions indicate an $M1$ character for them. Of these, the first two populate levels of spin 2^+. This information excludes the value 0^+ as a possibility for the 548.25-keV level. Similarly, the 596.6-keV transition is $M1$ in character and populates the 2^+ level at 40.84 keV, thus excluding the 0^+ values as a possibility for the 637.2-keV level, limiting the assignment to 1^+.

Some of the lower-lying levels in ^{60}Cu and ^{62}Cu could be discussed in terms of shell-model configurations in the j-j coupling approximation. In the decay of both ^{60}Zn and ^{62}Zn we may expect primarily to populate states in transitions of a $2p_{3/2}$ proton into a neutron. The most likely configuration for the ground state of ^{60}Cu appears to be a member of $[p\colon 2p_{3/2};\, n\colon (2p_{3/2})^{-1}]_J$, with $J=2^+$ as predicted by the Brennan-Bernstein coupling rules[17] on the basis of the zero-range limit with a proton-neutron residual interaction of the form $V_{ij}=V_0(0.9+0.1\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\delta_{ij}$. With this interaction the 3^+ and 1^+ states of the above configuration lie higher than the 2^+ state, and the 0^+ member lies even higher. Other configurations that can give rise to excited states seen in the β decay of ^{60}Zn are $[p\colon (2p_{3/2});\, n\colon (2p_{3/2})_0{}^2(f_{5/2})^1]_J$ ($J=1^+$, 4^+, 2^+, 3^+ in order of increasing excitation in the above zero-range limit), $[p\colon (2p_{3/2});\, n\colon (2p_{3/2})_0{}^2(2p_{1/2})]_J$ ($J=1, 2$), and others. Since these configurations do not give rise to low-lying 0^+ states or negative-parity states, it appears safe to exclude the value of 0^+ as a possibility for negative-parity states at least for energies up to 570 keV.

In the case of ^{62}Cu similar configurations seem to be applicable. The ground state could be interpreted as $p\colon (2p_{3/2})\colon n\colon (2p_{3/2})^4(1f_{5/2})^1$ in agreement with the Brennan-Bernstein rule,[17] while the first excited state could be described as $p\colon (2p_{3/2})\colon n\colon (2p_{3/2})^{-1}(1f_{5/2})_0{}^2$. For a more detailed description of these nuclides a complete shell-model calculation using the effective-interaction approach[18] may be necessary. Before such a calculation becomes feasible, further experimental information about the low-lying states in the Cu isotopes will be required.

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[17] M. H. Brennan and A. M. Bernstein, Phys. Rev. **120**, 927 (1960).

[18] N. Auerbach, Phys. Rev. **163**, 1203 (1967).

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Decay Scheme of the 86-sec ^{61}Zn†

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The decay of the 86-sec ^{61}Zn has been investigated using Ge(Li) and NaI(Tl) γ-ray detectors. Coincidence relationships among the γ rays were established in γ-γ coincidence experiments. It was found from observed coincident γ rays that the decay of the 86-sec ^{61}Zn populates levels at 476.3, 970.7, 1311.1, 1661.4, 1908.1, 2090.9, 2359.2, 2474.3, 2684.7, 2793.7, 2841.5, and 2932.7 keV. Levels in ^{61}Cu at 1394.9, 1934.8, level 2858.1, 3016.8, and 3090.4 keV are proposed on the basis of observed γ-ray intensities, energy sums, and positions established from studies of nuclear reactions. May spin assignments have been made from present logft values and previously reported correlation data from studies of nuclear reactions. The half-life of ^{61}Zn was measured and found to be 85.9±0.6 sec. The levels in ^{61}Cu are compared with previously reported theoretical calculations based on current models for the nucleus.

I. INTRODUCTION

THE decay of ^{61}Zn was first investigated by Cumming,[1] who assigned levels at 0.48, 0.98, and 1.64 MeV populated mainly by positron emission in the decay of ^{61}Zn. The levels of ^{61}Cu have been studied, however, by a number of investigators by means of scattering experiments from a variety of nuclear reactions. The most recent and definitive such work is the study of triple correlations in the ^{60}Ni(p, $\gamma\gamma$) ^{61}Cu reaction by Gossett and August,[2] the (^{3}He, d) reaction studies of Blair,[2,3] and the ^{58}Ni(^{4}He, p) work of Brown and co-workers.[4]

The investigation of the decay scheme of the 86-sec

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[1] J. B. Cumming, Phys. Rev. **114**, 1600 (1959).

[2] C. R. Gossett and L. S. August, Phys. Rev. **137**, B381 (1964).

[3] A. G. Blair (private communication), referred to in Ref. 2.

[4] G. Brown, J. G. B. Haigh, F. R. Hudson, and A. E. Macgregor, Nucl. Phys. **A101**, 163 (1967).