Decay of Zinc-62*

E. BRUN,† W. E. MEYERHOF, J. J. KRAUSHAAR,‡ AND D. J. HOREN
Stanford University, Stanford, California
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The excited levels of Cu^{62} have been investigated by studying the radiations from the decay of Zn^{62} with scintillation spectrometers. Gamma rays of 0.042-, 0.25-, 0.26-, 0.40-, 0.51-, and 0.59-Mev energy have been resolved and have been fitted into a consistent scheme of levels at 0.042, 0.30, 0.55, 0.63, and 0.70 Mev in Cu^{62}. Some information on the spins of these levels has been obtained by gamma-gamma directional correlation measurements.

Information on some gamma rays from the decay of Cu^{62} has also been obtained.

I. INTRODUCTION

THE energy levels of nuclei in the region of the periodic table from Ni to As are of interest from a shell-model point of view. In this region, beyond the magic nucleon number 28,[1–3] it may be possible to make shell-model calculations involving $2p_{\frac{3}{2}}$, $1f_{\frac{5}{2}}$, and perhaps higher configurations.[4] Cu^{62} is one of the few odd-odd nuclei in this region whose levels are accessible by radioactive decay. Initially an additional reason for undertaking the study of the decay of Zn^{62}, and incidentally Cu^{62} (see Appendix), was the previously existing discrepancy in the Cu^{62}-Ni^{62} mass difference[5] as inferred from mass spectroscopic and nuclear measurements. The masses have recently been remeasured[6] and no further mass discrepancy appears to exist.

Previous work on the decay of Zn^{62} has been summarized recently,[7] and original references will be mentioned below only if pertinent.

II. SOURCE PREPARATION

Sources of Zn^{62} and Cu^{62} in equilibrium (henceforth denoted by $Zn^{62}+Cu^{62}$) were made by the $(\gamma,2n)$ reaction on enriched[8] Zn^{64}, using the Stanford Mark II and Mark IV linear electron accelerators at about 33 and 45 Mev, respectively. The zinc was available both as a powdered oxide and as thin metallic foils. Measurements were started about six hours after the end of each bombardment, which allowed the 38-minute Zn^{63} to decay.

An attempt was made to produce a strong Zn^{62} source by a $(p,2n)$ reaction on enriched[9] Cu^{63}, using the Berkeley linear proton accelerator at 30 Mev. Unfortunately the source was weaker than the Zn^{64} $(\gamma,2n)$ sources.

Sources of Cu^{62} were obtained by the (γ,n) reaction on enriched Cu^{63} foils, using the Stanford Mark II linear electron accelerator at 25 to 33 Mev.

III. APPARATUS

Anthracene and sodium-iodide scintillation crystals were used for detecting the beta and gamma rays. A fast-slow coincidence circuit in conjunction with a 20-channel pulse-height analyzer, previously described,[10] was used for most of the present measurements.

For the half-life measurement of the 0.042-Mev state of Cu^{62} the time-to-pulse-height converter of Weber *et al.*[11] was used, with modifications proposed by the University of California Radiation Laboratory, Livermore, California.[12]

IV. BETA-RAY MEASUREMENTS

A. Previous Results

Hayward[13] and Nussbaum[5,7] have measured the intensity ratio of the positrons from Zn^{62} to the positrons from Cu^{62} in the $Zn^{62}+Cu^{62}$ decay and found, respectively, values of ~0.10 and ~0.14. The end point of the Zn^{62} spectrum was found to be 0.66 ± 0.01 Mev[13] and 0.675 ± 0.10 Mev[5,7] and that of the Cu^{62} spectrum 2.92 ± 0.02 Mev[13] and 2.91 ± 0.01 Mev.[5]

Conversion electrons have been found for a transition of 0.0418 ± 0.002[13] or 0.0413 ± 0.003 Mev,[5] which comes from an excited state of Cu^{62}. Nussbaum *et al.*[5] have measured the *K* conversion coefficient of this transition

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† Now at the Department of Physics, University of Zurich, Zurich, Switzerland.
‡ Now at the Department of Physics, University of Colorado, Boulder, Colorado.
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[3] R. H. Nussbaum, Revs. Modern Phys. **28**, 423 (1956).
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[6] Quisenberry, Scolman, and Nier, Phys. Rev. **104**, 461 (1956). We are indebted to Mr. K. S. Quisenberry for communicating his results to us prior to publication.
[7] *Nuclear Level Schemes*, $A=40-A=92$, compiled by Way, King, McGinnis, and van Lieshout, Atomic Energy Commission Report TID-5300, June 1955 (U. S. Government Printing Office, Washington, D. C., 1955).
[8] On loan from the Stable Isotopes Division, Oak Ridge National Laboratory. The composition of the target was 93.1% Zn^{64}, 6.3% Zn^{66}, 0.16% Zn^{67}, 0.43% Zn^{68}.
[9] On loan from the Stable Isotopes Division, Oak Ridge National Laboratory. The composition of the target was 99.4% Cu^{63} and 0.6% Cu^{65}.
[10] Kraushaar, Brun, and Meyerhof, Phys. Rev. **101**, 139 (1956).
[11] Weber, Johnstone, and Cranberg, Rev. Sci. Instr. **27**, 166 (1956).
[12] L. G. Mann (private communication).
[13] R. W. Hayward, Phys. Rev. **79**, 541 (1950).

and found it to be 0.49 ± 0.08[14] with $K/(L+M)=8.0\pm1.5$, indicating a predominantly $M1$ character.

B. Beta-Gamma Coincidences

It had been assumed previously[7] that an appreciable part of the Zn^{62} positron spectrum feeds the 0.042-Mev excited state of Cu^{62}. To check this we performed three separate experiments, each of which indicated no positron feeding within the detection sensitivity of the experiment.

In the first experiment a $Zn^{62}+Cu^{62}$ source in the form of a metallic foil (20 mg/cm² thick) was placed between a $\frac{1}{4}$-in.×1-in. diameter anthracene crystal covered with a 1-mil Al foil and a $1\frac{1}{2}$-in.×$1\frac{1}{2}$-in.-diameter sodium-iodide crystal in a $\frac{1}{32}$-in. Al container, and covered with $\frac{3}{32}$-in. Lucite. Beta-gamma coincidences were measured between all the positrons entering the anthracene crystal and gamma rays entering sodium-iodide crystal. The coincident gamma-ray pulse spectrum near 0.04 Mev was displayed on the pulse-height analyzer. 288 ± 43 coincident 0.042-Mev gamma rays were detected in 6 minutes. A $\frac{1}{8}$-in. Lucite absorber was then placed over the $Zn^{62}+Cu^{62}$ source to annihilate the positrons. An average of two determinations yielded a value of 328 ± 26 coincident 0.042-Mev gamma rays for a 6-minute period. From these results, the self-absorption of the beta and gamma rays in the source and the detection efficiency of the anthracene and sodium-iodide crystals for the 0.042-Mev and coincident gamma rays (see Sec. V, C), it is possible to set an upper limit for the positron branching to the 0.042-Mev state of Cu^{62}. Using the absolute gamma-ray intensities from the Zn^{62} decay scheme (shown below), the upper limit for the positron branch is found to be 0.45% of the total disintegrations of Zn^{62}.

In a second experiment a $Zn^{62}+Cu^{62}$ source in the form of a metallic foil 20 mg/cm² thick was suspended in tissue paper between two counters at 90° with respect to each other. One sodium-iodide detector ($\frac{1}{4}$ in.×$\frac{7}{8}$ in.×1 in.) was set to detect only pulses near 0.042 Mev (channel width = 0.008 Mev). The coincident pulses in the other sodium-iodide detector ($1\frac{1}{2}$ in.×$1\frac{1}{2}$ in. diameter) were displayed on the pulse-height analyzer. Gamma rays of 0.51 and 0.59 Mev were resolved (see Fig. 4 for a complete pulse-height spectrum for a similar experiment). To subtract coincident gamma-ray pulses due to the Compton distribution of higher-energy gamma rays beneath the 0.042-Mev photopeak, the small sodium-iodide detector was set to detect pulses near 0.06 Mev (channel width = 0.008 Mev). The net intensity ratio of the 0.51- to 0.59-Mev gamma rays was found to be 0.47 ± 0.06. After surrounding the Zn^{62} source with $\frac{1}{8}$-in. Lucite absorbers to annihilate the positrons, the same ratio was found to be 0.51 ± 0.03. From these results and the known intensity of the 0.51-Mev gamma ray (not to be confused with annihilation photons; see below), it is possible to set an upper limit of 2.3% for the positron branching to the 0.042-Mev level of Cu^{62}.

In a third experiment, a $Zn^{62}+Cu^{62}$ source in the form of several metallic foils, sandwiched between $\frac{1}{8}$-in. Lucite absorbers, was placed in the position normally occupied by the center crystal in a three-crystal pair spectrometer.[15] The side crystals were biased, in the usual fashion, to detect only the photopeaks of annihilation quanta. The center crystal was withdrawn until it was out of line with the side crystals. The coincidence pulses detected in the center crystals were displayed on the pulse-height analyzer. No coincident 0.042-Mev gamma ray was observed. The sensitivity of the experiment was determined by measuring the number 1.28-Mev gamma rays in coincidence with positrons in a similarly placed Na^{22} source. In this way it was found that less than 0.3% of the total number of positrons in the $Zn^{62}+Cu^{62}$ source could be in coincidence with the 0.042-Mev gamma rays. Correcting this for the ratio of the number of positrons in $Zn^{62}+Cu^{62}$ to Zn^{62} and for the internal conversion coefficient of the 0.042-Mev gamma ray, showed that the positron branch to the 0.042-Mev state in Cu^{62} is less than 0.6% of the decays.

In conclusion, the three separate experiments are consistent and indicate an upper limit of 0.45% to any possible positron feeding of the 0.042-Mev state of Cu^{62}. If one assumes an (allowed) ϵ/β^+ ratio[16,17] of 3.2, an upper limit of about 2% can be set for the total $\epsilon+\beta^+$ feeding of this state.

V. GAMMA-RAY MEASUREMENTS

A. Previous Results

Nussbaum *et al.*[5] have reported the intensity of the 0.042-Mev gamma ray to be $9.7\pm0.7\%$ of the total number of 0.51-Mev quanta in $Zn^{62}+Cu^{62}$. Although no other gamma rays from Zn^{62} have been reported, an indication of branching to higher excited states of Cu^{62} has been noted.[7]

B. Gamma-Ray Spectrum

The gamma-ray spectrum of Zn^{62} can be obtained only by subtracting a properly normalized Cu^{62} gamma-ray spectrum from a $Zn^{62}+Cu^{62}$ spectrum, measured under identical conditions. Because of the presence of the easily absorbed 0.042-Mev gamma ray, slightly different normalizing methods were used for the high-energy and low-energy parts of the gamma-ray spectrum.

In order to obtain a pure $Zn^{62}+Cu^{62}$ gamma-ray spectrum from our $Zn(\gamma)$ sources, which contained an appreciable amount of 245-day Zn^{65} [produced by $Zn^{66}(\gamma,n)$; see reference 8], a background gamma-ray

[14] This value has been calculated from the original value in reference 5 ($\alpha_K=0.52\pm0.08$) correcting for the presence of a 0.51-Mev gamma ray in Zn^{62}. (See Sec. V, B.)

[15] H. I. West, Jr., and L. G. Mann, Rev. Sci. Instr. 25, 129 (1954).

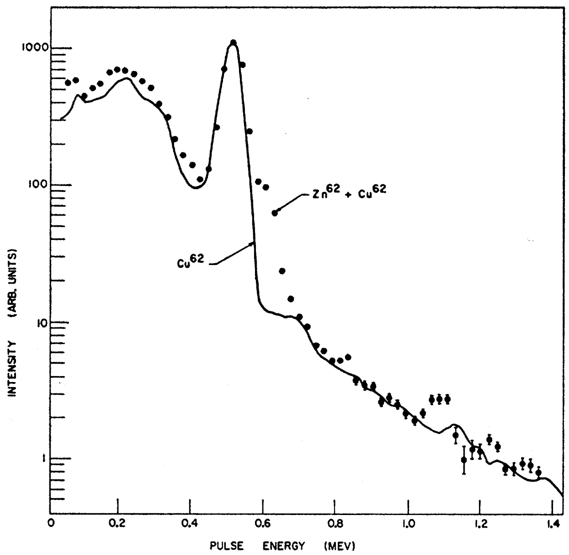

FIG. 1. Gamma-ray spectrum of $Zn^{62}+Cu^{62}$ and of Cu^{62}. The points refer to $Zn^{62}+Cu^{62}$ and the line refers to the spectrum of Cu^{62}, normalized to the $Zn^{62}+Cu^{62}$ spectrum by total counts above 1.4 Mev. Both sources were placed between $\frac{1}{16}$-in. copper absorbers. See Table I for a summary of the spectrum analysis.

spectrum was subtracted about three days after the original spectrum was taken. Figure 1 shows the resulting high-energy spectrum for $Zn^{62}+Cu^{62}$, with the source placed between $\frac{1}{16}$-in. copper absorbers, which is enough to produce complete annihilation of the positrons. On the same figure the Cu^{62} spectrum is shown, normalized to the $Zn^{62}+Cu^{62}$ spectrum by matching the total counts above 1.4 Mev. Since the decay energy[7] of Zn^{62} is 1.7 Mev, it is to be expected that practically all the counts above 1.4 Mev in a $Zn^{62}+Cu^{62}$ spectrum are due to gamma rays, bremsstrahlung, and annihilation in flight of the positrons of Cu^{62} alone, which has a decay energy[7] of 3.9 Mev. Hence the total counts above 1.4 Mev provide a convenient normalization for the two spectra. The presence of 0.25-, 0.40-, and 0.59-Mev gamma rays due to Zn^{62} can be noted on Fig. 1. Excess counts near 0.8 Mev appear to be spurious, since the *half*-width of a 0.8-Mev gamma-ray photopeak should be equal to three channels, i.e., three points on the curve. Excess counts near 1.1 Mev are probably also spurious, since a small gain shift in the Zn^{65} background spectrum could cause an apparent peak near this energy.

The low-energy gamma-ray spectrum of Zn^{62} was obtained by suspending identical foils (54 mg/cm^2) of zinc ($Zn^{62}+Cu^{62}$) and copper (Cu^{62}) in tissue paper in front of the sodium-iodide detector. Since the high-energy positrons from Cu^{62} could easily enter the crystal (canister wall $\frac{1}{32}$-in. Al+$\frac{1}{32}$-in. MgO) and since the Zn^{62} positrons have an upper limit[7] of 0.7 Mev, the total counts above 0.7 Mev provided a convenient normalization of the $Zn^{62}+Cu^{62}$ and Cu^{62} spectra. Figure 2 shows the subtraction of these two spectra after normalization. Gamma rays of 0.04, 0.25, 0.39, and 0.59 Mev are apparent on the figure. A possible 0.55-Mev gamma ray (see Sec. VI, A) cannot be excluded.

Comparison with the known[5,13] positron intensity in Zn^{62} shows the annihilation peak in Fig. 2 to be excessively high. We believe this is due to the presence of Cu^{64}, produced by the $Zn^{66}(\gamma,pn)$ reaction. As will be indicated below, our determination of the absolute branching ratios of Zn^{62} gamma rays is independent of the presence of this Cu^{64} impurity. From the way in which Fig. 2 was obtained, it is clear that some Zn^{62} positrons will contribute to the total spectrum. Hence, in the case of the weaker gamma rays only a rough intensity determination is possible from these data.

Table I summarizes the energies and intensities of the gamma rays found in the above-mentioned experiments. Upper limits for some gamma rays which could occur in the Zn^{62} decay are also given. Since the aforementioned normalization of the Cu^{62} gamma-ray spectra to the $Zn^{62}+Cu^{62}$ spectra allows a determination of the number of Cu^{62} positrons in equilibrium with Zn^{62}, this number is also given; it will be used below to calculate an absolute branching of the Zn^{62} gamma rays. The intensity values in Table I have of course been corrected for all absorption and detection effects.

C. Gamma-Gamma Coincidence Spectra

The prompt gamma-gamma coincidence spectra were measured in the geometry shown in Fig. 3. The $Zn^{62}+Cu^{62}$ sources were made relatively thin (0.1 g/cm^2) to avoid, as much as possible, coincidences resulting from Compton scattering of annihilation radiation in the sources and to minimize the absorption of the gamma rays. As a consequence of this arrangement, some positrons underwent annihilation in or near a counter and produced 0.51-Mev-gamma–0.51-Mev-gamma coincidences despite the $\frac{1}{2}$-in. thick lead shield between the counters.

For the 0.042-Mev gamma-gamma coincidence spectrum a $\frac{1}{4}$-in. thick NaI crystal was used for the detection of the 0.042-Mev gamma ray. For the other measurements both the NaI crystals were $1\frac{1}{2}$ in. thick. The use of the $\frac{1}{4}$-in. crystal for the 0.042-Mev gamma-gamma

TABLE I. Zn^{62} gamma-ray data from singles spectra.

Energy (Mev)	Intensity (relative)
0.70	$\leqslant 6$
0.63	$\leqslant 5$
0.595±0.010	100
0.55	$\leqslant 34$
0.40±0.02	5±3
0.25±0.01[a]	13±4
0.0416±0.002[b]	95±5
Cu^{62} positrons in equilibrium with Zn^{62} [c]	455±15

[a] Composite gamma ray.
[b] Energy from references 5 and 13.
[c] See text (Sec. V, B).

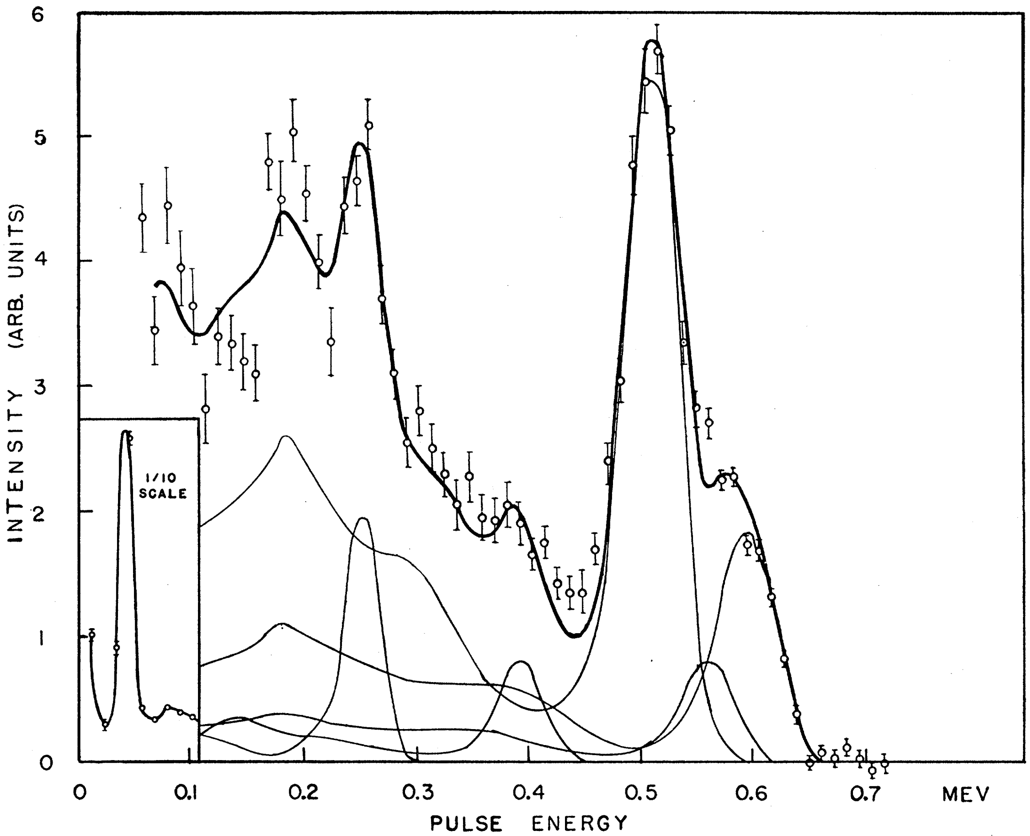

FIG. 2. Low-energy portion of Zn^{62} spectrum. This spectrum was obtained by subtracting a Cu^{62} spectrum from a $Zn^{62}+Cu^{62}$ spectrum in identical geometry. (See text for normalization procedure.) No absorber was placed between the sources and the detector, in order to emphasize the 0.042-Mev gamma ray. The circles are the experimental points; the full line is the sum of the analyzed distributions shown.

coincidence spectrum reduced the number of coincidences due to Compton pulses near 0.04 Mev from higher energy gamma rays.

Figure 4 shows the original coincidence data. A $Zn^{62}+Cu^{62}$ singles spectrum, curve (A), is shown for comparison. Curve (B) shows that 0.042-Mev gamma rays are coincident with 0.26-, 0.51-, and 0.59-Mev gamma rays. Since positrons are not in coincidence with the 0.042-Mev gamma ray, as far as could be detected (see Sec. IV, B), the peak at 0.51 Mev must be due either to scattering effects or to nuclear gamma rays. To test the first possibility, a 0.06-Mev gamma-gamma coincidence spectrum was measured. The resulting spectrum is shown in curve (C) in Fig. 6 after proper normalization to curve (B). It can be seen that by far the major part of the peak at 0.51 Mev is not due to scattering effects and hence must be due to a transition between levels in Cu^{62}. The appearance of a small peak at 0.04 Mev in curve (B) is due to Compton pulses from higher energy gamma rays in the discriminating crystal.

Curve (D) shows that 0.04-, 0.26-, 0.40-, and 0.51-Mev gamma rays are coincident with 0.25-Mev gamma rays. Detailed comparison with curves (E) to (G) showed that the peak at 0.51-Mev in curve (D) is due to the Compton pulses of annihilation quanta or higher energy gamma rays from Cu^{62} (see Appendix) in the discriminating crystal.

The appearance of a peak at 0.26 Mev in curve (D) is most reasonably interpreted as the result of two gamma rays of about 0.25 to 0.26 Mev being in cascade, which could not be resolved in singles work. The possibility of such a peak being due to Compton scattering of annihilation radiation was eliminated by coincidence work described later in connection with the directional correlation measurements.

Curves (E) to (G) of Fig. 4 are self-explanatory for the most part. The small peak near 0.08 Mev in curve (F) is due to lead x-rays.

The coincidence spectra, shown in Fig. 4, were analyzed in detail in order to obtain the relative intensities of the coincident gamma rays. Table II shows the results of this analysis. The only features brought out by this analysis, which are not directly obvious from Fig. 4 are (a) the presence of a low-intensity gamma ray of 0.40 Mev in curve (B), and (b) the Compton contribution from higher energy gamma rays, which fell within the discriminating energy band selected, to various coincidence peaks. As an

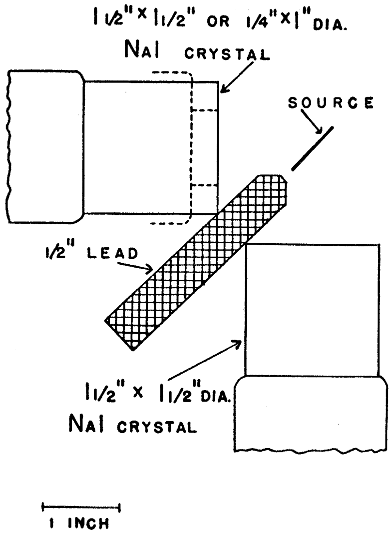

FIG. 3. Geometry used in gamma-gamma coincidence measurements.

example of this latter effect, in the 0.40-Mev gamma-gamma coincidence spectrum [curve (*E*)], approximately 85% of the peak at 0.042 Mev is due to the Compton contribution of the 0.51- and 0.59-Mev gamma rays. Table II includes correction for effect (b), as well as corrections for the angular anisotropy of the coincidences in some of the cascades (see Sec. V, E).

The relative intensity of the 0.40-Mev gamma ray in the decay scheme was obtained only with very poor accuracy from the analysis of curve (*B*) (see column 2, Table II). In order to get a better estimate of this intensity the various coincidence spectra were normalized by correcting the coincidence rates for the detection efficiencies in the discriminating counter. By then comparing the 0.40–0.04-Mev cascade intensity with the 0.59–0.04-Mev cascade it was possible to obtain a value of 0.05±0.03 for the ratio of the intensity of the 0.40-Mev to the 0.59-Mev gamma ray. This result was combined with the results in Table II and used for the final decay scheme. The absolute comparison of the coincidence spectra also served as a valuable consistency check for the various experiments and for the corrections that were applied.

TABLE II. Relative intensities of coincident gamma rays in Zn^{62}.

Discriminating γ ray (Mev)	0.042	0.25	0.40	0.51	0.59
Channel width (Mev)	0.008	0.04	0.04	0.04	0.04
Coincident γ ray (energy in Mev)					
0.042[a]	···	0.4±0.1[b]	0.3±0.2[b]	1.00[b]	1.00
0.08	···	≤0.1	···	≤0.03	···
0.15	···	≤0.1	···	≤0.15	···
0.26±0.01	0.085±0.02[b]	0.38±0.04[bcd]	1.00[c]	···	···
0.30	···	≤0.2	≤0.08	···	···
0.33	···	≤0.3	···	···	···
0.40±0.01	0.2±0.2[b]	1.00[c]	···	···	···
0.51±0.01	0.51±0.03[e]	···	···	···	···
0.59±0.01	1.00	···	···	···	···
0.66	≤0.02	···	···	···	···

[a] Energy used for calibration.
[b] Intensity corrected for contribution from Compton pulses in discriminating crystal.
[c] Intensity corrected for angular anisotropy.
[d] Intensity obtained from angular correlation measurements (see Sec. V, E).
[e] Error calculated from four separate experiments.

D. Half-Life of the 0.04-Mev State of Cu^{62}

Using a time-to-pulse-height converter[11,12] in conjunction with $\frac{1}{8}$-in. thick and $1\frac{1}{2}$-in. thick NaI crystals mounted on RCA 6810 photomultipliers, an attempt was made to measure the half-life of the 0.042-Mev excited state of Cu^{62}. The thin crystal was differentially biased, to detect pulses near 0.04 Mev and the thick crystal was biased to detect pulses near 0.60 Mev. An upper limit of 8×10^{-9} sec could be set on the half-life of the 0.04-Mev state.

E. Gamma-Gamma Directional Correlation Experiments

Of the various gamma-ray cascades in the decay of Zn^{62} the only two that were reasonably adaptable to directional correlation measurements were the 0.04–0.59-Mev and the 0.25–0.26-Mev cascades (see Fig. 4).

The counters and electronic apparatus were the same as those used in coincidence work (Sec. V, C). As before, the 0.04-Mev gamma ray was detected in the $\frac{1}{4}$-in. thick NaI crystal and the other gamma rays in the $1\frac{1}{2}$-in. thick NaI crystal. Lead shields surrounded both the sides and front of each counter.

A preliminary directional correlation was performed on the 0.04–0.59-Mev gamma-ray cascade with the source in the form of ZnO powder held in a Lucite cylinder of $\frac{1}{4}$-in. inside diameter, and $\frac{1}{32}$-in. wall thickness. The differential discriminator was positioned to cover the photopeak of the 0.042-Mev gamma ray. The coincidence spectrum from about 0.45 to 0.75 Mev was displayed on the 20-channel pulse-height analyzer. Coincidence spectra were obtained at 90°, 130°, 150°, 210°, 230°, and 270° with equal frequency. The total number of counts in the peak at 0.59 Mev was determined from each spectrum. The averaged values for the anistropy were thus found to be $\epsilon(130°)=-0.01_4\pm0.03_9$ and $\epsilon(150°)=0.01_0\pm0.03_5$.

Because of the predominantly dipole character of the 0.04-Mev transition (see Sec. IV, A) it is necessary to consider only an angular distribution of the form $W(\theta)=1+a_2\cos^2\theta$. A least-squares fit to the experimental points corrected for the finite angular resolution of the apparatus yielded $a_2=0.00_3\pm0.04_3$. Because of the rather large amount of scattering of the 0.04-Mev gamma ray, that took place in the source, it was estimated that the value of a_2 should be increased by about 15%. To minimize possible extranuclear perturbations of this angular correlation, measurements were repeated with the ZnO source dissolved in nitric acid. The Lucite source holder for the liquid had a $\frac{1}{8}$-in. inside diameter and a 0.030-in. wall thickness. After correcting for geometry and scattering it was found that $a_2=0.05_6\pm0.06_3$. The liquid-source data was also analyzed for the 0.04–0.51-Mev gamma-ray directional correlation. The 0.51-Mev photopeak areas were measured after subtracting the contribution from the Compton distribution of the 0.59-Mev gamma ray. A value of $a_2=0.34\pm0.09$ was obtained after correcting for the geometry and scattering. Unfortunately this value must also be corrected for the presence of 0.51-Mev gamma-ray coincidences resulting from the Compton background of high-energy gamma rays and annihilation quanta beneath the 0.04-Mev photopeak. The contribution of this effect to the coincident 0.51-Mev photopeak was about 15 to 20 % when the counters were at 90°, but higher at 150°. Because of the difficulty of making accurate corrections the anisotropy of the 0.04–0.51-Mev gamma-ray cascade was finally used only to exclude spin sequences that resulted in more positive anisotropies.

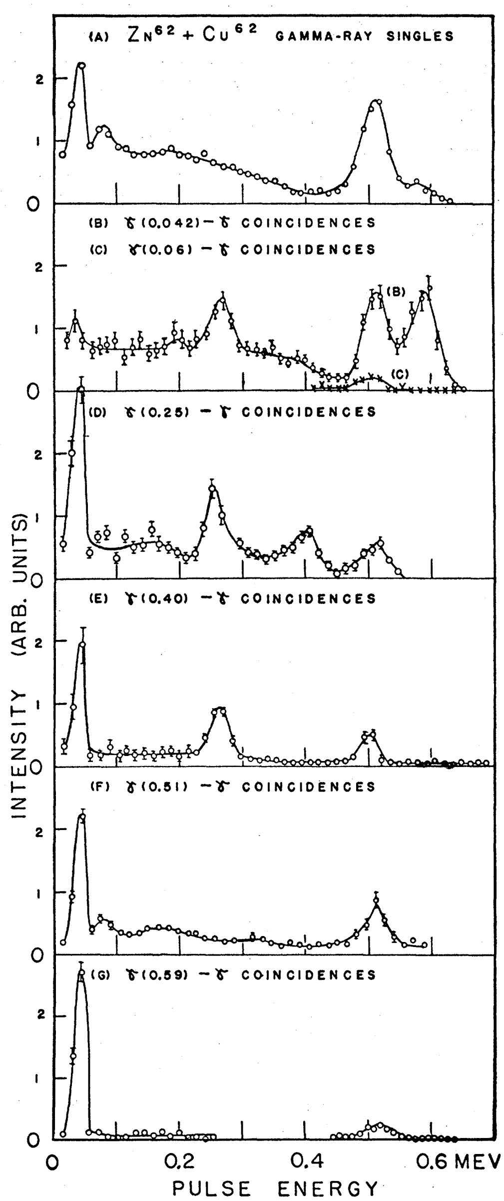

FIG. 4. Gamma-gamma coincidence spectra. See Table II for a summary of the analysis of these spectra.

The 0.25–0.26-Mev gamma-ray directional correlation was measured by differentially biasing the discriminating detector near 0.25 Mev and by displaying the coincidence spectrum from 0.14 to 0.58 Mev on the pulse-height analyzer. The source and holder were the same as used for the preliminary 0.04–0.59-Mev gamma-ray directional correlation. Because of the large Compton contribution of the annihilation radiation beneath the 0.25- and 0.26-Mev photopeaks in the discriminating crystal it was necessary to make a careful subtraction of the coincidence spectrum due to annihilation radiation under identical conditions.

To make the proper subtraction, a Cu^{62} source was made and mixed in with a quantity of unactivated ZnO equal to the amount used for the actual measurements. With the discriminator positioned as before, the coincidence spectrum was run at the various angles. The resulting spectra were subtracted from the $Zn^{62}+Cu^{62}$ coincidence spectra after normalizing to the areas of the 0.51-Mev photopeaks. A coincident 0.40-Mev gamma-ray spectrum then also had to be subtracted from the resulting coincidence spectrum [see Fig. 4 (D)].

The number of counts in 0.26- and 0.25-Mev coincidence photopeaks was furthermore corrected for the Compton contribution of 0.40–0.26-Mev gamma-ray coincidences. The final calculated anisotropy from the corrected number of counts in the 0.26- and 0.25-Mev photopeaks was $\epsilon(130°)=-0.16_7\pm0.05_5$ and $\epsilon(150°)=-0.07_7\pm0.06_7$ at 150°. A least-squares fit to a $\cos^2\theta$ distribution, corrected for the angular resolution, gave $a_2=-0.23\pm0.09$. If a $\cos^4\theta$ term is included, one finds $a_2=-1.2_5\pm0.3_5$ and $a_4=1.4_6\pm0.4_3$.

Unfortunately it was impossible to determine a meaningful anisotropy for the 0.26–0.40-Mev gamma-ray directional correlation. Large errors resulted from the low intensity of the 0.40-Mev line and the large 0.51-Mev Compton backgrounds. The data were analyzed, however, to obtain a ratio for the intensity of the 0.25–0.26 Mev cascade relative to the 0.40–0.26 Mev cascade. After making the usual corrections, the ratio was found to be 0.38 ± 0.04. This value was computed by combining the data at 90°, 130°, 150°, 210°, 230°, and 270°, so no further directional correlation correction was applied (see Table II).

VI. CONCLUSIONS

A. Decay Scheme of Zn^{62}

The gamma-ray intensities, given in Table I, were expressed in absolute branching ratios of the Zn^{62} decay, by assuming that most of the Cu^{62} positrons go to the ground state of Ni^{62}. The total Cu^{62} positron-plus-

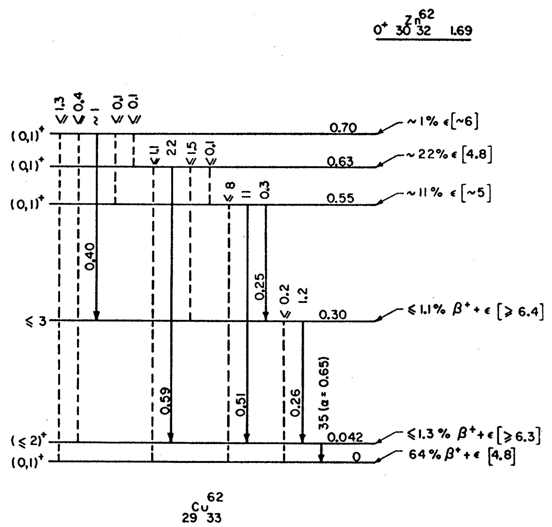

FIG. 5. Decay scheme of Zn^{62}. Gamma rays shown in dotted lines have not been detected and only upper limits for their intensity are given. Gamma-ray and level energies are in Mev; intensities in percent decay. Log*ft* values are given in square brackets. See Tables III and IV for errors on gamma-ray energies, intensities and branching ratios and Table V for possible spin assignments. The decay of Cu^{62} is discussed in the Appendix. See also note added in proof after reference 18.

electron-capture intensity (for the ground-state transition $\epsilon/\beta^+=0.022$)[16,17] is then equal to the total Zn^{62}-decay intensity, in the units of Table I. As shown in the Appendix, most of the Cu^{62} decays indeed lead to the ground state of Ni^{62}, so that this normalization is accurate to a few percent.

The data in Table II were used to construct the decay scheme shown in Fig. 5. The absolute branching ratios of the gamma rays, together with the experimental errors, are given in Table III. Within the errors, the decay scheme of Fig. 5 is consistent.

TABLE III. Absolute branching ratios of Zn^{62} gamma rays.

Energy (Mev)	Branching ratio (percent)
0.70	$\leqslant 1.3$
0.66	$\leqslant 0.4$
0.63	$\leqslant 1.1$
0.595 ± 0.010	21.5 ± 0.5
0.55	$\leqslant 7$
0.51 ± 0.01	11.0 ± 0.7
0.40 ± 0.01	0.9 ± 0.7
0.33	$\leqslant 1.5$
0.30	$\leqslant 0.2$
0.26 ± 0.01	1.2 ± 0.6
0.25 ± 0.01	$0.3_2\pm0.2_5$
0.15	$\leqslant 0.1$
0.08	$\leqslant 0.1$
0.0416 ± 0.002[a]	20.5 ± 1.1

[a] Energy from references 5 and 13.

[16] P. F. Zweifel, Phys. Rev. **96**, 1572 (1954). We are indebted to Dr. Zweifel for communicating to us certain corrections to his table prior to publication. [See P. F. Zweifel, Phys. Rev. **107**, 329 (1957).]

[17] M. E. Rose and J. L. Jackson, Phys. Rev. **76**, 1540 (1949).

Since the presence of Cu^{64} (see Fig. 2) did not allow a measurement of the ratio $\beta^+(Zn^{62})/\beta^+(Cu^{62})$, the value 0.14 of Nussbaum *et al.*[5] was assumed. [It should be mentioned, though, that this value affects only our derived ϵ/β^+ ratio for the ground-state transition of Zn^{62} (see Sec. VI, B) and nothing else.] With this ratio, we find also that the intensity of the 0.042-Mev *gamma rays* relative to the total number of 0.51-Mev quanta in $Zn^{62}+Cu^{62}$ is $8.6\pm0.5\%$, which can be compared with Nussbaum's value[5] of $9.7\pm0.7\%$.

B. Beta Decay

Table IV gives the branching ratios and log*ft* of the various transitions from Zn^{62} to Cu^{62}. Since for some of the gamma-ray intensities only upper limits could be set, the log*ft* values are necessarily approximate. Nevertheless one is probably justified in concluding that all the transitions, except to 0.042- and 0.30-Mev levels, are allowed and that the latter are perhaps forbidden. Hence the spins and parities of all the states of Cu^{62}, except the 0.042- and 0.30-Mev levels should be 0^+ or 1^+.

TABLE IV. Zn^{62} branching ratios to Cu^{62}.

Cu^{62} level (Mev)	Branching ratio (percent)	Log*ft*
0	66_{-5}^{+15}	4.8
0.042	$\leqslant 1.3$	$\geqslant 6.4$
0.30	$\leqslant 1.1$	$\geqslant 6.3$
0.55	11_{-2}^{+8}	~ 5
0.63	22_{-1}^{+2}	4.8
0.70	$0.9_{-0.7}^{+2.6}$	~ 6

Our results (Sec. IV, B) show that practically only the ground state of Cu^{62} is populated by positron decay from Zn^{62}. Balancing the intensities of total decays reaching the ground state and leaving it, we can calculate an ϵ/β^+ ratio of $3.7_{-0.4}^{+1.2}$ for the ground-state transition from Zn^{62} to Cu^{62}. This can be compared with the theoretical value[16,17] of 2.7 for an allowed transition. The experimental value assumes that the ratio[5] $\beta^+(Zn^{62})/\beta^+(Cu^{62})=0.14$; if this value were 0.18, good agreement with the theoretical ϵ/β^+ value would be obtained.

C. Conversion Coefficients

The intensity balance for the gamma rays leading to and from the 0.042-Mev level allows the conclusion that the total conversion coefficient of the 0.042-Mev transition is $\alpha_{tot}=0.65\pm0.10$. This can be compared with Nussbaum's value[5,14] (see Sec. IV, A) $\alpha_{tot}=0.55\pm0.09$ and the theoretical values[18]§ $\alpha_{tot}(M1)=0.61$ and

[18] M. E. Rose, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, New York, 1956). Using privately circulated tables of Rose, Goertzel, and Swift, it is possible to compare the experimental $K/(L+M)=8.0\pm1.5$ (reference 5) with the theoretical values $K/L=9.6$ and 6.4 for a $M1$ and $E2$ transition of 0.042 Mev, respectively.

§ *Note added in proof.*—The authors are very grateful to Dr. A. H. Wapstra for pointing out that the experimental conversion coeffi-

$\alpha_{tot}(E2)=16$. It can be concluded that the 0.042-Mev transition is predominantly $M1$ with at most 1% $E2$ admixture and that the parity of the 0.042-Mev state is even, since the ground-state parity is even. Hence, if the positron-plus-capture transition from Zn^{62} to the 0.042-Mev state is indeed forbidden (see Table IV), it must be second forbidden, and the spin of the ground state of Cu^{62} must then be 1^+ and that of the 0.042-Mev state 2^+. In any case, the spin of the 0.042-Mev level cannot be greater than 2^+.

D. Lifetime-Energy Relationship

It can hardly be expected that for a nucleus as complex as Cu^{62} gamma-ray transition probabilities can be predicted from the "single-particle" formula of Weisskopf.[19] Nevertheless it is probably reasonable to conclude that, since transitions from the upper (0^+ or 1^+) states of Cu^{62} to the 0.30-Mev state compete successfully with transitions from these states to ground or first excited states (spins $\leqslant 1^+$ and $\leqslant 2^+$), the spin of the 0.30-Mev state is not greater than 3.

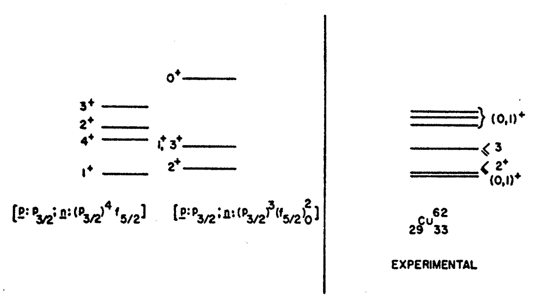

FIG. 6. Comparison of Cu^{62} levels with predictions of the zero-range odd-odd model (see references 23 and 26). The left side of the figure shows the predicted levels for two assumed proton-neutron configurations with a proton-neutron interaction of the form $V_{ij}=V_0[1+0.1\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j]\delta_{ij}$. The energy match to the experimental levels is completely arbitrary and indicates only one possible correspondence. The predicted absence of a low-lying spin-0 state may be noted.

The measured upper limit of 8×10^{-9} sec for the half-life of the 0.042-Mev state can be compared with the value $\sim3.5\times10^{-10}$ sec for an $M1$ transition and $\sim1.5\times10^{-4}$ sec for an $E2$ transition, calculated from the Weisskopf formula.[19] A more refined theoretical calculation on the basis of a shell-model configuration $[\mathbf{p}: p_{\frac{3}{2}}; \mathbf{n}: (p_{\frac{3}{2}})^4 f_{\frac{5}{2}}]_2$ for the 0.042-Mev state and $[\mathbf{p}: p_{\frac{3}{2}}; \mathbf{n}: (p_{\frac{3}{2}})^4 f_{\frac{5}{2}}]_1$ for the ground state of Cu^{62} happens to give the same numerical values.[20] The configurations for the 0.042-Mev state could be different, though (see Sec. VI, F and Fig. 6).

cients by themselves could hardly decide between an $E1$ ($\alpha_{tot}=0.76$, $K/L=10$) or $M1$ assignment for the 0.042-Mev gamma ray. A negative parity for the 0.042-Mev level would be consistent with the experimental beta- and gamma-transition probabilities, but would be unlikely on the basis of the shell model. (See Fig. 6, for example.)

[19] V. F. Weisskopf, Phys. Rev. 83, 1073 (1951). We used the formula given by S. A. Moszkowski; see reference 18.

[20] C. L. Schwartz (private communication).

E. Angular Correlation

From the preceding discussion it is clear that the parity of all the levels of Cu^{62}, except the 0.30-Mev level, is probably positive; no conclusion can be drawn about the parity of the 0.30-Mev level. The spins of the ground state and the three highest states (Fig. 5) are not greater than 1 and those of the 0.042- and 0.30-Mev states not greater than 2 and 3, respectively. The directional correlation data were evaluated under these considerations for the spins of the Cu^{62} states.

The 0.59–0.04-Mev gamma-ray directional correlation is consistent with 1–1–0, 1–1–1, 1–0–1 and 1–2–1 spins for the 0.63-Mev, 0.42-Mev, and ground states. This assumes there can be any mixture of dipole and quadrupole radiation in the first transition (0.59 Mev) but only up to 1% quadrupole radiation in the second transition (0.04 Mev) (see Sec. VI, C), if the spins of the respective levels are such as to permit mixing of the radiations.

Because of the difficulties that were discussed the 0.51–0.40-Mev gamma-ray directional correction results can be used only to exclude the 0–1–0 spin assignments for the 0.55-, 0.042-Mev, and ground states.

The 0.26–0.25-Mev gamma-ray directional correlation, because of the possibility of an unknown amount of mixing of dipole and quadrupole radiation in either or both of the transitions, is consistent with many sets of spin values for three levels involved. In fact, of all the spin possibilities allowed from consideration of the feeding of the 0.55-, 0.30-, and 0.042-Mev levels, only 0–1–0 and 0–2–0 can be definitely excluded. These particular sets of spins are also not consistent with the presence of the observed 0.51-Mev crossover gamma ray.

A summary of the spins and parities that are permitted from all considerations is shown in Table V. The possibility of having either the 0.70- or 0.55-Mev level with spin 0 and at the same time the 0.30-Mev level with spin 3 has been omitted because the observed branching ratios are so radically different from what would be expected for single-particle transitions in that case. Likewise, the possibility of having the 0.30-Mev level with spin 3 and the 0.04-Mev level with spin 0 has been omitted because the expected lifetime of the transition (10^{-1} to 10^{-2} sec) would not be consistent with the coincidence work.

TABLE V. Possible sets of spins and parities for the states of Cu^{62} based on the directional correlation measurements and other information.

Level energy (Mev)	Possible sets of spins and parities (a)	(b)	(c)	(d)	(e)	(f)	(g)
0.70	$0^+, 1^+$	$0^+, 1^+$	$0^+, 1^+$	$0^+, 1^+$	1^+	$0^+, 1^+$	1^+
0.63	1^+	1^+	1^+	1^+	1^+	1^+	1^+
0.55	1^+	1^+	0^+	1^+	1^+	$0^+, 1^+$	1^+
0.30	1, 2	1	1, 2	2	3	1, 2	3
0.042	0^+	1^+	1^+	1^+	1^+	2^+	2^+
0.00	1^+	$0^+, 1^+$	1^+	$0^+, 1^+$	$0^+, 1^+$	1^+	1^+

The 0.26–0.25-Mev gamma-ray directional correlation is consistent with spin 1–3–1 for the 0.55-, 0.30-, and 0.04-Mev levels, respectively, but requires mixing of quadrupole and octupole radiation in either or both of the transitions. This spin sequence is shown in Table V, column (*e*), although the mixing of such radiation to the extent that is needed would seem rather improbable. Aside from this there is little additional evidence that would make the spins shown in any one of the seven columns in Table V preferable over any other one.

F. Shell Model

According to recent measurements of Nussbaum *et al.*,[21] the ground-state spin of ${}_{28}Ni_{33}{}^{61}$ is $\frac{3}{2}$. On the shell model[1,2] this would be most reasonably interpreted as due to a $[(p_{\frac{3}{2}})^3(f_{\frac{5}{2}})_0{}^2]_{\frac{3}{2}}$ neutron configuration (with possible admixtures to explain the small magnetic moment of Ni^{61}). It would appear that a similar neutron configuration is predominant in ${}_{27}Co_{33}{}^{60}$.[22] If the same neutron configuration is also effective in ${}_{29}Cu_{33}{}^{62}$, its ground state could be expected to have spin 2 on a zero-range model.[23] On the other hand, the proton-neutron "stabilization"[24] by the $p_{\frac{3}{2}}$ proton may allow the $[(p_{\frac{3}{2}})^4 f_{\frac{5}{2}}]_{\frac{5}{2}}$ neutron configuration to compete favorably with the $[(p_{\frac{3}{2}})^3(f_{\frac{5}{2}})_0{}^2]_{\frac{3}{2}}$ configuration in ${}_{29}Cu_{33}{}^{62}$, despite the increased pairing energy[25] of $(f_{\frac{5}{2}})^2$ as compared to $(p_{\frac{3}{2}})^2$. This would give a ground-state spin of 1, 2, or 3 for Cu^{62} on the zero-range model.[26] Evidence for an apparent reversal of the ground state and first excited state configurations of Cu^{62} as compared to Ni^{61} may be seen in the predominant gamma transitions, which in Cu^{62} go to the first excited state and in Ni^{61} to the ground state. Whether or not these states are due to the aforementioned competition between the $[(p_{\frac{3}{2}})^4 f_{\frac{5}{2}}]_{\frac{5}{2}}$ and $[(p_{\frac{3}{2}})^3(f_{\frac{5}{2}})_0{}^2]_{\frac{3}{2}}$ neutron configurations or due to more complicated interactions can only be decided by accurate shell-model calculations.[4] For general interest, though, we show in Fig. 6 a possible matching of the states predicted by the zero-range model[23,26] with the experimentally-found states.

Another matter of possible interest in connection with the shell model is the close similarity in energy of the lowest states[7] of ${}_{27}Co_{33}{}^{60}$, ${}_{28}Ni_{33}{}^{61}$, and ${}_{29}Cu_{33}{}^{62}$. A fairly detailed search throughout the periodic table indicates, though, that this might well be accidental.

VII. ACKNOWLEDGMENTS

We are very much indebted to Dr. W. C. Barber for the use of the Mark II linear electron accelerator and for making the enriched Cu^{63} foils, which he had prepared, available to us. We are also very grateful to Dr. R. J. Debs for the use of the Mark IV accelerator and for making the enriched Zn^{64} foils, which he prepared, available to us. We wish to thank Dr. D. J. Gow of the Radiation Laboratory, University of California, for the bombardment of the Zn foils with the Berkeley linear proton accelerator. Discussions with Dr. C. L. Schwartz, Dr. R. H. Nussbaum, Dr. D. G. Ravenhall, and Dr. Murray Peshkin have been extremely stimulating and helpful. Mr. J. E. Neighbor, III, participated in some of the measurements.

APPENDIX. GAMMA SPECTRUM OF COPPER-62

The gamma-ray spectrum of Cu^{62} is shown in Fig. 1. In principle this spectrum can be analyzed for the energies and intensities of the gamma rays that are emitted in the decay of Cu^{62} to obtain information about the level structure of Zn^{62}. The obvious difficulties with this process are the very low intensities of the gamma rays above 0.51 Mev and the great complexity of the spectrum. Besides the spectrum shown in Fig. 1, a number of others were run under various conditions in an effort to obtain the most favorable experimental conditions. No spectrum was obtained that would permit an accurate decomposition into individual gamma-ray spectra, but a few gamma rays consistently evidenced themselves in the various measurements. They were at 0.66 ± 0.02, 0.85 ± 0.02, 1.18 ± 0.02, 1.35 ± 0.03, 1.46 ± 0.03, 1.98 ± 0.03, and 2.24 ± 0.03 Mev. The intensities relative to the total number of positrons were about 2% for the 0.66-Mev gamma ray and about 1% for the rest. Other gamma rays are most certainly present but it was not possible to resolve them with any certainty. In view of this it would appear more fruitful to investigate the levels of Ni^{62} by the decay of Co^{62}, in which gamma rays of 1.0, 1.17, $\sim$1.5, 1.7, 2.0, and $\sim$2.5 Mev have already been found.[5]

The 1.18-Mev gamma ray appears strongly in the Co^{62} decay[5] and presumably represents a transition from the first excited state[27] to the ground state of Ni^{62}. It is difficult to understand, however, why in Cu^{62} this transition is not more intense both relative to the other gamma rays and to the positrons. If one assumes that the 1.18-Mev level is populated entirely by positrons and electron capture from Cu^{62} a lower limit to the $\log ft$ of 6.2 is obtained, compared to the transition between ground states which has a $\log ft$ of 5.2.

Since the present measurements and analyses were completed, levels in Ni^{62} at 1.171, 2.047, and 2.304 Mev have been found by inelastic proton scattering.[27] This allows a tentative assignment of the 0.85- and 1.98-Mev gamma rays from Cu^{62} to transitions from the 2.05-Mev state to the 1.17-Mev and ground states of Ni^{62}, re-

[21] Nussbaum, Wapstra, Bruil, Sterk, Nijgh, and Groben, Phys. Rev. **101**, 905 (1956). See also Nierenberg, Shugart, and Silsbee, Bull. Am. Phys. Soc. Ser. II., **2**, 200 (1957) for the measured spin of Cu^{61}.

[22] Dobrowski, Jones, and Jeffries, Phys. Rev. **101**, 1001 (1956).

[23] C. L. Schwartz, Phys. Rev. **94**, 95 (1954).

[24] A. de-Shalit and M. Goldhaber, Phys. Rev. **92**, 1211 (1953).

[25] M. Goeppert-Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structures* (John Wiley and Sons, Inc., New York, 1955).

[26] A. de-Shalit, Phys. Rev. **91**, 1479 (1953).

[27] Spencer, Phillips, and Young, Bull. Am. Phys. Soc. Ser. II, **2**, 105 (1957).

spectively. It is of interest to compare these transitions with the probably analogous transitions from the 2.16-Mev state[27,28] in Ni^{60} and the 2.46-Mev state[27,29] in Ni^{58}. Table VI summarizes this comparison; the similarity of the energy ratios is striking[30] and has also been found for similar levels[31] in Zn^{64}, Zn^{66}, and Zn^{68}. The reduced transition probabilities in Table VI have been calculated by assuming the second excited state to be 2^+ and assuming the $M1$ contribution to the transition from the second excited to the first excited state to be negligible.[32]

TABLE VI. Similarities in *e-e* Ni nuclei.[a]

Nucleus	Energy of excited states First E_2 (Mev)	Second E_2' (Mev)	E_2'/E_2	Reduced transition probability $\frac{B(E2;\,2'\to0)}{B(E2;\,2'\to2)}$
Ni^{58}	1.453[b]	2.456	1.69	... [c]
Ni^{60}	1.329	2.161	1.63	(0.003)[d]
Ni^{62}	1.171	2.047	1.74	(~0.01)[e]

[a] The notation used is the same as that of reference 32.
[b] All energy values taken from references 27 and Gossett, Windham, Phillips, and Schiffer, Phys. Rev. **103**, 1321 (1956).
[c] Only the transition between second and first excited states has been seen up to now (see reference 29).
[d] Intensity ratio from reference 28.
[e] Intensity ratio from present work.

[28] Van Lieshout, Nussbaum, Nijgh, and Wapstra, Phys. Rev. **93**, 255 (1954); Nussbaum, Van Lieshout, Wapstra, Verster, Ten Haaf, Nijgh, and Ornstein, Physica **20**, 555 (1954).
[29] R. M. Sinclair, Phys. Rev. **102**, 461 (1956).
[30] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955); J. J. Kraushaar and M. Goldhaber, Phys. Rev. **89**, 1081 (1953).
[31] D. J. Horen and W. E. Meyerhof (to be published). In these nuclei the energy ratio is close to 1.8 and not 2.3 as was previously thought (see reference 32).
[32] Alder, Bohr, Huus, Mottelson, and Winther, Revs. Modern Phys. **28**, 432 (1956); see especially Table V, 6.

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Gamma Radiation from Resonance Neutron Capture in Mercury

H. H. LANDON,* *Brookhaven National Laboratory, Upton, New York*

AND

E. R. RAE, *Atomic Energy Research Establishment, Harwell, England*

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An experiment has been performed to detect individual high-energy gamma rays associated with resonance capture in mercury, using an electron linear accelerator as a pulsed neutron source. The gamma-ray spectrum from the 34-ev resonance in the compound nucleus Hg^{200} has intense components of higher energy than does the spectrum from thermal capture in this isotope. From this it can be inferred that the spin of the 34-ev resonance is most probably 1 with negative parity.

INTRODUCTION

AN investigation has been undertaken, using the A.E.R.E. linear electron accelerator[1] as a pulsed neutron source, to study the possibilities of observing individual high-energy capture gamma rays associated with resonance neutron capture. One of the pressing problems in slow, i.e., resonance energy neutron physics, has been the determination of spins associated with the individual sharp resonances in the compound nucleus, particularly the determination of the spin of more than one resonance in a single isotope. The problem in principle is straightforward. Accurate measurements of both total and scattering cross sections give unambiguous choices of all the Breit-Wigner parameters, including the spin. The scattering measurements, however, have proved to be very difficult, particularly when the level spacing is sufficiently small to permit observation of several resonances in a single isotope.[2] For some time we have wished to know what could be achieved by somewhat different approaches, utilizing differences in the decay schemes of the compound nucleus which might depend upon spin. Variations in the population of isomeric states have been observed[3] when activation is made through selected resonance states of the compound nucleus. It might be hoped that measurements of this type would show a division into two distinct groups from which the spins might be inferred after the establishment of at least one spin by a more direct method. One would certainly expect that the capture gamma-ray spectrum itself would change with the spin, although it has been evident for some time that such changes are not always obvious or easy to measure. We have felt, however, that if one could choose individual gamma rays, presumably of high energy, which originate at the

* Research performed at the Atomic Energy Research Establishment, Harwell, England, while on leave of absence from Brookhaven National Laboratory.
[1] E. R. Wiblin, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva* (United Nations, New York, 1956), Vol. 4, p. 35.
[2] E. R. Rae, Physica **22**, 1131 (1956).
[3] V. L. Sailor (private communication); R. E. Wood, Phys. Rev. **95**, 453 (1954).