PHYSICAL REVIEW VOLUME 112, NUMBER 4 NOVEMBER 15, 1958

Decay of Cu^{62}

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(Received May 9, 1958)

A source of Cu^{62} was prepared by means of the (p,γ) reaction on an enriched Ni^{61} target. The gamma rays following positron emission were detected with a scintillation spectrometer, and the following energies were measured: 0.88 ± 0.01, 1.13 ± 0.02, and 1.17 ± 0.01 Mev. The relative intensities with respect to the positrons are 0.3, 0.1, and 0.5% with uncertainties of a factor of two either way. Coincidence techniques and half-life measurements were used to identify the gamma rays with the decay of Cu^{62}. The half-life for positron emission was measured to be 9.9 ± 0.2 min. Branching ratios and log*ft* values have been calculated and are listed in tabular form.

I. INTRODUCTION

FOR some time the decay scheme of the radioactive isotope, Cu^{62}, has been open to considerable question. A number of investigators[1–3] have reported that the Kurie plot is linear from its end point at about 2.9 Mev down to less than 1 Mev, indicating no population of states in the residual nucleus below about 2 Mev. A gamma ray of energy 0.56 Mev following the decay of Cu^{62} was reported in a nuclear data table.[4] Later Nussbaum *et al.*[5] and Reid and Wright[6] reported that they found no evidence for a 0.56-Mev gamma ray and placed an upper limit of about 5% for the branching ratio to any state emitting such a gamma ray. Further, Reid and Wright estimated that any gamma-ray peak in the region 0.6 to 1.2 Mev having 0.25% of the counts in the annihilation total-capture peak would have been detectable, but they found none.

Since the production of this isotope is used in monitoring betatron bremsstrahlung beams by means of the (γ,n) reaction on Cu foils, it is important to establish the decay scheme with certainty. Further, it would be somewhat surprising, and therefore interesting from a theoretical point of view, if a beta emitter in the medium-weight region having an end point of 2.9 Mev should lead to no excited states in the product nucleus.

When the decay of Cu^{59} was investigated by the present authors,[7] there was developed a technique which was extremely sensitive in detecting the presence of gamma rays near and below (in energy) the annihilation radiation, as well as gamma rays well removed from the annihilation radiation. It was therefore decided to investigate the decay of Cu^{62} by means of this technique.

A preliminary account of the present work has been published.[8]

II. SOURCE PREPARATION

A moderately thick target of Ni^{61} was prepared by electroplating the Ni^{61} onto a Cu disk, $\frac{9}{16}$ in. in diameter and 0.002 in. thick. The isotopic composition of the Ni^{61} sample[9] was as follows: $2.78\pm0.15\%$ Ni^{58}, $10.36\pm0.11\%$ Ni^{60}, $83.06\pm0.29\%$ Ni^{61}, $2.41\pm0.09\%$ Ni^{62}, and $1.38\pm0.10\%$ Ni^{64}. The spectroscopic analysis was as follows: 0.05% Cu, 0.02% Fe, 0.01% Mg, and 0.01% Sn. The deposition was carried out as described in a previous communication[10] to a thickness of about 5 mg/cm^2. The target was bombarded by a beam of about 5 μa of 1.8-Mev protons from the NRL Nucleonics Division 2-Mv Van de Graaff accelerator, producing the Cu^{62} isotope by means of the radiative capture reaction. The target was not made thicker than about 0.5 Mev to the incident protons because the resonances appearing below a bombarding energy of 1.3 Mev are expected[10] to be too weak to contribute sufficiently to the (p,γ) yield to warrant the expenditure of additional target material. Proton capture reactions induced in the Cu backing do not produce positron activity since the residual nuclei from the (p,γ) reactions on both Cu isotopes are stable.

The use of (p,γ) reactions from low-energy protons to produce positron activities in this mass region has two distinct advantages over bremsstrahlung irradiation. First, the extremely small amounts of target material required for charged-particle targets allows economic use of highly enriched separated isotopes. Second, in most cases, where the bombarding energy is below the (p,n) threshold, the (p,γ) reaction is the only possible reaction of transmutation. The combination of these two advantages usually allows the production of the activity to be studied with very little contamination by other activities.

III. COINCIDENCE TECHNIQUE

The gamma rays were detected by a 3-in. diam×3-in. NaI(Tl) crystal in conjunction with a 256-channel pulse-height analyzer. The positrons were detected by

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[1] Becker, Kirn, and Buck, Phys. Rev. **76**, 1406 (1949).

[2] Katz, Penfold, Moody, Haslam, and Johns, Phys. Rev. **77**, 289 (1950).

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

[4] Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953); private communication from R. C. Thompson and D. R. Miller.

[5] Nussbaum, Wapstra, van Lieshout, Nijgh, and Ornstein, Physica **20**, 571 (1954).

[6] J. M. Reid and I. F. Wright, Nature **175**, 298 (1955).

[7] J. W. Butler and C. R. Gossett, Phys. Rev. **109**, 863 (1958).

[8] J. W. Butler and C. R. Gossett, Bull. Am. Phys. Soc. Ser. II, **3**, 62 (1958).

[9] The Ni^{61} isotope was obtained from the Stable Isotopes Division of the Oak Ridge National Laboratory. The composition analyses were made by ORNL.

[10] J. W. Butler and C. R. Gossett, Phys. Rev. **108**, 1473 (1957).

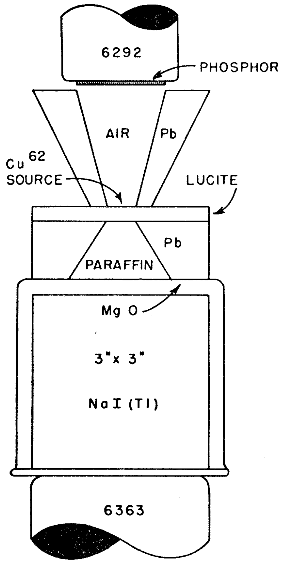

FIG. 1. Geometrical arrangement of the coincidence gamma-ray spectrometer. Cylindrical symmetry was used. The Lucite and paraffin stopped the positrons with a minimum of bremsstrahlung emission and gamma-ray attenuation. The two Pb cones shielded the NaI crystal from the annihilation radiation emitted from the vicinity of the plastic phosphor.

a $1\frac{1}{2}$-in. diam×0.012-in. thick disk of Pilot-B plastic scintillator in conjunction with conventional electronic equipment. The geometrical arrangement of the detectors is shown in Fig. 1, and the coincidence technique is similar in principle to the arrangement previously described.[7]

Briefly, the principle is as follows. The multichannel analyzer is gated "on" by a pulse from the Pilot-B phosphor. Since the thin plastic phosphor is very efficient for the detection of beta particles but is very insensitive to gamma rays, the analyzer will normally be gated on only when a positron enters the plastic phosphor. Such positrons can be expected to annihilate in the vicinity of the phosphor, or at least above the Pb cone shield. Therefore, the annihilation radiation from a "gating" positron may reach the NaI crystal only through the very small solid angle defined by the Pb cones; and a coincident nuclear gamma ray emitted by the residual nucleus in the source can therefore be detected in the large NaI crystal with only a small probability that the annihilation radiation from the positron would also enter the crystal. A resolving time of 0.5 μsec was used.

The Lucite plate was placed under the source to prevent positrons from entering the Pb with more than a few hundred kev of energy and thus to prevent the emission of higher-energy bremsstrahlung in the direction of the NaI crystal. The paraffin within the lower Pb cone stopped the positrons which had passed through the Lucite in the direction of the crystal with minimum bremsstrahlung emission and only slight attenuation of the gamma rays from the source. The inner surface of the upper Pb cone and the bottom of the lower Pb cone were covered with a thin sandwich of two foils (0.002-in. Sn and 0.002-in. Cu) to prevent the Pb K x-rays from entering the plastic phosphor or the NaI crystal, respectively.

In order to minimize the effects of other radioactive copper isotopes present (produced by proton capture by small amounts of the other nickel isotopes present in the target), the bombardment-counting cycle was as follows: two minutes of bombardment, two minutes of waiting (during which time the target was removed from the vacuum system of the Van de Graaff accelerator, and placed in position in the counting arrangement), twelve minutes of counting, and four minutes of waiting (during which time the target was replaced into the vacuum system). This cycle is hereinafter referred to as the "short cycle" to distinguish it from the "long cycle" which involved a continuous counting period of about 3 hours' duration following about 10 successive short cycles. The reasons for these different cycles are elucidated in the following paragraphs.

Cu^{59}, produced by proton capture by Ni^{58}, has a half-life of 81.5 sec and has nuclear gamma rays of 0.343, 0.463, 0.872, 1.305, and 1.70 Mev associated with its decay.[7] Cu^{61}, produced by proton capture by Ni^{60}, has a half-life of 3.3 hours and has nuclear gamma rays of 0.070, 0.282, 0.380, 0.580, 0.659, 0.940, 1.12, and 1.19 Mev associated with its decay.[7,11] These are the only radioactive contaminants expected because the other nickel isotopes produce stable copper isotopes upon proton capture, the (p,n) thresholds for all the stable nickel and copper isotopes are well above the bombarding energy used, and the Cu isotopes in the target backing lead to stable Zn isotopes following proton capture.

Since the Cu^{61} would continue to build up with respect to the Cu^{62} during succeeding cycles, not more than ten successive short cycles were made without giving the Cu^{61} at least three hours to decay, during which time the decay spectrum was separately recorded as the "long-cycle spectrum." The magnetic core memory of the 256-channel analyzer was divided into two equal parts; the short-cycle counts were recorded in the first half, and the long-cycle counts recorded in the second half. Four sets of short cycles (each set containing about eight individual short cycles) and four long cycles were made in all with a total counting time of 6.8 hr for the short cycles and 16.3 hr for the long cycles. The final spectra shown in Fig. 2 are the separate sums of the short cycles and the long cycles.

Figure 2(a) shows the short-cycle spectrum. The apparent peak about 0.04 Mev is due to a "cutoff" effect in the analyzer. Other spectra taken with expanded gain gave no evidence for a gamma ray or x-ray of that energy, but always showed the cutoff at the same channel number. The peak at 0.18 Mev is the back-scattered Compton peak of the annihilation radiation, and the peak at 0.511 Mev is the annihilation radiation itself. The peak at 0.69 Mev is due to one annihilation quantum plus the back-scattered Compton

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[11] Nussbaum, Wapstra, Bruil, Sterk, Nijgh, and Grobben, Phys. Rev. **101**, 905 (1956).

photon from the accompanying annihilation quantum. Evidence for this and other assignments is discussed in Sec. VI.

The peak at 0.88 Mev is a nuclear gamma ray associated with the decay of Cu^{62}, as is also the peak at 1.17 Mev. The latter peak, however, shows some evidence of a doublet nature. Other spectra taken with expanded gain showed even stronger evidence for a second peak about 40 kev lower in energy and of about $\frac{1}{5}$ the intensity of the primary peak. The counts of higher energy than 1.17 Mev are apparently due to bremsstrahlung. It is not expected that annihilation in flight will make an appreciable contribution to the yield here because of the coincidence requirement. During preliminary runs with different geometrical arrangements, the relative intensity of this "background" with respect to the 1.17-Mev peak was considerably greater than in the final run shown in Fig. 2(a). When the geometrical arrangement was changed in a way deliberately designed to reduce bremsstrahlung, this background was always reduced, thus tending to confirm that at least part of this "background" is indeed due to bremsstrahlung.

In preliminary runs, all 256 channels were used with the same gain as was used in Fig. 2(a), thus displaying the spectrum up to 3.2 Mev. Above about 1.7 Mev, there were only a few (of the order of two or three) counts per channel, thereby indicating that there are no gamma rays higher than 1.17 Mev associated with the decay of Cu^{62} to the limit of about 10% of the intensity of the 1.17-Mev gamma ray. However, the detection efficiency of the coincidence arrangement used here decreases rapidly below a positron end point of about 300 kev, corresponding to an excitation energy of about 2.6 Mev in the Ni^{62} nucleus. This effect is due to the fact that about 150 kev are required to trigger the positron counter. If the spectrum end point is below about 300 kev, the fraction of the positrons capable of triggering the coincidence gate is correspondingly small.

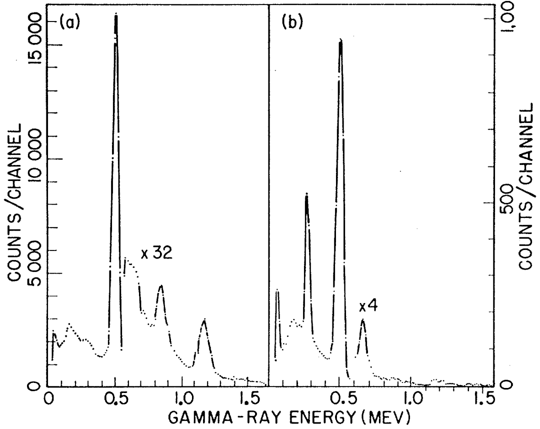

FIG. 2. Gamma-ray coincidence spectra during the (a) "short cycles," and (b) "long cycles." Spectrum (a) consists of about 99.5% Cu^{62} decays, and about 0.5% Cu^{61} decays. Spectrum (b) consists of about 70% Cu^{62} decays and 30% Cu^{61} decays. In (a) are shown the annihilation radiation, the 0.88-Mev gamma ray, and the unresolved doublet, 1.13- and 1.17-Mev gamma rays, following the decay of Cu^{62}. In (b) are shown the 0.070-, 0.282-, 0.659-, and 1.192-Mev gamma rays following the decay of Cu^{61}. Background was negligible and has not been subtracted.

Figure 2(b) shows the delayed, or long-cycle, spectrum. The lowest-energy peak in Fig. 2(b) represents the 0.070-Mev gamma ray of Cu^{61}. Likewise clearly evident are the peaks corresponding to the 0.282-Mev and 0.659-Mev gamma rays of Cu^{61}. The 1.19-Mev peak is barely evident; but this is in accord with expectations because of the coincidence requirement. The positrons leaving Ni^{61} in the 1.19-Mev state have an end point of only about 20 kev, and would therefore seldom, if ever, result in a gate pulse. The competing (and more probable) mode of excitation of this state, *K*-electron capture, would also not result in a gate pulse.

Throughout the course of the bombard-count cycles the beam intensities and times were recorded. By utilizing this information and the known half-lives of the activities, the percentages of the annihilation radiation in the two spectra due to the Cu^{61} and Cu^{62} activities were calculated to be 99.5% Cu^{62} and 0.5% Cu^{61} in Fig. 2(a), and 70% Cu^{62} and 30% Cu^{61} in Fig. 2(b). An additional check on the percentage of Cu^{61} in Fig. 2(b) was provided by recording a "pure" Cu^{61} spectrum under the same conditions as the spectra of Fig. 2, but beginning six hours after the last bombardment (equivalent to 24 half-lives of the Cu^{62}). A comparison of the ratio of the annihilation peak to the strong 282-kev peak in the "pure" Cu^{61} spectrum to the corresponding ratio from Fig. 2(b) indicates about 30% Cu^{61} in Fig. 2(b), in agreement with the above.

Since it is shown that Fig. 2(a) contains only 0.5% contribution from Cu^{61}, it is essentially a pure Cu^{62} decay spectrum. In particular, due to the weakness of the 1.19-Mev peak in the Cu^{61} coincidence spectra, as explained above, one may calculate that this gamma ray could give rise to no more than 1% of the counts in the 1.17-Mev peak of Fig. 2(a).

The two-minute waiting period, between the end of bombardment and the beginning of count in the short cycles, was evidently sufficient to make the contribution of the Cu^{59} decay (81-second half-life) negligible in the spectrum of Fig. 2(a), since there is no evidence for a 1.305-Mev peak from that activity. In particular, one may estimate that no more than 10% of the 0.88-Mev peak of Fig. 2(a) could be due to the 0.872-Mev gamma ray from the Cu^{59} decay, since this gamma ray should produce a peak of comparable size to that of the 1.305-Mev gamma ray which was not detected.

IV. HALF-LIFE

To determine the half-life for positron emission, the thin plastic phosphor and associated electronic equipment was used to count the positrons as a function of time. For these runs, the plastic phosphor and phototube were inverted from the position shown in Fig. 1, and the source was laid face down onto the thin aluminum foil (0.002 in. thick) covering the phosphor and tube. The other items shown in Fig. 1 were removed. Precautions were made to insure gain stability and counting efficiency as a function of time.

The half-life of Cu^{62} has been measured and reported by a number of investigators.[12] One adopted value[13] is 9.7 min. In order to check this value, and at the same time check the possibility of other radio-isotopes being present, the half-life was measured as described above, and the value of 9.9 ± 0.2 min was obtained. In order to determine if any appreciable amount of Cu^{59} was present, one half-life measurement was made with no deliberate additional waiting period after the bombardment. That is, the waiting period consisted of only the 10 sec necessary to remove the target from the vacuum system and place it on the counter. The bombardment was for only two minutes (and was made after all activities from previous bombardments had essentially disappeared), and the counts were recorded every 10 sec, but no evidence was found for a half-life less than 9.9 minutes. After one of the early runs involving about ten bombard-count cycles in which the bombarding and counting times were each ten minutes, a half-life measurement was made, and an appreciable amount of Cu^{61} (3.3-hour half-life) was observed. It was for this reason that the precautions of shortening the bombarding time to two minutes and introducing the "long-cycle" counts were taken to limit the relative amount of Cu^{61} and provide a means of measuring the Cu^{61} contribution.

V. GAMMA-RAY INTENSITIES

Because the annihilation radiation is deliberately discriminated against by the coincidence technique, one cannot obtain the relative intensities of positrons and gamma rays from the spectra obtained with that arrangement. The spectrum was therefore obtained without the coincidence requirement but with the source enclosed in a $1\frac{5}{8}$-in.-diam paraffin sphere having a removable plug to permit placing of the source at the center of the sphere. The paraffin was thick enough to stop the most energetic positrons, thus insuring that all positrons were annihilated within the paraffin sphere. The center of the sphere was 3 in. from the crystal face along the axis of the crystal. Paraffin was used because (1) its absorption of nuclear gamma rays and annihilation radiation would be low, and (2) bremsstrahlung emission would be low.

The resulting spectrum is shown in Fig. 3. The crystal was shielded from room background by two inches of Pb on all sides except the front face. The 0.07-Mev peak in Fig. 3 is the Pb x-ray. It arises from the ejection of *K* electrons from the Pb by the annihilation quanta and gamma rays from the Cu^{62} source. The other peaks have the same interpretation as in Fig. 2(a). The room background counts, taken for a time equal to that during which the decay spectrum was observed, were subtracted from the total spectrum in order to obtain the net spectrum shown in Fig. 3. A prominent peak at 1.46 Mev (apparently due to K^{40} in the floor and walls of the laboratory) appears in the background spectra, and it is believed that this peak was not completely subtracted out, leaving the slight anomaly in the vicinity of 1.5 Mev.

The relative intensities of positrons and gamma rays were then determined by the areas in the total capture peaks, corrected for relative efficiencies, and for the fact that for each positron, there are two annihilation quanta. The solid angles subtended by the crystal at the small gamma-ray source (a plane of less than $\frac{1}{8}$-in. diam) and the diffuse annihilation-quanta source were assumed to be the same. The intensities of the gamma rays with respect to the positrons were calculated to be as follows: 0.88 Mev, 0.3%; 1.13–1.17 Mev doublet, 0.6%. On the basis of the relative intensities of the members of the doublet, discussed in Sec. III, the relative intensities of the individual gamma rays are calculated to be the values listed in Table I.

Absorption of the annihilation quanta and nuclear gamma rays by the paraffin of the sphere was neglected, as was also the reduction of the number of the annihilation photopeak pulses due to removal from the photopeak by the addition of a back-scattered photon (thus

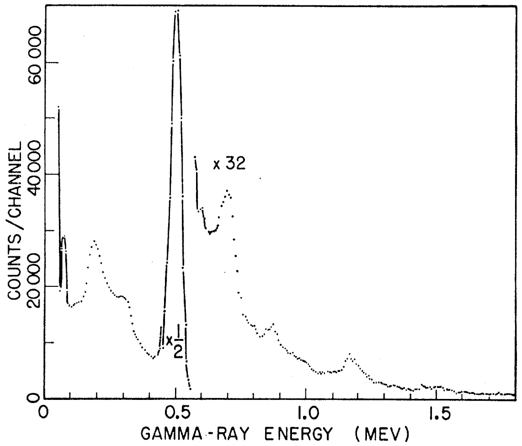

FIG. 3. The Cu^{62} decay spectrum with no coincidence requirement, and with the source enclosed in a $1\frac{5}{8}$-in. diam paraffin sphere, 3 in. from the crystal face. This spectrum was used to determine the relative intensities of the gamma rays and positrons. The background has been subtracted. The peaks are as follows: 0.07 Mev, Pb *K* x-ray; 0.18 Mev, back-scattered Compton photons from the annihilation radiation; 0.511 Mev, annihilation radiation; 0.69 Mev, annihilation quantum plus the coincident back-scattered Compton photon of the accompanying annihilation quantum; 0.88 Mev, gamma ray following positron decay of Cu^{62}; 1.13- and 1.17-Mev doublet, gamma rays following positron decay of Cu^{62}.

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[12] L. N. Ridenour and W. J. Henderson, Phys. Rev. **52**, 889 (1937); E. C. Crittenden, Jr., Phys. Rev. **56**, 709 (1939); Leith, Bratenahl, and Moyer, Phys. Rev. **72**, 732 (1947); Goldenberg, Sousa-Santos, and Silva, Ciencia e cultura **3**, 307 (1951); H. C. Martin and B. C. Diven, Phys. Rev. **86**, 565 (1952); A. I. Berman and K. L. Brown, Phys. Rev. **96**, 83 (1954).

[13] L. J. Lidofsky, Revs. Modern Phys. **29**, 773 (1957).

TABLE I. Energies and relative intensities of the gamma rays following the positron decay of Cu^{62}. The intensities are with respect to the positron intensity, and are uncertain by about a factor of two either way.

Gamma-ray energy (Mev)	Relative intensity
0.88 ± 0.01	0.3%
1.13 ± 0.02	0.1%
1.17 ± 0.01	0.5%

forming the 0.69-Mev peak) or bremsstrahlung or annihilation-in-flight photons. These effects were small compared to the over-all uncertainty which is about a factor of two.

VI. IDENTIFICATION OF GAMMA RAYS

Since the intensities of the gamma rays from the decay of Cu^{62} were so low compared with the annihilation radiation (or positrons themselves), and since the values of the gamma-ray energies were very close to some of those known to be present in the decay of Cu^{59} and Cu^{61}, the interpretation of the spectra of Fig. 2 is not straightforward. Some information affecting such interpretation was given in Sec. III and IV. The following additional steps were taken to insure that the identification given in earlier sections of this paper were indeed the unique and correct ones.

The 0.69-Mev peak was reported as a gamma ray in the preliminary account[8] of the present work. However, the 0.69-Mev peak was suspected of being the sum of an annihilation quantum and the back-scattered Compton photon of the accompanying annihilation quantum, when it was noticed that the channel number of the 0.69-Mev peak was exactly the same as the sum of the annihilation peak channel number and the back-scattered Compton peak channel number. A test was therefore carried out to determine with certainty whether or not the 0.69-Mev peak corresponded to a single gamma ray.

A sample of Teflon was kindly irradiated by McElhinney and the betatron group of this laboratory, producing the pure positron emitter, F^{18}. The Teflon sample was then placed in the same geometrical arrangement as was used to obtain the spectrum of Fig. 3 and described in Sec. V. The counting rate for the F^{18} source was approximately the same as for the Cu^{62} source previously used. The 0.69-Mev sum peak was observed in the F^{18} spectrum, and the relative intensities of the 0.69-Mev peak and 0.511-Mev peak were about the same as those observed in the Cu^{62} spectrum, thus confirming that the 0.69-Mev peak of the Cu^{62} spectrum is indeed due to annihilation radiation alone.

The 0.88- and 1.17-Mev gamma-ray peaks were not present in the background spectrum, and they were not even approximately erased by subtracting the background. Therefore, we conclude that these peaks are not due to background effects.

The beta half-life was measured as described in Sec. IV, yielding the proper value for the half-life of Cu^{62}, and only one other detectable half-life, the 3.3-hour half-life of Cu^{61}. An upper limit of about 1% (of the total disintegrations) could thus be placed on the amount of Cu^{61} decaying during the counting part of the "short cycles" [from which comes the spectrum of Fig. 2(a)]; and since the 81-sec half-life of Cu^{59} was not observed (during the beta half-life determination), an upper limit of about 1% could likewise be placed on its contribution to the total number of disintegrations during the counting periods.

In the spectrum[7] of Cu^{59}, the 1.305-Mev gamma ray is about the same intensity as the 0.872-Mev gamma ray. Since the spectrum of Fig. 2(a) shows no evidence for a 1.3-Mev gamma ray, it is reasonable to conclude that the 0.88-Mev gamma ray is not due to Cu^{59}. As mentioned earlier, an extrapolation of the intensity of the 1.19-Mev gamma ray of Fig. 2(b), to the counting periods of Fig. 2(a), indicate that less than 1% of the counts in the 1.17-Mev peak of Fig. 2(a) can be due to Cu^{61}.

As final conclusive evidence as to the origin of the 0.88- and 1.17-Mev gamma rays, the half-lives of the gamma rays themselves were measured. This could not be done in the usual manner because during any one of the short bombard-count cycles, only about 10 counts would be recorded in each of the entire photopeaks during a twelve-minute counting period. In order to determine the half-life with reasonably good statistics, the following procedure was devised and used.

From the measured value of the Cu^{62} half-life (9.9 minutes), it was calculated that $\frac{1}{4}$ of the nuclei decay in 4.1 minutes and another $\frac{1}{4}$ decay in the next 5.8 minutes. The magnetic core memory of the multichannel analyzer was therefore divided into two halves in such a manner that during each 9.9-min count period, counts were recorded in the first half of the memory during the first 4.1 minutes, and in the second half of the memory during the next 5.8 minutes. In this way the individual counts during each cycle could be accumulated until they were statistically significant.

If the assumed half-life (9.9 minutes) is correct for the gamma rays, the spectra in the two halves of the memory should be identical. If a peak were due to a shorter lived activity, this peak would contain more counts in the first half of the memory than in the second half. The reverse would be true for a longer lived activity. The relative number of counts in the peaks of the two halves of the memory vary with the half-life in a calculable relation. Thus, by comparing the total counts in each of the photopeaks, it was possible to compute upper and lower limits for the actual half-life. For the annihilation radiation itself, the upper and lower limits are thus found to be 10.5 min and 8.5 min. For the 1.17-Mev peak, the upper and lower limits are 13.8 min and 8.5 min. The number of counts in the 0.88-Mev peak could not be determined so well as the

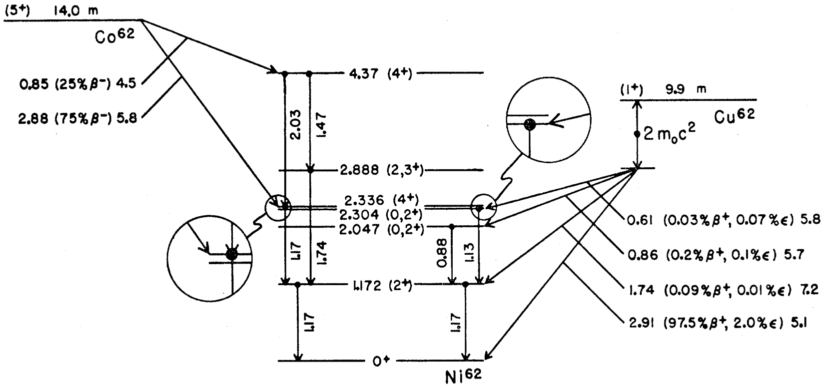

FIG. 4. Decay schemes of Cu^{62} and Co^{62}, and energy levels in Ni^{62}. The energies of the excited states are from Spencer *et al.* and Paris and Buechner, except that their levels above 3 Mev have been omitted. The Co^{62} decay data are from Gardner and Meinke. Their 1.47- and 1.74-Mev transitions have been interchanged to conform to the level scheme. The Cu^{62} decay data are from the present experiment, except that the ground-state positron end point comes from Nussbaum *et al.* The other positron end points were calculated from their ground-state end point and gamma-ray energies of the present experiment.

others because of the higher background under it. Even so, the two peaks looked quite similar, and one could place rough lower and upper limits of about 5 minutes and 15 minutes on the half-life of the 0.88-Mev gamma ray.

On the basis of the above discussion, the identification of the gamma rays listed in Table I with the decay of Cu^{62} is considered to be well established.

VII. DISCUSSION

The experimental work of this report was concerned with the detection of gamma rays arising from the de-excitation of levels in the Ni^{62} nucleus, and with the exception of the coincidence requirement described in Sec. III, was not concerned directly with the disintegration transitions (occurring during the decay of Cu^{62}) which populate these levels. However, when our work is considered with other recent information, a self-consistent scheme for the decay of Cu^{62} may be obtained.

Two recent experiments[14,15] concerning the precision magnetic analysis of the proton groups from the $Ni^{62}(p,p')Ni^{62*}$ reaction and a similar analysis of the alpha particle groups from $Cu^{65}(p,\alpha)Ni^{62}$ reaction[16] give information on the level scheme of the Ni^{62} nucleus. The Rice Institute group[14] found levels in Ni^{62} at 1.172 ±0.004, 2.047±0.004, and 2.304±0.005 Mev. The Massachusetts Institute of Technology group,[15,16] with higher bombarding energy, found with excellent agreement the same three levels, and in addition levels at 2.336±0.005, 2.888±0.005 Mev, and a group of more closely spaced levels beginning at an excitation energy of 3.055 Mev.

Figure 4 shows the energy levels of references 14 and 15, and it may be seen that the three gamma-ray transitions observed in the present experiment fit very well into such a level scheme. The 1.17-Mev gamma ray represents de-excitation of the first excited state, while the other two gamma rays, 0.88 and 1.13 Mev, represent the first members of stopover transitions from the 2.047- and 2.304-Mev states, respectively.

On the basis of the relative intensity measurements of Sec. V, listed in Table I, we conclude that in the decay of Cu^{62}, 0.1% of the transitions are to the 1.172-Mev state of Ni^{62}, 0.3% are to the 2.047-Mev state, and 0.1% are to the 2.304-Mev state. These estimates are probably accurate to within a factor of three, the uncertainty largely arising from the uncertainties in the relative gamma-ray intensities, but these uncertainties are amplified by the fact that the intensity of the 1.17-Mev gamma ray had to be apportioned among direct and stopover transitions. The branching ratios have been subdivided into contributions due to positron emission and K-electron capture separately by using the theoretical calculations of Feenberg and Trigg.[17] Table II lists these branching ratios and the positron end points for each group, calculated from the positron end point measured by Nussbaum *et al.*[5] for the ground-state group and from the gamma-ray energies reported herein.

Assuming that the four transitions ascribed to the decay of Cu^{62} are all allowed or, at worst, first-forbidden transitions, log*ft* values may be calculated from the information given above and the curves of Feenberg

TABLE II. The branching ratios and log*ft* values for the various positron groups in the decay of Cu^{62}. The precise energies of the final states in Ni^{62} are from the data of Spencer *et al.* and Paris and Buechner. The positron end points are calculated from the ground-state end point measured by Nussbaum *et al.*, and from the gamma-ray energies listed in Table I. The uncertainties in the branching ratios to the excited states are about a factor of three either way.

Final state of Ni^{62} (Mev)	Positron end point (Mev)	Branching ratios β^+ %	ϵ %	Log*ft*
0	2.91	97.5	2.0	5.1
1.172	1.74	0.09	0.01	7.2
2.047	0.86	0.2	0.1	5.7
2.304	0.61	0.03	0.07	5.8

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[14] Spencer, Phillips, and Young, Phys. Rev. **108**, 69 (1957).

[15] C. H. Paris and W. W. Buechner, Bull. Am. Phys. Soc. Ser. II, **3**, 38 (1958).

[16] Mazari, Buechner, and de Figueiredo, Phys. Rev. **108**, 373 (1957).

[17] E. Feenberg and G. Trigg, Revs. Modern Phys. **22**, 399 (1950).

and Trigg.[17] The resultant values are also listed in Table II.

The log*ft* values are all in the range of allowed transitions. The value of 7.2 for the transition to the first excited state of Ni^{62} is somewhat high, but perhaps may be explained by the trend for $1^+\rightarrow2^+$ transitions to yield higher log*ft* values. It is certainly unlikely that this transition is first forbidden, as the first excited state is very likely 2^+, according to the systematics of even-even nuclides. Since allowed transitions are observed to the first three excited states of Ni^{62}, of which two states are probably 2^+, it may be concluded that the ground state of Cu^{62} is 1^+ and that the first three excited states of Ni^{62} are limited to 0^+, 1^+, and 2^+. Because 1^+ states seldom occur in the first three or four levels of even-even nuclides, it is unlikely that any of these states is 1^+.

The fact that crossover transitions are not observed for the 2.047- and 2.305-Mev states, to a limit of about 20% of the stopover transitions, is not surprising in view of the probable 0^+ or 2^+ assignments to these states. Selection rules prohibit a $0^+\rightarrow0^+$ transition by means of a single gamma ray; and if certain collective quantum numbers are valid in this region, a $2^+\rightarrow0^+$ crossover transition should be suppressed with respect to a $2^+\rightarrow2^+\rightarrow0^+$ stopover transition.

In a recently published article, Gardner and Meinke[18] report gamma rays of 1.17±0.01, 1.47±0.02, 1.74 ±0.03, 2.03±0.03, and 2.5±0.2 Mev following the decay of Co^{62}, these gamma rays being emitted by the same nuclide, Ni^{62}, as the gamma rays of the present experiment. From these and other observations, they deduced the decay scheme reproduced on the left side of Fig. 4 with the exception that we have taken the liberty of interchanging their cascade sequence involving the 1.47- and 1.74-Mev gamma rays, in order to conform to the level scheme of references 14 and 15. From the allowed nature of the beta transitions, they concluded that the 2.34- and 4.37-Mev levels are probably 4^+. On this basis, we would not expect to populate the 2.34-Mev state in the positron decay of Cu^{62}, because to do so would require a second-forbidden $1^+\rightarrow4^+$ transition. Since the 2.34-Mev state decays by emission of two 1.17-Mev gamma rays in a cascade sequence through the 1.17-Mev state, the data of the present experiment are indeterminate as to whether or not the 2.34-Mev state is populated in the decay of Cu^{62}. If the 2.34-Mev state were excited in the decay of Cu^{62}, the branching ratios shown in Fig. 4 and listed in Table II would be incorrect, since they are based on the assumption that all of the 1.17-Mev radiation observed is due to the direct or cascade radiation from the de-excitation of the 1.17-, 2.05-, and 2.30-Mev levels.

One further indication that the spin of the 2.336-Mev state is relatively high, perhaps 4 or more (and therefore that the state does not contribute to the spectrum of the present experiment), is the fact that the Rice Institute group did not observe the 2.336-Mev state whereas the MIT group, using higher energy protons, did observe this state. At the bombarding energies used by the Rice Institute group, about 5 Mev, the intensity of the outgoing protons from a state of about 2.4 Mev of excitation would be sensitive to the angular momentum of the outgoing wave.

In another recently published article, Brun *et al.*[19] reported on the decay of Zn^{62}. As their experiment involved the decay of Cu^{62} in secular equilibrium with the Zn^{62}, they performed a secondary experiment to determine the gamma spectrum for the decay of Cu^{62}, the source being prepared by irradiation of an enriched Cu^{63} foil with the bremsstrahlung beam from an electron linear accelerator. They reported evidence for peaks corresponding to gamma rays of the following energies: 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.

Only their 0.85- and 1.18-Mev gamma rays are in agreement with the observations of the present experiment. Their 0.66-Mev gamma ray probably has the same interpretation as our 0.69-Mev peak. With respect to the higher energy gamma rays, it is possible that they had a more sensitive detection system, or a stronger source, and could detect weaker transitions from the higher states, or crossover transitions which were not observed in the present experiment. However, since the energies which they quote do not agree with possible transitions involving the states known from the work of references 14 and 15, it is possible that the higher-energy gamma rays were from longer-lived activities like Cu^{64} and Cu^{60}, and from room background, which (as mentioned before) included an outstanding 1.46-Mev gamma ray.

From the evidence presented herein, it may be concluded that no gamma rays other than those listed in Table I are present following the decay of Cu^{62} having an intensity as much as $\frac{1}{5}$ of that observed for the 1.17-Mev gamma ray, and that the decay scheme illustrated in Fig. 4 represents within the stated uncertainties the actual decay of Cu^{62}.

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[18] D. G. Gardner and W. W. Meinke, Phys. Rev. **107**, 1628 (1957).

[19] Brun, Meyerhof, Kraushaar, and Horen, Phys. Rev. **107**, 1324 (1957).