The Decay Scheme of Cu^{66}

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The decay scheme of Cu^{66} has been investigated using scintillation detectors. The half-life of Cu^{66} was found to be 5.17 ± 0.07 min. The main beta-ray spectrum has an end point of 2.7 ± 0.1 Mev. $5\frac{1}{2}\pm1\frac{1}{2}$ percent of the beta-rays lead to an excited state of 1.05 ± 0.03 Mev in Zn^{66}. The half-life of this excited state is less than 5×10^{-9} sec. These results agree with the recent investigations of Friedlander and Alburger, but imply the necessity for further study of the decay scheme of Ga^{66}, which also decays to Zn^{66}. Spin, parity and shell model assignments of the pertinent states of Cu^{66}, Zn^{66}, and Ga^{66} are proposed.

I. INTRODUCTION

PRIOR to the recent work of Friedlander and Alburger[1] on Cu^{66}, which was undertaken independently and approximately concurrently with the present study, the decay scheme of Cu^{66} had not been investigated very thoroughly. We refer to Friedlander and Alburger's paper for references and since our results essentially agree with theirs we wish to report them only briefly.

II. METHOD

Sodium iodide (TlI-activated) and anthracene scintillation detectors were used exclusively to study the decay scheme of Cu^{66}. The crystals, approximately $\frac{1}{2}$-in. cubes, were placed on RCA 5819 phototubes according to Hofstadter's method[2] and the phototube pulses were fed through linear amplifiers[3] to coincidence and counting circuits and to a Tektronix type 511 scope to be photographed.[2]

Cu^{66} samples were prepared by 3- to 6-min irradiations of electrolytic copper with slow neutrons produced by the Stanford cyclotron. For gamma-ray measurements sources up to a thickness of 0.6 cm were used and for beta-ray measurements the sources were approximately 0.01 cm thick.

III. HALF-LIFE DETERMINATION

The activity of the beta-rays, detected with an anthracene crystal, was followed for $1\frac{1}{2}$ hours. After subtraction of a long-lived background (mostly Cu^{64}) which represented about one percent of the initial activity, a half-life of 5.17 ± 0.07 min was obtained. The gamma-rays, detected with a sodium iodide crystal shielded by 0.6 cm Al from the source, yielded a half-life of 5.17-').10 min.[4] These values are in good agreement with the figures 5.18 ± 0.10 min[5] and 5.2 ± 0.2 min[1] rep ed recently, although they disagree with a value of 4.34 ± 0.03 min found by Silver[6] for the half-life of Cu^{66}.

IV. GAMMA-RAY MEASUREMENTS

Figure 1 shows some consecutive 5-min photographs of the pulse-height distribution from a single source of Cu^{66} placed over a sodium iodide scintillation detector. 0.6 cm Al was placed between the source and the detector. Photoelectron and Compton electron peaks of a 1.0-Mev gamma-ray of decreasing intensity and a 0.5-Mev gamma-ray of approximately constant intensity can be seen. Using a calibrated film, the successive intensities of the 1.0-Mev gamma-ray were found to be in the ratios of approximately $1:\frac{1}{2}:\frac{1}{4}$ showing the gamma-ray to be associated with the 5-min Cu^{66}. The 0.5-Mev gamma-ray pulses are undoubtedly due to annihilation radiation from Cu^{64}.

Figure 2 shows a photometer trace of a photograph taken for a more accurate measurement of the energy of the 1.0-Mev gamma-ray by "bracketing" its photoelectron line with the photoelectron lines of annihilation radiation and of the 1.33-Mev gamma-ray of Co^{60}. The resultant energy is 1.05 ± 0.03 Mev. The error quoted takes into account the accuracy with which the linearity of the electronic equipment and the photometering technique could be determined. The value given by Friedlander and Alburger[1] is 1.044 ± 0.010 Mev.

FIG. 1. Consecutive 5-min exposures of the gamma-ray pulses from slow neutron activated copper. Photoelectron and Compton electron distributions of a 1.0-Mev gamma-ray (from 5-min Cu^{66}) and of annihilation radiation (from 13-hr Cu^{64}) can be seen.

[1] G. Friedlander and D. E. Alburger, Phys. Rev. (to be published). The authors are very grateful to Dr. Friedlander for sending them a copy of the manuscript prior to publication.
[2] R. Hofstadter and J. A. McIntyre, Phys. Rev. **80**, 631 (1950).
[3] W. H. Jordan and P. R. Bell, Rev. Sci. Instr. **18**, 703 (1947).
[4] For this measurement a one-channel differential discriminator was set on the photoelectron peak of the 1.05-Mev gamma-ray. See Sec. IV.
[5] A. G. W. Cameron and L. Katz, Phys. Rev. **80**, 904 (1950).
[6] L. M. Silver, Phys. Rev. **76**, 589 (1949).

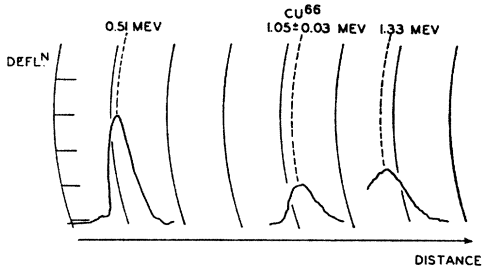

FIG. 2. Photometer trace of a single photograph for the measurement of the 1.0-Mev gamma-ray energy. Photoelectron peaks of 0.51- and 1.33-Mev calibration gamma-rays and of the Cu^{66} gamma-ray are shown.

Superposing the exposures of several 5-min irradiated sources of Cu^{66} on the same photograph and photometering the pulse-height distributions it was established that no other gamma-ray between 0.07 and 1.0 Mev could be present to more than 10 percent and between 1.0 and 4.0 Mev to more than 2 percent of the intensity of the 1.05-Mev gamma-ray in Cu^{66}.

V. BETA-RAY MEASUREMENTS

The beta-ray spectrum of Cu^{66} was obtained by photographing and photometering the pulse-height distribution from an anthracene scintillation detector. The intensity distribution was obtained by comparison with an artificial light wedge exposed on the same photograph to give film density *vs* exposure. The energy calibration was provided by the 0.97-Mev beta-spectrum of Au^{198}. Figure 3(A) shows the resulting Fermi-Kurie plot giving an end point of 2.7±0.1 Mev. The error quoted includes the uncertainty of the energy calibration. The deviation of the plot from a straight line at approximately 1.5 Mev indicates the presence of a low energy beta-spectrum (see below). The unevenness of the plot is due to statistical effects. The present endpoint is consistent with the value 2.63±0.02 Mev given in reference 1.

The beta-spectrum in coincidence with the 1.05-Mev gamma-ray was photographed by the technique of triggering the Tektronix scope with beta-gamma coincidences. For this purpose the gamma-rays were detected as described in Sec. IV, but pulses below 0.6 Mev were eliminated with an integral pulse-height discriminator. Figure 4 shows a comparison photograph of the complete beta-spectrum (A) and the coincident beta-spectrum (B). The beta-spectrum of Au^{198}, taken under identical conditions is shown also in (C). The same total number of pulses appears on all distributions. The pulses were shaped to be flat[7] to facilitate photometering. Although the statistics in Fig. 4 are poor and give rise to the intensity fluctuations, it can be seen that the coincident beta-spectrum has an end point approximately 1 Mev lower than the complete beta-spectrum. Indeed the Fermi-Kurie plot of the coincident beta-rays, shown in Fig. 3(B), yields an end point of 1.65±0.1 Mev. The deviation of the plot from a straight line below 0.8 Mev must be caused in part by source thickness (approximately 90 mg/cm²) and in part by inelastic back-scattering of electrons[8] by the anthracene crystal. The coincident beta-ray end point agrees with the expected value if the beta-ray is followed by the 1.05-Mev gamma-ray, going to the ground state of Zn^{66}.

[7] The authors are indebted to Mr. H. I. West for the design and construction of the pulse shaper.

VI. X-RAY MEASUREMENTS

An unsuccessful search was made for beta- (conversion) electron coincidences using anthracene crystal detectors. Most of the coincidences found were caused by scattered electrons which expended part of their energy in both crystals.

Also a search was made with sodium iodide crystals for the 8.6-kev *K* x-rays of Zn^{9}, but these were masked by the 7.5-kev x-rays of Ni produced in the decay of Cu^{64}. The results allowed only the setting of an upper limit of less than 0.05-Zn *K* x-rays per 1.05-Mev gamma-

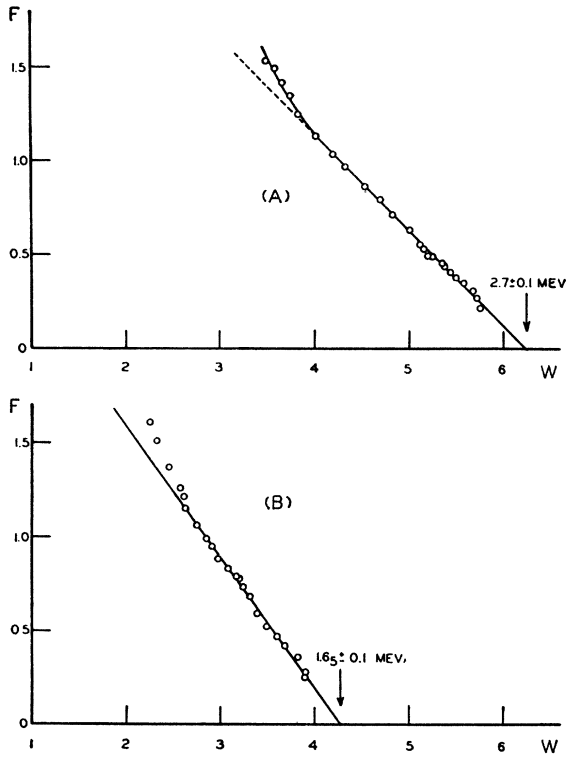

FIG. 3. (A) Fermi-Kurie plot of the complete be spectrum of Cu^{66}. *W* is the total energy of the electrons in uni their rest mass and *F* is the allowed Fermi-Kurie function. deviation from the straight line at approximately 1.5 Mev is to a lower energy beta-spectrum. (B) Fermi-Kurie plot of th coincident beta-rays. The deviation from the straight line at approximately 0.8 Mev is due to source thickness and inelastic backscattering from the anthracene crystal.

[8] W. Bothe, Z. Naturforsch. **4a**, 542 (1949).

[9] For the technique see West, Meyerhof, and Hofstadter, Phys. Rev. **81**, 141 (1951). For these measurements the sources were approximately 20 mg/cm² thick.

ray from Cu^{66}. This figure is not useful for the determination of a meaningful conversion coefficient, but does assure the absence of any highly converted gamma-rays which might not have been detected otherwise.

VII. COINCIDENCE MEASUREMENTS

In order to determine the branching ratio of the 1.6_5- and 2.7-Mev beta-rays the beta-ray pulses from anthracene and the gamma-ray pulses from sodium iodide crystals were passed through amplifiers and integral discriminators into a coincidence circuit of 0.25 μsec resolving time. The gamma-ray channel was biased against pulses below 0.6 Mev and the beta-ray channel against pulses below 0.2 Mev. Using both Au^{198} beta-gamma coincidences and Co^{60} gamma-gamma coincidences to calibrate the detector efficiencies, calculations of the branching ratio of the 1.6-Mev beta-rays yielded $5\frac{1}{2}\pm1\frac{1}{2}$ percent. These values were obtained consistently both from the Cu^{66} beta-gamma coincidence rates, and from the single counting rates in a manner analogous to that described by Friedlander and Alburger.[1] The effect of the bias and of self-absorption on the beta- and gamma-counting rates was taken into account in the calculations. Nevertheless the above value is slightly lower than the figure 9.2 ± 1 percent given in reference 1.*

Using anthracene crystal detectors and wide-band amplifiers in both channels of a coincidence circuit[10] of 0.03-μsec resolving time, an attempt was made to measure the half-life of the 1.05-Mev excited state of Zn^{66}, since Langer and Moffat[11] had postulated a half-life around 10^{-6} sec for this state. For these measurements 0.6-cm Al was placed between the source and one of the anthracene crystals. Figure 5 shows delayed coincidence curves for gamma-gamma coincidences in Co^{60} (o) and for beta-gamma coincidences in Cu^{66} (×). Accidental coincidences are subtracted. The curves are not of identical shape because the pulses in both cases are not produced by identical radiations and the coincidence circuit was sensitive to pulse heights. Since there is only one coincidence branch in Cu^{66}, the steep cutoff of the delay curve allows the setting of a conservative upper limit of 5×10^{-9} sec for the half-life of the 1.05-Mev excited state of Zn^{66}. (The dotted line in Fig. 5 shows the expected cutoff of the Cu^{66} curve for a metastable state of 5×10^{-9} sec half-life.)

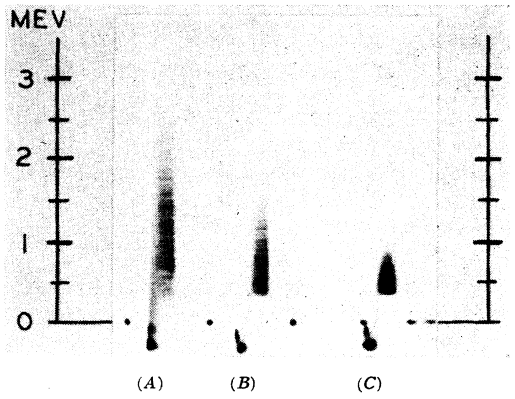

FIG. 4. Beta-ray pulse-height distributions. (A) Complete beta-spectrum of Cu^{66}. (B) Beta-spectrum coincident with gamma-ray pulses above 0.6 Mev. (C) Beta-spectrum of Au^{198} used for energy calibration.

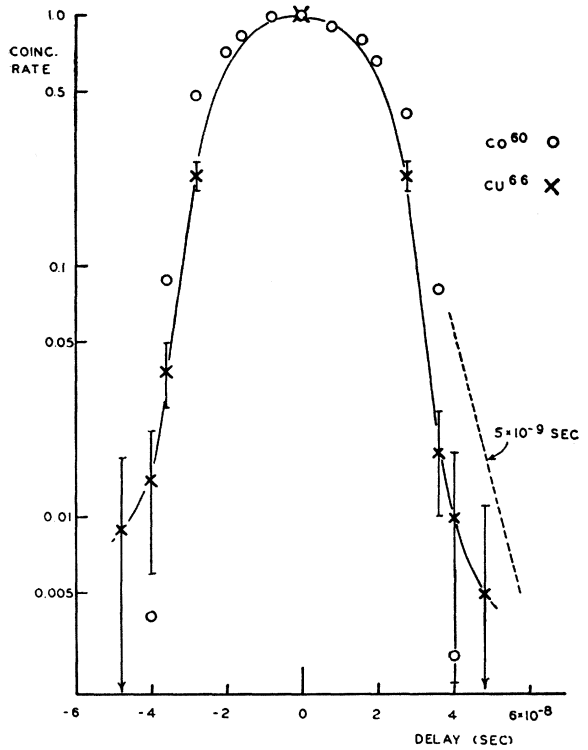

FIG. 5. Beta-gamma coincidence rate in Cu^{66} (×—×) *vs* delay of the beta-counter. The dotted line indicates the expected cutoff of the curve for a 5×10^{-9} sec metastable state. Gamma-gamma coincidences in Co^{60} (o o) are shown for comparison. The coincidence rates at zero delay are normalized to unity. Accidental coincidences are subtracted.

VIII. CONCLUSIONS

The present experimental results lead to the decay scheme of Cu^{66} shown in Fig. 6. The log *ft* values[12] for

* *Note added in proof:* Dr. Friedlander has kindly brought up the question as to a possible underestimation of the self-absorption of the beta-rays in our experiment. We have used the formula $f(1-e^{-\mu x})/\mu x$ to calculate the fraction of beta-rays issuing from a source of thickness x. With the values $\mu_{1.65}=4.6$ cm²/g, $\mu_{2.7}=2.6$ cm²/g, and $x=0.090$ g/cm² this formula yields $f_{1.65}=0.82$ and $f_{2.7}=0.89$. In the calculation using coincidence rates the final result for the branching ratio is proportional to $f_{2.7}/f_{1.65}$, where as using single rates the branching ratio is proportional to $1/f_{2.7}$. Increasing the effective μ by 40 percent would increase the branching ratio only by approximately 4 percent with either method of calculation.

[10] The authors are very much indebted to Dr. W. C. Barber for putting this coincidence circuit at their disposal. See W. C. Barber, Phys. Rev. **80**, 332 (1950).

[11] L. M. Langer and R. D. Moffat, Phys. Rev. **80**, 651 (1950).

[12] E. Feenberg and G. Trigg, Revs. Modern Phys. **22**, 399 (1950). One of the authors (WEM) is very much indebted to Dr. Trigg for sending him a set of log *ft* curves prior to publication.

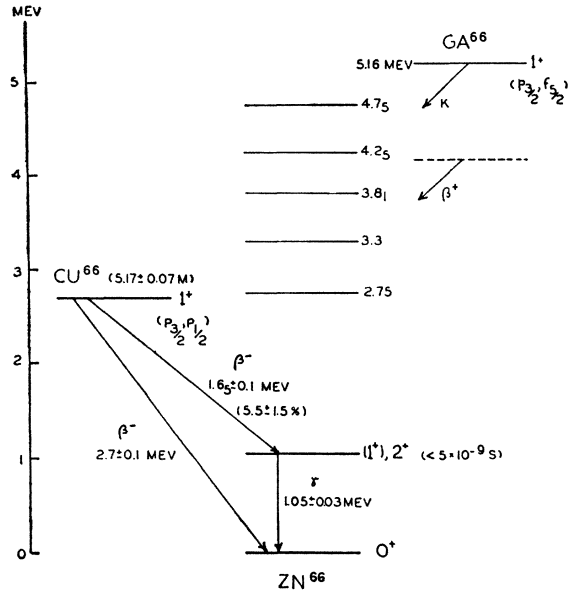

FIG. 6. The decay scheme of Cu^{66}. Excited states of Zn^{66} inferred from the decay of Ga^{66} are shown also.

the 2.7- and 1.6_5-Mev beta-rays are 5.3 and 5.6, respectively, indicating allowed transitions. Since the ground state of Zn^{66} presumably has zero spin and even parity and $0\rightarrow 0$ transitions are forbidden by Gamow-Teller selection rules, the spin of the ground state of Cu^{66} is probably 1 (even). This is consistent with the proton, neutron configurations $(p_{3/2}, p_{1/2})$ or $(p_{3/2}, f_{5/2})$ expected from the shell model[13] applied to beta-decay.[14] The 1.05-Mev excited state of Zn^{66} would then have a spin of 1 or 2 (even), consistent with the upper limit found for the half-life of the 1.05-Mev gamma-ray.[15] A spin 2 (even) would agree with Goldhaber and Sunyar's findings[15] that the first excited state of most (of the investigated) even-even nuclei has spin 2 (even).

As already pointed out by Friedlander and Alburger[1] these results contradict the decay scheme of Ga^{66} as proposed by Langer and Moffat[11] which can now be considered incorrect because of the recently determined value of 6.05 Mev for the $Zn^{66}(p, n)$ threshold.[16] But, furthermore, Mukerji and Preiswerk[17] propose a more nearly correct decay scheme of Ga^{66} in which a 1.06-Mev gamma-ray would be followed by a 2.75-Mev gamma-ray going to the ground state of Zn^{66}. (These gamma-rays would come from the 3.81- and 2.75-Mev levels of Zn^{66} shown in Fig. 6.) If this decay scheme is correct then the present investigation leads one to expect additional transitions to the 1.05-Mev excited state of Zn^{66} in the decay of Ga^{66}.[18]

The presently available information on Ga^{66} [2,11,17,18] would then lead to the excited states of Zn^{66} shown in Fig. 6. One may assume that a 3.1-Mev positron spectrum of the order of one percent intensity[19] was missed by previous investigators. The log ft value of this positron spectrum would be approximately 8. The 4.16-Mev positron spectrum of allowed shape[11] leading to the ground state of Zn^{66} has a log ft value of 7.9. Although these log ft values are rather high for allowed beta-spectra they are compatible with Nordheim's beta-decay rules.[14] In fact on the shell model essentially the same proton, neutron configurations are available for Ga^{66}, as for Cu^{66}. One may then assume a $(p_{3/2}, p_{1/2})$ configuration for Cu^{66} and a $(p_{3/2}, f_{5/2})$ configuration for Ga^{66} both having spin 1 (even). The beta-transitions to the ground state of Zn^{66} would be of the allowed types $\Delta I=-1$, $\Delta l=0$ and $\Delta I=-1$, $\Delta l=2$, respectively, the latter with an exceptionally high ft value as found by Nordheim[14] for odd A nuclei of this type.† The transitions to the 1.05-Mev excited state of Zn^{66} similarly could be $\Delta I=+1$, $\Delta l=0$ for Cu^{66} and $\Delta I=+1$, $\Delta l=2$ for Ga^{66}.

IX. ACKNOWLEDGMENTS

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[13] M. G. Mayer, Phys. Rev. **78**, 16 (1950). The other plausible configurations for 29 protons and 37 neutrons do not yield the expected spin values and/or parities.

[14] L. W. Nordheim, Phys. Rev. **78**, 294 (1950).

[15] For electric quadrupole radiation the expected half-life is approximately 10^{-10} sec [M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951)]. The authors are very grateful to Professor Goldhaber for sending them a copy of this paper prior to publication.

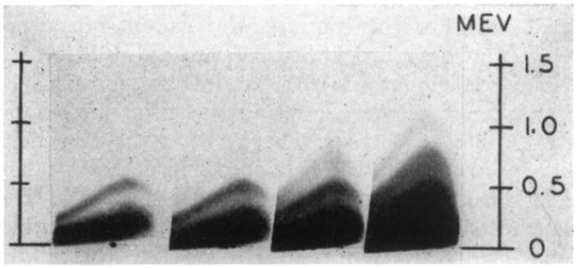
[16] Blaser, Boehm, Marmier, and Peaslee, Helv. Phys. Acta **24**, 2 (1951).

[17] A. Mukerji and P. Preiswerk, Helv. Phys. Acta **23**, 516 (1950).

[18] P. Preiswerk (private communication) has found weak gamma-rays from Ga^{66} which would support this interpretation. But this point bears further study since all the gamma-ray intensities cannot be matched as yet.

[19] This assumption is consistent with a rough analysis of the $(\beta^+\text{-}\gamma)/\beta^+$ coincidence curve (Fig. 6) in reference 11.

† *Note added in proof:* Data for even A nuclei have been published recently by L. Nordheim, Argonne National Laboratory Report No. 4626 (1951), to be published in Revs. Modern Phys. The present assignment of $p_{\frac{1}{2}}$ to a 37 nucleon configuration is not quite in accord with the strict shell model application to odd-odd nuclei, but might alleviate some of the difficulties mentioned in the report.



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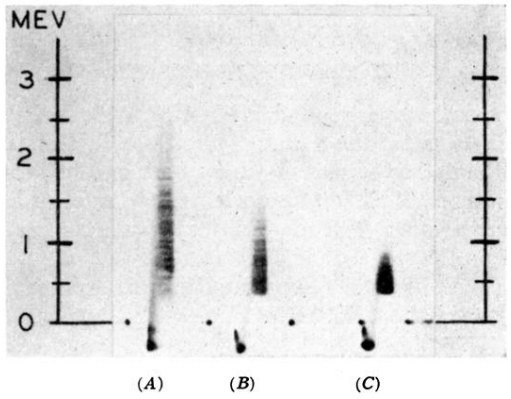

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