Gamma Rays from the Proton Bombardment of Separated Copper Isotopes*

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The energy spectrum of γ rays obtained from the proton bombardment of separated copper isotopes has been measured. It was found by coincidence measurements that the majority of these γ rays arise from the capture process when the bombarding energy is held below 2.2 Mev. The thick target cross section for proton capture at 1.9 Mev is found to be 0.1 millibarn. Above 2.2 Mev, excitation of the 0.67-Mev level in in Cu^{63} by either inelastic scattering or Coulomb excitation is observed. Excited level schemes for both Zn^{64} and Zn^{66} have been obtained. The first three levels in Zn^{64} are found to be at 0.97, 2.27, and 3.04 Mev. The scheme for Zn^{66} is essentially the same as that earlier proposed from the decay of Ga^{66}.

I. INTRODUCTION

THE original interest concerning this work arose as a result of curiosity regarding the spectrum of γ rays produced by 2-Mev proton bombardment of a copper foil being used in a Coulomb excitation experiment. The existence of several discrete lines in the vicinity of 1 Mev superimposed on a more or less continuous background extending upwards to 10 Mev suggested that some valuable information regarding nuclear excitation might be derived from a closer study of the energy spectrum. Curiously enough, very little quantitative work has been done in this direction. Malich and Harris[1] reported the existence of such gamma rays but to the best of our knowledge this comprises the only previous work.

In the principle, the γ radiation may appear as the result of (1) de-excitation of the copper nucleus following inelastic scattering of the protons; (2) proton capture and subsequent de-excitation of the residual zinc nucleus; (3) de-excitation of the zinc nucleus following a (p,n) reaction, and (4) de-excitation of the copper nucleus following Coulomb excitation. Several other possibilities, such as a (p,α) reaction, are possible but not probable considering the low energy of the bombarding protons. Possibility (3) above can be easily eliminated by holding the bombarding energy below the (p,n) threshold.[2] This was done throughout the experiment. A choice between the other possibilities (1), (2), and (4) can be made in a number of ways. In the first place, the existence of any γ radiation with energy higher than that available from the bombarding proton alone will indicate that proton capture is occurring. The source of any questionable low-energy radiation can then be checked by the presence or absence of coincidences with the high-energy radiation. A thick-target excitation curve of the questionable γ ray will in some cases allow one to decide between capture or inelastic scattering. Finally, correlation of the γ-ray energies with known excited levels in the possible residual nuclei can help determine the origin of the radiation. In the experiment to be described, all of these methods were used in some degree to interpret the results obtained.

II. EXPERIMENTAL DETAILS

The University of Texas electrostatic generator was used as a source of monoenergetic protons. The atomic (H^+) beam was separated from the molecular beam by means of an analyzing magnet (Fig. 1) and sufficiently collimated so that the beam current at the target was limited to approximately 3 microamperes. The target assembly was removed 9 feet from the magnet in order to reduce background radiations. An electrostatic "strong" focusing arrangement provided a well-concentrated beam at the target at all times.

Targets of separated copper isotopes,[3] Cu^{63} enriched to 99.85%, and Cu^{65} enriched to 98.16%, were used in the form of CuO. In order to secure a self-supporting target, finely ground CuO was made into the form of a thin paste by stirring it into distilled water. The paste was then painted on tin plates 0.020 inch thick which were cross-ruled to improve adhesion of the CuO. Under bombardment, the CuO was quickly reduced to metallic copper, so in practice the targets were thin

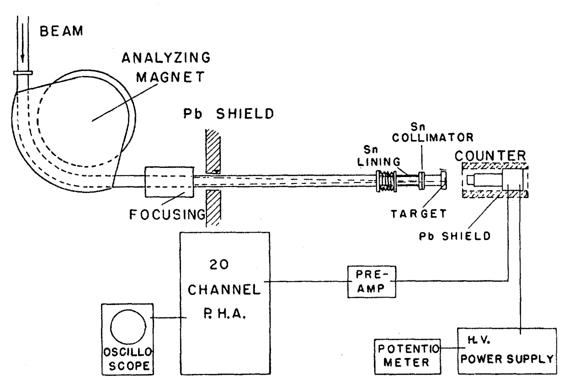

FIG. 1. Schematic diagram of experimental arrangement for detection of single γ-ray spectra.

* Assisted by the United States Air Force, through the Office of Scientific Research of the Air Research and Development Command.

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[1] C. W. Malich and J. C. Harris, Phys. Rev. 81, 318 (1951).

[2] The reported thresholds are $Cu^{63}(p,n)$, 3.6 Mev, and $Cu^{65}(p,n)$, 2.16 Mev. L. A. Delsasso *et al.*, Phys. Rev. 55, 113 (1939); Shoupp, Jennings, and Jones, Phys. Rev. 73, 421 (1948).

[3] Obtained from the Stable Isotopes Division, Oak Ridge National Laboratories.

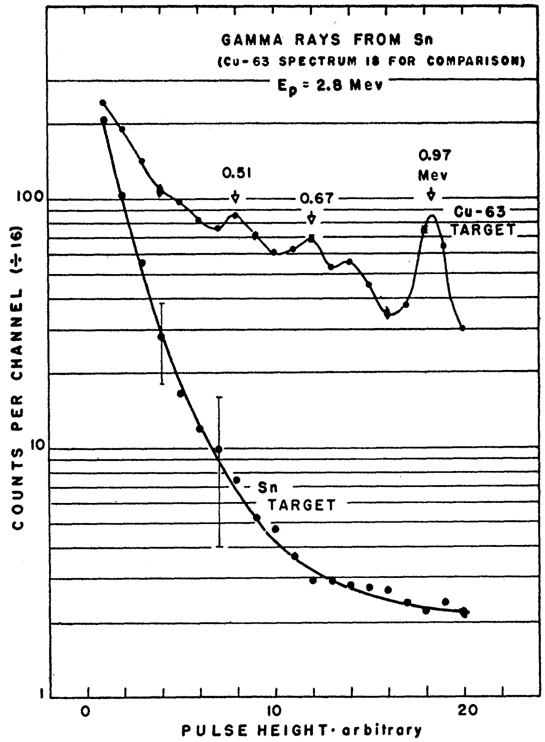

FIG. 2. Pulse-height spectrum of the γ rays from tin bombarded with 2.8-Mev protons. The spectrum of γ rays from Cu^{63} is shown for comparison.

metallic copper flakes which adhered (sometimes rather precariously) to the tin backing. These flakes were at all time thick to the bombarding protons. Tin is a good target backing in such experiments, for with a closed shell of protons, excitation by proton capture or Coulomb excitation is extremely unlikely. Figure 2 shows the complete absence of any structure in the radiation observed when a blank tin plate was bombarded with 2.8-Mev protons. The small amount of radiation present is presumably due to proton bremsstrahlung. The interior of the target assembly tube was also lined with tin foil to reduce background.

Gamma radiation was observed with a single $1\frac{1}{2}\times1\frac{1}{2}$

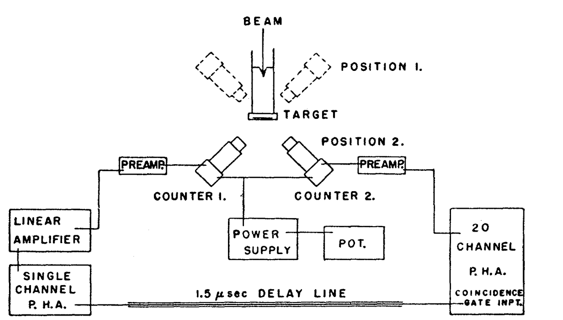

FIG. 3. Schematic diagram of experimental arrangement for detection of coincidence γ-ray spectra. Position 1 gave somewhat better resolution but with some reduction in counting rate.

inch NaI(Tl) crystal mounted on a DuMont 6292 photomultiplier tube. Electric pulses from the photomultiplier circuit were fed through a preamplifier into a twenty-channel pulse-height analyzer. Calibration of the analyzer was performed before and after each series of runs. The calibration was done at points corresponding to well known γ-ray energies: Cs^{137} (0.669 Mev), Co^{60} (1.17 and 1.33 Mev); two high-energy points were obtained at 5.62 Mev and 5.11 Mev corresponding to the pair-production peaks of a 6.13-Mev γ ray from the reaction $F^{19}(p,\alpha)O^{16}$. The twenty-channel analyzer was frequently checked for uniformity in channel width and the individual channel widths were held to within one percent accuracy. The regulated high-voltage

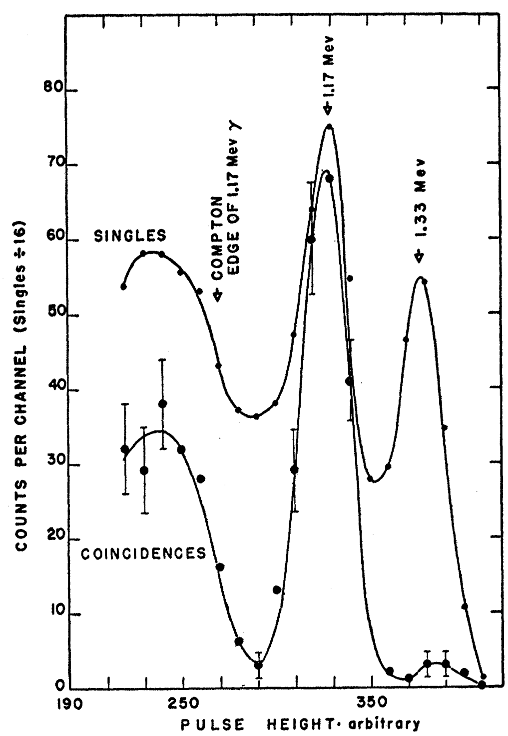

FIG. 4. Test coincidence spectrum taken with a Co^{60} source. The 1.33-Mev radiation was used to gate the 20-channel analyzer which recorded the coincidence spectrum shown. The singles spectrum is shown for comparison.

supply of the photomultiplier circuit was constantly monitored with a potentiometer and was held constant within ±0.001 volt.

In order to establish possible coincidences between two γ rays, the arrangement shown schematically in Fig. 3 was used. Two scintillation counters of identical design were used. A single-channel analyzer was used to select pulses of a given height from counter No. 1. These pulses were then used to gate the twenty-channel analyzer so that it became operative only on the arrival of a pulse of the proper size from counter No. 1. The coincidence spectrum from counter No. 2 was then recorded directly on the multichannel analyzer. In order to equalize the delay in each of the two circuits, proper lengths of RG-65/U delay cable were inserted as shown in the figure. The proper delay for a given pulse-height setting on the single-channel analyzer could be checked experimentally in two ways. First, test pulses were introduced simultaneously in both circuits and the coincidence in time of the pulses at the gating circuit checked by means of displaying one pulse on an oscilloscope sweep driven by the other pulse. The delay of the first pulse with respect to the beginning of the sweep was then observed. Secondly, a Co^{60} source was placed between the counters and the coincidence spectrum measured when one of the cascade γ rays was used to gate the multichannel analyzer. In practice the delay

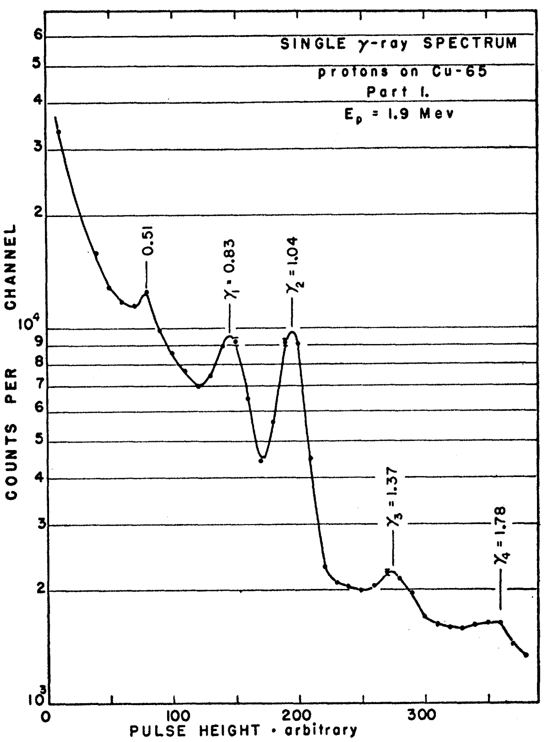

FIG. 5. The energy spectrum of γ rays in the interval 0–1.8 Mev observed when Cu^{65} is bombarded with 1.9-Mev protons. γ_i indicates the photopeak of a given γ ray.

line was always adjusted to give the best rejection of the gating pulse in this coincidence spectrum. Figure 4 depicts a single and a coincidence spectrum taken when the 1.33-Mev γ ray was used as the gating pulse. The rejection of this γ ray relative to the 1.13-Mev line is approximately 1:30.

III. RESULTS AND TREATMENT OF DATA

Single-crystal spectrometer measurement of the γ-ray spectrum from the two copper isotopes showed that γ rays up to $\sim$10 Mev were present. These high-energy γ rays can arise only from the capture process, considering the 2-Mev bombarding energy of the protons. Subsequent coincidence measurements showed that nearly all of the lower energy γ rays also arise as a result of capture. An analysis of the singles spectrum will therefore yield information concerning the excited states of the residual nuclei, Zn^{64} and Zn^{66}.

Mann, Meyerhoff, and West[4] and Mukerji and Preiswerk[4] have investigated in detail the radioactivity of Ga^{66} which decays by positron emission to Zn^{66}, and have succeeded in establishing the excited level scheme of Zn^{66} up to about 5 Mev. The experiment reported here essentially confirms their results. The structure of Zn^{64} is not as well known. In fact, the only data available are those of Cohen[5] on Ga^{64}, which does not include a decay scheme. We therefore devoted the majority of our efforts to the gamma rays from Cu^{63} in order to propose a level scheme for the residual nucleus Zn^{64}.

Copper-65

The singles gamma-ray spectrum from the proton bombardment of Cu^{65} is shown in Figs. 5 and 6 for γ-ray energies up to 4.5 Mev. The spectra appear to be quite complex, which is not surprising in view of the fact that

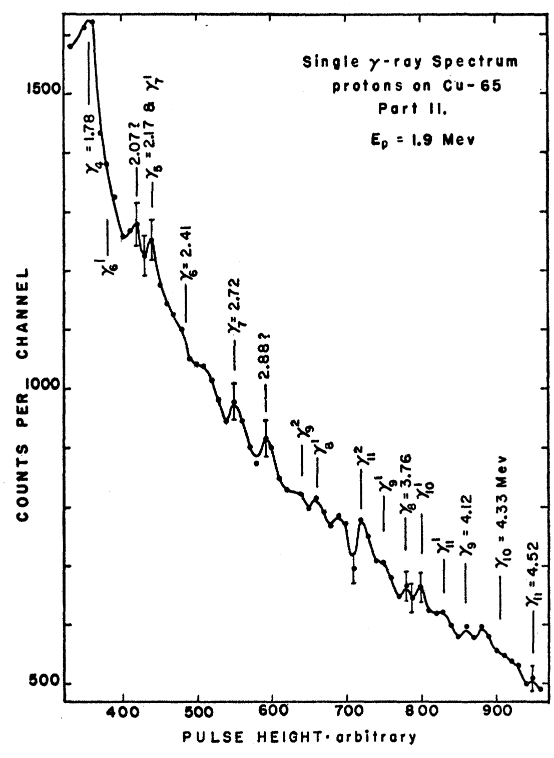

FIG. 6. The energy spectrum of γ rays in the interval 1.7–4.6 Mev observed when Cu^{65} is bombarded with 1.9-Mev protons. γ_i = photopeak; γ_i^1 = pair production with escape of one annihilation photon; γ_i^2 = pair production with escape of both annihilation photons.

[4] Mann, Meyerhoff, and West, Phys. Rev. **92**, 1481 (1953); A. Mukerji and P. Preiswerk, Helv. Phys. Acta **25**, 386 (1952).
[5] B. L. Cohen, Phys. Rev. **91**, 71 (1953).

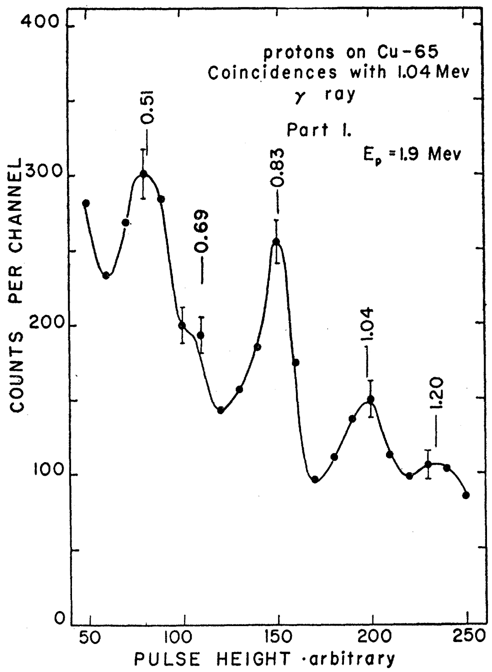

FIG. 7. The energy spectrum of γ rays in the interval 0–1.3 Mev which are in coincidence with the 1.04-Mev γ ray observed when Cu^{65} is bombarded with 1.9-Mev protons.

a Zn nucleus, excited to $\sim$10 Mev, may decay to its ground state in a great number of ways. With the exception of direct to ground transitions, all cascades and cross-overs terminate on the first excited level. Consequently the intensity of gamma radiations corresponding to the de-excitation of the first excited level is expected to be the greatest. Other γ rays may be identified as cascades, or crossovers, or direct to ground transitions by the lack or presence of coincidences between them and the "first-level-to-ground" gamma rays. Relative intensity measurements can also supplement the coincidence measurements in establishing the source of a particular γ ray. Unfortunately, the picture is

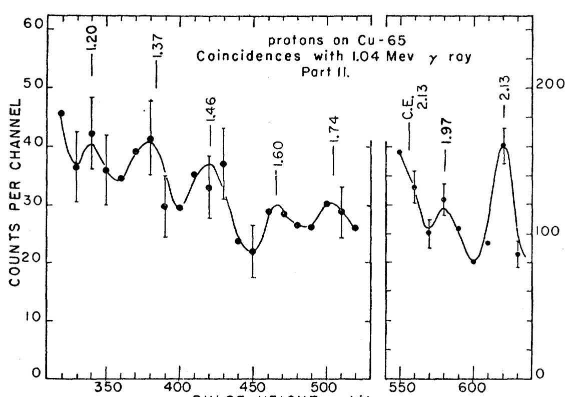

FIG. 8. The energy spectrum of γ rays in the interval 1.1–2.2 Mev which are in coincidence with the 1.04-Mev γ ray observed when Cu^{65} is bombarded with 1.9-Mev protons.

further complicated by the very behavior of scintillation crystals to impinging γ rays. In sodium iodide it is well known that a single γ ray will produce a photopeak pulse, a Compton pulse distribution, and for incident γ-ray energies greater than 1.02 Mev, pair-production peaks.

Inspection of Figs. 5 and 6 shows the most intense γ ray to be 1.04 Mev in energy. This then would indicate the first excited state of Zn^{66} to be at this energy. This is in agreement with the results of Mann *et al.*, and Mukerji and Preiswerk.[4] The identification of discrete γ-ray energies up to 2.72-Mev is possible from the present data without ambiguity. Above this energy, the multiplicity of peaks makes identification extremely difficult, and we have frankly labeled these peaks in Fig. 6 only on the basis of the known γ rays in this energy range found by Mann *et al.*,[4] using a 3-crystal pair spectrometer.

The spectrum of the γ rays in coincidence with the 1.04-Mev γ ray is shown in Figs. 7 and 8. The coincidences at 0.51 Mev are the result of annihilation

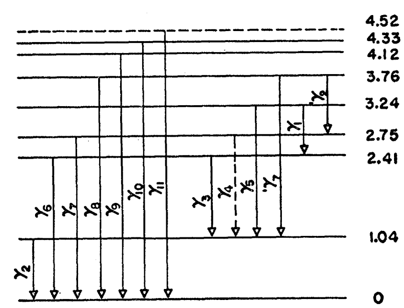

FIG. 9. The proposed decay scheme of Zn^{66} which is formed by proton capture in Cu^{65}. Energies are in Mev. Dotted levels and transitions are uncertain.

radiation produced in the target backing by high-energy cascade γ rays. The 0.83-, 1.37-, and 2.13-Mev lines are interpreted as photopeaks of γ rays of these energies. The 0.69- and 1.20-Mev lines are interpreted as "2-escape" and "1-escape" pair peaks of a 1.71-Mev γ ray. The 1.60 peak is the 1-escape peak of the 2.13-Mev radiation. The broad peak at 1.74 Mev is interpreted as a superposition of the photopeak of a 1.71-Mev γ ray and the 2-escape peak of a 2.75-Mev γ ray. All of these γ rays can be fitted into a decay scheme for Zn^{66} which is in good agreement with the one proposed by Mann.[4] This is displayed in Fig. 9. The 1.46- and 1.97-Mev lines are most likely the 2- and 1-escape peaks of a 2.48-Mev γ ray. Mann *et al.*[4] obtained a 2.40-Mev γ ray in coincidence with the 1.04-Mev radiation which was interpreted as a transition from a 3.41-Mev state to the 1.04-Mev state in Zn^{66}. This scheme can be further strengthened by an alternative interpretation of our Cu^{65} singles spectrum (Fig. 6) in which the peak labeled 2.88 Mev is ascribed to the 1-escape of a 3.39-Mev γ ray. The 2-escape peak of such a γ ray would be buried in the photopeak of the 2.41-Mev γ ray. The difficulty of such an interpretation from our data lies in the fact that the singles spectrum would place the level at 3.39 ± 0.05 Mev, while the coincidence spectrum would put it at $2.48+1.04=3.52\pm0.04$ Mev. The two values do not agree within the experimental error. We therefore are unable to make a definite assignment regarding a level in Zn^{66} in the neighborhood of 3.4 Mev.

It remains to mention the appearance of a 1.04-Mev γ ray in coincidence with the 1.04-Mev gating radiation. Although a 1.01-Mev γ ray can be fitted into the Zn^{66} scheme which would be in coincidence with the 1.04 line, we do not feel that the majority of observed coincidences at this energy are true coincidences. Rather they appear to be the result of a rather special kind of accidental coincidence which we have called "Compton coincidences." They are caused by the simultaneous appearance of a Compton recoil pulse of 1.04-Mev energy in the gating circuit and a 1.04-Mev photoelectron pulse in the 20-channel analyzer. There is a strong possibility that there will be many of these events in coincidence considering the nature of the decay of the Zn^{66} nucleus. This process and the magnitude of the effect is discussed in detail in an appendix.

TABLE I. Gamma rays from the proton bombardment of Cu^{65}.

γ ray	E_γ(Mev)	γ rays in coincidence with γ_2
γ_1	0.83 ± 0.02	
γ_2	1.04 ± 0.01	γ_1, γ_3, γ_4(1.71 Mev), γ_5, γ_7 (also 2.48-Mev γ ray)
γ_3	1.37 ± 0.02	
γ_4(?)	1.78 ± 0.03	
γ_5	2.17 ± 0.04	
γ_6	2.41 ± 0.04	
γ_7	2.72 ± 0.04	
γ_8	3.76 ± 0.05	
γ_9	4.12 ± 0.05	
γ_{10}	4.33 ± 0.05	
γ_{11}(?)	4.52 ± 0.05	

Table I summarizes the results of our measurements on Cu^{65}.

Copper-63

The singles γ-ray spectrum from the proton bombardment of Cu^{63} is shown in Figs. 10 and 11 for γ-ray energies up to approximately 3 Mev. The resolution of the spectrometer is shown at various energies. The most intense line here appears at an energy of 0.97 Mev. This is also the energy of the most intense line in the decay of Ga^{64}.[5] We therefore assign the first energy level of Zn^{64} to be 0.97 Mev above ground. Table II lists the γ rays which we observe in the decay of the residual nucleus Zn^{64}. γ_7 and γ_8 are not shown in the data of Figs. 10 and 11. Although photoelectric and pair-production peaks have been identified for these two γ rays, we do not feel that we have entirely convincing evidence of their presence.

The various peaks of the single pulse spectrum appear to be riding on a seemingly continuous background. It was found that for energies greater than 0.5 Mev, the background at any point was primarily due to the Compton pulse distribution of gamma rays with larger energies. (Below 0.5 Mev, proton bremsstrahlung becomes significant.) In order to calculate the true intensity of any given γ ray, the following procedure was used. McGowan's[6] data relating the number of counts in the full energy peak to the total number of counts in the entire pulse spectrum for a NaI crystal were supplemented by measurements of our own which extended up to 2.62 Mev (ThC″ γ ray). These data, together with the known cross sections for photoelectric, Compton, and pair-production events in NaI,

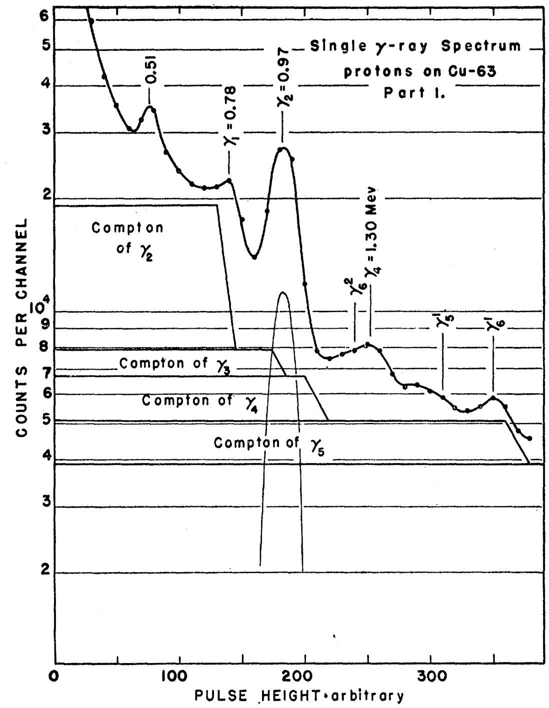

FIG. 10. The energy spectrum of γ rays in the interval 0–1.8 Mev observed when Cu^{63} is bombarded with 2.0-Mev protons. γ_i=photopeak; γ_i^1=pair production with escape of one annihilation photon; γ_i^2=pair production with escape of two annihilation photons. Resloution of the spectrometer is indicated at intervals.

TABLE II. Gamma rays from the proton bombardment of Cu^{63}.

γ ray	E_γ(Mev)	Relative intensity	γ rays in coincidence with γ_2
γ_1	0.78 ± 0.02	32	
γ_2	0.97 ± 0.01	100	γ_1, γ_3, γ_4, γ_5, γ_{10}(?)
γ_3	1.16 ± 0.03	17	
γ_4	1.30 ± 0.03	29	
γ_5	2.07 ± 0.04	41	
γ_6	2.27 ± 0.05	40	
γ_7	3.84 ± 0.05	···	
γ_8	5.64 ± 0.05	···	
γ_9	3.04 ± 0.05	···	
γ_{10}(?)	2.38 ± 0.05	···	

[6] F. K. McGowan, Phys. Rev. **93**, 163 (1954).

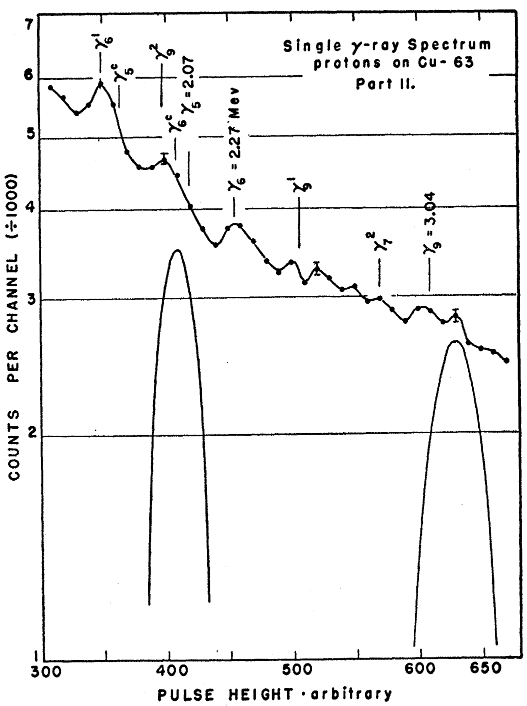

FIG. 11. The energy spectrum of γ rays in the interval 1.6–3.2 Mev observed when Cu^{63} is bombarded with 2.0-Mev protons. γ_i=photopeak; γ_i^1=pair production with escape of one annihilation photon; γ_i^2=pair production with escape of two annihilation photons. Resolution of the spectrometer is indicated at intervals.

and the relative heights of the 1-escape and 2-escape pair peaks for our geometry, were then used to calculate the total Compton contribution. The energy distribution of the Compton electrons was approximated by straight lines, as indicated in Fig. 10. Beginning with γ_6, the above procedure was repeated for the next γ ray, then for the next, all the way down to γ_2. In this way it was possible to fit the experimental spectra quite closely. The relative intensities given in Table II were computed from the observed number of counts in a given full-energy peak which were then corrected to the number of counts in the total spectrum by the method just described.

The spectrum of the γ rays in coincidence with the 0.97-Mev γ ray is shown in Figs. 12 and 13. Singles spectra are plotted at the top for reference. The peaks at 0.79, 1.9, 1.30, 2.07, and 2.38 Mev are assigned as photopeaks due to γ rays of these energies. The 1.56 peak is the 1-escape of the 2.07-Mev γ ray; the 2-escape is buried in the leading edge of the 0.97 peak. The 1.90 line is the 1-escape of the 2.38-Mev γ ray; the 2-escape of this γ ray is buried in the leading edge of the 1.30 peak. We have not been able to assign the origin of the peak at 1.75 Mev without ambiguity. The outstanding feature of these curves is found in the section labeled "D" in Fig. 13. It can be seen clearly that a 2.27-Mev γ ray which is present in the singles spectrum is not in

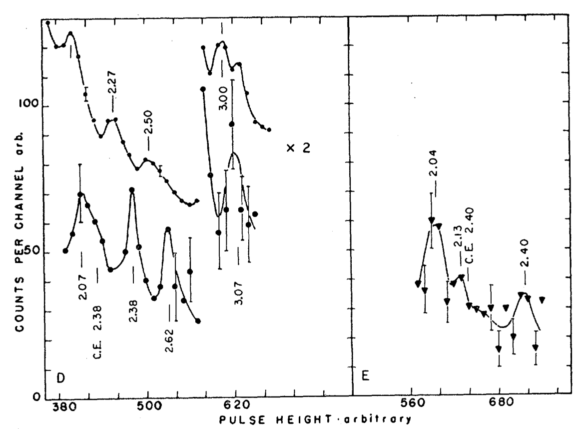

FIG. 13. Various 20-channel spectra of the γ rays in coincidence with the 0.97-Mev γ ray observed when Cu^{63} is bombarded with 2.5-Mev protons. —▼— position 1 (see Fig. 3); —▲— repeated spectrum, position 1; —●— position 2. Singles spectra are plotted at the top for comparison purposes.

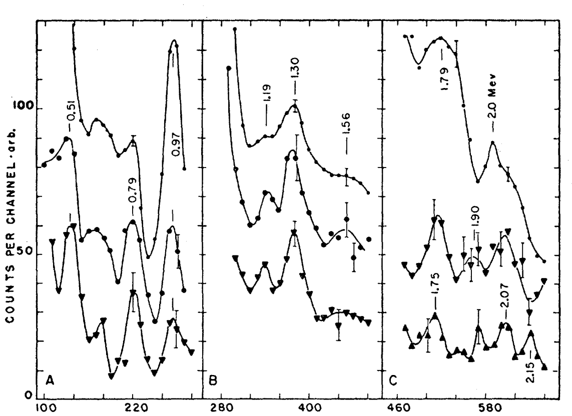

FIG. 12. Various 20-channel spectra of the γ rays in coincidence with the 0.97-Mev γ ray observed when Cu^{63} is bombarded with 2.5-Mev protons. —▼— position 1 (see Fig. 3); —▲— repeated spectrum, position 1; —●— position 2. Singles spectra are plotted at the top for comparison purposes.

coincidence with the 0.97-Mev γ ray. We therefore assign the second excited level of Zn^{64} as 2.27 Mev. This fits in nicely with the observed coincidence of the 0.97-Mev and 1.30-Mev γ rays. Above this level, the identification becomes more tedious and uncertain. Figure 14 depicts our best attempt in assignment of the various observed radiations. Everything above the 2.27-Mev level is subject to some doubt in almost every case. Dotted levels are very uncertain.

The chance coincidence rates were checked in all runs by simply removing part of the delay cable which was originally inserted to equalize the over-all delay in each of the coincidence channels. Chance rates were always quite small in comparison to the actual rate. A certain background will be evident in all the coincidence spectra. This is interpreted as being due to Compton recoils of higher energy γ rays which are in coincidence with the "gating" γ ray. As in the case of Cu^{65}, there appears a coincidence between the gating pulse (0.97) and a γ ray of exactly the same energy. This is also the result of Compton coincidences which are discussed in the Appendix.

The only example of a γ ray which did not arise from the capture process occurred for Cu^{63} when the bombarding energy of the protons was raised above 2.2 Mev. Figure 15 depicts the low-energy spectrum of γ rays for various bombarding energies. The emergence of a 0.67-Mev γ ray is quite clear. This energy corresponds exactly to the energy of the first excited state of Cu^{63} as determined by Schiffer *et al.*, and Heydenburg and Temmer.[7] This γ ray is being excited most probably by inelastic scattering in our case. Competition between the capture and inelastic processes can be seen if the thick-target yields of the 0.97- and 0.67-Mev γ rays are are plotted. This is shown in Fig. 16. The rise in the 0.97-Mev γ-ray yield above 3.0-Mev proton energy is due to inelastic excitation of the second excited state in Cu^{63} which happens to fall at precisely 0.97 Mev.

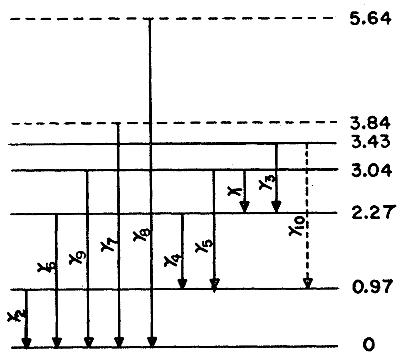

FIG. 14. The proposed decay scheme of Zn^{64} which is formed by proton capture in Cu^{63}. Energies are in Mev. Dotted levels and transitions are uncertain.

The cross section for proton capture by Cu^{63} has been calculated from the thick-target yield of the 0.97-Mev γ ray. Supposing the protons to produce 0.97-Mev γ rays uniformly until they reach the end of their range in the copper, we find the thick-target cross section to be 0.1 millibarn at 1.9-Mev incident proton energy. A similar figure holds for the other copper isotope.

IV. CONCLUSIONS

The present experiments establish conclusively that at moderate proton bombarding energies (<2.1 Mev) the exclusive nuclear process is proton capture for each of the two stable copper isotopes Cu^{63} and Cu^{65}. The emitted gamma radiation is therefore the result of the de-excitation of the respective compound nuclei, Zn^{64} and Zn^{66}.

In the case of Cu^{63}, at bombarding energies between 2.2 and 3.2 Mev the predominant process is still proton

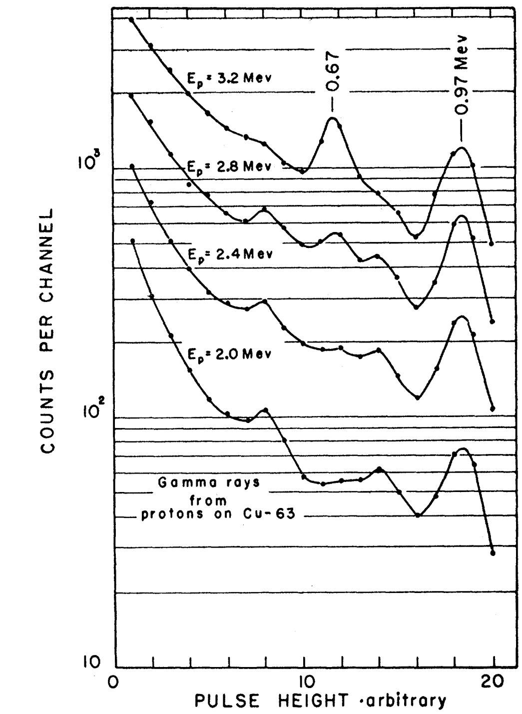

FIG. 15. The spectra of gamma rays from Cu^{63} when bombarded with protons of various energies.

capture, with inelastic proton scattering emerging at about 2.2 Mev. Because of the low (p,n) threshold for Cu^{65}, no detailed study of the emitted gamma radiation was undertaken beyond 2.0-Mev bombarding energy;

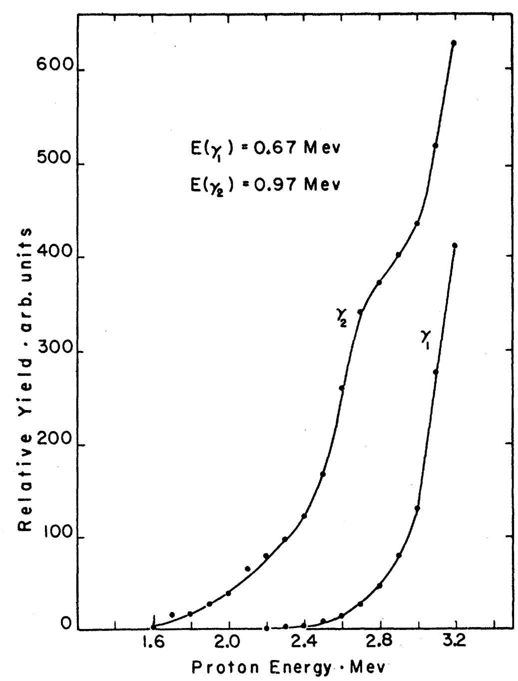

FIG. 16. Thick-target yield of the 0.67-Mev and 0.97-Mev γ rays observed when Cu^{63} is bombarded with protons.

[7] Schiffer, Windham, Gossett, and Phillips, Phys. Rev. **99**, 655 (1955); G. M. Temmer and N. P. Heydenburg, Phys. Rev. **100**, 961(A) (1955).

however, it is expected that neutron emission will replace proton capture soon after the (p,n) threshold is exceeded, leaving little room for inelastic proton scattering from Cu^{65}.

Two scintillation spectrometers, in conjunction with a twenty-channel differential pulse-height analyzer, were used to detect gamma rays in coincidence. The correlated single and coincidence results confirmed the decay scheme for Zn^{66}, previously obtained from the decay of Ga^{66}, the next higher element in the atomic table. It was also possible to propose a level scheme for the isotope Zn^{64} which, up to now, has been almost completely unexplored.

A more complete interpretation of the high-energy gamma-ray region would be possible with a three-crystal scintillation pair spectrometer.

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APPENDIX

The coincidence spectrum from each copper isotope contains counts over and above the expected accidental rate at an energy identical with that of the gating gamma ray (Fig. 7 and Fig. 12). We have not interpreted these as true coincidences, but rather as the result of a Compton recoil (or recoils) produced in counter 1 (Fig. 3) of proper energy to gate the 20-channel analyzer plus the simultaneous appearance in counter 2 of a photoelectron of the same energy. That there is a high probability of the simultaneity of such events is evident from the cascade nature of the decay of the Zn nucleus. There is also a good chance that many of the coincidences recorded at other energies in the spectra of Figs. 7, 8, 11, and 12 are of this nature rather than true coincidences. In order to establish a criterion for deciding whether an observed coincidence was true or not, we adopted the following test.

In the case of either isotope, the gating γ ray has been labeled γ_2. Now in the singles spectra (Fig. 5 and Fig. 10) at an energy E_2 there are a certain number of counts, m_2, which are due to photoelectrons produced in the crystal by γ_2 while the remainder of the counts, m_{2c}, are produced by Compton recoils from higher energy γ rays. A certain fraction of these Compton recoils, ξ_2, will be in coincidence with γ_2. Thus, if D_2 is the total number of γ_2 events per unit time produced in the target, the "Compton coincidence" rate at energy E_2 in the coincidence spectrum will be

$$C_{c2}=\xi_2 m_{2c} m_2/D_2.$$

At some higher energy, E_n, the rate will be

$$C_{cn}=\xi_n m_{2c} m_n/D_n,$$

where ξ_n is the fraction of m_{2c} which are in coincidence with γ_n.

Now we cannot calculate C_{cn} absolutely, since D_n and ξ_n are unknown. However, if one assumes that *all* of the observed coincidences at E_2 are due to Compton coincidences (after correction for the accidental rate), then one can write

$$C_{cn}=C_{c2}(\xi_n m_n D_2/\xi_2 m_2 D_n).$$

Now ξ_n is proportional to D_n, and since $\xi_n<\xi_2$, we can finally write

$$C_{cn}<C_{c2}(m_n/m_2).$$

The quantities m_n and m_2 can be read off the singles spectrum, and C_{c2} from the coincidence spectrum. In order to qualify as a true coincidence, the counting rate at a given energy was required to exceed $C_{c2}(m_n/m_2)$ by at least a factor of two.