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Decay of Copper-66†

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The decay of Cu^{66} (5.1 min) has been reinvestigated by scintillation spectroscopy. A (0.83 ± 0.01)-Mev gamma ray has been found to be in coincidence with the previously known 1.04-Mev gamma ray arising from the decay of the first excited state in Zn^{66}. This indicates a (second) excited state in Zn^{66} at 1.87 Mev in line with the level systematics of neighboring Zn isotopes.

I. INTRODUCTION

During a reinvestigation[1] of the decay[2] of Ge^{68}, evidence was found for excited states in Zn^{68} at 1.88 and 2.31 Mev in addition to the previously known state at 1.07 Mev.[3] (The 1.88-Mev state was already predicted by Way *et al.*[3] on the basis of neutron-capture gamma-ray work of Kinsey and Bartholomew.[4]) A comparison of the states of Zn^{68} with those of Zn^{66} and Zn^{64} made it seem likely that second excited states near 1.8 Mev should occur in the latter isotopes also. This induced us to reinvestigate[3,5] the decay of Cu^{66} (5.1 min) in which a state near 1.8 Mev in Zn^{66} should be weakly populated by a 0.8-Mev beta ray.[6]

Our original suspicions were strengthened by a reinterpretation of gamma-gamma coincidence work of Weller and Grosskreutz[7] in the $Cu^{63}(p,\gamma)Zn^{64}$ and $Cu^{65}(p,\gamma)Zn^{66}$ reactions, which indicated levels in the final products at 1.75 and 1.87 Mev, respectively. More direct evidence for these levels has meanwhile been found by Sinclair[8] from the inelastic scattering of neutrons on separated Zn isotopes. Furthermore, Jacobi[9] has found a 1.77-Mev level in Zn^{64} from a study of the decay of Ga^{64}.

The level systematics of the even-even isotopes in this general mass region were recently reviewed.[10]

II. EXPERIMENTAL METHOD AND RESULTS

A. Source Preparation and Apparatus

The sources consisted of 1-inch by 1-inch by $\frac{1}{8}$-inch blocks of natural copper. These were irradiated for 10 minutes with slow neutrons produced by the Stanford cyclotron. The apparatus consisted of two $1\frac{1}{2}$-inch diameter by $1\frac{1}{2}$ inches long NaI(Tl) crystals mounted on Dumont 6292 photomultipliers, a conventional fast-slow coincident circuit of 0.2-μsec resolving time and an *RCL* 256-channel pulse-height analyzer.

B. Gamma-Ray Spectrum

Because of low-counting rates in the energy region of interest, a very close geometry was used both in the singles and coincidence work. The geometry is indicated on Fig. 1. The pulse-height distribution from every copper source was measured for 10 minutes immediately after irradiation and again several hours later in order to determine the background (mostly Cu^{64}). Figure 1 shows the pulse-height spectrum after subtraction of

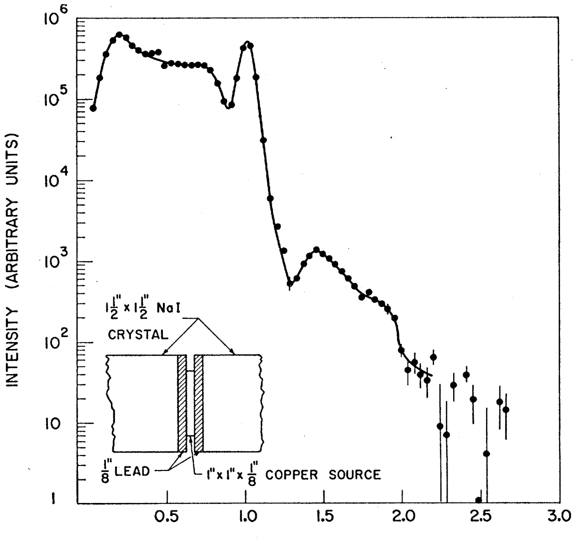

Fig. 1. Singles and coincidence geometry and Cu^{66} gamma-ray singles spectrum. Natural copper was irradiated with thermal neutrons. The Cu^{66} singles spectrum was obtained by subtracting the room and Cu^{64} background. The peaks near 1.6 and 1.9 Mev are caused by coincident 1.04- and 0.83-Mev gamma rays and scattering.

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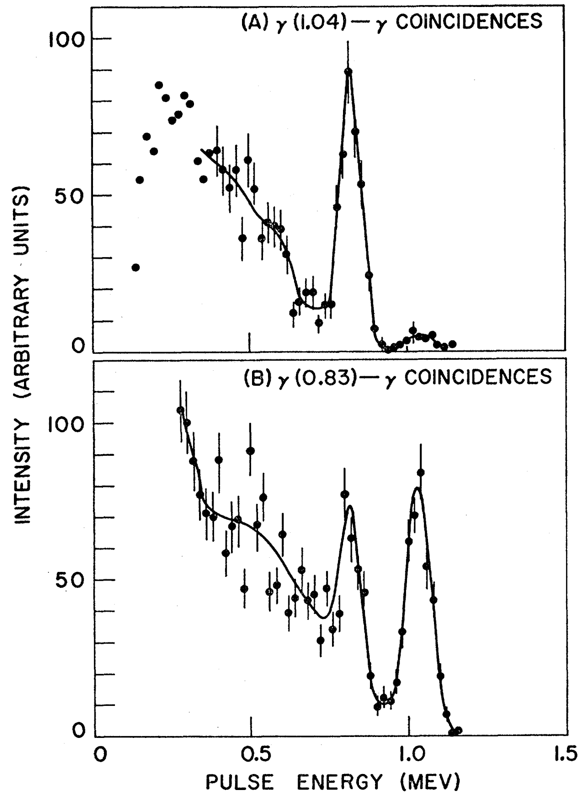

FIG. 2. (A) Gamma-ray spectrum from Cu^{66} in coincidence with 1.04-Mev pulses. The peak at 1.04 Mev presumably is caused by coincidences due to bremsstrahlung of the beta rays feeding the 1.04-Mev state in Zn^{66}. (B) Gamma-ray spectrum from Cu^{66} in coincidence with 0.83-Mev pulses. The peak at 0.83 Mev is due to coincidences with Compton pulses from the 1.04-Mev gamma ray lying near 0.83 Mev.

the background (only the Cu^{64} background was corrected for decay). Most, if not all, of the counts near 1.9 Mev can be accounted for by solid-angle addition of coincident 1.04- and 0.83-Mev gamma rays (see Sec. II.C). The counts below 1.9 Mev down to the 1.04-Mev photopeak are due to the scattering of the coincident gamma rays in the very poor geometry.

From Fig. 1 one calculates a conservative upper limit of 0.001 for the relative intensity of a 1.9-Mev gamma ray compared to the 1.04-Mev gamma ray.

C. Gamma-Gamma Coincidence Spectra

Coincidence spectra were taken with the crystals placed as shown in Fig. 1. The discriminating detector was allowed to accept pulse energies around 1.04 Mev [Fig. 2(A)] and around 0.83 Mev [Fig. 2(B)]. In order to demonstrate that the coincidence spectra were indeed due to Cu^{66}, the spectrum from each source was displayed for two consecutive 5-minute intervals on two separate halves of the *RCL* pulse-height analyzer. The total coincident counts in the two halves were in a ratio very close to 2:1 as is to be expected from the 5.1-min half-life[3] of Cu^{66}. On Fig. 2 the sum of these two spectra is displayed for better statistical significance.

Figures 2(A) and 2(B) show quite conclusively that a 0.83±0.01-Mev gamma ray is in coincidence with the 1.04-Mev gamma ray, indicating a level in Zn^{66} at 1.87 Mev. The intensity of the 0.83-Mev gamma ray relative to the 1.04-Mev gamma ray was determined by comparison with a Co^{60} source in identical geometry and was found to be 0.025±0.005. This result does not include the known anisotropy[3] of the Co^{60}-gamma rays nor the (unknown) anisotropy of the Cu^{66}-gamma rays.

On Fig. 2(A) a small peak at 1.04 Mev may be noted. One can calculate roughly that most, if not all, of this is due to coincidences caused by bremsstrahlung from the 1.65-Mev beta rays feeding the 1.04-Mev state in Zn^{66}.

III. CONCLUSIONS

The present results confirm the existence of a (second) excited state of Zn^{66} at 1.87 Mev which presumably is fed by a 0.76-Mev beta ray from Cu^{66}. Assuming that the 1.65-Mev beta ray from Cu^{66} has a branching ratio[3] of 9%, one can calculate from the results of Sec. II.C that the 0.76-Mev beta-ray branch has a branching ratio of about 0.2% and a log*ft* value of 5.7. This is very close to the log*ft* values of the 1.59-Mev and 2.63-Mev beta branches.[3] Figure 3 shows the decay scheme[3] of Cu^{66} modified by our work.

Since the spin and parity[5] of Cu^{66} are 1+, the spin of the 1.87-Mev level of Zn^{66} is 0, 1, or 2 with even parity. The very small upper limit for the ground-state decay of the 1.87-Mev level makes a spin 1 unlikely. It is of interest, though, to note that the very small crossover to cascade ratio of the gamma rays from the 1.87-Mev level is exceptional in comparison with the decay of levels in Zn^{64} and Zn^{68} lying at a similar energy.[10]

The existence of a 1.87-Mev level in Zn^{66} necessitates a re-examination of the decay[3] of Ga^{66} (whose spin has

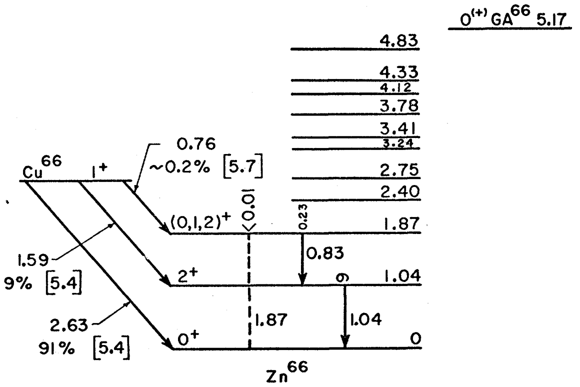

FIG. 3. Decay scheme of Cu^{66}. Gamma-ray and level energies are in Mev, intensities in percent decay. Log *ft* values are given in square brackets. Levels of Zn^{66} inferred from the decay of Ga^{66} are also shown. A spin of 2 is the most likely one for the 1.87-Mev level (see text).

been shown to be zero[11]). We do not wish to go into a detailed discussion of the Ga^{66} decay here, but merely want to state that the previous beta[12] and gamma[13] work is consistent with no direct feeding of the 1.04-, 1.87-, and 2.40-Mev levels of Zn^{66} (see Fig. 3) making 2+ a likely assignment for these levels if the parity of Ga^{66} is even, as may be expected from the shell model. The 1.87-Mev level could be populated easily in the decay of Ga^{66} by transitions from the 3.78- and/or 3.24-Mev levels. In this connection it might be noted that it is quite possible that the spin of the 3.78-Mev level is 0.

A discussion of the level systematics of the other even-even Zn isotopes is postponed,[1] but it may be of interest to point out that a close similarity in energy seems to exist between at least the three lowest excited states of Zn^{64}, Zn^{66}, and Zn^{68}.[1,3,8,9]

IV. ACKNOWLEDGMENTS

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Photoproduction of Alpha Particles from Several Metallic Elements

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Photoproduction of alpha particles from copper has been investigated by using 22-Mev bremsstrahlung to irradiate a "sandwich" consisting of a thin copper foil (2.75 mg/cm^2) placed between two Ilford E-1, 100-micron thick nuclear emulsions. The observed yield was $(3.9\pm0.6)\times10^4$ alpha particles per mole-roentgen. The energy distribution of the alpha particles has a maximum near 8 Mev. In addition, photo-produced alpha particles from thin foils of eleven elements, including copper, have been detected by means of their tracks in nuclear emulsions. "Sandwiches" containing two target foils on either side of a lead stopping foil were exposed to 21.5-Mev bremsstrahlung hardened by 147.4 g/cm^2 of graphite. The photo-alpha yields observed with the hardened spectrum are given in terms of unhardened bremsstrahlung, having been multiplied by the calculated ratio of effective photons in the two spectra. These yields, in units of 10^4 alphas per mole-roentgen, are: Al—1.3, V—0.4, Fe—1.9, Co—2.3, Ni—3.9, Cu—2.6, Cu^{63}—3.6, Zn—8.2, Nb—0.5, Rh—0.3, Ag—0.17, and In—0.09. For the seven elements having $Z\leq30$, there seems to be a correlation between the yield and the difference between the alpha and neutron binding energies.

I. INTRODUCTION

THE photodisintegration of nuclei in which alpha particles are produced has been studied primarily by means of the radioactivity of the resulting nucleus and by means of alpha-particle tracks in nuclear emulsions. Because of low yields, much of the work using radioactivity has required a chemical separation of the resulting element. Yield curves and cross sections have been obtained by this method for $Cu^{65}(\gamma,\alpha)Co^{61}$ by Haslam, Smith, and Taylor,[1] $Br^{81}(\gamma,\alpha)As^{77}$ by Taylor and Haslam,[2] $Rb^{87}(\gamma,\alpha)Br^{83}$ by Haslam and Skarsgard,[3] and $Ag^{109}(\gamma,\alpha)Rh^{105}$ by de Laboulaye and Beydon.[4] Erdos, Jordan, and Stoll[5] have recently reported values for the integrated cross section up to 31.5 Mev for the $Cl^{37}(\gamma,\alpha)P^{33}$, $K^{39}(\gamma,n\alpha)Cl^{34}$, $Br^{81}(\gamma,\alpha)As^{77}$, $Ag^{109}(\gamma,\alpha)Rh^{105}$, and $Sb^{121}(\gamma,\alpha)In^{117}$ reactions.

Many investigations of photoproduction of alpha particles from the constituents of nuclear emulsions have been undertaken. For the lighter elements the track of the recoiling nucleus, as well as the alpha track, can be observed. For alpha tracks not accompanied by a recoil track, it is not possible to determine whether the parent nucleus was silver or bromine. Since alpha tracks are clearly distinguishable from proton tracks in nuclear emulsions, photo-alpha particles have been observed as a by-product in several experiments designed to investigate photoprotons. Investigation of the photodisintegration of copper by Byerly and Stephens[6] gave an indication of the yield of photo-alpha particles. Numerous alpha particles were observed from cobalt by Toms and Stephens[7]; however, since the target thickness was chosen for protons, the

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