after scission.[10] In the present framework, the sawtooth character observed in binary fission[11] for the function $\nu(M)$, the average number of neutrons emitted per fragment as a function of fragment mass, is understandable: the number of emitted neutrons is small in the mass region 85-90 amu (where $N\cong50$) and in the mass region 130–135 amu (where $N\cong82$ and $Z\cong50$) and increases as a function of mass away from these regions. Difficulties in obtaining data for symmetric and near-symmetric fission of U^{235} have thus far precluded a determination of $\nu(M)$ in the crucial mass region below $\sim$130 amu. However, a measurement has been carried out by Apalin *et al.*[3] whereby the total number of neutrons emitted (for both fragments) as a function of mass ratio was determined in the region of symmetric fission for U^{235}. These results are reproduced in Fig. 1(c), as are the earlier results of Apalin *et al.*[11] showing $\nu(M)$ for U^{235}. Of most significance for the present discussion are the strong increase in total number of neutrons toward symmetric fission and the definite minimum in this function for $M\cong130$ amu. The symmetric fragments from U^{235} neutron-induced fission are removed from the closed-shell regions, have large deformations, and, since they are highly neutron-rich, should emit a relatively large number of neutrons, as indeed is observed.

[10] R. R. Wilson, Phys. Rev. **72**, 189 (1947); J. S. Fraser, *ibid.* **88**, 536 (1952).
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Coulomb Excitation of Cu^{63} and Cu^{65}

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Properties of levels Coulomb excited in Cu^{63} and Cu^{65} with 4- to 8-MeV alpha particles have been investigated. The $B(E2)$'s for excitation determined from the yields of gamma rays observed in singles and coincidence spectra for the (668±4)-, (961±6)-, and (1323±16)-keV levels in Cu^{63} are, respectively, (1.16±0.12), (3.49±0.34), and $(4.0\pm0.5)\times10^{-50}$ e^2 cm^4; for the (771±7)-, (1115±11)-, and (1474±19)-keV levels in Cu^{65}, they are (1.02±0.11), (3.45±0.38), and $(4.3\pm0.8)\times10^{-50}$ e^2 cm^4. These results give $B(E2)$'s for decay which are 13 to 16 times the single-particle $B(E2)$. This similarity of $B(E2)$'s was predicted by de Shalit for levels which result from the coupling of the odd particle to the first excited state of the even-even core. From angular correlation studies the 961- and 1115-keV levels have been assigned spin $\frac{5}{2}$ and the 1323-keV level spin $\frac{7}{2}$. Mixing ratios obtained from these measurements along with the $B(E2)$'s establish values of 0.09 and 0.4 $(e\hbar/2\,Mc)^2$ for the $B(M1)$'s of the 961- and 1115-keV transitions.

I. INTRODUCTION

BECAUSE Cu^{63} and Cu^{65} have a structure of one odd proton beyond a closed shell, a study of their level properties should provide an excellent means for testing the validity of the single-particle core coupling model. According to this model some low-lying levels can result from the coupling of the odd particle to the even-even core. With this type of model Lawson and Uretsky[1] derived a relation (the center-of-gravity theorem) between energies of states arising from the coupling of the odd particle to the core in its first excited state and of the energy of the first excited state in the neighboring even-even nucleus. For nuclei like Cu^{63} and Cu^{65} which have a ground-state spin of $\frac{3}{2}$, four excited levels with spins of $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ result from this coupling. Lawson and Uretsky found the center-of-gravity theorem was satisfactorily fulfilled by the first four excited levels in both copper nuclides for the proper choice of spins.

In a generalization of Lawson and Uretsky's weak-coupling model, de Shalit[2] predicted that the reduced $E2$ transition probabilities for decay, $B(E2)_d$, from the four members of the multiplet to the ground state will be equal to the $B(E2)_d$ between the 2+ and 0+ states in the adjacent even-even nucleus. de Shalit also pointed out that for pure states the $M1$ transition probabilities are forbidden. However, a small admixture of states can give appreciable $M1$ rates.[2,3]

Another approach to the single-particle core coupling model has been taken by Bouten and Van Leuven.[4] They treated levels of the odd-mass nuclei $Cu^{59,61,63,65}$ as arising from intermediate coupling between the single particle in either the $p_{1/2}$, $p_{3/2}$, or $f_{5/2}$ orbital and the core in the ground state or first or second phonon state. In a third approach Bayman and Silverberg[5] have performed an intermediate coupling calculation

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[2] A. de Shalit, Phys. Rev. **122**, 1530 (1961).
[3] A. Braunstein and A. de Shalit, Phys. Letters **1**, 264 (1962).
[4] M. Bouten and P. Van Leuven, Nucl. Phys. **32**, 499 (1962).
[5] B. F. Bayman and L. Silverberg, Nucl. Phys. **16**, 625 (1960).

for a nucleon confined to move in a $j=\frac{3}{2}$ orbit and coupled to a nuclear surface that is capable of performing quadrupole oscillations of any phonon number. An excellent comparison of the level properties of Cu^{63} as deduced from Coulomb excitation[6–8] and from resonance fluorescence techniques[9,10] has been made by Gove[11] with the predictions based on these three nuclear models.[2,4,5]

In the present study the properties of the low-lying levels of Cu^{63} and Cu^{65} were investigated by means of the Coulomb excitation process. The excitation was produced by 4- to 8-MeV alpha particles. From the yields and angular distributions of the ensuing gamma rays, information was obtained about the $E2$ and $M1$ transition probabilities and about the spins and parities of the excited states.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A. Apparatus

The alpha particles for this investigation were obtained from the Oak Ridge 5.5-MV Van de Graaff generator. Electrodeposited thick targets of Cu^{63} and Cu^{65} which were isotopically enriched to 99.7% and 97.4%, respectively, were used. The gamma rays were detected with 3-in.×3-in. NaI crystals. The resolution for the 662-keV gamma ray of Cs^{137} was 7.5%. Details of the geometry of the target and detectors have been discussed in previous papers.[12,13] For the coincidence studies the resolving time 2τ of the coincidence circuit was 0.11 μsec.

B. Singles Gamma-Ray Spectra

Figures 1 and 2 illustrate representative gamma-ray spectra that were observed for alpha-particle bombardment of Cu^{63} and Cu^{65}. For these spectra the alpha-particle energy was 6.55 MeV and the source-to-detector distance was 5 cm. All spectra were decomposed into the individual gamma rays which contribute to them, and from this decomposition the gamma-ray yields were determined. These yields were then compared to the excitation functions predicted for Coulomb excitation. This establishes that the 668-, 961-, and 1323-keV gamma rays are transitions to the ground state from Cu^{63} states which are populated by the electric quadrupole ($E2$) Coulomb excitation process. This can be seen in Fig. 3 which illustrates by points the relative yields obtained for these transitions as a function of alpha-particle energy, and by solid curves the energy dependence predicted for $E2$ Coulomb excitation of states with energies ΔE.

The fourth level of Cu^{63} has a reported energy of 1412 keV.[14] In the present study a weak transition was seen with this energy. Its yields are included in Fig. 3. For spectra taken with alpha-particle bombarding energies of less than 7.6 MeV, the data can be fitted within the large experimental errors to the yield curve resulting from $E2$ Coulomb excitation of a 1412-keV level. But in the spectra observed for an incident beam of 8.03- and 8.10-MeV alpha particles, the 1.41-MeV gamma-ray yields lie considerably above the curve predicted for Coulomb excitation. Such a deviation could result from a second 1.41-MeV transition that is a consequence of a nuclear reaction. However, it was found that all the yields of the 1.41-MeV gamma ray are much larger than expected on the basis of the Coulomb excitation studies made with oxygen ions by Gove *et al.*[15]

The uncertainty in the origin of the 1.41-MeV transition prompted us to re-examine Cu^{63} by means of Coulomb excitation with 30-, 33-, and 36-MeV oxygen ions. These ions were accelerated by the Oak Ridge Tandem Van de Graaff generator. The absence of a peak at 1.41 MeV in the resulting gamma-ray spectra attests that the 1.41-MeV transition in the spectra observed for alpha-particle bombardment cannot be due to Coulomb excitation.[16]

Recently, Sen Gupta and Van Patter[17] have found evidence for a state in Zn^{66} at 2.462 MeV which decays by a cascade gamma ray with an energy of 1.425 MeV to the first 2+ state. It is quite likely that the 1.41-MeV gamma ray observed in the present work results from the $Cu^{63}(\alpha,p)Zn^{66}$ reaction which populates this state. That Zn^{66} was produced is indicated by the 0.840- and 1.039-MeV gamma rays (see Fig. 1). These transitions have energies given for those from the second and first excited levels of Zn^{66}. There is also evidence for the (α,p) reaction with Cu^{65}. The weak 1.33-MeV gamma ray observed in the Cu^{65} spectrum in Fig. 2 is probably due to the cascade decay of a state in Zn^{68} at 2.41 MeV.[18]

Yields obtained for the gamma rays in the Cu^{65} spectra (Fig. 2 illustrates one of these spectra) show that the levels in Cu^{65} at 771, 1115, and 1474 keV are populated by the $E2$ Coulomb excitation process. A comparison of the yields of these transitions with the

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[7] K. I. Erokhina and I. Kh. Lemberg, Bull. Acad. Sci., USSR, Phys. Ser. (English transl.) **26**, 205 (1962).
[8] B. Elbek, H. E. Gove, and B. Herskind (to be published).
[9] J. B. Cumming, A. Schwarzschild, A. W. Sunyar, and N. T. Porile, Phys. Rev. **120**, 2128 (1960).
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[11] H. E. Gove, Phys. Letters **4**, 249 (1963).
[12] P. H. Stelson and F. K. McGowan, Phys. Rev. **110**, 489 (1958).
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[14] M. Mazari, W. W. Buechner, and R. P. de Figueiredo, Phys. Rev. **108**, 373 (1957).
[15] H. E. Gove, A. E. Litherland, C. Broude, and M. A. Eswaran (private communication).
[16] In a previous publication the 1.41-MeV transition was mistakenly attributed to Cu^{63} [R. L. Robinson, F. K. McGowan, and P. H. Stelson, Bull. Am. Phys. Soc. **8**, 548 (1963)].
[17] A. K. Sen Gupta and D. M. Van Patter, Nucl. Phys. **50**, 17 (1964).
[18] J. K. Dickens, F. G. Perey, and R. J. Silva (private communication).

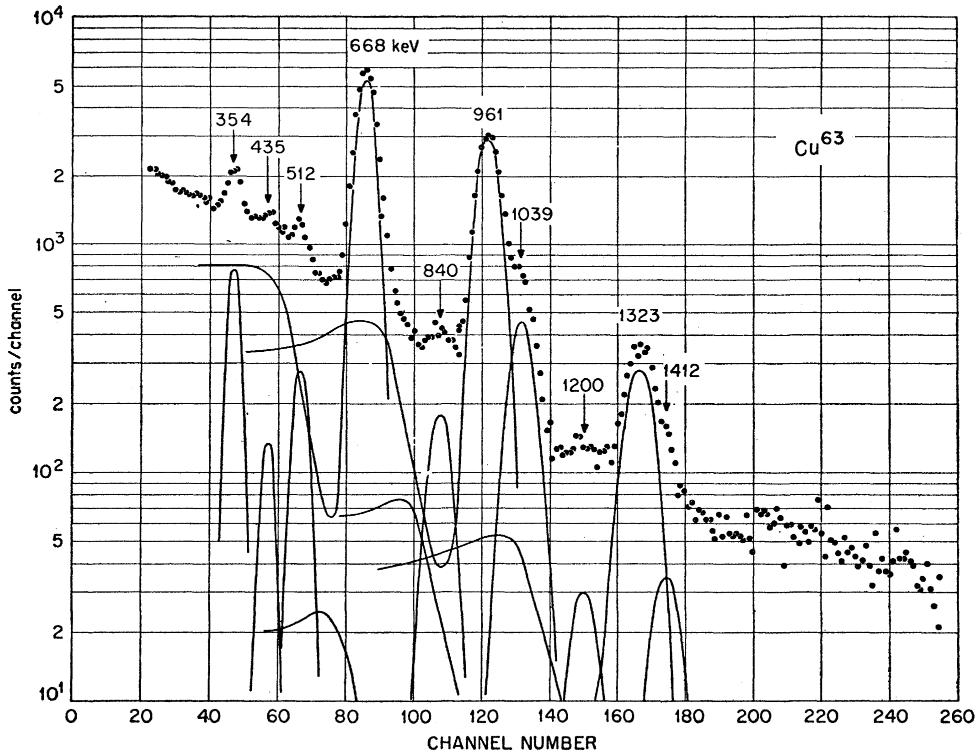

FIG. 1. Gamma-ray spectrum for 6.55-MeV alpha particles on a target of Cu^{63}.

excitation curves associated with $E2$ Coulomb excitation is given in Fig. 4. Coulomb excitation of the 2.6% Cu^{63} contained in the target accounts for the peak at 661 keV in Fig. 2. Through coincidence studies (see Sec. II.C), it was found that the peaks at 358 keV in the Cu^{65} spectrum in Fig. 2 and 354 keV in the Cu^{63} spec-

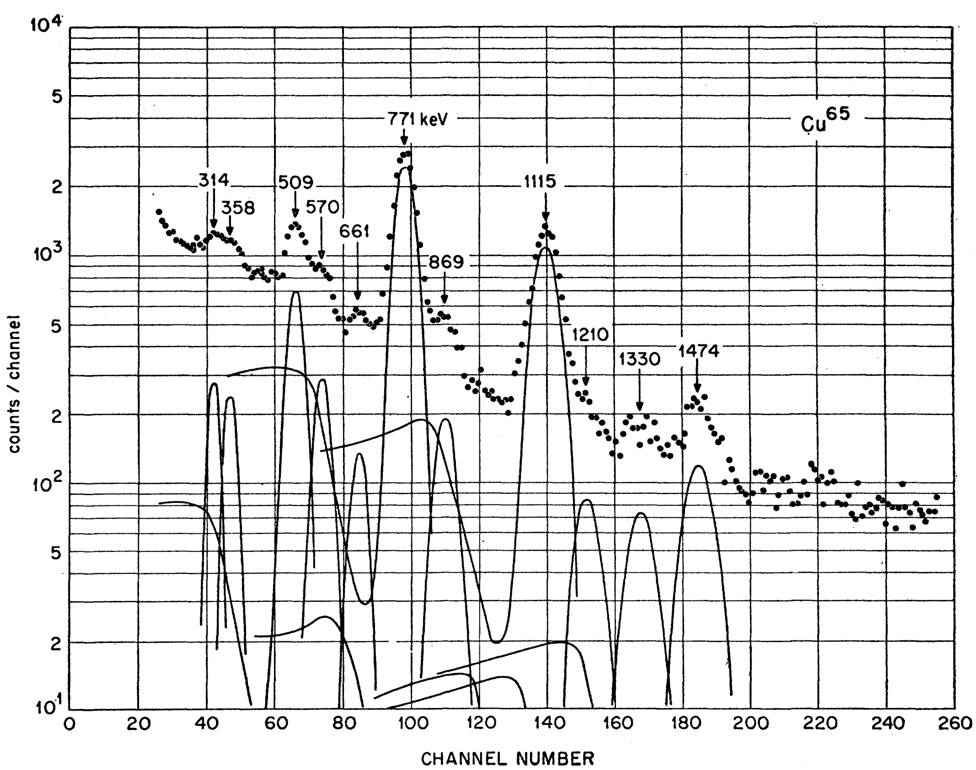

FIG. 2. Gamma-ray spectrum for 6.55-MeV alpha particles on a target of Cu^{65}.

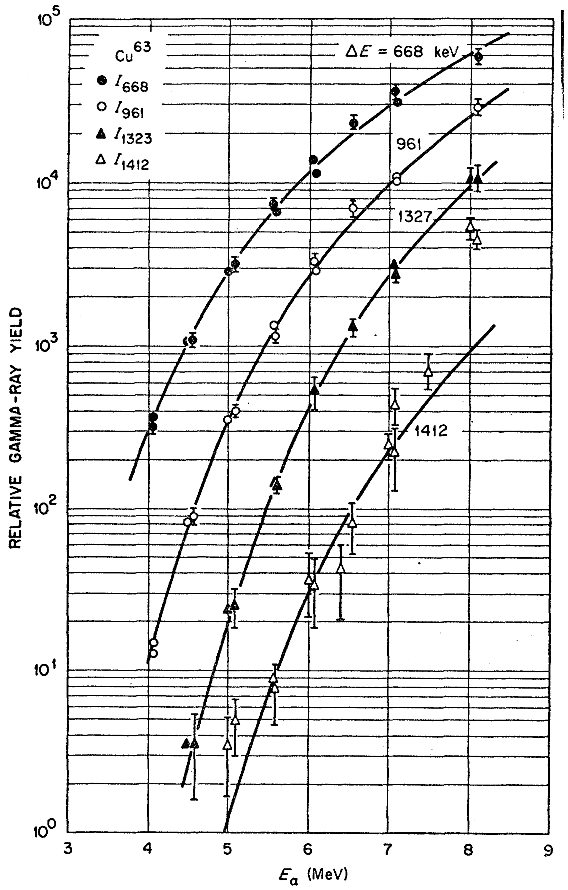

FIG. 3. Relative yields of the 668-, 961-, and 1323-keV Cu^{63} gamma rays as a function of the alpha-particle energy. Yields of the 1412-keV gamma ray, which is believed to result from the reaction $Cu^{63}(\alpha,p)Zn^{66}$, are also shown. The solid curves illustrate the predicted energy dependence for $E2$ Coulomb excitation of levels with energies ΔE.

trum in Fig. 1 result in part from cascade transitions between the third and second excited states of the copper nuclides. The other gamma rays contributing to these peaks and the remaining undiscussed peaks in Figs. 1 and 2 are presumed to arise from reactions with surface contaminants and impurities in the target.

C. Gamma-Gamma Coincidence Spectra

Spectra in coincidence with the 668- and 961-keV gamma rays of Cu^{63} and the 771- and 1115-keV gamma rays of Cu^{65} were measured for an incident alpha-particle beam with energy of 5.58 MeV. In order to be able to account for contributions from coincidences due to pulses in the gate from other gamma rays, a third spectrum was taken with both targets with the gating window centered between the two peaks. After correcting for this contribution and also for chance coincidences, no transitions were observed in coincidence with the 668-keV gamma ray and only one, a 364-keV gamma ray, in coincidence with the 961-keV gamma ray of Cu^{63}. (The latter spectrum is illustrated in Fig. 5.) Its energy indicates it de-excites the 1323-keV level. The ratio of its intensity to the intensity of the ground-state transition from the 1323-keV level is 0.16 ± 0.04.

In Cu^{65} an analogous transition was observed with an energy of 362 keV in coincidence with the 1115-keV gamma ray (see Fig. 6). From the intensity of the 362-keV gamma ray, the branching ratio of cascade to crossover gamma rays from the 1474-keV level was estimated to be 0.26 ± 0.13. No transition of Cu^{65} was found in coincidence with the 771-keV gamma ray.

Another effort was made to determine if the known 1412-keV level of Cu^{63} was excited by searching for possible transitions from this state to the first or second excited state. Coincidence spectra for alpha-particle energies of 7.0 and 8.0 MeV showed no evidence for either a 451- or a 744-keV gamma ray which would terminate at the 961- and 668-keV levels, respectively. However, the yields deduced from these spectra for the 364-keV gamma ray corroborate that this transition deexcites a Coulomb excited level at 1323 keV.

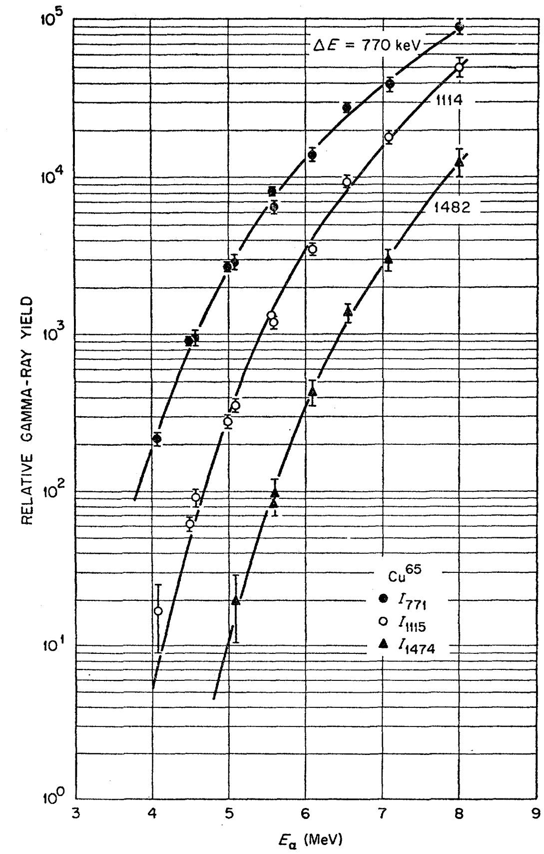

FIG. 4. Relative yields of Cu^{65} gamma rays as a function of the alpha-particle energy. The solid curves illustrate the predicted energy dependence for $E2$ Coulomb excitation of levels with energies ΔE.

TABLE I. Angular distribution results.

	E_α(MeV)	E_γ(keV)	R	$a_2g_2A_2$	A_2
Cu^{63}					
	5.04	668		$+0.004\pm0.012$	$+0.005\pm0.014$
	5.54	668		$+0.016\pm0.020$	$+0.019\pm0.024$
	5.04	961		-0.187 ± 0.018	-0.186 ± 0.018
	5.54	961		-0.171 ± 0.020	-0.180 ± 0.021
	5.54	1323		$+0.25\ \pm0.05$	$+0.24\ \pm0.05$
	6.08	1323	1.216 ± 0.139		$+0.14\ \pm0.09$[a]
	7.08	1323	1.297 ± 0.061		$+0.20\ \pm0.04$[a]
Cu^{65}					
	5.54	771		-0.004 ± 0.016	-0.005 ± 0.018
	5.54	1115		-0.141 ± 0.016	-0.142 ± 0.016

[a] In obtaining this value, $a_4g_4A_4$ was taken as -0.01.

D. Gamma-Ray Angular Distributions

Angular distributions of several gamma rays were measured relative to the direction of the incident alpha-particle beam. The results are listed in Table I. In two cases data were only taken at the two angles 0 and 90°. For these the ratio $R=W(0°)/W(90°)$ is given. In the other cases data were taken at ten angles and fitted to the equation

$$W(\theta)=1+a_2g_2A_2P_2(\cos\theta)+a_4g_4A_4P_4(\cos\theta),$$

where a_ν's are the thick-target particle parameters[13,19] and g_ν's are the corrections for the finite angular resolution of the detector.[20,21] As the a_4 particle parameters are very small, A_4's can only be poorly determined and do not furnish any useful information concerning the properties of the levels. However, since it was known that the coefficients of $P_4(\cos\theta)$ should be small, their magnitude provided a check on the accuracy of the measurements.

In employing the angular distribution results, only certain spins needed to be considered for the excited states. Since these states are each populated by the $E2$ Coulomb excitation process and since Cu^{63} and Cu^{65} both have measured ground-state spins of $\frac{3}{2}$,[22] the spins of the excited states can only be $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, or $\frac{7}{2}$. Furthermore, their parities are the same as those of the ground state.

The isotropic distribution of the 668-keV transition in Cu^{63} is in agreement with the unambiguous spin assignment of $\frac{1}{2}$ for the 668-keV level as established through nuclear resonance studies of Cumming *et al.*[9] The isotropic distribution of the 771-keV transition in

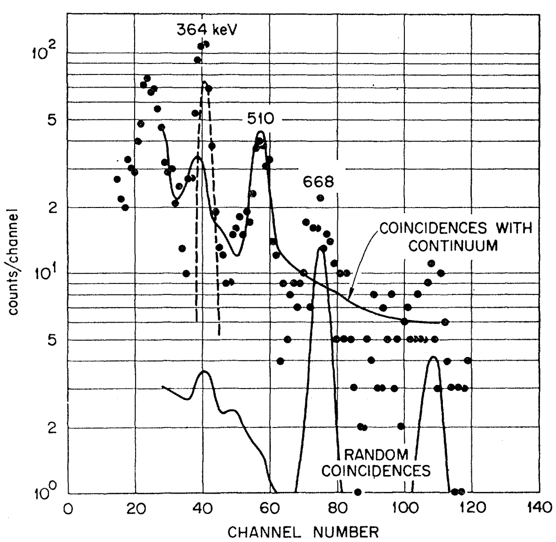

FIG. 5. Gamma-ray spectrum in coincidence with gamma rays accepted by a 95-keV-wide window centered on the 961-keV peak of Cu^{63}. The dashed curve is a fit to the data after subtraction of the coincidences with pulses due to the continuum and of random coincidences.

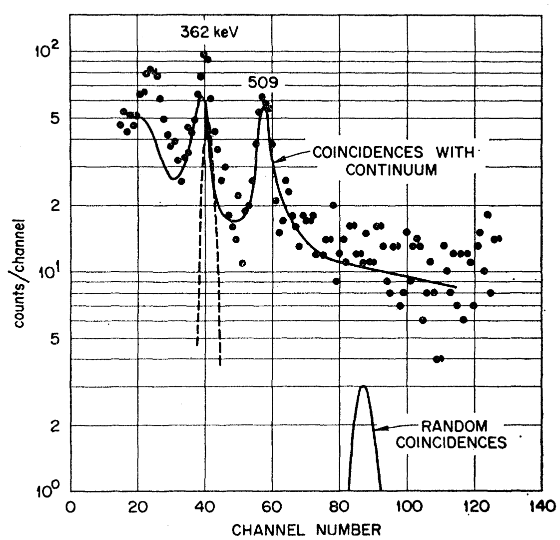

FIG. 6. Gamma-ray spectrum in coincidence with gamma rays accepted by an 83-keV-wide window centered on the 1115-keV peak of Cu^{65}. The dashed curve is a fit to the data after subtraction of the coincidences with pulses due to the continuum.

[19] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Rev. Mod. Phys. **28**, 432 (1956).
[20] M. E. Rose, Phys. Rev. **91**, 610 (1953).
[21] C. W. Reich (private communication).
[22] *Nuclear Data Sheets*, compiled by K. Way *et al.* (National Academy of Sciences–National Research Council, Washington, D. C.).

Cu^{65} is compatible with spins for the 771-keV level of $\frac{1}{2}$ or $\frac{3}{2}$ (the distributions for these spins are isotropic for any value of the mixing ratio δ, where $\delta^2=E2/M1$ in the notation of Biedenharn and Rose[23]), as well as spin $\frac{5}{2}$ for the proper choice of δ. Of these three possible spins, the most likely assignment is $\frac{1}{2}$ since the neighboring nuclei Ni^{65} and Zn^{65}, which have ground-state spins of $\frac{5}{2}$, do not decay to this level.[22]

The angular correlation coefficients uniquely determine the spins of the 961-keV level in Cu^{63} and the 1115-keV level in Cu^{65} as $\frac{5}{2}$. Of the two values -0.41 and -1.2 found for δ of the 961-keV gamma ray, only the former one along with the $E2$ transition probability (see Sec. II.E) gives a half-life which is compatible with the previously reported values of the half-life of the 961-keV level.[22] The two δ's for the 1115-keV gamma ray consistent with the A_2 correlation coefficient are -0.22 and -1.8. From these and the $E2$ transition probability, the half-lives deduced for the 1115-keV level are $(0.66\pm0.36)\times10^{-13}$ and $(10.9\pm1.5)\times10^{-13}$ sec, respectively. Neither of these two numbers agrees with the half-life value of $(2.6\pm0.5)\times10^{-13}$ sec recently reported by Eswaran *et al.*[24] However, somewhat better agreement is obtained for $\delta=-0.22$.

The average value of $+0.21\pm0.03$ obtained for the A_2 coefficient from the three measurements of the 1323-keV gamma-ray correlation indicates the spin of the 1323-keV level is $\frac{7}{2}$. This coefficient is in excellent agreement with the theoretical value of $+0.219$ predicted for the spin $\frac{7}{2}$ assignment. It is significantly larger than the maximum value of A_2 ($A_2\leq0.17$) if the spin were $\frac{5}{2}$.

E. Level Properties

The reduced $E2$ transition probabilities for excitation, $B(E2)_{ex}$, were extracted from the gamma-ray yields by a method outlined in a previous publication.[25] For the determination of the thick-target yields that come into these calculations, the level energies of Mazari, Buechner, and de Figueiredo,[14] which have with one exception smaller errors than our values [see columns (1) and (2) of Table II], were used. The $B(E2)_{ex}$'s obtained are listed in column (3) of Table II. Corrections for the 364- and 362-keV cascade transitions have been applied to the $B(E2)_{ex}$'s of the 961-, 1323-, 1115-, and 1474-keV levels. Corrections to the $B(E2)_{ex}$'s due to internal conversion of the gamma rays are all less than 0.1% and have not been included. The upper limit shown for the $B(E2)_{ex}$ of the 1412-keV state was deduced from our Coulomb excitation studies with oxygen ions.

[23] L. C. Biedenharn and M. E. Rose, Rev. Mod. Phys. **25**, 729 (1953).

[24] M. A. Eswaran, H. E. Gove, A. E. Litherland, and C. Broude, Bull. Am. Phys. Soc. **8**, 375 (1963); and private communication.

[25] F. K. McGowan and P. H. Stelson, Phys. Rev. **116**, 154 (1959).

As already pointed out, the 0.840-, 1.039-, and 1.41-MeV gamma rays give evidence for the $Cu^{63}(\alpha,p)Zn^{66}$ reaction. This reaction could also produce a 1.345-MeV transition[17] which would contribute to the intensities of the peaks at 1.323 MeV in the gamma-ray spectra. If the 1.345-MeV gamma-ray yields increase with alpha-particle energy like those observed for the 1.41-MeV gamma ray, the agreement between the yields of the 1.323-MeV gamma ray and the prediction for $E2$ Coulomb excitation (see Fig. 3) indicates the intensity of the 1.345-MeV gamma ray was <25% of the intensity of the 1.323-MeV gamma ray for bombardment with 8-MeV alpha particles. It would then follow for $E_\alpha\leq7$ MeV that the contribution of the 1.345-MeV gamma ray would be <6% of the 1.323-MeV gamma-ray intensity. The $B(E2)_{ex}$ shown for the 1.323-MeV gamma ray in Table II has been consequently reduced by (3 ± 3)% to account for the possibility that some 1.345-MeV gamma rays were present.

Columns (4) and (5) of Table II list the absolute errors in the $B(E2)_{ex}$'s and the errors of the $B(E2)_{ex}$'s relative to the $B(E2)_{ex}$'s of the first excited states. The major contribution to these errors originated in the uncertainties of the stopping power (±6% was adopted for this error) and in the areas under the photopeaks. Errors in the alpha-particle energies, in the solid angle subtended by the detector, in the level energy, and the ratio of counts in the photopeak to the Compton distribution, were also taken into consideration.

The $B(E2)$'s for decay given in column (7) are related to the $B(E2)_{ex}$ by the equation

$$B(E2)_d=\frac{2I_i+1}{2I_f+1}B(E2)_{ex},$$

where I_i and I_f are the ground and excited state spins, respectively. The I_f's are in column (6). Evidence for these spins except those of the 1412- and 1474-keV states was presented in the preceding section. Since the 1474-keV level in Cu^{65} appears analogous to the third excited level in Cu^{63} at 1323 keV, its spin has been taken as $\frac{7}{2}$. This spin has been recently confirmed by the Coulomb-excitation studies of Elbek, Gove, and Herskind.[8] A spin of $\frac{3}{2}$ has been tentatively assigned to the 1412-keV level. For this assignment the four levels satisfy the center-of-gravity theorem presented by Lawson and Uretsky.[1]

In column (8) of Table II the $B(E2)_d$'s are compared to the single-particle estimate as given by the equation $B(E2)_{sp}/e^2=(1/4\pi)|\frac{3}{5}R_0^2|^2$. R_0 was taken as $1.2\times10^{-13}\times A^{1/3}$ cm. Column (9) contains the mixing ratios δ deduced from the angular distributions of the 961- and 1115-keV transitions. From these quantities and the $B(E2)_d$'s, it is possible to calculate the values of the $B(M1)_d$'s of the 961- and 1115-keV gamma rays. These are presented in column (10) in approximately single-particle units.

TABLE II. Summary of level and gamma-ray properties.

(1) E(keV) Present study	(2) E(keV) Mazari *et al.*[a]	(3) $B(E2)_{ex}\times10^{50}$ / e^2(cm)^4	(4) Relative error (%)	(5) Absolute error (%)	(6) I_f	(7) $B(E2)_d\times10^{50}$ / e^2(cm)^4	(8) $B(E2)_d$ / $B(E2)_{sp}$	(9) δ	(10) $B(M1)_d$ / $(e\hbar/2Mc)^2$	(11) $T_{1/2}$(sec)
Cu^{63}										
364±8									0.19±0.05	
668±4	668±5	1.16		±10	1/2	2.32	16		0.66±0.10	
961±6	961±5	3.49	±6	±10	5/2	2.33	16	$-0.41^{+0.07}_{-0.11}$	$0.09^{+0.03}_{-0.05}$	$(4.2^{+2.3}_{-1.6})\times10^{-13}$
1323±16	1327±5	3.98	±8	±13	7/2	1.99	13			$(6.0\pm0.8)\times10^{-13}$
	1412±5	<0.3			3/2	<0.3	<2			
Cu^{65}										
362±8									0.6 ±0.3	
771±7	770±4	1.02		±11	1/2	2.04	13		0.53	
1115±11	1114±4	3.45	±6	±11	5/2	2.30	15	−0.22±0.06	0.4 ±0.2	$(6.6\pm3.6)\times10^{-14}$
1474±19	1482±4	4.32	±14	±18	7/2	2.16	14			$(2.9\pm0.6)\times10^{-13}$
Ni^{62}[b]										
1171		8.3		±9	2	1.7	11			
Ni^{64}[c]										
1340		8.7			2	1.7	12			

[a] See Ref. 14. [b] See Ref. 30. [c] See Ref. 31.

For the 668- and 771-keV transitions, the $B(M1)_d$'s were obtained from the $B(E2)_d$'s and reported half-lives for the corresponding levels. The values used for the half-lives are $(2.0\pm0.3)\times10^{-13}$ sec,[10,22] and 1.63×10^{-13} sec,[26] for the 668- and 771-keV levels, respectively. The $B(M1)_d$'s for the 364- and 362-keV transitions were determined from the $B(E2)_d$'s of the 1323- and 1474-keV transitions and from the ratios of cascade-to-crossover gamma rays from levels of these energies. It was assumed that the $B(E2)_d$'s of the 364- and 362-keV transitions are less than 100 $B(E2)_{sp}$. The final column of Table II contains the half-lives of the levels as deduced from the $B(E2)_d$'s and $B(M1)_d$'s listed in the Table.

III. DISCUSSION

Erokhina and Lemberg[7] using 36-MeV nitrogen ions and Elbek *et al.*[8] using 24–40-MeV oxygen ions have also recently investigated the low-lying levels of Cu^{63} and Cu^{65} by means of the Coulomb excitation process. Their results are listed in Table III along with those determined in the present paper. Values obtained in the early Coulomb excitation studies of Temmer and Heydenburg[6] are also included.

The values obtained by the different groups for the mixing ratios and the branching ratios are in reasonable agreement. However, the $B(E2)_{ex}$'s reported by Elbek *et al.*[8] are consistently smaller than those found by Erokhina and Lemberg[7] and by us.

The small $B(E2)_d$ of the 1412-keV gamma ray listed in Table III is rather surprising in view of recent inelastic proton scattering studies performed by Perey, Silva, and Satchler.[27] They found that the $B(E2)_d$ of the 1412-keV gamma ray is only a factor of four smaller than the $B(E2)_d$'s of the gamma rays from the 668-, 961-, and 1323-keV levels.

TABLE III. Comparison of level properties of Cu^{63} and Cu^{65} determined from Coulomb excitation studies.

Isotope	E_γ(keV)	Present study	Erokhina and Lemberg[a]	Elbek, Gove, and Herskind[b]	Temmer and Heydenburg[c]
$B(E2)_{ex}\times\frac{10^{50}}{e^2\,cm^4}$					
Cu^{63}	668	1.16±0.12	1.3±0.2	0.87	1.0
Cu^{63}	961	3.49±0.35	3.8±0.6	2.6	2.9
Cu^{63}	1323	3.98±0.50	5.3±1.1	3.8	
Cu^{63}	1412	<0.3		<0.04[d]	
Cu^{65}	771	1.02±0.11	1.0	0.67	0.87
Cu^{65}	1115	3.45±0.38	2.8	2.2	2.7
Cu^{65}	1474	4.32±0.78	3.4	2.6	
Mixing ratio (δ)					
Cu^{63}	961	$-0.41^{+0.07}_{-0.11}$		−0.27±0.08	
Cu^{65}	1115	−0.22±0.06		−0.30±0.13	
Cascade to crossover ratio from third excited state					
Cu^{63}		0.16±0.04	0.10	0.10	
Cu^{65}		0.26±0.13	0.13	0.32	

[a] See Ref. 7. [b] See Ref. 8. [c] See Ref. 6. [d] See Ref. 15.

[26] E. C. Booth, Bull. Am. Phys. Soc. 5, 239 (1960).
[27] F. Perey, R. J. Silva, and G. R. Satchler, Phys. Letters 4, 25 (1963).

According to the inelastic proton studies of Mazari *et al.*,[14] the next two levels in Cu^{63} are at 1547 and 1862 keV, and in Cu^{65} at 1623 and 1725 keV. In the present investigation there was no evidence for transitions from these levels to the ground states. From upper limits placed on the yields of these gamma rays, the $B(E2)_{ex}$'s for the 1547-, 1862-, 1623-, and 1724-keV levels are, respectively, less than 0.5, 2, 0.5, and $1\times10^{-50}e^2$ cm^4.

The gamma-gamma angular correlation of the 362–1115-keV cascade in Cu^{65} has been measured by Hartmann and Asplund[28] and by Jambunathan, Gunye, and Saraf.[29] From their results and the presently measured mixing ratio of the 1115-keV gamma ray, δ_{1115}, it is possible to deduce δ_{362}. For a value of $+0.24\pm0.01$ as given by Hartmann and Asplund for the A_2 angular correlation coefficient of the 362–1115-keV cascade, $\delta_{362}=+0.14\pm0.03$ or $\geq|35|$. For $A_2=0.190\pm0.055$ as published by Jambunathan *et al.*, $\delta_{362}=+0.09\pm0.06$ or $>|9|$. The larger value of δ_{362} in each case can be discarded since it would mean that the $B(E2)_d$ of the 362-keV gamma ray is several thousand times that predicted by the single-particle estimate. The smaller values for δ_{362} coupled with the $B(E2)_d$ of the 1474-keV level and the relative intensities of the 362- and 1474-keV gamma rays can be used to determine the $B(E2)_d$ of the 362-keV transition. If the average value of δ_{362} is taken as $+0.12\pm0.03$, this $B(E2)_d=(61\pm44)\times B(E2)_{sp}$.

[28] B. Hartmann and I. Asplund, Arkiv Fysik **13**, 339 (1958).

[29] R. Jambunathan, M. R. Gunye, and B. Saraf, Phys. Rev. **120**, 1839 (1960).

According to the discussion of de Shalit,[2] if four of the low-lying levels in Cu^{63} and Cu^{65} are pure states which result from the weak-coupling of the single odd particle to the first core state, the $B(E2)_d$'s of transitions from these levels to the ground states will be equal to each other and to the $B(E2)_d$'s for the $2+\rightarrow0+$ transitions in the neighboring even-even nuclei. The similarity of the $B(E2)_d$'s for three transitions in both Cu^{63} and Cu^{65} is consistent with this simple picture although their values are 20% to 40% larger than the $B(E2)_d$'s of the $2+\rightarrow0+$ transitions in Ni^{62} and Ni^{64}. The latter $B(E2)_d$'s have been included in Table II for comparison.[30,31]

On the other hand, this model fails to explain the small $B(E2)_d$'s of the $\frac{3}{2}\rightarrow\frac{3}{2}$ transitions or the large $B(M1)_d$'s of the transitions to the ground states. As can be seen in Table II, if the 1412-keV level in Cu^{63} is assumed to have spin $\frac{3}{2}$, the $B(E2)_d$ of the transition from this level is ≤0.15 the values of the $B(E2)_d$'s of the transitions from the other members of the multiplet. If in Cu^{65} the spin $\frac{3}{2}$ state is the 1623-keV level, as suggested by Lawson and Uretsky,[1] its $B(E2)_d$ is a factor of four or more smaller than the other $B(E2)_d$'s. However, Gove[11] for Cu^{63} and Vervier[32] for both Cu^{63} and Cu^{65} have demonstrated that these experimental results can be reasonably accounted for if one includes some intermixing of the two model states with $I=\frac{3}{2}$ and a small admixture of the $p_{1/2}$ single-particle state.

[30] P. H. Stelson and F. K. McGowan, Nucl. Phys. **32**, 652 (1962).

[31] D. S. Andreyev, A. P. Grinberg, K. I. Erokhina, and I. Kh. Lemberg, Nucl. Phys. **19**, 400 (1960).

[32] J. Vervier, Nuovo Cimento **28**, 1412 (1963).