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Electromagnetic properties of states in ^{63}Cu through the inelastic scattering of protons

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Levels in ^{63}Cu up to an excitation energy of 2.8 MeV were studied through the ^{63}Cu$(p,p'\gamma)$ reaction at an incident proton energy $E_p = 5.0$ MeV. Singles γ-ray spectra were obtained with a high resolution Ge(Li) detector at angles of observation $\Theta_\gamma = 0°$, 30°, 55°, 70°, 90°, and 125° and a second (monitor) Ge(Li) fixed at Θ_γ(monitor) = 90°. The lifetimes of 18 levels were determined through the Doppler shift attenuation method by studying the systematic energy shift of γ-ray peaks in the angular distribution data. The analysis of angular distributions yielded multipole mixing ratios and J^π values for several states. The experimental information, wherever complete, was employed to calculate reduced transition probabilities. The results obtained here are compared with theoretical predictions in the framework of the weak-coupling model.

[NUCLEAR REACTIONS ^{63}Cu$(p,p'\gamma)$, $E_p = 5.0$ MeV enriched target. Measured E_γ, $I_\gamma(\Theta)$, $\Delta E_\gamma(\Theta)$, deduced τ, δ, $B(\Lambda)$ values; Ge(Li) detector.]

I. INTRODUCTION

The applicability of the weak-coupling model in the description of low-lying levels in the odd-copper isotopes has recently been the subject of a considerable amount of experimental and theoretical investigation. In this model a single proton, which may occupy the $1f_{5/2}$, $2p_{1/2}$, and $2p_{3/2}$ shell-model orbitals, is coupled to the corresponding Ni even-even core. Calculations performed to date have considered two parallel approaches. In the first approach, termed the *particle-core model*,[1,2] the extra nucleon is coupled to states of the core, usually derived from experiment. No explicit form is assumed for the core Hamiltonian, while the interaction between particle and core is expressed as a series of dipole-dipole and quadrupole-quadrupole terms. Alternatively, in the *particle-phonon model*[3-6] the basis states of the core are assumed to be the quadrupole oscillations of a quantized liquid drop. Castel *et al.*[7] have presented a critical comparison of the various calculations performed in this model. More recently, the comparative accuracy of the particle-core and the particle-phonon models has been studied by de Jager and Boeker.[8] The results of these authors indicate that the former approach is more successful in reproducing properties of low-lying levels in ^{63}Cu, although the latter considers a much larger configuration space.

The calculations mentioned above usually employ available experimental information on the properties of energy levels in order to obtain the model parameters through fitting procedures. For ^{63}Cu, the nuclear structure data available through August 1974 have been summarized by Auble.[9] Most results were taken from the β^+ decay[10-3] of ^{63}Zn ($T_{1/2} = 38.1$ m). Inelastic scattering of protons,[14] angular correlation studies[15] of γ rays from Coulomb excited ^{63}Cu, and the resonance fluorescence study of Swann[16] have also yielded limited information on the decay scheme, branching ratios, and spin assignments. Stripping reaction studies[17-19] have furnished energy levels, orbital angular momentum transfers, and spectroscopic factors, while pickup reactions[20,21] have established L transfer values and through them limits on spin assignments. While this work was in progress, Dayras, Čujec, and Szöghy[22] have published more extensive data on properties of the first 13 states in ^{63}Cu, up to an excitation of 2.4 MeV, obtained through the ^{60}Ni$(\alpha,p\gamma)^{63}$Cu reaction.

In this work, which forms part of a more extensive study[23] on the odd-copper and -zinc isotopes, 39 transitions from 20 energy levels of ^{63}Cu, up to an excitation energy of 2.8 MeV, have been studied through the inelastic scattering of protons. The decay scheme of ^{63}Cu has not been directly extracted from the experimental spectra presented here, since this has been the object of a parallel investigation[24,25] based on complementary data taken with a high accuracy Compton suppression spectrometer. These results have been privately communicated and are included in the $A = 63$ compilation by Auble.[9] They are also reproduced here in Fig. 1 in a modified format con-

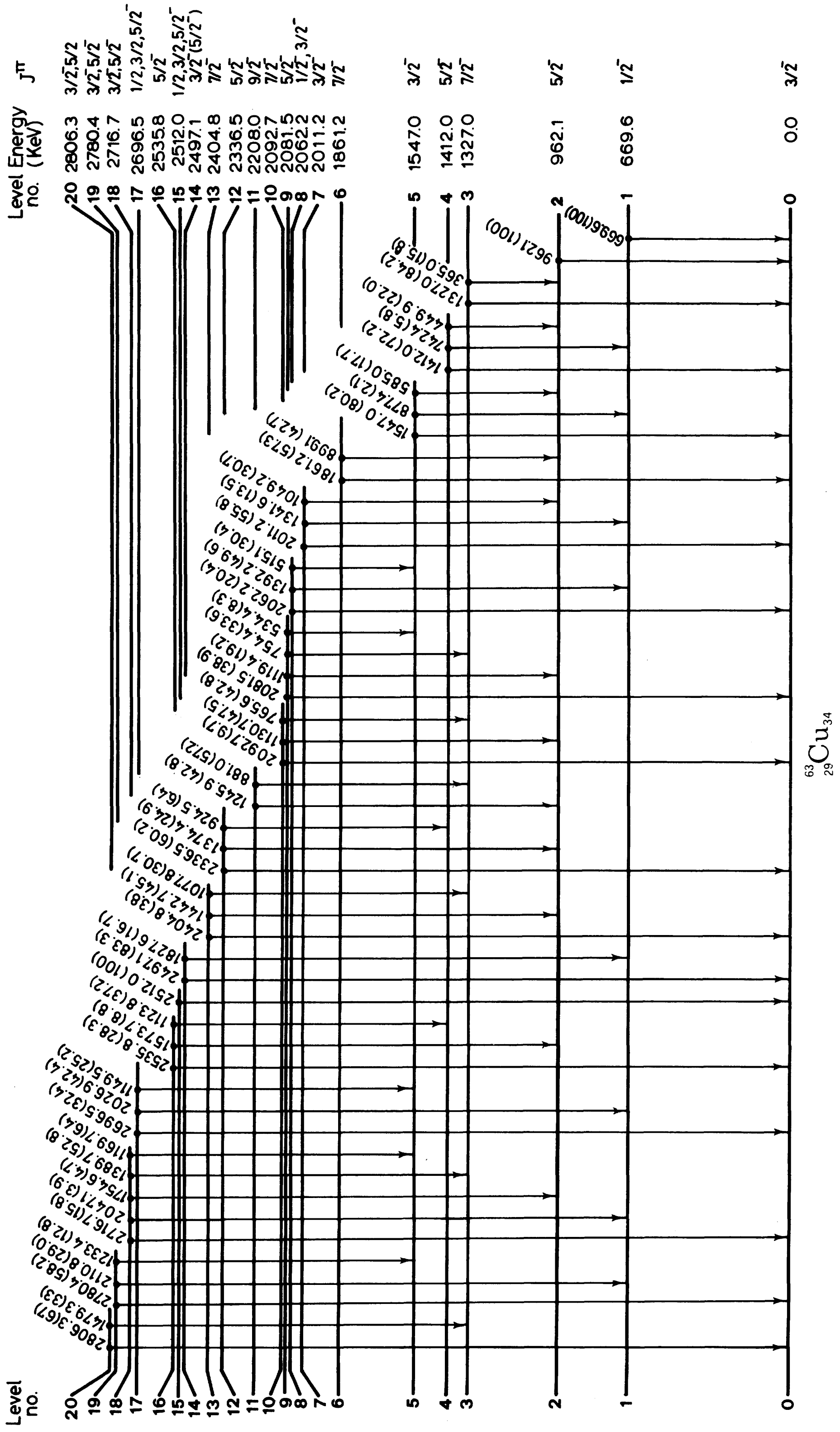

FIG. 1. Decay scheme of ^{63}Cu excited through the ^{63}Cu$(p,p'\gamma)$ reaction[9, 24, 25]. The energies are in keV. The energies of individual γ-rays and percent branching ratios (in parentheses) are also indicated. Spin assignments on the basis of the present work are discussed in part III.

venient to the presentation and with the inclusion of new spin assignments obtained in this work. For 33 transitions exhibiting an energy shift in the angular distribution spectra, the lifetimes of the corresponding levels were determined through a particular variant[26] of the Doppler shift attenuation method. In addition, singles angular distributions established spins for several excited states and multipole mixing ratios in the γ-ray transitions observed. Reduced transition probabilities $B(\Lambda)$ have been calculated for cases where the level spin sequence is established and the needed parameters are determined in the present or are known from previous work. These results are compared with existing calculations and the ensuing agreement or deviations are discussed.

II. EXPERIMENTAL PROCEDURE AND DATA

States in ^{63}Cu up to an excitation energy of 2.8 MeV were populated through inelastic scattering of protons supplied by the high intensity T11/25 tandem Van de Graaff accelerator of the Nuclear Research Centre, Demokritos. The proton beam was directed into a 5 cm diam aluminum chamber at the center of an angular distribution table, while the size of the beam was defined by two tantalum collimators with 1.2 mm apertures at 40 and 90 cm from the target. The interior of the chamber and the 2.5 cm diam entrance tube to the nearest collimator were lined with 2.5 mm of tantalum to avoid exposing the chamber walls to scattered protons. The scattering chamber and entrance tube to the nearest collimator were insulated electrically and served as a Faraday cup.

The target (manufactured by AERE Harwell) was a 3.8 mg/cm^2 self-supporting copper foil, enriched to 99.7% in ^{63}Cu. The target, placed at a 45° angle with respect to the incident beam, presented an effective thickness of about 250 keV to 5.0 MeV protons. This ensured the applicability of the statistical theory of nuclear reactions for the validity of the subsequent analysis.

Singles γ-ray spectra were taken with a 37 cm^3 Ge(Li) detector with a resolution of full width at half maximum (FWHM) = 1.9 keV for the ^{60}Co 1.33 MeV peak. The detector was placed at a distance of 35 cm from the target and was shielded with 5 cm of lead. The geometry of the lead envelope was such that the detector was effectively shielded from radiation emanating from the beam collimators and, except for $\Theta_\gamma = 0°$, from the stopped beam. Data were taken at angles of observation $\Theta_\gamma = 0°$, 30°, 55°, 70°, 90°, and 125° for incident proton energy $E_p = 5.0$ MeV. Standard electronics were employed for the accumulation of spectra over 4096 channels in a PDP-15 computer. The γ-ray spectrum obtained in this manner for $\Theta_\gamma = 90°$ is presented in Fig. 2. A second Ge(Li) detector, placed at a fixed angle $\Theta_\gamma = 90°$ with respect to the incident beam and at a distance of 50 cm from the target served as a monitor. The monitor spectra were stored in 2048 channels and were employed in the normalization of the angular distribution spectra.

The proton beam current required for a counting rate of 8000 cps was 150–200 nA. However, according to standard practice, the high current capability of the T11/25 tandem was utilized in order to minimize background radiation from the collimating apertures near the target. In a typical run, a beam of 20–30 μA of protons from the tandem was heavily collimated by 1 mm object and image slits of the analyzing magnet. Under these conditions a very small portion of the beam phase space was selected which resulted in essentially zero current on the beam collimators in the target area.

Between the accumulation of each spectrum which required from 3 to 4 h, energy calibration runs were taken with the use of standard radiation sources. The detector efficiency as a function of γ-ray energy was determined through a ^{56}Co source from the relative yield data of Camp and Meredith.[27]

III. ANALYSIS AND RESULTS

The γ-ray energies associated with the decay of ^{63}Cu that were observed in the experimental spectra, together with the associated branching ratios are summarized[9,24,25] in Fig. 1. They are also indicated in the $\Theta_\gamma = 90°$ spectrum of Fig. 2. The corresponding peaks in the experimental spectra were analyzed in two distinct ways in order to extract lifetimes and mixing ratios and whenever possible, to determine the spin and parity of the levels involved.

A. Lifetime measurements

The lifetimes of 18 levels in ^{63}Cu were extracted from γ-ray photopeaks exhibiting an energy shift as a function of detector angle. According to the particular variant[26,28] of the Doppler shift attenuation method employed here, the energy of the emitted γ ray E_γ, observed at an angle Θ_γ with respect to the beam, is given by

$$E_\gamma = E_0[1 + \tilde{F}(\tau)\beta_{\text{c.m.}}\cos\Theta_\gamma] \,, \tag{1}$$

where E_0 is the energy of the transition (observed at $\Theta_\gamma = 90°$), $\beta_{\text{c.m.}}$ is the center of mass velocity, and $\tilde{F}(\tau)$ is the attenuation factor averaged over all initial velocities of the recoil nucleus by employing the angular correlation function as a weighting

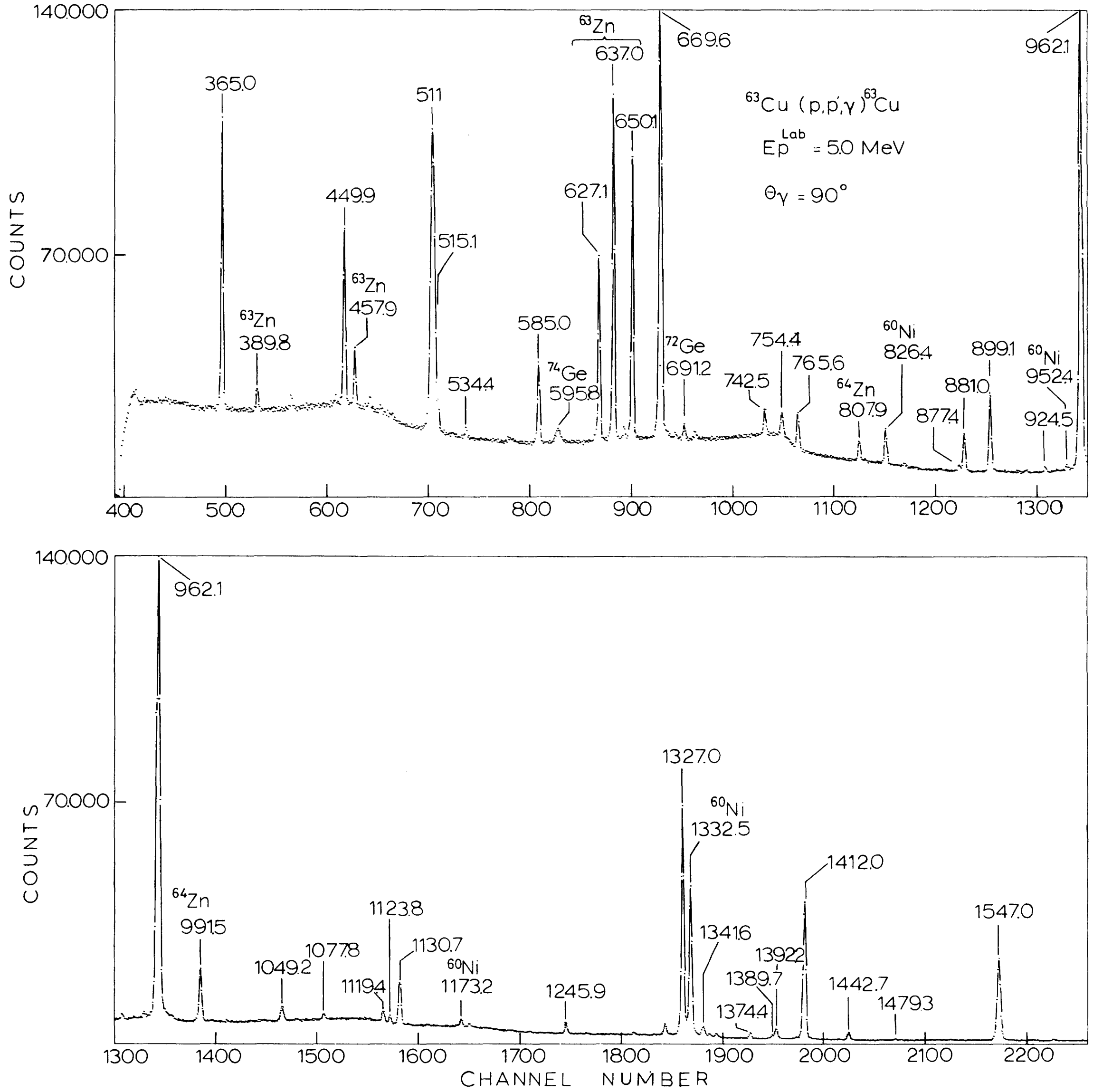

FIG. 2. Singles γ-ray spectra from the ^{63}Cu$(p,p'\gamma)$ reaction at $E_p = 5.0$ MeV and $\Theta_\gamma = 90°$. The energy of transitions in ^{63}Cu is given in keV. Peaks arising from competing reactions are labeled with the symbol of the corresponding residual nucleus.

factor.

As indicated in Eq. (1), experimental values of $\bar{F}(\tau)$ may be obtained through a linear fit of the energy E_γ observed in the angular distribution spectra versus $\cos\Theta_\gamma$. For some of the cases examined here this procedure is shown in Fig. 3. These values were compared with theoretical calculations of $\bar{F}(\tau)$ as described in Ref. 26. In the calculation of the attenuation factor the slowing-down theory of Lindhard, Scharff, and Schiott[29] (LSS) and the average scattering in the stopping material estimated by Blangrund,[30] were used.

The functional form of the nuclear stopping power was approximated by the expression

$$\left(\frac{d\epsilon}{d\rho}\right)_n = \frac{\epsilon^{1/2}}{0.67 + 2.07\epsilon + 0.03\epsilon^2}\,, \qquad (2)$$

where ϵ and ρ denote the dimensionless energy and length parameters introduced by LSS. Since the applicability of the statistical theory of nuclear reactions was ensured by the experimental conditions, the averaging of the attenuation factor was performed by considering an expression[26,31] for the angular correlation function $W(\Theta_\gamma, \Theta_N, \Phi_N)$ symmetric about the recoil c.m. angle $\Theta_N = \frac{1}{2}\pi$ and almost independent of the azi-

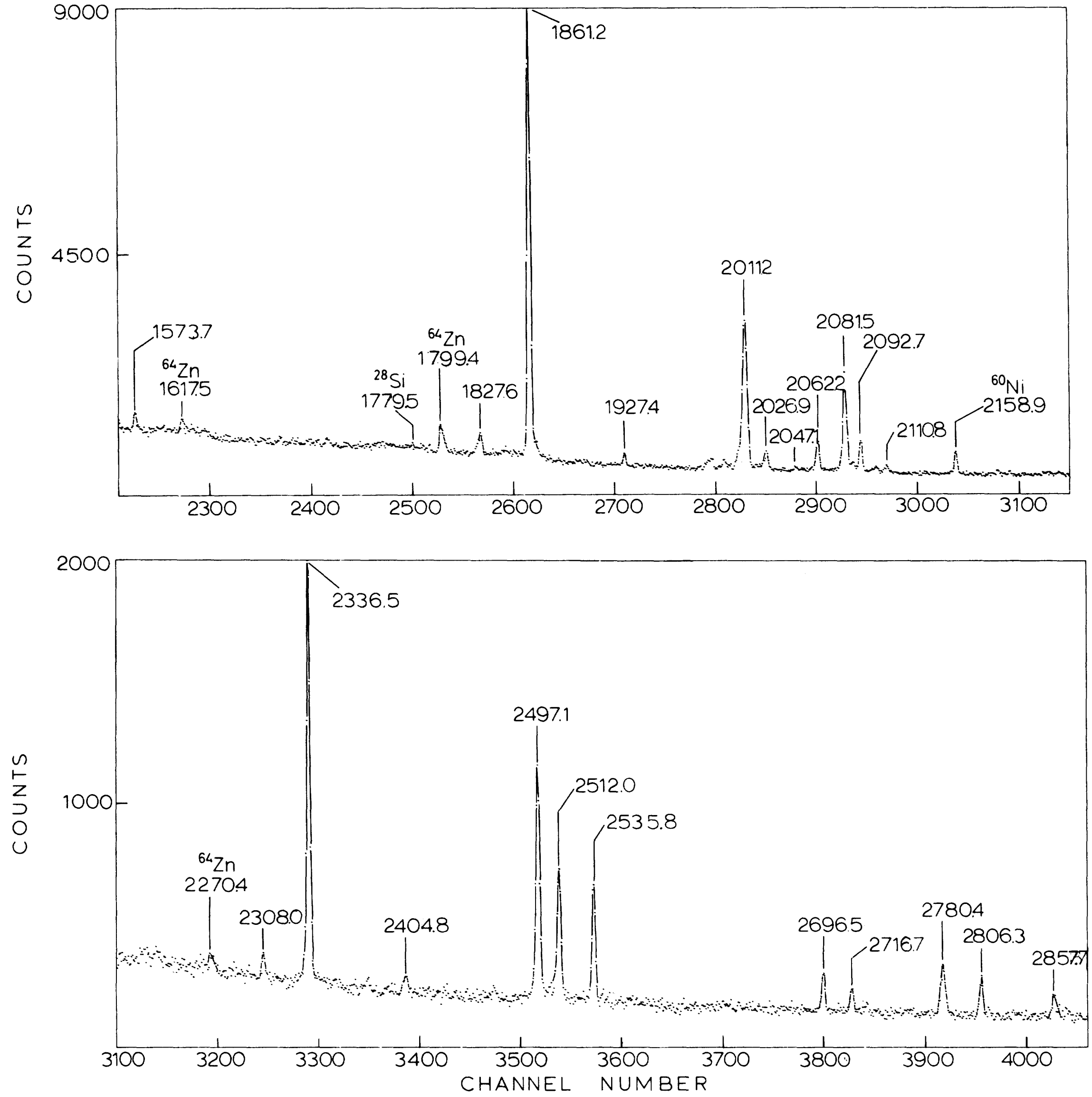

FIG. 2 (*continued*)

muthal recoil angle Φ_N. The averaged attenuation factor resulting from this calculation is shown in Fig. 4.

Table I contains the averaged attenuation factors measured in this experiment for transitions emanating from 18 levels in ^{63}Cu. The lifetimes of these states, extracted from the comparison with the theoretical $\bar{F}(\tau)$ in Fig. 4, are given in the fifth column of the table. The experimental error associated with the extracted value of the lifetime contains a 20% uncertainty in the LSS prediction for the stopping power and a 6% estimated error arising from realistic variations in the expression employed for the angular correlation function. The lifetimes obtained here are compared in the adjacent column of Table I with the results of Swann.[16] With the exception of levels Nos. 12 and 16 the two sets of results are seen to agree within the experimental error. For these cases of agreement the next column of Table I contains the weighted average of lifetimes obtained here and in Ref. 16. The averaged lifetimes are subsequently adopted for the calculation of reduced transition probabilities.

B. Analysis of angular distributions

Singles γ-ray spectra were taken at detector angles $\Theta_\gamma = 0°$, 30°, 55°, 70°, 90°, and 125° with

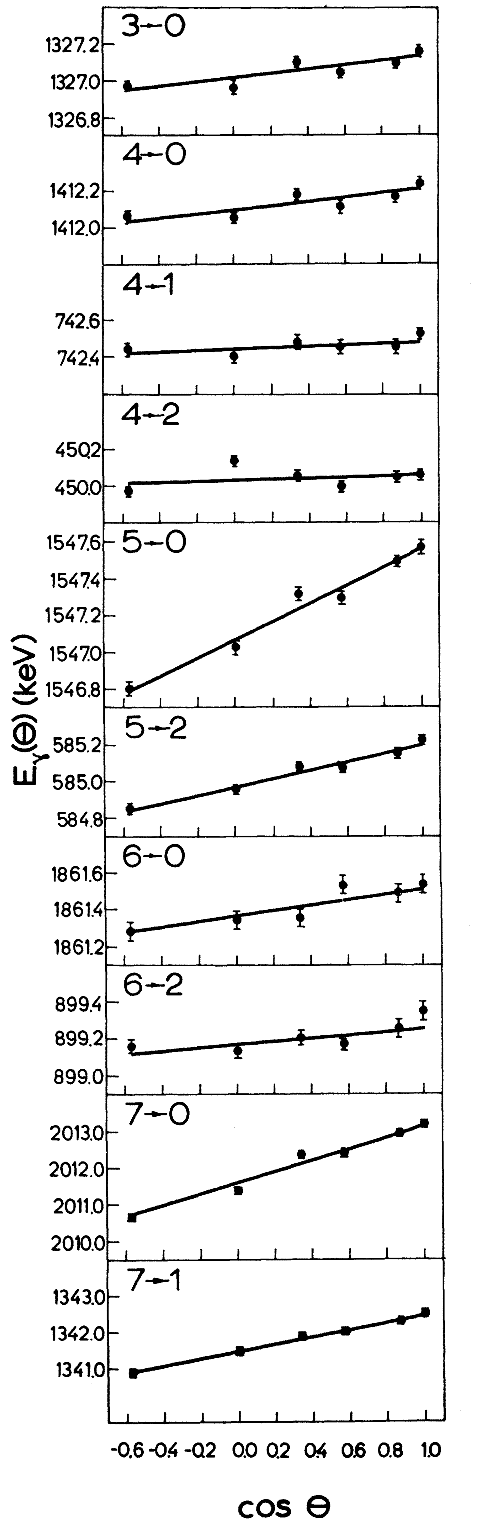

FIG. 3. Linear fit to the γ-ray energies observed in the angular distribution spectra versus $\cos\Theta_\gamma$. The levels involved in the transitions are indicated according to the numbering in Fig. 1.

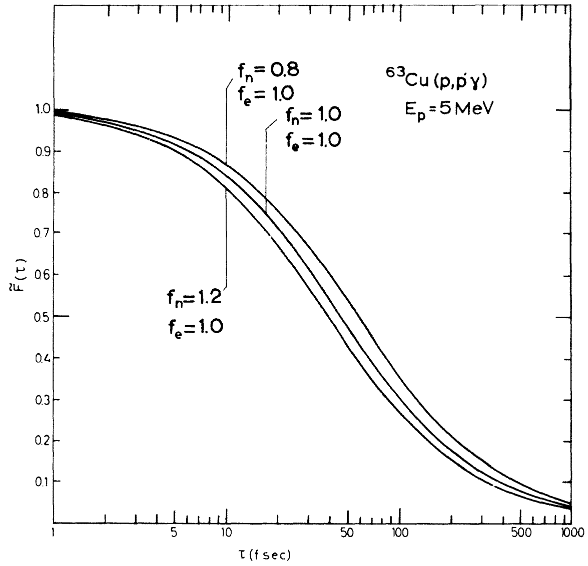

FIG. 4. The averaged attenuation factor $\tilde{F}(\tau)$ versus lifetime for ^{63}Cu recoiling in ^{63}Cu. The central curve is computed for the exact LSS stopping power, while the adjacent curves represent a 20% deviation in the nuclear stopping term. The same amount of deviation in the electronic term results in $\tilde{F}(\tau)$ curves within the limits shown in the figure.

respect to the incident proton beam. The normalization of the spectra was effected with the help of isolated high intensity peaks in the associated monitor spectra.

The angular distribution for each transition was analyzed through a least squares fit to the expression

$$W(\Theta) = A_0[1 + A_2P_2(\cos\Theta) + A_4P_4(\cos\Theta)] \ . \qquad (3)$$

The coefficients of the Legendre polynomials obtained in this way were not corrected for solid angle due to the large distance of the detector from the target which essentially reduces the corresponding geometrical attenuation factors to unity. The experimentally obtained A_2 and A_4 coefficients for each transition are given in Table II.

Theoretical angular distributions were calculated in the framework of the Hauser-Feshbach theory of nuclear reactions[32] with a modified version of program MANDY originally written by Sheldon and Strang.[33] Transmission coefficients were taken by interpolation from the proton penetrability tables of Mani, Malkenoff, and Lori.[34] 20 proton channels up to an excitation energy of 2.8 MeV were included in the calculation. For the available energy in the neutron exit channel (~800 keV) it was found that only neutrons to the ^{63}Zn ground state contributed significantly to the cross sec-

TABLE I. The experimental averaged attenuation factors and lifetimes deduced for states in ^{63}Cu.

Level No.	Level energy (keV)	Transition energy (keV)	$\tilde{F}(\tau)$	Experimental τ (fsec)			Theoretical τ (fsec)	
				Present experiment	Swann (Ref. 16)	Adopted value	Castel *et al.* (Ref. 7)	de Jager (Ref. 8)
3	1327.0	1327.0	0.053 ± 0.007	740^{+200}_{-140}	730 ± 80	760 ± 46[a]	1400	940
4	1412.0	449.9	0.023 ± 0.011	>740	1600 ± 300	1600 ± 300	1000	2150
		742.4	0.030 ± 0.022					
		1412.0	0.046 ± 0.007					
5	1547.0	585.0	0.232 ± 0.009	140^{+32}_{-26}[a]	166 ± 17	159 ± 13	260	180
		1547.0	0.193 ± 0.006					
6	1861.2	899.1	0.054 ± 0.012	760^{+190}_{-120}	1010 ± 200	850^{+140}_{-110}	1200	2050
		1861.2	0.047 ± 0.008					
7	2011.2	1049.2	0.523 ± 0.029	46^{+9}_{-6}	74 ± 8	58^{+14}_{-9}	150	280
		1341.6	0.462 ± 0.017					
		2011.2	0.483 ± 0.012					
8	2062.2	1392.2	0.066 ± 0.020	440^{+140}_{-70}	>110	440^{+140}_{-70}	120	230
		2062.2	0.090 ± 0.008					
9	2081.5	754.4	0.170 ± 0.030	166^{+37}_{-18}	200 ± 50	172^{+29}_{-17}	130	170
		2081.5	0.199 ± 0.012					
10	2092.7	765.6	0.042 ± 0.019	535^{+155}_{-85}	>65	535^{+155}_{-85}		
		1130.7	0.070 ± 0.012					
		2092.7	0.076 ± 0.020					
11	2208.0	881.0	0.087 ± 0.020	445^{+140}_{-70}		445^{+140}_{-70}		
		1245.9	0.076 ± 0.015					
12	2336.5	1374.4	0.065 ± 0.027	510^{+170}_{-95}	1555 ± 360	510^{+170}_{-95}		
		2336.5	0.074 ± 0.011					
13	2404.8	1077.8	0.137 ± 0.049	180^{+53}_{-30}		180^{+53}_{-30}		
		1442.7	0.191 ± 0.026					
14	2497.1	1827.5	0.142 ± 0.063	145^{+32}_{-26}	150 ± 20	148^{+17}_{-16}		
		2497.1	0.223 ± 0.017					
15	2512.0	2512.0	0.152 ± 0.016	220^{+65}_{-42}		220^{+65}_{-42}		
16	2535.8	2535.8	0.076 ± 0.020	470^{+250}_{-110}	150 ± 75	470^{+250}_{-110}		
17	2696.5	2026.9	0.093 ± 0.048	265^{+136}_{-64}		265^{+136}_{-64}		
		2696.5	0.137 ± 0.041					
18	2716.7	2716.7	0.062 ± 0.049	>310		>310		
19	2780.4	2780.4	0.377 ± 0.046	67^{+24}_{-16}		67^{+24}_{-16}		
20	2806.3	2806.3	0.077 ± 0.048	>270		>270		

[a] Averaging also includes $\tau = 779 \pm 58$ fsec from Ref. 9.

[b] Value corrected for feeding from above.

tion. The influence of α channels on ^{60}Ni was even less significant in the evaluation of angular distributions. The theoretical A_2 and A_4 coefficients from this calculation for various assumptions on the spin of the decaying state are given in Table II below the corresponding experimental quantities. Initial spin values were considered in the range $\frac{1}{2} \leq J_i \leq \frac{9}{2}$. The possible J_i values were further restricted by the condition $\Delta J \equiv |J_i - J_f| \leq 2$ for all branches observed.

The theoretical A_2 and A_4 coefficients correspond to the best χ^2 fit of the theoretical distribution to the data presented in Fig. 5 through a variation of the mixing ratio δ. The minimum χ^2 value and the corresponding δ value at the minimum are contained in the fourth and fifth columns of Table II. The errors reported with the proposed δ values are extracted from a 95% confidence limit according to the procedure prescribed by Cline and Lesser.[36] In several instances our results are compared in column six to the δ values of Dayras *et al.*[22] obtained through the ^{60}Ni($\alpha,p\gamma$) ^{63}Cu reac-

TABLE II. Summary of angular distribution analysis.

Transition (keV) $J_i \to J_f$	A_2	A_4	χ^2	Mixing ratio[a]		Criteria[b] for spin assignment
	Experimental Theoretical	Experimental Theoretical		Present work	Dayras *et al.* (Ref. 22)	
1327.0 → 0	0.23 ± 0.03	-0.05 ± 0.02				
$\frac{7}{2} \to \frac{3}{2}$	0.21	-0.03	0.7	-0.017 ± 0.052 or -10^{+4}_{-18}*	-0.012 ± 0.042	$A(9, {}^{c}22), C, D$
1327.0 → 962.1	-0.27 ± 0.03	0.02 ± 0.02				
$\frac{7}{2} \to \frac{5}{2}$	-0.24	0.00	0.6	$-0.10^{+0.03}_{-0.05}$ or $-2.6^{+0.2}_{-0.5}$*	$-0.18^{+0.08}_{-0.10}$ or $-1.8^{+1.0}_{-1.2}$	$A(9, {}^{c}22), C, D$
1412.0 → 0	0.15 ± 0.02	-0.01 ± 0.02				
$\frac{3}{2} \to \frac{3}{2}$	0.09	0.00	3.2	$0.75^{+1.21}_{-0.54}$	$0.19^{+0.14}_{-0.11}$ or $2.1^{+0.7}_{-0.6}$	
$\frac{5}{2} \to \frac{3}{2}$	0.14	0.00	0.3	$0.62^{+0.05}_{-0.07}$ or $3.5^{+1.2}_{-0.8}$	$0.61^{+0.09}_{-0.08}$	$A(9, {}^{c}22), C, D$
1412.0 → 669.6	0.09 ± 0.05	-0.03 ± 0.05				
$\frac{3}{2} \to \frac{1}{2}$	0.08	0.00	0.4	$0.30 \leq \delta$	$0.31^{+0.18}_{-0.16}$ or $-4.33^{+1.8}_{-10.0}$	C
$\frac{5}{2} \to \frac{1}{2}$	0.08	0.00	0.4	$-6.3 \leq \delta \leq 0.2$	$-0.04^{+0.16}_{-0.19}$	$A(9, {}^{c}22), C, D$
1412.0 → 962.1	0.14 ± 0.02	-0.05 ± 0.03				
$\frac{3}{2} \to \frac{5}{2}$	0.03	0.00	4.5			
$\frac{5}{2} \to \frac{3}{2}$	0.12	0.00	1.2	$0.09^{+0.49}_{-0.23}$ or $1.33^{+1.14}_{-0.75}$*	$0.11^{+0.25}_{-0.18}$	$A(9, {}^{c}22), C, D$
1547.0 → 0	0.04 ± 0.02	0.00 ± 0.02				
$\frac{3}{2} \to \frac{3}{2}$	0.04	0.00	0.1	$0.05^{+0.06}_{-0.08}$ or $3.27^{+1.06}_{-0.73}$*	$0.13^{+0.05}_{-0.04}$ or $2.47^{+0.33}_{-0.35}$	$A(9, {}^{c}22), C, D$
1547.0 → 669.6	-0.15 ± 0.09	0.01 ± 0.10				
$\frac{3}{2} \to \frac{1}{2}$	-0.09	0.0	0.4	$-0.58^{+0.67}_{-1.56}$		$A(9, {}^{c}22), C$
1547.0 → 962.1	-0.02 ± 0.03	-0.01 ± 0.03				
$\frac{3}{2} \to \frac{5}{2}$	-0.03	0.00	0.1	$0.17^{+0.16}_{-0.17}$ or pure $E2$*	$0.05^{+0.14}_{-0.15}$ or $-6.0^{+2.8}_{-51}$	$A(9, {}^{c}22), C, D$
1861.2 → 0	0.29 ± 0.02	-0.06 ± 0.03				
$\frac{3}{2} \to \frac{3}{2}$	0.09	0.00	12			
$\frac{5}{2} \to \frac{3}{2}$	0.21	0.00	2.2	$1.35^{+3.35}_{-0.53}$		$A(10)$
$\frac{7}{2} \to \frac{3}{2}$	0.28	-0.01	0.5	$0.07^{+0.07}_{-0.05}$	0.01 ± 0.04	$A(20, 22), C, D$
1861.2 → 962.1	-0.12 ± 0.02	0.00 ± 0.03				
$\frac{3}{2} \to \frac{5}{2}$	-0.08	0.00	1.8	$1.23^{+2.78}_{-0.79}$	0.13 ± 0.08 or $-11.4^{+5.5}_{-103}$	
$\frac{5}{2} \to \frac{5}{2}$	-0.11	0.00	0.3	$-1.73^{+0.54}_{-1.17}$	$-0.60^{+0.16}_{-0.19}$	$A(10), C$
$\frac{7}{2} \to \frac{5}{2}$	-0.12	0.00	0.1	$0.05^{+0.03}_{-0.02}$ or $-5.1^{+0.9}_{-1.6}$	0.05 ± 0.05	$A(20, 22), C, D$
2011.2 → 0	0.05 ± 0.03	-0.03 ± 0.03				
$\frac{3}{2} \to \frac{3}{2}$	0.04	0.00	0.7	$0.00^{+0.34}_{-0.30}$ or $3.7^{+\infty}_{-2.3}$	$0.06^{+0.09}_{-0.08}$ or $3.08^{+1.25}_{-0.78}$	$A(10, 14), C, D$
$\frac{5}{2} \to \frac{3}{2}$	0.04	0.00	0.6	$0.26^{+0.10}_{-0.07}$ or pure $E2$	$0.46^{+0.11}_{-0.10}$	C
$\frac{7}{2} \to \frac{3}{2}$	0.08	-0.07	0.9	$-0.36^{+0.11}_{-0.17}$ or $-2.14^{+0.48}_{-0.61}$	0.11 ± 0.01	C
2011.2 → 669.6	-0.13 ± 0.04	-0.01 ± 0.04				
$\frac{1}{2} \to \frac{1}{2}$	0.00	0.00	8.5			$A(20, 39)$
$\frac{3}{2} \to \frac{1}{2}$	-0.09	0.00	2.7	$-0.58^{+0.67}_{-1.56}$		$A(10, 14), C$
$\frac{5}{2} \to \frac{1}{2}$	0.06	0.01	14			

TABLE II. (*Continued*).

Transition (keV)	A_2	A_4		Mixing ratio[a]		
$J_i \to J_f$	Experimental Theoretical		χ^2	Present work	Dayras *et al.* (Ref. 22)	Criteria[b] for spin assignment
2011.2 → 962.1	0.01 ± 0.05	0.00 ± 0.05				
$\frac{3}{2} \to \frac{5}{2}$	0.01	0.00	0.4	$\delta \le 0.36$	$0.23^{+0.15}_{-0.09}$ or $95^{+\infty}_{-88}$*	*A*(10, 14), *C*, *D*
$\frac{5}{2} \to \frac{5}{2}$	0.01	0.00	0.4	$-0.36^{+0.17}_{-0.22}$ or $4.5^{+\infty}_{-2.0}$	$-0.70^{+0.22}_{-0.41}$	*C*, *D*
2062.2 → 0	-0.07 ± 0.07	0.05 ± 0.07				
$\frac{1}{2} \to \frac{3}{2}$	0.00	0.00	0.6	Indeterminate	Indeterminate	*C*
$\frac{3}{2} \to \frac{3}{2}$	-0.04	0.00	0.4	$\delta \le 0$	$-0.26^{+0.16}_{-0.18}$ or $7 < \lvert\delta\rvert$	*C*, *D*
$\frac{5}{2} \to \frac{3}{2}$	-0.04	0.00	0.4	$0.09^{+0.20}_{-0.19}$		*C*
2062.2 → 669.6	0.05 ± 0.04	-0.02 ± 0.04				
$\frac{1}{2} \to \frac{1}{2}$	0.00	0.00	2.0			
$\frac{3}{2} \to \frac{1}{2}$	0.04	0.00	1.8	$0.49^{+\infty}_{-0.58}$	$0.27^{+0.16}_{-0.15}$ or $-3.7^{+1.2}_{-2.5}$	*C*, *D*
$\frac{5}{2} \to \frac{1}{2}$	0.06	0.01	2.2	$-0.70^{+0.84}_{-3.63}$		*C*
2062.2 → 1547.0	-0.05 ± 0.05	-0.02 ± 0.05				
$\frac{1}{2} \to \frac{3}{2}$	0.00	0.00	1.3	Indeterminate	Indeterminate	
$\frac{3}{2} \to \frac{3}{2}$	-0.05	0.00	0.1	$-1.30^{+0.55}_{-1.17}$*	$-0.10^{+0.08}_{-0.10}$ or $-3.2^{+1.0}_{-1.8}$*	*C*, *D*
$\frac{5}{2} \to \frac{3}{2}$	-0.06	0.00	0.1	$0.05^{+0.04}_{-0.05}$ or $-4.0^{+0.73}_{-1.14}$		*C*
2081.5 → 0	-0.06 ± 0.04	-0.01 ± 0.04				
$\frac{3}{2} \to \frac{3}{2}$	-0.06	0.00	0.5	$-1.25^{+0.83}_{-5.86}$		*C*
$\frac{5}{2} \to \frac{3}{2}$	-0.06	0.00	0.4	$0.03^{+0.11}_{-0.10}$ or $-3.7^{+1.0}_{-3.4}$		*A*(16, 22), *C*
$\frac{7}{2} \to \frac{3}{2}$	0.00	-0.04	1.3	$-0.92^{+0.50}_{-0.96}$*		
2081.5 → 962.1	0.03 ± 0.05	-0.07 ± 0.07				
$\frac{3}{2} \to \frac{5}{2}$	0.00	0.00	0.8	Any δ		*C*
$\frac{5}{2} \to \frac{5}{2}$	0.00	0.00	0.8	$-0.41^{+0.31}_{-0.46}$ or $6.3^{+\infty}_{-4.1}$		*A*(16, 22), *C*
$\frac{7}{2} \to \frac{5}{2}$	-0.02	0.00	0.6	$0.16^{+0.06}_{-0.05}$ or pure $E2$		
2081.5 → 1327.0	-0.14 ± 0.04	0.03 ± 0.04				
$\frac{3}{2} \to \frac{7}{2}$	-0.07	0.00	3.3	$2.0^{+\infty}_{-1.9}$*	$0.75^{+0.21}_{-0.15}$ or $26^{+\infty}_{-20}$*	
$\frac{5}{2} \to \frac{7}{2}$	-0.14	0.00	2.0	$0.36^{+0.46}_{-0.34}$ or $5.7^{+\infty}_{-4.5}$*	0.28 ± 0.08 or $6.04^{+5.4}_{-2.3}$*	*A*(16, 22), *C*, *D*
$\frac{7}{2} \to \frac{7}{2}$	-0.10	-0.02	2.5	$-0.87^{+0.27}_{-1.01}$		*C*
2081.5 → 1547.0	0.01 ± 0.09	0.03 ± 0.10				
$\frac{3}{2} \to \frac{3}{2}$	0.02	0.00	0.1	$-0.10^{+0.44}_{-0.55}$ or pure $E2$		*C*
$\frac{5}{2} \to \frac{3}{2}$	0.01	0.00	0.1	$0.23^{+0.13}_{-0.11}$ or pure $E2$*		*A*(16, 22), *C*
$\frac{7}{2} \to \frac{3}{2}$	0.07	-0.06	0.4	$-0.38^{+0.22}_{-0.46}$* or $-1.96^{+0.96}_{-2.05}$*		*C*
2092.7 → 0	0.23 ± 0.07	-0.08 ± 0.08				
$\frac{3}{2} \to \frac{3}{2}$	0.09	0.00	1.1	$0.65^{+5.02}_{-0.74}$		
$\frac{5}{2} \to \frac{3}{2}$	0.20	0.00	0.4	$1.43^{+3.71}_{-0.92}$		*C*
$\frac{7}{2} \to \frac{3}{2}$	0.20	-0.01	0.4	0.10 ± 0.22		*A*(13, 20, 22), *C*

TABLE II. (*Continued*)

Transition (keV) $J_i \rightarrow J_f$	A_2	A_4	χ^2	Mixing ratio[a]		Criteria[b] for spin assignment
	Experimental Theoretical			Present work	Dayras *et al.* (Ref. 22)	
2092.7 → 962.1	-0.72 ± 0.03	0.04 ± 0.03				
$\frac{3}{2} \rightarrow \frac{5}{2}$	-0.08	0.00	174			
$\frac{5}{2} \rightarrow \frac{5}{2}$	-0.11	0.00	159			
$\frac{7}{2} \rightarrow \frac{5}{2}$	-0.54	0.02	15		$-1.06^{+0.23}_{-0.22}$	*A*(13, 20, 22), *C*
2092.7 → 1327.0	0.16 ± 0.04	0.03 ± 0.04				
$\frac{3}{2} \rightarrow \frac{7}{2}$	0.03	0.00	4.4		$-2.15 \leqslant \delta \leqslant 0.18$	
$\frac{5}{2} \rightarrow \frac{7}{2}$	0.10	0.00	1.7	$-0.84^{+0.55}_{-1.41}$	$-0.27^{+0.18}_{-0.26}$ or $-2.48^{+0.94}_{-1.85}$	*D*
$\frac{7}{2} \rightarrow \frac{7}{2}$	0.17	0.00	0.9	-0.10 ± 0.19 or $1.28^{+0.68}_{-0.50}$	$0.25^{+0.17}_{-0.24}$ or $1.28^{+0.64}_{-0.49}$	*A*(13, 20, 22), *C*, *D*
2208.0 → 962.1	0.31 ± 0.05	-0.08 ± 0.05				
$\frac{3}{2} \rightarrow \frac{5}{2}$	0.03	0.00	9.0			
$\frac{5}{2} \rightarrow \frac{5}{2}$	0.16	0.00	2.6	$0.54^{+1.19}_{-0.57}$	$2.0^{+0.5}_{-0.3}$	*D*
$\frac{7}{2} \rightarrow \frac{5}{2}$	0.25	0.01	1.0	$0.53^{+0.20}_{-0.15}$ or $3.73^{+5.78}_{-2.00}$		
$\frac{9}{2} \rightarrow \frac{5}{2}$	0.30	-0.06	0.2	$-0.01^{+0.04}_{-0.05}$	-0.05 ± 0.05	*C*, *D*
2208.0 → 1327.0	-0.53 ± 0.03	0.02 ± 0.03				
$\frac{3}{2} \rightarrow \frac{7}{2}$	-0.07	0.00	89			
$\frac{5}{2} \rightarrow \frac{7}{2}$	-0.21	0.00	41		$0.56^{+0.14}_{-0.10}$ or $2.38^{+0.23}_{-0.22}$	
$\frac{7}{2} \rightarrow \frac{7}{2}$	-0.21	-0.03	37			
$\frac{9}{2} \rightarrow \frac{7}{2}$	-0.52	0.04	1.0	$-0.24^{+0\ 06}_{-0\ 08}$ or -2.0 ± 0.4	-0.28 ± 0.05	*C*, *D*
2336.5 → 0	-0.08 ± 0.04	0.00 ± 0.04				
$\frac{3}{2} \rightarrow \frac{3}{2}$	-0.06	0.00	0.7	$-1.25^{+0.78}_{-3.89}$	$-0.53^{+0.13}_{-0.20}$ or $-4.2^{+1.8}_{-3.9}$	*C*, *D*
$\frac{5}{2} \rightarrow \frac{3}{2}$	-0.08	0.00	0.4	0.00 ± 0.09 or $-3.6^{+1.0}_{-1.5}$	0.04 ± 0.07 or $-2.6^{+0.8}_{-1.2}$	*A*(9, [c]22), *C*, *D*
$\frac{7}{2} \rightarrow \frac{3}{2}$	0.00	-0.09	2.1	$-0.93^{+0.53}_{-1.03}$		
2336.5 → 962.1	0.10 ± 0.07	0.04 ± 0.07				
$\frac{3}{2} \rightarrow \frac{5}{2}$	0.03	0.00	0.7	$-0.84^{+0.84}_{-3.86}$	$0.08^{+0.40}_{-0.23}$ or $-7.5^{+4.9}_{-\infty}$	*C*, *D*
$\frac{5}{2} \rightarrow \frac{5}{2}$	0.11	0.00	0.2	$0.08^{+0.45}_{-0.26}$ or $1.43^{+1.17}_{-0.85}$	$-0.58^{+0.24}_{-0.33}$ or $11.2^{+\infty}_{-8.2}$	*A*(9, [c]22), *C*, *D*
$\frac{7}{2} \rightarrow \frac{5}{2}$	0.11	0.00	0.2	$0.32^{+0.06}_{-0.07}$ or $16^{+\infty}_{-9}$	$0.08^{+0.10}_{-0.14}$	*C*
2404.8 → 962.1	-0.32 ± 0.05	-0.06 ± 0.05				
$\frac{3}{2} \rightarrow \frac{5}{2}$	-0.08	0.00	13		$0.58 \leqslant \delta \leqslant 3.1$	
$\frac{5}{2} \rightarrow \frac{5}{2}$	-0.11	0.00	11			
$\frac{7}{2} \rightarrow \frac{5}{2}$	-0.35	0.00	0.3	-0.24 ± 0.06 or $-2.0^{+0.5}_{-0.6}$	$-0.26^{+0.06}_{-0.08}$ or $-1.28^{+0.58}_{-0.38}$	*A*(20, 22), *C*, *D*
$\frac{9}{2} \rightarrow \frac{5}{2}$	-0.09	-0.21	7			
2404.8 → 1327.0	0.23 ± 0.10	-0.01 ± 0.11				
$\frac{3}{2} \rightarrow \frac{7}{2}$	0.03	0.00	1.2	Any δ	$-1.54 \leqslant \delta \leqslant 0.035$	*D*
$\frac{5}{2} \rightarrow \frac{7}{2}$	0.10	0.00	0.6	$-0.84^{+0.63}_{-1.91}$	$-0.41^{+0.17}_{-0.43}$ or $1.9^{+0.7}_{-0.8}$	*D*
$\frac{7}{2} \rightarrow \frac{7}{2}$	0.23	0.00	0.1	$0.07^{+0.29}_{-0.19}$ or 0.92 ± 0.41	0.12 ± 0.21	*A*(20, 22), *C*, *D*
$\frac{9}{2} \rightarrow \frac{7}{2}$	0.21	0.01	0.1	$0.34^{+0.08}_{-0.05}$ or $6.3^{+\infty}_{-2.3}$	0.34 ± 0.10	*C*, *D*

TABLE II. (*Continued*)

Transition (keV) $J_i \rightarrow J_f$	A_2 Experimental Theoretical	A_4	χ^2	Mixing ratio[a] Present work	Dayras *et al.* (Ref. 22)	Criteria[b] for spin assignment
2497.1 → 0	0.02 ± 0.04	-0.01 ± 0.05				
$\frac{1}{2} \rightarrow \frac{3}{2}$	0.00	0.00	0.5	Indeterminate		*C*
$\frac{3}{2} \rightarrow \frac{3}{2}$	0.01	0.00	0.5	$-0.14^{+0.43}_{-0.51}$ or pure $E2$		*A*(13, 35), *C*
$\frac{5}{2} \rightarrow \frac{3}{2}$	0.02	0.00	0.4	$0.25^{+0.11}_{-0.15}$ or pure $E2$		*C*
2497.1 → 669.6	-0.02 ± 0.04	-0.01 ± 0.05				
$\frac{1}{2} \rightarrow \frac{1}{2}$	0.00	0.00	0.4			*C*
$\frac{3}{2} \rightarrow \frac{1}{2}$	-0.07	0.00	0.2	$-7.1 \leqslant \delta \leqslant 0.4$		*A*(13, 35), *C*
$\frac{5}{2} \rightarrow \frac{1}{2}$	0.06	0.01	0.9	$-0.75^{+0.96}_{-6.36}$		
2512.0 → 0	0.05 ± 0.05	-0.05 ± 0.06				
$\frac{1}{2} \rightarrow \frac{3}{2}$	0.00	0.00	0.4	Indeterminate		*C*
$\frac{3}{2} \rightarrow \frac{3}{2}$	0.03	0.00	0.3	$-0.05^{+0.56}_{-0.45}$ or pure $E2$		*C*
$\frac{5}{2} \rightarrow \frac{3}{2}$	0.02	0.00	0.3	$0.25^{+0.17}_{-0.11}$ or pure $E2$		*C*
$\frac{7}{2} \rightarrow \frac{3}{2}$	0.07	-0.07	0.2	$-0.39^{+0.08}_{-0.14}$* or $-1.96^{+0.53}_{-0.64}$*		*C*
2535.8 → 0	-0.09 ± 0.07	-0.03 ± 0.08				
$\frac{1}{2} \rightarrow \frac{3}{2}$	0.00	0.00	1.8	Indeterminate		
$\frac{3}{2} \rightarrow \frac{3}{2}$	-0.06	0.00	1.1	$-1.2^{+1.2}_{-\infty}$		*C*
$\frac{5}{2} \rightarrow \frac{3}{2}$	-0.11	0.00	1.0	$-0.05^{+0.24}_{-0.42}$ or -3^{+2}_{-26}		*C*
$\frac{7}{2} \rightarrow \frac{3}{2}$	0.00	-0.09	1.3	$-0.93^{+0.61}_{-1.43}$		
2535.8 → 1412.0	0.17 ± 0.08	-0.23 ± 0.09				
$\frac{3}{2} \rightarrow \frac{5}{2}$	0.03	0.00	2.6	Any δ		
$\frac{5}{2} \rightarrow \frac{5}{2}$	0.05	0.00	2.5	Any δ		
$\frac{7}{2} \rightarrow \frac{5}{2}$	0.06	0.00	2.4	0.24 ± 0.20		
2696.5 → 0	0.19 ± 0.14	0.00 ± 0.16				
$\frac{1}{2} \rightarrow \frac{3}{2}$	0.00	0.00	1.0	Indeterminate		*A*(17)
$\frac{3}{2} \rightarrow \frac{3}{2}$	0.09	0.00	0.4	$0.8^{+8.7}_{-0.9}$		*C*
$\frac{5}{2} \rightarrow \frac{3}{2}$	0.19	0.00	0.2	$0.4 \leqslant \delta \leqslant 7.1$		*C*
2716.7 → 0	0.01 ± 0.20	-0.13 ± 0.25				
$\frac{1}{2} \rightarrow \frac{3}{2}$	0.00	0.00	0.3	Indeterminate		*C*
$\frac{3}{2} \rightarrow \frac{3}{2}$	-0.04	0.00	0.2	Any δ		*C*
$\frac{5}{2} \rightarrow \frac{3}{2}$	-0.04	0.00	0.2	0.09 ± 0.38 or $4.5^{+2.8}_{-\infty}$		*C*
$\frac{7}{2} \rightarrow \frac{3}{2}$	0.00	-0.09	0.2	$-0.92^{+0.62}_{-1.55}$		*C*
2780.4 → 0	0.09 ± 0.09	-0.12 ± 0.10				
$\frac{1}{2} \rightarrow \frac{3}{2}$	0.00	0.00	0.8	Indeterminate		*C*
$\frac{3}{2} \rightarrow \frac{3}{2}$	0.04	0.00	0.7	Any δ		*A*(17), *C*
$\frac{5}{2} \rightarrow \frac{3}{2}$	0.04	0.00	0.7	$0.30^{+0.60}_{-0.32}$ or pure $E2$		*C*
$\frac{7}{2} \rightarrow \frac{3}{2}$	0.05	-0.07	0.4	$-0.47^{+0.31}_{-0.22}$ or $-1.92^{+0.98}_{-0.32}$		*C*

TABLE II. (*Continued*)

Transition (keV) $J_i \to J_f$	A_2 Experimental Theoretical	A_4	χ^2	Mixing ratio[a] Present work	Mixing ratio[a] Dayras *et al.* (Ref. 22)	Criteria[b] for spin assignment
2806.3 → 0	-0.20 ± 0.13	0.07 ± 0.17				
$\frac{1}{2} \to \frac{3}{2}$	0.00	0.00	2.4	Indeterminate		
$\frac{3}{2} \to \frac{3}{2}$	-0.05	0.00	0.6	$-1.7^{+1.6}_{-\infty}$		*C*
$\frac{5}{2} \to \frac{3}{2}$	-0.17	0.00	0.1	$-0.22^{+0.19}_{-0.29}$ or $-1.73^{+0.80}_{-1.54}$		*C*
$\frac{7}{2} \to \frac{3}{2}$	0.00	-0.09	0.9	$-0.93^{+0.71}_{-1.54}$		

[a] An asterisk indicates that the mixing ratio leads to unrealistic $B(\Lambda)$ value.

[b] The criteria for spin assignment are discussed in the text. The symbols employed are: $A(n)$, assigned in reference n. C, theoretical A_2 and A_4 within experimental errors. D, compatibility of δ value obtained here with Ref. 22.

[c] See also previous work cited in Ref. 9.

tion. Since these authors employ a different convention, the signs of δ values given in Ref. 22 have been reversed.

In order to establish the initial spin value in each transition several criteria were considered concerning the fit of theoretical calculations to the experimental data. These criteria are contained in the last column of Table II. The notation employed is as follows: Criterion $A(n_1, n_2, \ldots)$ denotes a definite previous assignment of J_i in references $n_1, n_2, \ldots$; Criterion C denotes agreement within the experimental error of theoretical and experimental angular distribution coefficients; Criterion D denotes agreement within the experimental error of our δ values with those of Dayras *et al.*[22] Under the latter criterion an agreement of the two δ values is an indication in favor of the particular J_i assumption. On the other hand, since the two results are obtained through different reactions, an agreement for the wrong initial state spin could only be fortuitous.

For the δ values obtained in each $J_i^\pi \to J_f^\pi$ sequence assumed we have also calculated the corresponding transition rates wherever the lifetime of the initial state is known. As indicated in the footnote of Table II, mixing ratio values that lead to unrealistic reduced transition probabilities are marked with an asterisk.

With the help of the criteria contained in the last column of Table II and the elimination of δ values leading to unacceptable transition rates, several spins of levels in ^{63}Cu have been determined. Some of the cases are discussed in more detail below.

1861.2 keV level. Bachner *et al.*[20] assign $J^\pi = \frac{7}{2}^-$ to this level from an $l = 3$ angular momentum transfer observed in the ^{64}Zn(t, α) reaction. On the other hand, Borchert,[10] from the assignment of an 1866 keV γ ray observed in the ^{63}Zn decay spectrum to the ground state transition, gives $J^\pi = \frac{5}{2}^-$ on the basis of $\log ft = 6.8$ deduced for feeding of this level. Subsequent analysis of ^{63}Zn decay data,[13] however, reveals that the 1866 keV transition belongs to a weak branch of the 2535.8 keV level, while the 1861.2 keV level is fed with $\log ft > 7.1$. The latter $\log ft$ value is consistent with $J^\pi = \frac{7}{2}^-$. The angular distribution data of Dayras *et al.*[22] are compatible with $J = \frac{7}{2}$. They predict a pure $E2$ transition to the ground state and a pure $M1$ to the 962.1 keV level. The ground state angular distribution data in the present experiment are only compatible with $J = \frac{7}{2}$, while the data from the other branch also show preference for $J = \frac{7}{2}$. For both transitions our δ values are compatible with those of Ref. 22 only for $J = \frac{7}{2}$. However, an additional value of δ, predicting a large $E2$ contribution, is also compatible with the 1861.2 → 962.1 keV angular distribution. From the above evidence the value $J^\pi = \frac{7}{2}^-$ is adopted for this state.

2011.2 keV level. Both ^{64}Zn(t, α) and ^{62}Ni$(^3$He$, d)$ reaction studies[20,39] observe an $l = 1$ transfer to this level and assign tentatively $J^\pi = \frac{1}{2}^-$ without excluding $\frac{3}{2}^-$. The ^{63}Zn decay data[10,13] are also compatible with $J^\pi = \frac{1}{2}^-, \frac{3}{2}^-$. The angular distribution of resonantly scattered radiation obtained by Swann,[16] however, exhibits a marked anisotropy which permits the rejection of the $J^\pi = \frac{1}{2}^-$ value. $J^\pi = \frac{1}{2}^-$ is also rejected from the lifetime measured here in Ref. 16, which predicts an unreasonably large $E2$ rate [250 Weisskopf units (W.u.)] for the transition to the 962.1 keV, $\frac{5}{2}^-$ level. The three angular distributions obtained from the decay of this state in this experiment clearly favor the $J^\pi = \frac{3}{2}^-$ assignment, which is therefore adopted for this state.

2062.2 keV level. There is no definite spin and parity assignment for this level from previous work. Both stripping[17] and pickup[35] reaction data are compatible with $J^\pi = \frac{1}{2}^-, \frac{3}{2}^-$ while ^{63}Zn decay data[10,13] cannot distinguish between $J^\pi \leq \frac{5}{2}$. Our data favor slightly $J = \frac{3}{2}$ without being able to eliminate the other possibilities. Thus, on the evidence of reaction data, $J^\pi = \frac{1}{2}^-, \frac{3}{2}^-$ are both considered in the subsequent calculation of reduced transition probabilities.

2081.5 keV level. This level has not been observed in the transfer reactions considered above. The value $\log ft = 6.5$ measured[13] for the β^+ decay of ^{63}Zn to this state permits the restriction of the spin to $J^\pi = \frac{3}{2}^-, \frac{5}{2}^-$. The value $J = \frac{7}{2}$ is also rejected here from the large δ values obtained in the analysis of the $2081.5 \rightarrow 0$ keV and $2081.5 \rightarrow 1547.0$ keV angular distribution data. Both our data and those of Ref. 22 reject $J^\pi = \frac{3}{2}$ from the δ value measured in the $2081.5 \rightarrow 1327.0$ keV transition. We therefore adopt $J^\pi = \frac{5}{2}^-$ for this level in accordance with the assignment proposed by Dayras *et al.*[22] and Swann.[16]

2092.7 keV level. Bachner *et al.*[20] observe $l = 3$ in the ^{64}Zn(t, α) reaction for population of this state, which permits the assignment of negative parity. These authors, as well as Klaasse and Goudsmit,[13] propose $J^\pi = \frac{7}{2}^-$. The analysis of the three angular distributions for transitions emanating from this state, presented in Table II, shows an overwhelming preference for $J^\pi = \frac{7}{2}^-$. This is particularly true for the markedly anisotropic $2092.7 \rightarrow 962.1$ keV transition, although the χ^2 value obtained from this fit is abnormally high.

2208.0 keV level. There is no spin-parity assignment in the literature for this state which is seen neither in transfer reactions nor in the β^+ decay of ^{63}Zn. This, together with the observed decay to levels with $J^\pi \geq \frac{5}{2}$, point to a high spin value. Our angular distribution data uniquely determine $J = \frac{9}{2}$. For positive parity of this level the δ values obtained for $J = \frac{9}{2}$ lead to completely unacceptable rates for $(E3 + M2)$ and $(E1 + M2)$ transitions to the 962.1 and 1327.0 keV levels, respectively. Thus $J^\pi = \frac{9}{2}^-$ is assigned to this state.

2336.5 keV level. The low $\log ft = 5.8$ value obtained from the ^{63}Zn decay[10,13] restricts the possible spin assignment to $J^\pi = \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$. However, $J^\pi = \frac{1}{2}^-$ may be rejected from the observed weak 4.4% branch to the 1861.2 keV, $\frac{7}{2}^-$ level. There is conflicting evidence on the angular momentum value observed in transfer reactions. Both Blair[17] and Smith, Chen, and Enge[39] observe $l = 3$ in the ^{62}Ni$(^3$He$, d)^{63}$Cu reaction and assign $J^\pi = \frac{5}{2}^-$. On the other hand, Bachner *et al.*[20] determine $l = 2$ through the ^{64}Zn$(t, \alpha)^{63}$Cu reaction and propose $J^\pi = \frac{3}{2}^+$. The last assignment may be immediately rejected from the measured lifetime which for the 4.4% branch to the $\frac{7}{2}^-$ level gives a $B(M2)$ of the order

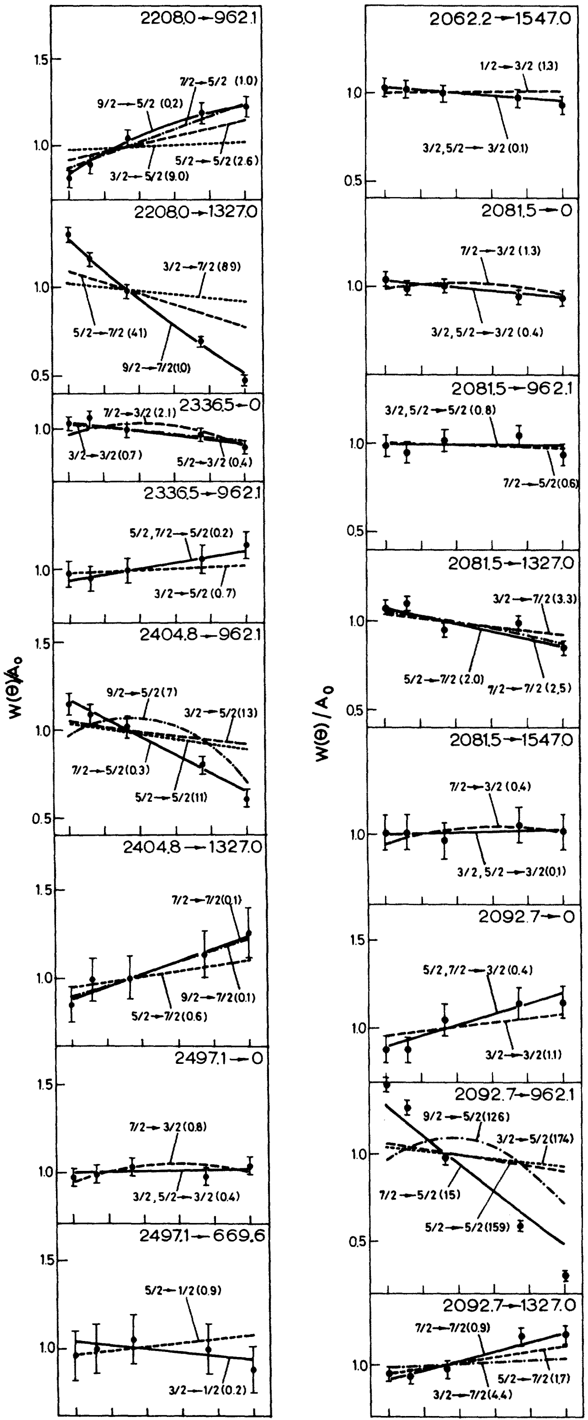

FIG. 5. Angular distribution of transitions in ^{63}Cu from the ^{63}Cu$(p, p'\gamma)$ reaction. The energies of levels involved and the final J^π values are indicated in the figure. Theoretical angular distributions are drawn for alternate values of the initial spin. The number in parentheses indicates the minimum χ^2 value through a variation of the mixing ratio.

of 10^5. The same assignment also gives unreasonable $(E1+M2)$ rates for the 2336.5 → g.s. transition. The analysis presented in Table II shows a preference for $J=\frac{5}{2}$ without eliminating entirely the possibility $J=\frac{3}{2}$. However, in view of the previous evidence from transfer reactions,[17,39] we have adopted $J^\pi=\frac{5}{2}^-$ for this level.

2404.8 keV level. The experimental angular distribution obtained for the 2404.8 → 962.1 transition is only compatible with $J=\frac{7}{2}$, while the second transition from this state, presented in Fig. 5, favors the same assignment. Positive parity assignment for this level is rejected from both the 3.8% branch to the ground state and the δ values obtained in the 2404.8 → 962.1 keV transition. This permits the unique assignment $J^\pi=\frac{7}{2}^-$ in accordance with Bachner *et al.*[20] and Dayras *et al.*[22]

2497.1 keV level. This level was first seen by Markham and Fulbright[35] as a member of an unresolved triplet around 2.5 MeV in the reaction $^{65}\mathrm{Cu}(p,t)^{63}\mathrm{Cu}$. These authors assign $J^\pi=\frac{3}{2}^-$ on the basis of a distorted wave Born approximation (DWBA) analysis obtained from the angular distribution of the unresolved group. Klaasse and Goudsmit[13] also obtain data from the ^{63}Zn decay consistent with the above assignment. Finally, Ramavataram *et al.*,[40] from an observed marked anisotropy in the angular distribution of the 2497.1 → g.s. transition, are able to reject $J=\frac{1}{2}$ and also accept $J^\pi=\frac{3}{2}^-$. The angular distributions obtained in this experiment are compatible with both $J^\pi=\frac{3}{2}^-$ and $\frac{5}{2}^-$ although the 2497.1 → 669.6 keV transition slightly favors the $J^\pi=\frac{3}{2}^-$ value. We thus feel that from the evidence presented here and the available indication from previous work the value $J^\pi=\frac{5}{2}^-$ cannot be excluded and have indicated the spin and parity on the adopted level scheme as $\frac{3}{2}^-(\frac{5}{2}^-)$.

2535.8 keV level. From the $\log ft=5.4$ measured by both Borchert[10] and Klaasse and Goudsmit[13] in the ^{63}Zn decay the spin of this level is determined in the range $J\leq\frac{5}{2}^-$. From the three weak branches to lower $\frac{7}{2}^-$ states[13] $J^\pi=\frac{1}{2}^-$ can be easily excluded. Similarly, from the unreasonable $B(E2)$ value obtained for the 6.3% transition to the 2092.7 keV, $\frac{7}{2}^-$ level we have been able to eliminate the $J^\pi=\frac{3}{2}^-$ possibility. Thus $J^\pi=\frac{5}{2}^-$ is proposed for this state.

Remaining levels in ^{63}Cu. The weak population of the four remaining states observed in this work resulted in poor quality angular distribution data which were unable to determine uniquely the spin and parity of each level. However, from the known $\log ft$ values measured[10,13] in the ^{63}Zn decay and the decay properties observed[10,24,25] the range of J^π could be considerably restricted. The result of this evaluation is indicated in Fig. 1 without being discussed in more detail since it does not differ substantially from that found in Refs. 9 and 13.

C. Reduced transition probabilities

Reduced transition probabilities $B(E2)$ and $B(M1)$ have been calculated for transitions where the level spin sequence has been established and the needed parameters (branching ratio, lifetime, and mixing ratio) are known from the present or previous work. These values are summarized in Table III. All transition energies and branching ratios are taken from Hartas *et al.*[24,25] The lifetimes employed in the calculation are taken from the seventh column of Table I which contains the average value of the results obtained here and in Ref. 16. An exception is made in the cases of the 2336.5 and 2535.8 keV levels where the measured lifetimes differ by several standard deviations. In these cases the results of the present experiment have been employed for the calculation of reduced transition probabilities. Similarly our results for the mixing ratio δ have been averaged with those of Dayras *et al.*[22] for several transitions below the 13th excited state. The resulting $B(\Lambda)$ values are given in Weisskopf single particle units in the last two columns of Table III. The conversion factors to $e^2\mathrm{fm}^4$ for $B(E2)$ values and μ_N for $B(M1)$ values are contained in the footnote of the table.

IV. DISCUSSION AND CONCLUSIONS

There have been several attempts in the literature to describe ^{63}Cu in the framework of the weak-coupling model with successive refinements of the two parallel approaches mentioned in the Introduction. In the particle-core model, pioneered by Thankappan and True,[1] a recent calculation by de Jager[8] has been extended to include up to five states for the ^{62}Ni core. On the other hand, calculations in the particle-phonon model have been improved through the use of anharmonic terms in the vibrational Hamiltonian and to a lesser extent through the concept of quasi-particle protons for the introduction of pairing effects. In this manner the single particle space is extended to include $f_{7/2}$ quasihole states. The most recent of the latter type of calculations is presented by Castel *et al.*[7]

Figure 6 compares the order and excitation energy of levels in ^{63}Cu up to 2.5 MeV with predictions of calculations which exemplify the two approaches described above. On the basis of excitation energy, it is immediately seen that the overall agreement is markedly better for the particle-core model which essentially predicts the right order and energy of states up to an excitation of

TABLE III. Electromagnetic transition rates in ^{63}Cu.

Transition	$J_i^\pi \rightarrow J_f^\pi$	Transition energy (keV)	Branch (%)	τ [a] (fsec)	δ [b]	$B(E2)$ [c] (W.u.)	$B(M1)$ [c] (W.u.)
1 → 0	$\frac{1}{2}^- \rightarrow \frac{3}{2}^-$	669.6	100	317 ± 43 [d]	$\lvert\delta\rvert = 0.11$ [e]	15.4 ± 2.1	0.33 ± 0.04
2 → 0	$\frac{5}{2}^- \rightarrow \frac{3}{2}^-$	962.1	100	880 ± 43 [d]	−0.48 ± 0.04 [f]	14.1 ± 2.0	0.033 ± 0.002
3 → 0	$\frac{7}{2}^- \rightarrow \frac{3}{2}^-$	1327.0	84.2 ± 0.4	760 ± 46	Pure $E2$	14.8 ± 0.9	
3 → 2	$\frac{7}{2}^- \rightarrow \frac{5}{2}^-$	365.0	15.8 ± 0.4		−0.11 ± 0.02 [g]	21.0 ± 7.7	0.14 ± 0.01
4 → 0	$\frac{5}{2}^- \rightarrow \frac{3}{2}^-$	1412.0	72.2 ± 1.2	1600 ± 300	0.62 ± 0.05	1.22 ± 0.27	$(3.7 \pm 0.7) \times 10^{-3}$
4 → 1	$\frac{5}{2}^- \rightarrow \frac{1}{2}^-$	742.4	5.8 ± 0.3		Pure $E2$	8.8 ± 1.7	
4 → 2	$\frac{5}{2}^- \rightarrow \frac{5}{2}^-$	449.9	22.0 ± 1.0		$0.11^{+0.22}_{-0.14}$	5^{+19}_{-5}	0.047 ± 0.009
5 → 0	$\frac{3}{2}^- \rightarrow \frac{3}{2}^-$	1547.0	80.2 ± 0.5	159 ± 13	0.10 ± 0.04	0.31 ± 0.25	0.043 ± 0.004
5 → 1	$\frac{3}{2}^- \rightarrow \frac{1}{2}^-$	877.4	2.1 ± 0.2		$-0.58^{+0.67}_{-1.56}$	$3.5^{+14.6}_{-3.5}$	$(4.6^{+2.4}_{-4.6}) \times 10^{-3}$
5 → 2	$\frac{3}{2}^- \rightarrow \frac{5}{2}^-$	585.0	17.7 ± 0.4		0.10 ± 0.11	9^{+20}_{-9}	0.18 ± 0.2
6 → 0	$\frac{7}{2}^- \rightarrow \frac{3}{2}^-$	1861.2	57.3 ± 2.1	850^{+140}_{-110}	Pure $E2$	$1.65^{+0.22}_{-0.28}$	
6 → 2	$\frac{7}{2}^- \rightarrow \frac{5}{2}^-$	899.1	42.7 ± 2.1		0.05 ± 0.03	$0.12^{+0.14}_{-0.12}$	0.022 ± 0.004
7 → 0	$\frac{3}{2}^- \rightarrow \frac{3}{2}^-$	2011.2	55.8 ± 2.1	53^{+14}_{-9}	0.06 ± 0.09	$0.06^{+0.19}_{-0.06}$	$0.041^{+0.007}_{-0.011}$
					or $3.12^{+1.25}_{-0.74}$	$15.9^{+3.0}_{-4.3}$	$(3.8^{+1.8}_{-3.0}) \times 10^{-3}$
7 → 1	$\frac{3}{2}^- \rightarrow \frac{1}{2}^-$	1341.6	13.5 ± 1.8		$-0.58^{+0.67}_{-1.56}$	8^{+32}_{-8}	$0.025^{+0.014}_{-0.025}$
7 → 2	$\frac{3}{2}^- \rightarrow \frac{5}{2}^-$	1049.2	30.7 ± 1.8		$0.23^{+0.15}_{-0.09}$	$12.5^{+15.7}_{-9.9}$	$0.15^{+0.03}_{-0.04}$
8 → 0	if $\frac{3}{2}^- \rightarrow \frac{3}{2}^-$	2062.2	20.4 ± 1.8	440^{+140}_{-70}	$-0.26^{+0.16}_{-0.18}$	$0.043^{+0.056}_{-0.043}$	$(1.6^{+0.3}_{-0.5}) \times 10^{-3}$
					or $\lvert\delta\rvert > 7$	>0.45	$<4.0 \times 10^{-5}$
8 → 1	if $\frac{1}{2}^- \rightarrow \frac{1}{2}^-$	1392.2	49.6 ± 3.5		Pure $M1$		$0.013^{+0.002}_{-0.004}$
	if $\frac{3}{2}^- \rightarrow \frac{1}{2}^-$				$0.27^{+0.16}_{-0.15}$	$0.80^{+0.90}_{-0.80}$	$0.012^{+0.002}_{-0.004}$
					or $-3.7^{+1.2}_{-2.5}$	$11.0^{+2.2}_{-3.6}$	$(9.0^{+5.7}_{-9.0}) \times 10^{-4}$
8 → 5	if $\frac{3}{2}^- \rightarrow \frac{3}{2}^-$	515.1	30.4 ± 4.6		$-0.10^{+0.16}_{-0.10}$	$10.3^{+20.5}_{-10.3}$	$0.16^{+0.04}_{-0.06}$
9 → 0	$\frac{5}{2}^- \rightarrow \frac{3}{2}^-$	2081.5	38.9 ± 2.2	172^{+29}_{-17}	$0.03^{+0.11}_{-0.10}$	$(3^{+21}_{-3}) \times 10^{-3}$	$(8.0^{+0.9}_{-1.4}) \times 10^{-3}$
					or $-3.7^{+1.0}_{-3.4}$	3.0 ± 0.5	$(5.4^{+2.3}_{-5.4}) \times 10^{-4}$
9 → 2	$\frac{5}{2}^- \rightarrow \frac{5}{2}^-$	1119.4	19.2 ± 1.5		$-0.41^{+0.31}_{-0.46}$	$5.0^{+9.6}_{-5.0}$	$0.022^{+0.005}_{-0.008}$
					or $6.3^{+\infty}_{-4.1}$	34^{+265}_{-6}	$(6.2^{+7.9}_{-6.2}) \times 10^{-4}$
9 → 3	$\frac{5}{2}^- \rightarrow \frac{7}{2}^-$	754.4	33.6 ± 2.7		0.28 ± 0.08	32 ± 17	0.13 ± 0.02
9 → 5	$\frac{5}{2}^- \rightarrow \frac{3}{2}^-$	534.4	8.3 ± 0.9		$0.23^{+0.13}_{-0.11}$	31^{+33}_{-28}	$0.095^{+0.015}_{-0.018}$
10 → 0	$\frac{7}{2}^- \rightarrow \frac{3}{2}^-$	2092.7	9.7 ± 0.8	535^{+135}_{-85}	Pure $E2$	$0.25^{+0.04}_{-0.07}$	
10 → 2	$\frac{7}{2}^- \rightarrow \frac{5}{2}^-$	1130.7	47.5 ± 1.8		$-1.06^{+0.23}_{-0.22}$	$13.9^{+3.5}_{-4.6}$	$(9.2^{+2.6}_{-3.1}) \times 10^{-3}$
10 → 3	$\frac{7}{2}^- \rightarrow \frac{7}{2}^-$	765.6	42.8 ± 2.0		$-0.17^{+0.13}_{-0.15}$	$4.7^{+8.1}_{-4.7}$	$0.055^{+0.009}_{-0.014}$
					or $1.28^{+0.42}_{-0.35}$	104 ± 34	$0.021^{+0.008}_{-0.011}$
11 → 2	$\frac{9}{2}^- \rightarrow \frac{5}{2}^-$	1245.9	42.8 ± 2.0	445^{+140}_{-70}	Pure $E2$	$17.6^{+2.9}_{-5.6}$	
11 → 3	$\frac{9}{2}^- \rightarrow \frac{7}{2}^-$	881.0	57.2 ± 2.0		−0.27 ± 0.04	$9.0^{+2.9}_{-3.8}$	$0.056^{+0.009}_{-0.018}$
					or −2.0 ± 0.4	106^{+19}_{-34}	$0.012^{+0.004}_{-0.005}$
12 → 0	$\frac{5}{2}^- \rightarrow \frac{3}{2}^-$	2336.5	60.2 ± 2.3	510^{+170}_{-95}	0.02 ± 0.06	$(3.7^{+22.3}_{-3.7}) \times 10^{-4}$	$(2.9^{+0.6}_{-0.9}) \times 10^{-3}$
					or $-2.9^{+0.6}_{-0.9}$	$0.83^{+0.17}_{-0.28}$	$(3.1^{+1.3}_{-2.0}) \times 10^{-4}$
12 → 2	$\frac{5}{2}^- \rightarrow \frac{5}{2}^-$	1374.4	24.9 ± 1.6		$-0.28^{+0.27}_{-0.31}$	$0.40^{+0.82}_{-0.40}$	$(5.5^{+1.3}_{-2.1}) \times 10^{-3}$
					or 1.5 ± 1.2	$3.8^{+2.0}_{-2.3}$	$(1.8^{+2.1}_{-1.8}) \times 10^{-3}$

TABLE III. (*Continued*).

Transition	$J_i^\pi \rightarrow J_f^\pi$	Transition energy (keV)	Branch (%)	τ[a] (fsec)	δ[b]	$B(E2)$[c] (W.u.)	$B(M1)$[c] (W.u.)
13→0	$\frac{7}{2}^- \rightarrow \frac{3}{2}^-$	2404.8	3.8 ± 1.2	180^{+53}_{-30}	Pure $E2$	$0.14^{+0.05}_{-0.06}$	
13→2	$\frac{7}{2}^- \rightarrow \frac{5}{2}^-$	1442.7	45.1 ± 2.5		−0.25 ± 0.04	1.3 ± 0.5	$0.025^{+0.004}_{-0.008}$
					or −1.58 ± 0.35	$15.7^{+3.4}_{-5.1}$	$(7.6^{+2.7}_{-3.3}) \times 10^{-3}$
13→3	$\frac{7}{2}^- \rightarrow \frac{7}{2}^-$	1077.8	30.7 ± 2.2		−0.03 ± 0.15	$0.06^{+0.58}_{-0.06}$	$0.043^{+0.008}_{-0.013}$
					or 0.92 ± 0.41	30^{+15}_{-17}	$0.023^{+0.010}_{-0.012}$
14→0	$\frac{3}{2}^- \rightarrow \frac{3}{2}^-$	2497.1	83.3 ± 2.0	148^{+17}_{-16}	$-0.14^{+0.43}_{-0.51}$	$0.06^{+0.44}_{-0.06}$	0.011 ± 0.002
					or Pure $E2$	3.2 ± 0.4	
14→1	$\frac{3}{2}^- \rightarrow \frac{1}{2}^-$	1827.5	16.7 ± 2.0		$-7.1 \leq \delta \leq 0.4$	$0.4 \leq B(E2) \leq 2.5$	$1 \times 10^{-4} \leq B(M1$ $\leq 58 \times 10^{-4}$
16→0	$\frac{5}{2}^- \rightarrow \frac{3}{2}^-$	2535.8	28.3 ± 1.6	470^{+250}_{-110}	$-0.05^{+0.24}_{-0.42}$	$(0.7^{+13.1}_{-0.7}) \times 10^{-3}$	$(0.12^{+0.03}_{-0.06}) \times 10^{-2}$
					or -3^{+2}_{-26}	$0.28^{+0.50}_{-0.16}$	$(0.12^{+0.14}_{-0.12}) \times 10^{-3}$

[a] Average lifetime from present work and Ref. 16 unless otherwise indicated.

[b] Average δ value from present work and Ref. 22 (if available) unless otherwise indicated.

[c] In Weisskopf units. The conversion is $B(E2)$: 1 W.u. = 14.89 $e^2\,\mathrm{fm}^4$, $B(M1)$: 1 W.u. = $1.79\mu_N^2$.

[d] From Ref. 9.

[e] From Ref. 37.

[f] Average δ value from Refs. 15, 22, and 36.

[g] Averaging includes also value from Ref. 15.

2 MeV. On the other hand, the level order in the particle phonon model already breaks down at about 1.5 MeV, while the $(\frac{1}{2}^-)_2$ level is predicted at about 450 keV lower in excitation energy. It should be emphasized, however, that the association of experimental and theoretical levels above 1.6 MeV indicated in Fig. 6 is not necessarily the one considered in the corresponding calculations. This is due to the unavailability at the time of the calculations of definite spin assignments[9] to levels above 1.6 MeV. Since both types of calculation involve a fitting procedure to experimental data it is quite possible that a different identification may ensue in this region from a different determination of model parameters. For example, the $(\frac{7}{2}^-)_2$ level in the particle-core model[8] could be made to coincide in energy with either the 1861.2 keV or the 2092.7 keV level through a small change in the model parameters. These were at the time suspected and are now known to be $J^\pi = \frac{7}{2}^-$ levels. The lack of unambiguous one-to-one correspondence between experimental and theoretical levels above 1.6 MeV is further made evident from the comparison[23,24] of branching ratios which should provide a more meaningful test for the character of the states.

The lifetimes of levels up to 2 MeV of excitation predicted in both models have been compared with experimentally available values in Table I. A further comparison between theoretical predic-

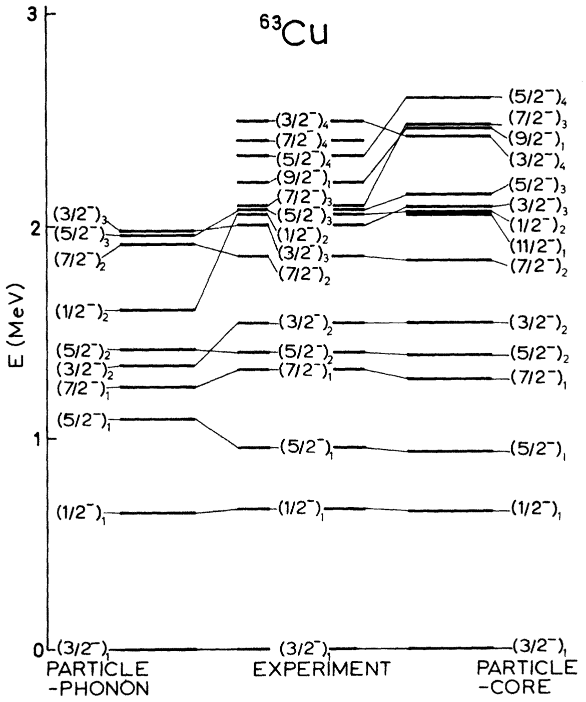

FIG. 6. Predictions of the weak-coupling model to experimental energy levels of ^{63}Cu. Calculations in the particle-phonon model are from Castel *et al.* (Ref. 7) while the particle-core predictions are due to de Jager (Ref. 8). The indicated identification of states is made only on the basis of excitation energy.

TABLE IV. Comparison of experimental electromagnetic properties of transitions in ^{63}Cu to theoretical predictions in the particle-phonon and particle-core models.

		$\delta(E2/M1)$		$B(E2)$ (W.u.)			$B(M1)$ (W.u.)		
Transition	$J_i^\pi \to J_f^\pi$	Experiment	Castel *et al.* (Ref. 7)	Experiment	Castel *et al.* (Ref. 7)	de Jager (Ref. 8)	Experiment	Castel *et al.* (Ref. 7)	de Jager (Ref. 8)
1 → 0	$(\frac{1}{2}^-)_1 \to (\frac{3}{2}^-)_1$	$\lvert\delta\rvert = 0.11$	0.09	15.4 ± 2.1	13.2	16.2	0.33 ± 0.04	0.46	0.33
2 → 0	$(\frac{5}{2}^-)_1 \to (\frac{3}{2}^-)_1$	-0.48 ± 0.04	4.5	14.1 ± 2.0	7.4	16.0	0.033 ± 0.002	3×10^{-4}	0.013
3 → 0	$(\frac{7}{2}^-)_1 \to (\frac{3}{2}^-)_1$	Pure $E2$		14.8 ± 0.9	13.5	12.0			
3 → 2	$(\frac{7}{2}^-)_1 \to (\frac{5}{2}^-)_1$	-0.11 ± 0.02	0.02	21.1 ± 7.7	0.33	11.5	0.14 ± 0.01	0.05	0.11
4 → 0	$(\frac{5}{2}^-)_2 \to (\frac{3}{2}^-)_1$	0.62 ± 0.05	2.4	1.22 ± 0.27	5.4	0.13	$(3.7 \pm 0.7) \times 10^{-3}$	1.2×10^{-3}	3.3×10^{-3}
4 → 1	$(\frac{5}{2}^-)_2 \to (\frac{1}{2}^-)_1$	Pure $E2$		8.8 ± 1.7	4.1	8.5			
4 → 2	$(\frac{5}{2}^-)_2 \to (\frac{5}{2}^-)_1$	$0.11^{+0.22}_{-0.14}$	0.05	5^{+19}_{-5}	1.9	5.6	0.047 ± 0.009	0.064	0.034
5 → 0	$(\frac{3}{2}^-)_2 \to (\frac{3}{2}^-)_1$	0.10 ± 0.04	1.9	0.31 ± 0.25	11.4	4.0	0.043 ± 0.004	3.4×10^{-3}	0.018
5 → 1	$(\frac{3}{2}^-)_2 \to (\frac{1}{2}^-)_1$	$-0.58^{+0.67}_{-1.56}$	0.01	$3.5^{+14.1}_{-3.5}$	0.11	6.2	$(4.6^{+2.4}_{-4.6}) \times 10^{-3}$	0.14	5.6×10^{-4}
5 → 2	$(\frac{3}{2}^-)_2 \to (\frac{5}{2}^-)_1$	0.10 ± 0.11	~0	9^{+20}_{-9}	0.13	8.9	0.18 ± 0.02	0.31	0.43
6 → 0	$(\frac{7}{2}^-)_2 \to (\frac{3}{2}^-)_1$	Pure $E2$		$1.65^{+0.22}_{-0.28}$	0.009	1.0			
6 → 2	$(\frac{7}{2}^-)_2 \to (\frac{5}{2}^-)_1$	0.05 ± 0.03	0.05	$0.12^{+0.14}_{-0.12}$	0.31	3.7	0.022 ± 0.004	0.049	5.6×10^{-4}
7 → 0	$(\frac{3}{2}^-)_3 \to (\frac{3}{2}^-)_1$	0.06 ± 0.09	3.1	$0.06^{+0.19}_{-0.06}$	0.39	0.47	$0.041^{+0.007}_{-0.011}$	9×10^{-3}	3.3×10^{-3}
		or $3.12^{+1.25}_{-0.74}$		or $15.9^{+3.0}_{-4.3}$			or $(3.8^{+1.8}_{-3.0}) \times 10^{-3}$		
7 → 1	$(\frac{3}{2}^-)_3 \to (\frac{1}{2}^-)_1$	$-0.58^{+0.67}_{-1.56}$	1.2	8^{+32}_{-8}	10.8	0.67	$0.025^{+0.014}_{-0.025}$	7×10^{-3}	0.016
7 → 2	$(\frac{3}{2}^-)_3 \to (\frac{5}{2}^-)_1$	$0.23^{+0.15}_{-0.09}$	0.04	$12.5^{+15.7}_{-9.9}$	0.32	4.6	$0.15^{+0.03}_{-0.04}$	0.07	7.8×10^{-3}
8 → 1	if $(\frac{1}{2}^-)_2 \to (\frac{1}{2}^-)_1$	Pure $M1$			0.04^{a}	0	$0.013^{+0.002}_{-0.004}$		9.5×10^{-3}
9 → 0	$(\frac{5}{2}^-)_3 \to (\frac{3}{2}^-)_1$	$0.03^{+0.11}_{-0.10}$		$(3^{+21}_{-3}) \times 10^{-3}$	0.03	0.60	$(8.0^{+0.9}_{-1.4}) \times 10^{-3}$	~0	0.0000
		or $-3.7^{+1.0}_{-3.4}$		or 3.0 ± 0.5			or $(5.4^{+2.8}_{-5.4}) \times 10^{-4}$		
9 → 2	$(\frac{5}{2}^-)_3 \to (\frac{5}{2}^-)_1$	$-0.41^{+0.39}_{-0.46}$	~0	$5.0^{+9.6}_{-5.0}$	0.06	0.13	$0.022^{+0.005}_{-0.008}$	0.090	0.021
		or $6.3^{+\infty}_{-4.1}$		or 34^{+265}_{-6}			or $(6.2^{+7.9}_{-6.2}) \times 10^{-4}$		
9 → 3	$(\frac{5}{2}^-)_3 \to (\frac{7}{2}^-)_1$	0.28 ± 0.08	0.05	32 ± 17	1.5	0.20	0.13 ± 0.02	0.28	0.19
9 → 5	$(\frac{5}{2}^-)_3 \to (\frac{3}{2}^-)_2$	$0.23^{+0.13}_{-0.11}$	0.32	31^{+33}_{-28}	2.2	7.4	$0.095^{+0.015}_{-0.018}$	6.9×10^{-3}	5.6×10^{-4}
10 → 0	$(\frac{7}{2}^-)_3 \to (\frac{3}{2}^-)_1$	Pure $E2$		$0.25^{+0.04}_{-0.07}$		0.067			

TABLE IV. (*Continued*).

Transition	$J_i^\pi \to J_f^\pi$	$\delta(E2/M1)$ Experiment	$\delta(E2/M1)$ Castel *et al.* (Ref. 7)	$B(E2)$ (W.u.) Experiment	$B(E2)$ (W.u.) Castel *et al.* (Ref. 7)	$B(E2)$ (W.u.) de Jager (Ref. 8)	$B(M1)$ (W.u.) Experiment	$B(M1)$ (W.u.) Castel *et al.* (Ref. 7)	$B(M1)$ (W.u.) de Jager (Ref. 8)
10 → 2	$(\frac{7}{2}^-)_3 \to (\frac{5}{2}^-)_1$			$13.9^{+3.5}_{-4.6}$		1.14	$(9.2^{+2.6}_{-3.9}) \times 10^{-3}$		2.8×10^{-3}
10 → 3	$(\frac{7}{2}^-)_3 \to (\frac{7}{2}^-)_1$			$4.7^{+8.1}_{-4.7}$		0.13	$0.055^{+0.009}_{-0.014}$		8.4×10^{-3}
				or 104 ± 34			or $0.021^{+0.008}_{-0.011}$		
11 → 2	$(\frac{9}{2}^-)_1 \to (\frac{5}{2}^-)_1$	Pure $E2$		$17.6^{+2.9}_{-5.6}$		4.6			
11 → 3	$(\frac{9}{2}^-)_1 \to (\frac{7}{2}^-)_1$			$9.0^{+2.9}_{-3.8}$		2.2	$0.056^{+0.009}_{-0.018}$		1.7×10^{-3}
				or 106^{+19}_{-34}			or $0.012^{+0.004}_{-0.005}$		
12 → 0	$(\frac{5}{2}^-)_4 \to (\frac{3}{2}^-)_1$			$(3.7^{+22.3}_{-3.7}) \times 10^{-4}$		0.13	$(2.9^{+0.6}_{-0.9}) \times 10^{-3}$		0.0000
				or $0.83^{+0.17}_{-0.28}$			or $(3.1^{+1.3}_{-2.0}) \times 10^{-4}$		
12 → 2	$(\frac{5}{2}^-)_4 \to (\frac{5}{2}^-)_1$			$0.40^{+0.82}_{-0.40}$		0	$(5.5^{+1.3}_{-2.1}) \times 10^{-3}$		0.0000
				or $3.8^{+2.0}_{-2.3}$			or $(1.8^{+2.1}_{-1.8}) \times 10^{-3}$		

[a] Although this value has no meaning it is nevertheless reported by Castel *et al.*

tions and experimental values determined here for electromagnetic decay properties is given in Table IV. Due to the large body of data contained in the table it is probably helpful to employ the χ^2 function

$$\chi^2(N) = \frac{1}{N} \sum_{\kappa=1}^{N} \frac{(x_\kappa^{\text{th}} - x_\kappa^{\text{exp}})^2}{(\sigma_\kappa^{\text{exp}})^2} \tag{4}$$

as a figure of merit for the comparison of experimentally determined quantities with theoretical predictions. In Eq. (4) x_κ^{th}, x_κ^{exp}, and $\sigma_\kappa^{\text{exp}}$ represent the theoretical prediction, experimental value, and associated error, respectively, and N is the number of data compared. In the identification scheme of levels in Fig. 6, which is explicitly assumed in Table IV, the values of χ^2 for the two calculations are given in Table V. The comparison in the latter table also favors the description of ^{63}Cu afforded by the particle-core model. It should be noted that the χ^2 function defined in Eq. (4) does not take into account the number of free parameters employed in each calculation. The calculation of Castel *et al.*[7] contains only one such parameter, namely, the coupling strength in the interaction Hamiltonian, while the vibrating core parameters and quasiparticle amplitudes are derived from experiment. In the particle-core calculation of de Jager[8] the number of free parameters is considerably increased. This is, however, due only to the lack of sufficient experimental data on the electromagnetic properties of the five ^{62}Ni core states included in the calculation and the number of free parameters may be decreased as soon as these data become available.

The states of ^{63}Cu observed here or calculated in the theoretical work considered above are all negative parity states. Positive parity states may arise from the coupling of a negative parity state in the ^{62}Ni core to a proton in the f-p shell. In particular the coupling of the 3.76 MeV, 3^- state in ^{62}Ni to a $p_{3/2}$ proton is expected to lead to a $\frac{9}{2}^+$ level, predicted by Thankappan and True[1] at 3.29 MeV. This level should decay predominantly to the $(\frac{7}{2}^-)_1$ level which arises from the coupling of the 2_1^+ state in ^{62}Ni to a $p_{3/2}$ proton with a $B(E1;\ \frac{9}{2}^+ \to \frac{7}{2}^-)$ rate comparable to the $B(E1, 3_1^- \to 2_1^+)$ rate in ^{62}Ni. The corresponding $\frac{9}{2}^+$ state in ^{65}Cu

TABLE V. Overall comparison of theoretical predictions to experimental values of reduced transition probabilities in ^{63}Cu, through the χ^2 function.

Calculation	$\chi^2(N)$ N	$\chi^2(N)$ $B(E2)$	$\chi^2(N)$ N	$\chi^2(N)$ $B(M1)$
Castel *et al.* (Ref. 7)	19	120	16	95
de Jager (Ref. 8)	26	67	22	19

has now been definitely identified[23] at 2525.5 keV and is seen to decay to the $(\frac{7}{2}^-)_1$ state of ^{65}Cu with a 100% branch. In the compilation of Auble[9] a ^{63}Cu state at 2507± 10 keV is tentatively assigned $J^\pi = \frac{9}{2}^+$ on the basis of $l_p = 4$ observed in reaction data.[19] If this assignment is correct and the state is populated through inelastic scattering of protons, then its subsequent decay to the $(\frac{7}{2}^-)_1$ level should give rise to a γ ray with energy around 1183 keV. No such peak with significant statistics was observed in the spectra obtained here. It would be, however, interesting to investigate the J^π assignment and electromagnetic decay properties of this state through some other reaction since the above mentioned comparison to the corresponding $E1$ rate in ^{62}Ni would constitute a significant test for the weak-coupling model.

It is hoped that the substantial body of information on ^{63}Cu obtained in this research will trigger further theoretical investigation on the description of this nucleus and the accuracy of the weak-coupling scheme.

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