Mean lifetimes of levels in ^{59}Cu†

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The mean lifetimes of levels in ^{59}Cu below 3.6 MeV have been investigated with the Doppler-shift attenuation method and the ^{58}Ni(^{3}He,d)^{59}Cu reaction at 11.6 MeV. Scattered particles were detected in two E-ΔE telescopes at $\pm 55°$ with respect to the beam axis, in coincidence with γ rays observed at 90° in a 50-cm^3 Ge(Li) detector. New levels were observed at 3114 and 3615 keV. Mean lifetimes are reported for the following levels (energy in keV, lifetime in fs): 491 (830 ± 300), 914 (> 1600), 1399 (570 ± 240), 2266 (310 ± 140), 2324 (36 ± 5), 3043 (1150 ± 500), 3114 (20 ± 11), 3130 (10 ± 4), 3551 (< 15), 3580 (2400 ± 1400), and 3615 (< 35). The experimental results are compared with the predictions of a core-particle coupling calculation.

[NULCEAR REACTIONS ^{58}Ni(^{3}He,$d\gamma$), $E_{^3He}$ = 11.6 MeV; measured $E_\gamma(\theta)$, Doppler-shift attenuation, ^{59}Cu deduced levels, $T_{1/2}$. Enriched target, Ge(Li) detector.]

INTRODUCTION

Considerable experimental and theoretical work has recently been focused on the structure of nuclei in the mass region near doubly magic ^{56}Ni. The results of shell-model calculations of Glaudemans, de Voigt, and Steffens[1] have been compared with extensive data available for the Ni isotopes. For the odd Cu isotopes, Castel, Johnstone, Singh, and Steward[2] have described the low-lying states as $f_{7/2}$, $f_{5/2}$, $p_{3/2}$, and $p_{1/2}$ particles coupled to an even Ni core including pairing and anharmonic effects. This unified model gives reasonable agreement with data available ^{63,65}Cu. However, the lack of experimental information prevented Castel *et al.*[2] from making meaningful comparisons with ^{59,61}Cu.

In recent studies of the ^{58}Ni($\alpha,p\gamma$)^{61}Cu reaction,[3-5] the decay properties for levels of ^{61}Cu have been extensively investigated. Yet detailed properties of ^{59}Cu have remained largely unknown due primarily to the limited number of reactions which form this nucleus. Most experimental knowledge of ^{59}Cu has come from the study of the ^{58}Ni(^{3}He, d) reaction[6] and ^{58}Ni(d, n) reaction.[7,8] Until recently only a few γ-ray transitions observed in ^{58}Ni(p,γ) work[9-11] had been reported.

The present investigation was undertaken to study the decay properties of the levels of ^{59}Cu and to further assess the applicability of the unified model in this mass region. This paper reports the measurement of mean lifetimes with the Doppler-shift attenuation method for levels populated with the ^{58}Ni(^{3}He, d)^{59}Cu reaction. Accurate excitation energies were also determined for these levels. While the geometry of the experimental apparatus did not allow extraction of branching ratios, main decay modes could be identified. In a concurrent study of the ^{58}Ni(p,γ)^{59}Cu reaction,[12] branching ratios have been measured.

EXPERIMENTAL PROCEDURE AND ANALYSIS

An 11.6-MeV ^{3}He^{++} beam from the Triangle Universities Nuclear Laboratory FN tandem Van de Graaff was used to bombard a 325-μg/cm^2 target enriched to 99.9% in ^{58}Ni and backed with a 135-μg/cm^2 layer of gold. The target was prepared by vacuum deposition of first nickel and then gold onto a glass substrate. Rutherford scattering of a 3.0-MeV proton beam was used to determine the thickness of the layers.

The scattered particles from the ^{3}He induced reactions were detected in two E-ΔE counter telescopes located at θ_d = ±55° with respect to the beam. Each telescope consisted of a totally depleted 50-μm ΔE detector and a 300-μm detector. A 175-μm Mylar foil in front of each telescope was used to stop the elastically scattered ^{3}He particles. The γ rays coincident with particles were observed with a 50-cm^3 Ge(Li) detector located at θ_γ = 90° at a distance 8 cm from the target.

For each coincidence event five digital words were generated corresponding to the γ-ray energy, the ΔE energy, the full-particle energy $(E+\Delta E)$, the time signal, and the routing information identifying which telescope processed the event. A DDP-224 computer was used to collect digitized information, calculate the mass of the particle, and sort the γ-ray energy subject to various mass, particle energy, and time windows. Each event was also stored on magnetic tape for further detailed analysis.

The mass spectrum from coincident particles and the associated deuteron energy spectrum are shown in Fig. 1. The relative yield of the protons and deuterons, denoted in the mass spectrum with the letters *p* and *d*, respectively, gives a clear indication that particle identification is essential in a study of the weak $^{58}Ni(^{3}He, d)$ reaction. The broad low-mass shoulder of the proton mass peak is due to energetic protons which fail to stop within the *E* detector. With particle identification there was little background in the deuteron spectrum. The over-all deuteron energy resolution of ~250 keV was due primarily to straggling in the Mylar absorber. The observed ground-state group is due to random coincidences occurring within the 200-ns resolving time of the electronic system. During off-line reduction of the data stored on magnetic tape, the coincidence time window was reduced to ~20 ns.

γ-ray spectra were generated for each of the six prominent particle groups in Fig. 1. Of these groups only the 491-, 914-, and 1399-keV peaks are due to single levels; the other composite peaks are indicated in Fig. 1 with the excitation energies in keV of the strongly populated levels. Although the deuteron energy resolution was poor, the high resolution of the Ge(Li) detector enabled unique identification of the transitions associated with the γ rays. Particle windows set in energy regions for weakly populated levels at 1865, 1988, 2586, and 2714 keV produced γ-ray spectra with no evidence for transitions from these levels.

The Doppler shifts were determined from the γ-ray energy shift between the spectra in coincidence with the two counter telescopes. These energies were obtained from first-moment calculations for peaks in the coincidence spectra and calibrated with accurately known lines in the ^{56}Co and ^{57}Co spectra obtained before and after the coincidence measurements. The experimental Doppler-shift attenuation factors $F(\tau)$ were computed as the ratio of the observed Doppler shift to the expected full shift, as calculated from the reaction kinematics. Possible corrections to the full Doppler shift due to finite-geometry effects are known to be small in experimental geometries similar to those used here[13] and were therefore neglected in the present analysis.

The theoretical $F(\tau)$ values were calculated with the code FTAU[14] which is based on the work of Blaugrund[15] and the stopping-power theories of Lindhard, Scharff, and Schiøtt.[16] The electronic stopping parameter was obtained from the experimental data for the slowing of Cu ions in carbon.[17] The total error in the mean lifetimes was determined by quadratically adding the statistical error, the error derived from an assumed uncertainty of 20% in the electronic stopping power of the target and backing, and the error due to a 10% uncer-

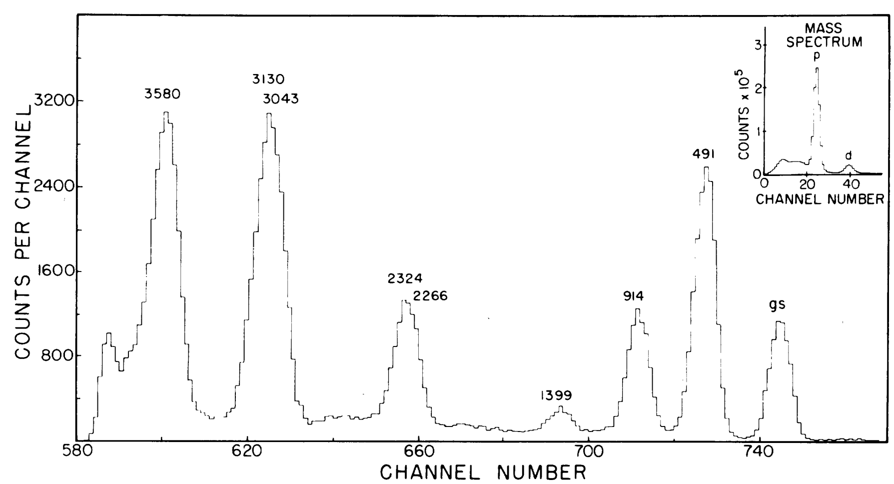

FIG. 1. Mass and deuteron spectra obtained at 55° in coincidence with γ rays in the $^{58}Ni(^{3}He, d\gamma)^{59}Cu$ reaction at 11.6 MeV. The particle spectrum is subject to a mass window selecting events within the deuteron peak labeled *d* in the mass spectrum. Prominent particle groups are labeled with the excitation energy in keV.

tainty in the target thickness. In all cases the total error is dominated by the statistical part.

EXPERIMENTAL RESULTS

The excitation energies, attenuation factors, and lifetimes obtained in the present study are listed in Table I. The excitation energies determined in (p,γ) work[12] are compared with the present results in columns one and two. The energies and relative intensities of the observed decay branches are given in columns three and four. Again for comparison, branching ratios from capture work[12] are listed in column five. Except for levels populated only in a decay cascade, attenuation factors for each transition are given in column six. For levels where more than one branch was observed, lifetimes in the last column were determined from the weighted attenuation factor indicated in column seven. The decay properties of Table I and the results of (p,γ) measurements[12] which populate states not observed in the present study are summarized in Fig. 2.

To indicate the general quality of the data, portions of γ-ray spectra measured in coincidence with particle groups are shown in Figs. 3–6. A detailed discussion of individual levels follows in this section.

A. 491-, 914-, and 1399-keV levels

Figure 3 shows the coincidence γ-ray spectra for the first three excited states. For the first and third levels, the experimental $F(\tau)$ values of (9 ± 3) and $(13\pm 5)\%$ imply lifetimes of 830 ± 300 and 570 ± 240 fs, respectively. Only a lower limit of 1600 fs may be inferred for the second excited state. Spins and parities for these three levels have been established in previous work.[6-8]

B. 2266- and 2324-keV levels

Peaks corresponding to the ground-state γ-ray branches for the decay of levels near 2.3 MeV are

TABLE I. Decay properties of the low-lying levels of ^{59}Cu observed in this work.

E_x (keV) (^{3}He,d) [a]	E_x (keV) (p,γ) [b]	E_γ [a] (keV)	Relative intensities [a] (%)	Branching ratios [b] (%)	$F(\tau)$ (%)	$\langle F(\tau)\rangle$ (%)	τ (fs)
491.0 ± 0.1	491.5 ± 0.1	491.0 ± 0.1	100	100	9 ± 3	9 ± 3	830 ± 300
913.8 ± 0.1	914.1 ± 0.1	913.8 ± 0.1	100	98.5	1 ± 3	1 ± 3	>1600
1398.8 ± 0.2	1398.8 ± 0.1	1398.8 ± 0.2	93	89	13 ± 5	13 ± 5	570 ± 240
		484.3 ± 0.4	7	11	24 ± 15		
1865.2 ± 0.2 [c]	1865.1 ± 0.1	1865.7 ± 0.3	35	25			
		951.3 ± 0.4	47	49			
		465.8 ± 0.2	18	26			
1987.8 ± 0.5 [c,d]	1988.1 ± 0.2						
2265.7 ± 0.4	2266.0 ± 0.2	2265.9 ± 0.6	49	60	29 ± 11	22 ± 8	310 ± 140
		1755.5 ± 0.5	51	40	15 ± 11		
2323.8 ± 0.2	2323.8 ± 0.2	2324.0 ± 0.2	88	74	72 ± 3	72 ± 3	36 ± 5
		1409.1 ± 0.4	12	17	67 ± 12		
2587.2 ± 0.6 [c,d]	2586.3 ± 0.4						
3042.8 ± 0.2	3042.5 ± 0.3	1644.2 ± 0.1	73	76	7 ± 3	7 ± 3	1150 ± 500
		1177.4 ± 0.2	25	22	9 ± 7		
		455.6 ± 0.6	2	2	−48 ± 61		
3114.0 ± 0.5		3114.0 ± 0.5	100		84 ± 8	84 ± 8	20 ± 11
3129.5 ± 0.2		3129.5 ± 0.2	45		88 ± 3	91 ± 3	10 ± 4
		2638.6 ± 0.3	23		98 ± 5		
		2215.7 ± 0.3	32		92 ± 5		
3550.5 ± 1.3		3550.5 ± 1.3	100		105 ± 17	105 ± 17	<15
3580.1 ± 0.2		3579.9 ± 0.3	5		3 ± 4	4.1 ± 2.4	2400 ± 1400
		2666.3 ± 0.2	34		6 ± 4		
		2182.3 ± 0.4	14		1 ± 9		
		1714.8 ± 0.4	11		−3 ± 12		
		1592.3 ± 0.4	10		16 ± 13		
		1314.0 ± 0.2	23		3 ± 6		
		536.4 ± 1.1	3		19 ± 98		
3614.9 ± 1.0		3614.9 ± 1.0	100		87 ± 14	87 ± 14	<35

[a] This study.
[b] Reference 12.
[c] Observed in cascade only.
[d] Very weak intensity of γ rays from level. Energy determined by transitions to level.

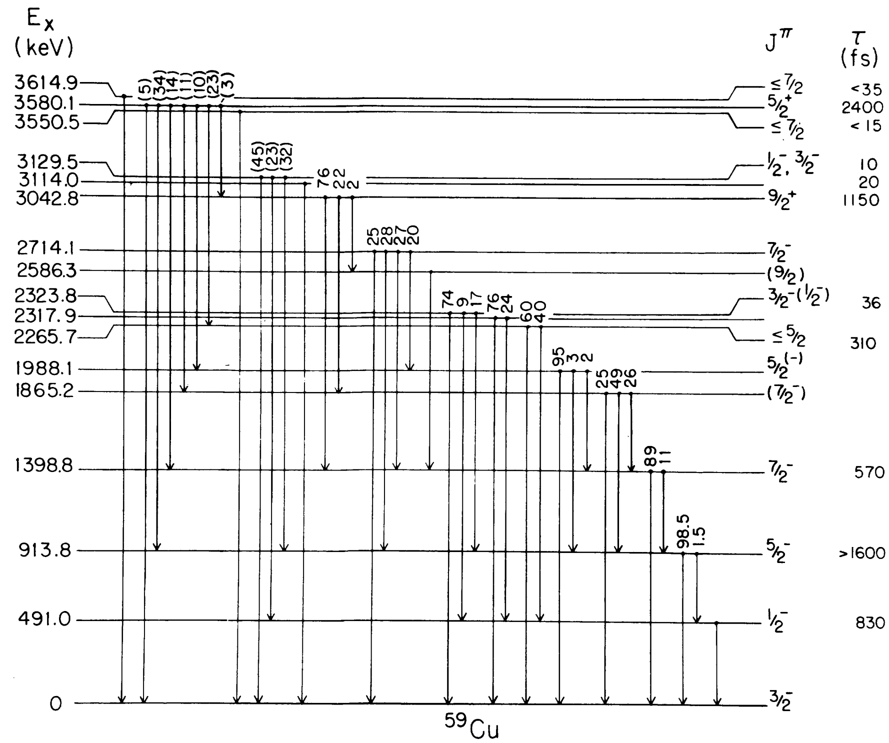

FIG. 2. Decay properties for levels of ^{59}Cu below 3.6 MeV. The excitation energies given in keV at the left are taken from this work or (p,γ) work (see Ref. 12 and Table I). Lifetimes measured in the present study are indicated in fs in the column at the right. The unbracketed branching ratios are from Ref. 12. Numbers in parentheses are relative intensities from this experiment. The J^{π} assignments are from Refs. 6–8, 12, and this work.

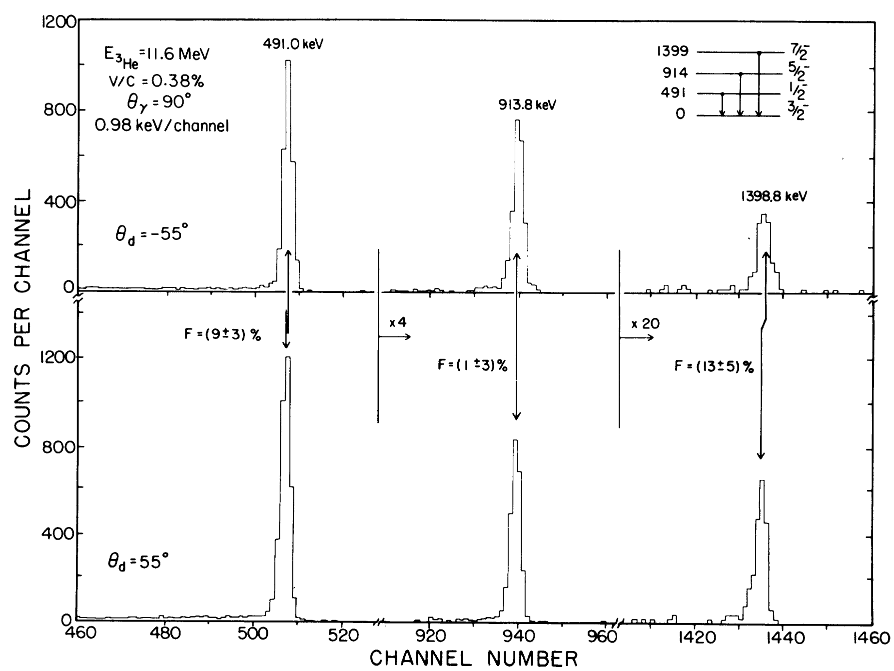

FIG. 3. Portions of γ-ray spectra obtained with the 50-cm^3 Ge(Li) at 90° to the right of the beam in coincidence with deuterons populating the 491-, 914-, and 1399-keV levels in ^{59}Cu. The upper spectrum is in coincidence with deuterons scattered to the left of the beam and the lower spectrum is in coincidence with deuterons scattered to the right. Note that the peaks are scaled separately for each γ ray. The peak centroids are indicated with the joined arrows beside which are given the experimental attenuation factors.

shown in Fig. 4. Any significant population of a level at 2318 keV recently observed in (p, γ) work[12] would result in a γ-ray doublet near 2324 keV which could be resolved in one of the Doppler-shifted coincidence spectra. As Fig. 4 shows, apparently only the 2324-keV level is excited. It is more difficult to determine whether a tentative new level at 2264 keV, which only decays to the ground state,[12] is populated since the resulting ~2-keV doublet could not be resolved after Doppler broadening. However, the close agreement of the energy of the ground-state crossover branch with the unambiguous sum of the cascade transition via the first excited state suggest that only the 2266-keV level is populated. The experimental $F(\tau)$ values for the ground-state transitions were statistically averaged with the other observed branches (see Table I) to yield lifetimes of 310 ± 140 and 36 ± 5 fs for the 2266- and 2324-keV levels, respectively.

In a distorted-wave Born-approximation (DWBA) analysis of the ^{58}Ni(^{3}He, d) angular distributions, Pullen and Rosner[6] have assigned $l = 1$ to the transition populating the 2324-keV level. A $\frac{1}{2}^-$ assignment would result in a somewhat large $E2$ enhancement of 55 Weisskopf units (W.u.) for the branch to the $\frac{5}{2}^-$ second excited state. A J^π assignment of $\frac{3}{2}^-$ is therefore favored for this level although $\frac{1}{2}^-$ cannot be rigorously excluded. For the 2266-keV level, the lifetime measurement restricts the multipolarity for γ-ray transitions to be ≤ 2 so that the observed decay to a $\frac{1}{2}^-$ state limits the spin to be $\leq \frac{5}{2}$.

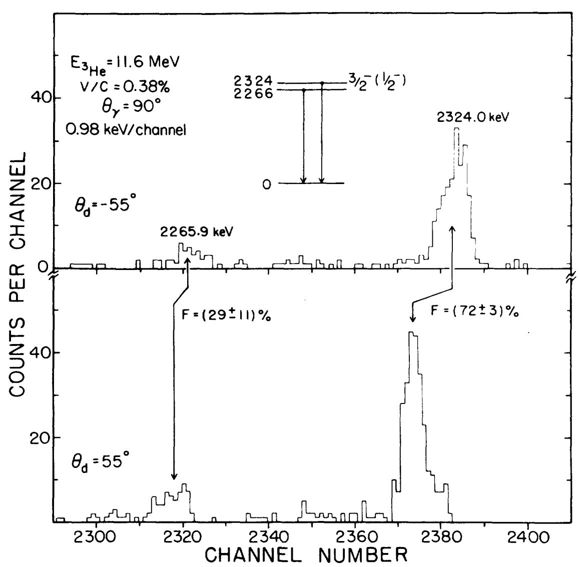

FIG. 4. The γ-ray spectrum obtained in coincidence with deuterons leading to the 2266- and 2324-keV levels in ^{59}Cu. If the 2318-keV level were populated, the ground-state transition for this level would give rise to a doublet or shoulder with the 2324-keV peak in the upper spectrum if the 2318-keV γ ray was not Doppler-shifted, in the lower spectrum if fully shifted, or possibly both for intermediate shifts. Since none of these effects are apparent, it is assumed than any population of the 2318-keV level may be neglected.

C. 3043-, 3114-, and 3130-keV levels

Figure 5 shows portions of coincidence γ-ray spectra associated with levels near 3.1 MeV. The $\frac{9}{2}^+$ level at 3043 keV primarily decays to the two low-lying $\frac{7}{2}^-$ states. The strong 1644-keV transition yields an $F(\tau)$ value of $(7 \pm 3)\%$ and a lifetime of 1150 ± 500 fs. The ground-state transition from the 3130-keV level is one of three branches observed for this state. From the weighted average of the $F(\tau)$ measurements, a lifetime of 10 fs is implied. Unfortunately, the decay properties are not sufficient to discriminate between the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ assignments established from angular distributions of proton-transfer reactions.[6-8]

The peak below the 3130-keV γ ray in Fig. 5 is assigned to the ground-state transition from a proposed new level at 3114 keV with a lifetime of 20 $\pm$ 10 fs. The restriction on the multipolarity of the γ decay implied by the short lifetime, and observation of the transition to the $\frac{3}{2}^-$ ground state, require the spin for this level to be $\leq \frac{7}{2}$.

D. 3550-, 3580-, and 3615-keV levels

Spectra for the ground-state transitions for excited states near 3.6 MeV are shown in Fig. 6.

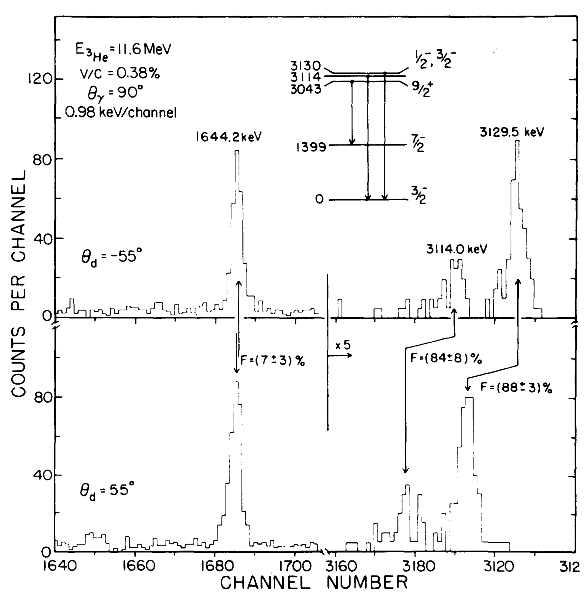

FIG. 5. Portions of γ-ray spectra in coincidence with deuterons populating the 3043-, 3114-, and 3130-keV levels in ^{59}Cu.

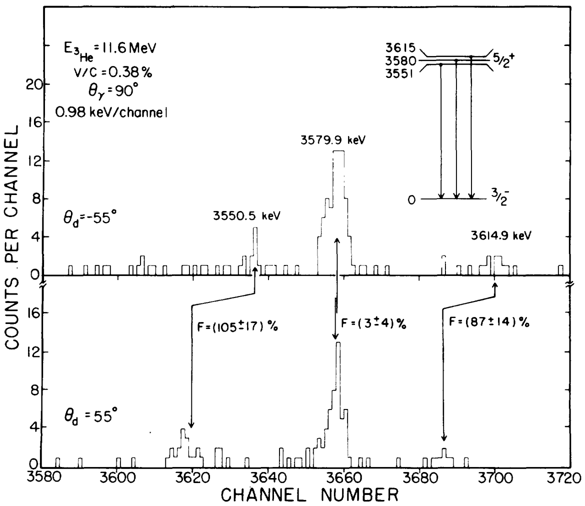

FIG. 6. The coincidence γ-ray spectra for ground-state transitions from the 3551-, 3580-, and 3615-keV levels in ^{59}Cu. The 3551- and 3615-keV γ rays are fully Doppler-shifted within errors in contrast to the nearly unshifted 3580-keV γ ray.

TABLE II. Comparisons of experimental lifetimes and branching ratios with theoretical predictions. Theoretical predictions (shown in parentheses) were calculated from the $B(M1)$ and $B(E2)$ values of Castel *et al.* (Ref. 2) using the experimental transition energies.

J^π	E_x (keV)	τ [a] (ps)	Branching ratios [b] (%) $\frac{3}{2}_1$	$\frac{1}{2}_1$	$\frac{5}{2}_1$	$\frac{7}{2}_1$
$\frac{1}{2}_1^-$	491	0.83	100			
		(0.34)	(100)			
$\frac{5}{2}_1^-$	914	>1.6	98.5	1.5		
		(15)	(99)	(1)		
$\frac{7}{2}_1^-$	1399	0.57	89		11	
		(0.67)	(64)		(36)	
$\frac{7}{2}_2^-$	1865		25		49	26
		(0.65)	(3)		(95)	(2)
$\frac{5}{2}_2^-$	1988		95	3	2	
		(0.15)	(84)	(4)	(12)	
$\frac{3}{2}_2^-$	2324	0.036	74	9	17	
		(0.037)	(46)	(11)	(43)	

[a] Present study.
[b] Reference 12.

Within statistical errors, the 3580-keV γ ray is unshifted. But when combined with the results of six other branches, an average $F(\tau)$ value of (4.1 ± 2.4)% is obtained, implying a lifetime of 2.4 ± 1.4 ps. Earlier (^{3}He, d) work[6] has established a l value of 2 for this level resulting in a $\frac{3}{2}^+$ or $\frac{5}{2}^+$ assignment. A spin of $\frac{3}{2}^+$ would require that the branch to the nearby $\frac{9}{2}^+$ level at 3043 keV would be an $M3$ transition with an enhancement of ~10^8 W.u., and therefore a $\frac{5}{2}^+$ assignment is made for this level.

The two weak peaks seen in the spectra of Fig. 6 are due to ground-state transitions from levels at 3550 and 3615 keV. The lower level has been observed in spectrograph work,[6] but the upper level has not been previously reported. Within errors both γ-ray peaks are fully shifted and give upper limits of 15 and 35 fs for lifetimes of the 3550- and 3615-keV levels, respectively. As with the 3114-keV level, the decay properties indicate $J \leq \frac{7}{2}$ for both levels.

DISCUSSION

With the experimental information now available for ^{59}Cu, it is possible to make meaningful comparisons with the theoretical core-particle coupling calculation of Castel *et al.*[2] In this treatment for odd Cu nuclei, the core properties, particle occupation numbers, and particle energy spacings were derived from experimental data leaving the core-particle interaction strength as the only adjustable parameter. The core-particle strengths resulting from the calculations for ^{61,63,65}Cu were used to determine the strength for a parameter-free prediction for ^{59}Cu. The theoretical energy levels agree well with the experimental energies for the lowest three states but generally fall below measured values for the higher excited states.

Using the experimental transition energies, the predicted lifetimes and branching ratios can be obtained from the $B(M1)$ and $B(E2)$ values of Castel *et al.*[2] A comparison of the experimental and theoretical results is made in Table II, where the experimental numbers are shown directly above the corresponding theoretical predictions in parentheses. The majority of these predictions fall within a factor of 2 of the measured value. Only the calculations for the second $\frac{7}{2}^-$ level give poor agreement with experiment. For at least the lower levels of ^{59}Cu the core-particle coupling model then appears relatively successful. Measurements of the mixing ratios for a number of these transitions would allow more detailed conclusions.

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[1]P. W. M. Glaudemans, M. J. A. de Voigt, and E. F. M. Steffens, Nucl. Phys. A198, 609 (1972).
[2]B. Castel, I. P. Johnstone, B. P. Singh, and K. W. C. Steward, Can. J. Phys. 50, 1630 (1972).
[3]D. G. Sarantities, J. H. Barker, N. H. Lu, E. J. Hoffman, and D. M. Van Patter, Phys. Rev C 8, 629

(1973), and references therein.
[4]G. H. Dulfer, B. O. ten Brink, T. J. Ketel, A. W. B. Kalshoven, and H. Verheul, Z. Phys. 251, 416 (1972).
[5]B. Heusch, B. Čujec, R. Dayras, J. N. Mo, and I. M. Szöghy, Nucl. Phys. A169, 145 (1971).
[6]D. J. Pullen and B. Rosner, Phys. Rev. 170, 1034 (1968).
[7]J. Bommer, H. Fuchs, K. Grabisch, H. Kluge, W. Ribbe, and G. Röschert, Nucl. Phys. A199, 115 (1973).
[8]A. Marusak, Oak Ridge National Laboratory Report No. ORNL-TM-2472, 1969 (unpublished).
[9]S. Maripuu, J. C. Manthuruthil, and C. P. Poirier, Phys. Lett. 41B, 148 (1972).
[10]I. Fodor, I. Szentpétery, and J. Szücs, Phys. Lett. 32B, 689 (1970).
[11]J. W. Butler and C. R. Gossett, Phys. Rev. 108, 1473 (1957).
[12]D. M. Van Patter, F. Rauch, and E. Obst, Bull. Am. Phys. Soc. 18, 654 (1973); D. M. Van Patter, private communication.
[13]G. A. P. Engelbertink and G. van Middlekoop, Nucl. Phys. A138, 588 (1969).
[14]C. E. Ragan, III, R. V. Poore, N. R. Roberson, G. E. Mitchell, and D. R. Tilley, Phys. Rev. C 1, 2012 (1970).
[15]A. E. Blaugrund, Nucl. Phys. 88, 501 (1966).
[16]J. Lindhard, M. Scharff, and H. E. Schiøtt, K. Dan. Vidensk. Selsk., Mat.-Fys. Medd. 33, No. 14 (1963).
[17]P. Hvelplund and B. Fastrup, Phys. Rev. 165, 408 (1968).