Low-Lying Excited States of ^{64}Cu and ^{66}Cu Populated in Thermal-Neutron Capture Reactions*

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The level structures of the odd-odd nuclei ^{64}Cu and ^{66}Cu have been studied by use of the thermal-neutron-capture reactions ^{63}Cu$(n,\gamma)^{64}$ Cu and ^{65}Cu$(n,\gamma)^{66}$Cu. Capture γ-ray spectra from isotopically separated targets have been studied in the approximate energy intervals 100–1500 keV and 5000–8000 keV with a Li-drifted Ge spectrometer system. A number of new transitions are reported. The levels obtained from these data are compared with those excited by the corresponding (d,p) reactions. γ-γ coincidence measurements with Ge(Li) and NaI detectors have also provided considerable information about the low-lying level structures of these nuclei. Tentative spin assignments for the excited states below 1 MeV are proposed on the basis of the γ-ray decay modes of these levels. The low-lying excited states of ^{64}Cu and ^{66}Cu are discussed in terms of $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ proton-neutron configurations.

I. INTRODUCTION

THE low-lying excited states of the odd-odd nuclides ^{64}Cu and ^{66}Cu have been the subject of several experimental investigations over the last few years. Despite these efforts, many details of the two level structures are either unknown or poorly established. The (d,p) stripping investigations of de Figueiredo *et al.*[1] have established the excitation energies of many levels up to ~3800 keV in both nuclides. However, their studies did not include proton angular distributions, and therefore specifications of the angular momenta of these states are lacking. Previous thermal-neutron capture γ-ray studies[2–7] have revealed some interesting and useful features but, in the main, have not possessed the necessary detail required to specify the excitation energies or the properties of many of these states. Several investigations of the capture γ-ray spectrum from a natural copper target have been reported.[2,6] The interpretation of these results is complicated by the fact that neither stable isotope completely dominates the capture reaction in natural copper. In an early study, Sklyarevskii *et al.*[7] used a scintillation spectrometer to study the spectra from isotopically separated Cu targets. Preliminary results from the present investigation have also been reported previously.[8]

As a result of the statistical nature of the thermal-neutron-capture state and the large number of possible primary and secondary γ-ray cascades proceeding from it to the low-lying excited states of the product nucleus, the population of these states is largely independent of their character. Thus, this reaction can be expected to reveal levels of either parity and with spins that may be significantly different from that of the capture state, without regard to their detailed configurations. The catholic features of this process afford the opportunity for population of states seen in (d,p) or other charged-particle reactions as well as those levels not observed in one or more of these reactions because of restrictions based on angular momentum, spin, etc. Therefore, detailed experimental investigations of the (n,γ) process can provide a valuable complement and extension of the information obtained from studies of other reactions.

With respect to the shell-model interpretation of the low-lying excited states of ^{64}Cu$_{35}$ and ^{66}Cu$_{37}$, regional systematics suggest the dominance of configurations based on the coupling of a $p_{3/2}$ proton to $f_{5/2}$, $p_{1/2}$, and $p_{3/2}$ neutron orbitals. It would be expected that the lowest seniority couplings of these orbitals should give rise to level structures in ^{64}Cu and ^{66}Cu that are quite similar. It was felt that a comprehensive examination of the levels of these nuclides by means of more refined (n,γ) techniques would provide new information concerning these low-lying states and that this could be of effective aid in elucidating their detailed character.

The present paper describes the results of a study of the low-lying excited states of ^{64}Cu and ^{66}Cu populated

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[3] J. Vervier, Nucl. Phys. **26**, 10 (1961); G. A. Bartholomew and J. Vervier, *ibid.* **50**, 209 (1964).

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[8] A preliminary report of these investigations was presented at the American Physical Society meeting, New York, January, 1967: E. B. Shera, H. H. Bolotin, and H. J. Fischbeck, Bull. Am. Phys. Soc. **12**, 128 (1967).

in the thermal-neutron-capture γ-ray reactions ^{63}Cu$(n,\gamma)^{64}$Cu and ^{65}Cu$(n,\gamma)^{66}$Cu. This investigation included the study of primary and secondary transitions by means of singles and coincidence γ-ray spectroscopic techniques which employed both Ge(Li) and NaI(Tl) detectors.

II. EXPERIMENTAL METHODS

A. High-Energy Primary Transitions

In studies of the high-energy primary transitions, samples were installed at the center of a tangential-through-tube facility in the Argonne CP-5 reactor. The thermal-neutron flux at the sample position was $\sim 3\times 10^{13}$ neutrons/cm^2 sec. A detailed description of this facility has been published elsewhere.[9] High-purity graphite sample containers were used. These graphite holders provide the advantages of low capture cross section and virtual freedom from contaminating background. The only two high-energy transitions that result from capture in the sample holder are at 4945 and 3684 keV, and these provide convenient γ-ray energy standards. Nitrogen contamination was effectively removed by a continuous flow of He gas through the reactor tube, while other sources of background were removed or materially reduced by appropriate shielding. The Ge(Li) detector employed has a sensitive volume of ~ 4 cm^3 and an energy resolution width of ~ 6 keV at a deposited energy of 6 MeV.

The data were collected in a 4096-channel pulse-height analyzer. The entire capture γ-ray spectrum was accumulated at the same time; no electronic bias arrangement was used. Digital gain stabilization was applied to the analyzer ADC to obviate electronic drifts. No line broadening or gain shifts were observed for runs lasting in excess of 24 h.

To establish accurate γ-ray energies, a series of pulser calibration lines (spaced at ~ 60-channel intervals) was fed into the analyzer before and after each sample run. A sample spectrum was accumulated during the pulser-calibration procedure and the digital gain stabilizer was locked on the same Cu γ-ray peak as in the spectral runs. This procedure maintains the same correspondence between energy and channel in both calibration and sample runs. A high-precision digital voltmeter was used to record the dc voltage from which the calibration pulse was derived. This arrangement provides an accurate determination of each of the calibration pulse heights.

The local nonlinearity of the electronic system was determined by fitting the positions of the pulser calibration peaks in every pulse-height region to a polynomial of second order. Contact potentials and/or other effects produced a small but detectable digital voltmeter reading at zero pulse height. This zero correction required the use of at least two accurately known energy standards to define the linear relationship between pulse height and energy. For this purpose, three transitions whose energies have been accurately determined, and which appear in all spectra obtained, were employed—namely, the 4945.4- and 3684-keV lines[10] from the ^{12}C$(n,\gamma)^{13}$C and the 1293.4-keV line[11] of ^{41}Ar.

The centroids of the calibration and γ-ray peaks were accurately determined with the aid of a variable-metric minimization[12] computer program which least-squares-fitted a Gaussian function to the observed peaks. These techniques permit the energies of the stronger and/or more isolated γ-ray transitions to be determined with an accuracy of ~ 1 keV.

In interpreting the observed singles spectra, it was necessary to take into account double- and single-escape peaks, as well as the full-energy peaks. The detection efficiency for the double-escape peak was obtained empirically as a function of γ-ray energy by comparing the areas of the double-escape peaks of the high-energy transitions from a nitrogen sample with the known[13] intensities of these transitions. The double-escape/single-escape intensity ratio was found to be ~ 10, independent of energy. The ratio of the intensity of the double-escape to that of the full-energy peak showed a monotonic variation from ~ 10 at $E_\gamma = 4$ MeV to ~ 20 at $E_\gamma = 6$ MeV. Some regions of these spectra were inconveniently complex because of the close juxtaposition of the various types of lines associated with different γ rays. To clarify the analysis of these regions, the detector system was also operated in a pair-spectrometer mode in which two 4×4-in. NaI(Tl) detectors were mounted 180° apart and straddled the Ge(Li) detector. The relative inefficiency inherent in this particular pair-spectrometer arrangement reduced the counting rate in the double-escape peaks to $\sim 5\%$ of that obtained in the singles mode. Hence, the pair-spectrometer data were used primarily for clarification; the singles spectra were used for the primary analysis.

B. Low-Energy Transitions

The thermal-column through-port facility at the Los Almos Omega West Reactor was used to record the low-energy spectra from thermal-neutron capture. This facility has been described in detail elsewhere.[14] An ~ 1-cm^3 Ge(Li) detector, surrounded by a large NaI(Tl) annulus and operated in the anticoincidence mode, was used to detect the low-energy transitions. The spectra obtained with this arrangement are substantially free of underlying Compton distributions.

[9] G. E. Thomas, D. E. Blatchley, and L. M. Bollinger, Nucl. Instr. Methods (to be published).

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[14] E. Jurney, H. T. Motz, and S. Vegors, Nucl. Phys. **A94**, 351 (1967).

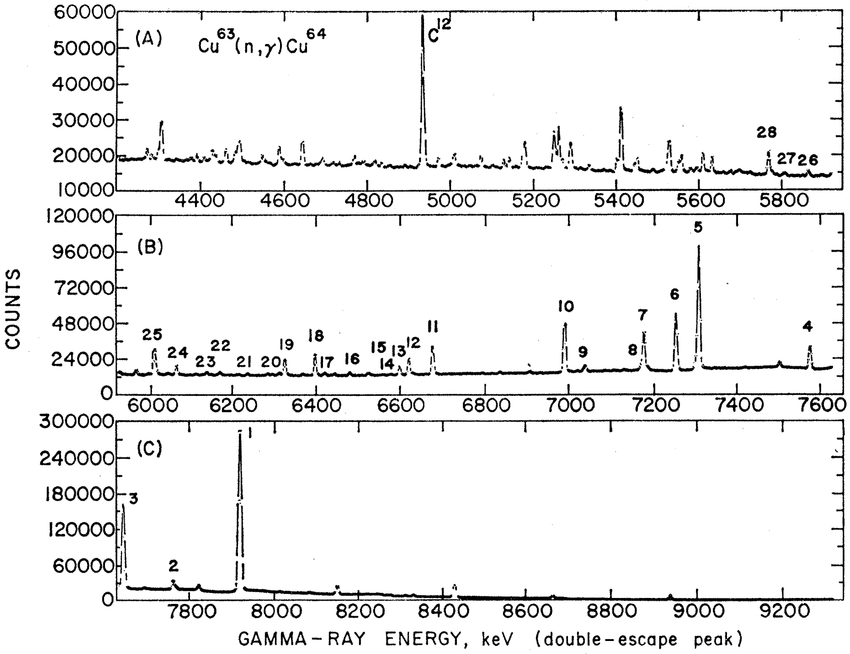

FIG. 1. Typical singles high-energy γ-ray spectrum observed for the $^{63}Cu(n,\gamma)^{64}Cu$ reaction in a sample enriched in ^{63}Cu. The abscissa is the γ-ray energy to be associated with the double-escape peaks in the spectrum. The numbered double-escape peaks correspond to the entries in Table I.

The low-energy detection efficiency of the spectrometer has been determined from measurements on a series of calibrated radioactive sources. The measured intensity of the 411-keV ^{198}Hg line from a weighed Au foil which was irradiated and counted at the normal target position was then used to calculate the partial cross sections of the copper lines. The energy resolution width of the detector was typically 3.7 keV at a γ-ray energy of 662 keV.

C. γ-γ Coincidence Studies

In order to remove the ambiguities which may be present in any level scheme based solely on the singles high-energy and low-energy spectra, coincidences between high- and low-energy transitions and between low- and low-energy transitions were studied with the capture-γ-ray coincidence facility at Los Alamos. This facility, which uses an external neutron beam from the Omgea West Reactor, has been described in detail

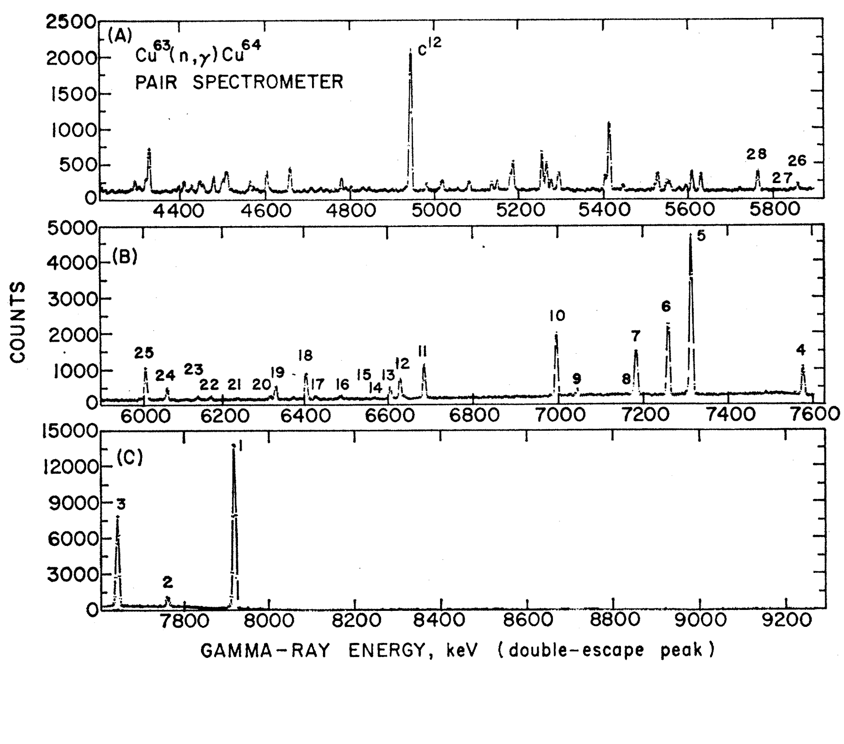

FIG. 2. Pair-spectrometer high-energy γ-ray spectrum observed for the $^{63}Cu(n,\gamma)^{64}Cu$ reaction in a sample enriched in ^{63}Cu. Only double-escape peaks are present in this spectrum. The numbered peaks correspond to the γ rays listed in Table I and Fig. 1.

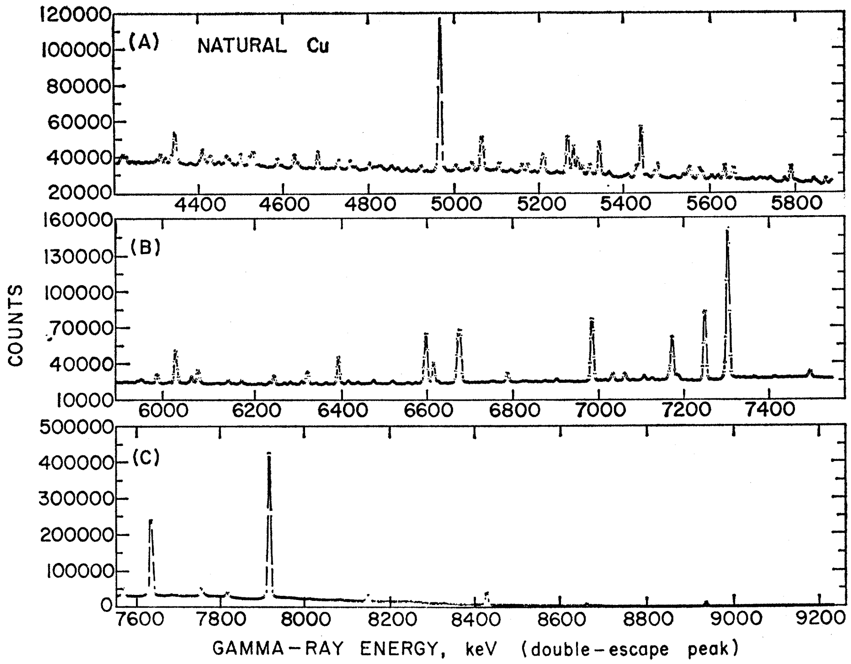

FIG. 3. Typical singles high-energy γ-ray spectrum observed in a natural copper target. The abscissa is the γ-ray energy to be associated with the double-escape peaks in the spectrum.

in a previous paper.[15] The coincidence detection system employs a 1.5-cm^3 Ge(Li) detector in conjunction with a 3×3-in. NaI(Tl) scintillator. In those coincidence studies that involve high-energy primary transitions, the Ge(Li) branch of the coincidence arrangement was used to detect the high-energy transitions. This method is more selective of the state populated directly than would be the case if the poorer-resolution NaI(Tl) detector viewed the high-energy portion of the γ-ray spectrum. With this selectivity imposed on the high-energy transitions, the resolution of the scintillator is adequate in the low-energy portion of the spectrum. A 400×400-channel two-parameter magnetic-tape storage system was used to record the coincidence spectra. The primary mode of data processing was to impose pulse-height restrictions on the high-energy primary transitions and scan the tape for the low-energy spectrum in coincidence with the selected transition. A coincidence resolving time $2\tau = 50$ nsec was employed. In none of the measurements was the true/chance coincidence ratio less than 10.

The coincidence studies between high- and low-energy transitions required roughly three weeks, during which time periodic gain and calibration checks were made to assure the stability and reproducibility of the spectra. The investigations of coincidences between low-energy γ rays required only 2–3 days. All coincidence spectra were recorded in segments of 8×10^4 events, and the line

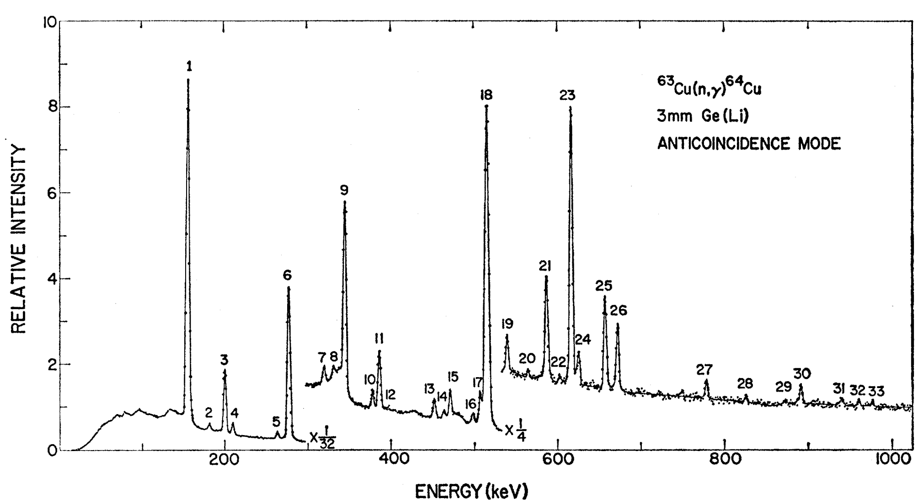

FIG. 4. Low-energy portion of the γ-ray spectrum from the $^{63}Cu(n,\gamma)^{64}Cu$ reaction, obtained with a Ge(Li) detector. The detector was operated inside a large anticoincidence NaI annulus (Sec. II B).

[15] E. B. Shera and D. W. Hafemeister, Phys. Rev. **150**, 894 (1966).

positions were required to be reproducible before these segments were summed to obtain the final composite spectra. The coincidence spectra were sorted and analyzed with the Los Alamos MANIAC computer.

III. EXPERIMENTAL RESULTS

A. ^{63}Cu$(n,\gamma)^{64}$Cu

Figure 1 shows a typical high-energy singles γ-ray spectrum obtained for the reaction ^{63}Cu$(n,\gamma)^{64}$Cu with a sample enriched[16] to 99.6% in ^{63}Cu. Several regions below 6 MeV were sufficiently complex to require the clarification provided by the pair-spectrometer spectrum (Fig. 2) taken over the same energy range. In this latter arrangement, the spectrum is composed almost exclusively of double-escape peaks. Although a few regions still contain a number of closely spaced lines, essentially all ambiguities in the singles spectrum are removed by the absence of single-escape and full-energy peaks. The spectrum displayed in Fig. 3 is that obtained with a natural Cu sample. The mass of the natural sample was specifically chosen to contain an amount of ^{63}Cu equal to that present in the highly enriched sample of ^{63}Cu. Thus, lines resulting from capture in ^{63}Cu are of the same relative intensity in both sample runs. All lines ascribed to the ^{63}Cu$(n,\gamma)^{64}$Cu reaction were present in the spectra of both the natural and the enriched targets. The neutron binding energy of ^{64}Cu was determined to be 7916±1 keV. This value is in excellent agreement with the value 7916±8 keV obtained from the (d,p) Q value reported by de Figueiredo *et al.*[1] and the mass-adjusted value of 7916±4 keV given by Mattauch *et al.*[17]

The energies and intensities of the observed high-energy transitions are listed in Table I. This table also compares the level energies derived from the high-energy transitions (assumed to be primary) with the

TABLE I. High-energy capture γ rays from the ^{63}Cu$(n,\gamma)^{64}$Cu reaction. The ^{63}Cu(d,p) excitation energies are from de Figueiredo *et al.*[a]

Line No.	γ-ray energy (keV)	Partial cross section (mb)	Excitation energy (keV)	Excitation energy for Cu$^{63}(d,p)$
1	7916±1	1230 ±250	0	0
2	7756±1	64 ± 13	160	159
3	7637±1	670 ± 13	279	277
4	7571±1	70 ± 14	345	343
...	...	...	...	360
...	...	...	...	574
5	7307±1	420 ± 84	609	607
6	7252±1	200 ± 40	664	664
7	7176±1	123 ± 24	740	743
8	7168±2	17 ± 3.5	748	...
9	7036±2	27 ± 7.4	880	877
...	...	...	...	894
10	6988±1	173 ± 34	928	925
11	6674±1	110 ± 30	1242	1239
12	6628±2	7 ± 2.0	1288	1295
13	6617±1	64 ± 13	1299	...
14	6594±1	34 ± 7	1322	...
...	...	...	...	1352
15	6553±3	5.3± 1.6	1363	...
16	6476±2	11 ± 2.2	1440	1437
...	...	...	...	1464
17	6418±2	10 ± 2.0	1498	...
18	6394±1	87 ± 17	1522	1519
...	...	...	...	1547
19	6322±1	70 ± 14	1594	1592
20	6309±2	11 ± 2.2	1607	...
21	6233±2	8.3± 2.5	1683	1682
...	...	...	...	1704
22	6169±2	14 ± 2.2	1747	...
23	6136±2	14 ± 2.2	1780	1779
24	6062±1	42 ± 10	1854	1852
25	6010±1	136 ± 27	1906	1904
...	...	...	...	1939
...	...	...	...	2020
26	5866±2	11 ± 2.3	2050	2053
27	5824±2	13 ± 2.4	2092	...
28	5771±1	45 ± 9	2145	2145

[a] Reference 1.

TABLE II. Low-energy γ rays from the reaction ^{63}Cu$(n,\gamma)^{64}$Cu.

Line No.	Energy (keV)	Partial cross section (mb)	Assignment	Confidence
1	159.2±0.5	470 ±100	159 → 0	a
2	184.6±0.5	11 ± 4	344 → 159	b
3	202.7±0.5	156 ± 30	362 → 159	b
4	212.1±0.5	27 ± 6	574 → 362	b
5	264.9±0.5	32 ± 10	609 → 344	c
6	278.1±0.5	870 ±175	278 → 0	a
7	320.0±0.6	28 ± 6	663 → 344	c
8	330.2±0.6	44 ± 11	609 → 278	a
9	343.8±0.5	200 ± 40	344 → 0	a
10	376.8±0.7	24 ± 6	739 → 362	a
11	384.6±0.6	91 ± 19	663 → 278	a
12	395.2±1.0	3.3± 1.5	739 → 344	a
13	449.4±0.7	40 ± 8	609 → 159	a
14	460.5±0.8	10 ± 3	739 → 278	a
15	467.9±0.7	60 ± 12	746 → 278	a
16	495.2±0.7	33 ± 11	1242 → 746	a
17	503.5±0.6	104 ± 24	663 → 159	a
18	511.0±0.5	...	Annihilation radiation	
19	533.9±0.6	28 ± 6	895 → 362	c
20	558.4±1.5	3.6± 1.4	...	
21	579.7±0.6	108 ± 22	739 → 159	a
22	595.3±1.5	3.3± 1.5	...	
23	608.7±0.5	316 ± 64	609 → 0	a
24	616.9±0.8	37 ± 8	895 → 278	c
25	648.6±0.6	120 ± 24	927 → 278	a
26	662.9±0.6	87 ± 18	663 → 0	a
27	767.8±1.0	27 ± 6	927 → 159	a
28	814.3±1.2	8.8± 2.5	...	
29	859.6±1.1	13 ± 4	...	
30	878.5±1.0	50 ± 11	878 → 0	c
31	896.6±2.0	9.0± 5	895 → 0	c
32	926.8±1.5	18 ± 8	927 → 0	a
33	946.8±1.5	12 ± 5	1291 → 344	c
34	959.7±1.3	31 ± 9	1322 → 362	c
35	1080.3±1.5	38 ± 11	1242 → 159	a
36	1138.2±1.2	39 ± 11	...	
37	1158.7±1.5	23 ± 8	...	
38	1195.7±1.5	13 ± 7	...	
39	1242.5±1.2	37 ± 10	1242 → 0	a
40	1262.2±1.2	52 ± 13	...	

[a] Definite—coincidence evidence.
[b] Probable—not certain.
[c] Energetically possible.

[16] These isotopically enriched samples were obtained from Stable Isotopes Sales, Oak Ridge National Laboratory, Nuclear Division, Oak Ridge, Tenn.

[17] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. 67, 32 (1965).

levels reported from the (d,p) reaction studies. Of the 31 levels below 2 MeV observed in either reaction, about 70% are populated by both reactions. For these states the reported energies agree well within the quoted errors (±8 keV) for the (d,p) values. For the higher excited states, particularly in ^{66}Cu, there appears to be a systematic discrepancy in the excitation energies; the (d,p) values are about 4 keV lower than the (n,γ) results. We have taken this energy displacement into account in comparing data from the two reactions. A number of the high-energy γ-ray transitions correspond to levels with excitation energies in the range 2300–2500 keV and suggest the existence of states not reported in the (d,p) study. A similar phenomenon has been observed in a comparison[15] of the ^{59}Co(n,γ) and ^{59}Co(d,p) reactions. Such evidence may imply that some of these high-energy transitions are, in fact, *not* primary, but originate from states at about 6 MeV.

Figure 4 shows the low-energy γ-ray spectrum obtained with a sample enriched[16] to 99.6% in ^{63}Cu. The energies and partial cross sections of these transitions are presented in Table II. By comparison with a similar spectrum obtained with an enriched ^{65}Cu target, all lines listed in Table II are unambiguously assigned to the ^{63}Cu$(n,\gamma)^{64}$Cu reaction.

The results of the coincidence measurements for the ^{63}Cu(n,γ) reaction are presented in Table III. Coincidences between the primary high-energy lines and the low-energy transitions were recorded as described in Sec. II C. Some typical low-energy coincidence spectra are shown in Fig. 5. In order to obtain a maximum amount of information from these data and to provide an indication of the sensitivity limitations of the coincidence experiment, the results are presented in terms of the relative intensity of each of the lines as observed in coincidence with a given primary transition. The coincidence intensity is influenced by several factors, including the partial capture cross section of the pri-

TABLE III. Relative intensities of transitions from the reaction ^{63}Cu$(n,\gamma)^{64}$Cu as observed in coincidence with primary high-energy lines. Intensities are normalized to unity for the strongest line in coincidence with each primary transition. Blanks indicate that no coincidence was observed. The errors in the listed intensities are about ±30%.

Excitation energy (keV)	279	609	664	740 748	928	1242
γ-ray energy (keV)	7637	7307	7252	7176 7168	6988	6674
159		0.13	0.51	1.00	0.18	0.85
203				<0.16		
278	1.00	0.11	1.00	0.47	0.90	1.00
330		0.15				
344				0.15		
377				0.15		
385			0.77			
395				0.17		
449		0.11				
460				0.28		
468				0.19		0.59
495						0.87
503			0.88			
580				0.70		
609		1.00				
649					1.00	
663			0.77			
768					0.19	
928					0.06	
1080						0.39
1242						0.32

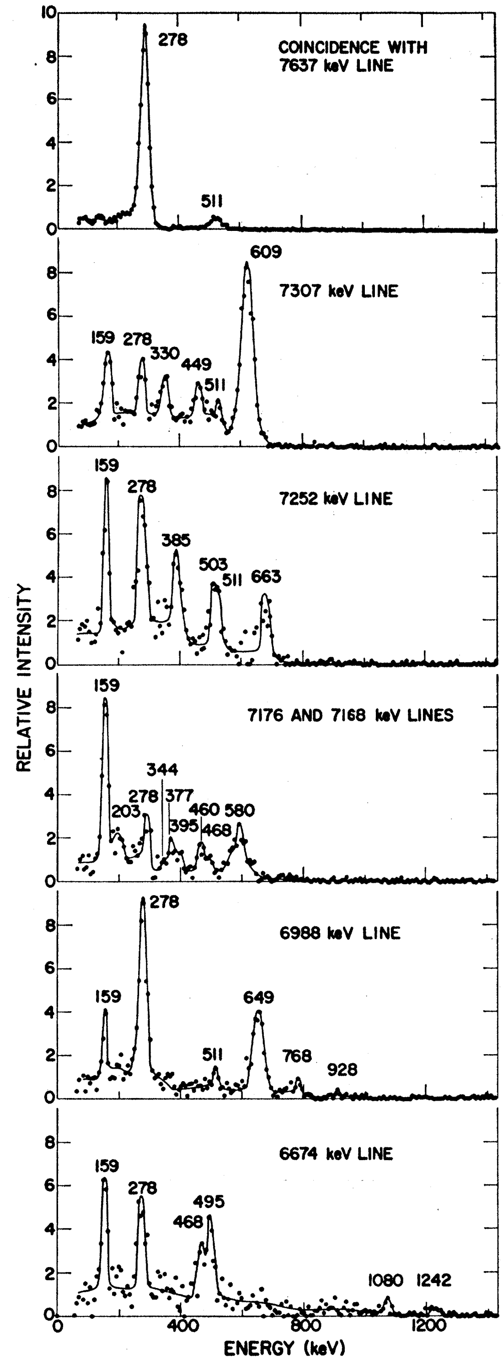

FIG. 5. Representative low-energy spectra from the ^{63}Cu(n,γ)-^{64}Cu reaction, as recorded by the NaI scintillator in coincidence with particular high-energy γ-rays viewed by the Ge(Li) detector.

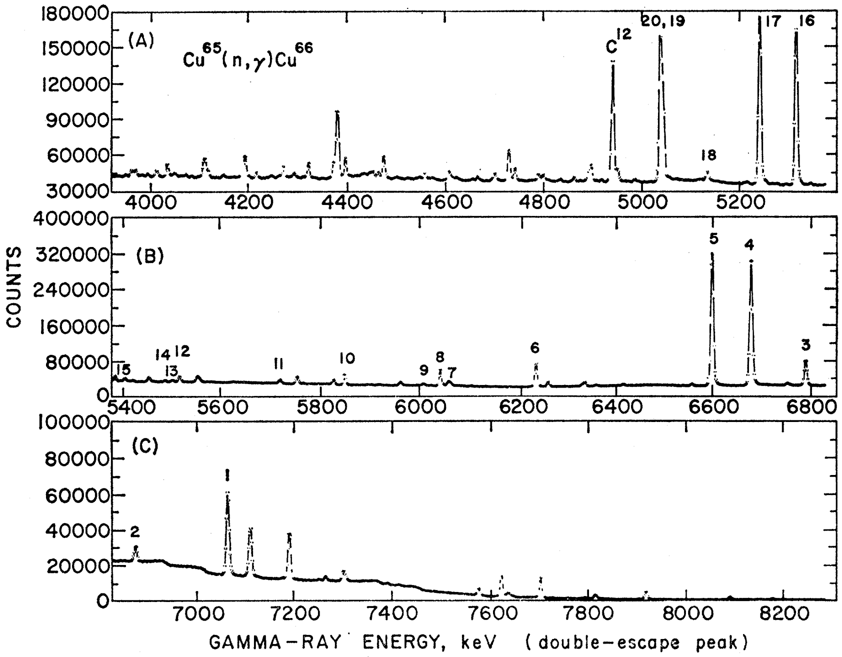

FIG. 6. Typical singles high-energy γ-ray spectrum observed for the reaction $^{65}Cu(n,\gamma)^{66}Cu$ in a target enriched in ^{65}Cu. The abscissa is the γ-ray energy to be associated with the double-escape peaks present in the spectrum. The numbered double-escape peaks correspond to the entries in Table IV.

mary transition and the branching ratio of the low-energy transition. The measured coincidence intensities, as listed in Table III, suggest the intensity limit below which coincidences were not detectable.

B. $^{65}Cu(n,\gamma)^{66}Cu$

Figure 6 shows a typical high-energy singles γ-ray spectrum obtained with a sample enriched[16] to 99.7% in ^{65}Cu. The somewhat less complex character of this spectrum, when coupled with the high-energy spectra obtained with the ^{63}Cu and natural Cu targets, did not necessitate a pair-spectrometer measurement to allow unambiguous assignments of the transitions in ^{66}Cu. A few of the very intense ^{64}Cu lines do appear in this spectrum as very weak but easily identifiable peaks. The energies and relative intensities of the high-energy transitions assigned to ^{66}Cu are listed in Table IV.

The ^{66}Cu neutron binding energy was measured to be 7066 ± 1 keV, in excellent agreement with the value 7067 ± 8 keV derived from the (d,p) Q value of de Figueiredo *et al.*[1] and the mass-adjusted value 7061 ± 7 keV listed in the compilation of Mattauch *et al.*[17]

The low-energy singles spectrum from ^{66}Cu, obtained with a Ge(Li) detector as described in Sec. II B, is shown in Fig. 7. The transition energies and intensities derived from these data are listed in Table V.

Two sets of coincidence studies were made in the investigation of the radiative transitions associated with the $^{65}Cu(n,\gamma)^{66}Cu$ reaction. In one set of measure-

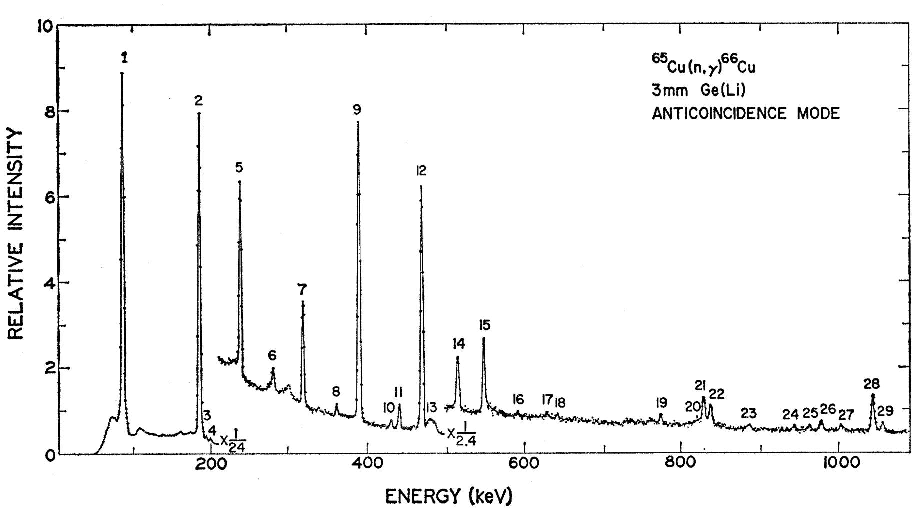

FIG. 7. Low-energy portion of the γ-ray spectrum from the $^{65}Cu(n,\gamma)^{66}Cu$ reaction, obtained with a Ge(Li) detector. The detector was operated inside a large anticoincidence NaI annulus (Sec. II B).

ments, high-energy primary transitions were detected in the Ge(Li) counter while the low-energy secondary γ rays were viewed with a NaI scintillator. In the second coincidence study, both detectors registered the low-energy transitions.

The "low-low" coincidence data are frequently a valuable addition to the "high-low" data since they can define the γ-ray decay mode of levels that are not directly populated from the capture state. Also, the higher efficiency of the Ge(Li) detector at low energies allows data of good statistical accuracy to be obtained in a shorter time than in a "high-low" experiment. The results of these two experiments are listed in Tables VI and VII.

IV. INTERPRETATION

A. General Considerations

The proposed level schemes of ^{64}Cu and ^{66}Cu are shown in Figs. 8 and 9, respectively. The primary γ-ray transitions together with the (d,p) results were used to locate the low-lying levels. The coincidence data were then used to define the positions of the observed low-energy transitions in the level scheme. Some of the transitions whose locations were not definitely established by the coincidence data can be assigned a position in the level scheme with considerable confidence on the basis of energy and intensity considerations. There remain a few transitions, usually of low intensity, for which several assignments are energetically possible and for which no unique assignment can be determined from the existing data. Tables II and V include our assignment for each of the transitions as well as an indication of the measure of confidence ascribed to that assignment. Confidence in these assignments are indicated by (a) *definite*—unambiguous coincidence evidence, (b) *probable*—based on excellent energy and intensity balances, but no definite coincidence evidence, and (c) *energetically* possible—no definite intensity imbalance. All assigned transitions are shown on the level schemes. In order to search for alternative level schemes that might also satisfy the available experimental data, a computer program was used to investigate other possible placements of the transitions among the known levels as well as to attempt to define new levels on the basis of the known transitions. The degree of confidence in the assignments listed in Tables II and V fully reflects the results of such investigations.

TABLE IV. High-energy capture γ rays from the $^{65}Cu(n,\gamma)$-^{66}Cu reaction. The $^{65}Cu(d,p)$ excitation energies are from de Figueiredo *et al.*[a]

Line No.	γ-ray energy (keV)	Partial cross section (mb)	Excitation energy (keV)	Excitation energy for $^{65}Cu(d,p)$
1	7066±1	31 ± 7	0	0
2	6880±1	6.1± 1.4	186	183
3	6791±1	40 ± 9	275	272
4	6680±1	211 ±42	386	383
5	6600±1	225 ±45	466	462
...	...	...	...	589
...	...	...	...	724
6	6243±1	42 ± 9	823	819
7	6057±3	1.5± 0.9	1009	...
8	6049±1	31 ± 7	1017	1015
9	6014±1	3.4± 0.8	1052	1051
...	...	...	...	1152
10	5853±1	21 ± 5	1213	1209
...	...	...	...	1247
11	5721±1	7.4± 1.5	1345	1339
...	...	...	...	1433
12	5518±1	13 ± 2.7	1548	1544
13	5504±2	2.9± 0.7	1562	1557
14	5490±2	2.5± 0.6	1576	1572
15	5387±1	11 ± 2.2	1679	...
...	...	...	...	1730
16	5320±1	137 ±28	1746	...
17	5245±1	164 ±33	1821	1816
18	5139±1	9.0± 2.2	1927	1923
...	...	...	...	1976
19	5048±1	85 ±17	2018	2015
20	5042±1	135 ±27	2024	...

[a] Reference 1.

TABLE V. Low-energy γ rays from the reaction $^{65}Cu(n,\gamma)^{66}Cu$.

Line No.	γ-ray energy (keV)	Partial cross section (mb)	Assignment	Confidence
1	89.11±0.2	151 ± 32	275 → 186	a
2	185.79±0.2	530 ±102	186 → 0	a
3	194.4 ±0.5	4.1± 1.0	1017 → 823	c
4	200.1 ±0.5	6.8± 1.5	386 → 186	a
5	237.7 ±0.4	51 ± 10	238 → 0	b
6	278.7 ±0.8	10.3± 2.5	465 → 186	a
7	315.6 ±0.3	60 ± 12	591 → 257	a
8	357.5 ±0.8	6.0± 1.4	823 → 465	b
9	385.7 ±0.4	298 ± 60	386 → 0	a
10	426.3 ±0.7	7.4± 1.7	1017 → 591	b
11	436.6 ±0.5	30 ± 6	823 → 386	a
12	465.1 ±0.3	352 ± 70	465 → 0	a
13	478.0 ±3.0[d]	30 ± 10	...	
14	511.0 ±0.4	...	Annihilation radiation	
15	543.9 ±0.5	74 ± 16	1009 → 466	a
16	586.7 ±1.0	5.0± 3.0	1052 → 466	c
17	625.0 ±1.2[d]	12.6± 4.0	1009 → 385	c
18	637.2 ±1.0	7.2± 2.1	823 → 186	a
19	769.9 ±0.8	17 ± 4	1821 → 1052	a
20	815.8 ±1.2	20 ± 5	1052 → 238	c
21	824.5 ±0.8[d]	86 ± 18	1009 → 186	c
22	833.0 ±1.0	67 ± 23	1017 → 186	c
23	881.5 ±1.4[d]	22 ± 5	1346 → 465	c
24	938.7 ±1.0	15 ± 5	1213 → 257	b
25	958.3 ±1.8	13 ± 5	1549 → 591	c
26	973.9 ±1.5	41 ± 9	1213 → 238	c
27	998.9 ±1.5	21 ± 6	1821 → 823	a
28	1039.9 ±1.2	...	From ^{66}Cu decay	
29	1052.6 ±1.0	54 ± 12	1051 → 0	b
30	1197.2 ±2.0[d]	34 ± 9	2018 — 823	c
31	1212.6 ±1.6	41 ± 10	1213 → 0	b
32	1261.7 ±1.2	57 ± 12	...	
33	1355.6 ±1.5	37 ± 8	1821 → 465	c
34	1440.3 ±1.5	37 ± 9	1440 → 0	c
35	1560.7 ±1.2	134 ± 28	1746 → 186	b
36	1584.2 ±1.5	32 ± 10	1821 → 238	c
37	1638.7 ±1.4	71 ± 18	2026 → 386	c
38	1745.9 ±1.5	109 ± 26	1746 — 0	b

[a] Definite—coincidence evidence.
[b] Probable—not certain.
[c] Energetically possible.
[d] Complex.

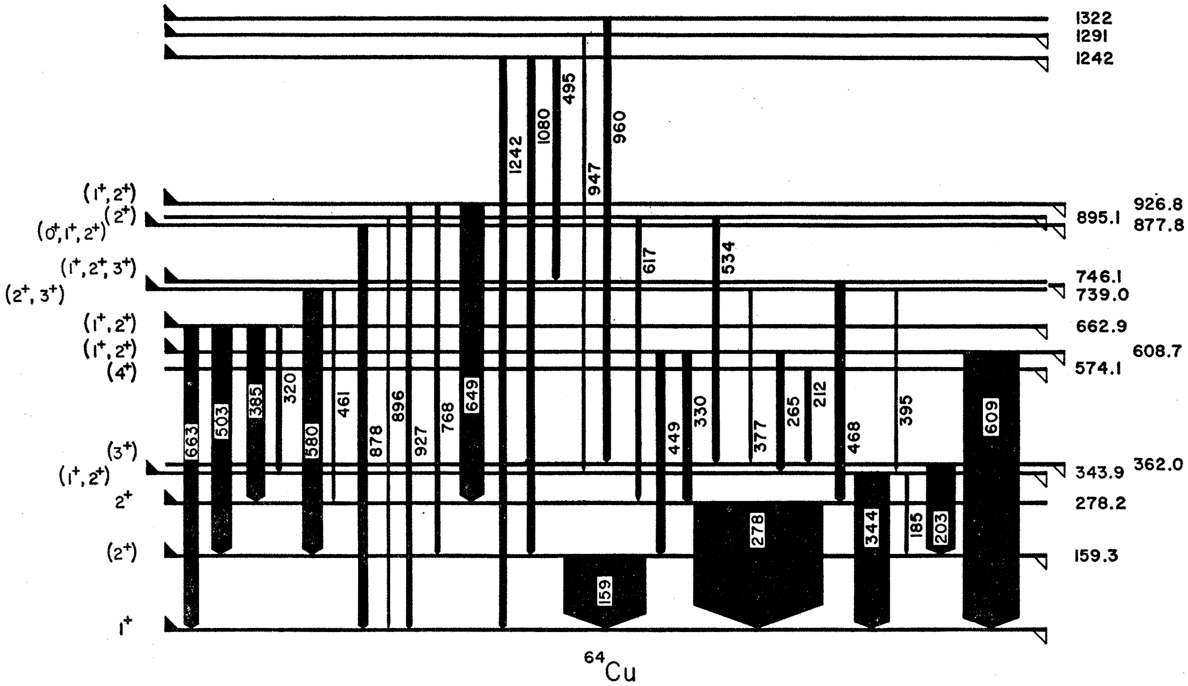

FIG. 8. Level structure of ^{65}Cu. All energies are in keV. γ-ray intensities are proportional to the widths of the lines representing them. Flags on the left and right ends of the levels indicate direct population by primary (n,γ) transitions and by the (d,p) reaction, respectively.

B. $^{63}Cu(n,\gamma)^{64}Cu$

The ground-state spin and parity of ^{64}Cu are known[18] to be 1^+. Measurements of the circular polarization of γ rays emitted following capture of polarized neutrons, performed by Vervier[3] and by Kopecky *et al.*,[5] indicate that the level at 278 keV has $I^\pi = 2^+$. This result is also suggested by the directional-correlation experiments of Bartholomew and Vervier.[3] The work of duToit and Bollinger[4] sets an upper limit of $\tau \leq 0.3$ nsec on the lifetime for the 159-keV transition which depopulates the first excited state. This limit restricts the spin of the 159-keV state to $I = 0$, 1, or 2. The existence of the γ-ray cascade (Fig. 8) starting at the 574-keV level and decaying progressively through the levels at 362 and 159 keV, without cross-over transitions, suggests that the spins for these states are 2^+ (159 keV), 3^+ (362 keV), and 4^+ (574 keV). The absence of a direct transition from the capture state ($I^\pi = 1^+, 2^+$) to the 574-keV level is consistent with these assignments. These tentative spin assignments, together with the observed γ-ray transitions, provide a basis from which to estimate the spins of other low-lying levels. If spins are assigned in such a way as to reflect the dominance of low-multipolarity transitions, the spin values shown in Fig. 8 result. It should be emphasized that although the proposed spin-

TABLE VI. Relative intensities of transitions from the reaction $^{65}Cu(n,\gamma)^{66}Cu$ as observed in coincidence with the low-energy transitions. Intensities are normalized to unity for the most intense transition in each vertical column. Only the more intense coincidence transitions were detectable. The errors in the listed intensities are about ±30%.

γ-ray energy (keV)	89	186	316	386	465
89	···	1.00	0.80	···	···
186	1.00	···	1.00	···	···
316	0.26	0.50	···	···	···
437	···	···	···	1.00	···
544	···	···	···	···	1.00

[18] *Nuclear Data Sheets*, compiled by K. Way *et al.* (U. S. Government Printing Office, National Academy of Sciences—National Research Council, Washington 25, D. C., 1961), NRC 59-2-13 and NRC 59-2-16.

TABLE VII. Relative intensities of low-energy transitions from the reaction $^{65}Cu(n,\gamma)^{66}Cu$ as observed in coincidence with primary high-energy lines. Intensities are normalized to unity for the strongest line in coincidence with each primary transition. Blanks indicate that no coincidence was observed. The errors in the listed intensities are about ±30%.

Excitation energy (keV)	386	466	1821
γ-ray energy (keV)	6680	6600	5245
186	0.02	0.04	0.04
200	0.03	···	···
238	···	···	1.00
279	···	0.04	···
386	1.00	···	0.46
437	···	···	0.38
465	···	1.00	0.84
770	···	···	0.27
999	···	···	0.25

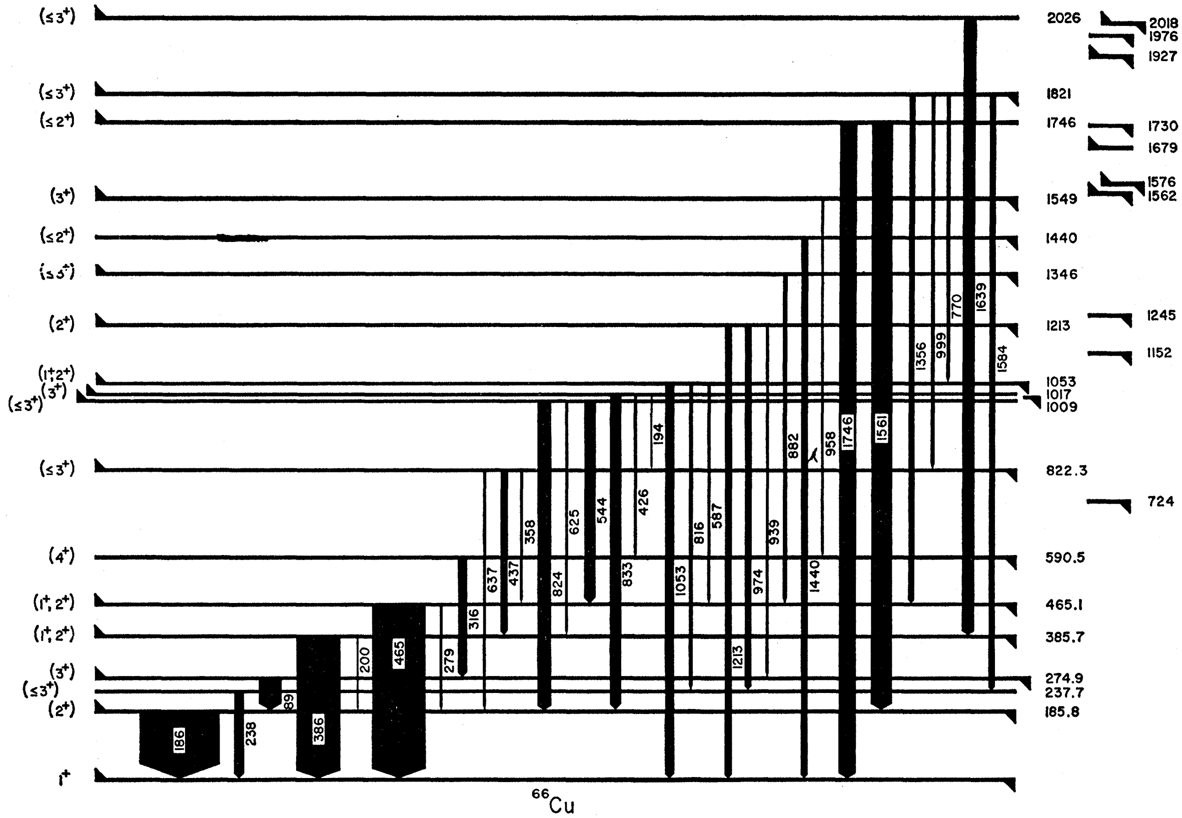

FIG. 9. Level structure of ^{66}Cu. All energies are in keV. γ-ray intensities are proportional to the widths of the lines representing them. Flags on the left and right ends of the levels indicate direct population by primary (n,γ) transitions and by the (d,p) reaction, respectively. Unassigned levels are indicated on the extreme right.

parity assignments are consistent with the available experimental evidence, most of the assignments are not unique.

C. ^{65}Cu$(n,\gamma)^{66}$Cu

The ground-state spin and parity of ^{66}Cu are known[19] to be 1^+. The existence of a γ-ray cascade starting at the 591-keV level and progressing without cross-over transitions to the ground state through the levels at 275 and 186 keV, coupled with the existence of direct transitions from the capture state to all of these states except the 591-keV level, suggests (in analogy with ^{64}Cu) that the spins of these levels are 2^+ (186 keV), 3^+ (275 keV), and 4^+ (591 keV). Based on the assumption that these spin assignments are correct, limits can be placed on the possible spins of the other excited states by noting to which of the assigned states the other levels decay. The tentative assignments derived from these considerations are shown in Fig. 9. With the exception of the level at 237.7 keV, the existence of each level shown in Fig. 9 is established by observation of a direct transition from the capture state or by (d,p) excitation. The existence of the 237.7-keV level is suggested by four otherwise unassigned low-energy γ rays which could connect a level at this energy with the ground state and with the levels at 1053, 1213, and 1821 keV. Using the procedure suggested by Schult,[20] we have calculated that the probability of such a combination of γ transitions occurring by accident is about 0.005. Thus, the level at 237.7 keV can be regarded as established with reasonable confidence.

V. CONCLUSIONS

The low-lying excited states of $^{64}Cu_{35}$ and $^{66}Cu_{37}$ (Figs. 8 and 9, respectively) display a considerable degree of similarity, especially below an excitation energy $\sim$600 keV. This similarity is reflected in the excitation energies of the states, the assigned spins and parities, and the general decay characteristics of these levels. Although the proposed spins and parities of the low-lying ^{64}Cu and ^{66}Cu states are based on a self-consistent interpretation of the level schemes assuming the dominance of $M1$ transitions, in comparing these two nuclei it must be borne in mind that these spins are only tentative.

[19] *Nuclear Data Sheets*, compiled by K. Way *et al.* (U. S. Government Printing Office, National Academy of Sciences—National Research Council, Washington 25, D. C., 1961), NRC 60-4-23 and NRC 60-4-24.

[20] O. W. B. Schult, Argonne National Laboratory Report No. ANL-7282, 1966 (unpublished).

The $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ shell-model nucleon orbitals are expected to play the dominant role in the makeup of these states. Within this framework, it is expected that the states up to an excitation energy of $\sim$1 MeV should be of positive parity and low spin ($I \leq 4$). This expectation is consistent with the tentative assignments for the low-lying states of ^{64}Cu and ^{66}Cu (Figs. 8 and 9) made on the basis of the present investigation. The calculations of Auerbach[21] have given a reasonably good description of the lowest-lying $\frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$ states of the odd-mass Ni isotopes in terms of seniority-one $p_{1/2}$, $p_{3/2}$, and $f_{5/2}$ neutron shell-model orbital configurations. Our approach to understanding the level structures of ^{64}Cu and ^{66}Cu has been to assume that the low-lying states can be characterized by the couplings of the $p_{3/2}$ proton orbital to Auerbach's[21] neutron configurations.

The ground state of ^{63}Ni has been found[21] to be $\frac{1}{2}^-$. Auerbach[21] predicts the configuration of this state to have approximately equal admixed contributions arising from various seniority-one $[p_{1/2}(f_{5/2})_0^{2n}(p_{3/2})_0^{2m}]_{1/2^-}$ components. This $\frac{1}{2}^-$ neutron configuration, when coupled to the $p_{3/2}$ proton in ^{64}Cu, will give rise to a pair of states with spins 1^+ and 2^+. The jj coupling rules of Brennan and Bernstein[22] predict that the 1^+ member of this multiplet should lie lowest, consistent with observation. Since the $\frac{5}{2}^-$ first excited state of ^{63}Ni (for which Auerbach[21] prescribes a seniority-one $f_{5/2}$ neutron configuration) lies close to the ground state, the ^{64}Cu ground state may also contain a sizable contribution from the coupling of the $p_{3/2}$ proton to this neutron configuration.

For the case of ^{65}Ni (an isotone of ^{66}Cu) the $\frac{5}{2}^-$ ground state and $\frac{1}{2}^-$ first excited state are a closely spaced doublet and are attributed[21] to seniority-one $f_{5/2}$ and $p_{1/2}$ configurations, respectively. According to the jj coupling rules,[22] the 1^+ member of each multiplet in ^{66}Cu that results from the $p_{3/2}$ proton coupling to these seniority-one neutron configurations is favored to lie lowest.

The ^{64}Cu and ^{66}Cu ground states, although likely to consist mainly of various seniority-one neutron components coupled to the $p_{3/2}$ proton, may also contain certain seniority-three neutron components, which appear[21] to contribute to some of the low-lying states in ^{63}Ni and ^{65}Ni. The Zn ground states populated by the allowed β^- decays of these 1^+ Cu ground states are presumed to be $(p_{3/2})^{2n}$ proton configurations. The low $\log ft$ values of these β^- transitions suggest that the β^- decay proceeds to a considerable extent by means of the allowed $\nu(p_{3/2}$ or $p_{1/2}) \rightarrow \pi(p_{3/2})$ transitions rather than by the l-forbidden $\nu(f_{5/2}) \rightarrow \pi(p_{3/2})$ mechanism.

From the considerations outlined above, the spin-4^+ state, seen in both Cu nuclides, can reflect only the $\pi(p_{3/2})\nu(f_{5/2})$ coupling in lowest seniority. However, it is recognized that these 4^+ states may also contain components with higher seniority.

Although the information obtained in the present work on the level structures of ^{64}Cu and ^{66}Cu does not clearly define the particular component admixtures of the excited states of these nuclei, the observed structural features support a reasonable shell-model interpretation of these states. [*Note added in proof.* Since the submission of this article for publication, the authors have become aware of a recent investigation by L. M. Bollinger and G. E. Thomas that corroborates the existence of the 237.7-keV level in ^{66}Cu deduced from the low-energy singles and coincidence spectroscopic studies reported here. Bollinger and Thomas employed a technique which yields the average capture γ-ray spectrum over many slow-neutron resonances. Their spectrum for Cu revealed a 6828-keV primary transition to the 237.7-keV state which was absent in the thermal capture γ-ray spectrum, presumably due to statistical fluctuations in the decay of the capture state. The strength of the 6828-keV γ ray is consistent with that of an $E1$ transition and therefore is in agreement with the proposed upper limit of 3^+ for the spin of the 237.7-keV level. The authors wish to thank these investigators for communication of these results prior to publication.]

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[21] N. Auerbach, Nucl. Phys. **76**, 321 (1966). This paper also cites pertinent experimental work on the Ni isotopes.

[22] M. H. Brennan and A. M. Bernstein, Phys. Rev. **120**, 927 (1960).