Spectroscopy of 1f-2p Nuclei with Direct (d, α) and (d, p) Reactions. II. Cu^{64}†

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Levels of Cu^{64} were studied with 12.08-MeV deuterons via the $Zn^{66}(d, \alpha)$ reaction with 11–12-keV resolution and the $Cu^{63}(d, p)$ reaction with 7–8-keV resolution. About 85 levels were identified for $E_{ex} \leq 3$ MeV, i.e., 35 more than reported in the most recent literature. $Zn^{66}(d, \alpha)Cu^{64}$ angular distributions were obtained over the range $15° \leq \theta \leq 90°$, and L values were extracted from comparison with distorted-wave Born-approximation (DWBA) calculations which incorporated finite-range and nonlocality corrections as well as microscopic form factors. Good agreement was found between the observed and calculated angular distributions. $Cu^{63}(d, p)Cu^{64}$ angular distributions were obtained over the range $8° \leq \theta \leq 50°$, and l values and spectroscopic factors were extracted from the comparison with DWBA calculations which included finite-range and nonlocality corrections and spin-orbit coupling for the bound neutron. It was possible to make unique 1^+ and 3^+ assignments for many levels from the recognition of $L=0$ transfers, L mixing in (d, α) transitions, and overlap between (d, α) and (d, p) J^π limits. Good agreement in J^π assignments was found between the present work and (n, γ) work for almost all levels below 1-MeV excitation.

I. INTRODUCTION

THE $Zn^{66}(d, \alpha)$ reaction allows a study of levels in Cu^{64} not easily assigned by the more familiar single-nucleon transfer reactions.[1] Direct (d, α) reactions are viewed as the removal of a proton-neutron pair from the target nucleus in a one-step process, and thus should populate levels in the product nucleus whose configuration corresponds to two holes in the target nucleus. This reaction is also highly sensitive to the details of the nuclear wave functions, since many different configurations of the transferred pair can contribute to a given angular momentum transfer.[2] In particular, coherence in the two-nucleon transfer may be used as a powerful probe to check theoretical predictions for the relative phases of the amplitudes of the various components in the nuclear wave functions.[3]

Distorted-wave treatments of two-nucleon transfer reactions have recently been formulated by many authors.[2–9] Studies on (d, α) reactions to check the usefulness of the current distorted-wave theories have been conducted mainly for light targets.[10] The number of publications on direct (d, α) reactions with targets of mass $A > 40$ has been scant, in part because the level density increases rapidly and the cross sections become smaller as the mass number increases, and partly because the needed refinements of experimental techniques have only recently become practical. The extent to which (d, α) angular distributions can be useful for the spectroscopy of odd-odd nuclei has been pointed out previously,[11,12] and at that time the first preliminary J^π assignments for Cu^{64} were presented.

Shera and Bolotin[13] independently made assignments for levels of Cu^{64} via the thermal-neutron capture reaction $Cu^{63}(n, \gamma)$. However, because of complications of the γ-ray decay modes, their assignments are tentative and limited to the low-lying states. The levels of Cu^{64} were previously studied at this laboratory by Hjorth and Allen[14] via the $Cu^{63}(d, p)$ and $Cu^{65}(d, t)$ reactions with a deuteron energy of 15 MeV. The extracted l values, however, are not always reliable, due to the fact that their experimental energy resolution [$\sim$30 keV for the (d, p) and $\sim$80 keV for the (d, t) experiment] was generally insufficient to resolve single levels. Their (d, p) spectroscopic factors were based on conventional zero-range DWBA calculations with local potentials performed, not for Cu^{63}, but for the $Zn^{66}(d, p)Zn^{67}$ reaction. The levels of Cu^{64} were also studied recently by Young[15] at MIT via the $Ni^{62}(He^3, p)$ reaction, at $E_{He^3} = 13$ MeV, but no J^π assignments have been reported.

The present paper, the second in a series on the spectroscopy of odd-odd Cu isotopes, presents L and J^π assignments up to about 3-MeV excitation in Cu^{64}, based primarily on the $Zn^{66}(d, \alpha)Cu^{64}$ reaction. The $Cu^{63}(d, p)Cu^{64}$ reaction was also studied in order to obtain unique parity assignments and J^π limits. The

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[15] H. J. Young, Bull. Am. Phys. Soc. **13**, 105 (1968).

experimental results are compared to current DWBA calculations which incorporate finite-range and nonlocality corrections via the local-energy approximation[16,17] into the conventional zero-range calculations with local potentials. In addition, the $Cu^{65}(d, t)$ reaction was studied at one angle ($\theta_L = 35°$) in order to spot $(j^2)_{J=\text{even}}$ levels which are inhibited in (d, α) reactions.

II. EXPERIMENTAL PROCEDURE

A. $Cu^{63}(d, p)$ Reaction

High-resolution spectra were taken at $E_d = 12.0$ MeV for six forward angles: 8°, 14°, 20°, 30°, 40°, and 50°. The protons were magnetically analyzed and recorded on Kodak Type NTB photographic plates in the focal plane of the Enge split-pole magnet spectrograph. Graduated aluminum absorbers were placed in front of the plates to stop deuterons with the same magnetic rigidities as the protons of interest and to reduce the proton energies to about 5 MeV for better visibility of tracks.

Detailed descriptions of the scattering system were presented previously.[18–20] To obtain a better ratio of peak to background, a "line target"[19] was used in place of an ordinary target. The target material was deposited on carbon backing ($\sim$20 μg/cm^2) only in the central rectangular area of 0.5-mm width and 3-mm length. This line target eliminated the necessity of using narrow beam-defining target and antiscattering slits, thereby reducing background counts due to degraded deuterons scattered from these slits. The target material was 99.7% enriched Cu^{63} in the form of CuO. The oxygen in CuO should present no problem because it becomes disassociated from Cu before evaporation takes place and because of the reaction kinematics.

Figure 1 shows a typical proton energy spectrum for this experiment. The peak-to-background ratio is better than 500 to 1. The over-all energy resolution was about 7.5 keV, as expected when taking into account all contributions to resolution.[18,19] We see about 85 levels up to 3-MeV excitation, 30 more than the recent *Nuclear Data Sheets*[21] exhibit, and there is evidence for $\sim$15 unresolved doublets.

The peaks are labeled by the excitation energies assigned in this experiment. Many excitation energies are known from previous work[21]; however, the listed values were determined independently in the present work by a computer program SPECTRE.[18] The program requires as inputs the positions of peaks (in cm) on the

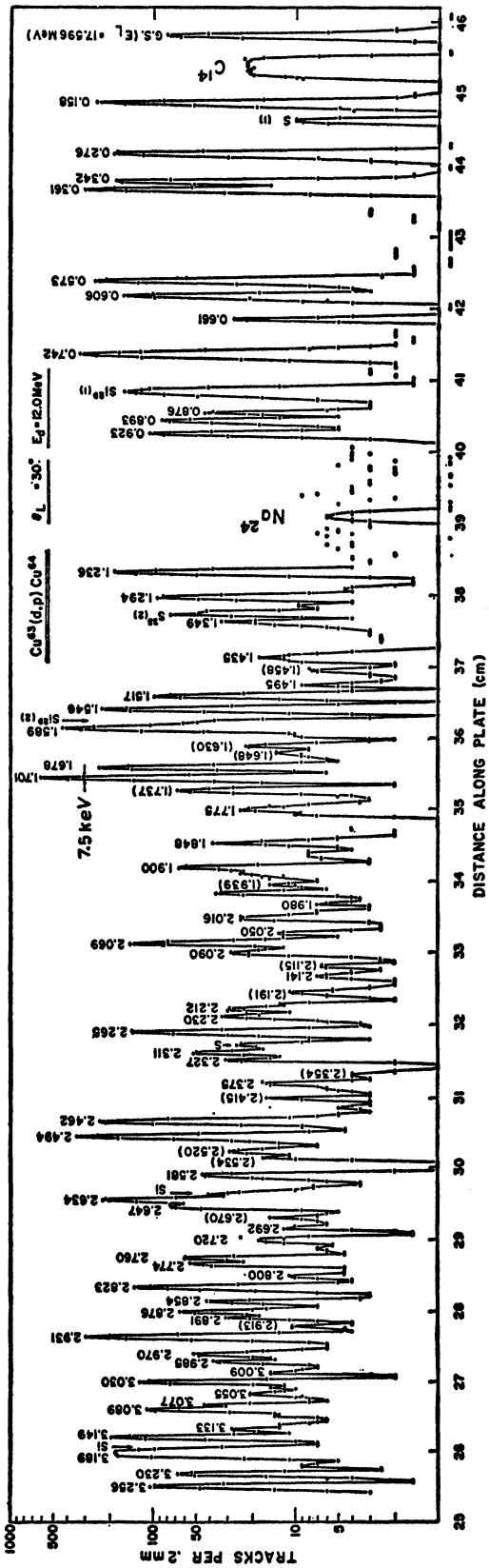

FIG. 1. Typical proton spectrum for the $Cu^{63}(d, p)Cu^{64}$ reaction induced by 12.0-MeV deuterons at $\theta_{lab} = 30°$. The protons were magnetically analyzed and recorded on photographic plates in the focal plane of the Enge split-pole magnet spectrograph. Levels in Cu^{64} are identified by their measured excitation energies.

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plate and calculates the ground-state Q value and the corresponding excitation energies. The quoted values of the excitation energies were obtained by averaging the calculations for four angles. The Q values of excited states referred to in the ground state are in excellent agreement with *Nuclear Data Sheets* assignments. Our values are estimated to have random errors of ± 2 keV and a systematic error of less than $\pm 0.3\%$ up to 3-MeV excitation.

The main uncertainty in the energy and l-value assignments arises from the interference of impurity peaks resulting chiefly from Si^{28} and S^{32} in the target. Nevertheless, strong impurities could be traced through the spectra, and Cu^{64} peaks overlapping them were not used for the angular distributions. Numbers in parentheses are energy assignments which have additional uncertainties due to interference by impurity peaks, poor resolution, or poor statistics.

The assignment of energies to states not previously reported[21] are based on both the (d, p) and the (d, α) results and the values are weighted averages. The method of the (d, α) assignments will be discussed later.

The use of a "line target" makes charge normalization for cross-section calculations meaningless, since only a limited portion of the beam hits the target material. Hence, the beam was monitored by detecting elastically scattered deuterons with two silicon surface-barrier detectors at $\pm 38°$ during the entire run. The energy resolution of these detectors was about 60 keV, good enough to separate the Cu^{63} elastic peak from peaks due to carbon and other impurities. Signals from the digital output of the current integrator served as beam-dependent "external clock pulses" to the analyzers to determine the counting losses of the analyzers. The average counting loss was 3% with a typical beam of 1.5 μA for this run. The absolute deuteron elastic scattering cross section for monitor normalization was taken from the literature[22] and its uncertainty ($\pm 5\%$) contributes to the uncertainty of our absolute (d, p) cross sections.

Experimental errors in this reaction are the following:

(a) Errors in absolute excitation energies are believed to be less than $\pm 0.3\%$ of excitation energy except for values in parentheses which are accurate to ± 10 keV.

(b) The zero-angle position was determined by measuring and comparing elastically scattered deuterons with a position-sensitive detector at spectrograph angles of $\pm 10°$. Shifts in angle of incidence of the beam were checked by two symmetrically installed monitor detectors, and amounted to less than $\pm 1°$.

(c) The scale error in the absolute cross section is $\pm 15\%$ (due mainly to systematic monitoring and plate scanning errors).

[22] L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. **134**, 765 (1964).

B. $Zn^{66}(d, \alpha)$ Reactions

1. Spectrograph Runs

As the (d, p) spectrum in Fig. 1 manifests, the study of odd-odd nuclei near $A = 60$ demands that the experimental energy resolution should be in the neighborhood of 10 keV. The combination of Pittsburgh tandem Van de Graaff and Enge split-pole broad-range spectrograph allows total resolving powers of 2000 and better[20,23] without the excessive loss of counting rate that used to restrict high-resolution work. Detection of α groups with photographic plates presents the problem of biasing out strong deuteron groups, especially at small angles. Detailed accounts of the versatility of position-sensitive counters for particle discrimination have been given earlier[19,23]; consequently, only deviations from or additions to our standard experimental technique will be discussed here.

Figure 2 shows a block diagram of the electronic setup used for the (d, α) experiment at 12 MeV, the highest deuteron energy available at the beginning of the experiment. This setup is identical with that used for the (d, t) experiments, and the reader is advised to see Ref. 19 for details. Deuterons and tritons from the competing 12-MeV deuteron-induced reactions, having the same magnetic rigidity ($H\rho$) as the α particles, will interfere with α particles in the energy range of interest (3-MeV excitation for this work). The E signals from the position-sensitive counters were utilized to reject these unwanted particles by selecting the proper energy level with the single-channel discriminators in the diagram. A typical spectrum taken with an array of four position-sensitive counters in the focal plane of the spectrograph is shown in Fig. 3. In a pair of overlapping runs, sections taken from approximately linear portions of the counters were connected in the spectrum. The total energy resolution was ~ 12 keV.

The energy calibration for position-sensitive counters was described in Ref. 19. Excitation energies based on this calibration were checked with the adopted (d, p) assignments for previously known states, and agreement within ± 5 keV was found. The values for new states were averaged with those determined from the (d, p) experiment.

The targets used consisted of 99.35% isotopically pure Zn^{66} evaporated onto thin carbon foils (~ 20 $\mu g/cm^2$) by an electron gun. The initial target thickness was about 30 $\mu g/cm^2$ of Zn^{66}. In an attempt to check for isotopic impurities in the spectra, a few of the (d, α) runs on Zn^{64} and Zn^{68} were investigated at the same spectrograph magnetic field frequency as for $Zn^{66}(d, \alpha)$ runs at the start of the (d, α) project. As expected, no isotopic impurities were observed, since Zn^{64} and Zn^{68} targets also had more than 99% enrichment.

[23] W. W. Daehnick and Y. S. Park, Bull. Am. Phys. Soc. **12**, 461 (1967).

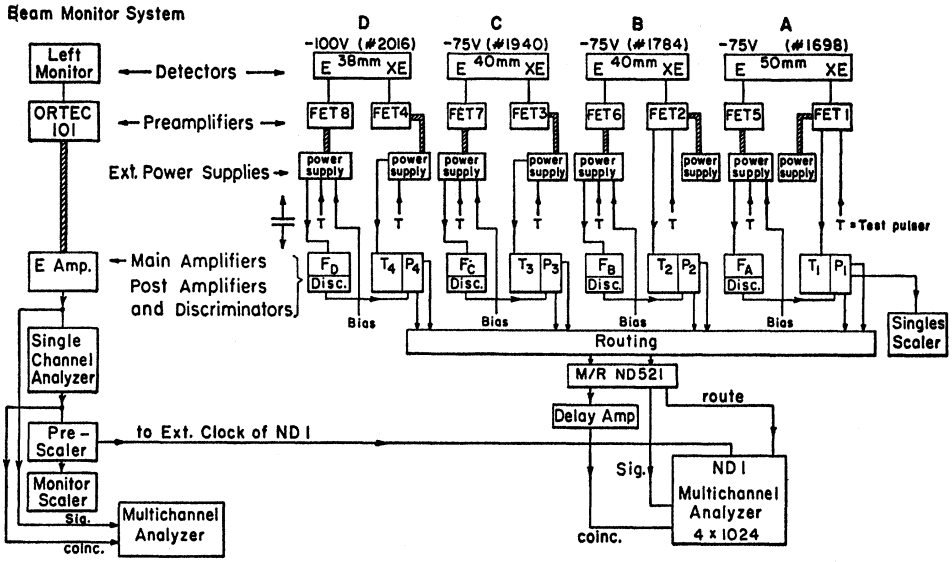

FIG. 2. Block diagram for electronic setups for (d, α) runs with four position-sensitive detectors in the Enge spectrograph focal plane. The counters A, B, C, and D are shown to scale in the diagram. For a detailed description of this standard setup, see Ref. 19.

The most significant impurity peak throughout the entire $Zn(d, \alpha)$ analyses was represented by the first excited state of C^{12} via the $N^{14}(d, \alpha)$ reaction.

2. *Normalization Runs*

Great care had been taken to assure a consistent "internal normalization" between the overlapping runs. The vertical position of the counter system was checked at the beginning of every run to insure that all α's of interest would be intercepted by the active areas of the counters which are vertically limited to 8 mm by an aperture. The check was necessary, because the vertical magnification of our double-focussing Enge split-pole magnet is 2.7 and the focal image (of height 5.4 mm) has to be reasonably well centered on the detectors.

In spite of the care which preceded the data-taking an inconsistency in the internal normalization was sometimes found, due to the fact that the spectrograph Si-monitor counters suffered radiation damage and slowly became less reliable. In order to obtain more accurate relative and absolute normalizations, the (d, α) experiments were repeated in our 18-in. scattering chamber. The geometry and function of the chamber were described earlier[24]; only modifications for the present experiment will be described here. The normalization experiment was performed with five silicon surface-barrier detectors of 250–350 μ depth. With these thin detectors it was possible to identify α groups over a broad energy range without interference from other particle groups because the $Zn^{66}(d, \alpha)$ reaction has a high positive Q value (7.26 MeV) and α's have a high specific-energy loss. Thus complications associated with utilizing a particle identification system would be avoided.

The α detectors were mounted 10° apart on aluminum bases with centering grooves which permitted the setting of any desired detector distance from the target. In order to partially offset the decrease in counting rate for successively higher angles, solid angles between 0.815 msr for the smallest angle detector and 1.30 msr for the largest angle detector were chosen. The aluminum bases made good thermal contact with the turntable, which was cooled to −30°C by means of a freon coolant system. Detector collimators were equipped with small bar magnets at the entrance for electron suppression. The effects of the cooling and the magnets on resolution are described in Ref. 25.

The success of this run was again partially dependent upon the reliability of the beam-target monitor system. The monitoring was done by detecting elastically scattered deuterons with a good 1500-μ silicon surface-barrier detector which was set at $\theta_L = -40°$. The block diagram for the (d, α) setup looks similar to Fig. 2, the main difference being that for this experiment the electronics associated with the E pulses are, of course, not present. The energy calibrations were obtained with α groups with known energies from the $Al^{27}(d, \alpha)Mg^{25}$ reaction.

The monitor signal after amplification was fed simultaneously into a single-channel analyzer and a Nuclear Data 512-channel analyzer. The output from the single-channel analyzer, which was set to accept

[24] R. H. Fulmer and W. W. Daehnick, Phys. Rev. **139**, 579 (1965).

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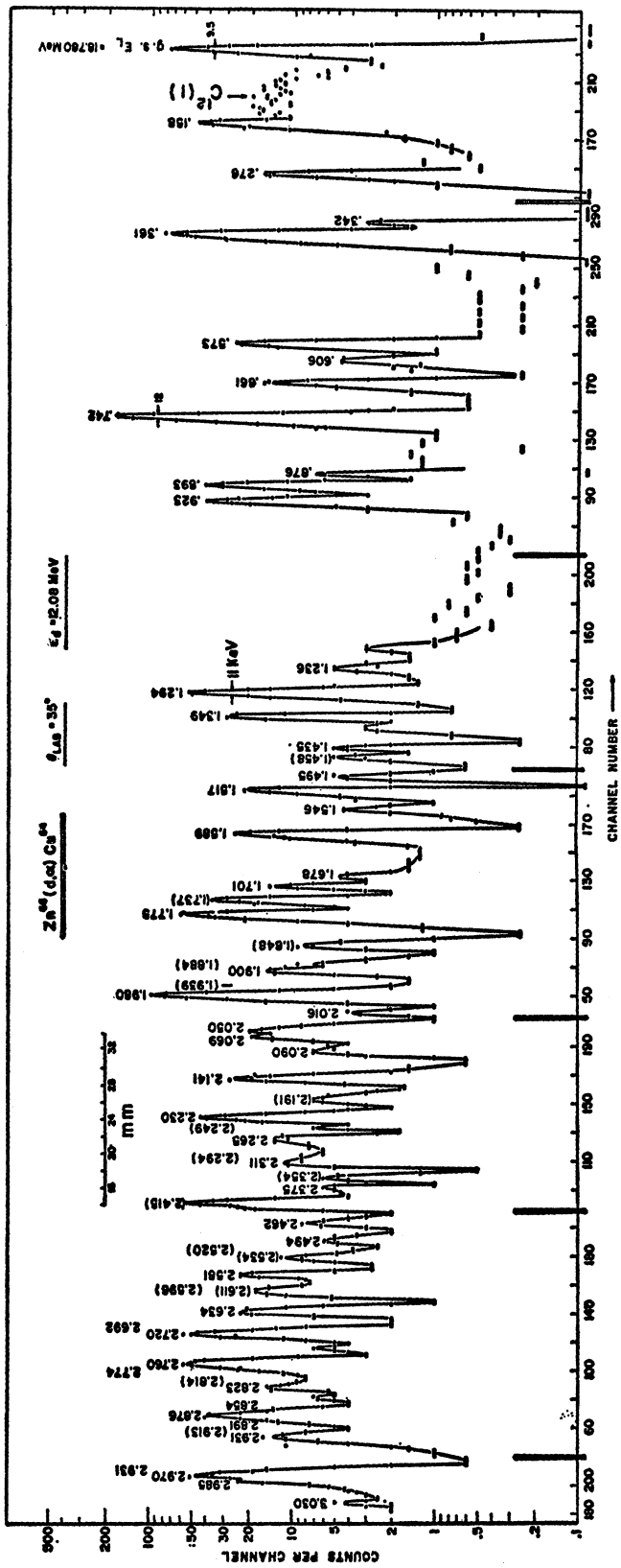

FIG. 3. α spectrum for $Zn^{66}(d,\alpha)Cu^{64}$ at $E_d = 12$ MeV and $\theta_{lab} = 35°$. Spectra were taken with the electronic setup shown in Fig. 2. The spectrum is a composite of seven overlapping spectra, the junctions of which are indicated at the bottom by pairs of vertical lines. Points with poor statistics in the figure were averaged over 2–4 neighboring channels in the original spectra.

the elastic Zn peak, was fed into a monitor scaler. The analyzer's dead-time correction was made by feeding the digital output pulse from the current integrator into the external clock inputs of the analyzers. A typical energy resolution of the (18 MeV) α peaks was about 45 keV. No attempts to improve this resolution were made inasmuch as the attention was focused solely on obtaining accurate cross-section normalizations. Only three states—the ground state, the 0.361 state, and the 0.742 state—were considered, since they were strongly excited and therefore easily identified. Furthermore, the background in this region of the spectra was negligible. Again, the (d, α) cross sections were normalized with the monitor counter and the aid of the known elastic cross sections from Ref. 26. The (d, α) cross sections for the three states for each angle were then compared to the α counts for these states in the spectrograph spectra. Thus, there existed three independent normalization constants for each angle, and their weighted average was taken as the final normalization. The same procedure was followed for all angles of interest.

3. *Experimental Errors*

(1) Zero-angle error: The θ-reading accuracy was checked and corrected prior to the experiment. The remaining error was $\Delta\theta < 0.2°$.

(2) Errors in the cross sections:

(a) Random errors are represented by vertical bars in Figs. 4 and 6. They are due to counting statistics, background subtraction, the ambiguity in separating poorly resolved neighboring doublets or multiplets, and random monitoring uncertainties.

(b) Scale error: The dominant factors contributing to this error are the uncertainty of the elastic cross-section values employed, as well as errors in θ and the solid angle for the monitor counter. Elastic deuteron scattering data on the Zn^{66} isotope for the correct deuteron energy (12.08 MeV) were unavailable; accordingly, the Heidelberg data[26] taken with a natural Zn target at 11.8 MeV were used as the basis for this normalization. In order to correct for the difference in energy and isotope, the Heidelberg values were extrapolated by optical-model calculations to Zn^{68} to 12.08 MeV. This correction should lead to errors below 5%. Here are the significant scale-error contributions:

(i) Error in the elastic scattering cross section[26] is $\pm 5\%$.
(ii) Error due to the monitor angle ($\Delta\theta = 1°$) is $\pm 10\%$.
(iii) Error due to the solid angles is $\pm 5\%$.

Thus the total scale error for $Zn^{66}(d, \alpha)Cu^{64}$ is estimated to be $\pm 13\%$.

[26] G. Mairle and U. Schmidt-Rohr, Max Planck Institut für Kernphysik, Report No. 1965 IV 113 (unpublished).

III. EXPERIMENTAL RESULTS AND DWBA ANALYSIS

A. $Cu^{63}(d, p)Cu^{604}$ Reaction

Figure 4 shows experimental angular distributions for (d, p) transitions to final states up to 3-MeV excitation of Cu^{64}, which are compared with DWBA curves calculated for the relevant l transfers (solid lines). The calculations were made with the DWBA code DWUCK,[27] which incorporates finite-range and nonlocality corrections into the conventional zero-range DWBA with local potentials.

The value of 0.621 for the finite-range parameter, suggested by Goldfarb,[28] was used. The recommended nonlocality parameters[28] of $\beta_p = 0.85$ and $\beta_d = 0.54$ were employed for the free-proton and -deuteron channels, respectively; in some calculations a range parameter of 0.85 was tried for the bound neutron. The optical potentials used are listed in Table I. The deuteron-channel optical-model parameters are from work by Perey and Perey,[29] obtained by a six-parameter analysis of the deuteron elastic scattering from Cu at 11.8 MeV. The proton-channel potential parameters are from work by Perey,[30] obtained also by a six-parameter analysis of the proton elastic scattering from Cu at 17 MeV. The well geometries for the bound neutron were the standard set of $a = 0.65$ F, $r_0 = r_c = 1.25$ F. l values for the transitions and spectroscopic factors were extracted by comparing the experimental angular distributions with these calculations. From shell-model-structure considerations the (d, p) transitions are expected to go by $l = 1$, 3 or their mixture to positive-parity final states, and by $l = 0$, 2, 4 or their mixture to negative-parity states, as J^π of the target is $3/2^-$. DWBA calculations agree well with the data for all transitions except for $l = 0$ and 4. All our $l = 0$ angular distributions in Fig. 4 have a second stripping peak which is sharper than that of the DWBA calculations. The $l = 0$ experimental angular distribution for the transition to the 2.611 state of Cu^{64} was chosen as the best empirical curve, which was then used for identifying other $l = 0$ transitions. The observed $l = 4$ transfers tend to have a rise at forward angles while the calculated ones do not. Nevertheless, the majority of the angular distributions are distinctive enough to give unique l assignments and, therefore, correct J^π limits. Uncertain l values are put in parentheses in Fig. 4 and Table II.

The extraction of spectroscopic factors was achieved by the aid of the relation

$$\left(\frac{d\sigma}{d\Omega}\right)_{lj}^{\text{expt}} = 1.5\,\frac{2I_f+1}{2I_i+1}\,S_{lj}\left(\frac{2S+1}{2}\,\frac{\sigma_{lj}^{\text{DW}}(\theta)}{2j+1}\right). \quad (1)$$

Here $(d\sigma/d\Omega)_{lj}^{\text{expt}}$ is measured absolute differential

[27] P. D. Kunz, University of Colorado, 1967 (unpublished).
[28] As listed in the manual for DWUCK written by P. D. Kunz (unpublished).
[29] C. M. Perey and F. G. Perey, Phys. Rev. **132**, 755 (1963).
[30] F. G. Perey, Phys. Rev. **131**, 745 (1963).

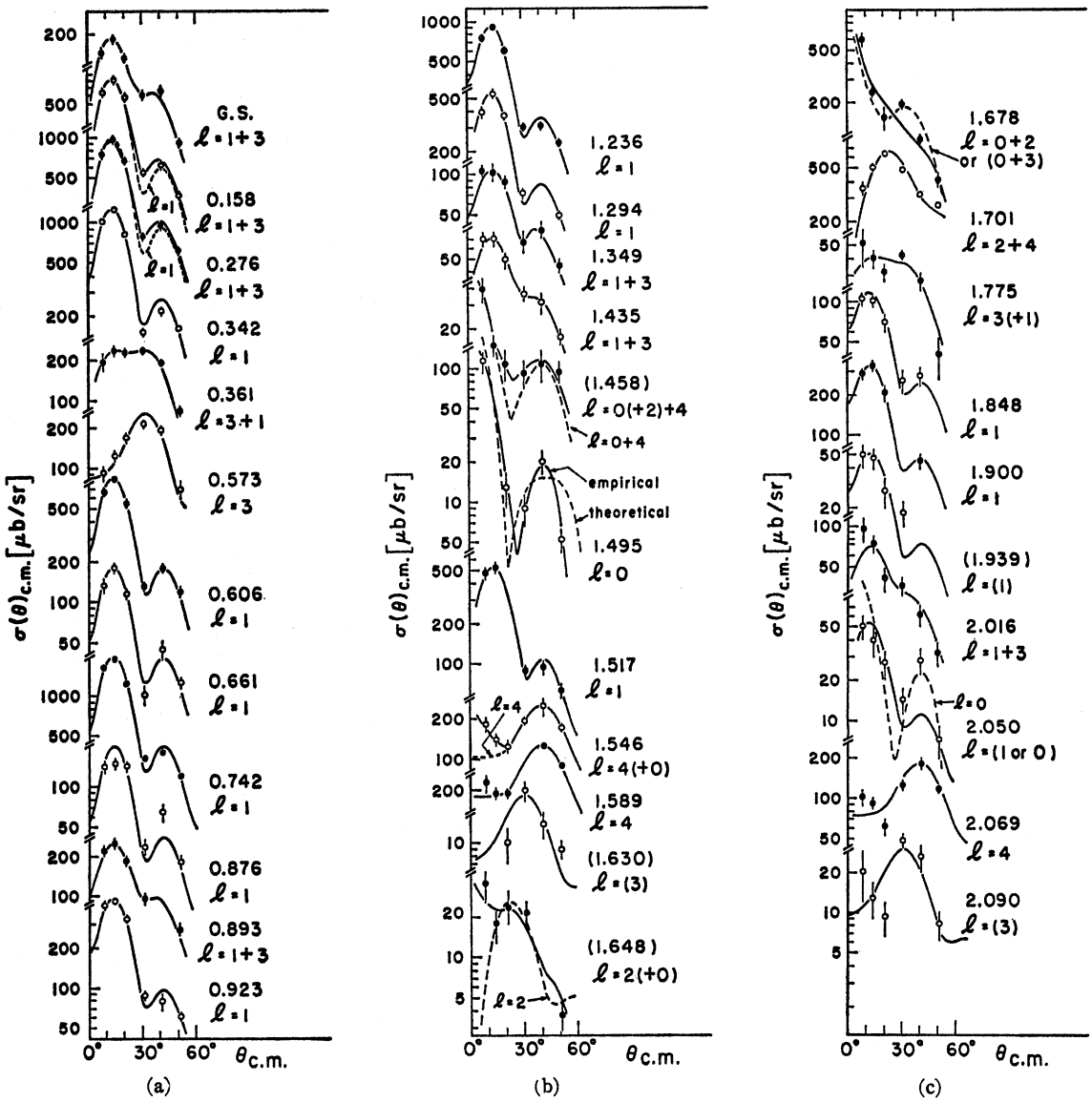

FIG. 4. Angular distributions for $Cu^{63}(d, p)Cu^{64}$ obtained at $E_d = 12.0$ MeV. The curves represent the DWBA predictions calculated by DWUCK (Ref. 27), which incorporates finite-range and nonlocal corrections into the conventional zero-range DWBA calculations with local potentials. The dotted curves represent alternative l transfers. Those that arise as the sum of two l values are so indicated. Error bars on the data points indicate all known random errors.

cross section; I_f and I_i are the spins of the residual and target nucleus, respectively; s and j are the spin and total angular momentum of the transferred particle, respectively; S_{lj} is the spectroscopic factor; and $\sigma_{lj}(\theta)^{DW}$ is the cross section calculated by the DWBA code DWUCK.[27] The present DWBA calculations include spin-orbit coupling for the neutron bound state. Experimentally, it was not possible to distinguish a $p_{3/2}$ transfer from a $p_{1/2}$ transfer because the j effect for an $l=1$ transfer is not observable at small angles. Thus, it was decided to take an average of the DWBA predictions for $j=\frac{3}{2}$ and $\frac{1}{2}$ transfers, and this average value was used for extracting the experimental spectroscopic factors. The values of "actual" spectroscopic factors for $j=\frac{3}{2}$ and $j=\frac{1}{2}$ transfers should then be 4.5% lower and 4.5% higher, respectively, than those listed. All $l=3$ transfers are interpreted as $j=\frac{5}{2}$ transfers on the assumption that the $1f_{7/2}$ shell is full. The spectroscopic factors for $l=4$ transfers were extracted on the basis of the DWBA cross sections for $j=\frac{9}{2}$ transfers, since $g_{7/2}$ stripping is unlikely for levels below 3 MeV. However, if any one of the analyzed $l=4$ transitions should later be identified as $g_{7/2}$, its listed spectroscopic factors should be multiplied by 1.67.

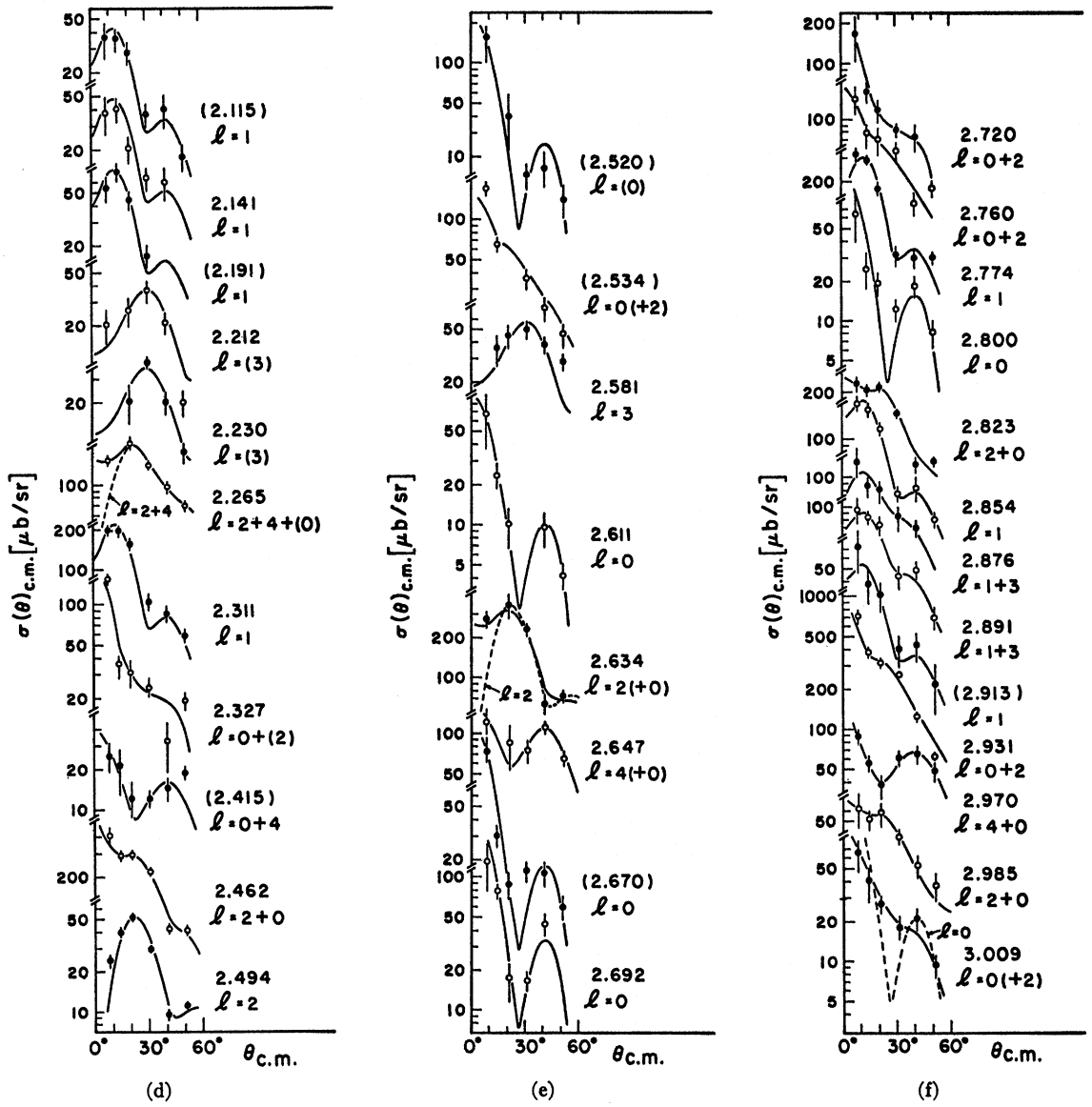

FIG. 4 (*Continued*)

The spectroscopic factors for $l=2$ transfers listed in Table II were obtained on the basis of calculated $d_{5/2}$ cross sections, since the single-particle energy of the $2d_{5/2}$ orbit is lower than that of the $2d_{3/2}$ orbit. However, some low $d_{3/2}$ transitions may be expected, and in such cases the listed spectroscopic factors should be multiplied by 1.3 to obtain those for $d_{3/2}$ transfers. The spectroscopic factors for $l=0$ transfers were obtained by comparing the experimental angular distributions to the DWBA curves at the smallest angles only, since

TABLE I. Optical-model parameters used in the $Cu^{63}(d, p)Cu^{64}$ distorted-wave calculations.

		Real-well parameters				Imaginary-well parameters			
Channel	Ref.	V (MeV)	a (F)	r_0 (F)	r_c (F)	W_{vol} (MeV)	W_{surf} (MeV)	a' (F)	r_0 (F)
d-Cu	29	90.7	0.822	1.172	1.172	...	73.36	0.661	1.410
p-Cu	30	45.67	0.668	1.301	1.25	...	69.76	0.343	1.305

TABLE II. A listing of level energies from the present Cu^{64} studies in comparison with earlier work, and a listing of the extracted angular momentum transfers $l_{d,p}$ and $L_{d,\alpha}$ and maximum cross sections for the $Cu^{63}(d,p)Cu^{64}$ and $Zn^{66}(d,\alpha)Cu^{64}$ reactions as well as (d,p) spectroscopic strengths. J^π assignments derived from the (d,p) and (d,α) results are tabulated and compared with tentative J^π assignments from $Cu^{65}(n,\gamma)$ studies. Bracketed values denote tentative assignments. If used after other values, brackets denote less likely assignments which have not been ruled out.

Present work								Ref. 21 (n,γ) (d,p)	Ref. 13 (n,γ)	
	$Cu^{63}(d,p)$				$Zn^{66}(d,\alpha)$					
Excitation energy E^* (MeV)	l_n	$(d\sigma/d\Omega)_{max}$ (μb/sr)	$(2J+1)S$	J^π limit	L	$(d\sigma/d\Omega)_{max}$ (μb/sr)	J^π assignment	E^* (MeV)	J^π assignment	J^π (best value)
0	1	190	0.17	1^+–3^+	0+(2)	40	1^+	0	1^+	1^+
	3	52	0.73							
0.158	1	962	0.84	1^+–3^+	2(+0)	(14)	$2^+(1^+)$	0.159	(2^+)	2^+
	3	78	1.09							
0.276	1	1100	0.85	1^+–3^+	2	4.5	$2^+(1^+3^+)$	0.278	2^+	2^+
	3	67	0.92							
0.342	1	1420	1.18	0^+–3^+	weak		(2^+0^+)[a]	0.344	(1^+2^+)	2^+
0.361	1	157	0.14	1^+–3^+	4	44	3^+	0.362	(3^+)	3^+
	3	246	3.29							
...	not seen				not seen		...	0.557	b	...
0.573	3	290	3.64	1^+–4^+	4	17	$4^+(3^+)$	(0.574)[c]	(4^+)	4^+
0.606	1	930	0.74	0^+–3^+	2	2	$2^+(1^+3^+)$[a]	0.609	(1^+2^+)	$2^+(1^+)$
0.661	1	202	0.16	0^+–3^+	4	8	3^+	0.663	(1^+2^+)	3^+
0.742[d]	1	2180	1.73	0^+–3^+	2+(4)	(70)	1^+–3^+	0.739	(2^+3^+)	(2^+3^+)
								(0.746)[c]	$(1^+2^+3^+)$	$(1^+2^+3^+)$
0.876	1	224	0.17	0^+–3^+	weak		(0^+2^+)	0.880	$(0^+1^+2^+)$	$0^+(1^+2^+)$
0.893	1	246	0.20	1^+–3^+	4	18	3^+	0.894	(2^+)	3^+
	3	74	0.89							
0.923	1	526	0.40	0^+–3^+	0+(2)	38	1^+	0.927	(1^+2^+)	1^+
1.236	1	1030	0.74	0^+–3^+	(0+2)	2	1^+2^+[a]	1.237		$2^+(1^+)$
(1.285)	very weak				not seen		...	(1.291)[c]		...
1.294	1	616	0.44	0^+–3^+	0+2	17	1^+	1.299		1^+
1.349	1	112	0.09	1^+–3^+	4(+2)	10	3^+	(1.352)[c]		3^+
	3	20	0.22							
(1.360)	not seen				very weak		...	1.362		...

TABLE II (*Continued*)

Excitation energy E^* (MeV)	l_n	Present work: $Cu^{63}(d, p)$ $(d\sigma/d\Omega)_{max}$ (μb/sr)	$(2J+1)S$	J^π limit	Present work: $Zn^{66}(d, \alpha)$ L	$(d\sigma/d\Omega)_{max}$ (μb/sr)	J^π assignment	Ref. 21 (n, γ) (d, p) E^* (MeV)	Ref. 13 (n, γ) J^π assignment	J^π (best value)
1.435	1	69	0.05	1^+–3^+	0+(2)	2.2	1^+	1.440		1^+
	3	13	0.15							
(1.458)[d]	0	~56	~0.005	1^-–2^-			1^-2^-	(1.464)[b,c]		1^-2^-
	(2)	(4)	(0.005)							
	4	7	0.093	3^-–6^-	3	3	(3^-4^-)			$3^-4^-(5^-6^-)$
1.495	0	~213	~0.018	1^-2^-	(1+3)	(4)	$2^-(1^-)$	1.497		$2^-(1^-)$
1.517	1	582	0.40	0^+–3^+	2+(4)	(10)	$3^+(2^+1^+)$	1.522		$3^+(2^+1^+)$
1.546[d] ?	4	280	3.68	(3^-–6^-)	(3+1)	(6)	$2^-(3^-4^-)$	1.547[b]		(3^-4^-)
	...				(or 2)		(1^+–3^+)			
1.589[d]	4	481	6.34	3^-–6^-	...		3^-–6^-	1.594		3^-–6^-
	...				4	14	$3^+4^+5^+$			$3^+4^+5^+$
1.607		very weak			0+(2)	3	1^+	...		1^+
(1.630)	(3)	(26)	(0.29)	(1^+–4^+)	not seen		...	...		...
(1.648)	(0)	(36)	(0.002)	(1^-2^-)	not seen		?	...		?
	2	24	0.022	0^-–4^-						
1.678[d]	0	~784	~0.063	1^-2^-	(1) or 0+2	3.5	1^-2^- (1^+)	1.683		1^-2^- (1^+)
	(3)	(123)	(1.23)	1^+–4^+						
1.701	2	672	0.64	0^-–4^-	3	(7)	3^-4^-	1.704[b]		3^-4^-
	4	179	2.35	3^-–6^-						
(1.737)	?	weak			4	20	$3^+4^+5^+$	...		$3^+4^+5^+$
1.775	(1)	(30)	(0.02)	$1^+2^+3^+(4^+)$	4	35	$3^+(4^+)$	1.780		$3^+(4^+)$
	3	37	0.38							
1.848	1	132	0.09	0^+–3^+	4	5.5	3^+	1.854		3^+
(1.884)	weak				(2 or 3)	(2)	?	...		?
1.900	1	370	0.245	0^+–3^+	(0+2)	5	$1^+(2^+3^+)$	1.906		$1^+(2^+3^+)$
(1.939)	(1)	(56)	(0.04)	(0^+–3^+)	2(+0)	2	$1^+2^+3^+$	1.939[b]		$1^+2^+3^+$
1.980	(1 or 3)	(28)	?	(0^+–4^+)	4	50	$3^+4^+5^+$	...		3^+–5^+

TABLE II (*Continued*)

Excitation energy E^* (MeV)	Present work: $Cu^{63}(d, p)$ l_n	$(d\sigma/d\Omega)_{max}$ (μb/sr)	$(2J+1)S$	J^π limit	Present work: $Zn^{66}(d, \alpha)$ L	$(d\sigma/d\Omega)_{max}$ (μb/sr)	J^π assignment	Ref. 21 (n, γ) (d, p) E^* (MeV)	Ref. 13 (n, γ) J^π assignment	J^π (best value)
2.016	1	67	0.042	1^+–3^+	2	2	$2^+(3^+1^+)$	2.020[b]		$2^+(3^+1^+)$
	3	25	0.235							
2.050	(1) or (0)?	(60)	(0.039)	(0^+–3^+)	4(+2)	14	(3^+)	2.050		(3^+)
2.069	4	202	2.51	3^-–6^-	3	(9)	3^-4^-	2.072[b]		3^-4^-
2.090	(3)	(34)	(0.325)	1^+–4^+	2(+0)	(4)	$1^+2^+3^+$	...		$1^+2^+(3^+)$
(2.115)	1	47	0.028	0^+–3^+	not seen		$0^+(1^+2^+3^+)$	...		(0^+)
2.141	1	54	0.032	0^+–3^+	4+(2)	(12)	3^+	2.145		3^+
2.191	1	83	0.074	0^+–3^+	(4)	2.5	(3^+)	2.191[b]		(3^+)
2.212	(3)	(41)	(0.38)	(1^+–4^+)	not resolved		(1^+–4^+)	...		(1^+–4^+)
2.230	(3)	(39)	(0.36)	(1^+–4^+)	4	22	$3^+4^+(5^+)$	2.232[b]		3^+4^+
(2.249)	not seen				(2) or (1, 3)?	(2)	?	...		?
2.265[d]	...				?	7	?			?
	2	190	0.16	0^-–4^-						
	4	67	0.80	3^-–4^-			3^-4^-	(2.268)[b,c]		3^-4^-
...	not seen				not resolved		...	2.279		...
(2.294)	not seen				2 or (1, 3)?	5	?	...		?
2.311	1	246	0.142	0^+–3^+	4	6	3^+	2.316		3^+
2.327	0	~190	~0.017	1^-2^-	not seen		1^-2^-	...		1^-2^-
	(2)	(26)	(0.023)							
(2.354)	very weak				2 or (3)	5	?	...		?
2.375	weak				0+(2)	2	1^+	...		1^+
2.389	not seen or very weak				0+(2)	2	1^+	...		1^+
(2.415)[e]	0	~39	~0.004	1^-2^-	...		1^-2^-	...		1^-2^-
	4	15	0.168	3^-–6^-			3^-–6^-			3^-–6^-
	...				4	35	$3^+4^+5^+$	...		$3^+4^+5^+$
2.462	0	~504	~0.042	1^-2^-	(1)	(4.5)	1^-2^-	2.466		1^-2^-
	2	302	0.258							
2.494	2	58	0.050	0^-–4^-	3	(3.5)	$2^-3^-4^-$	2.498		$2^-3^-4^-$

TABLE II (*Continued*)

Excitation energy E^* (MeV)	Present work: $Cu^{63}(d, p)$ l_n	$(d\sigma/d\Omega)_{max}$ (μb/sr)	$(2J+1)S$	J^π limit	$Zn^{66}(d, \alpha)$ L	$(d\sigma/d\Omega)_{max}$ (μb/sr)	J^π assignment	Ref. 21 (n, γ) (d, p) E^* (MeV)	Ref. 13 (n, γ) J^π assignment	J^π (best value)
(2.520)[d]	(0)	(280)	(0.023)	(1^-2^-)	...		(1^-2^-)	...		(1^-2^-)
	...				[0+(2)]	3	(1^+)			(1^+)
(2.534)[d]	0	~168	0.014		...		1^-2^-	2.534[b]		1^-2^-
	(2)	(58)	(0.049)	1^-2^-	[0+(2)]	3	(1^+)			1^+
	...									
(2.550)	not seen				4(+2)	6	$3^+4^+(5^+)$	...		$(3^+4^+5^+)$
2.581	3	63	0.515	1^+–4^+	4+(2)	12	$3^+(4^+)$	2.576		$3^+(4^+)$
(2.596)	not seen or very weak				(0+2)	4	(1^+)	...		(1^+)
2.611)[d]	0	~134	~0.012	1^-2^-	...		1^-2^-	...		1^-2^-
	...				4	17	$3^+4^+5^+$			$3^+4^+5^+$
(2.622)	not seen or weak				0+2	2.5	1^+	...		1^+
2.634[d]	0 or (1)	(280)	(0.023)		0+(2)	20	1^+			1^+
	2	336	0.27	0^-–4^-	...		0^-–4^-	2.636		0^-–4^-
2.647[d] ?	(0)	(202)	(0.017)	(1^-2^-)	not seen		?	...		?
	4	103	1.17	$(2^-$–$6^-)$						
(2.670)	0	~224	~0.019	1^-2^-	[3(+1)]	(3)	$2^-(1^-)$	...		$2^-(1^-)$
2.692[d] ?	0	~336	~0.028	1^-2^-	1(+3)		1^-2^-	...		1^-2^-
	...				or 4+(2)?	30	$3^+(4^+)$?			(3^+)?
2.720[d] ?	0	~224	~0.019	1^-2^-	3(+1)	(9)	1^-2^-	2.727		1^-2^-
	2	37	0.03		or 2?		$(1^+2^+3^+)$?			?
2.760[d]	0	~190	~0.016	1^-2^-	(3)?	(35)	1^-2^-	2.764		1^-2^-
	2	65	0.053		or 2+4	35	(3^+)			(3^+)
2.774	1	336	0.180	0^+–3^+	not resolved		0^+–3^+	...		0^+–3^+
2.800	0	~146	~0.012	1^-2^-	not seen or not resolved		1^-2^-	...		1^-2^-
(2.814)	not seen				(0+2)	5	(1^+)	...		(1^+)

TABLE II (*Continued*)

Excitation energy E^* (MeV)	l_n	Present work: $Cu^{63}(d, p)$ $(d\sigma/d\Omega)_{max}$ (μb/sr)	Present work: $Cu^{63}(d, p)$ $(2J+1)S$	Present work: J^π limit	Present work: $Zn^{66}(d, \alpha)$ L	Present work: $Zn^{66}(d, \alpha)$ $(d\sigma/d\Omega)_{max}$ (μb/sr)	Present work: J^π assignment	Ref. 21 (n, γ) (d, p) E^* (MeV)	Ref. 13 (n, γ) J^π assignment	J^π (best value)
2.823[d] ?	0	~280	~0.023	1^-2^-	(3)	(7)	1^-2^-	2.830		1^-2^-
	2	213	0.172		or (2)?		$(1^+2^+3^+)$?			?
2.854[d] ?	1	218	0.116	0^+–3^+	...		0^+–3^+	2.860[b]		0^+–3^+
	...				(3)?	(3)	$(2^-3^-4^-)$?			?
2.876	1	101	0.054	1^+–3^+	4	25	3^+	2.876[b]		3^+
	3	39	0.29							
2.891	1	90	0.048	1^+–3^+	0+(2)	5	1^+	2.895		1^+
	3	18	0.140							
(2.913)	1	60	0.031	0^+–3^+	(0+2)	(8)	$1^+(2^+)$	...		$1^+(2^+3^+)$
2.931	0	~784	~0.065	1^-2^-	[3(+1)]	(2)	$2^-(1^-)$	2.934[b]		$2^-(1^-)$
	2	324	0.258							
2.970[e] ?	0	~112	~0.008	1^-2^-	...		1^-2^-			1^-2^-
	4	67	0.72	$(3^-$–$6^-)$			$(3^-$–$6^-)$	2.975[b]		$(3^-$–$6^-)$
	...				4	28	$3^+4^+5^+$			$3^+4^+5^+$
2.985	0	~78	~0.006	1^-2^-	f		1^-2^-	...		1^-2^-
	2	56	0.043							
3.009	0	~123	~0.011	1^-2^-	f		1^-2^-	...		1^-2^-
	(2)	(25)	(0.019)							
3.030	2	202	0.161	0^-–4^-	f		0^-–4^-	3.032[b]		0^-–4^-
3.043	weak				f		...	...		...
3.055	?	~78	?		f		...	...		...
3.077	4	47	0.49	2^-–6^-	f		2^-–6^-			2^-–6^-
3.089	(4)	(123)	(1.17)	$(2^-$–$6^-)$	f		$(2^-$–$6^-)$	3.087		$(2^-$–$6^-)$

[a] Strong in (d, t).
[b] Not seen in (n, γ).
[c] Not adopted.
[d] Doublet.
[e] Triplet.
[f] Not analyzed.

they failed to reproduce the second maximum of an observed angular distribution.

There have been doubts as to the need for inclusion of nonlocality corrections into the potential for the neutron bound state,[31] and it has been suggested[32] that the nonlocality correction should be applied to the elastic waves only. We investigated both approaches and found no difference in the (d, p) angular distributions. However, without bound-state nonlocality the calculated cross sections are about 20% lower than those obtained when the nonlocality correction was applied to all three waves.

The spectroscopic factors obey sum rules related to the occupation probabilities V_j^2 and U_j^2 appearing in pairing theory.[33-35] For an odd-even target nucleus Yoshida[36] gives

$$\sum_{\kappa,I_f}(2I_f+1)S_{jI_f}^{\kappa}(d,p)\approx(2I_i+1)(2j+1)U_j^2, \quad (2)$$

$$\sum_{\kappa,I_f}S_{jI_f}^{\kappa}(d,t)\approx(2j+1)V_j^2, \quad (3)$$

where U_j^2 and V_j^2 are the emptiness and fullness of a single-particle state j of the target nucleus.

When Eq. (2) was summed for all $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ spectroscopic factors, we found $\sum\sum S_{jI_f}^{\kappa'}=20$ with bound-state nonlocality and $\sum\sum S'=24.5$ without. Provided all p and f transitions are detected, the expected value for the right-hand side would be 24 (as there are about six neutrons in the $2p-1f_{5/2}$ shell). The spectroscopic factors obtained from calculations with nonlocality only in the scattered waves are presented in Table II along with the measured excitation energies E^*, l values, J^π limits, and the maximum absolute cross sections $(d\sigma/d\Omega)_{\max}$, at $\theta_{\text{c.m.}}=0°$, 13°, 23°, 31°, and 39° for $l=0$, 1, 2, 3, and 4, respectively. The relative spectroscopic factors for single l transfers except those for $l=0$ transfers are believed to be accurate within $\pm10\%$; those for mixed l transfers are uncertain to about $\pm25\%$, because of an appreciable ambiguity in the fitting procedure; those involving $l=0$ transfers may be uncertain by more than $\pm30\%$, owing to the uncertain extrapolation of data to $\theta=0°$.

Some recent DWBA calculations[37,38] have used $r_0=1.2$ instead of 1.25. The effect of changing the radius r_0 for the well geometry of the form factor on the predicted cross sections for $Cu(d, p)$ was also studied; a reduction of $\sim20\%$ in cross sections was observed for all of the l transfers.

Varying differences in cross sections were observed between the calculation with inclusion of finite-range and nonlocality corrections and the conventional local, zero-range calculations. The zero-range cross sections for $l=0$, 1, 2, 3, and 4 transfers were larger than those for finite-range, nonlocality calculations by +20, −8, +2.5, −4 and +4%, respectively.

B. Spin Assignments from Spectroscopic Factors

The occupation probability U_j^2 for a given j can be determined from Eq. (2). Once U_j^2 is known, spin assignments for members of multiplets resulting from the vector-coupling of j and the target spin, may be feasible through the sum rule[39]

$$\sum_{\kappa}(2I_f+1)S_{jI_f}^{\kappa}(d,p)=(2I_f+1)U_j^2, \quad (4)$$

where the sum is to be taken over all the components $S_{jI_f}^{\kappa}$ for like-j transfer and I_f. The sum rule, when applied to the $f_{5/2}$ neutron transfer, may thus help pinpoint the J^π assignments of 1^+, 2^+, 3^+ and 4^+ for the members of the $(\frac{3}{2}, \frac{5}{2})$ quadruplet, provided that the strengths for the I_f are not further fractionated. Equation (2), with the measured spectroscopic factors for $l=3$ in Table II, gives $U_{5/2}^2=0.58$. This value, of course, depends on our particular DWBA calculations, which may not fully represent the actual situation. The average values of theoretical predictions and various experimental (d, p) and (d, t) results available in the literature have been tabulated by Bayman and Hintz[40] for the Ni isotopes. Assuming that the neutron configurations and the U_j^2 of the $f_{5/2}$ single-particle state are identical for Cu^{63} and Ni^{62}, it might be justifiable to adopt the average value of $U_{5/2}^2=0.60$ quoted from Ref. 40, which is in full agreement with our value of 0.58. The predicted spectroscopic strength [the right-hand side of Eq. (4)] then becomes 1.8, 3.0, 4.2, and 5.4 for $I_f^\pi=1^+$, 2^+, 3^+, and 4^+ levels, respectively.

The observed spectroscopic strengths for the $f_{5/2}$ single-particle state are plotted versus excitation energy at the top of Fig. 5; the numbers at the top of individual vertical bars whose lengths represent the values of $(2I+1)S$ are our best J^π assignments for which detailed arguments are given in Sec. IV. Also shown in Fig. 5 are the predicted strengths for given I_f (the right-hand scale). A survey of Fig. 5 reveals the difficulty of applying the sum rule to the $f_{5/2}$ transfer: The strengths are widely fractionated and as a result not a single level meets the predicted strength for a certain I_f. The sum of strengths for 1^+ levels exceeds the predicted value if the (1^+) assignment for the 1.678 level is taken seriously. The sum of all 3^+ strengths also is found to exceed the prediction. The sums of 2^+ and

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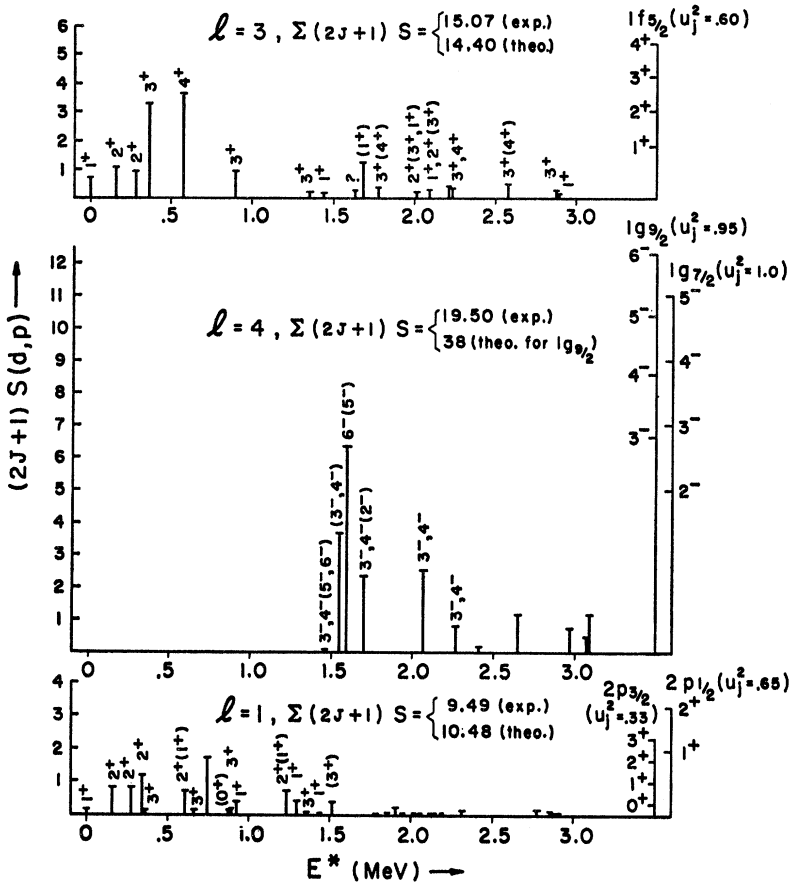

FIG. 5. Spectroscopic strengths for $l=3$, 4, and 1 transfers for $Cu^{63}(d, p)Cu^{64}$. The vertical bars denote the values of spectroscopic factors up to 3-MeV excitation associated with a certain l transfer. Our best J^π assignments are shown at the top of the bars. The predicted strengths for J_f's of members belonging to a certain l transfer are indicated on the right-hand side scale; the values of U_j^2 are derived from Ref. 40.

4^+ strengths, on the other hand, are short of the predicted values.

An attempt to apply the sum rule for the $g_{9/2}$ transfer to identify 3^-, 4^-, 5^-, and 6^- members of the quadruplet also met with a failure. This is immediately recognized from Fig. 5, where the strength distribution for $l=4$ transfers is shown in the center section. The indistinguishability between the $p_{3/2}$ and $p_{1/2}$ transfers in the present work diminishes a possibility of applying the sum rule to identify J^π for either transfer.

C. $Zn^{66}(d, \alpha)$ Reaction

Angular distributions for transitions to the states of Cu^{64} populated in the $Zn^{66}(d, \alpha)$ reaction are shown in Fig. 6. They are characterized by orbital angular momenta L carried by the transferred proton-neutron pair. The transitions can proceed by either pure L's or by mixtures of two L's according to conservation rules for direct (d, α) reactions on 0^+ targets.

All curves represent distorted-wave calculations performed in the manner described in Sec. IV of Paper I.[1] In judging the quality of agreement, it should be remembered that neither cutoffs nor arbitrary parameter changes were employed in the calculations presented in Fig. 6. The calculated curves for pure transfers or a mixture of two L transfers are arbitrarily normalized with regard to the observed angular distributions, whose absolute cross sections are shown for c.m. angles from 10° to 90°. The dotted curves represent possible alternatives for L transfers in cases where assignments of L values are not considered unique. The angular distributions which seemingly correspond to mixed L transfers are compared to theoretical curves generated by a mixture of two curves of allowed L's; the degree of the mixture is denoted in such a manner that

$$\sigma_{\text{mix}}^{\text{theoret}}(\theta) = a_{l_1}^2 \sigma_{l_1}(\theta)^{\text{theoret}} + b_{l_2}^2 \sigma_{l_2}(\theta)^{\text{theoret}},$$

in which $a_{l_1}^2$ and $b_{l_2}^2$ measure the fractions of $\sigma_{l_1}(\theta)^{\text{theoret}}$ and $\sigma_{l_2}(\theta)^{\text{theoret}}$ mixed in, respectively, expressed in percentages. L values so determined are listed in Fig. 6 and in Table II, in which we also present $(d\sigma/d\Omega)_{\max}$, the maximum cross sections at $\theta_{\text{c.m.}}=48°$, 36°, and 26° for $L=0$, 2, and 4, respectively. For the angular distributions corresponding to the other L's and having no distinctive maxima, the $(d\sigma/d\Omega)_{\max}$ are those at $\theta_{\text{c.m.}} \simeq 10°$.

IV. J^π ASSIGNMENTS: DISCUSSION OF INDIVIDUAL LEVELS

A detailed account of the procedure by which J^π assignments for levels of odd-odd Cu isotopes can be

achieved via direct (d, α) and (d, p) reactions has been outlined in Paper I[1] and is not repeated here. Although angular distributions were not taken for the $Cu^{65}(d, t)Cu^{64}$ reaction, a high-resolution spectrum of this reaction taken at $\theta_L = 35°$, shown in Fig. 7, can be exploited as an auxiliary aid for J^π assignments, for the population of states in (d, t) reactions is subject to well-known selection rules that differ from those for (d, α).

J^π assignments for states below 1-MeV excitation of Cu^{64} were previously reported by us[12] and independently by Shera and Bolotin,[13] who studied γ decay following thermal neutron capture. Thus, reliable assignments can be made for these levels by comparing the two independent results. For the levels above 1-MeV excitation no assignments were provided by (n, γ) or any other work, and therefore the assignments are based entirely on our (d, p) and (d, α) work. As a consequence the J^π assignments made for those levels are somewhat less certain. A possible source of error also results from the fact that a considerable fraction of levels above 2-MeV excitation may belong to multiplets that remain unresolved even with our experimental resolution of $\sim$8 keV. A rough estimate suggests that at least 25% of the levels in this energy interval remain unresolved in this investigation.

J^π assignments based on (d, p), (d, α), and (d, t) reactions, excitation energies adopted by the *Nuclear Data Sheets*,[21] J^π assignments given by Shera and Bolotin,[13] and the best J^π value suggested by comparing the two independent results are listed in Table II; the values in parentheses are either uncertain assignments or less favored choices still consistent with our data.

The ground state is known to have $J^\pi = 1^+$, which is also the unique assignment from our (d, α) angular distribution. The (d, α) angular distribution for the transition to the first excited state at 0.158 MeV has a peculiar shape which none of the calculated curves fit well. The transition may, nevertheless, be recognized as containing $L = 2$, plus possibly a weak $L = 0$ admixture. Thus, the choices for J^π are 2^+ and possible 1^+ in agreement with the (d, p) J^π limits. 1^+ is ruled out, however, by the (n, γ) work,[13] because the state is fed by a strong γ decay from the 0.361 state to which 3^+ is assigned by both experiments, and the observation that $M1$ is the predominant decay mode at such low γ energy.

The (d, α) transition to the 0.276 level is made by pure $L = 2$, and thus the most likely candidate for J^π is 2^+, with 1^+ and 3^+ as allowed alternatives. However, 3^+ is ruled out as the strongest γ transition goes to the 1^+ ground state; 1^+ is ruled out as the state is fed by a reasonably strong γ decay originating from the 0.661 state for which 3^+ is our unique assignment.

The 0.342 state is very weakly populated in the (d, α) reaction and its angular distribution has not been obtained. On the other hand, the state is strongly excited in (d, t), suggesting that we have a proton-neutron hole state in a rather pure $(2p_{3/2}^{\pi}, 2p_{3/2}^{\nu})$ configuration with $J^\pi = 0^+$ or 2^+. 0^+ is ruled out, however, from the (n, γ) work.

Our $J^\pi = 3^+$ assignment for the 0.361 state is unique and also agrees with the value suggested by (n, γ). A state at 0.557 MeV listed in the *Nuclear Data Sheets*[21] has been seen neither in the three reactions nor in the (n, γ) study by Shera and Bolotin.

The transition to the 0.573 state via the (d, α) reaction is made by a pure $L = 4$ transfer. Thus, the candidates for J^π are 4^+ and possibly 3^+. There is only one γ transition, to the 3^+ state at 0.361 MeV; and the absence of γ decays to any of the lower 2^+ states indicates that 4^+ is the best assignment. This decision is also supported by the observation that the (d, p) spectroscopic strength for the transition to the 0.573 state is largest among $l = 3$ transfers.

The state at 0.606 MeV is populated weakly in (d, α), yet an $L = 2$ transfer can be recognized. A strong transition is seen in (d, t), however, suggesting a predominantly $(j^2)_{J=\text{even}}$ configuration. Therefore, 2^+ is preferred, but both 1^+ and 3^+ are not definitely ruled out as the (d, α) strength is still noticeable. A strong γ transition to the ground state is seen in (n, γ), thus eliminating 3^+.

The overlap between the (d, α) and (d, p) J^π limits dictates 3^+ for the 0.661 state. Shera and Bolotin, however, assign $(1^+, 2^+)$ for the state. The discrepancy is easily resolved when one postulates $E2$ decay for the γ transition to the ground state. The 3^+ assignment is compatible with γ transitions to other states with J^π already assigned.

The state at 0.742 MeV is probably an unresolved doublet in both the (d, p) and (d, α) reactions. Some evidence for this is seen in the peak structure in the (d, t) spectrum in Fig. 7. The (n, γ) work deduces a doublet at the energies 0.739 and 0.746 MeV. At least one level of the doublet is strongly populated in all three deuteron-induced reactions. The transition appears to be a pure $l = 1$ in (d, p), but in (d, α) the L value for the transition is not very certain. Although an $L = 2$ component is definitely present, no combination of $L = 2$ and 4 satisfactorily fits the observed angular distribution everywhere, so that our data show only that the more strongly excited level has $J^\pi = 1^+$, 2^+, or 3^+. In (n, γ) neither level decays to the (1^+) ground state or to the 4^+ state at 0.574 MeV. The 0.739 level decays to all lower 2^+ and 3^+ states, which makes a $3^+(2^+)$ assignment most likely. The 0.746-MeV state decays only to the 0.276-MeV 2^+ state. It is fed by a level at 1.242 MeV [probably our 1.236-MeV level, for which our data indicates 1^+ or 2^+], hence the most probable assignment is $2^+(3^+)$.

There is only one γ transition from the 0.876 state observed and that is to the ground state. Thus 0^+, 1^+, and 2^+ are equally suited for J^π. The (d, α) transition to the state is very weak and the angular distribution was

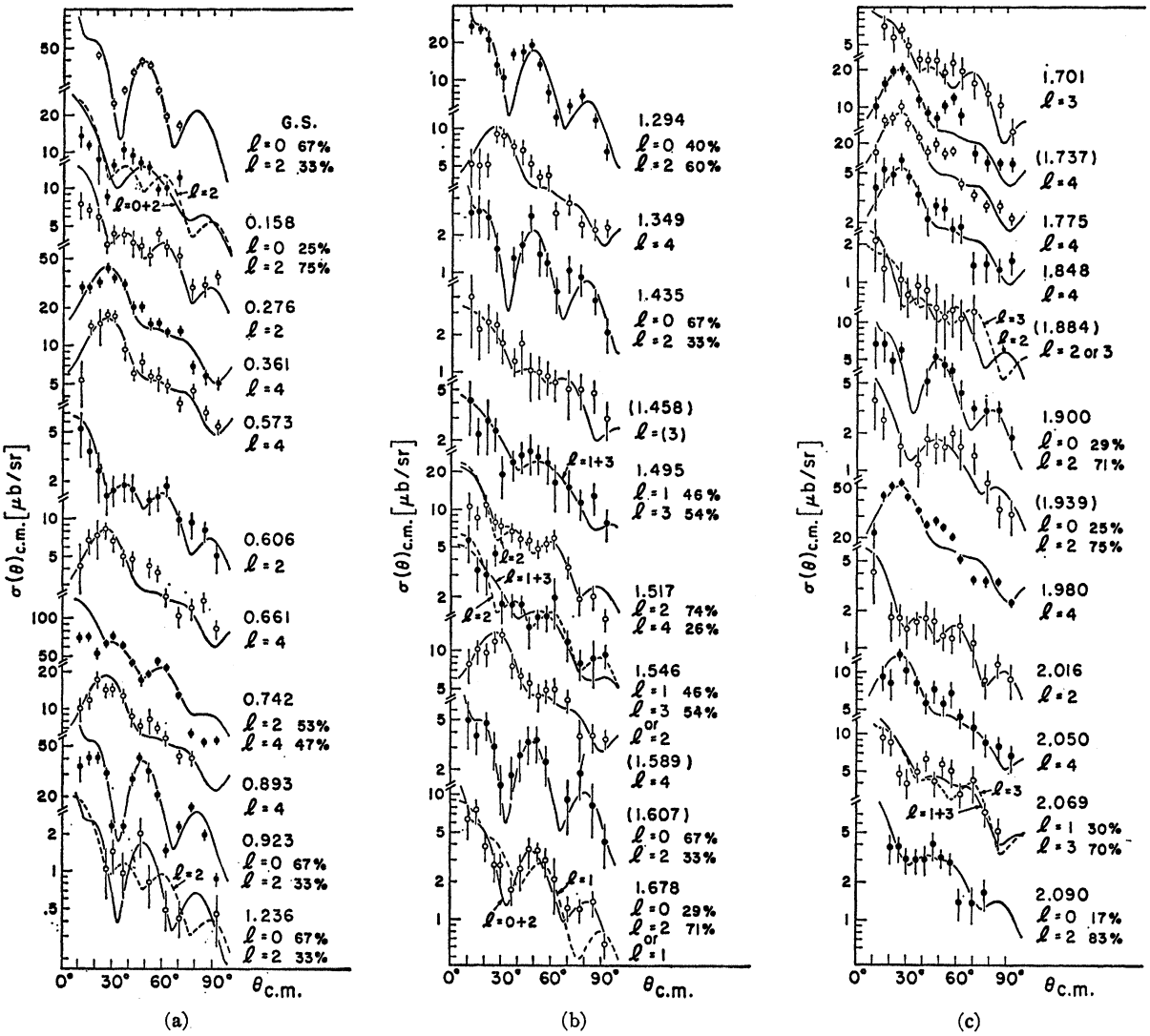

FIG. 6. Angular distributions for $Zn^{66}(d, \alpha)Cu^{64}$ obtained at $E_d = 12.08$ MeV. All curves represent DWBA calculations (as described in the text) which are normalized arbitrarily with respect to observed angular distributions (see also the caption for Fig. 4).

not obtained. The (d, t) transition, on the other hand, is strong enough for us to assume $(0^+, 2^+)$ as the probable candidates. The evidence for a $(j^2)_{J=\text{even}}$ configuration is not established beyond doubt, however, and so we assign $0^+(2^+, 1^+)$. This level is the best candidate for the low-lying $(2p_{3/2^\pi}, 2p_{3/2^\nu})_{0+}$ configuration.

The (d, p) and (d, α) J^π limits dictate 3^+ for the 0.893 state which is in conflict with the (2^+) assignment by Shera and Bolotin. If the extremely weak γ decay to the ground state is classified as $E2$, the 3^+ assignment is compatible with $M1$ decay modes for all other and stronger γ transitions.

The state at 0.923 MeV is uniquely determined as 1^+ by the (d, α) angular distribution. $(1^+, 2^+)$ suggested by (n, γ) is in accord with this assignment.

The (d, p) data for the 1.236 state demands $0^+ \leq J^\pi \leq 3^+$. The (d, α) transition to the 1.236 state is very weak, with L being either 2 or an admixture of 2 and 0, which is indicative of 2^+ or 1^+. These limits and the fact that the state is weak in (d, α) but strongly excited in (d, t) suggest $J^\pi = 2^+$. The 2^+ assignment permits classification of all observed γ transitions from this state as $M1$.

A weak state is seen at $\sim$1.285 MeV in (d, t) and possibly in (d, p), but it is not resolved in (d, α). Shera and Bolotin see it as having a very weak γ transition to the 0.342 state. No assignments can be made.

The J^π assignments for the 1.294, 1.349, and 1.435 states follow uniquely from the (d, p) and (d, α) angular distributions. No γ-decay information pertinent

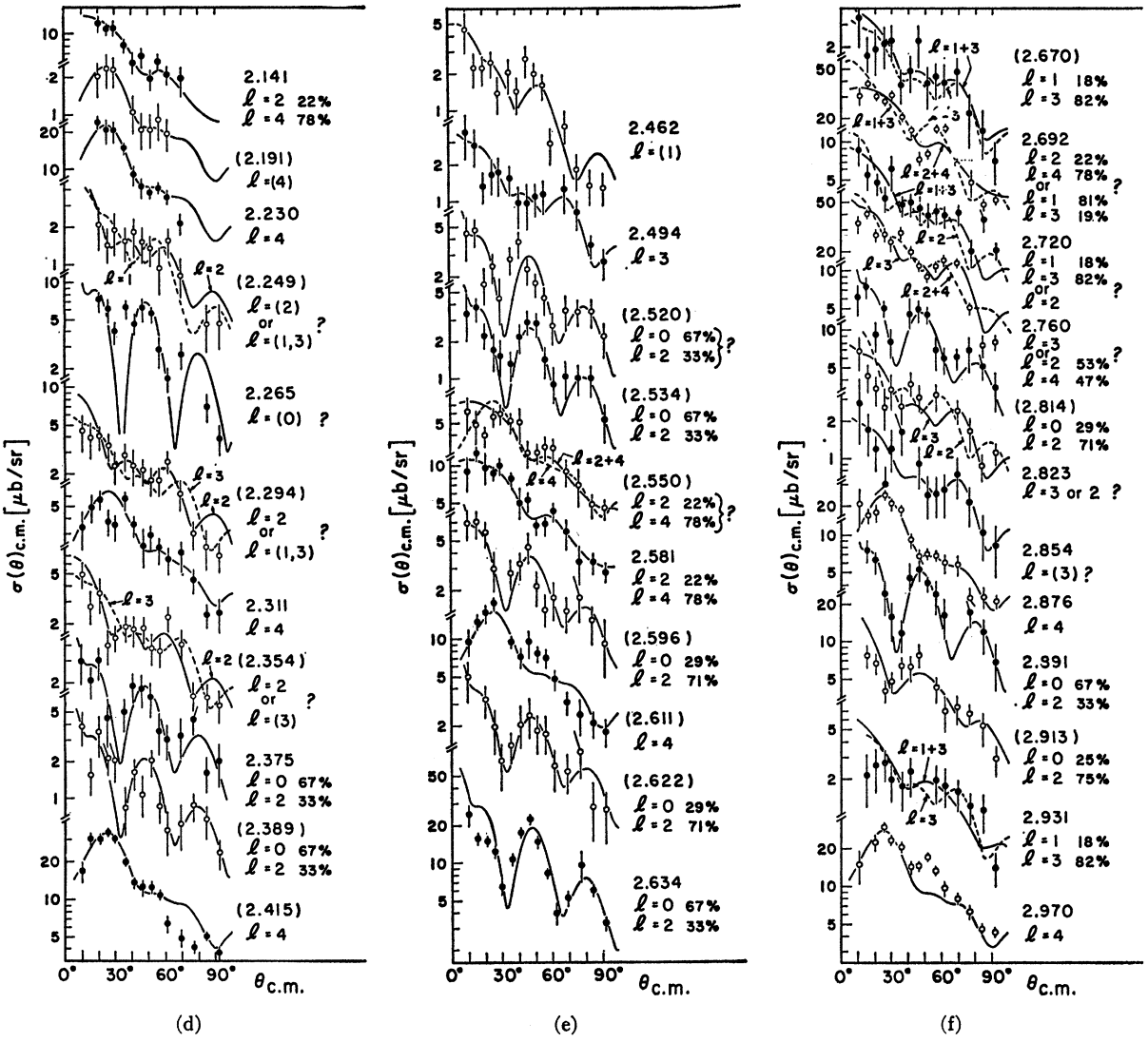

FIG. 6 (*Continued*)

to these levels is available. A very weak state is seen at ~1.360-MeV excitation in (d, α) and (d, t), but is not seen in (d, p); the state is seen in (n, γ) at 1.362 MeV.

One of the first major difficulties is met for the level at ~1.458 MeV. The level is weakly populated in all the reactions considered. The (d, p) angular distribution can best be fitted to an admixture of $l=0$ and 4. In order for the state to be a single state, $l=4$ must be associated with $1g_{7/2}$ instead of $1g_{9/2}$, but it would be rather difficult to explain a $1g_{7/2}$ component at such a low excitation energy. One is thus led to postulate a doublet with a spacing of less than 6 keV, since there is no broadening of the peak seen in any of the reactions. The (d, α) angular distribution can best be fitted to the $L=3$ curve, supporting the negative-parity assignments made above for the doublet.

The 1.495 state is also weakly populated in all of the three reactions. The (d, p) transition proceeds by $l=0$, thus limiting J^π to 1^- and 2^-. The extraction of the L value for the (d, α) transition is somewhat uncertain since the cross sections are very small, which is to be expected from a pickup of a pair involving a $1g_{9/2}$ neutron. 2^- is preferred to 1^-, however, as the (d, α) angular distribution is better fitted to an admixture of $L=1$ and 3 than a pure $L=1$.

For the state at 1.517 MeV the (d, α) transition is dominated by $L=2$. A weak $L=4$ component may be mixed in; hence $J^\pi=3^+(2^+, 1^+)$.

A strong $l=4$ (d, p) transition leads to a state at 1.546 MeV. Again, the weak (d, α) transition makes it difficult to single out the correct L value assignment. To conform with the negative-parity assignment from

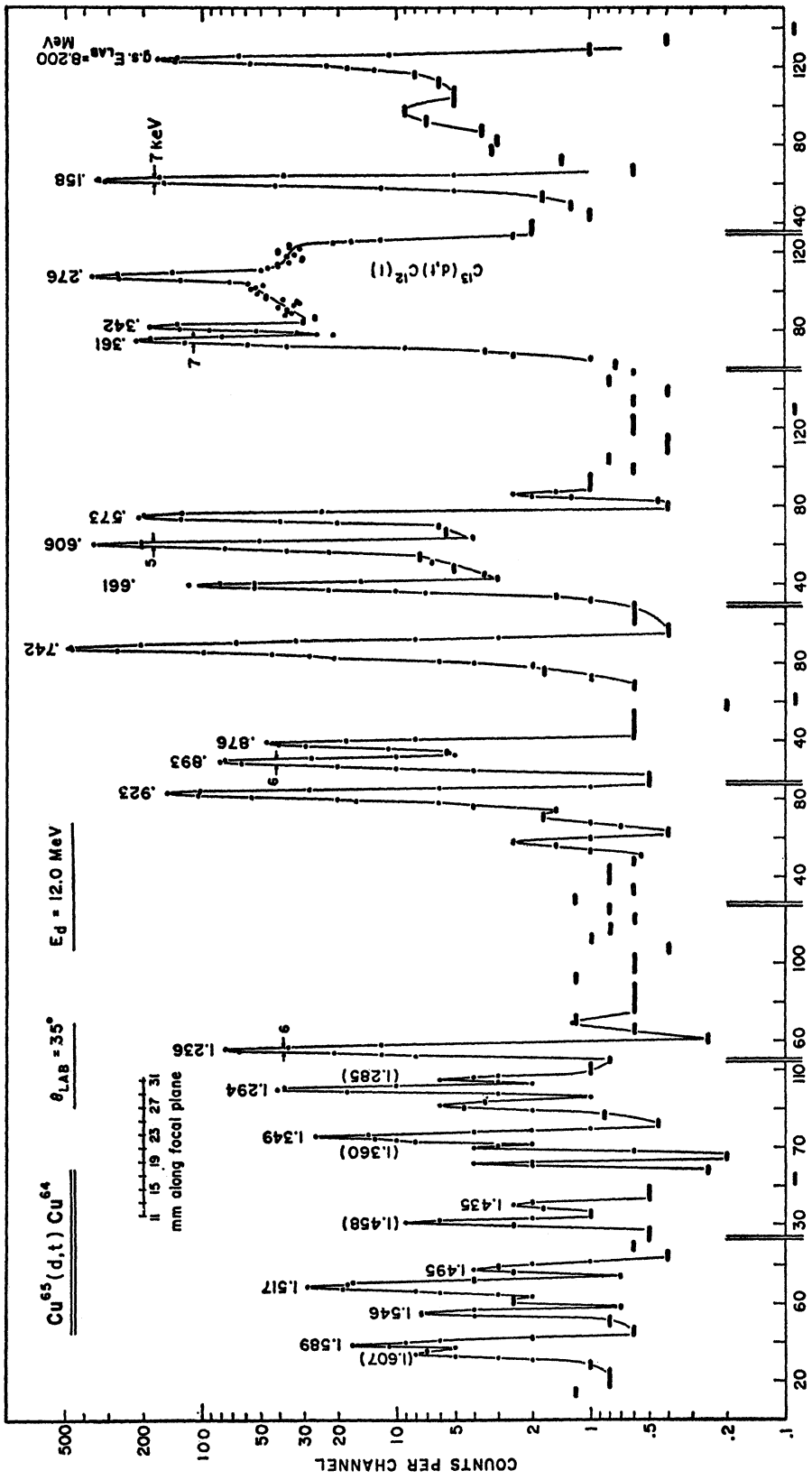

FIG. 7. Triton spectrum for $Cu^{65}(d, t)Cu^{64}$ taken at $E_d = 12.0$ MeV and $\theta_{lab} = 35°$. The spectrum was obtained with an array of four position-sensitive detectors in the Enge split-pole magnet spectrograph focal plane (see Ref. 19 for a detailed experimental procedure).

(d, p) the angular distribution can be roughly fitted to $L=1$, $1+3$, or possibly 3, but not to $L=5$; thus, $(3^-, 4^-)$ seem to be likely candidates. However, the (d, α) angular distribution can best be fitted by $L=2$ requiring positive-parity $(1^+, 2^+, 3^+)$ assignment. If this is the correct choice then the level must be a doublet, (d, p) exciting a negative-parity state and (d, α) exciting a positive-parity state. We prefer the first interpretation, since the level is only weakly excited in (d, α) and (d, t).

A state at 1.589 MeV is strongly populated by both reactions; the (d, p) transition is made by the strongest observed $l=4$, while the (d, α) transition is made by a strong $L=4$, indicating that the state is a doublet. The large (d, p) spectroscopic factor favors the larger values in the range $J^\pi=3^-$–6^-. No preferred choice can be made among 3^+, 4^+, and 5^+ for the positive-parity state, however.

The (d, p) transition to the 1.607 state is very weak, while the (d, α) transition is characterized by $L=0$, giving a unique assignment of 1^+.

The states at ~1.630 and ~1.648 MeV are observed neither in (d, α) nor in (n, γ). The (d, p) transitions are weak and the extracted l values are not firmly established.

The level at 1.678 MeV is strongly excited by the (d, p) transition, yet none of the curves fit the observed angular distribution well; the $l=0$ component is certain, but an admixture of either $l=2$ or 3 can reproduce the angular distribution. The (d, α) transition is not very strong, but the angular distribution is distinctly better fitted with an admixture of $L=0$ and 2 than by $L=1$. The conflict caused by the best l and L assignments can be resolved when a doublet for the level is assumed; the $l=0$ component in the (d, p) angular distribution narrows the J^π limit to $(1^-, 2^-)$ for the negative-parity state. The classification of $L=0+2$ for the (d, α) transition results in the unique assignment of 1^+ for the other member of the doublet, which would account for the $l=3$ component in the (d, p) angular distribution.

A strong (d, p) transition to a state at 1.701 MeV is recognized as an $l=2+4$ transfer. The (d, α) angular distribution fails to show much structure, yet it fully agrees with $L=3$.

An atypical shape of the weak (d, p) angular distribution for the transition to a state at ~1.737 MeV makes it difficult to extract an l value. On the other hand, the strong (d, α) transition can be identified as $L=4$; no admixtures constructed between $L=4$ and 2 reproduce the second maximum at around $\theta_{c.m.}=55°$. This "hump" at $\theta_{c.m.}=50°$–$55°$ seen on a fair fraction of $L=4$ transitions may possibly represent some J effect for $L=4$ transitions in the (d, α) reaction.

The angular distribution for the (d, p) transition to the 1.775-MeV level could be a pure $l=3$ or an admixture of $l=3$ and 1. We prefer the latter fit, and a 3^+ assignment is favored over 4^+.

The 3^+ assignment for the 1.848 state is unique unless we have a doublet. The state at ~1.884 MeV is too weakly populated in (d, p) and (d, α) to obtain a unique assignment.

The next two states at 1.900 and ~1.939 are both reached by a $l=1$ transfer in the (d, p) reaction. The L assignments in the (d, α) angular distributions for transitions to these states are not unique. An admixture of $L=0+2$ gives the best agreement for the 1.900 state, giving more weight to 1^+ than to 2^+ or 3^+. For the 1.939 state the evidence for admixture of $L=0$ is too weak to make any choice among 1^+, 2^+, and 3^+.

The (d, p) transition to the 1.980 state is very weak and its angular distribution is atypical, whereas (d, α) shows a strong $L=4$ angular distribution. Hence, we have a hole state with $J^\pi=3^+$, 4^+, or 5^+.

The 2.016 state is weakly populated in both reactions. Some preference is felt for 2^+, since the (d, α) angular distribution shows no evidence of an admixture.

The (d, p) transition to the 2.050 state is weak; the angular distribution can be associated with $l=1$ provided that a stray point at $\theta_{c.m.}=40°$ is discarded; $l=0$ would be the alternative choice. The (d, α) transition can be recognized either as $L=4$ or $L=4$ plus 2. Provided we do not have a doublet, $J^\pi=3^+$.

A strong $l=4$ transition to the 2.069 state is observed in (d, p). The (d, α) angular distribution compares well to a pure $L=3$ curve. 3^- and 4^- are therefore candidates for J^π.

The (d, α) angular distribution for the transition to the 2.090 state can be best fitted to an admixture of $L=2$ and 0, but evidence for the presence of an $L=0$ component is not strong, hence 1^+, 2^+, and 3^+ are permissible.

A level at ~2.115 MeV is weakly populated in (d, p) by an $l=1$ transfer. It is not at all seen in (d, α), pointing to $J^\pi=0^+$; unfortunately, there are no (d, t) data for this level to check the above assignment. The 3^+ assignment for the 2.141 state seems unique.

The angular distribution for the (d, α) transition to a state at 2.191 MeV is characteristic of $L=4$, although the number of data points is not large enough to allow a firm assignment. Thus, 3^+ is tentatively assigned to the level.

The (d, p) transitions to the 2.212 and 2.230 states are identified as $l=3$ transfers. The (d, α) transition to the 2.212 state is not resolved, so that no definite J^π assignment can be made. The (d, α) transition to the 2.230 state is clearly $L=4$, so that $J^\pi=3^+$ or 4^+. The identification of the level at ~2.249 MeV is subject to some doubt. The state is not seen in (d, p) and the (d, α) transition is extremely weak. No L or J^π assignments were attempted.

The (d, p) transition to the 2.265 state can best be represented by an admixture of $l=0+2+4$ or $l=2+4$. If the latter choice is made on account of an uncertainty in the $l=0$ component, then 3^- and 4^- are the

J^π candidates. No calculated (d, α) curves with or without admixtures satisfactorily reproduce the data. Since this highly excited level is strongly seen in both reactions, it very likely is a mixed-parity doublet.

The 2.279 state adopted in *Nuclear Data Sheets*[21] is not observed in our (d, p) experiment, and is either not seen or not resolved in the (d, α) reaction.

A moderately strong state is seen at ~2.294 MeV in (d, α). The L assignment is ambiguous, although the angular distribution can best be represented by $L=2$. The level is seen neither in the (d, p) nor in the (n, γ) work.

The 3^+ assignment for the 2.311 state appears unique. The (d, p) angular distribution for the transition to a state at 2.327 MeV shows a strong $l=0$ component, hence $J^\pi=1^-, 2^-$. It also contains an $l=2$ component, although the magnitude is uncertain. The state is not seen in (d, α).

A state at ~2.354 MeV is seen in both (d, p) and (d, α). The (d, α) angular distribution can best be represented by $L=2$, although $L=3$ cannot be ruled out. The very weak excitation in (d, p) suggests a positive-parity (hole) state.

The (d, α) transitions to the 2.375 and 2.389 states clearly show strong $L=0$ contributions, i.e., $J^\pi=1^+$. The very weak excitation of these levels in (d, p) confirms the 1^+ assignments.

The state at ~2.415 MeV should be interpreted as a triplet if the $l=4$ component of the $l=0+4$ mixture in (d, p) is associated with $1g_{9/2}$. The third level is proposed as the strong (d, α) transition is uniquely recognized as a pure $L=4$ transition, leading to a positive-parity state with $J^\pi=3^+$, 4^+, or 5^+. The broadening of the 2.415 peak in the (d, α) spectrum in Fig. 3 supports this multiplet scheme.

A strong transition to the 2.462 state is observed in (d, p) and the corresponding angular distribution is reproduced well with an $l=0+2$ admixture. The (d, α) angular distribution has a gross structure characteristic of $L=1$, confirming the (d, p) J^π value of $1^-, 2^-$.

A pure and strong $l=2$ transition to the 2.494 level is observed in (d, p). However, only a broad J^π limit of 0^-–4^- can be given as a consequence of the indistinguishability between the $2d_{3/2}$ and $2d_{5/2}$ neutron transfers. The $L=3$ (d, α) assignment narrows the limit to 2^-–4^-.

The (d, p) angular distribution for the transition to a state at ~2.520 MeV is best represented by $l=0$ (i.e., $J^\pi=1^-, 2^-$). The weak (d, α) angular distribution, on the other hand, can best be identified as that of an $L=0+2$ admixture ($J^\pi=1^+$). The disagreement is resolved by the assumption of a doublet, but in view of poor statistics both assignments must be considered tentative. The same problem is observed for the state at ~2.534 MeV except that the l and L assignments for this case are more certain and thus there exists little doubt that the state populated in (d, p) is not that populated in (d, α).

The state at ~2.550 MeV is not seen in (d, p) and it is only poorly resolved in (d, α). Nevertheless, the (d, α) angular distribution is recognized as either $L=4$ or an admixture of $L=4$ and 2.

Distinct l and L assignments are possible in both reactions for the transitions to the 2.581 state. 3^+ is preferred over 4^+ because the (d, α) angular distribution is represented much better by an admixture of $L=4$ and 2 than by a pure $L=4$.

A level at ~2.596 is either not seen or very weakly excited in (d, p) for most angles investigated. The (d, α) angular distribution is well fitted with an admixture of $L=0$ and 2, and the state is tentatively assigned as 1^+.

Certain $l=0$ and $L=4$ assignments can be made for both transitions to a state near 2.611 MeV. Clearly, such transitions cannot populate the same state, and we again postulate a doublet.

No (d, p) transition to the state at ~2.622 MeV is seen; in (d, α) we find $L=0+2$; hence, we have an $f_{7/2}$ hole state with $J^\pi=1^+$. A strong transition to a state at 2.634 MeV is seen in both (d, p) and (d, α). The (d, p) angular distribution agrees with $l=2$, with possibly a weak $l=0$ or $l=1$ component. On the other hand, the strong (d, α) angular distribution is clearly dominated by $L=0$, which demands a unique 1^+ assignment. Thus, again a doublet must be postulated.

The state at 2.647 MeV is populated in (d, p) by $l=4$ (with possibly a weak $l=0$ admixture). As the evidence for the $l=0$ admixture is not convincing, a J^π assignment cannot be made. The transition is not seen in (d, α). It must be mentioned at this point that near and above this excitation energy it becomes increasingly questionable if our (d, α) experimental resolution of ~12 keV is sufficient to resolve many of the weaker states and whether our energy calibrations are accurate enough to equate the levels observed in the two independent experiments. Furthermore, we expect to see increasingly pure particle states in (d, p) and pure $f_{7/2}$ hole states in (d, α), so that relatively few levels should be populated by both reactions.

The (d, p) transition to a state at ~2.670 MeV is recognized as $l=0$, assuring the narrow J^π limit of 1^- or 2^-. The population of this level in (d, α) is not well established. The angular distribution shows large errors for most points. It is best represented by an admixture of $L=3$ and a weak $L=1$ component in agreement with the (d, p) limits.

The (d, p) transitions to the 2.692 state is identified as $l=0$, hence $J^\pi=1^-, 2^-$. The (d, α) transition to a level near 2.692 MeV is observed with a large cross section. Although it is compatible with $L=1(+3)$ (supporting $J^\pi=2^-$), we suspect that we see a second state, tentatively assigned as $J^\pi=3^+$.

In (d, p) both the 2.720- and 2.760-MeV states are

populated by admixtures of $l=0+2$, leading to 1^- or 2^- for J^π. Strong (d, α) transitions seem to lead to the states seen in (d, p). No unique (d, α) L assignment can be made for the 2.720 level. The very strong (d, α) transition labeled 2.760 MeV is best represented by $L=2+4$ and seems to lead to a 3^+ level.

A surprisingly strong $l=1$ (d, p) transition leads to the 2.774 state. In (d, α) the state is not resolved from the "2.760" state, which may explain the L ambiguity for the latter. A weak $l=0$ transition populates the 2.800 state in (d, p) and the corresponding J^π assignment is 1^- or 2^-.

A state at $\sim$2.814 is seen, poorly resolved, in (d, α). The angular distribution agrees well with $L=0+2$. Thus 1^+ is a likely assignment, supported by the fact that the state is not observed in (d, p). The J^π value for the 2.823-MeV state is based on the (d, p) $l=2+0$ assignment which is considered reliable.

The 2.854-MeV (d, p) transition agrees with $l=1$. Surprisingly, the (d, α) transition is very weak and best fitted by $L=3$. We disregard the (d, α) result because of its low cross section.

The l and L assignments for the levels at 2.876 and 2.891 MeV appear to be well established. In both cases the (d, p) angular distributions are well reproduced by admixtures of $l=1$ and 3. The (d, α) transitions are recognized as $L=4$ and $0+(2)$, respectively, and thus unique assignments of 3^+ and 1^+, respectively, are obtained.

The (d, p) transition to a state at $\sim$2.913 is made by $l=1$, while the (d, α) angular distribution for the transition is best represented by a weak admixture of $L=0$ and 2. 1^+ is thus preferred, but 2^+ and 3^+ are not ruled out.

A strong $l=0+2$ (d, p) transition is observed to the 2.931 state, confining J^π to 1^- or 2^-. The experimental error bars for the corresponding (d, α) angular distribution are very large due to the difficulty in resolving the level from the (2.913) state. The gross structure of the angular distribution can be associated with either a pure $L=3$ or admixture of $L=3$ and 1, in agreement with the (d, p) J^π limits. Hence, $J^\pi=2^-$ is preferred.

The (d, p) transition to the 2.970 state is made by an admixture of $l=0$ and 4, leading to the assignment of 2^-, provided we have a single level. On the other hand, if the $l=4$ component is associated with $1g_{9/2}$, then we are led to propose a doublet for the level. The strong $L=4$ (d, α) transition apparently excites a different level with $J^\pi=3^+$, 4^+, or 5^+.

The last seven states between 2.985 and 3.089 MeV were studied only in (d, p). l values are still recognized, and in two cases rather narrow J^π limits can be established.

V. SUMMARY AND CONCLUSIONS

Levels of Cu^{64} were studied via the $Zn^{66}(d, \alpha)$ reaction with an experimental resolution of 11–12 keV, and via the $Cu^{63}(d, p)$ reaction with resolution of 7–8 keV at $E_d=12$ MeV. With such resolutions we were able to identify about 85 levels of Cu^{64} in the energy range studied ($\leq$3-MeV excitation). This means we see about 35 more levels than reported in the most recent literature[21] in the same energy range. However, it is estimated that over 25% of the levels populated in these reactions still remain unresolved.

$Zn^{66}(d, \alpha)Cu^{64}$ angular distributions were obtained for the majority of the transitions; they are forward-peaked and in general exhibit diffractionlike patterns, characteristic of a direct reaction. For the majority of (d, α) transitions reported, unique L assignments were possible by comparing the observed angular distributions with theoretical curves calculated for definite angular momentum transfers.[41]

The calculations were performed with a DWBA code, DWUCK,[27] which incorporates finite-range and nonlocal corrections into the conventional zero-range DWBA calculations with local potentials. A detailed discussion for the DWBA calculations was presented in Sec. IV of Paper I.[1] Neither the spin dependence nor arbitrary low cutoffs were used in the DWBA calculations for (d, α), yet the agreement in shape between the observed angular distributions and the theoretical curves for $L=0$, 2, and 4 transfers, at least, is very satisfactory.

Some ambiguities in the extraction of $L=$odd transfers existed (a) because the corresponding observed cross sections were in general smaller by an order of magnitude than those for neighboring L-equals-even transfers, as can be expected from the observation that the L-equals-odd transfers involve picking up a neutron from the $1g_{9/2}$ orbit for which the occupation probability is very small for the Zn^{64} target, and (b) because the calculated angular distributions did not possess distinctive features which could easily be distinguished from those for neighboring L-equals-even transfers.

Unique J^π assignments for some positive-parity states, in particular $J^\pi=1^+$ and to a lesser degree 3^+, were possible by (d, α) L assignments alone; but more information was needed to make definite J^π assignments for the rest of the levels populated by either pure L transfers [except $L=0$ and $0(+2)$] or uncertain admixtures of two L transfers.

The $Cu^{63}(d, p)Cu^{64}$ reaction was studied at $E_d=12.0$ MeV in order to find final-state parities, to facilitate further J^π assignments from the overlaps between the (d, α) and (d, p) J^π limits, and to check the energy assignments made in the (d, α) spectra. Unique neutron l values were obtained by comparing the observed angular distributions with the DWBA curves calculated by the code DWUCK,[27] including finite-range and non-

[41] No separate calculations were made for the $Zn^{66}(d, \alpha)Cu^{64}$ reaction, but instead the curves calculated for the $Zn^{68}(d, \alpha)Cu^{66}$ reaction were used for the extraction of L values for all the $Zn(d, \alpha)Cu$ transitions.

locality corrections for the conventional zero-range DWBA formalism. The effects of these refinements on the shapes of angular distributions were negligible for all l transfers except for $l=3$ and 4. However, changes in magnitudes of cross sections ranged from 2 to 20% as compared to the conventional zero-range calculations.

Attempts were made to pick out the 1^+, 2^+, 3^+, and 4^+ levels of the $(p_{3/2}f_{5/2})$ quadruplet of Cu^{64} by applying (d, p) sum rules[39] to the $f_{5/2}$ transfer. However, the fractionization of the $f_{5/2}$ spectroscopic strength seems to rule out simple conclusions. A similar difficulty was encountered in the attempt to assign 3^-, 4^-, 5^-, and 6^- levels with the help of the sum rules when they were applied to the $g_{9/2}$ orbit.

The sum rules used [Eqs. (2) and (3)] are approximations to the exact equations[36]

$$\sum_{\kappa,I_f}(2I_f+1)S_{jI_f}{}^{\kappa}(d,p)$$

$$=(2I_i+1)(2j+1)\left[U_j{}^2+\frac{2\lambda+1}{2j+1}\sum_{j'}(\phi_{jj'}{}^{\lambda})^2V_{j'}{}^2\right], \quad (2')$$

$$\sum_{\kappa,I_f}S_{jI_f}{}^{\kappa}(d,t)=(2j+1)\left[V_j{}^2+\frac{2\lambda+1}{2j+1}\sum_{j'}(\phi_{jj'}{}^{\lambda})^2U_{j'}{}^2\right], \quad (3')$$

where $\phi_{jj'}{}^{\lambda}$ are the amplitudes of excited states of two quasiparticles with j and j', coupled to the total angular momentum λ. Thus, Eqs. (2) and (3) are correct only to the extent that the second terms in Eqs. (2') and (3') can be neglected with respect to the first terms. The contributions from the second term in Eq. (2'), may not be negligible in the case that the shell-model state into which the neutron goes is not completely empty.

Without recourse to the (d, p) sum rule, however, it was possible to make unique 1^+ and 3^+ assignments for many levels up to 3-MeV excitation of Cu^{64} from the recognition of $L=0(+2)$ transfers, L mixing in (d, α) transitions, and overlaps between (d, α) and (d, p) J^{π} limits.

Good agreement in J^{π} assignments was found between the present work and (n, γ) work[13] for the levels below 1-MeV excitation, except for the levels at 0.661 and 0.893 MeV. Our 3^+ assignments are unique from the overlap between (d, α) and (d, p) J^{π} limits, while the (n, γ) work assigns $(1^+, 2^+)$ and (2^+), respectively, on the assumption that $M1$ mode is the only possible one for the observed γ decays. However, if two weak transitions are reclassified as $E2$, then our 3^+ assignments are compatible with the (n, γ) work.

Analysis of data in terms of absolute (d, α) cross sections was not attempted, since the present literature does not offer sufficiently realistic nuclear wave functions relevant to the reaction. It has been shown, however, that theoretical angular distributions for given L transfers can be obtained without the complete knowledge of the nuclear wave functions. It is evident that the refined DWBA calculations employed in this work should replace the conventional zero-range calculations if a good reproduction of experimental (d, α) angular distributions is sought.

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