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Level Structures of Cu^{59} and Cu^{61} Studied by means of the $Ni^{58,60}(He^3,d)$ Reactions†

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The reactions $Ni^{58,60}(He^3,d)Cu^{59,61}$ have been studied at 16.4-MeV incident energy. Forty-two states up to 7.1-MeV excitation were observed in Cu^{59}, and 82 states up to 8.5 MeV were observed in Cu^{61}. Deuteron angular distributions were recorded in the angular interval 7°–60° and, with the aid of distorted-wave analysis, spectroscopic information has been obtained for those states which are fed by the more intense transitions. The low-lying level structures are compared with the unified-model predictions.

I. INTRODUCTION

Considerable attention has been given to the location and properties of the low-lying levels of the odd-A copper isotopes. Having just a single proton outside the $Z=28$ closed-shell configuration, these nuclei may be expected to be rather well described by the shell model. On the other hand, quite good agreement has been obtained between the observed low-lying level structures of Cu^{63} and Cu^{65} and the predictions of the core-excitation model[1] in its more sophisticated versions.[2,3]

In contrast to Cu^{63} and Cu^{65}, relatively little is known about the level schemes of Cu^{59} and Cu^{61}. Blair[4] has studied the low-lying states in these nuclei using the (He^3,d) reaction at 22 MeV but with rather low energy resolution. The properties of some of these states have also been studied by means of proton-capture radiation measurements.[5,6] The present (He^3,d) experiments were undertaken in the hope of obtaining a more thorough understanding of the proton states of these two nuclei, and also to extend the range of measurements up to the analog-state regions.

II. EXPERIMENTAL PROCEDURE

The $Ni^{58,60}(He^3,d)Cu^{59,61}$ reactions were studied using a 16.4-MeV $(He^3)^{++}$ beam from the University of Pennsylvania tandem accelerator. The deuterons were momentum-analyzed in a broad-range magnetic spectrograph and detected in 50-μ-thick Ilford K2 nuclear emulsions. The latter were covered with a suitable Mylar absorber to prevent charged reaction products other than deuterons and protons from reaching the emulsions.

It was found in an earlier test run at this bombarding energy that no j dependence[7] could be observed in the deuteron angular distributions corresponding to $l_p=1$ transitions for angles less than 90°. Therefore, since most of the spectroscopic information could be obtained from the forward angles alone, angular-distribution measurements were limited to the angular interval 7°–60°. For each angle, a total charge of 1000 μC was collected. A solid-state detector mounted at 135° to the beam direction served to monitor the target thickness throughout the experiment.

The reactions were studied, using self-supporting Ni^{58} and Ni^{60} targets purchased from the Isotopes Division, Oak Ridge National Laboratory. In each case, deuteron spectra were first recorded at three angles, using targets of approximately 85 $\mu g/cm^{-2}$ thickness and isotopically enriched to better than 99%. These measurements, from which the level excitation energies were extracted, gave an over-all energy resolution of 19 keV (full width at half-maximum) for the deuteron groups. Deuteron angular distributions were then measured, using somewhat thicker targets (approximately 170 $\mu g/cm^{-2}$) to reduce the duration of the measurements.[8] For each reaction, an absolute cross-section scale was established by means of a differential weighing procedure.

III. DISTORTED-WAVE ANALYSIS

The deuteron angular distributions were analyzed by the distorted-wave (DW) theory, using the code

Table I. Optical-model potentials.[a]

Particle	V	r_0	a	W	W_d	r_0'	a'	V_{so}	r_{0c}
He^3	177.8	1.14	0.72	25.7	0	1.54	0.80	0	1.40
d	92.7	1.15	0.81	0	19.6	1.34	0.68	0	1.15
p	b	1.20	0.65	0	0	0	0	c	1.25

[a] The potentials for He^3 and d were of the form $V(r)=-V(1+\exp x)^{-1}-i[W-4W_d(d/dx')](1+\exp x')^{-1}+V_c(r,r_c)$, with $x=(r-r_0A^{1/3})/a$, $x'=(r-r_0'A^{1/3})/a'$ and $r_c=r_{0c}A^{1/3}$. V_c is the Coulomb potential. V, W, W_d, and V_{so} are given in MeV and r_{0c}, r_0, a, r_0', and a' are in fm.

[b] Adjusted to give the transferred proton a binding energy equal to $[Q(He^3,d)+5.49]$ MeV.

[c] The spin-orbit part of the bound-state potential was proportional to V and its strength was 25 times the Thomas value.

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[1] R. D. Lawson and J. L. Uretsky, Phys. Rev. **108**, 1300 (1957); A. de-Shalit, *ibid.* **122**, 1530 (1961).

[2] B. F. Bayman and L. Silverberg, Nucl. Phys. **16**, 625 (1960); M. Harvey, *ibid.* **48**, 578 (1963); V. K. Thankappan and W. W. True, Phys. Rev. **137**, B793 (1965); J. Vervier, Nuovo Cimento **28**, 1412 (1963).

[3] M. Bouten and P. Van Leuven, Nucl. Phys. **32**, 499 (1962).

[4] A. G. Blair, in *Proceedings of the International Congress on Nuclear Physics, Paris, 1963*, edited by P. Gugenberger (National Center of Scientific Research, Paris, 1964), p. 471.

[5] J. W. Butler and C. R. Gossett, Phys. Rev. **108**, 1473 (1957).

[6] C. R. Gossett and L. S. August, Phys. Rev. **137**, B381 (1965).

[7] L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. **136**, B405 (1964).

[8] The Ni^{60} target used for this measurement was obtained from U.K. A.W.R.E., Aldermaston, England.

JULIE. A Saxon-Woods potential was used for the proton bound state as well as for the entrance and exit channels. The bound-state potential also included a spin-orbit coupling term. Calculations were made for Q values of 0, -2, -4, and -5 MeV, for $2p_{3/2}$, $2p_{1/2}$, $1f_{5/2}$, $1f_{7/2}$, and $1g_{9/2}$ proton capture. For Q values more negative than -5.5 MeV, which corresponds to the breakup energy of the He^3 projectile, no DW calculations are available. For transitions with intermediate Q values, results were extracted by interpolation. The optical-model parameters employed in the calculations were obtained from Bassel[9] and are given in Table I.

For a (He^3,d) reaction on a spin-zero target nucleus, the measured cross section is related to the predicted DW cross section through the equation

$$(d\sigma/d\Omega)_{\text{expt}}=N(2J+1)C^2S\sigma_{\text{DW}}, \qquad (1)$$

where J is the final-state spin, S is the spectroscopic factor, and C is an isotopic-spin Clebsch-Gordan coefficient, which takes into account the fact that states with the same J but different isospin T can be excited in the (He^3,d) reaction. The value 4.4 has been proposed by Bassel[10] for the normalization factor N which is related to the overlap for dissociation of the He^3 nucleus into a deuteron plus a proton.

IV. RESULTS AND DISCUSSION

A. $Ni^{58}(He^3,d)Cu^{59}$ Reaction

In Fig. 1 a deuteron spectrum from the $Ni^{58}(He^3,d)Cu^{59}$ reaction is shown, measured at a reaction angle of 30°. Forty-two deuteron groups could be identified as corresponding to states in Cu^{59} up to 7.1-MeV excitation energy, and these are labeled numerically in the spectrum. The observed contaminant groups are due to the presence of C^{12} and O^{16} in the target. Angular distributions have been measured for 17 of the stronger or well isolated groups, and these are displayed in Fig. 2. For ease of presentation an arbitrary logarithmic cross-section scale has been used, and the solid curves are the results of DW calculations.

The data for this reaction are summarized in Table II. The excitation energies listed in column 2 are the means of values obtained at three angles with the thinner Ni^{58} target, and, for comparison, the energies determined by Butler and Gossett[5] from radiative proton-capture measurements on Ni^{58} are shown in the next column. The states at 1.78 and 2.00 MeV proposed by these authors were not observed in the present study. The differential cross sections given in column 5 are the values measured at the first maximum in each distribution, except for the nonstripping transitions, for which they were measured at 30°. The estimated uncertainty in these values is ±25%, due mainly to the uncertainty in target thickness. Since all strong transitions were accounted for in the analysis, the spectroscopic strengths $(2J+1)C^2S$, which are listed in column 6, were evaluated by assuming the full $1f_{5/2}$, $2p_{3/2}$, and $2p_{1/2}$ transition strengths were observed in the present study and equating this total strength to 12, the number of proton vacancies in these orbits.

TABLE II. Results from the $Ni^{58}(He^3,d)Cu^{59}$ reaction.

	E_x (MeV)					
Level	Present work[a]	Ref.b	l_p	$\sigma(\theta)$[c] (mb/sr)	$(2J+1)C^2S$	Probable J^π
0	0	0	1	13.3	2.1	$\frac{3}{2}^-$
1	0.497	0.492	1	6.1	1.1	$\frac{1}{2}^-$
2	0.921	0.908	3	1.9	4.0	$\frac{5}{2}^-$
3	1.401	1.38	3	0.23	0.54	$(\frac{5}{2}^-)$
		1.78				
		2.00				
4	2.275			0.20		
5	2.325		1	1.8	0.26	$(\frac{3}{2}^-)$
6	2.709		3	0.1	0.12	$(\frac{5}{2}^-)$
7	3.046		4	1.5	3.1	$\frac{9}{2}^+$
8	3.134		1	2.1	0.40	$(\frac{1}{2}^-)$
9	3.300			0.08		
10	3.453					
11	3.555			0.24		
12	3.591		(2)	3.7		$(\frac{5}{2}^+)$
13	3.627			0.29		
14	3.709			0.18		
15	3.759		1	0.76	0.12	$(\frac{1}{2}^-)$
16	3.904[d]		1	4.1	0.60	$\frac{3}{2}^-$
17	4.014		1	1.7	0.36	$(\frac{1}{2}^-)$
18	4.065			0.21		
19	4.122		(2)	0.55		$(\frac{5}{2}^+)$
20	4.273	4.260		0.12		
21	4.315[d]		3	1.5	1.74	$\frac{5}{2}^-$
22	4.364[d]	4.351	1	1.4	0.32	$\frac{1}{2}^-$
		4.413				
		4.501				
23	4.550			0.07		
		4.626				
24	4.720	4.706 4.714		0.08		
25	4.777	4.773		0.11		
26	4.846	4.820	(1)	0.45		
		4.916				
		4.934				
		4.975				
27	5.063	5.045 5.055		0.11		
		5.107				
		5.222				
28	5.248	5.233	(1)	0.68		
29	5.321			0.10		
30	5.502			0.10		
31	5.625			0.12		
32	5.680			0.13		
33	5.868			0.26		
34	6.124			0.20		
35	6.204			0.40		
36	6.314			0.23		
37	6.525			0.18		
38	6.740			0.14		
39	6.845			0.33		
40	6.910			0.55		
41	7.128			0.16		

[a] The estimated uncertainty in excitation energy is ±12 keV for levels up to 2.5 MeV, ±18 keV for levels between 2.5 and 5 MeV, and ±25 keV for higher excited levels.

[b] See Ref. 5.

[c] The differential cross sections are the values obtained at the first maximum in the angular distributions, except for the nonstripping transitions for which they were measured at 30°. The uncertainty in the cross section scale was estimated to be ±25%.

[d] Analog state ($T=\frac{3}{2}$).

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[9] R. H. Bassel (private communication).

[10] R. H. Bassel, Phys. Rev. 149, 791 (1966).

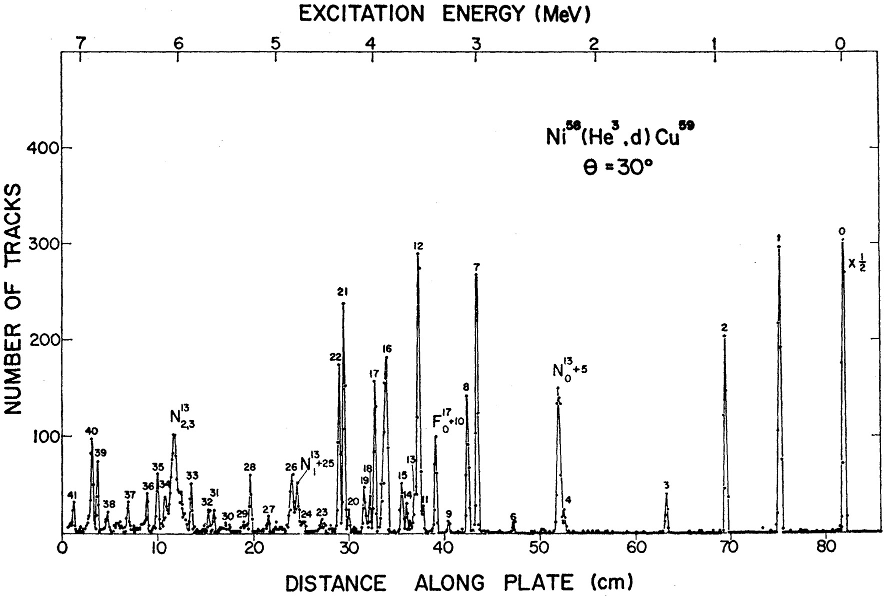

FIG. 1. Deuteron spectrum from the $Ni^{58}(He^3,d)$-Cu^{59} reaction, measured at 16.4-MeV incident energy and at 30° laboratory angle. The number of deuterons counted in 1.0-mm wide strips across the exposed area of the nuclear emulsions is plotted versus distance along the plate.

For the optical-model parameters listed in Table I, this procedure leads to a value of 3.2 for the normalization constant N in Eq. (1). Although somewhat smaller than the value 4.4 proposed by Bassel,[10] it is not inconsistent with values found by other workers (e.g., Ref. 11).

The $l_p=1$ transition to the ground state is the most intense transition observed in this reaction, and is consistent with the $\frac{3}{2}^-$ assignment expected from the shell model. The core-excitation model predicts a low-lying quadruplet of states in Cu^{59} with $J^\pi=\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$, and $\frac{7}{2}^-$, formed by coupling the odd $2p_{3/2}$ proton to the first excited one-phonon 2^+ state in Ni^{58}. In the simplest form of this model, these states are not expected to be strongly populated by the (He^3,d) stripping reaction. This is clearly at variance, however, with the observed spectroscopic strengths for most of the low-lying states, in which quite large amounts of the $2p$ and $1f$ single-particle strengths are observed. Blair[11] has also obtained similar results from the (He^3,d) reaction leading to Cu^{63} and Cu^{65}. These observations are more consistent with the extended models, such as the unified model of Bouten and Van Leuven,[3] in which a $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ proton is allowed to couple with the ground, one-, and two-phonon states of the Ni core. In

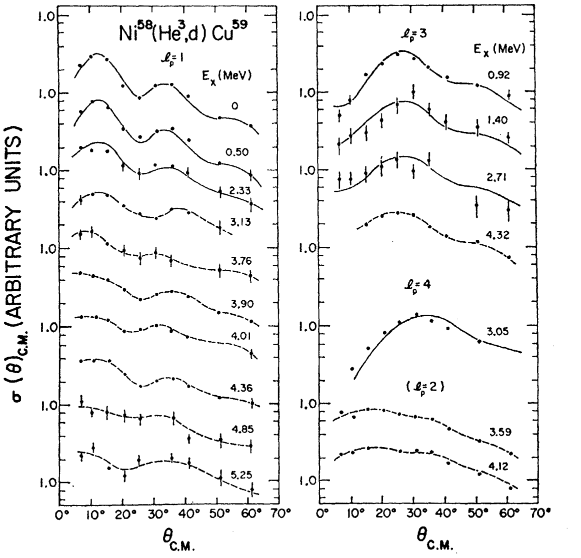

FIG. 2. Deuteron angular distributions measured in the $Ni^{58}(He^3,d)Cu^{59}$ reaction. For ease of presentation the cross section scale has been made arbitrary in each case; the absolute values are given in Table II. The full curves are from distorted-wave calculations using the parameters listed in Table I. The dashed curves were drawn through the experimental points and have no theoretical significance.

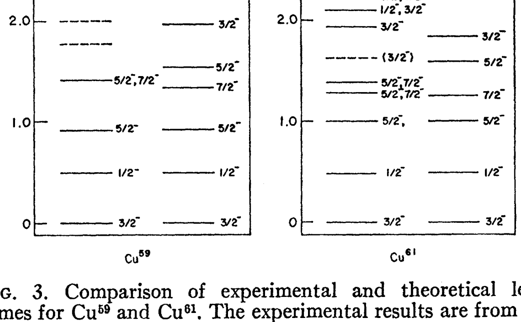

FIG. 3. Comparison of experimental and theoretical level schemes for Cu^{59} and Cu^{61}. The experimental results are from the present work and also from Refs. 5 and 6. The levels indicated by dashed lines were not observed in this study. The calculated level schemes are from the unified model of Bouten and Van Leuven (Ref. 3).

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[11] A. G. Blair, Phys. Rev. 140, B648 (1965).

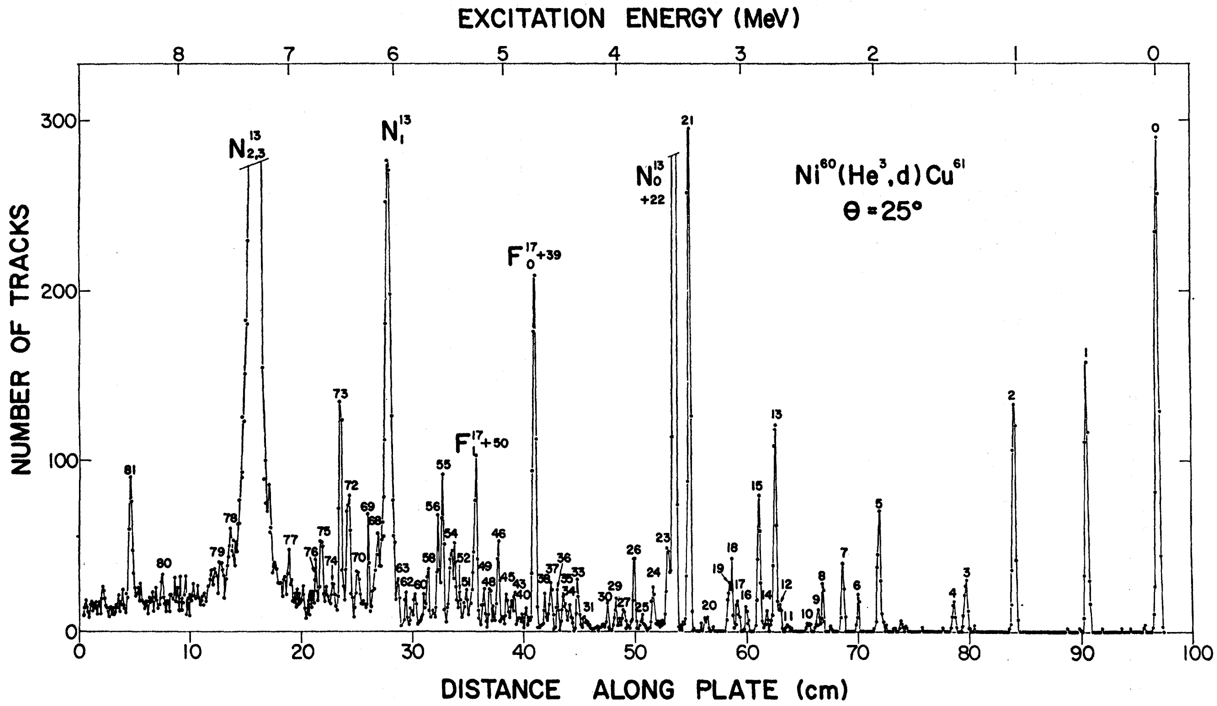

FIG. 4. Deuteron spectrum from the $Ni^{60}(He^3,d)Cu^{61}$ reaction, measured at an incident energy of 16.4 MeV and a laboratory angle of 25°.

this model, quite large single-particle strengths are predicted in the low-lying states.

The $l_p=1$ transition to the first excited state has about 45% of the ground-state transition strength and presumably corresponds to a $\frac{1}{2}^-$ level, as expected from the unified model. The strong $l_p=3$ transition to the second excited state at 0.921 MeV is consistent with a spin parity of $\frac{5}{2}^-$ for this level, since the $1f_{7/2}$ proton shell is expected to be full, or very nearly so, in Ni^{58}. The calculations of Bouten and Van Leuven predict an additional $\frac{5}{2}^-$ state at 1.5 MeV and a $\frac{7}{2}^-$ state at 1.3 MeV. Only one level is observed in this region, however, which occurs at 1.40 MeV and is excited by only a very weak $l_p=3$ transition. In view of its low transition strength, the possibility of $\frac{7}{2}^-$ cannot be easily ruled out for this state, since such an identity would require the $1f_{7/2}$ proton shell to be only 7% empty in Ni^{58}. Departures of up to 10% from complete shell closure in the nickel isotopes have been indicated in other studies.[11,12] Blair[4] has suggested that more than one level may be excited at this excitation energy; this is not apparent from the present study, however, and no state is observed in the deuteron spectrum with a separation greater than 15 keV from the known level at 1.401 MeV. The only other possible candidate for the expected $\frac{7}{2}^-$ state would appear to be the 2.27-MeV level. This is again only very weakly excited and its distribution exhibits no typical stripping form. The $\frac{3}{2}^-$ core-excited state is predicted to lie at 2.0 MeV. If this can be identified with the level at 2.32 MeV which is excited with $l_p=1$, the agreement with the observed location is quite good. The experimental level scheme of Cu^{59} up to 2.5-MeV excitation is compared with the calculated scheme of Bouten and Van Leuven in Fig. 3.

The identification of the levels at 3.904 ($l_p=1$), 4.315 ($l_p=3$), and 4.364 MeV ($l_p=1$) as the $T=\frac{3}{2}$

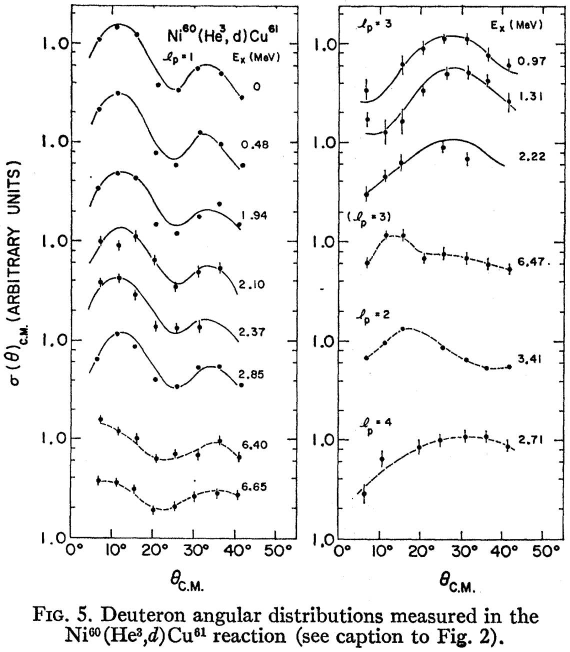

FIG. 5. Deuteron angular distributions measured in the $Ni^{60}(He^3,d)Cu^{61}$ reaction (see caption to Fig. 2).

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[12] A. G. Blair, Phys. Letters 9, 37 (1964).

TABLE III. Results from the $Ni^{60}(He^3,d)Cu^{61}$ reaction.

	E_x (MeV)						
Level	Present work[a]	Reference b	J^π Reference b	l_p	$\sigma(\theta)$[c] (mb/sr)	$(2J+1)C^2S$	Probable J^π
0	0	0	$\frac{3}{2}^-$	1	8.3	0.96	$\frac{3}{2}^-$
1	0.477	0.47	$(\frac{1}{2}^-)$	1	3.5	0.49	$\frac{1}{2}^-$
2	0.972	0.95	$\frac{5}{2}^-$	3	0.56	1.0	$\frac{5}{2}^-$
3	1.306			3	0.13	0.22	$(\frac{7}{2}^-)$
4	1.390	1.37	$\frac{5}{2}^-$	(3)	0.15	(0.27)	$(\frac{5}{2}^-)$
		1.63	$\frac{3}{2}^-$				
5	1.940	1.89	$\frac{3}{2}^-$	1	1.0	0.11	$\frac{3}{2}^-$
6	2.104	2.07	$(\frac{1}{2}^-)$	1	0.32	0.03	$(\frac{1}{2}^-)$
7	2.216			3	0.08	0.20	$\frac{5}{2}^-$
8	2.368			1	0.26	0.03	$(\frac{1}{2}^-)$
9	2.390				0.03		
10	2.478				0.02		
11	2.629				0.01		
12	2.680	2.64			0.05		
13	2.711			4	0.74	1.4	$\frac{9}{2}^+$
14	2.794				0.03		
15	2.846	2.83		1	1.6	0.14	$(\frac{1}{2}^-)$
16	2.942				0.04		
17	3.019				0.06		
18	3.063	3.02			0.09		
19	3.094				0.07		
20	3.276				0.03		
21	3.411			(2)	1.92		$(\frac{5}{2}^+)$
22	3.526						
23	3.588				0.18		
24	3.708				0.09		
25	3.790				0.03		
26	3.860				0.12		
27	3.943				0.02		
28	3.970						
29	4.013				0.05		
30	4.102				0.03		
31	4.273				0.03		
32	4.296						
33	4.349				0.07		
34	4.420				0.04		
35	4.477				0.08		
36	4.523				0.05		
37	4.581				0.08		
38	4.621				0.06		
39	4.738						
40	4.790				0.03		
41	4.827						
42	4.860						
43	4.900				0.06		
44	4.925				0.04		
45	4.973				0.05		
46	5.042				0.15		
47	5.081				0.03		
48	5.111				0.07		
49	5.170				0.07		
50	5.235						
51	5.329				0.08		
52	5.383				0.06		
53	5.433				0.16		
54	5.463				0.15		
55	5.532				0.22		
56	5.574				0.17		

TABLE III. (*continued*).

Level	E_x (MeV) Present work[a]	E_x (MeV) Reference b	J^π Reference b	l_p	$\sigma(\theta)$[c] (mb/sr)	$(2J+1)C^2S$	Probable J^π
57	5.624						
58	5.669				0.11		
59	5.704						
60	5.788				0.06		
61	5.829						
62	5.872				0.05		
63	5.937				0.09		
64	6.004						
65	6.045						
66	6.075						
67	6.119				0.20		
68	6.149						
69	6.216				0.14		
70	6.314				0.13		
71	6.350						
72	6.402[d]			1	0.30		$\frac{3}{2}^-$
73	6.469[d]			(3)	0.36		$\frac{5}{2}^-$
74	6.543				0.10		
75	6.650[d]			1	0.18		$\frac{1}{2}^-$
76	6.712				0.12		
77	6.954				0.15		
78	7.520				0.21		
79	7.589				0.16		
80	8.177				0.10		
81	8.504				0.25		

[a] See footnote a of Table II. [b] See Ref. 6. [c] See footnote c of Table II. [d] Analog state ($T=\frac{3}{2}$).

analogs to the ground ($J^\pi=\frac{3}{2}^-$), 0.341 ($\frac{5}{2}^-$), and 0.466 MeV ($\frac{1}{2}^-$) states in Ni^{59} has already been reported elsewhere (Ref. 13). The observed spectroscopic strengths for these analog states (see Table II) are 0.60, 1.74, and 0.32, respectively, which are in quite close agreement with the values 0.68, 1.86, and 0.39 predicted[14] from (d,p) measurements on Ni^{58}.[15] The 3.9-MeV level, however, has an observed width of 38 keV which is just twice the experimental width, and probably arises from an unresolved doublet.[16] In this case, if one member is a $T=\frac{1}{2}$ state the strength of the $T=\frac{3}{2}$ member will be less than the expected value. From the excitation energy of the ground-state analog and the atomic masses of Mattauch *et al.*,[17] the Coulomb displacement energy is calculated to be 9.48±0.03 MeV.

Only one $l_p=4$ transition can be clearly identified in this study and this leads to the 3.046-MeV level, which is therefore presumably a $\frac{9}{2}^+$ state. This transition takes about 30% of the total $1g_{9/2}$ strength.

Relatively intense transitions are observed to the 3.59- and 4.12-MeV states, although their angular distributions exhibit little structure. DW calculations are not available in these cases in view of their large, negative Q values, but the general form of the distributions appears to be consistent with $l_p=2$ transitions. If this identification is correct, then they most probably correspond to states arising from the $2d_{5/2}$ single-particle configuration. Such an assignment for the lower-lying state is in accord with the systematic behavior of low-lying $\frac{5}{2}^+$ states in other odd-A copper isotopes, which are also known to be strongly excited by the (He^3,d) reaction.

B. $\mathrm{Ni}^{60}(\mathrm{He}^3,d)\mathrm{Cu}^{61}$ Reaction

A deuteron spectrum measured at 25° from the $\mathrm{Ni}^{60}(\mathrm{He}^3,d)\mathrm{Cu}^{61}$ reaction is presented in Fig. 4. A total of 82 states could be identified in Cu^{61} up to 8.5-MeV excitation energy. Up to 2-MeV excitation, the level structure is very similar to that in Cu^{59}. However, at higher excitations the level density is nearly twice that

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[13] B. Rosner, C. H. Holbrow, and D. J. Pullen, in *Proceedings of Conference on Isobaric Spin in Nuclear Physics, Tallahassee, 1966*, edited by J. D. Fox and D. Robson (Academic Press Inc., New York, 1966), p. 595. (The excitation energies in Cu^{61} listed in Table I of this reference are in error. The correct values are 6.40, 6.47, 6.65, 7.59, and 8.50 MeV. This changes the Coulomb displacement energy for Cu^{61} given in Table II of this reference, the revised value being 9.42±0.03 MeV.)

[14] J. B. French and M. H. MacFarlane, Nucl. Phys. **26**, 168 (1961).

[15] E. R. Cosman, C. H. Paris, A. Sperduto, and H. A. Enge, Phys. Rev. **142**, 673 (1966).

[16] G. C. Morrison and J. P. Schiffer, in *Proceedings of Conference on Isobaric Spin in Nuclear Physics, Tallahassee, 1966*, edited by J. D. Fox and D. Robson (Academic Press Inc., New York, 1966), p. 748.

[17] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. **67**, 1 (1965).

in Cu^{59}, and is presumably due to the increased degree of freedom introduced by the two additional neutrons in Cu^{61}. With the exception of three strongly excited analog states, deuteron angular distributions could be obtained only for states up to 3.5 MeV, since with the thicker target employed in these measurements few levels could be clearly resolved at higher excitation energies. The distributions are shown in Fig. 5, and the experimental results obtained from this reaction are summarized in Table III. Also shown for comparison in columns 3 and 4 are the level energies and spin-parity assignments obtained by Gossett and August[6] from radiative proton capture measurements on Ni^{60}. Except for the first excited state, their energies appear to be consistently lower by 20–40 keV than the values obtained in the present study. Since a significant fraction of the total $2p$ transition strength may be expected to lie above 3.5-MeV excitation, and since only a few level distributions were analyzed in this region, the spectroscopic strengths listed in column 7 of Table III were calculated from the measured peak cross sections and assuming the value $N=3.2$ for the normalization constant in Eq. (1), as determined from the analysis of the $Ni^{58}(He^3,d)$ reaction.

The transitions observed to the ground ($l_p=1$), first-excited ($l_p=1$) and second-excited ($l_p=3$) states are consistent with the assignments $J^\pi=\frac{3}{2}^-$, $\frac{1}{2}^-$, and $\frac{5}{2}^-$, respectively, obtained by Gossett and August and also predicted by the unified model (see Fig. 3).

Only relatively weak transitions were observed to the next two states at 1.306 and 1.390 MeV, the first of these corresponding to a $l_p=3$ transition. A complete angular-distribution measurement for the latter state was not possible because of the proximity of a relatively strong deuteron group in the spectrum, corresponding to the ground-state transition to Cu^{59}, which arose due to the presence of a significant amount of Ni^{58} in the thicker Ni^{60} target. However, measurements made in the angular range 20°–30° with the thin target, which was enriched to better than 99% in Ni^{60}, also suggested a probable $l_p=3$ transition to the 1.39-MeV level. Gossett and August[6] observed only one level in this region at 1.37 MeV, to which they assigned $J^\pi=\frac{5}{2}^-$. This state may correspond to either member of the doublet observed in the present work, although its identification with the 1.39-MeV level may be slightly favored in view of their excitation energies being consistently lower than the values obtained in this study. The 1.306-MeV level may then be the $\frac{7}{2}^-$ state required by the core-excitation model and predicted by Bouten and Van Leuven[3] to lie at 1.20-MeV. This state was not observed in the Zn^{61} β^+-decay measurements of Cumming[18] which also, therefore, supports a $\frac{7}{2}^-$ assignment.

Gossett and August assign $\frac{3}{2}^-$ to a level at 1.89 MeV. This is in accord with the present measurement if this can be identified with the level at 1.94 MeV, to which a $l_p=1$ transition is observed. The higher levels at 2.104, 2.368, and 2.846 MeV, which are also populated with $l_p=1$, are most probably $\frac{1}{2}^-$ states. The $\frac{3}{2}^-$ level previously reported at 1.63 MeV, and apparently observed in both the $Ni^{60}(p,\gamma\gamma)$ experiment and the β^+ decay of Zn^{61}, was not observed in this study.

The $l_p=4$ transition to the 2.711-MeV level and the $l_p=2$ transition to the 3.411-MeV level most probably lead to $\frac{9}{2}^+$ and $\frac{5}{2}^+$ states, respectively. On comparing the first $\frac{9}{2}^+$ and $\frac{5}{2}^+$ states in all four odd-A copper isotopes, it is apparent that only a weak dependence is exhibited by their excitation energies on neutron configuration.

On the basis of its excitation energy, transition strength and $l_p=1$ character, the 6.402-MeV level may be identified as the $T=\frac{5}{2}$, $J^\pi=\frac{3}{2}^-$ analog to the Ni^{61} ground state, as reported earlier (Ref. 13). The Coulomb displacement energy evaluated from this excitation energy is 9.42 ± 0.03 MeV. The levels at 6.469 MeV and 6.650 MeV, which are excited by probable $l_p=3$ and $l_p=1$ transitions, respectively, may also be similarly identified as analogs to the 0.069 ($\frac{5}{2}^-$) and 0.290-MeV ($\frac{1}{2}^-$) states in Ni^{61}, respectively.

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