(^{3}He, d) stripping to unbound analog states in Cu isotopes

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The (^{3}He, d) reaction on Ni isotopes was studied at 30.2 MeV bombarding energy. Twenty-six unbound analog states in Cu isotopes were populated, and the observed differential cross sections are presented. Two different distorted-wave Born-approximation methods for stripping calculations to unbound analog states were used in the analysis. Proton spectroscopic factors were deduced and compared with published neutron spectroscopic factors for the parent states. The agreement is generally good, except for the pair of isotopes ^{62}Ni-^{62}Cu. The different sensitivity to the transferred angular momentum of the corresponding (d, p) and (^{3}He, d) reactions is discussed. The present data are compared with the results of previous studies of the (^{3}He, d) reaction in the $A \sim 90$ mass region. It is concluded again that the (^{3}He, d) reaction to analog states is complementary to the (d, p) reaction for the study of levels in the parent states which are populated through large angular momentum transfers.

[NUCLEAR REACTIONS ^{64,62,61,60}Ni(^{3}He, d), $E = 30.2$ MeV; measured $\sigma(\theta)$, levels; Enriched targets, DWBA analyses, analog states, deduced S.]

I. INTRODUCTION

A great deal of experimental[1-5] and theoretical[6-9] attention has been given to the study of proton-stripping reactions to isobaric analog resonances. The analysis of such reactions is difficult since the final states are unbound, and the usual distorted-wave Born-approximation (DWBA) analysis to bound states requires modification. The usefullness of modified DWBA calculations was demonstrated in recent studies of unbound analog states in the Tc and Nb isotopes.[1-3] In these studies 37 analog states were populated by the (^{3}He, d) reaction. Two different models for the calculation of the form factor were used in the analysis: The "single-particle-resonance" model (described in Ref. 1) and the "analog-resonance" model (described in Ref. 6). Proton spectroscopic factors for the analog states were obtained in both methods. They were generally found to be in good agreement with the published neutron spectroscopic factors of the corresponding parent states, obtained in the analysis of (d, p) reactions on the same target nuclei. The (^{3}He, d) reaction, which populates analog states, was found to have better sensitivity to large angular momentum transfer than the (d, p) reaction which populates the corresponding parent states.

In the present paper we report the results of a similar study carried out in the $A \sim 60$ mass region by investigating the (^{3}He, d) reaction on Ni isotopes. We present here the data and the results of DWBA calculations. The degree of agreement between data and calculations is then compared with the degree of agreement in the studies of $A \sim 90$ mass region.[1-3] Two previous calculations[10,11] of the proton spectroscopic factors of unbound analog states, populated by transfer reactions in this mass region, are known. These were carried out for the reactions ^{58}Ni(^{3}He, d)^{59}Cu and ^{60}Ni(^{3}He, d)^{61}Cu. These calculations were done by extrapolating DWBA results from bound states and were restricted to states unbound by less than 1.7 MeV. In the present work the (^{3}He, d) reaction was studied on ^{60}Ni, ^{61}Ni, ^{62}Ni, and ^{64}Ni. Unbound analog states up to 6 MeV above the separation energy of the proton were observed and analyzed.

II. EXPERIMENTAL PROCEDURE

A 30.2-MeV ^{3}He beam from the Centre d'Etudes Nucléaires de Saclay cyclotron was used to bombard isotopically enriched ^{60}Ni, ^{61}Ni, ^{62}Ni, and ^{64}Ni targets. The thicknesses and enrichments of the targets are listed in Table I. The ^{60}Ni target was a self-supporting foil; the other targets were evaporated on a thin (~ 25 μg/cm^2) carbon backing. The outgoing deuterons were detected with two ΔE-E silicon-detector telescopes coupled to

TABLE I. Thickness and isotopic enrichment of targets.

	^{60}Ni	^{61}Ni	^{62}Ni	^{64}Ni
Thickness (μg/cm^2)	134	135	119	159
Enrichment (%)	95.4	92.3	99.0	97.6

Chaivre type[12] particle-identification systems. The obtained energy resolution was ~50 keV. Angular distributions were measured from 10° to 45° in steps of 2–5°. For the ^{60}Ni target data were collected only at four angles. The absolute values of the differential cross sections were determined from the measured thickness of the target, the solid angle of the detectors, and the beam charge integration. Dead time corrections were made according to the procedure described in Ref. 2. As a check of our procedure for determination of absolute cross sections we analyzed several low lying bound states, which were also populated in the present experiment, by performing standard DWBA calculations with the computer code DWUCK.[13] The resulting spectroscopic factors were found to be in good agreement with the results of previous[11] (^{3}He, d) studies of the same levels.

III. RESULTS

Typical deuteron spectra from the ^{60}Ni and ^{61}Ni targets are shown in Figs. 1 and 2; spectra from the ^{62}Ni and ^{64}Ni targets have similar features. Deuteron peaks, which correspond to analog states in the residual nucleus were integrated, and a smooth background was subtracted. The resulting angular distributions are displayed in Figs. 3–8. The displayed uncertainties are due to statistics and to the procedure of the peak integration. The uncertainty in the absolute value of the cross sections due to systematic errors is 10%. The uncertainty in the determination of excitation energies is about 30–40 keV. DWBA calculations were carried out with the two methods which were described in Refs. 1 and 6, and are further discussed in Sec. IV. The optical-model parameters used in the computer code DWUCK[13] are listed in Table II and the form of the potentials is described in Ref. 2. The solid curves in Figs. 3–8 represent angular distributions which were calculated with the single-particle-resonance method. The shapes of the angular distributions which were calculated with the analog-resonance method are essentially the same. The agreement between the experimental angular distributions and the theoretical distributions is good for most of the levels. The excitation energies and the deduced proton spectroscopic factors (S_p), as calculated with both the single-particle-resonance model and the analog-resonance model, are listed in Table III. Also listed there are the neutron spectroscopic factors (S_n), and l values for the parent states, which were obtained from studies of the (d, p) reaction on the same target nuclei.[16-19] The analogs of some levels, which are known from the corresponding (d, p) studies to be populated through $l = 1$ and $l = 2$ transitions with small spectroscopic factors ($S_n < 0.1$), were too weakly excited to be analyzed and are not listed in Table III.

One of the main purposes of this work was to produce the experimental data which is required for the calculations of the spectroscopic factors of the analog states and to compare the results with those obtained for corresponding parent states in (d, p) studies. In general, the shape of the angular distribution is sensitive enough to the l value

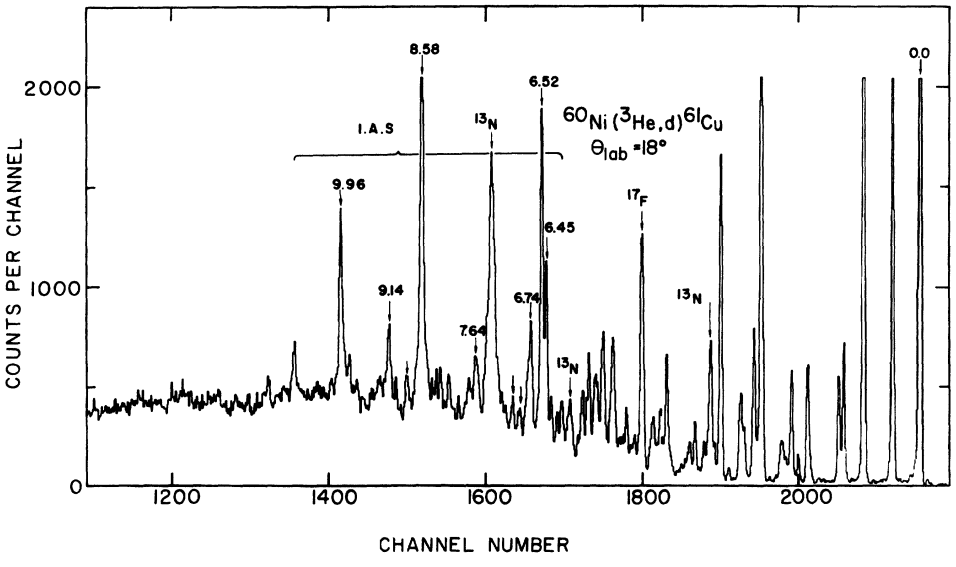

FIG. 1. Deuteron spectrum from the ^{60}Ni(^{3}He, d)^{61}Cu reaction taken at 18°.

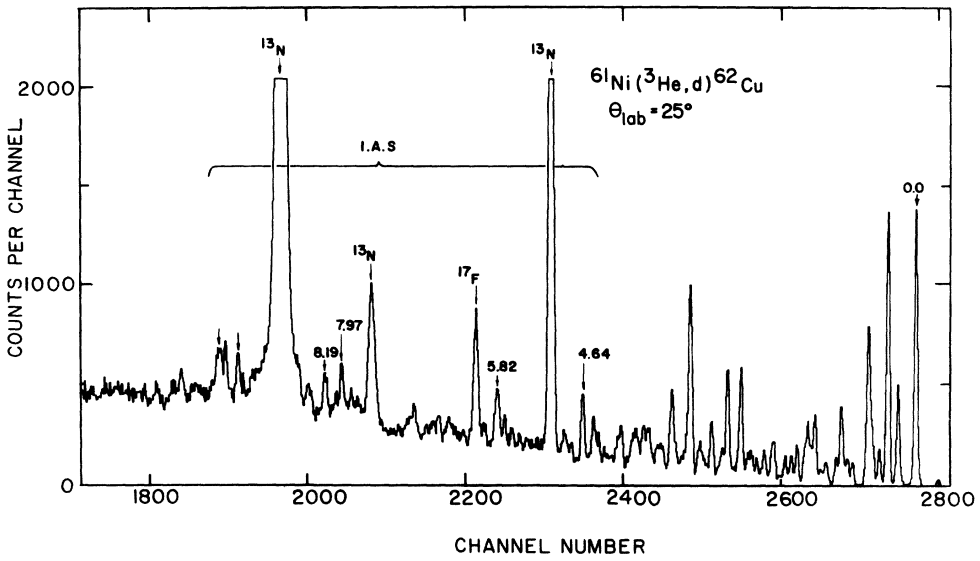

FIG. 2. Deuteron spectrum from the ^{61}Ni(^{3}He,d)^{62}Cu reaction taken at 25°.

to allow distinction between $l=1$ and higher l values. On the other hand, it is difficult to distinguish between members of a pair of large l values such as $l=3$ and $l=4$. We therefore did not attempt to assign l values; instead we used the l value assignments of the (d,p) studies in our determination of proton spectroscopic factors. In a few cases, and unlike the situation in the corresponding (d,p) studies, we could not resolve the analogs of several groups of states (see Table III). The absolute values of the spectroscopic factors in these cases were determined by using the total strength of the group as measured in the present work, and assuming the relative strength deduced from the (d,p) experiments. The results which were obtained in this way are of interest, since comparison with the absolute value of the corresponding neutron spectroscopic factors can still be done.

A. ^{61}Cu

The results of the ^{60}Ni$(d,p)^{61}$Ni studies, which are listed in Table III, are those of Aymar *et al.*,[16] and for the states which were not reported in Ref. 16 we quote the results of the earlier work of Cosman *et al.*[18] The agreement between the results of these two groups is generally good, with the exception of the level at 2.13 MeV. This level was found by Aymar *et al.* to be a doublet of states, one of them populated through $l=1$ transition with $(2j+1)S_n=0.25$ and the other state populated through $l=4$ transition with $(2j+1)S_n=5.37$. Cosman *et al.* reported 0.39 and 8.45, respectively, for these two states. The disagreement here is attributed[16] to the fact that the spin-orbit term

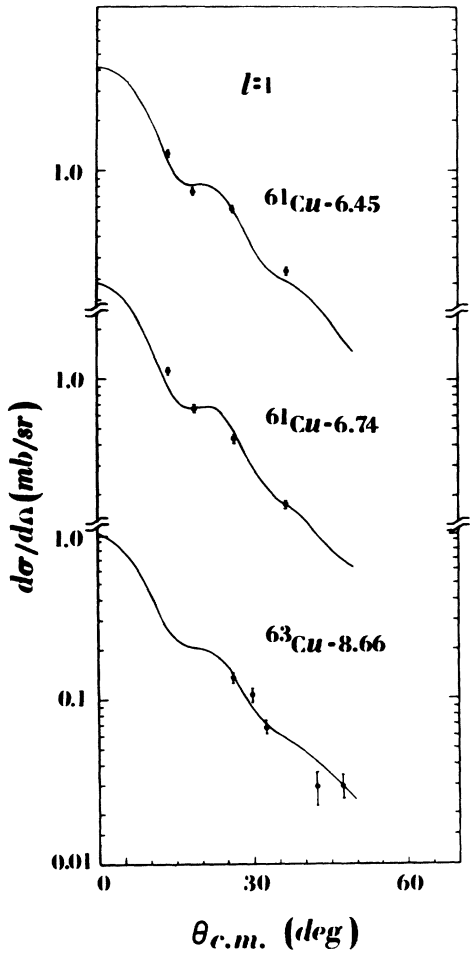

FIG. 3. Angular distribution of deuterons populating states through angular momentum transfer $l=1$.

was not included in the analysis in the earlier (d,p) study of Cosman *et al.* Both studies report a large difference between the strengths of the $l=1$ and $l=4$ transitions. This difference causes the $l=1$ contribution to the excitation of the analog state in the $(^3\mathrm{He},d)$ reaction to be not more than 5%. After making a small correction we treated this peak as if it corresponds to a pure $l=4$ transition. Our results are in better agreement with the more recent work of Aymar *et al.*[16]

At excitation energies of 6.86, 6.98, and 8.67 MeV (see arrows in Fig. 1) we observed levels for which no corresponding parent states were reported in the (d,p) studies. It is possible that these are highly excited $T_<$ states. On the other hand, these levels could be analog states populated through transitions with large l values. If such were the case the population of their parent states in the (d,p) reaction would be relatively weak due to poor angular momentum matching for large l values and this would account for their absence in those studies. The over-all agreement between the proton spectroscopic factors which we determined in the $^{60}\mathrm{Ni}(^3\mathrm{He},d)^{61}\mathrm{Cu}$ reaction, and the neutron spectroscopic factors which were deduced from the $^{60}\mathrm{Ni}(d,p)^{61}\mathrm{Ni}$ studies is good. The agreement is slightly better for the single-particle-resonance method than for the analog-resonance method. The proton spectroscopic factor for the 9.14 MeV level (2.69 MeV in the parent nucleus) is much larger than the corresponding neutron spectroscopic factor obtained in (d,p) studies. The reason for that could be that either this level is a doublet of $T_<$ and $T_>$ states, or that it is a doublet of states, one of them populated

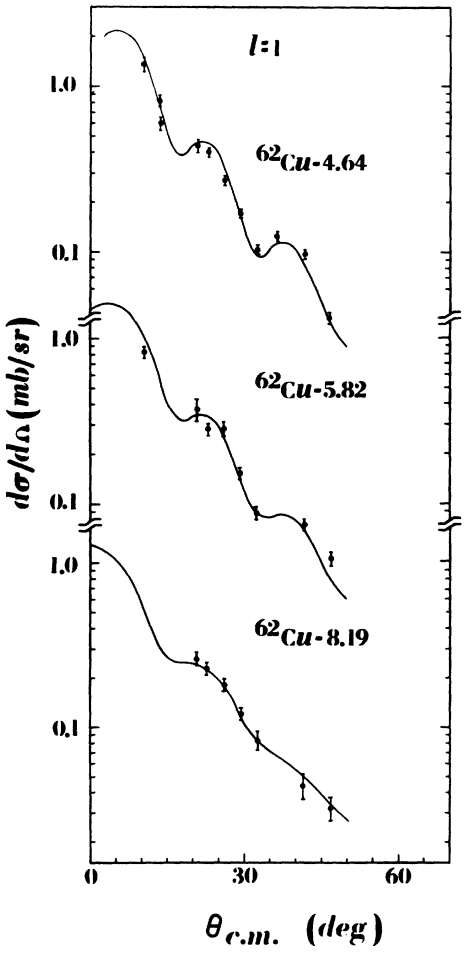

FIG. 4. Angular distribution of deuterons populating states through angular momentum transfer $l=1$.

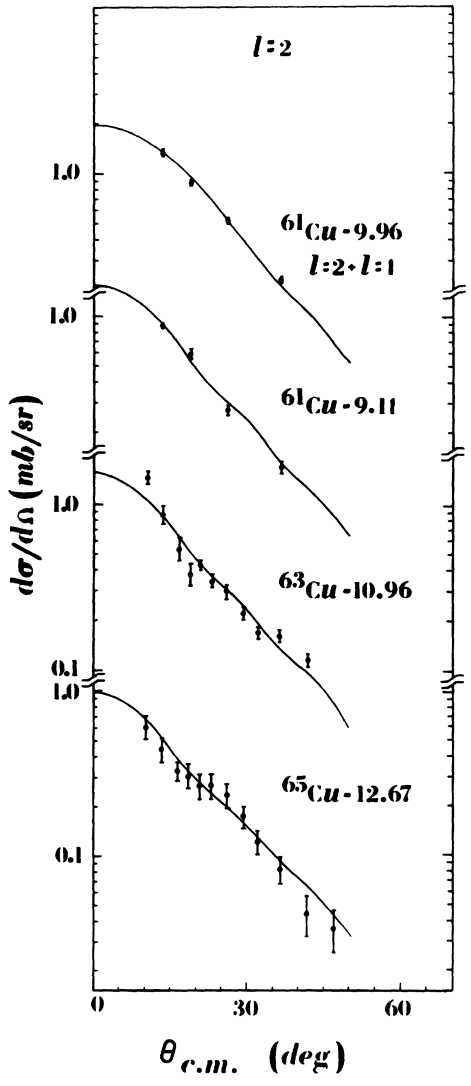

FIG. 5. Angular distribution of deuterons populating states through angular momentum transfer $l=2$, $l=2+l=4$.

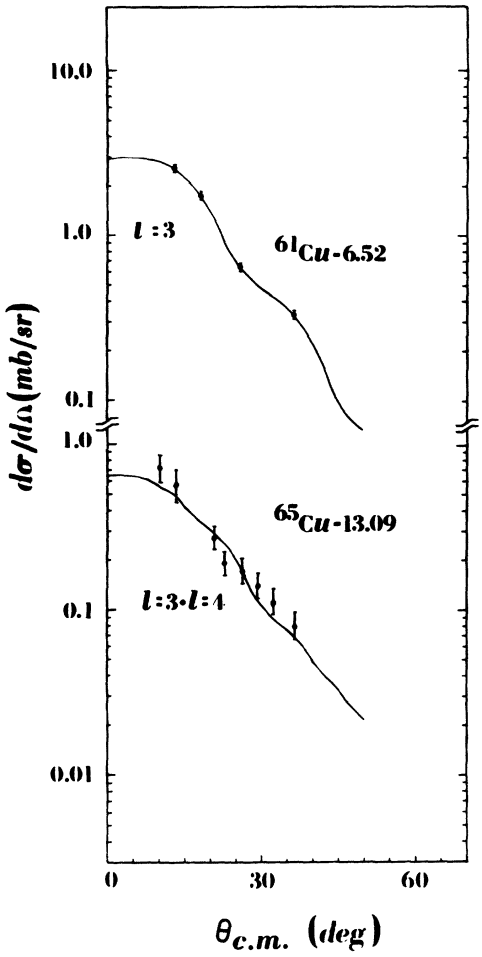

FIG. 6. Angular distribution of deuterons populating states through angular momentum transfer $l = 3$, $l = 3 + l = 4$.

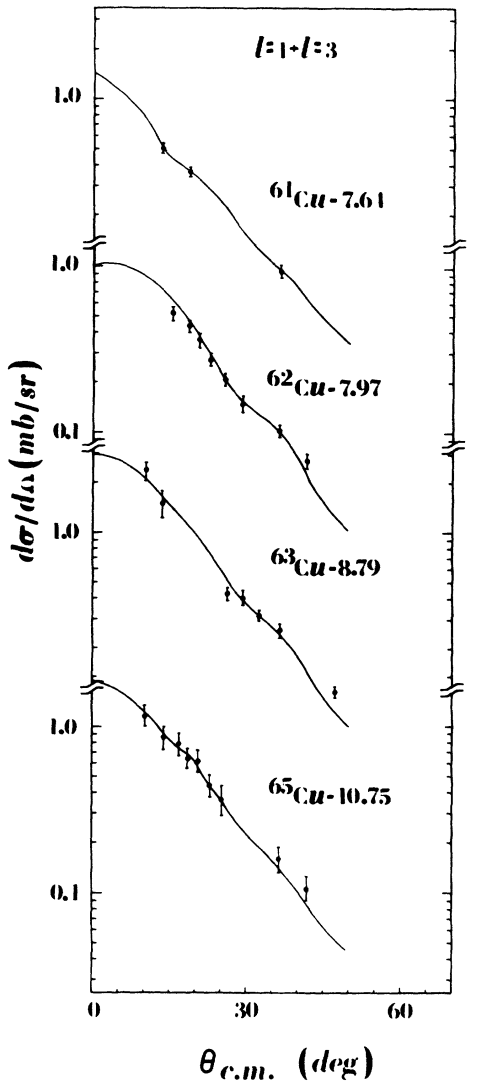

FIG. 7. Angular distribution of deuterons populating states through angular momentum $l = 1 + l = 3$.

through $l = 2$ transition and the other through a large l value. The contribution of the latter to the (d, p) cross section would then be relatively small.

B. ^{62}Cu

The results of the ^{61}Ni$(d, p)^{62}$Ni study which we listed in Table III are taken from Ref. 19. The two analog states which were observed at excitation energies of 4.64 and 5.82 MeV in ^{62}Cu (0.0 and 1.18 MeV in the parent nucleus) are bound. The spectroscopic factors for these two levels were obtained with the usual method of DWBA calculations for bound states, using the computer code DWUCK. The spectroscopic factors for all the analog states, bound and unbound, which were observed in this isotope, are systematically larger than the corresponding values, which were determined for the parent states in the (d, p) reaction.

At excitation energies of 5.72, 9.43, and 9.64 MeV we observed levels for which no corresponding parent states were reported in the (d, p) studies. As we discussed above (Sec. III A) these are either highly excited $T_<$ states or $T_>$ states populated through large angular momentum transfers.

C. ^{63}Cu, ^{65}Cu

The results of the ^{62}Ni$(d, p)^{63}$Ni and the ^{64}Ni$(d, p)^{65}$Ni studies, which we listed in Table III, are taken from Ref. 17. A good over-all agreement is found for both isotopes between the proton spectroscopic factors which we determined with either of the two methods of calculation and the neutron spectroscopic factors which were

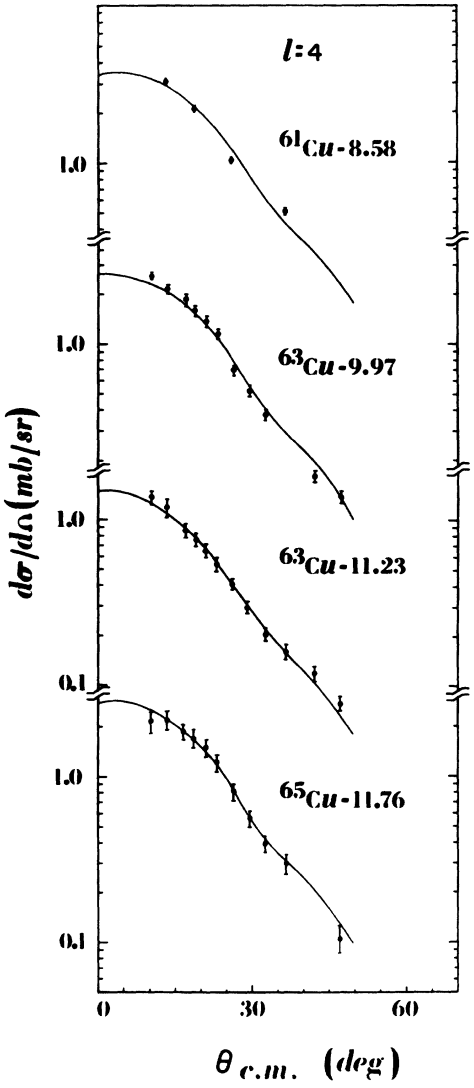

FIG. 8. Angular distribution of deuterons populating states through angular momentum $l = 4$.

found in the (d, p) studies. For the level at 2.291 MeV in the ^{63}Ni there is a marked disagreement between the value of 1.99 quoted in Ref. 17 for $(2j+1)S_n$ and 0.85 quoted in Ref. 20. The level at 2.330 MeV in ^{65}Ni is found by Turkiewicz *et al.*[17] to be a doublet populated through $l = 3$ and $l = 4$ transitions, while Anfinsen *et al.*[20] treated this level as if it were a pure $l = 3$ transition. For both levels our results confirm those of Turkiewicz *et al.*

IV. DISCUSSION

We employ in this work two different methods for calculation of the form factor for the unbound proton which is transferred in the (^{3}He, d) reaction. In the single-particle-resonance method[10] we use the computer code ABACUS[21] and carry out a search for a real potential depth which corresponds to a phase shift equal to 90°. The form factor for the single particle resonance is then obtained and used to describe the isobaric analog state. In the analog-resonance method[6] the form factor is derived using a fine structure theory of isobaric analog resonances. Relations between the analog and its parent bound state as well as the micro-giant structure of the analog states are considered. The form factor is calculated taking into account the coupling of the analog state to the continuum and to the compound states surrounding it. In spite of the difference between these two approaches the two methods yield similar results. The shapes of the calculated angular distributions are almost identical for both methods. The absolute values of the cross sections found with the analog-resonance method are usually larger by 10–30% than those found with the single-particle-resonance method.

Except for the levels populated in ^{62}Cu, there is good agreement between the proton spectroscopic factors of the analog states calculated with the single-particle-resonance method and the published neutron spectroscopic factors of the corresponding parent states. A difference of 30–35% is found in two cases: the 9.6-MeV level in ^{61}Cu and the 9.97-MeV level in ^{63}Cu. The agreement between proton spectroscopic factors calculated with the analog-resonance method and the published neutron spectroscopic factors is also good

TABLE II. Optical model parameters for DWBA calculations. Energies are in MeV; lengths are in fm.

Particle	V_R	W	W_S	V_{so}	r_{0R}	a_R	r_{0I}	a_I	r_{0C}	λ
^{3}He [a]	−180.0	−19.0	...	...	1.14	0.71	1.54	0.78	1.25	...
d [b]	−96.31	...	50.52	6.37	1.119	0.735	1.261	0.842	1.25	...
p [c]	...	...	...	...	1.20	0.65	...	...	1.25	25

[a] From Ref. 14.
[b] From Ref. 15.
[c] From Ref. 11.

TABLE III. Excitation energies, l values, and proton spectroscopic factors (S_p) which were deduced in the present work, and neutron spectroscopic factors (S_n) which were deduced in previous (d,p) studies. Only the states observed in the present work are listed.

Residual nucleus	Excitation energy (MeV)	Relative excitation energy (MeV)	Parent excitation energy (MeV)	l	J^π	$\frac{2J_f+1}{2J_i+1}S_p$ [a]		$\frac{2J_f+1}{2J_i+1}S_p$ [b]	$\frac{2J_f+1}{2J_i+1}S_n$	$\frac{S_p}{S_n}$ [a]		$\frac{S_p}{S_n}$ [b]
^{61}Cu	6.45	0.00	0.00 [c]	1	$\frac{3}{2}^-$	1.67		2.12	1.37 [d]	1.22		1.55
	6.52	0.07	0.068 [c]	3	$\frac{5}{2}^-$	4.06		5.16	3.89 [d]	1.04		1.33
	6.74	0.29	0.284 [c]	1	$\frac{1}{2}^-$	1.29		1.72	1.17 [d]	1.10		1.47
	7.64	1.19	1.106 [c]	1	$\frac{3}{2}^-$	0.13 [e]		0.14 [e]	0.108 [c]	1.20		1.30
			1.139 [c]	3	$\frac{5}{2}^-$	0.49 [e]		0.54 [e]	0.400 [c]	1.22		1.35
			1.192 [c]	1	$\frac{3}{2}^-$	0.31 [e]		0.34 [e]	0.255 [c]	1.21		1.33
	8.58	2.13	2.130 [c]	4		4.62		6.5	5.37 [d]	0.86		1.21
	9.14	2.69	2.707 [c]	2		0.98		1.08	0.44 [d]	2.23		2.45
	9.96	3.51	3.492 [c]	4		1.50 [e]		1.80 [e]	2.12 [c]	0.71		0.85
			3.507 [c]	2		0.59 [e]		0.71 [e]	0.84 [c]	0.71		0.85
^{62}Cu	4.64	0.00	0.00 [f]	1	0^+		0.83 [g]		0.45 [f]		1.84	
	5.82	1.18	1.176 [f]	1	2^+		0.65 [g]		0.31 [f]		2.09	
	7.97	3.33	3.286 [f]	1		0.118 [h]		0.148 [h]	0.076 [f]	1.55		1.95
				3		1.26 [h]		1.60 [h]	0.82 [f]	1.53		1.95
	8.19	3.55	3.536 [f]	1		0.68		0.81	0.32 [f]	2.12		2.53
^{63}Cu	8.66	0.00	0.00 [i]	1	$\frac{1}{2}^-$	0.78		0.86	0.85 [i]	0.92		1.01
	8.79	0.13	0.088 [i]	3	$\frac{5}{2}^-$	2.90 [j]		3.50 [j]	3.40 [i]	0.85		1.03
			0.155 [i]	1	$\frac{3}{2}^-$	0.98 [j]		1.18 [j]	1.15 [i]	0.85		1.03
	9.97	1.31	1.292 [i]	4	$\frac{9}{2}^+$	4.80		5.8	6.72 [i]	0.71		0.85
	10.96	2.30	2.291 [i]	2	$\frac{5}{2}^+$	1.80		1.80	1.99 [i]	0.90		0.90
	11.23	2.57	2.514 [i]	4	$\frac{9}{2}^+$	2.24		2.9	2.58 [i]	0.87		1.12
^{65}Cu	10.75	0.00	0.00 [i]	3	$\frac{5}{2}^-$	2.39 [j]		2.67 [j]	2.52 [i]	0.95		1.06
			0.062 [i]	1	$\frac{1}{2}^-$	1.34 [j]		1.49 [j]	1.41 [i]	0.95		1.06
	11.76	1.01	1.013 [i]	4	$\frac{9}{2}^+$	7.0		8.0	7.39 [i]	0.95		1.08
	12.67	1.92	1.915 [i]	2	$\frac{5}{2}^+$	1.76		1.62	1.46 [i]	1.21		1.11
	13.09	2.34	2.330 [i]	3	$\frac{5}{2}^-$	0.53 [j]		0.60 [j]	0.52 [i]	1.06		1.15
				4	$\frac{9}{2}^+$	1.07 [j]		1.17 [j]	1.02 [i]	1.05		1.15

[a] Proton spectroscopic factors as deduced with the single-particle-resonance method.
[b] Proton spectroscopic factors as deduced with the analog-resonance method.
[c] From Ref. 18.
[d] From Ref. 16.
[e] Unresolved group. S_p was calculated using the relative strength implied by S_n (from Ref. 18) and the absolute values were determined from the (^{3}He, d) data (see Sec. III).
[f] From Ref. 19.
[g] Bound state.
[h] See footnote e, S_n taken from Ref. 19.
[i] From Ref. 17.
[j] See footnote e, S_n taken from Ref. 17.

except for ^{62}Cu and for the first few levels in ^{61}Cu. The agreement is generally better for ^{63}Cu and ^{65}Cu than for ^{61}Cu, when either of the two methods of calculation is used. A marked disagreement exists between the S_p values obtained in the ^{61}Ni(^{3}He, d)^{62}Cu reaction and the published S_n values obtained in the ^{61}Ni(d, p)^{62}Ni reaction. This disagreement is found for all the levels observed in ^{62}Cu and with both methods of calculation. A similar disagreement was observed between the results of the ^{91}Zr(^{3}He, d)^{92}Nb and the ^{91}Zr(d, p)^{92}Zr reactions.[3] In contrast with the general good agreement between S_p and S_n for the even Ni and Zr targets, the S_p values which were found for the odd Ni and Zr targets are much larger than the corresponding S_n values. It should be mentioned that this disagreement is found in the present work even for the first two analog states in ^{62}Cu, which are bound. This effect is therefore not related to the unbound nature of the analog states. We have no explanation for this disagreement.

As was previously observed[3] in the $A \sim 90$ mass region there is a large difference between the sensitivity to angular momentum transfers in the (d, p) reaction and the (^{3}He, d) reaction. In the (d, p) reaction on Ni isotopes the cross section for population of states through $l = 3$ or $l = 4$ transitions is several times smaller than the cross sections for $l = 1$ or $l = 2$ transitions to states with the same spectroscopic factors (S_n). In the present (^{3}He, d) reaction we find that the cross section increases gradually for large l transitions. As a consequence, analog states populated through large angular momentum transfer are better observed in the (^{3}He, d) reaction than their corresponding parent states in the (d, p) reaction.

The use of this different sensitivity to angular momentum transfer can be demonstrated in the case of a doublet of states. For example, in the (d, p) studies the level at 2.330 MeV in the ^{65}Ni was found by Turkiewicz *et al.*[17] to be a doublet populated through $l = 3$ and $l = 4$ transitions, while Anfinsen *et al.*[20] treated this level as if it were a pure $l = 3$ transition (Sec. III A above). An analysis of the corresponding analog state, assuming a pure $l = 3$ transition, would yield a spectroscopic factor of 1.8, a value which is much larger than the value of 0.86 found by Anfinsen *et al.*, while a good agreement with Turkiewicz[17] was achieved when a doublet was assumed. Thus, whenever a doublet of states, involving at least one large l value is treated, a comparison of (^{3}He, d) and (d, p) can establish the nature of the doublet. Another case where this difference in sensitivity between the two reactions is observed is when highly excited states, for which no parent states were reported, are populated in the (^{3}He, d) reaction. As noted above these could be analog states populated through large l value transition, whose parent states were too weakly excited in the (d, p) reaction. Such cases were observed also in the $A \sim 90$ mass region.[3]

In summary, we have demonstrated that the two methods which were used for the calculation of the form factors of unbound analog states are useful in both $A \sim 60$ and $A \sim 90$ mass regions. Based on our observation we conclude again that the (^{3}He, d) reaction to analog states is complementary to the (d, p) reaction especially for the study of levels which are populated through large angular momentum transfers.

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