Single-Particle Strengths for Quasibound Levels in ^{33}Cl†

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The reaction ^{32}S(^{3}He, d)^{33}Cl has been studied at bombarding energies of 29.7 and 34.5 MeV. Angular distributions measured for levels up to 8.7-MeV excitation were analyzed with the distorted-wave Born approximation, utilizing for the quasibound levels a resonance-form-factor technique developed previously. The resulting spectroscopic factors are compared with the 15-MeV (^{3}He, d) results of Morrison, with values deduced from elastic scattering widths, and with recent theoretical calculations. Significant disagreements with the 15-MeV results are observed for the ground state ($l_p = 2$) and 2.69-MeV level ($l_p = 3$), while reasonable agreement with the elastic scattering results are observed for $l_p = 3$ levels of higher excitation.

I. INTRODUCTION

Nuclei in the 2s-1d shell have been investigated quite extensively, and a vast amount of information from single-nucleon-transfer reactions is available.[1] The ^{33}Cl nucleus can be produced in such a reaction only by the transfer of a proton to ^{32}S. This presents a special problem in spectroscopic interpretation, since ^{33}Cl levels above 2.28 MeV in excitation are proton unstable and thus excluded from conventional analyses with the distorted-wave Born approximation (DWBA). The spectroscopic properties of many of the unbound levels have been determined by Olness, Haeberli, and Lewis (OHL),[2] who studied proton elastic scattering on ^{32}S, while the low-lying levels of ^{33}Cl have been investigated with the reaction ^{32}S(^{3}He, d)-^{33}Cl at bombarding energies of 12[3] and 15 MeV.[4] We have studied the (^{3}He, d) reaction at 29.7- and 34.5-MeV bombarding energies, and have performed DWBA calculations for levels "quasibound" by the Coulomb-plus-centrifugal barrier using a resonance-form-factor technique reported previously.[5,6] A comparison of spectroscopic factors obtained from the (^{3}He, d) reaction with those deduced from proton elastic scattering[2] provides a further test of their reliability for quasibound levels. Also, a comparison of the results with those from lower-energy (^{3}He, d) experiments provides a measure of the consistency of spectroscopic information obtained at various bombarding energies.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The experimental configuration and data analysis procedure for these experiments was similar to that reported previously.[6] Natural H_2S gas (95.0% ^{32}S) contained in a 8.9-cm-diam by 1.3-cm-high cylindrical gas cell with 1.8-mg/cm^2-thick Havar windows was used as a target. The pressure (nominally 20 cm of Hg) was monitored continuously with a Hg manometer. A solid-state detector telescope was used to detect deuterons and elastically scattered helions simultaneously. Data were taken with a 1-mm-thick silicon surface-barrier ΔE detector and Si(Li) E detectors of 1.8- and 3-mm thickness at 29.7 and 34.5 MeV, respectively, with an over-all resolution of 80–100 keV. A spectrum taken at 34.5 MeV is shown in Fig. 1.

An energy calibration was obtained from previously measured ^{33}Cl levels,[2,3] and from the reactions ^{16}O(^{3}He, d)^{17}F and ^{14}N(^{3}He, d)^{15}O using air in the gas cell. Angular distributions were measured for laboratory angles between 9.5 and 55.0° at 29.7 MeV, and between 10.4 and 42.7° at 34.5 MeV, with an uncertainty in the absolute cross section of about 10% (Figs. 2-5). Beam current integration was monitored with a detector fixed at a scattering angle of 35°.

III. DWBA CALCULATIONS AND DISCUSSION OF RESULTS

DWBA calculations were performed in the local zero-range approximation with the computer code DWUCK,[7] using a (^{3}He, d) normalization of 4.42[8] to extract spectroscopic factors. Optical-model and form-factor potential parameters are given in Table I. The ^{3}He parameters were obtained by fitting elastic scattering data taken in this experiment, while the deuteron parameters were obtained from Hiebert, Newman, and Bassel[9] and from Perey and Perey.[10] The form factors were obtained by adjusting the depth of a Woods-Saxon potential to obtain an eigenfunction (or resonance) for a given l and j of the transferred proton at the appropriate binding energy. The functions were normalized by setting equal to unity the probability integral between the origin and the external classical turning radius (infinity for bound states). Further details regarding DWBA calculations for quasibound levels are presented elsewhere.[5,6]

Low-Lying Levels

Angular distributions and DWBA calculations for levels below 4-MeV excitation energy are shown in Figs. 2–5. The results are summarized and compared with the experimental work of Morrison,[4] with shell-model calculations,[11] and with intermediate-coupling vibrational-model calculations[12] in Table II. The excitation energies are in good agreement with those obtained by Moss,[3] who studied the reaction $^{32}S(^{3}He, d)^{33}Cl$ at 12-MeV bombarding energy. Three of these levels are above the $^{32}S+p$ separation energy (2.2776 MeV[13]), and are therefore unbound with respect to proton emission.

The $l_p=0$, 1, and 2 DWBA calculations produced generally better fits to the 34.5-MeV data (Fig. 4) than the 29.7-MeV data (Fig. 2), although the spectroscopic factors obtained at these two bombarding energies are generally in good agreement (Table II). Our C^2S values for the $\frac{3}{2}^+$ ground-state transition (0.70, 0.63) are in excellent agreement with the (d,p) spectroscopic factor for the ^{33}S mirror-nucleus ground state (0.69)[14] and with the $A=33$ theoretical predictions of Wildenthal *et al.*[11] (0.64) and Castel, Stewart, and Harvey (CSH)[12] (0.77). The value obtained by Morrison[4] from the $(^{3}He, d)$ reaction at 15-MeV bombarding energy (0.90) is considerably larger. The spectroscopic factor obtained at 29.7 MeV for the 0.810-MeV $(\frac{1}{2}^+)$ first excited state is in good agreement with the values of Refs. 4, 12, and 14, while the 34.5-MeV value is about 25% higher. The angular distribution for the 2.36-MeV level (Fig. 4) is consistent with the $l_p=2$ assignment of Moss,[3] and our $\frac{3}{2}^+$ spectroscopic factor (0.061) is in agreement with both the (d,p) result to the mirror state in ^{33}S and the theoretical predictions (Table II).

The deuteron group corresponding to 2.84-MeV excitation (a known doublet[1]) is due mainly to an $l_p=1$ transfer, and contains about one half of the $2p_{3/2}$ single-particle strength. Spectroscopic factors obtained for this level at the three bombarding energies are in good agreement. The angular distributions for the strongly excited $l_p=3$ level at 2.69-MeV excitation (shown in Figs. 3 and 5) are not well reproduced by the DWBA for either bombarding energy at the forward angles. The spectroscopic factors measured in the present work for this level (0.50, 0.41) are in reasonable agreement, although both values are considerably smaller than that obtained at 15-MeV bombarding energy (0.73).[4] Although the spectroscopic factors of Ref. 4 for the 2.69- and 2.84-MeV levels were

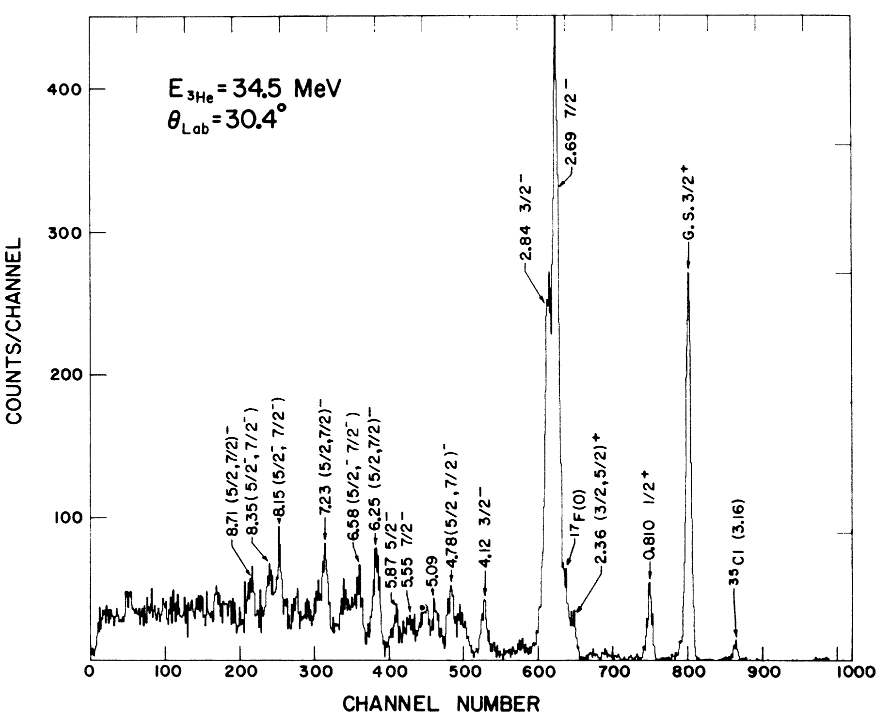

FIG. 1. Deuteron spectrum for the reaction $^{32}S(^{3}He,d)^{33}Cl$ at 34.5-MeV bombarding energy. All levels above 2.28-MeV excitation are proton unstable. The ^{17}F ground-state transition indicates the presence of a small (~3%) oxygen contaminant in the target.

TABLE I. Potential parameters for DWBA calculations.

Particle	V (MeV)	W (MeV)	$4W_D$ (MeV)	r_0 (F)	a (F)	r_I (F)	a_I (F)	λ_{so}	E (MeV)
^{3}He	178.4	43.8		1.20	0.64	0.83	1.29		29.7
d	98.5		81.1	1.07	0.93	1.57	0.48		
^{3}He	174.0	28.1		1.24	0.68	1.07	1.34		34.5
d	111.0		57.9	0.98	0.82	1.36	0.68		
p				1.25	0.65			25.	

obtained by extrapolation of the DWBA from the bound to unbound region, little error should arise from this, since these levels are only about 400–600 keV unbound.[5]

The spectroscopic factors for the $l_p = 2$ (ground state) and $l_p = 3$ (2.69 MeV) transitions discussed above decrease with bombarding energy, while those for the $l_p = 1$ transfer are in reasonable agreement ($\lesssim 20\%$), with no apparent systematic trend. Although a slight increase in C^2S with $E_{^3\text{He}}$ is noted for the $l_p = 0$ transition, this change is smaller than the uncertainties involved in normalizing an $l_p = 0$ DWBA curve to the data. For small l_p transfers, the (^{3}He, d) DWBA calculations result in unrealistic contributions from the nuclear interior at our bombarding energies because of momentum mismatch between entrance and exit channels. Thus, contrary to the present results, better agreement with the 15-MeV data might be expected for the larger l_p values, where the calculations are more confined to the surface and exterior regions. (A lower cutoff of the DWBA radial integrals at 4.0 F $\approx 1.25A^{1/3}$ F changes the cross section by <10% at angles smaller than 20° for an $l_p = 2$ transition, while an increase of about 50% is observed at 15° for an $l_p = 0$ transition.) It is possible that multistep processes are important for the ground and 2.69-MeV levels at low ^{3}He bombarding energies. The spectroscopic factors obtained at 29.7 and 34.5 MeV are in excellent agreement for the more unbound $l_p = 3$ levels.

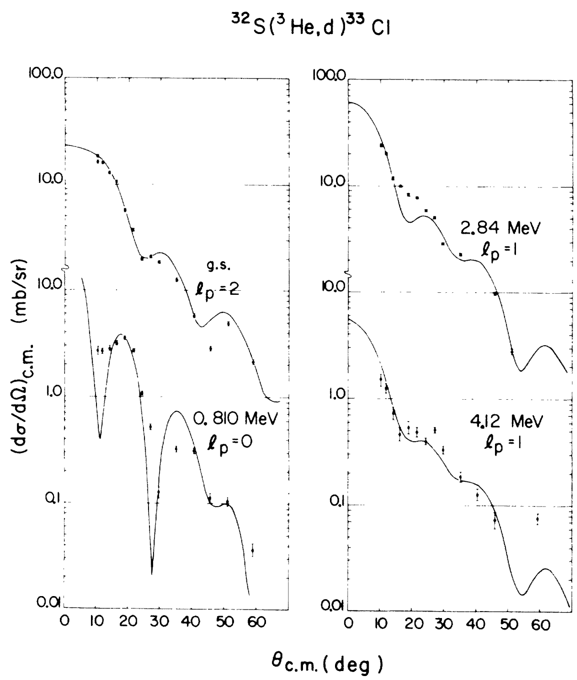

FIG. 2. Deuteron angular distributions for the reaction ^{32}S(^{3}He,d)^{33}Cl at 29.7-MeV bombarding energy. The curves are DWBA calculation. Resonance form factors were used for the unbound levels.

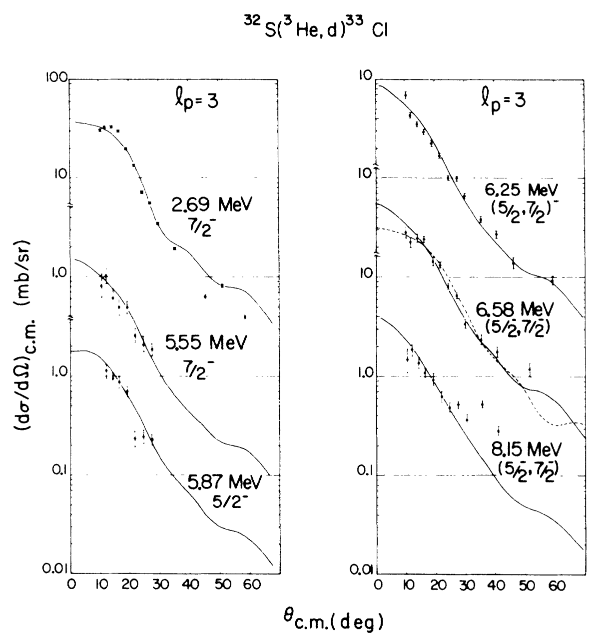

FIG. 3. Angular distributions for $l_p = 3$ levels at 29.7-MeV bombarding energy. The curves are DWBA calculations performed with a resonance form factor. An $l_p = 4$ calculation for the 6.58-MeV level is shown by the dashed curve.

TABLE II. Summary of results for low-lying levels in ^{33}Cl.

$E(^{33}\mathrm{Cl}^*)$ (MeV ± keV)	l_p	J^{π} [a]	$C^2S(^3\mathrm{He}, d)$ 29.7 MeV	34.5 MeV	15 MeV [b]	$S(d,p)$ [c]	Theory Shell model [d]	ICVM [e]
0.00	2	$\frac{3}{2}^+$	0.70	0.63	0.90	0.69	0.64	0.77
0.810 ± 6	0	$\frac{1}{2}^+$	0.32	0.37	0.29	0.27	0.27	0.28
2.358 ± 25	2	$\frac{3}{2}^+$	···	0.061	···	0.05	0.07	0.04
		$\frac{5}{2}^+$	···	0.033	···	···	···	···
2.686 ± 15	3	$\frac{7}{2}^-$ [b]	0.50	0.41	0.73	···	···	···
2.842 ± 15	1	$\frac{3}{2}^-$	0.50	0.58	0.55	0.33	···	···

[a] See also Ref. 1.
[b] See Ref. 4.
[c] See Ref. 14.
[d] See Ref. 11.
[e] Intermediate-coupling vibrational model (see Ref. 12).

Levels of High Excitation

Several levels above 4 MeV of excitation in ^{33}Cl have been observed by OHL[2] via proton elastic scattering. Angular distributions for the $\frac{3}{2}^-$ level at 4.12 MeV and several $l_p = 3$ levels at higher excitations have been measured in the present work. These data are shown in Figs. 2–5 along with DWBA calculations performed with quasibound resonance form factors. A summary of the results is given in Table III, where (^{3}He, d) spectroscopic factors are compared with those obtained from the resonance scattering data. Laboratory widths of single-particle resonances (Γ_{sp})[15] were calculated using the optical-model code JIB[16] with the same potential as that used for the corresponding DWBA

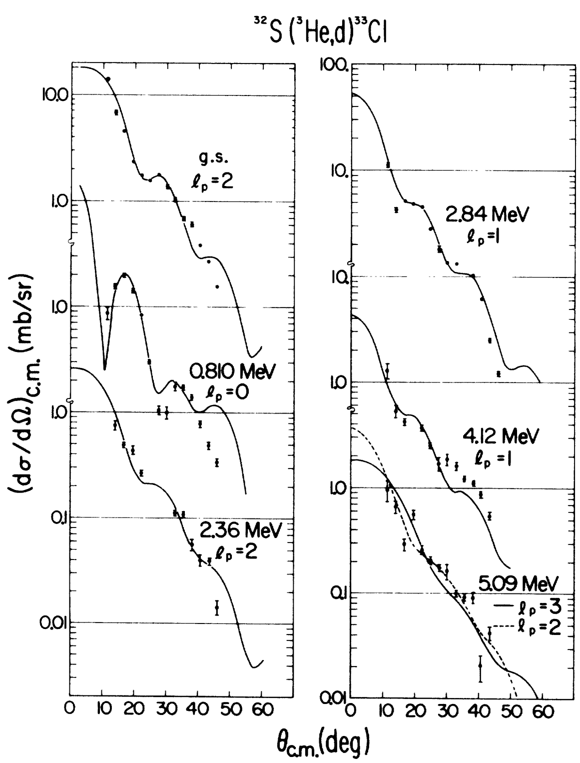

FIG. 4. Angular distributions and DWBA calculations at 34.5-MeV bombarding energy. (See also Fig. 2 caption.)

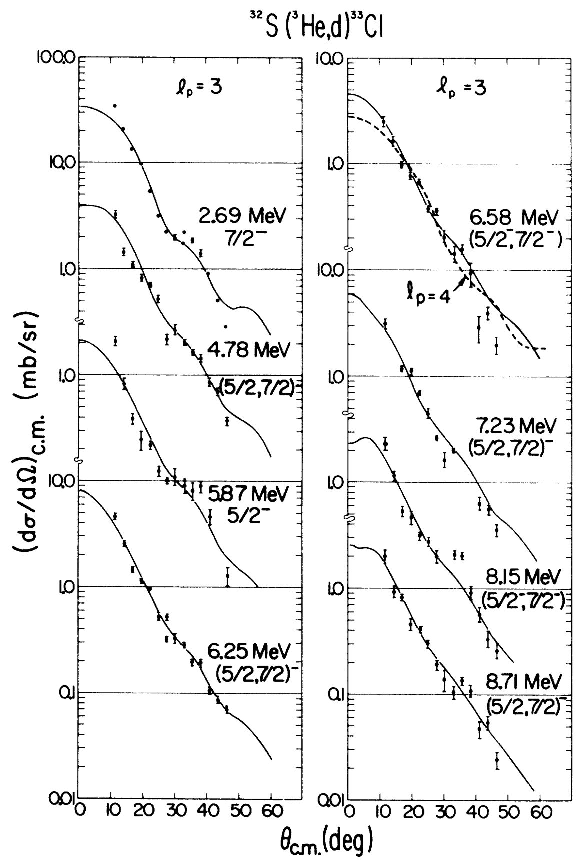

FIG. 5. Angular distributions and DWBA calculations for $l_p = 3$ levels at 34.5-MeV bombarding energy. (See also Fig. 3 caption.)

form factors (see Table I). The elastic scattering spectroscopic factors shown in the last column of Table III are ratios of the measured elastic lab widths of Ref. 2 to the calculated widths

$$S_{el} = \Gamma/\Gamma_{sp} .$$

This definition of S_{el} is consistent with that given previously in terms of reduced widths [see, e.g., Eqs. (6) and (11) in Ref. 5]. The excitation energies for the levels below 6 MeV are in excellent agreement with those deduced from the resonance energies of Ref. 2, using the proton separation energy measured in Ref. 13.

The 4.12-MeV level has been assigned $\frac{3}{2}^-$ in Ref. 2, and our angular distributions are best described by an $l_p = 1$ DWBA calculation (Figs. 2 and 4), although the fits to the data are not particularly good. The spectroscopic factors obtained at 29.7 and 34.5 MeV differ by about 25%, but some of this may be owing to the uncertainties in normalizing the DWBA curves to the data. Our C^2S values (0.060, 0.075) are considerably lower than S_{el} for this level (0.10 ± 0.02), although the usual DWBA errors (~30%) would overlap the experimental errors shown for S_{el}.

The angular distribution for the weakly excited 5.09-MeV level is shown in Fig. 2 with $l_p = 2$ and $l_p = 3$ DWBA curves. Levels having $J^\pi = \frac{1}{2}^-$, ($\frac{5}{2}^-$, $\frac{7}{2}^-$), and $\frac{3}{2}^+$ have been observed by OHL[2] at 5.084, 5.091, and 5.106 MeV, respectively. The $\frac{1}{2}^-$ level is quite broad (360 keV) and probably is the background under the narrow peak in our spectra. Our (^{3}He, d) spectroscopic factors for $l_p = 3$ are consistent with the upper limits of Ref. 2, while our $\frac{3}{2}^+$ result is too large by a factor of 3. It therefore appears that most of the observed strength is due to an $l_p = 3$ transfer.

Angular distributions for other $l_p = 3$ levels are shown in Figs. 3 and 5 for the 29.7- and 34.5-MeV bombarding energies, respectively. The distribution for the 4.78-MeV level is best described by an $l_p = 3$ calculation, in agreement with the ($\frac{5}{2}$, $\frac{7}{2}$)$^-$

TABLE III. Summary of results for resonance levels in ^{33}Cl.

$E(^{33}\mathrm{Cl}^*)$ (MeV ± keV)	l_p	J^π	$C^2S(^3\mathrm{He}, d)$ 29.7 MeV	$C^2S(^3\mathrm{He}, d)$ 34.5 MeV	S_{el} [a]
4.12 ± 20	1	$\frac{3}{2}^-$ [b]	0.060	0.075	0.10 ± 0.02
4.78 ± 20	3	$\frac{5}{2}^-$ [b]		0.074	0.076 ± 0.015
		$\frac{7}{2}^-$ [b]		0.040	0.053 ± 0.010
5.09 ± 20	3	$\frac{5}{2}^-$ [b]		0.031	<0.07
		$\frac{7}{2}^-$ [b]		0.017	<0.05
	(2)	$(\frac{3}{2}^+)$ [b]		0.059	0.021 ± 0.007
5.55 ± 30	3	$\frac{7}{2}^-$ [b]	0.010	0.013	0.017 ± 0.002
5.87 ± 20	3	$\frac{5}{2}^-$ [b]	0.027	0.027	0.030 ± 0.006
6.25 ± 30	3	$\frac{5}{2}^-$	0.097	0.091	
		$\frac{7}{2}^-$	0.054	0.050	
6.58 ± 30	(3)	$(\frac{5}{2}^-)$	0.059	0.061	
		$(\frac{7}{2}^-)$	0.034	0.034	
	(4)	$(\frac{9}{2}^+)$	0.032	0.024	
7.23 ± 40	3	$\frac{5}{2}^-$	0.073	0.073	
		$\frac{7}{2}^-$	0.041	0.041	
8.15 ± 40	(3)	$(\frac{5}{2}^-)$	0.041	0.042	
		$(\frac{7}{2}^-)$	0.024	0.025	
8.35 ± 50	(3)	$(\frac{5}{2}^-)$		(0.03)	
		$(\frac{7}{2}^-)$		(0.02)	
8.71 ± 50	3	$\frac{5}{2}^-$		0.05	
		$\frac{7}{2}^-$		0.03	

[a] Calculated from ^{32}S(p, p)^{32}S results of Ref. 2. The errors represent only the experimental errors of Ref. 2.
[b] See also Refs. 1 and 2.

assignment of OHL,[2] and the (^{3}He, d) spectroscopic factor is in agreement with S_{el} (Table III). The spectroscopic factors obtained for the weakly excited 5.55-MeV level (assigned $\frac{7}{2}^-$ in Ref. 2) are somewhat lower than S_{el}; however, it appears that the elastic width for this state may have been overestimated. An assignment of $\frac{5}{2}^-$ for the 5.87-MeV level has been made by OHL,[2] although our 34.5-MeV data (Fig. 5) changes more rapidly with angle than the $l_p = 3$ DWBA prediction. Our $\frac{5}{2}^-$ spectroscopic factors for this level (0.027 at both energies) are in excellent agreement with the value of 0.030 ± 0.006 obtained from the elastic scattering width.

Angular distributions for levels at 6.25, 7.23, and 8.71 MeV are described quite well by $l_p = 3$ DWBA calculations. A proton resonance at 7.24-MeV excitation in ^{33}Cl has been observed previously.[17] It is difficult to distinguish between $l_p = 3$ and $l_p = 4$ transfers for the 6.58-MeV level, although the $l_p = 3$ calculation provides a slightly better fit to the 34.5-MeV data at forward angles. The $l_p = 3$ curves provide significantly better fits to the 34.5-MeV angular distributions for other levels observed above 6-MeV excitation. The 8.15-MeV distribution is very similar in shape to that for the 5.87-MeV ($\frac{5}{2}^-$) level (Fig. 5), although both are fitted rather poorly by the $l_p = 3$ calculation.

The $l_p = 3$ (^{3}He, d) spectroscopic factors obtained at the 29.7- and 34.5-MeV bombarding energies for all levels having 5.87-MeV or more excitation energy agree to within <10% (Table III), which is about the uncertainty associated with normalizing the DWBA curves to the data. Agreement such as this is surprising, since the C^2S values for the tightly quasibound 2.69-MeV level ($\frac{7}{2}^-$) are in disagreement by about 20%. However, as mentioned earlier, the fits to the data for the 2.69-MeV level are relatively poor for both bombarding energies.

Levels corresponding to the major portion of the $2p_{1/2}$ strength were observed at 4.517- and 5.084-MeV excitation in the elastic scattering experiment of OHL[2] but are weakly excited in the (^{3}He, d) reaction and unresolved from other nearby levels in our spectra. The weak intensity of these peaks is qualitatively predicted by the calculated $l_p = 1$ DWBA cross sections, which decrease by about a factor of 2 as the excitation energy is increased from 3 to 5 MeV. In addition, the 5.084-MeV level is quite broad (360 keV, or about 4 times our resolution), and would not be prominent, in spite of its significant single-particle strength ($S_{el} = 0.49 \pm 0.06$).

IV. SUMMARY AND CONCLUSIONS

The $l_p = 3$ (^{3}He, d) spectroscopic factors for the more unbound ^{33}Cl levels obtained at 29.7- and 34.5-MeV bombarding energies are in excellent agreement, while reasonable agreement was obtained for the bound and tightly quasibound levels. Significant discrepancies with the 15-MeV results[4] are observed for the ground-state ($l_p = 2$) and the 2.69-MeV level ($l_p = 3$), however, which suggests that the (^{3}He, d) reaction should be studied in more detail as a function of bombarding energy. The over-all agreement of our (^{3}He, d) results with those deduced from the elastic scattering widths is quite reasonable (Table III), although the C^2S values are at least slightly smaller in each case (ignoring the $l_p = 2$ calculation for the 5.09-MeV level). This could be due to systematic errors in the present experiment or that of Ref. 2.

In addition to the lower-lying $f_{5/2}$ and $f_{7/2}$ levels observed previously,[1-4] five relatively strongly excited levels above 6 MeV in ^{33}Cl are tentatively assigned $l_p = 3$. Each of these levels, however, represents less than 10% of the available single-particle strength. Approximately one half of the $1f_{7/2}$, $2p_{3/2}$, and $2p_{1/2}$ strengths are contained in the 2.69-, 2.84-, and 5.084-MeV levels, respectively, while no single level contains more than ~10% of the $f_{5/2}$ strength. The summed spectroscopic factors for the $f_{7/2}$ and $f_{5/2}$ shells are ≤ 0.8 and ≤ 0.5, respectively.

The low-lying positive-parity levels of ^{33}Cl have been discussed by other authors[3,4] in terms of various shell-model calculations and the Nilsson model. The $K = \frac{3}{2}$ and $K = \frac{1}{2}$ Nilsson orbits are consistent with the general ordering of levels for an oblate deformation. Each of these orbits can contain only two protons, which implies the sum of $(2J+1)C^2S$ over a given rotational band (given K) should equal 2. Our spectroscopic factor for the ground state alone exceeds this limit, which implies further modifications of the Nilsson model (such as rotational-band mixing) would be required to explain the results. A similar situation exists for explaining other single-nucleon-transfer data on nuclei in this region.[18] Both the shell-model calculations of Wildenthal *et al.*,[11] in which all $2s$-$1d$ shell orbitals are included in the model space, and the intermediate-coupling vibrational-model calculations of CSH[12] are in excellent agreement with our experimental results.

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Reactions Induced by He^3 Ions on Zn^{64}†

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Foils of enriched Zn^{64} (99.85%) were bombarded with He^3 particles with energies of 22.2, 29.5, 37.7, and 43.4 MeV after which γ-ray spectra were accumulated from the radioactive foils with a large Ge(Li) detector and a 4096-channel pulse-height analyzer system. The isotopes produced were determined by the β-delayed γ rays and their corresponding half-lives. No chemical separation of the foils was performed.

Cross sections for a particular reaction were determined for each isotope and beam energy. The resulting excitation functions for the 13 reactions which were detected are presented, and are compared with similar reactions including those induced by He^3 on Cu isotopes. Possible reaction mechanisms are discussed. Direct reactions appear to be the principal reaction mechanism, especially at higher He^3-particle energies where cluster-transfer reactions are common.

INTRODUCTION

The origin of this research was a cooperative effort between the Nuclear Physics Laboratory of the University of Wyoming and the Cyclotron Laboratory of the University of Colorado to produce the unreported isotope Ge^{64}. It was envisioned that this isotope could be produced by bombarding a highly enriched target of Zn^{64} with He^3 particles to produce the compound nucleus Ge^{67*}. If the compound nucleus were produced with sufficient excitation energy, then the emission of three neutrons to yield Ge^{64} should become one possible reaction.

The first attempts to produce Ge^{64} revealed vast gaps in the knowledge of the reactions which are induced by He^3 on Zn^{64}. Very little was known about the type of reaction, direct or compound-nuclear, which might take place, the kinds of particles likely to be emitted, or the cross sections for these reactions. Thus before a systematic search for Ge^{64} could be done, these properties needed to be defined. The type and cross sections for the reactions induced and an indication of the type of reaction induced were found to be somewhat distinguishable by subsequent detection of the radioisotopes produced.

The use of He^3 nuclei as accelerated particles for the study of nuclear reactions has increased steadily,[1-8] since a practical means of obtaining He^3 has been developed. Owing to the small binding energy of He^3 it is possible to produce compound nuclei with sufficient excitation energy to cause multiple-particle evaporation at relatively low bombarding energies. This makes He^3 particles