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Fractionated single-particle states of ^{33}S at $E_x = 8.6$–9.5 MeV*

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A total of 21 states of ^{33}S in the region of excitation from about 8.6 to 9.5 MeV have been studied using the reaction $^{32}S(d,p)$ at 12 MeV incident deuteron energy and a biased quadrupole spectrometer. Fractionated single-particle states are identified via their forward-angle cross sections, using distorted-wave Born-approximation predictions with resonance state form factors for the residual ^{33}S system. Results are compared with those from (n,n) and/or (n,γ) studies over the same region of excitation, where this is possible. It is shown that states strongly populated in (n,n) do not often show up in (d,p) spectra and vice versa.

NUCLEAR REACTIONS $^{32}S(d,p)$, $E_d = 12$ MeV, measured $\sigma(\theta)$. ^{33}S deduced levels, l, j, π, spectroscopic factors. DWBA analysis, resolution 12 keV; comparison to neutron total σ, ^{32}S.

I. INTRODUCTION

Low-energy neutron cross sections have been the subject of extensive study by nuclear physicists for many decades, principally because of the needs of nuclear technology. Our basic understanding of nuclear structure has also been enhanced by such studies, which have led, e.g., to the concepts of the optical model and the single-particle strength function.

A recently published compilation of resolved neutron resonance parameters lists some 51 000 resonances in the zero to 1 MeV region of resonance energy over the broad range of β-stable nuclei.[1] Almost all of this information has come from (n,n) and/or (n,γ) experiments.

Until recent years, except in very light nuclei, direct nuclear reaction spectroscopy has not been used to study particle-unbound states in the residual nucleus. Recently, however, a number of studies have been reported in which direct light-ion reactions such as (d,p), (d,n), and $(^3He,d)$ were used to carry out spectroscopic analyses of states at excitations above the neutron or proton separation energy.[2-8] In these efforts, various techniques[9,10] which have been recently developed for treatment of single-nucleon-transfer reactions populating particle-unbound states within the framework of the distorted-wave Born-approximation (DWBA) have made it possible to extract resonance widths which may be compared directly to those obtained, say, from elastic nucleon scattering on the same targets.

For the isobaric analog resonances, the agreement between widths extracted via (d,n) or $(^3He,d)$ and those obtained from (p,p) resonance studies is very good.[3-5] In other words, the same spectroscopic factor $S_p = (2T_0+1)(\Gamma_p/\Gamma_{sp})$ is obtained from both types of experiments, within experimental error—here T_0 is the isobaric spin of the target nucleus, Γ_{sp} is the single-particle proton resonance width, and Γ_p is the measured proton decay width.

However, there have been no convincing investigations of the agreement, or the lack thereof, between (d,p) and (n,n) analyses of neutron resonances. In previous work,[6-8] either the (d,p) or the (n,n) analyses were to some degree ambiguous or (n,n) data were lacking for comparison. Thus the extent to which (d,p) determinations of the widths of neutron resonances are reliable has remained an open question.

It is also an important question, because as discussed in Sec. II of this paper, the (d,p) reaction can populate many resonances which could never be observed in (n,n) and/or (n,γ) cross sections because of penetrability considerations. Thus the construction of d and f wave neutron strength functions, for example, becomes a real possibility.

Here we present a study of the $^{32}S(d,p)^{33}S$ reaction at 12 MeV incident deuteron energy. We have covered the same region of excitation in ^{33}S—from 8.64 to 9.46 MeV—for which well-resolved neutron resonances are reported from (n,n) and (n,γ) experiments.[1] There are eight such resonances reported of which five have $l>0$. In our work, we have observed 20 resonances in the same region of excitation and have attempted to make a comparison of neutron widths where we were reasonably certain that the same level had been populated both in the (d,p) and the (n,n) experiments. We have extracted neutron widths, and assigned orbital angular momentum values, for most of the resonances we have observed.

II. QUALITATIVE COMPARISON OF (n,n) AND (d,p)

In (n,n) and (n,γ) studies the resonance is populated as an intermediate or compound state, whereas in (d,p) the resonance is populated as a residual nuclear state. As a result the selectivity of the two types of reactions is very different, as we will now show.

Neutron resonance spectroscopy has generally been confined for resolvable resonances to incident neutron energies from thermal to about 1 MeV. At such energies, for nuclei with radii comparable to that of ^{32}S, it is not possible for the neutron to carry more than one unit of angular momentum into the compound system. It is thus no surprise that the (n,n) and (n,γ) data are dominated by s and p resonances.

Elementary quantum mechanical considerations applied to the nuclear plus centrifugal barrier faced by an incoming neutron show that the neutron resonance width at a fixed resonance energy decreases roughly exponentially as a function of the orbital angular momentum l of the neutron. That is, $\Gamma_n(E_r, l) \sim e^{-\alpha l}$, where for the sulfur case α is about 3.6 for a resonance at 300 keV, for example. On the other hand, for a resonance of given l, again from elementary considerations of potential scattering, the neutron width increases approximately exponentially as the square root of the resonance energy. That is, $\Gamma_n(E_r, l) \sim e^{+\beta\sqrt{E}_r}$, where for the sulfur case again, β is about 10 MeV$^{-1/2}$.

At an isolated resonance, the (n,n) and (n,γ) cross sections are of course given by $\sigma(n,n) \sim \Gamma_n^2/\Gamma^2$ and $\sigma(n,\gamma) \sim \Gamma_n \Gamma_\gamma/\Gamma^2$, where Γ is the total width of the resonance and Γ_γ is its photon decay width. The point of this is to emphasize that since the total width is relatively insensitive to penetrability considerations, as compared to the neutron width, because of the generally large number of open channels, the observability of a given resonance in (n,n) and/or (n,γ) depends rather critically on its orbital angular momentum through Γ_n.

However, there is no such selectivity in the (d,p) reaction. The (d,p) cross section is given by[10] $\sigma(d,p) = S_n \sigma_l(\text{DWBA}) = [\Gamma_n/\Gamma_{sp}]\sigma_l(\text{DWBA})$, where S_n is the neutron spectroscopic factor of the residual state and Γ_{sp} is the single-particle width of the resonance. Since the single-particle width and the neutron width Γ_n have the same dependence on l and E_r, the observability of the resonance in (d,p) depends mainly upon its spectroscopic factor S_n—that is, on the degree to which the nuclear state function contains a continuum neutron plus ground-state core term.[10] Selectivity in l enters only through the angular momentum matching required to produce an angular distribution with large magnitude and good diffractive structure, namely, $|k_d R_d - k_p R_p| \approx l$, where k_i and R_i are the center-of-mass wave number and nuclear radius in channel i. Using 12 MeV deuterons and observing states at 7 to 10 MeV in excitation in ^{33}S, one has good angular momentum matching for two units of orbital angular momentum. Thus one can rather easily discriminate among p, d, and f states.[8] As we will see, however, p states with widths such as those observed in the neutron work have very small cross sections. The comparison between (n,n) and (d,p) thus becomes very difficult.

In our DWBA calculations we use a technique developed by Coker.[10] Complex-energy eigenstates (Gamow states) are used to describe the residual unbound nuclear state. This method provides a "single-particle" form factor for the DWBA calculations, and a single-particle width. When the DWBA calculations are compared to the data, a spectroscopic factor S_n is extracted as is normally the case with bound states. Once the spectroscopic factor is known, the actual neutron width Γ_n is also, since $\Gamma_n = S_n \Gamma_{sp}$. This width Γ_n may be compared directly to the neutron partial width measured in (n,n) and/or (n,γ) experiments.[1]

III. EXPERIMENTAL PROCEDURE

The natural isotopic abundance of ^{32}S is 95%. Our experiment used natural PbS targets of thickness 100 μg/cm^2 prepared by evaporation onto thin carbon foils. The Pb contamination in the target presented no problems since at the incident deuteron energy of 12 MeV all competing reactions on Pb are sub-Coulomb with cross sections orders of magnitude less than those on ^{32}S. Kinematic separation of reactions involving lead from those involving sulfur or carbon is also trivial. The only problem presented by the use of PbS targets is the instability of the PbS film thickness. The film, under bombardment with deuteron beams of any appreciable current over any significant period of time, seems to flow slightly. Thus a monitor detector had to be used as well as a Faraday cup. The monitor detector was fixed at 115° laboratory angle.

The Center for Nuclear Studies biased quadrupole spectrometer was used to achieve excellent particle identification while enabling the use of a single high-resolution lithium-drifted silicon detector. Details of the experimental setup and performance of the quadrupole spectrometer are given elsewhere.[8,11]

The over-all experimental resolution for protons was 14 keV full width at half-maximum. States in

^{33}S populated via ^{32}S(d,p) were identified via kinematic tracking. It was assumed that no states corresponding to ^{33,34}S(d,p) were observed in the spectra. Calibration was established by relying heavily, of necessity, on identification of lower-lying ^{33}S states. Thus, extreme care was taken in extending the calibration into the region of excitation from 7 to 9 MeV in ^{33}S. The deuteron breakup background under the peaks analyzed in this study was very similar to that seen in Fig. 4 of Ref. 11 for ^{30}Si(d,p) at $E_d = 10.0$ MeV.

Absolute cross sections were obtained via measurement of deuteron elastic scattering at 12 MeV, which was also fitted with the optical model to obtain the deuteron optical potential parameters used in the DWBA calculations reported in the next section. The error bars associated with the (d,p) data points are almost entirely due to systematic errors in background subtraction, statistical errors having been kept to a minimum.

A total of 21 states in ^{33}S in the region of excitation of interest, from 8.58 to 9.46 MeV, was observed in this experiment. The state at 8.58 MeV is bound by about 57 keV, while all other states are neutron unbound, corresponding to neutron resonances between 0.003 and 820 keV incident neutron energy. We have obtained reasonably complete angular distributions for all but two of these states.

Table I summarizes the spectroscopic information for these states from the present and earlier experiments. The angular distributions are displayed in Figs. 1 and 2, together with the results of the DWBA calculations to be discussed in the next section.

IV. ANALYSIS AND DISCUSSION OF DATA

Theoretical angular distributions for p, d, and f resonances in ^{33}S were calculated using a technique developed by Coker.[10] We made use of the program GAMOW-3, which computes complex-energy eigenstates of single particles in a real Woods-Saxon potential, including spin-orbit coupling. For all the calculations the geometrical parameters of this potential were $r = r_{so} = 1.23$ fm, $a = a_{so} = 0.65$ fm, and $V_{so} = 5.8$ MeV, in the usual notation.[12] The depth of the real Woods-Saxon potential was adjusted for each resonance to produce a resonance energy in agreement with experiment; thus, this method is analogous to the usual "separation-energy procedure" used for bound

TABLE I. States of ^{33}S between 8.58 and 9.46 MeV in excitation, observed in the present experiment. The absolute excitation energies are reliable to ±10 keV.

E_x (MeV)	E_R (MeV)	l_j	Γ_{sp} (keV)	S	$\Gamma_n^{(d,p)}$ (keV)	$\Gamma_n^{(n,n)}$ (keV)
8.584	−0.056	$f_{7/2}$	···	0.012	···	
8.644	0.004	$d_{3/2}$	0.29×10^{-3}	0.021	5.3×10^{-6}	
8.670	0.030	$p_{1/2}$	9.26	0.007	0.065	≃0.04
8.729	0.089	$f_{7/2}$	0.0066	0.031	0.2×10^{-3}	
8.749	0.109	$s_{1/2}$	···	···	···	17
8.838	0.192	$f_{7/2}$	0.058	0.002	0.13×10^{-3}	
		$p_{1/2}$	160	0.005	0.82	1.3
8.873	0.233	$f_{7/2}$	0.089	0.034	3×10^{-3}	
8.907 [a]	0.274	$p_{1/2}$	291			1.2
8.923 [a]	0.290	$p_{1/2}$	319			1.1
8.939	0.298	$f_{7/2}$	0.18	0.007	1.2×10^{-3}	
8.975	0.335	$f_{7/2}$	0.329	0.003	1.0×10^{-3}	
9.005	0.365	$s_{1/2}$	···	···	···	4.8
9.035	0.395	$d_{3/2}$	21.1	0.0034	0.071	
9.115	0.475	···	···	···	···	
9.138	0.498	$d_{3/2}$	35.93	0.027	0.960	
9.175	0.535	···	···	···	···	
9.209	0.567	$d_{3/2}$	49.36	0.011	0.55	<1.5 [b]
9.245	0.607	$f_{7/2}$	2.34	0.006	0.014	
9.280	0.64	$f_{7/2}$	2.89	0.007	0.019	
9.320	0.68	$s_{1/2}$	···	···	···	<12 [b]
9.350	0.71	$f_{7/2}$	3.99	0.004	0.016	
9.400	0.76	$d_{3/2}$	97.22	0.021	2.06	
9.460	0.82	$p_{1/2}$	···	···	···	

[a] Not seen in present experiment; reported in Ref. 1.
[b] Total width.

final states in DWBA. For each resonance the program GAMOW-3 provided the complex-energy eigenstate and the resonance pole position, i.e., the resonance energy and single-particle width. DWBA calculations were performed using these state functions, as described in Ref. 10, and spectroscopic factors were obtained by comparison with the (d,p) cross sections at forward angles. As in our earlier work, the slope of the (d,p) cross section at forward angles is a fairly sensitive indicator of the l transferred to the residual nucleus. Most of our assignments of l value are based on this indicator and not on any presumed correspondence of the states seen in this work to those seen in the (n,n) and (n,γ) studies.

The optical potentials which we used in our DWBA analysis were, in the order V_0, W, W_D, V_{so}, r, r', r_{so}, a, a', a_{so}, given as: 111.2, 0.0, 16.0, and 8.0 MeV, 1.05, 1.53, 0.90, 0.85, 0.505, and 0.60 fm for the deuteron; 52.14, 0.0, 6.12, and 5.56 MeV, 1.15, 1.32, 0.85, 0.654, 0.547, and 0.41 fm for the proton. The proton potential was selected from the tabulation by Perey and Perey.[12]

For the single bound state we considered, the form factor was obtained in the standard way, using the same geometry as for the unbound states, and with the separation-energy or "well-depth" prescription.[13]

As is illustrated in Figs. 1 and 2, over the angular range from 0° to about 70°, it is possible in many cases to determine the transferred orbital angular momentum from the slope of the angular distribution.[7,8] Although high backgrounds produce a certain degree of scatter in our data, the l assignments are relatively unambiguous.[8]

As summarized in the last column of Table I, a total of eight neutron resonances, at energies ranging from 30 to 700 keV, are known from neutron studies. All of these resonances are assigned as s or p except for the one at 585 keV, which is assigned as a d state on the basis of on-resonance angular distributions.[14] Of the 20 resonances we observe in our work, six—those at excitation energies of 8.670, 8.749, 8.838, 9.005, 9.209, and 9.320 MeV—appear to correspond with those seen in the neutron work. Thus we are forced to base our comparison on these six states.

Using the widths measured via the neutron scattering and capture studies we can, in fact, predict the (d,p) cross sections which should be observed

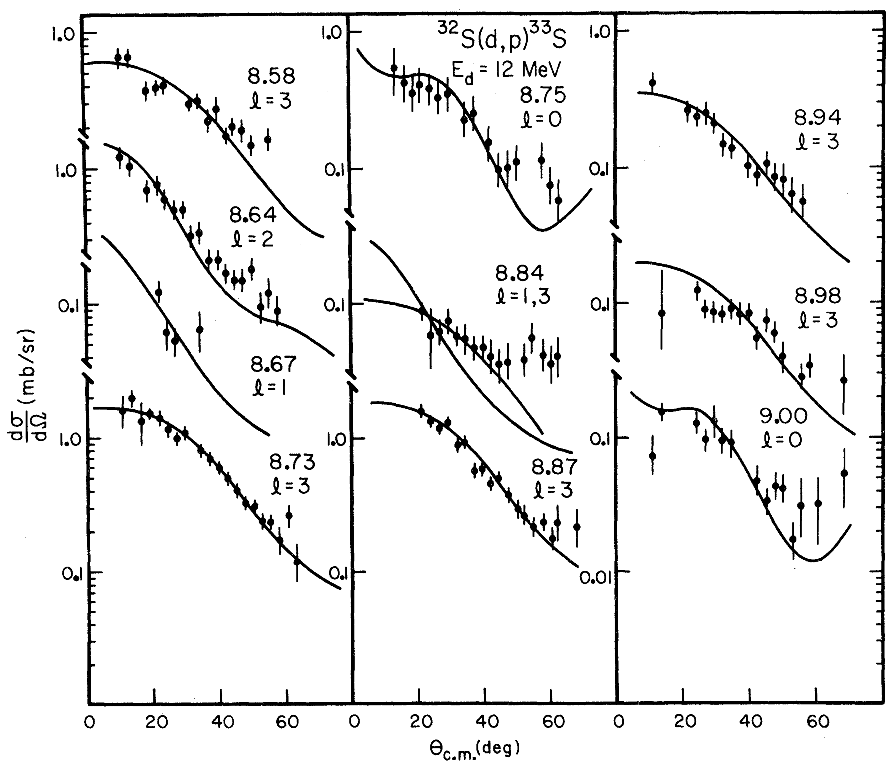

FIG. 1. Experimental angular distributions and DWBA calculations for states of ^{33}S ranging from 8.58 to 9.00 MeV in excitation. The solid curves are DWBA predictions obtained as explained in the text. Extracted spectroscopic factors and neutron widths are summarized in Table I.

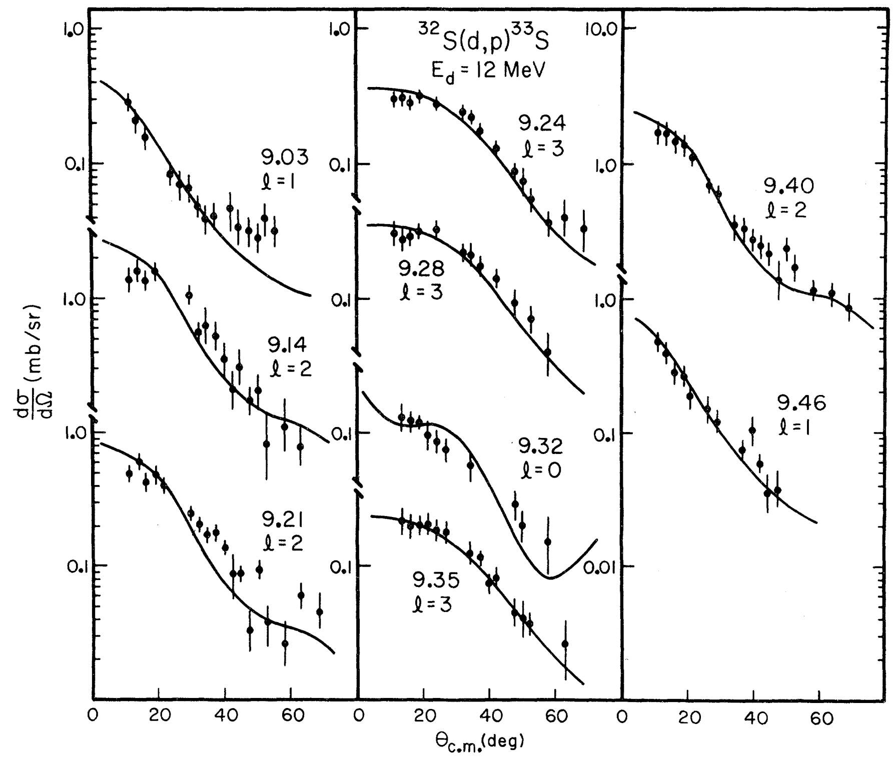

FIG. 2. Experimental angular distributions and DWBA calculations for states of ^{33}S ranging from 9.03 to 9.46 MeV in excitation. The solid curves are DWBA predictions obtained as explained in the text. Extracted spectroscopic factors and neutron widths are summarized in Table I.

for the $l=1$ states at 8.670, 8.838, 8.907, and 8.923 MeV. At 30° these cross sections are uniformly less than 0.05 mb/sr, which is about at the limit of our ability to extract the state from the deuteron-breakup proton background. On the other hand, cross sections for the $l=2$ and 3 states are much higher, reaching 1.0 mb/sr at forward angles. In our spectra, we do not in fact observe proton groups corresponding to the 8.907 and 8.923 MeV states at all, and only a few points could be obtained for the state at 8.670 MeV. Thus one can make a comparison in at most two cases for $l=1$, and the comparison is unfortunately further suspect because compound nuclear contributions at 12 MeV deuteron energy are predicted to be about 0.03 mb/sr at all angles. In fact, this compound nuclear contribution can be clearly observed in the angular distribution of the weakly excited 8.838 MeV state, as seen in Fig. 1.

A serious problem is also posed by the neutron resonances reported at 8.749, 9.005, and 9.320 MeV, which are assigned as *s* states in the neutron work. There are no $l=0$ potential resonances for neutrons above zero energy, so that it is not possible to describe these states with Gamow functions. Furthermore, since the observed states would in fact be rather complicated "bound states in the continuum," they could not be reached by a direct (d,p) reaction. Thus, either the states we

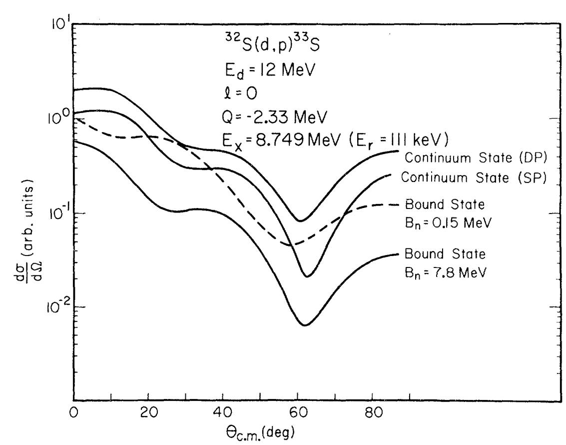

FIG. 3. Results of DWBA calculations to predict the angular distribution expected from population of an $l=0$ neutron state in the continuum. Two continuum state and two bound state form factors were used as discussed in the text.

observe at these three energies are states with $l > 0$ which happen to lie within about 7 keV of the "right" energy, in all three instances, or the states are being populated via a multistep process. If they are being reached by a multistep process, then the expected shape of their angular distributions is by no means obvious.

In Fig. 3 we show several results of efforts to predict the angular distribution expected from population of an $l = 0$ neutron state in the continuum. Two of the curves shown in Fig. 3, marked DP and SP, are performed with a nonresonant continuum state function as form factor; as the Woods-Saxon well depth is quite arbitrary, two calculations are shown, one with a deep potential (DP, 45 MeV, two nodes inside the nuclear radius) and one with a shallow potential (25 MeV, no nodes inside the nuclear radius, and close to the depth that gives a just-bound $2s_{1/2}$ state in ^{33}S).

An alternate suggestion, due to one of us (WRC) and Tamura[15] is to assume that the final ^{33}S is a highly excited compound nuclear state in which the single neutron term is that of a bound $2s_{1/2}$ state. The DWBA calculation is then done with this bound-state form factor, in order to obtain a crude approximation of the shape of the multistep angular distribution.[15] However, the separation energy is now as arbitrary as was the potential energy in the previous two calculations, and we show two extreme cases, first for a binding energy of 7.8 MeV, equivalent to that of the bound $s_{1/2}$ state of ^{33}S at 0.84 MeV, and the second for a just-bound $2s_{1/2}$ state at 0.15 MeV binding energy. All of the calculated angular distributions except for the last mentioned case look remarkably alike. The weakly bound $s_{1/2}$ angular distribution looks somewhat different; however, this difference is mainly connected with the realistic Q value assumed, namely, -2.33 MeV for all the calculations shown in Fig. 3. As is illustrated in Fig. 4, the absence of a strong forward peak in the case of the weakly bound state is related to the use of the proper Q value—that is, to the long wavelength of the outgoing proton state function taken together with the long nonoscillating tail of the weakly bound state form factor.

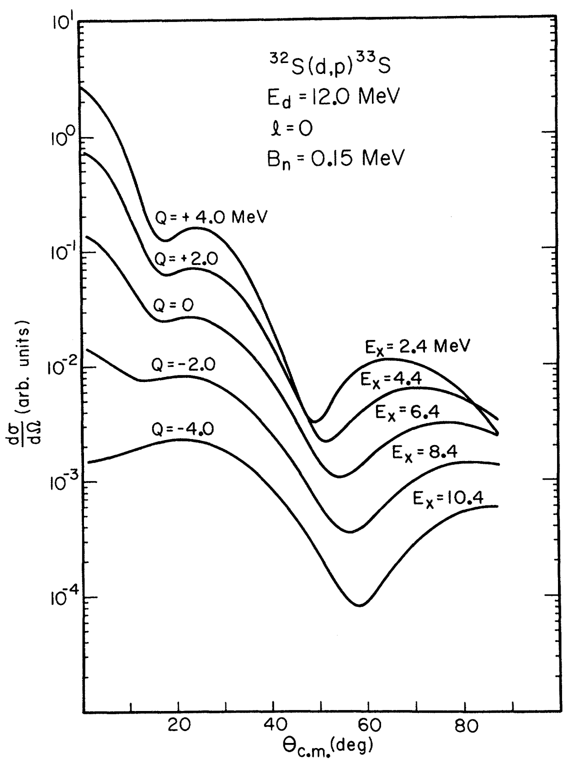

FIG. 4. Results of DWBA calculations for $l = 0$ transitions in ^{32}S$(d,p)^{33}$S at 12 MeV which demonstrate the "Q-value dependence" of the forward angle structure of the angular distributions as discussed in the text.

This leaves the question of what shape to expect for the unbound s neutron state (d,p) angular distributions unsatisfactorily answered. *If* the three states we see indeed correspond to the states observed in neutron scattering, *then* the weakly bound state calculation (Fig. 4) gives the best description of the data. However, we do not take the agreement—or lack thereof—very seriously in this case. Our spectroscopic analyses concentrate on the p, d, and f states we have observed.

There are thus at most three states observed in common between the (n,n) and (d,p) studies, which are not assigned $l = 0$ in the neutron studies. These are the weakly populated states at 8.670 and 8.838 MeV, both assigned $p_{1/2}$, and the state at 9.209 MeV, assigned $d_{3/2}$.[14]

Unfortunately, contaminant peaks from (d,p) on light target contaminants concealed the 8.67 MeV state except at angles between about 20 to 40° (see Fig. 1) so that the slope of the (d,p) angular distribution could *not* be unambiguously used to assign the l value of the transition. On the assumption that this state is indeed the $l = 1$ state observed at 8.670 MeV in excitation in ^{33}S in the (n,n) work, our analysis yields a neutron width of $\Gamma_n = 0.065 \pm 0.025$ keV, compared to about 0.036 ± 0.009 keV obtained in the neutron work.[16] The state at 8.838 MeV seen in this experiment is also very weakly populated and has an angular distribution (shown in Fig. 1) which is essentially isotropic except for slight forward angle peaking. Hence, the (d,p) reaction cross section to this state very likely has a substantial compound nuclear contribution. However, identifying this state with the $l = 1$ state at 8.838 MeV reported from the (n,n) studies and normalizing at 20°, we obtain a neutron width of 0.82 ±0.33 keV, compared to 1.3 keV from the neutron work.[1] Finally, the angular distribution for the 9.209 MeV state (see Fig. 2) appears to be $l=2$ which is consistent with the $l=2$ assignment in the neutron tables[1] for a state at this energy. For the 9.209 MeV state, assumed $d_{3/2}$, we obtain 0.55 keV for the neutron partial width, which can only be compared in this case to an estimated 1.5 keV for the *total* neutron width.[1,14] The error in our absolute cross sections, depending upon their size, is on the order of 35 to 40%. Thus, our (d,p) analysis of these three states leads to neutron widths, obtained from $\Gamma_n = S_n \Gamma_{sp}$, which are not inconsistent with those obtained in the (n,n) studies.

A total of 14 other p, d, and f resonances are observed in this experiment, none of which have been previously reported in neutron studies because of their small partial widths and relatively high angular momenta. As Table I shows, a typical partial width for these resonances is 1 to 0.01 keV, yet they are readily observable in (d,p).

Large basis shell model calculations of Wildenthal *et al.*[17] for ^{33}S account reasonably well for the known states below about 5 MeV in excitation. Above 5 MeV, the systematics of the shell model suggest that the spectrum of fractionated single-particle states will be dominated by $d_{3/2}$, $f_{7/2}$, $p_{3/2}$, and $p_{1/2}$ states. As one cannot reliably distinguish $p_{3/2}$ from $p_{1/2}$ states on the basis of their angular distributions, we have arbitrarily assigned all the $l=1$ states as $p_{1/2}$. Similarly, all $l=2$ states are taken as $d_{3/2}$ and all $l=3$ states as $f_{7/2}$ for the purposes of the DWBA analysis.

Some 100-odd bound states are known in ^{33}S up to an excitation of 8.015 MeV, from earlier (d,p) studies. However, spectroscopic information is available only for the low-lying states. Hence, extension of sum rules to the resonance region is not possible at present; at any rate, earlier work on ^{31}Si suggests that the resonance region will in general make a negligible contribution to single-particle sum rules.[8]

Of the states we observed between 8.584 and 9.460 MeV, eight can be fairly definitely assigned as $l=3$, five as $l=2$, and five as $l=1$, confirming the expectation of fairly equal distribution of strength for the single-particle states. It might be mentioned that because of the large width of the assigned $l=1$ state at 9.46 MeV, we have only attempted a shape fit to the angular distribution.

V. COMPARISON WITH AN ALTERNATE METHOD

Since this work was completed a paper has appeared by Bommer *et al.*[18] in which an alternate, direct method of comparison between (n,n) and (d,p) excitation spectra is proposed. In this approach the (d,p) cross section for a given resonance at a given angle is divided by the total neutron cross section integrated over resonance. Because, as discussed in Sec. II, this ratio is directly proportional to σ_l (DWBA) and independent of S_n and Γ_n, the authors maintain that a theory-independent criterion can be used to assign the resonance l values. That is, the cross section ratios for $l=0,1,2$, etc., fall on distinct curves as a function of E_n, the neutron resonance energy.

Bommer *et al.* give results for two cases, ^{24}Mg-$(d,p)^{25}$Mg and ^{32}S$(d,p)^{33}$S. They observe seven of the resonances between 0.004 and 0.82 MeV neutron energy which we have studied in the present work. In all but one case, that of the 9.350 MeV state which we assign $l=3$ and they $l=1$ (see Fig. 2), their independent l assignments agree with ours. The independent assignments are 8.749 MeV ($l=0$), 8.838 MeV ($l=1$), 9.005 MeV ($l=0$), 9.209 MeV ($l=2$), 9.320 MeV ($l=0$), and 9.400 MeV ($l=2$).

VI. CONCLUSIONS

This work was begun with the hope of making a clear-cut comparison between neutron widths extracted from neutron elastic scattering studies versus those from (d,p) studies. Despite the fact that we chose a target for which there are eight well-resolved neutron resonances, we are able to make a comparison between (d,p) and (n,n) partial widths in only *two* cases: the states at 8.670 and 8.838 MeV.

The major difficulty with such a comparison is the very different intensity with which the resonances are populated in (d,p) versus (n,n). A single example will make this clear. Suppose there were a $d_{3/2}$ state in ^{33}S at an excitation of 8.670 MeV. Even if its neutron partial width were only 2 eV, corresponding to a single-particle spectroscopic factor of 0.06, its presence would completely account for the magnitude of the observed 8.670 MeV state's cross section. However, this resonance would be quite undetectable in present (n,n) experiments.

In short, spectroscopic strategies such as that of Medsker *et al.*,[7] in which l values were assigned for states seen in (d,p) on the basis of the agreement of the extracted neutron partial widths with those obtained in (n,n) and (n,γ) studies, are generally doomed to failure. Only in very rare circumstances can one be sure that one is seeing in the (d,p) spectrum the same state populated in the (n,n) reaction. Our careful energy calibration indicates that at least in three cases, we *are* seeing the same state reported in the (n,n) work, but this is in three cases out of twenty.

Problems of this nature did not arise in the isobaric analog resonance studies, since the only strongly populated states there are of necessity the very well-separated isobaric analog states themselves.[3-5] To perform unambiguous comparisons of (d,p) and (n,n) one clearly requires in general a very low level density, lower even than that in ^{33}S perhaps. Unfortunately, the use of light nuclei[9] as targets leads to even more serious problems, since for example the reaction mechanism of (d,p) becomes exceedingly uncertain and one then cannot extract reliable widths from (d,p) analyses.[19]

However, we do not claim (d,p) studies of neutron-unbound states are doomed to fruitlessness and futility—far from it. One sees states via the (d,p) reaction which could hardly be seen in any other way. This advantage follows because in general (d,p) does *not* select the same nuclear states as (n,n). We caution merely that this particular blessing does become a curse in making comparisons between the two independent methods of investigating the low-energy neutron continuum.

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