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INVESTIGATION OF THE ^{34}S(d, p)^{35}S REACTION AT E_d = 10 MeV

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Abstract: Angular distributions of proton groups, corresponding to fifteen levels observed in the reaction ^{34}S(d, p)^{35}S at E_d = 10 MeV have been measured with a split-pole spectrograph equipped with position-sensitive detectors. For the levels at E_x = 0, 1.58, 1.99, 2.34, 2.73, 3.68, 3.80 and 4.20 MeV, l_n = 2, 0, 3, 1, (2, 3), (1), 1 and 1, respectively, has been found from a DWBA analysis. Experimental spectroscopic factors and those following from many-particle shell-model calculations for the lowest four states are in satisfactory agreement. The ground state Q-value has been measured as Q = 4757±5 keV.

E NUCLEAR REACTION ^{34}S(d, p), E = 10 MeV; measured Q_0, $\sigma(\theta)$. ^{35}S deduced levels, l, J, π, spectroscopic factors; enriched target.

1. Introduction

Nuclear spectroscopy on nuclei in the mass region A = 32–40 has received a stimulating impulse from many-particle shell-model calculations [1–6]). Experimentally determined excitation energies, electromagnetic transition rates and multipole moments have been reproduced by this theory with promising accuracy [7, 8]). The measurement of angular momentum transfers l and spectroscopic factors S, resulting from the analysis of stripping and pick-up reactions also provides valuable testing material. The information from these reactions on the sulphur nuclei is rather sketchy, which may partly be due to difficulties in target preparation.

Investigations of the (d, p) reaction on natural sulphur targets [9]) (^{34}S abundance 4.2 %) have yielded some proton groups assigned to ^{35}S levels, as well as the l_n values for three states [10]). The first investigation of the ^{34}S(d, p)^{35}S reaction, in which an enriched target was used, was undertaken to locate levels in ^{35}S [ref. [11])]. The study of this reaction, presented here, aimed for the measurement of l_n values and spectroscopic factors for comparison with the above mentioned shell-model calculations.

2. Experimental procedure

A 10.02 MeV deuteron beam from the Utrecht 6 MV tandem accelerator was focussed on a circular diaphragm 1 mm in diameter and 1 cm in front of a Faraday cup, located 10 cm downstream from the target. A silicon surface-barrier detector at θ = 60° monitored elastically scattered deuterons.

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Protons were detected in the focal plane of the Utrecht split-pole magnetic spectrograph (solid angle 2 msr) by one 15 mm long and seven 30 mm long, 0.6 mm thick position-sensitive detectors (PSD). The PSD's, oriented at 45° to the incident particles, stop protons up to $E_p = 11$ MeV, whereas the energy of the ^{34}S(d, p) ground state proton group rises at small scattering angles to 14.5 MeV. By means of teflon absorber foils in front of the detectors the proton energy was reduced to below 11 MeV, whereas in addition undesired reaction products such as deuterons and α-particles were stopped.

The multi-detector electronics consists of a system of linear gates, two linear adding networks, and routing logic. The two Laben ADC's (for position and energy pulses) are connected with a CDC 1700 computer, which stores the raw data event by event on magnetic tape. Both on-line and off-line data analysis can be performed with the program SPECTR [12]). One of the features of this program is that it generates the ratio between the position and energy pulses, such that optimum position resolution (0.3 mm) could be achieved in spite of the additional energy straggling caused by the teflon foils.

Two different targets were used, one consisting of 100 μg/cm^2 PbS on carbon plus formvar foils, the other of 5 μg/cm^2 pure ^{34}S embedded in aluminium foil. The PbS was prepared from lead nitrate, enriched to 99.9 % in ^{208}Pb and elemental sulphur enriched to 85.6 % in ^{34}S, both obtained from Oak Ridge. The reaction ^{208}Pb(d, p) ^{209}Pb leads to some weak groups in the low-energy part of the proton spectrum because of the high Coulomb barrier and low Q-value (1.71 MeV). However, the ^{32}S(d, p)^{33}S proton group exciting the $E_x = 3.22$ MeV level coincided with the proton group to the ^{35}S $E_x = 1.58$ MeV level [13]) up to $\theta = 60°$. This fact, together with the low intensity of the latter group at large angles, may explain why this state has not been observed in (d, p) work until recently [11]).

An isotopically pure target, produced by bombarding a 70 μg/cm^2 aluminium foil with 60 keV ^{34}S ions from a mass separator, was used to measure the angular distribution of this group at small angles. No ^{32}S(d, p) groups were detected from this target, nor did protons from the ^{27}Al(d, p)^{28}Al reaction interfere in the region of interest.

Besides the contaminants already discussed, the targets contained C, O and Si while some small peaks observed when the PbS target was used have been proven to originate from the $^{35, 37}$Cl(d, p)$^{36, 38}$Cl reactions.

The angular distributions of the proton groups were measured in steps of 5° from $\theta = 5°$ to 90°. The positioning of the PSD's in the focal plane was arranged such that the angular distributions for all known groups [11]) below $E_x = 5$ MeV could be fully measured in two runs at slightly different magnetic field settings.

The proton intensities observed with the PbS target were calculated relative to the intensity of the Pb elastic peak observed in the monitor detector. The ratio of the intensity of the two elastic deuteron peaks originating from lead and sulphur, which was continuously checked during the measurement, was found to be constant within the statistical error.

Absolute differential cross sections were determined by comparing the proton yield with the yield for the elastic scattering of 4 MeV deuterons from ^{34}S at forward angles. The elastic scattering cross section under these conditions was assumed to be equal to the Rutherford cross section. The deuteron yield has been found to follow the $1/\sin^4(\frac{1}{2}\theta)$ law within 5 % at scattering angles below $\theta = 35°$. It was preferred to use the pure ^{34}S target for these measurements since at 4 MeV small-angle scattering from lead in the PbS target made the charge collection less reliable.

3. Results

The $\theta = 5°$ proton spectrum, obtained with the PbS target, is shown in fig. 1. States in ^{35}S up to $E_x = 4.84$ MeV are indicated by their excitation energies while contaminant peaks are specified by the relevant final nucleus, followed by the excitation energy in brackets. At excitation energies greater than 4.31 MeV identification of ^{35}S proton groups was uncertain due to strong peaks from the ^{32}S(d, p)^{33}S reaction. The FWHM of the peaks, 10 keV, mainly results from the combined effects of beam spot size, energy straggling in the target foil and spectrograph aberrations [14]).

The shift of the position of the proton groups on the detectors, due to kinematics, as a function of the angle and the mass of the target nucleus, provided in most cases an unambiguous peak identification.

Although the PSD is not suitable for absolute energy measurements, this mass-dependent shift enables the determination of the Q-values of ^{34}S(d, p)^{35}S proton groups from the known Q-values of (d, p) reactions on contaminants [15]). At the angle, found by interpolation, where a ^{35}S peak coincides with a contaminant peak, the Q-value of the former can be derived from the known deuteron energy and the proton energy, calculated by means of the Q-value equation applied to the contaminant.

The crossing of the ^{34}S(d, p)^{35}S ground state group with the ^{28}Si(d, p)^{29}Si first excited state group at $\theta = 95.5° \pm 0.9°$ yields the ^{34}S(d, p) ground state Q-value as $Q_0 = 4757 \pm 5$ keV, which is in good agreement with the value of 4760.9 ± 2.9 keV from the 1964 mass table [16]). The quoted error is mainly determined by the error in the comparison Q-value (4 keV). Errors arising from uncertainties in the crossing angle and in the particle energies, due to non-homogeneous mixing of ^{28}Si with ^{34}S, have been quadratically added. In the calculation of excitation energies as $E_x = Q_0 - Q$, similar errors in Q have been taken into account, in addition to the error in Q_0.

Table 2 contains the excitation energies thus derived, except for the $E_x = 1.99$ MeV state for which no crossing contaminant group was available; the value quoted has been taken from γ-ray decay data [17]). As much higher accuracy is to be expected from γ-ray decay work the present values have only significance in that they check the results of ref. [11]). The following disagreements were found.

The state at $E_x = 3885 \pm 10$ keV listed in ref. [11]) has most probably to be identified with a proton group corresponding to $E_x = 3907 \pm 10$ keV. The observation of a new

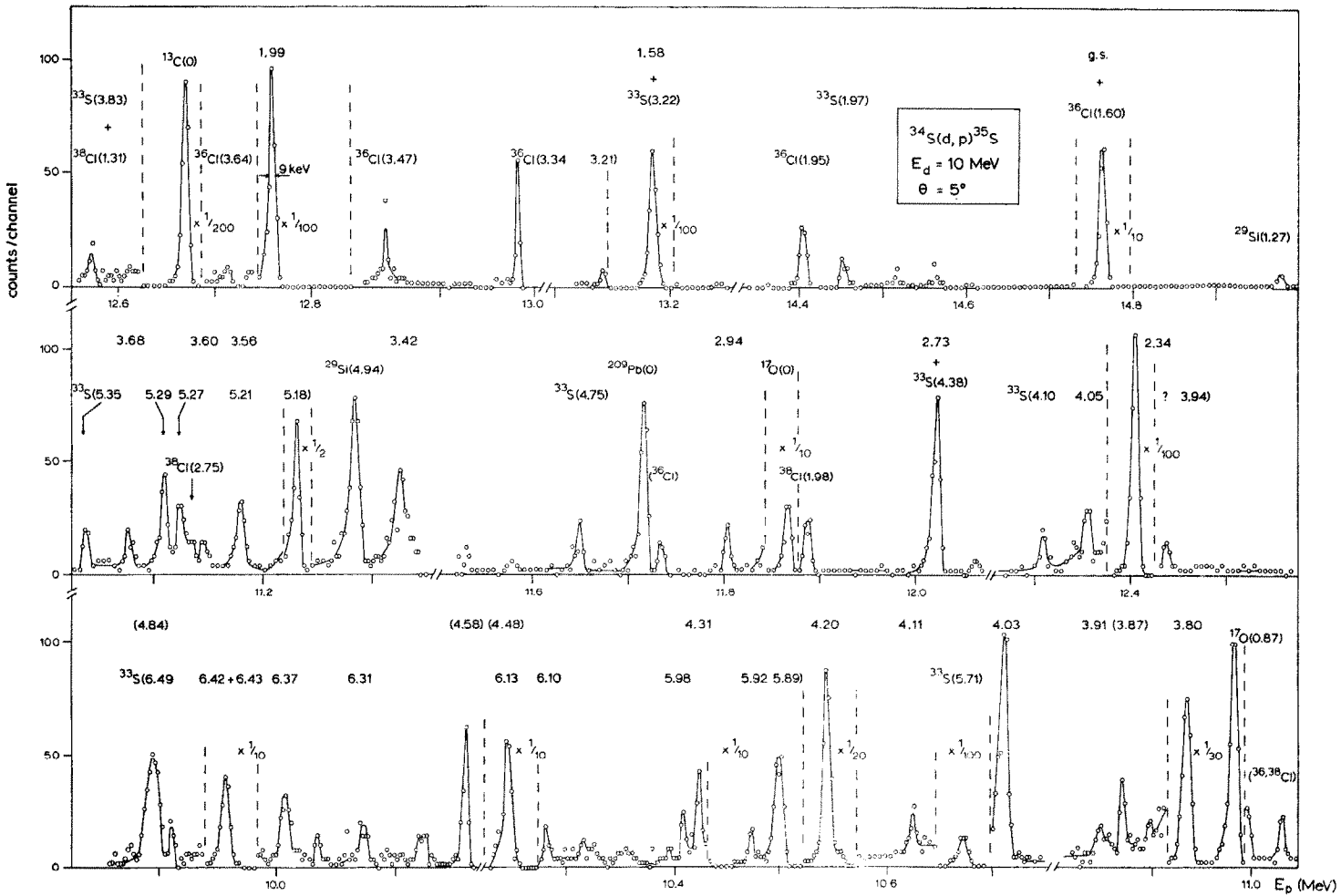

Fig. 1. Spectrum of protons from the ^{34}S(d, p)^{35}S reaction taken at $\theta = 5°$ with eight position-sensitive detectors and two slightly different settings of the spectrograph magnetic field. The target was 100 μg/cm^2 PbS, enriched to 99.9 % in ^{208}Pb and 85.6 % in ^{34}S, respectively. The presence of foils in front of all detectors prevents the detection of other reaction products.

level at $E_x = 3866 \pm 10$ keV is doubtful because the corresponding weak proton group has only been observed at three angles. A new level has been located at $E_x = 3675 \pm 10$ keV. The corresponding proton group has been observed at angles up to 40°.

Angular distributions are displayed in fig. 2, in which the solid lines represent the results of DWBA calculations (see sect. 4). Only statistical errors have been indicated. A systematic error of 8 % is introduced by the normalization procedure (see sect. 2). At missing points the corresponding proton groups were obscured by contaminant groups.

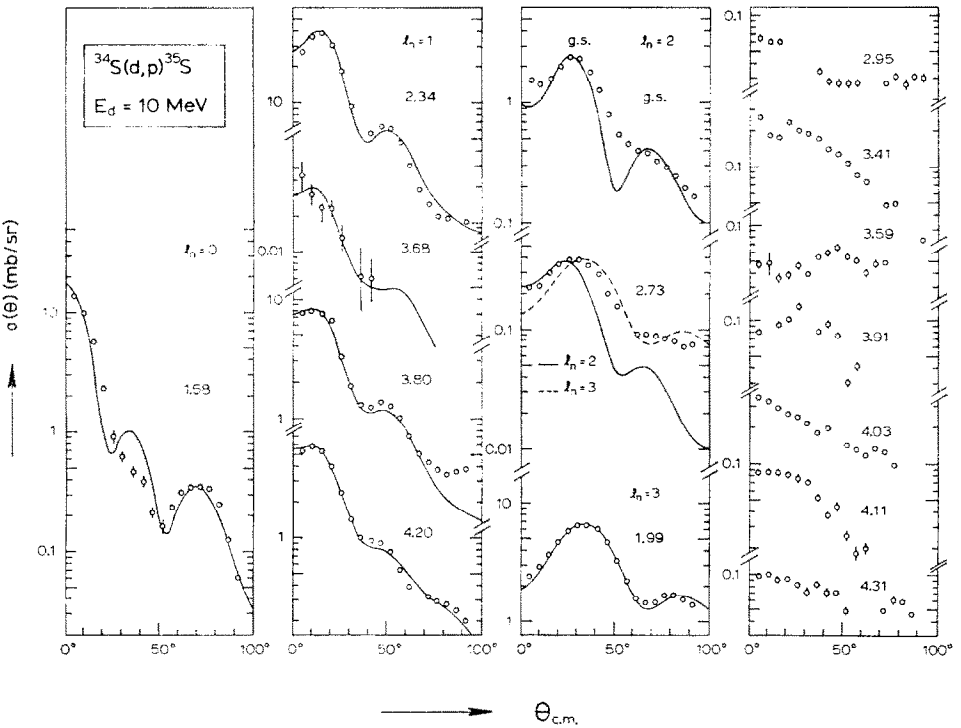

Fig. 2. Angular distributions of protons from the ^{34}S(d, p)^{35}S reaction at $E_d = 10$ MeV. The curves are the results of a DWBA analysis.

4. The DWBA analysis

The l_n values and spectroscopic factors S_n have been extracted from the angular distributions by fitting the theoretical expression

$$\sigma(\theta) = 1.53 \frac{2J_f+1}{2J_i+1} S_n \sigma(\theta)_{\mathrm{DWBA}}. \qquad (1)$$

The l_n dependence is absorbed in the factor $\sigma(\theta)_{\mathrm{DWBA}}$, calculated with the computer code DWUCK; J_i and J_f are the spins of the target and product nucleus, respectively.

TABLE 1

Optical potential parameters used in the analysis [a])

		Deuteron [b])	Proton [c])	Neutron
V	(MeV)	107.34	$\approx$ 50 [d])	[e])
r	(fm)	1.05	1.25	1.25
a	(fm)	0.85	0.65	0.65
W_D	(MeV)	10.63	9.81	
r	(fm)	1.63	1.25	
a	(fm)	0.56	0.47	
V_S	(MeV)	8	7.5	[f])
r	(fm)	0.9	1.25	1.25
a	(fm)	0.6	0.65	0.65
finite-range parameter				0.621 [g])
non-local range parameter		0.55 [g])	0.85 [g])	

[a]) The potential depths refer to the expression, given by Hjorth *et al.* [26])

$$U(r) = U_C(r) - \frac{V}{e^x+1} + 4iW_D \frac{d}{dx'}\left(\frac{1}{e^{x'}+1}\right) + \left(\frac{\hbar}{m_\pi c}\right)^2 V_S \frac{d}{r dr}\left(\frac{1}{e^x+1}\right) \boldsymbol{L}\cdot\boldsymbol{\sigma}.$$

[b]) Ref. [18]). [c]) Ref. [19]).

[d]) The depth of the potential varies with the proton energy corresponding to the level under consideration from 49.6 to 51.9 MeV for $E_x = 0$ to 4.20 MeV.

[e]) The value, generated by DWUCK to fit the neutron binding energy, is of the order of 50 MeV.

[f]) The spin-orbit coupling factor λ was taken equal to $\lambda = 25$ [ref. [25])].

[g]) Ref. [24]).

TABLE 2

Spectroscopic data from the ^{34}S(d, p)^{35}S reaction

E_x (keV) this work	E_x (keV) ref. [11])	l_n	J^π	$(2J_f+1)S_n$ experiment [a])	theory [b]) model I	model II	model II+III	model I+III
0	0	2	$\frac{3}{2}^+$ [c])	1.72	1.76	1.52		
1575 ± 9	1581 ± 8	0	$\frac{1}{2}^+$	0.34	0.22	0.26		
1994.6 ± 1.0 [d])	1995 ± 8	3	$(\frac{5}{2}, \frac{7}{2})^-$	5.44			2.72	5.20
2336 ±10	2347 ± 8	1	$\frac{3}{2}^-$ [e])	2.08			1.24	2.36
2726 ± 8	2722 ± 8	(2, 3)	$(\frac{3}{2}-\frac{7}{2})$					
2939 ±10	2943 ±10							
3415 ±12	3422 ± 8							
3555 ± 9	3563 ± 8							
3595 ± 9	3596 ± 8							
3675 ±10		(1)	$(\frac{1}{2}^-, \frac{3}{2}^-)$	($<$ 0.005)				
3795 ±10	3804 ± 8	1	$(\frac{3}{2})^-$	0.37				
(3866 ±10)								
3907 ±10	3885 ±10							
4025 ±10	4025 ±10							
4105 ±10	4112 ±10							
4196 ±12	4190 ± 8	1	$(\frac{1}{2})^-$	0.24				
4312 ±12	4302 ± 8							

[a]) A 25% error is estimated from comparison with calculations with other optical model parameters.

[b]) For definitions of the models I–III see sect. 5.

[c]) Ref. [15]).

[d]) Value adopted from ref. [17]). See sect. 3.

[e]) Ref. [17]).

Table 1 contains the optical model parameters used in the calculation. The deuteron parameters are taken from ref. [18]), the proton parameters from ref. [19]). An improved fit to the data was obtained by the inclusion of a finite-range correction and non-locality corrections for the in- and outgoing particles.

Because the target nucleus has $J_i^\pi = 0^+$, the measured l_n values limit the possible J_f^π values to $J_f = l_n \pm \frac{1}{2}$ and $\pi = (-)^{l_n}$. Through the spin-orbit term in the potential $\sigma(\theta)_{\mathrm{DWBA}}$ depends somewhat on J_f, but the difference in $(2J_f+1)S_n$ for the two spin possibilities was always less than 10 %.

Table 2 summarizes the l_n and $(2J_f+1)S_n$ values extracted from the DWBA analysis. As shown in fig. 2 the values $l_n = 2$, 3 and 1 previously found for the $E_x = 0$, 1.99 and 2.34 MeV states [10]) are reproduced by the present experiment. The 1.58 MeV level has $l_n = 0$ and consequently $J^\pi = \frac{1}{2}^+$. Unambiguous $l_n = 1$ fits were found for the $E_x = 3.80$ and 4.20 MeV levels. The $l_n = 1$ assignment to the state at $E_x = 3.68$ MeV remains doubtful because of the large statistical errors.

It has not been possible to extract an unambiguous l_n assignment from the proton angular distribution for the weakly excited $E_x = 2.73$ MeV state, although a stripping pattern is obvious. In fig. 2 is shown that $l_n = 3$ is most probable, but the fit is inferior to the $l_n = 3$, $E_x = 1.99$ MeV case. Although compound nucleus contributions were expected to be small for particle energies involved here, the effect of the inclusion of a constant cross section in the fitting procedure has been examined. However, both $l_n = 2$ and $l_n = 3$ remained equally probable. Close inspection of the proton spectrum at different angles revealed no evidence of the $E_x = 2.73$ MeV state either being a doublet or interfering with a proton group of unknown origin.

It has been demonstrated by Lee and Schiffer [20]) that at large angles $l_n = 1$ angular distributions show experimental evidence of a J-dependence, which enters into the theoretical calculations through the inclusion of the spin-orbit potentials. In fig. 2 the angular distribution for the $E_x = 4.20$ MeV level has been fitted with a $J^\pi = \frac{1}{2}^-$ curve while the other $l_n = 1$ states fit best for $J^\pi = \frac{3}{2}^-$.

5. Discussion

In addition to the experimentally determined values of l_n, J^π and $(2J+1)S_n$, table 2 contains the theoretical spectroscopic factors for the lowest four states from shell-model theory. To calculate these spectroscopic factors the wave functions of the ^{34}S ground state and the relevant ^{35}S states are required. Positive-parity wave functions of ^{34}S and ^{35}S have been calculated in two different configuration spaces. In model I a ^{28}Si core has been taken with nucleons in the $2s_{\frac{1}{2}}$ and $1d_{\frac{3}{2}}$ shell [1]). In model II the space of model I has been extended such that also up to two holes in the $1d_{\frac{5}{2}}$ shell are taken into account [22]). The negative-parity wave functions in ^{35}S have been calculated in model III with $d_{\frac{3}{2}}^2 f_{\frac{7}{2}}$ or $d_{\frac{3}{2}}^2 p_{\frac{3}{2}}$ configuration coupled to a ^{32}S core [6]).

From model I as well as II spectroscopic factors can be derived for positive-parity states in ^{35}S. Table 2 shows that for both models the agreement with experiment is

very good. The spectroscopic factors for ^{35}S negative-parity states cannot be calculated straightforwardly. The best theoretical estimate follows from the combination of wave functions based on model I and III, as these models are most closely related [ref. [23])]. As is seen in table 2 these values agree with experiment while estimates based on the models II and III are too low by a factor of two.

An additional source of information is the investigation of analogue resonances in the ^{34}S(p, p_0) reaction [21]). From the measured proton widths Γ_p of these resonances, spectroscopic factors can be calculated for the parent states in ^{35}S. For the negative-parity states of ^{35}S at E_x = 1.99 and 2.34 MeV, one calculates in this way $(2J+1)S_n$ = 3.6 and 1.6, respectively. These values are in reasonable agreement with the results of the present experiment.

From DWBA calculations an uncertainty in $(2J+1)S_{exp}$ of 25 % or more may be expected and large uncertainties in both experimental and theoretical values may obscure systematic differences. To illustrate this, it is found that the value of $(2J+1)S_{theory}$ = 2 for the ^{35}S ground state, valid for a pure $1d_{\frac{3}{2}}$ configuration, still agrees with experiment.

6. Conclusion

The high-energy resolution of the split-pole spectrograph has overcome most of the difficulties in accurate (d, p) yield measurements, especially at small scattering angles where the data are of prime importance. The large number of angular distributions without stripping pattern demonstrates that for many ^{35}S states the excitation through a (d, p) reaction cannot be described by the rather simple direct reaction process. This also supports the shell-model theory applied here, which predicts negligibly small spectroscopic factors for all but the four positive-parity lowest states [1, 22]).

The calculation of wave functions for both positive- and negative-parity states in the same shell-model space is highly desirable.

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