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INVESTIGATION OF THE $^{33}S(d, p)^{34}S$ REACTION

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Abstract: Angular distributions have been measured of proton groups, corresponding to ^{34}S states up to $E_x = 6.63$ MeV excited in the reaction $^{33}S(d, p)^{34}S$ at $E_d = 12$ MeV, with the use of a split-pole magnetic spectrograph. The ground state Q-value has been measured as $Q_0 = 9195 \pm 6$ keV. A DWBA analysis yields l_n values and spectroscopic factors. The results of many-particle shell-model calculations for ^{34}S positive-parity states are found to agree well with experiment.

E NUCLEAR REACTIONS $^{33}S(d, p)$, $E = 12$ MeV; measured Q_0, $\sigma(\theta, E_p)$, ^{34}S deduced levels, l_n, spectroscopic factors. Enriched target.

1. Introduction

Recent investigations of stripping and pick-up reactions, carried out in this laboratory [1, 2]) were stimulated by theoretical studies of nuclei in the $A = 29$–40 region, based on the many-particle shell model [3–5]). The spectroscopic factors predicted by this theory usually agree well with experiment.

The investigation of the $^{33}S(d, p)^{34}S$ reaction has been undertaken because theoretical results have become available [5]) which could be tested against experiment. An earlier investigation of the (d, p) reaction was devoted to the measurement of ^{34}S excitation energies [6]). In the present work l_n values and spectroscopic factors for ^{34}S states have been determined.

2. Experiment

The target was prepared by bombarding a 40 $\mu g/cm^2$ aluminium foil with ^{33}S ions accelerated to 40 keV in a mass separator. The starting material was natural sulphur. The ^{33}S was collected on an area of 1.5 mm × 3 mm and the target had an estimated thickness of 10 $\mu g/cm^2$. The spectrum of elastically scattered deuterons showed that the target contained 23 % ^{32}S, most probably due to the admixture of $H^{32}S$ ions in the mass separator beam.

The 12 MeV deuteron beam from the Utrecht 6 MV tandem accelerator was focussed on the target with the use of a diaphragm with 1 mm diameter, placed 10 cm behind the target. A Faraday cup behind the diaphragm was used for charge collection. A monitor detector at 60° detected deuterons, elastically scattered from ^{32}S and

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^{33}S. The intensity of the unresolved deuteron peak in the monitor, relative to the collected charge, indicated that the target could stand deuteron currents up to 1 μA without noticeable change in target thickness.

Proton intensities were measured at 5° intervals from 5° to 95° with position-sensitive detectors (PSD), placed in the focal plane of the Utrecht split-pole magnetic spectrograph. Teflon foils of 0.5–1.0 mm thickness placed 1 mm in front of the PSD's stopped undesired reaction products such as deuterons and α-particles and degraded the initial proton energy (up to 21 MeV) in order to increase the fraction of the total energy, dissipated in the thin detectors. The resulting improvement of the signal to noise ratio of the position and energy pulses contributed to the good position resolution (0.5 mm), obtained after division of the two pulse-heights by computer to eliminate energy straggling effects. By proper arrangement of seven PSD's along the focal plane all of the proton groups corresponding to the seventeen known ^{34}S states below $E_x = 6.1$ MeV could be detected. With an eighth detector the angular distributions of four more proton groups in the region of $E_x(^{34}\text{S}) = 6.1$–6.7 MeV could be measured, but four other groups in this region were missed because they were obscured by contaminant groups, or because they hit the gap between the seventh and eighth detector. The data-handling system including a CDC 1700 computer has been described in detail in refs. [1, 2]). The proton intensities were measured relative to the deuteron yield in the monitor detector, so that possible variations in target thickness are automatically taken into account.

To normalize the data to absolute cross sections, a target thickness measurement was performed by means of 3 MeV deuterons, elastically scattered from ^{33}S, for which it was assumed that the cross section was due to Rutherford scattering only. The target stability has been checked by comparison of the yield of two (d, p) measurements at 12 MeV, immediately preceding and following the 3 MeV experiment.

To test the correct magnitude of the (d, p) cross sections thus found, the target thickness measurement was repeated with 12 MeV deuterons. It was assumed that the elastic scattering cross section was correctly predicted by an optical model calculation with the use of the parameters of ref. [7]).

Although the latter approach is not necessarily very reliable, it is worth mentioning that the two normalizations yielded equal results.

3. Results

The proton spectrum observed at 20° is displayed in fig. 1. Peaks corresponding to ^{34}S states are indicated by the excitation energies in MeV while contaminant peaks are fully specified. Two proton groups have a FWHM exceeding the average of 12–14 keV. To indicate their complex, presumably doublet, structure they have been labelled with an additional (d) in figs. 1 and 2.

The proton groups corresponding to the doublet already known [8]) at $E_x = 4.88$ MeV could be resolved at several angles, such that the intensities of the components

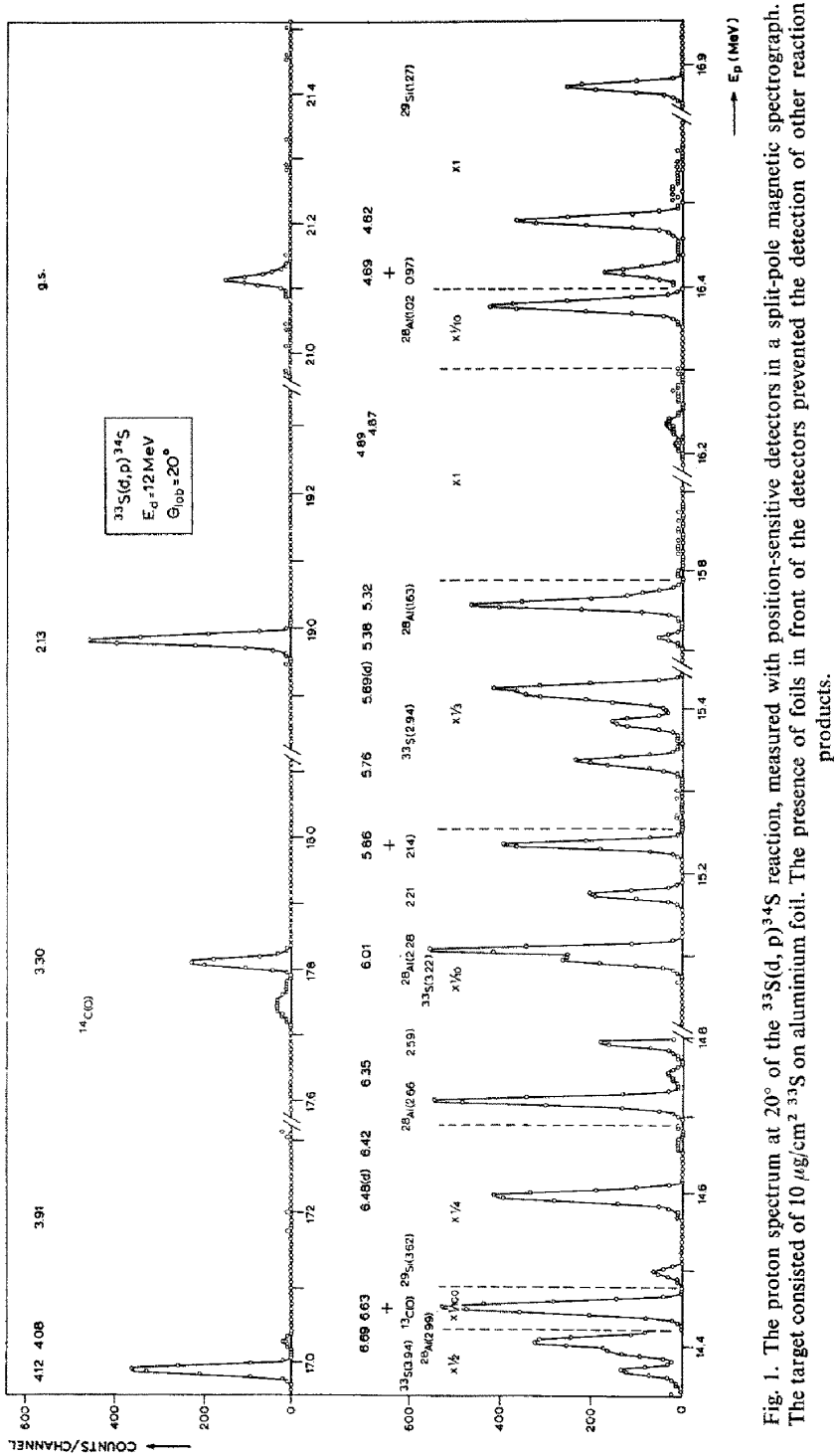

Fig. 1. The proton spectrum at 20° of the $^{33}S(d, p)^{34}S$ reaction, measured with position-sensitive detectors in a split-pole magnetic spectrograph. The target consisted of 10 $\mu g/cm^2$ ^{33}S on aluminium foil. The presence of foils in front of the detectors prevented the detection of other reaction products.

could be measured separately. The proton groups corresponding to doublets at E_x = 5.69 and 6.48 MeV are separated by about 10 keV. For the observed levels below $E_x \leqq 5.38$ MeV the excitation energies, estimated from the kinematic shift of the positions of the ^{34}S peaks relative to those of well-known contaminants, agreed to within 15 keV with the accurate values obtained from γ-ray decay work [8-11]). In the region of E_x = 5.4–6.7 MeV the excitation energies of the levels observed are not in contradiction with those given in ref. [11]).

The Q-value for the ^{33}S(d, p)^{34}S ground state transition Q_0 has been calculated from the Q_2 value of the transition to the $E_x = 3303.1 \pm 0.4$ keV state of ^{34}S. The proton peak corresponding to the latter transition coincides with the ^{13}C(d, p)^{14}C ground state transition peak at $\theta = 12.5° \pm 0.8°$. The proton energy, used in the Q-value equation for the ^{33}S(d, p)^{34}S (E_x = 3.30 MeV) transition to derive Q_2, has been obtained by application of the Q-value equation to the ^{13}C(d, p)^{14}C reaction. The error in Q_2 has been estimated by varying the crossing angle. This error appeared to be mainly responsible for the error in the final result, which was found as Q_0 = 9195 ± 6 keV, in agreement with the value $Q_0 = 9197.8 \pm 3.7$ keV from the 1964 mass table [13]).

Angular distributions of proton groups are shown in fig. 2 where the curves are the results of a DWBA analysis (sect. 4). At points where large errors are indicated the proton yield had to be corrected for contributions of proton groups from the ^{27}Al (d, p)^{28}Al reaction. In general the statistical errors were small compared to the 5 % error from the normalization (sect. 2).

4. Analysis

Since the ^{33}S ground state has $J^\pi = \frac{3}{2}^+$, more than one angular momentum transfer l_n may be involved in the excitation of a ^{34}S state in the (d, p) reaction. To extract the l_n values and the spectroscopic factors S_n the proton angular distributions have been fitted with the DWBA expression

$$\sigma(\theta) = 1.53[(2J_f+1)/(2J_i+1)]S_n\sigma_{DWBA}(\theta)$$

in a least-squares procedure. The computer code DWUCK was used for the calculation of $\sigma_{DWBA}(\theta)$. The best fit to the data was obtained with optical model parameters, given for deuterons in ref. [7]) and for protons in ref. [14]). A further improvement of the fit was obtained when non-locality corrections for the scattered waves and a finite-range correction were included in the DWBA calculations. Table 1 lists the set of parameters used.

To reduce the complexity, due to the l_n mixing, the orbitals into which the neutrons could enter were assumed to be restricted to $2s_{\frac{1}{2}}$, $1d_{\frac{3}{2}}$, $1f_{\frac{7}{2}}$ and $2p_{\frac{3}{2}}$. The l_n mixing partly obscures the fact that the individual DWBA curves do not fit too well, as demonstrated in the pure $l_n = 2$ angular distribution for the ground state transition. For this reason the S_n values have been extracted from a fit to experimental points in the region

TABLE 1

Optical model parameters used in the DWBA calculations [a, b])

	U_R (MeV)	r_R (fm)	a_R (fm)	W_D (MeV)	r_D (fm)	a_D (fm)	$U_{s.o.}$ (MeV)	$r_{s.o.}$ (fm)	$a_{s.o.}$ (fm)	r_{oc} (fm)
d	106.5	1.05	0.85	10.65	1.62	0.57	8.0	0.90	0.60	1.3
p	$57.39-0.32\,E_p$ (MeV)	1.17	0.75	$12.47-0.25\,E_p$ (MeV)	1.32	0.55	6.2	1.01	0.75	1.3
n	[c])	1.25	0.65	0			$\lambda_{s.o.} = 25$			

[a]) The optical model potential, to which the well depths refer is

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

[b]) Non-locality corrections were included with parameters 0.55 and 0.84 fm for deuterons and protons, respectively. The finite-range parameter was taken as 0.621 fm.

[c]) Fitted to the binding energy; the result is of the order of 50 MeV.

TABLE 2

Values of l_n and $(2J_f+1)S_n$ as obtained from the $^{33}S(d, p)^{34}S$ reaction

E_x [a]) (keV)	J^π [f])	l_n	$(2J_f+1)S_n$	E_x [b]) (keV)	J^π [f])	l_n	$(2J_f+1)S_n$
0	0^+	2	1.9	5383	1^+	0+2	0.20, 0.36
2127	2^+	0+2	0.15, 5.2	5680	$\pi = -$ [g, e])	1(+3)	
3303	2^+	0+2	0.22, 1.7	5687	5^- [h])	(1+)3	1.2, 7.9 [c])
3915 [c])	0^+			5759	1^-	1(+3)	0.64, (0.62)
4072	1^+	0+2	0.033, 0.059	5859 [c])	0^+		
4114	2^+	0+2	0.46, 2.4	6008 [d])	2^+		
4622	3^-	1+3	0.35, 1.4	6128 [d])	2^+		
4688	4^+			6175 [d])			
4874	$3^{(-)}$ [g])	(1+3)	(0.013, 0.29)	6253 [d])			
4891	2^+	(0) [i])	(0.08)	6346 [d])	1^-		
5225 [c])	0^+			6423 [c])			
5318	2^- [g])	(1+)3	(0.029), 2.7	6482 [c])	$\pi = -$ [g, e])	1(+3)	1.20, (0.89)
				6533 [c])			
				6636	$\pi = -$ [g])	(1+)3	(0.041), 2.2

[a]) Average of values in refs. [8-12]).

[b]) Ref. [11]).

[c]) Weak.

[d]) The corresponding proton group was obscured by a contaminant group or happened to fall in a gap between two detectors.

[e]) The corresponding proton group has a complex structure. The l_n and $(2J+1)S_n$ values have been extracted from the summed angular distributions. The parity assignment applies to at least one of the components.

[f]) Ref. [9]) unless specified otherwise.

[g]) The parity has been assigned from the l_n value(s) observed in the present work.

[h]) Ref. [12]).

[i]) An acceptable fit could be obtained only by the inclusion of an isotropic compound nucleus contribution.

of the first maximum. In table 2 the resulting l_n and $(2J_f+1)S_n$ values have been collected. The error in the spectroscopic factors has been estimated by comparing the present results with those from a DWBA analysis in which the proton parameters of ref. [15]) were used. These parameters gave a worse fit to the experimental data and yielded spectroscopic factors which were lower by about 5 %, 25 %, 15 % and 40 % for $l_n = 0$, 1, 2 and 3, respectively. For the strongest transitions the errors are believed to be of this order of magnitude. The estimated errors in some spectroscopic factors for weak transitions exceed 50 %. The corresponding l_n and $(2J_f+1)S_n$ values are

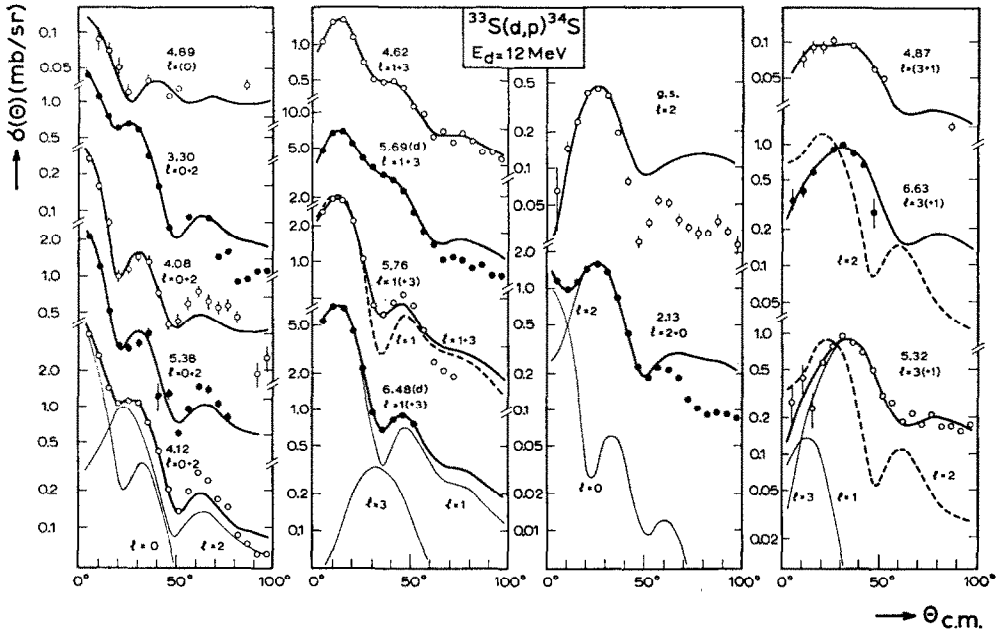

Fig. 2. Angular distributions of protons from the ^{33}S(d, p)^{34}S reaction at $E_d = 12$ MeV. The curves are the results of a DWBA analysis.

given in brackets. The reliability of the results of the DWBA analysis is supported by the observation that the summed stripping strength, defined as $[(2J_f+1)/(2J_i+1)]S_n$, of all the observed $l_n = 2$ transfers equals 2.8, which is close to the $d_{\frac{3}{2}}$ sum-rule limit of 3, valid in the extreme single-particle shell model. The value obtained by Wildenthal *et al.* [5]) was 2.5 (see sect. 5).

5. Discussion

Earlier parity assignments [8-12]) are consistent with the l_n values extracted from the present experiment, except for one case. The measured odd l_n value indicates negative parity for the $E_x = 5.32$ MeV state, in contradiction to the positive parity, suggested in ref. [9]). In fig. 2 it is shown that the dotted $l_n = 2$ curve does not fit the an-

gular distribution for this state; any $l_n = 0$ admixture would even make the fit worse. The previous even-parity assignment was based on the measured lifetime [8]) and the mixing ratio [9]) of the 5.32 → 2.14 MeV γ-ray transition, which for the odd-parity assumption, would lead to 15 ± 11 W.u. M2 admixture in this transition. This proof is inconclusive because the large error limits do not exclude the possibility that actually the M2 admixture is small, say of the order of a few W.u.

In table 2, negative-parity assignments to the $E_x = 6.63$ MeV state and to at least one of the components of the doublet at $E_x = 6.48$ MeV are reported for the first time.

Shell-model calculations on sd shell nuclei, including $A = 34$ have been carried out by Erné [4]), Glaudemans *et al.* [3]) and Wildenthal *et al.* [5]). In ref. [4]) four negative-parity states in ^{34}S were obtained at $E_x = 4.57$, 5.03, 5.08 and 5.57 MeV, originating

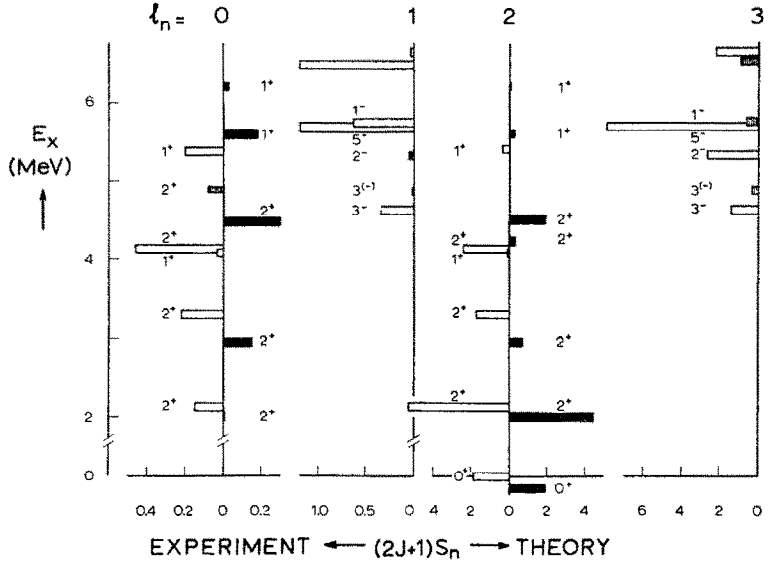

Fig. 3. Experimental and theoretical $(2J_f+1)S_n$ values for ^{34}S states. The theoretical values result from the calculations [5]) in which the FPSDI version of the interaction was used (see text).

from the $d_{\frac{3}{2}}f_{\frac{7}{2}}$ multiplet in the order $J^\pi = 3^-, 2^-, 5^-$ and 4^-. As seen from table 2 the first three levels may be identified with the strongest $l_n = 3$ levels found at $E_x = 4.62$, 5.32 and 5.69 MeV, respectively. Inspection of the complex $E_x = 5.69$ MeV peak suggests that the component corresponding to a state at $E_x = 5680$ keV has predominantly $l_n = 1$, whereas the second member at $E_x = 5687$ keV with strong $l_n = 3$ must be the 5^- level recently found at this excitation energy [12]). The spectroscopic factors for these states are 0.20, 0.54, and 0.72, respectively. The missing 4^- level, if identified with the strong $l_n = 3$ transition to the $E_x = 6.64$ state, would have had 0.25. These values differ significantly from the model prediction of 1. The consequences of extending this model to include the $p_{\frac{1}{2}}$ orbital have been considered, but preliminary

results indicate that the problem requires a more extensive investigation [16]). For positive-parity states in ^{34}S such an investigation has recently become available [5]). It extends the model of ref. [3]) by choosing a vector space, spanned by all Pauli-allowed $(s_{\frac{1}{2}})^4(1p)^{12}(1d_{\frac{3}{2}})^{n_1}(2s_{\frac{1}{2}})^{n_2}(1d_{\frac{5}{2}})^{n_3}$ states, which satisfy the condition that n_1 is greater than or equal to 10. The calculations are based on two closely related types of effective interactions indicated as MSDI (modified surface-delta interaction) and FPSDI (free-parameter surface-delta interaction). A description of the former type of interaction may be found in ref. [17]). The FPSDI Hamiltonian was derived from a least-squares search starting from the MSDI Hamiltonian to fit experimental energies, in which the two-body matrix elements, not involving the $d_{\frac{5}{2}}$ orbit, were treated as free parameters. The results based on the FPSDI, which were found to agree better with experiment, are displayed in fig. 3. The theoretical spectroscopic factors have not been tabulated because of difficulties in the identification of calculated and measured levels, except for the three lowest positive-parity states. Although the $E_x = 4.11$ MeV state has been used in the fitting procedure [5]) the calculated small spectroscopic factors disagree strongly with the large values measured for this state. Most probably the level calculated at $E_x = 4.48$ MeV has to be identified with the strongly excited $E_x = 4.11$ MeV state.

6. Conclusion

A straightforward test of the reliability of shell-model wave functions, as given in refs. [3–5]), is obtained by comparison of the calculated with the measured spectroscopic factors. Among the experimentally determined spectroscopic factors, those from the analysis of (d, p) stripping reactions are the most reliable, as the DWBA theory is probably best founded for this reaction. The good agreement between theory and the present experiment therefore is a support of the ideas involved in this type of many-particle shell-model calculations. Although the observed spectroscopic strength for $p_{\frac{1}{2}}$ and $f_{\frac{7}{2}}$ particles is still small compared to the sum rule limits and the corresponding levels have rather high excitation energies, the experimental data presented here indicate that a theoretical investigation of these states based on the many-particle shell model is worth consideration. This is examplified by the success of the calculations of Erné and Maripuu *et al.* [4]).

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