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Calculation of ^{32}S(t, p) cross sections using sd-shell-model transfer amplitudes

H. T. Fortune and L. Bland

Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104

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We have performed distorted-wave Born approximation calculations for the ^{32}S(t, p)^{34}S reaction, using two-neutron transfer amplitudes from a complete $2s$-$1d$-shell-model calculation. Results are in good agreement with previously published data for low-lying 0^+ and 4^+ levels, but fail to account for mixing of strengths among 2^+ levels. Location of $(fp)^2$ strength is confirmed.

[NUCLEAR REACTIONS ^{32}S(t,p); calculated $\sigma(\theta, E_p)$ with shell-model transfer amplitudes.]

Data for the ^{32}S(t, p)^{34}S reaction have been previously analyzed by Crozier *et al.*,[1] in the framework of the distorted-wave Born approximation (DWBA). However, at that time, microscopic two-nucleon transfer amplitudes from a shell-model calculation were not available. Subsequently, Chung and Wildenthal[2] (CW) have performed shell-model calculations for nuclei throughout the $2s$-$1d$ shell and have calculated the needed transfer amplitudes.[3]

An analysis[4] of absolute g.s. (t, p) cross sections for a number of sd-shell targets has revealed that the ^{32}S(t, p)^{34}S(g.s.) cross section fits in well with the trend across the entire shell. It is thus appropriate to investigate the degree of agreement (or disagreement) between the data of Ref. 1 and the shell-model calculations.

Figure 1 displays all the known[5] positive-parity levels of ^{34}S up to an excitation energy of 7.22 MeV, in comparison with the shell-model results[3] for the lowest four states of each J^π. It is obvious from inspection of the figure that, at least as far as excitation energies are concerned, the correspondence between experimental and theoretical states is unique for all levels between the 0^+ g.s. and the 1^+ state at 5.38 MeV. Above that energy the correspondence is not clear, but it has already been suggested[6] that the 5.85-MeV 0^+ state lies outside the sd-shell model space.

We have performed DWBA calculations for the four lowest states of each $J^\pi = 0^+$, 2^+, and 4^+ using the optical-model parameters of Ref. 1 and two-nucleon transfer amplitudes[3] from CW. The first two columns of Table I list the experimental energies and J^π values from the latest compilation.[5] The third column lists peak differential cross sections of Ref. 1, in arbitrary units. (The cross section scale of Table I is 2.0×10^{-4} of that of Ref. 1.) The absence of absolute cross sections

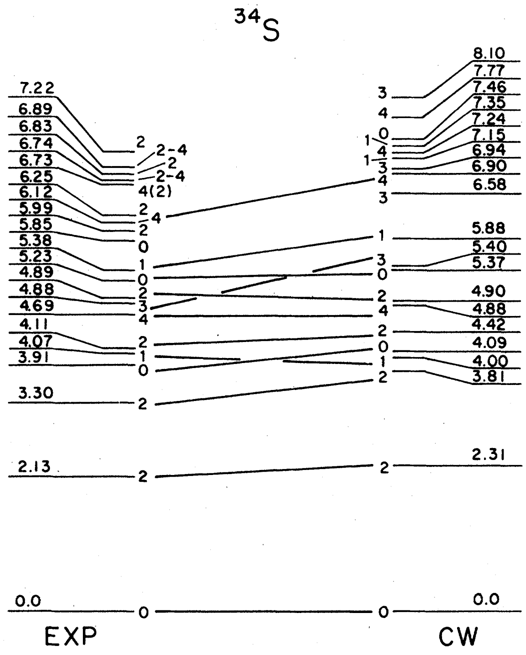

FIG. 1. Comparison of experimental (Ref. 5) and theoretical (Ref. 3) excitation energies and J^π values for positive-parity levels of ^{34}S.

TABLE I. Comparison of experimental and theoretical results for ^{32}S(t,p).

Experimental			Theoretical			
E_x[a] (MeV)	J^{π}[a]	$\sigma_{\max}$[b] (a.u.)	E_x[c] (MeV)	J^{π}[c]	$\sigma_{\max}$[d] (mb/sr)	ϵ[e]
0.00	0^+	2.44	0.00	0^+	2.67	0.98
3.91	0^+	0.13	4.09	0^+	0.099	1.28
5.22	0^+	0.20	5.37	0^+	0.088	2.25
5.86	0^+	0.94	7.46	0^+	8.8×10^{-4}	$\sim10^3$
				$0^+(1f_{7/2})^2$	0.56	1.67
8.02	0^+	0.33	7.46	0^+	8.8×10^{-4}	3.30
$\sum$(first 3 0^+ levels)		2.77	$\sum$(first 4 0^+ levels)		2.86	1.03
2.13	2^+	0.070	2.31	2^+	0.017	4.0
3.31	2^+	0.070	3.81	2^+	0.20	0.36
4.12	2^+	0.036	4.42	2^+	8.8×10^{-3}	3.6
4.89	2^+	0.029	4.90	2^+	1.7×10^{-5}	1.6×10^3
6.00	2^+	0.56				
6.12	2^+	0.13				
$\sum$(first 4 2^+ levels)		0.205	$\sum$(first 4 2^+ levels)		0.226	0.91
4.69	4^+	15×10^{-3}	4.88	4^+	7.6×10^{-3}	2.8
6.25	4^+	20×10^{-3}	6.90	4^+	2.3×10^{-3}	0.9
6.73 6.74	$4^+(2^+)$ $(2-4)^+$	0.043	7.24	4^+	4.8×10^{-3}	~9
			7.76	4^+	2.3×10^{-2}	~2.1
7.24		0.18	7.76	4^+	2.3×10^{-2}	7.5
$\sum$(first 3 entries)		78×10^{-3}	$\sum$(first four 4^+ states)		58.4×10^{-3}	1.3

[a] Reference 5.

[b] From Ref. 1. The present arbitrary unit scale is 2.0×10^{-4} of that of Ref. 1.

[c] Reference 3.

[d] Obtained from DWBA calculation, using $\sigma_{\text{th}} = 267\ \sigma_{\text{DWBA}}$.

[e] $\sigma_{\text{exp}} = \epsilon\sigma_{\text{th}}$.

presents no problem since (as mentioned above), the absolute g.s. cross section for ^{32}S(t,p) is in accord with that for several other *sd*-shell nuclei.[4]

Columns 4 and 5 of Table I contain the theoretical energies and J^{π} values and column 6 lists the maximum theoretical DWBA cross sections calculated from the shell-model transfer amplitudes. These are obtained from the expression

$$\sigma_{\text{th}}(\theta) = N\sigma_{\text{DWBA}}, \quad \text{with } N = 267.$$

Enhancement factors ϵ were then obtained for each state by comparing the experimental and theoretical cross sections for that state. The resulting values of ϵ are listed in the last column of Table I. They are not simply the ratios of the entries in columns 3 and 6 because the theoretical angular distribution may peak at an experimentally inaccessible angle (as, e.g., for 0^+ states), or the theoretical curve (after normalizing for a visual best fit) may not exactly pass through the data at the angle where the cross section is a maximum.

A few simple observations emerge from inspection of the ϵ's. The shell model gives a reasonably good account of the cross sections for the three lowest 0^+ states. However, the fourth model 0^+ state is predicted to be much weaker (about a factor of 1000) than the measured cross section for the fourth experimental 0^+ state. This is consistent with the suggestion of Ref. 6 that the 5.86-MeV 0^+ state consists principally of excitations into the *fp* shell. In fact, the state has roughly the correct cross section to consist entirely of a $(1f_{7/2})^2$ neutron pair coupled to the ^{32}S g.s. [Inclusion of a small amount of $(2p_{3/2})^2$ known to exist in the g.s. of ^{42}Ca—would give an enhancement factor of unity.] The 8.02-MeV 0^+ level is also considerably stronger than the fourth 0^+ model state—perhaps because of mixing with the $(fp)^2$ state, or perhaps implying that a weak 0^+ state remains to be identified near 7.5 MeV excitation.

Summarizing the situation for the 0^+ states, the three lowest experimental 0^+ levels contain approximately the same (t,p) strength as the summed strength for the three lowest model 0^+ states (the fourth model state contributes virtually nothing to the sum).

TABLE II. Calculated DWBA cross sections for higher-lying 2^+ CW states.

E_x (MeV)	$\sigma_{\max}$ (mb/sr)
6.46	0.002
7.01	0.013
7.38	0.13
7.72	0.018
8.21	0.041
8.53	0.009
8.65	0.005
9.29	0.006
Sum	0.224

For the 2^+ levels the situation is very bad. The shell model puts virtually all the (t,p) strength in one state (the model 2^+ level at 3.81 MeV), whereas experimentally the four lowest 2^+ levels have comparable cross sections. However, the summed cross sections for the lowest four 2^+ states are in good agreement. Thus, at least insofar as (t,p) strengths are concerned, the shell model completely fails to describe the mixing between the low-lying 2^+ levels. It would be interesting to see if this failure shows up in other observables. It is very unlikely that the failure is due to mixing of other configurations [e.g., $(fp)^2$] into the low-lying 2^+ states because the summed cross section is about right and because the lowest intruder 0^+ level is at 5.86 MeV and the first four 2^+ states are all lower than this. In fact the next two 2^+ states, at 6.00 and 6.12 MeV, must contain a lot of $(fp)^2$ strength, since their cross sections are so large—about 3.5 times as large as the summed cross sections for the first four 2^+ states.

Because the situation with the 2^+ levels is so bad, we present in Table II the calculated cross sections for the next seven 2^+ levels calculated by CW. This table demonstrates even more clearly that the 6.00-MeV level must be outside the CW model space. The summed cross section for *all* of the twelve lowest CW 2^+ states is only 0.45, less than that observed for the 6.00-MeV level.

Only two experimental levels (at 4.69 and 6.25 MeV) have unambiguous 4^+ assignments.[5] Their excitation energies and (t,p) cross sections are in fairly good agreement with predictions. States at 6.73 and 6.74 MeV have J^π restrictions[5] of $4^+(2^+)$ and $(2\text{-}4)^+$, respectively, and a combined (t,p) cross section[1] that could contain an $L=4$ component (but another L value also appears to be present from the angular distribution of Ref. 1). The (t,p) cross section for the doublet is more in line with expectation for the fourth 4^+ model state than for the third one, but the comparison is inconclusive. If the experimental 7.24-MeV state has $J^\pi=4^+$, it must contain appreciable $(fp)^2$ admixtures, since it is so much stronger in (t,p) than the lower 4^+ levels. But omitting this level, the summed 4^+ strengths are in reasonable agreement. This comparison also suggests that a 4^+ state remains to be identified below about 8 MeV excitation.

In summary, a shell-model calculation in an entire $2s$-$1d$-shell space reproduces adequately the excitation energies and (t,p) cross sections for low-lying 0^+ and 4^+ states, but completely fails to account for the splitting of strength among low-lying 2^+ states. In addition, the presence of large $(fp)^2$ amplitudes is indicated for 0^+, 2^+, and 4^+ levels at 5.86, 6.00, and 7.24 MeV, respectively.

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