Empirical evidence for the importance of coherence effects in the $^{34}S(p,\alpha)^{31}P$ reaction

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Differential cross sections have been measured for the $^{34}S(p,\alpha)^{31}P$ reaction at an incident energy of 35.5 MeV. The (p,α) relative strengths obtained by distorted wave analyses with a triton cluster form factor are well reproduced by current shell model wave functions. The large differences observed between the $^{34}S(p,\alpha)^{31}P$ and $^{32}S(d,^3He)^{31}P$ strengths are due to coherence effects which play an important role in the (p,α) reaction amplitude.

[NUCLEAR REACTIONS $^{34}S(p,\alpha)^{31}P$, E = 35.5 MeV; measured $\sigma(E,\theta)$; enriched target. DWBA analysis.]

I. INTRODUCTION

There has been great interest shown in the dynamics of the (p,α) direct reaction mechanism.[1-3] It is generally assumed that this reaction proceeds through the pickup of three nucleons from the target nucleus. More quantitative spectroscopic results have been obtained[2] using the "spectator model" in which the removed neutrons are in a state of zero seniority and the (p,α) reaction populates mainly those states which come from proton hole excitation. A considerable improvement to this simple picture has been obtained[3] by including the coherence effect between the picked-up proton and the dineutron configuration. With this coherence effect the (p,α) reaction will excite, on a spin zero target, those states which come from the coupling of the proton hole with the neutron pair, either in a seniority zero or two state. In order to test such coherence effects, the present $^{34}S(p,\alpha)^{31}P$ reaction was investigated at an incident energy of 35.5 MeV. The choice of the ^{34}S target nucleus was motivated by its neutron configuration, in which the $2s_{1/2}$-$1d_{3/2}$ extra core neutrons are mainly in a seniority zero state.[4] In addition, a direct comparison of the present experiment with the results obtained in the $^{32}S(d,^3He)^{31}P$ reaction at 52 MeV (Ref. 5) can be a sensitive test for the dynamics of (p,α) reaction.

II. EXPERIMENTAL PROCEDURE

The momentum-analyzed beam from the Milano azimuthally varying field cyclotron provided the source of a 35.5 MeV proton beam. The scattered particles were detected with a ΔE-E telescope of surface-barrier detectors. Reaction products were selected by an Ortec particle identifier model No. 423. The target was prepared by vacuum evaporation of cadmium sulfide, enriched to (90 ± 0.1) % in ^{34}S, onto a 40 $\mu g/cm^2$ carbon backing. The CdS was provided by the Oak Ridge Isotopes Division. The absolute cross sections were determined by reference to the optical model fit of 16.9 MeV elastically scattered protons from Cd nuclei in the angular range 20°–55°. The accuracy of the absolute cross section thus determined is estimated to be about ±20%.

III. EXPERIMENTAL RESULTS

Two typical pulse height spectra from the multichannel analyzer are shown in Fig. 1. The energy resolution (full width at half maximum) is between 130–140 keV. For additional information, the (p,t) and (p,α) spectra were taken together. The (p,t) spectrum shown at $\theta_{lab}=30°$ strongly populates the $J^\pi=0^+$ ground state transition and this is confirmed by Nann and Wildenthal[6] in a paper published after the completion of the present work. The (p,α) reaction populates only three positive parity states up to an excitation energy of 7 MeV. Few states between 7 and 8 MeV excitation energy are excited. Two of these have been observed in the $^{32}S(d,^3He)^{31}P$ reaction[5] and identified as negative parity states at 7.22 and 8 MeV, respectively.

In Fig. 2 the experimental angular distributions with the distorted wave Born approximation (DWBA) curves are shown. Also the $^{34}S(p,t)^{32}S$ ground state angular distribution is included. The experimental (p,t) cross section, within the experimental uncertainty, is in agreement with the one measured by the authors of Ref. 6. The theoretical calculations for the (p,α) transitions were

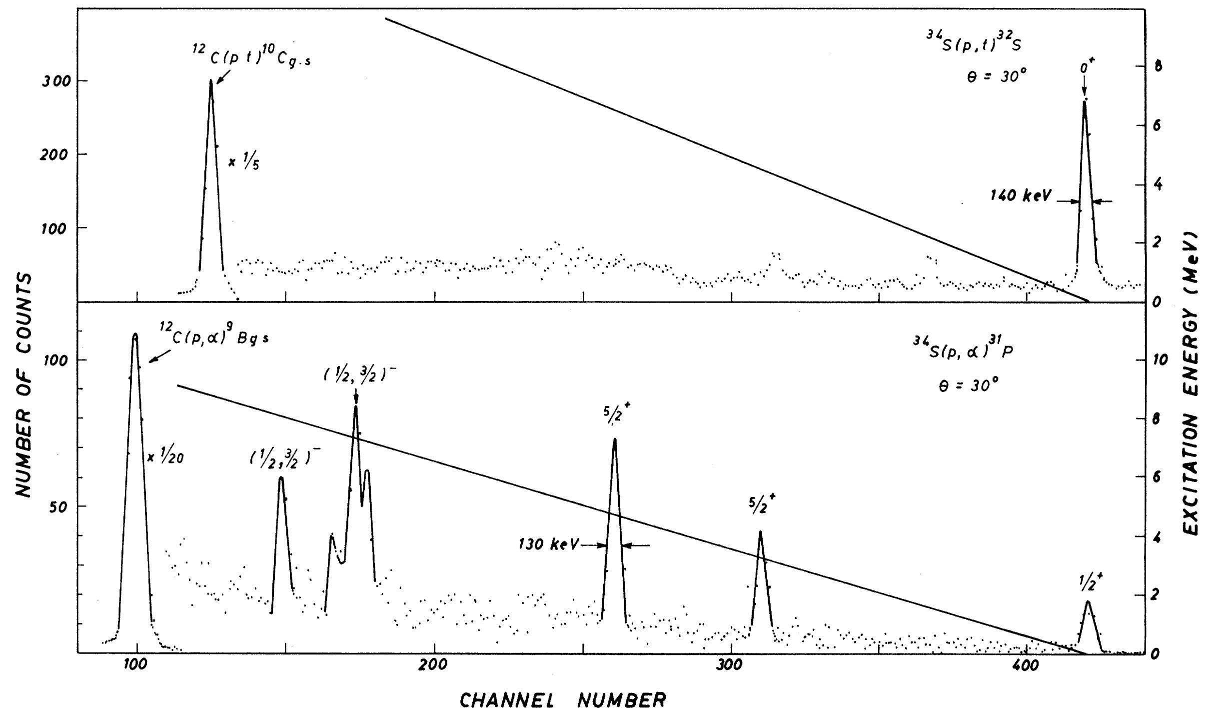

FIG. 1. Triton and α spectra for the $^{34}S(p,t)^{32}S$ and $^{34}S(p,\alpha)^{31}P$ reactions.

carried out with the code DWUCK,[7] using a cluster form factor for the transferred nucleons. The number of nodes in the radial cluster wave function was determined by the "harmonic oscillator energy" conservation rule,[8] where $n=0$, $l=0$ quantum numbers were assumed for internal motion of the triton cluster. This rule gives $2N+L=6$ for nucleons coming from the $0d_{5/2}$, $1s_{1/2}$, and $0d_{3/2}$. Since for a spin zero target the transferred angular momentum L is uniquely determined by the spin and parity of the final state, the above equation yields N. For the $L=0$ and $L=2$ transitions we have $N=3$ and $N=2$, respectively. Assuming that the $L=1$ transitions are excited by $[(sd)p^{-1}]$, $[(d)^2p^{-1}]$, and (or) $[(s)^2p^{-1}]$ transfers, we have $N=2$. This assumption is corroborated by the $(d,{}^3\text{He})$ experimental results[5] which show the $(p)^{-1}$ character for these states. The optical model parameters used in the present study were adapted from the literature[9] and are given in Table I. The calculated angular distributions for the same L transfer have different behavior for $J=L-\frac{1}{2}$ and $J=L+\frac{1}{2}$. This is shown in Fig. 2 for the negative parity state transitions. The comparison between the experimental and calculated angular distributions, indicates a $J^\pi=\frac{3}{2}^-$ attribution to both states.

A direct comparison shown in Fig. 3 between the (p,α) relative strength (given in Table II) and C^2S spectroscopic strength obtained in the $(d,{}^3\text{He})$ reaction at 52 MeV (Ref. 5) shows peculiar differences. The largest discrepancy is observed for the positive parity state transitions. In fact the $J^\pi=\frac{3}{2}^+$, 1.266 MeV and the $J^\pi=\frac{5}{2}^+$, 2.233 MeV states are strongly excited in the $(d,{}^3\text{He})$ reaction but not in the (p,α) reaction. In addition the $J^\pi=\frac{5}{2}^+$ states at 3.295 and 4.783 MeV are strongly excited in the (p,α) reaction, but in the $(d,{}^3\text{He})$ they have a weak strength, corresponding to a small $d_{5/2}$ proton hole components.

IV. DISCUSSION

In the attempt to explain if these features are caused by coherence effects, let us consider the cross section for a (p,α) reaction. Assuming that the DWBA cross section does not depend on the microscopic neutron and proton configuration, we can write for the (p,α) reaction[1,3]:

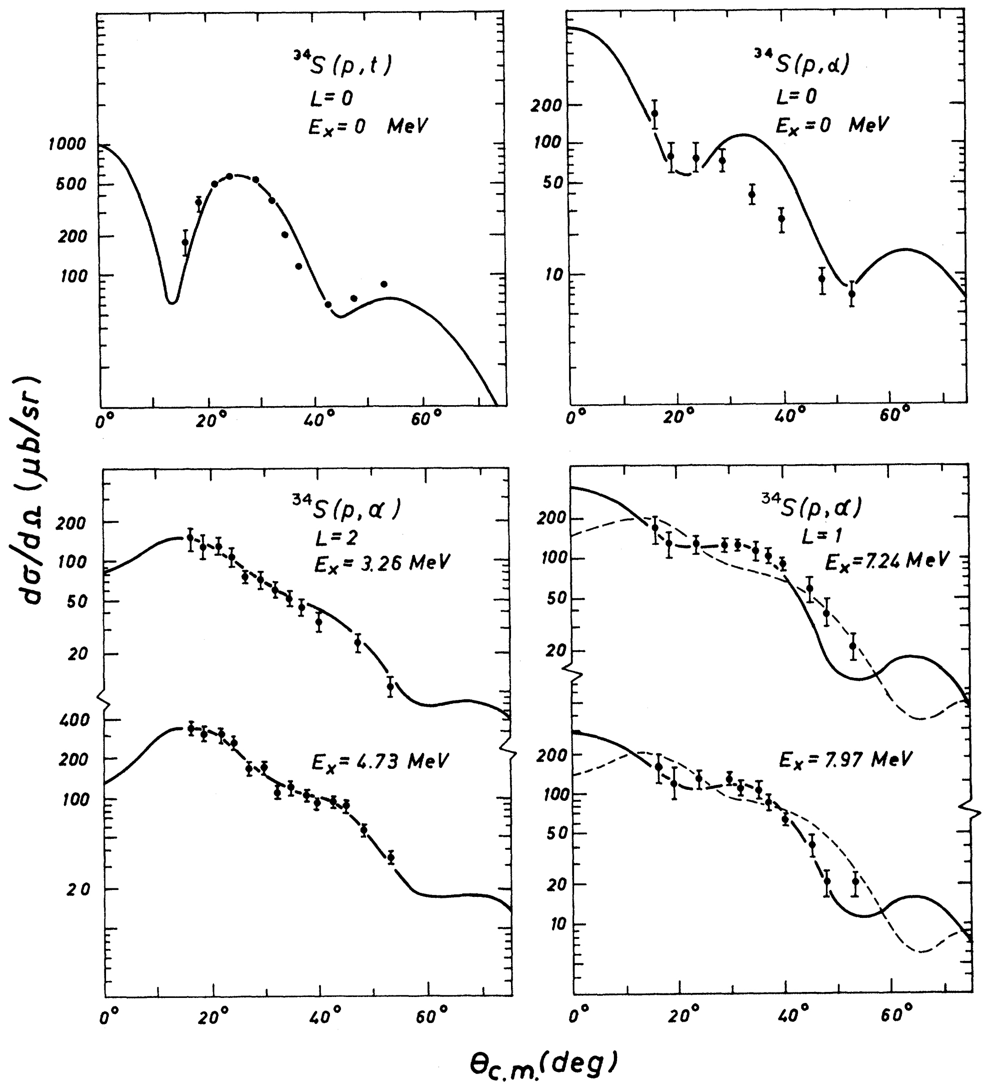

FIG. 2. Angular distributions observed for the ground state $^{34}S(p,t)\,^{32}S$ transition and for the $^{34}S(p,\alpha)\,^{31}P$ reaction. The solid lines are the results of DWBA calculations. The dashed lines for the negative parity states of ^{31}P, correspond to a $J^{\pi}=\frac{1}{2}^{-}$ triton transfer.

$$\left(\frac{d\sigma}{d\Omega}\right)^{NLJ}_{\text{exp}} = D\left|\sum_{J_{12},j_3}\left(\frac{A}{A-3}\right)^{N+L/2}\begin{pmatrix} l_1 & s_1 & j_1\\ l_2 & s_2 & j_2\\ \overline{L} & \overline{S} & J_{12}\end{pmatrix}\begin{pmatrix} l_3 & s_3 & j_3\\ \overline{L} & \overline{S} & J_{12}\\ L & S & J\end{pmatrix}\langle \overline{N}\overline{L}|n_1l_1n_2l_2\rangle\langle NL|n_3l_3\overline{N}\overline{L}\rangle\sqrt{S_J}\right|^2 (2J+1)^{-1}\sigma^{NLJ}_{\text{DW}}(\theta)\,.$$

The factor D is a normalization constant, the first term is the center of mass correction, and the brackets ( ) are the normalized $9j$ symbols,[8] which perform the transformation from jj to LS coupling. The Moshinsky brackets[10] transform the dinucleon n_1l_1, n_2l_2, with orbital angular momentum $\overline{L}$ and radial quantum number $\overline{N}$, and the n_3l_3 nucleon to a triton with quantum numbers of center of mass motion N, L, J. Finally the $\sqrt{S_J}$ is the spectroscopic amplitude for three nucleon transfer and $\sigma^{NLJ}_{\text{DW}}(\theta)$ is the differential cross section as given by the code DWUCK.

In order to calculate the spectroscopic amplitude we have taken the shell model wave functions of ^{31}P calculated by Wildenthal *et al.*[4] For simplicity we have assumed that the ^{34}S target nucleus

TABLE I. Optical model parameters used in the calculation with the code DWUCK.

Channel	V (MeV)	W (MeV)	W_D (MeV)	V_{so} (MeV)	r (fm)	a (fm)	r' (fm)	a' (fm)	r_{so} (fm)	a_{so} (fm)	r_c (fm)
$^{34}S+p$	52.90		7.23	7.19	1.12	0.69	1.19	0.76	0.84	0.81	1.25
$^{32}S+t$	150	16			1.1	0.7	1.5	0.8			1.4
$^{31}P+\alpha$	200	25			1.3	0.4	1.6	0.4			1.4
$^{31}P+t$	a	0	0	($\lambda=25$)	1.25	0.65					1.4

[a] Adjusted to give the transferred triton a binding energy of $-Q\ (p,\alpha)+19.814$.

is described mainly by the $[(1d_{5/2})^{12}{}_{00}(2s_{1/2})^4{}_{00}(1d_{3/2})^2{}_{01}]$ configuration. The available ^{31}P wave functions which interest us are those describing the $J^\pi=\frac{1}{2}^+$ ground state, the $\frac{3}{2}^+$ (1.266 MeV), the $\frac{5}{2}^+$ (2.233 MeV), and the $\frac{5}{2}^+$ (3.295 MeV) states. The spectroscopic factor involves the separation of three nucleons in the same or different subshells from the target nucleus wave function. For instance, for an $(s)^3{}_{1/2,1/2}$ transfer in a transition from the target nucleus to a ^{31}P wave function component of amplitude α, described as $\alpha\{[(d_{5/2})^{12}{}_{00}2s_{1/2}]_{1/2,1/2}\times(d_{3/2})^2{}_{01}\}_{J,T=1/2}$, the spectroscopic factor is given by:

$$\sqrt{S_J}=\alpha\sqrt{4}\,U(\tfrac{1}{2}\tfrac{1}{2}00|0\tfrac{1}{2})\,U(\tfrac{1}{2}\tfrac{1}{2}11|0\tfrac{1}{2}),$$

where the $U(\ |\ )$ are normalized Racah coefficients[8]

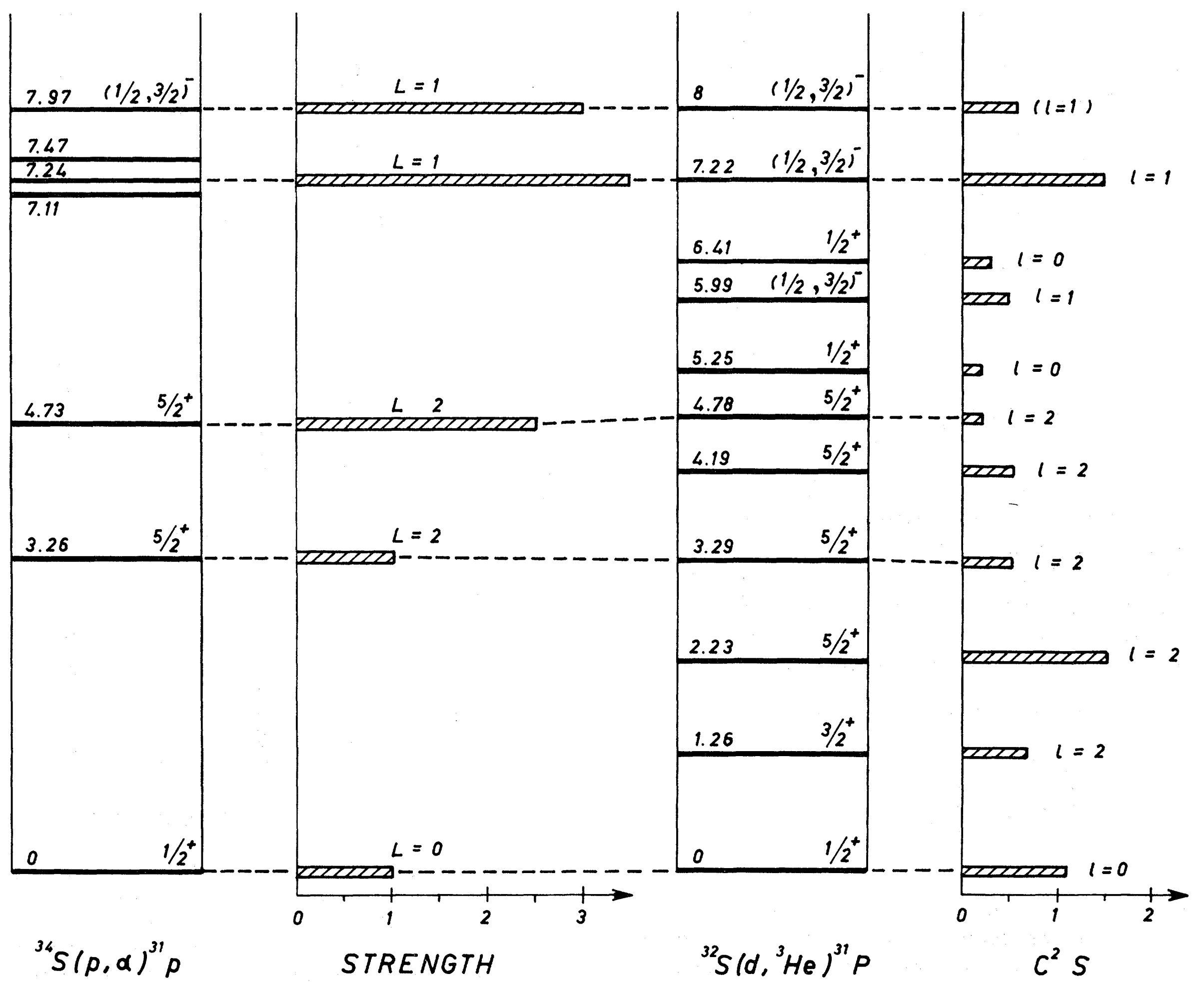

FIG. 3. Comparison of levels and relative strengths observed in (p,α) and $(d,{}^3He)$ (Ref. 9).

TABLE II. Summary of results from the $^{34}S(p,\alpha)^{31}P$ reaction.

E_x (MeV)	J^π	L	Integrated σ [a] (μb)	Relative strength [b]
0	$\frac{1}{2}^+$	0	86± 13	1
3.26± 0.03	$\frac{5}{2}^+$	2	121± 12	1.03
4.73± 0.03	$\frac{5}{2}^+$	2	290± 14	2.52
7.24± 0.04	$(\frac{3}{2})^-$	1	204± 15	3.51
7.97± 0.03	$(\frac{3}{2})^-$	1	177± 13	3.07

[a] Integrated center of mass cross section over the angular range corresponding to $\theta_{lab}=15°-50°$.
[b] Obtained as the ratio of integrated experimental and calculated cross sections in the same angular range. The relative strengths have an estimated uncertainty of ±15%.

which involve the different coupling of nucleons from the target to residual nuclei. For a transfer in which the three nucleons occupy different subshells as in the $\{[d_{5/2}s_{1/2}]_{J'T'}d_{3/2}\}_{J,T=1/2}$ transfer, we have for the spectroscopic amplitude in a transition to a ^{31}P wave function component of amplitude β, described as $\beta\{[(d_{5/2})^{11}{}_{5/2,1/2}(s_{1/2})^3{}_{1/2,1/2}]_{J'T'} \times d_{3/2,1/2}\}_{J,T=1/2}$, the following value:

$$\sqrt{S_J}=\beta\sqrt{96}\begin{pmatrix}\frac{5}{2} & \frac{1}{2} & J'\\ \frac{5}{2} & \frac{1}{2} & J'\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}J' & \frac{3}{2} & J\\ J' & \frac{3}{2} & J\\ 0 & 0 & 0\end{pmatrix}$$

$$\times\begin{pmatrix}\frac{1}{2} & \frac{1}{2} & T'\\ \frac{1}{2} & \frac{1}{2} & T'\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}T' & \frac{1}{2} & \frac{1}{2}\\ T' & \frac{1}{2} & \frac{1}{2}\\ 0 & 1 & 1\end{pmatrix},$$

where the ( ) are normalized $9j$ symbols which take into account the different coupling schemes from the target and residual nuclei. Finally, for a $[(d_{5/2})^2{}_{J'T'}d_{3/2}]_{J,T=1/2}$ transfer, in a transition to a ^{31}P wave function component of amplitude γ, described as $\gamma\{[(d_{5/2})^{10}{}_{J'T'}(s_{1/2})^4{}_{00}]_{J'T'}d_{3/2}\}_{J,T=1/2}$, the spectroscopic factor is simply given by

$$\sqrt{S_J}=\gamma\sqrt{132}\langle d^{12}00|d^{10}J'T'd^2J'T'\rangle$$

$$\times\begin{pmatrix}J' & \frac{3}{2} & J\\ J' & \frac{3}{2} & J\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}T' & \frac{1}{2} & \frac{1}{2}\\ T' & \frac{1}{2} & \frac{1}{2}\\ 0 & 1 & 1\end{pmatrix},$$

where $\langle\,|\,\rangle$ is a coefficient of fractional parentage.[8] For other transitions the spectroscopic amplitudes are calculated in a similar fashion. The results of calculations for the (p,α) relative strengths are shown in Fig. 4 and are compared with the experimental ones. The calculations reproduce the experimental spectrum fairly well, showing that the $\frac{3}{2}^+$ (1.266 MeV) and $\frac{5}{2}^+$ (2.233 MeV) states are weakly excited. In order to prove how destructive interference is responsible for the above transitions, we have calculated the partial contribution to the (p,α) strength of $[(j_1j_2)_{T=0}j_3]$ and $[(j_1j_2)_{T=1}j_3]$ transfers. The results of these calculations are also displayed in Fig. 4 and clearly show a destructive interference between these components for the $\frac{3}{2}^+$ (1.266 MeV) and $\frac{5}{2}^+$ (2.233 MeV) states. For the ground state transition we have only one possible $[(j_1j_2)_{T=0}j_3]$ transfer, which

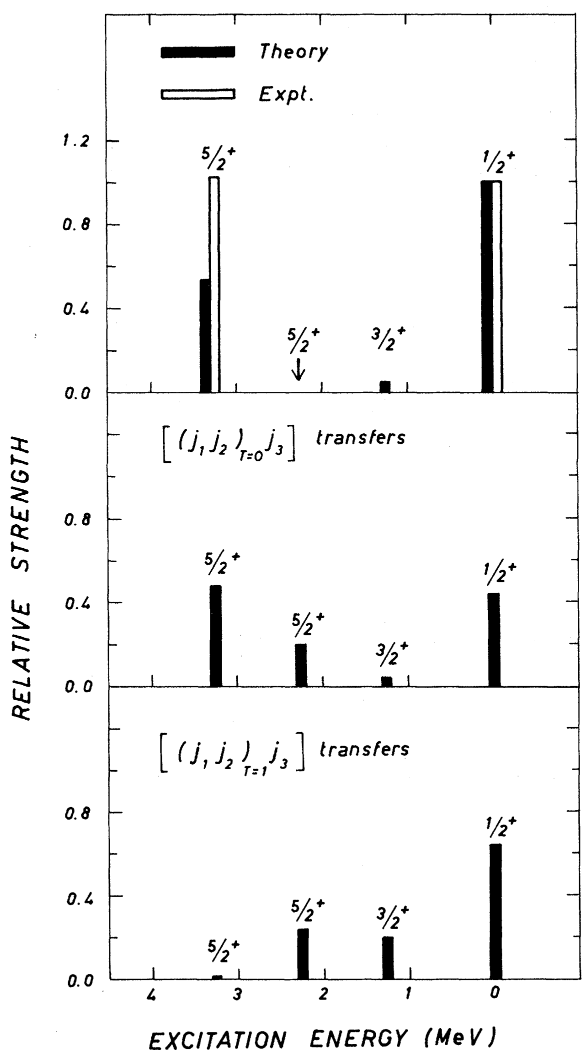

FIG. 4. Comparison of calculated and experimental (p,α) relative strengths. Below are shown the partial contributions to the (p,α) cross section of the $[(j_1j_2)_{T=0}j_3]$ and $[(j_1j_2)_{T=1}j_3]$ transfers. The destructive interference between these two components explains the absence of $\frac{3}{2}^+$ (1.266 MeV) and $\frac{5}{2}^+$ (2.233 MeV) states in the experimental (p,α) spectrum.

is the $(s)^3{}_{1/2,1/2}$ configuration. This three nucleon system can be considered as $(1/\sqrt{2})[(s)^2{}_{01}s-(s)^2{}_{10}s]$; therefore, the above transfer contributes to the total $(s)^3$ squared amplitude with a weight equal to $\frac{1}{2}$.

In conclusion, the present experiment has shown the importance of coherence effects in the (p, α) reaction, which has more degrees of freedom than the $(d, {}^3\mathrm{He})$ reaction. The interference among these additional degrees of freedom explains very well the large differences observed between the ${}^{34}\mathrm{S}(p, \alpha){}^{31}\mathrm{P}$ and ${}^{32}\mathrm{S}(d, {}^3\mathrm{He}){}^{31}\mathrm{P}$ reactions.

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