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Ground-state (p,t) cross sections for *sd*-shell nuclei

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Ground-state (p,t) cross sections measured for five *sd*-shell nuclei are, with one exception, explained well by the shell-model calculations of Chung and Wildenthal. The deviation in the case of the $^{18}O(p,t)^{16}O$ reaction is quantitatively explained by taking account of the core-excited components in ^{16}O and ^{18}O.

[NUCLEAR REACTIONS ^{18}O, ^{22}Ne, ^{26}Mg, ^{30}Si, $^{34}S(p,t)$ to ground states, $E_p = 23$ MeV, measured $\sigma(\theta)$, enriched targets. DWBA analysis; comparison with shell model.]

I. INTRODUCTION

This article reports on the observed systematics of ground-state (p,t) cross sections for five *sd*-shell nuclei at a constant bombarding energy and its comparison with theoretical predictions. The motivation for doing this was twofold: (i) To test the recently calculated wave functions of Chung and Wildenthal,[1] which have been obtained for the ground and low-lying excited states of all *sd*-shell nuclei in the full $(sd)^m$ space; two-nucleon transfer reactions provide a sensitive test of these wave functions, since they probe the correlations between the nucleons. (ii) To complement the recent (t,p) work from the University of Pennsylvania on the ground-state transitions between *sd*-shell nuclei.[2]

II. EXPERIMENTAL PROCEDURE

A 50–100 nA beam of 23.0 MeV protons from the University of Rochester MP tandem accelerator was used to bombard targets enriched in ^{18}O, ^{22}Ne, ^{26}Mg, ^{30}Si, and ^{34}S. These are the only even-even *sd*-shell nuclei on which (p,t) reactions can be studied at tandem energies; the Q values for other possible nuclei are too negative.

Table I gives some details about the target materials. The Ta_2O_5 foil was prepared in Strasbourg by anodizing a thin evaporated layer of Ta using as an electrolyte water enriched in ^{18}O to 98.5%; but at the time of the experiment, only 30% of the oxygen in the target was ^{18}O, the rest being ^{16}O. For ^{22}Ne, two gas cells were used, one in the angular range 5°–20° and the other[3] in the range 15°–60°.

The outgoing tritons were detected by a sonic spark counter[4] positioned along the focal plane of an Enge split-pole spectrograph. For all five targets, clean and strong peaks corresponding to the ground-state transition were observed in the spectra. The resulting angular distributions are shown in Fig. 1.

Accuracy in absolute cross section determination is, of course, crucial in a systematic comparison of data from different nuclei. For the solid targets, the principal factor affecting this accuracy was the target thickness measurement. This was done by elastically scattering 15-MeV ^6Li ions at forward angles, where the cross section was determined to be pure Rutherford. Two independent sets of measurements were carried out for each target and these agreed to within 15%. For the gas target, an absolute manometer was used to measure the pressure in the cell. The absolute cross section in this case is estimated to be accurate to better than 10%.

TABLE I. Target materials.

Nucleus	Chemical form	Support	Isotopic enrichment	Surface density ($\mu g/cm^2$)
^{18}O	Ta_2O_5	Self-supp.	30%	~100
^{22}Ne	Gas	Gas cell	99.9%	~16 cosecθ
^{26}Mg	Element	Self-supp.	99.2%	~450
^{30}Si	SiO_2	C backed	99.0%	~15
^{34}S	PbS	C backed	85%	~20

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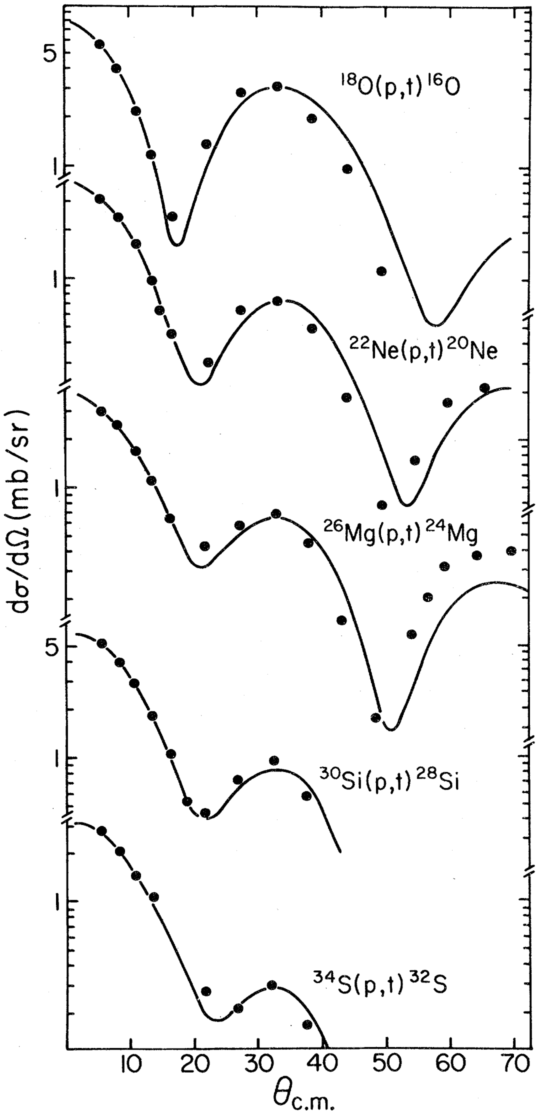

FIG. 1. Angular distributions for five (p,t) ground-state transitions at $E_p = 23$ MeV. The curves are results of DWBA calculations.

III. ANALYSIS

TABLE II. Two-neutron ground-state pickup amplitudes (β) for the Chung-Wildenthal wave functions.

Target	$\beta(d_{5/2})^2$	$\beta(s_{1/2})^2$	$\beta(d_{3/2})^2$
^{18}O	0.8657	0.4131	0.2827
^{22}Ne	0.8180	0.2341	0.2853
^{26}Mg	0.7329	0.2839	0.2970
^{30}Si	0.4849	0.4679	0.5411
^{34}S	0.4326	0.2875	0.7438

For $0^+ \to 0^+$ two-neutron pickup in the *sd* shell, there are contributions from three different amplitudes corresponding to $(d_{5/2})^2$, $(s_{1/2})^2$, and $(d_{3/2})^2$ transfer. The Chung-Wildenthal (CW) predictions for these amplitudes are shown in Table II.[1,5] Using these amplitudes as inputs, angular distributions were calculated with the microscopic option of the distorted wave Born approximation (DWBA) code DWUCK,[6] in which the two-nucleon form factor is generated by the method of Bayman and Kallio.[7]

A variety of optical and bound-state parameters were tried; those finally selected as giving the best fits are listed in Table III. The proton parameters are from an analysis by Watson *et al.*,[8] evaluated for ^{26}Mg, while the triton parameters are from the work of Morsch and Santo,[9] as adapted by Nann and Wildenthal.[10] The same optical potential parameters were used for all nuclei, with radii varying as $A^{1/3}$. In calculating the bound-state wave function, the two-neutron separation energy was divided equally between the two transferred neutrons.

The shape of the calculated angular distribution was especially sensitive to the bound-state radius in the case of the ^{18}O(p,t) reaction. This greater sensitivity may be because the Q value for this reaction is significantly less negative than for the others. The radius that gave the best fit to the measured angular distribution for this case was used, with an $A^{1/3}$ variation for the other reactions. The calculated angular distributions are shown as the solid lines in Fig. 1, individually normalized to the data. The fits are good at forward angles. The deviations found at larger angles, especially near the minima, may be due to a two-step process involving the sequential transfer of two neutrons.[11] This does not introduce any

TABLE III. Optical-model parameters used in the DWBA analysis of the (p,t) reactions at $E_p = 23$ MeV.

Particle	V_0 (MeV)	r_0 (fm)	a (fm)	W (MeV)	$W' = 4\,W_D$ (MeV)	r_0' (fm)	a' (fm)	$V_{s.o.}$ (MeV)	Ref.
p	57.1	1.128	0.57		36.2	1.128	0.50	5.5	8
t	173.9	1.15	0.72	20.6		1.50	0.82	0.0	10
n	a	1.21	0.65					0.0	

[a] Adjusted to give each neutron equal binding.

uncertainty in the determination of the normalization factor between experiment and calculation, since that is determined by the forward-angle data.

IV. RESULTS AND DISCUSSION

According to the normalization procedure of Baer *et al.*,[12]

$$(d\sigma/d\Omega)_{\text{exp}} = 9.72\, D_0{}^2 \epsilon\, (d\sigma/d\Omega)_{\text{DWUCK}} \ ,$$

when the isospin of the residual nucleus and the total angular momentum of the transferred neutron pair are both zero. The factor $D_0{}^2$ is a normalization constant which arises from making the zero-range approximation. The factor ϵ indicates the goodness of the wave function description of the initial and final states, with a value of unity corresponding to an ideal description. Assuming the empirical value[10] $D_0{}^2 = 33\times 10^4\ \text{MeV}^2\,\text{fm}^3$, the value of ϵ determined from the data for the ^{26}Mg(p,t) reaction is 1.17. This is in satisfactory agreement with the ideal value of unity.

Figure 2 shows plots of the measured (crosses) and calculated (dots) differential cross sections at $\theta_{\text{lab}} = 5°$ for the various reactions as ratios of the corresponding cross sections for the ^{26}Mg(p,t) reaction. $A_<$ denotes the mass of the final nucleus. The error bars shown with the experimental points correspond to the 15% uncertainty associated with the absolute cross section measurements.

It is seen that the agreement between the measured and calculated cross sections is good for all the ground-state transitions with the exception of $^{18}\text{O} \rightarrow {}^{16}\text{O}$. This shows that the two-nucleon amplitudes determined from the CW wave functions for the ground states of the nuclei involved give a good account of the observed systematics as a function of $A_<$, except for $A_< = 16$. A similar conclusion was reached by Fortune *et al.*[2] from their study of the (t,p) reaction on *sd*-shell nuclei.

The deviation in the case of the $^{18}\text{O} \rightarrow {}^{16}\text{O}$ transition was qualitatively explained in Ref. 2 as being due to the presence of core-excited components in the ground states of both ^{16}O and ^{18}O. We have performed a quantitative calculation taking this into account, using the two-neutron pickup amplitudes calculated by Fleming *et al.*[13] on the basis of the Brown-Green wave function[14] for ^{16}O and a simple 2p-0h plus 4p-2h wave function for ^{18}O. The amplitudes corresponding to $(d_{5/2})^2$, $(s_{1/2})^2$, $(d_{3/2})^2$, $(p_{3/2})^2$, and $(p_{1/2})^2$ transfers are 0.454, 0.655, 0.371, −0.149, and −0.105, respectively. With these amplitudes, the calculated cross section for the $^{18}\text{O} \rightarrow {}^{16}\text{O}$ transition increases by 30%, which is exactly the amount required to bring agreement with the observed value.

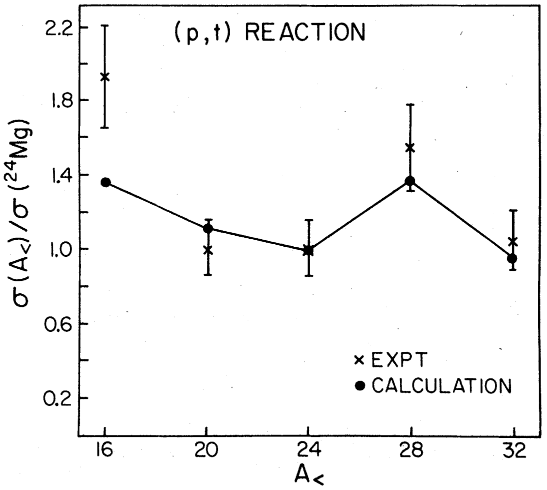

FIG. 2. Plot of experimental and calculated differential cross sections at $\theta_{\text{lab}} = 5°$ as ratios of the corresponding quantities for the ^{26}Mg(p,t) reaction. $A_<$ is the mass of the final nucleus.

The CW wave functions have also been used for calculating the ground-state α-particle strengths of *sd*-shell nuclei.[15] The trend of α-particle strengths extracted from (^{6}Li, d) data depends sensitively on the A dependence of the radii appearing in the optical and bound-state potentials employed in reducing measured cross sections to strengths. A procedure which takes into account the finite size of ^{6}Li yields a trend that is in general agreement with the CW predictions[16] but there is a marked disagreement with the prediction in the case of the ^{22}Ne(^{6}Li, d)^{26}Mg reaction and small deviations are present for ^{18}O(^{6}Li, d)^{22}Ne and ^{20}Ne(^{6}Li, d)^{24}Mg. The present results show that such disagreement is absent in the case of the two-nucleon transfers $^{26}\text{Mg} \rightarrow {}^{24}\text{Mg}$ and $^{22}\text{Ne} \rightarrow {}^{20}\text{Ne}$. This suggests that the source of the disagreement in the case of α-particle transfer is not in the shell-model wave functions.

In conclusion, two-nucleon transfer amplitudes calculated from the Chung-Wildenthal shell-model wave functions give a satisfactory account of ground-state (p,t) cross sections for a number of *sd*-shell nuclei.

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