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THE (^{3}He, n) REACTION IN THE LOWER 2s1d SHELL †

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Abstract: The two-proton transfer reaction (^{3}He, n) has been measured on four gas targets, ^{16}O, ^{18}O, ^{20}Ne, and ^{22}Ne, with an incident ^{3}He energy of 18.3 MeV. The data were taken with a neutron time-of-flight spectrometer in the angular range 0° to 40° c.m. The results for selected transitions are compared to DWBA predictions using shell-model spectroscopic amplitudes. In addition, the data for the ^{18}O(^{3}He, n)^{20}Ne reaction are compared to predictions of the SU(3) strong coupling model.

E NUCLEAR REACTIONS ^{16,18}O, ^{20,22}Ne(τ, n), E_τ = 18.3 MeV; measured $\sigma(E_n, \theta)$. ^{18,20}Ne, ^{22,24}Mg deduced levels, L, J, π. Enriched targets.

1. Introduction

The magnitudes of light-ion two-nucleon transfer cross sections are known to often be particularly sensitive to certain components of the spectroscopic amplitudes. For example, in the 2s1d shell a pure $(s)^2$ $L = 0$ transfer is about four times stronger than a $(d)^2$ transfer. A similar enhancement occurs for a (2s1d) $L = 2$ configuration compared to a $(1d)^2$ $L = 2$. This effect has two main causes. First, the 2s orbital has an extra node compared to the 1d; so it extends further at the nuclear surface where two-nucleon transfer reactions occur. Second, $(2s)^2$ and (2s1d) two-particle wave functions contain a larger amount of relative $l = 0$ motion and thus have a larger overlap with the initial relative s-state of the two transferred nucleons in the light projectile. A small $(2s)^2$ or (2s1d) component in a spectroscopic amplitude, especially since it is added coherently, can thus have a very marked effect on the magnitude of the cross section. The shape of the angular distribution is not affected by the composition of the spectroscopic amplitude if the components are all in the same oscillator shell [1]).

If wave functions are given for the states connected by a two-nucleon transfer reaction, a spectroscopic amplitude can be generated and used in a DWBA calculation of the cross section. Although DWBA is known not to give absolute cross

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sections accurately, it can be expected to produce reliable relative cross sections for different states observed in a single reaction. The possibility exists then of testing theoretical wave functions for consistency with two-nucleon transfer data. The present work represents this application of the two-proton transfer reaction (^{3}He, n) on four isotopes in the lower 2s1d shell.

2. Experimental method

The data were obtained with the neutron time-of-flight spectrometer at the University of Michigan Cyclotron Laboratory [2]). Using the gas target system that was developed in conjunction with the spectrometer, the (^{3}He, n) reaction was measured on natural oxygen (99.8 % ^{16}O) and enriched (> 98 %) samples of ^{18}O, ^{20}Ne, and ^{22}Ne. A 20 MeV ^{3}He$^+$ beam with a time spread typically of 1.5 ns FWHM was delivered by the 83 inch cyclotron. Passage of the beam through the 0.3 mm tantalum entrance window of the gas cell reduced the energy to 18.3 MeV.

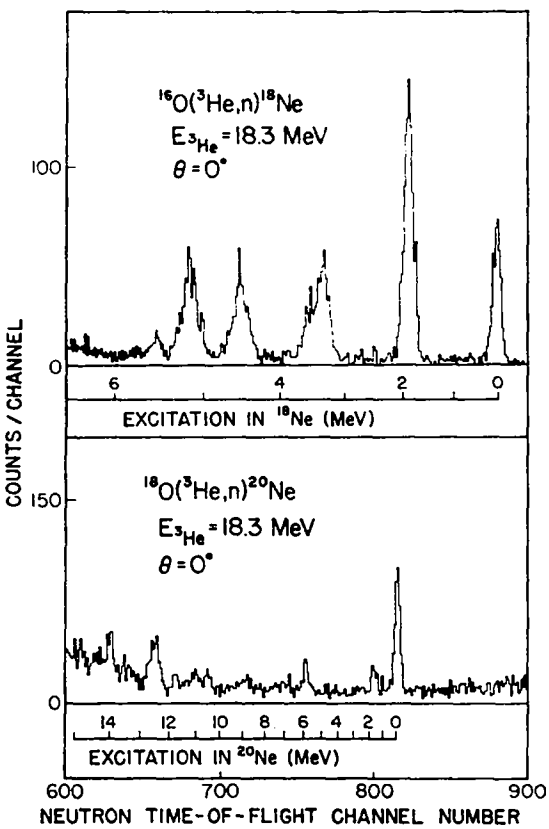

Fig. 1. Neutron time-of-flight spectra.

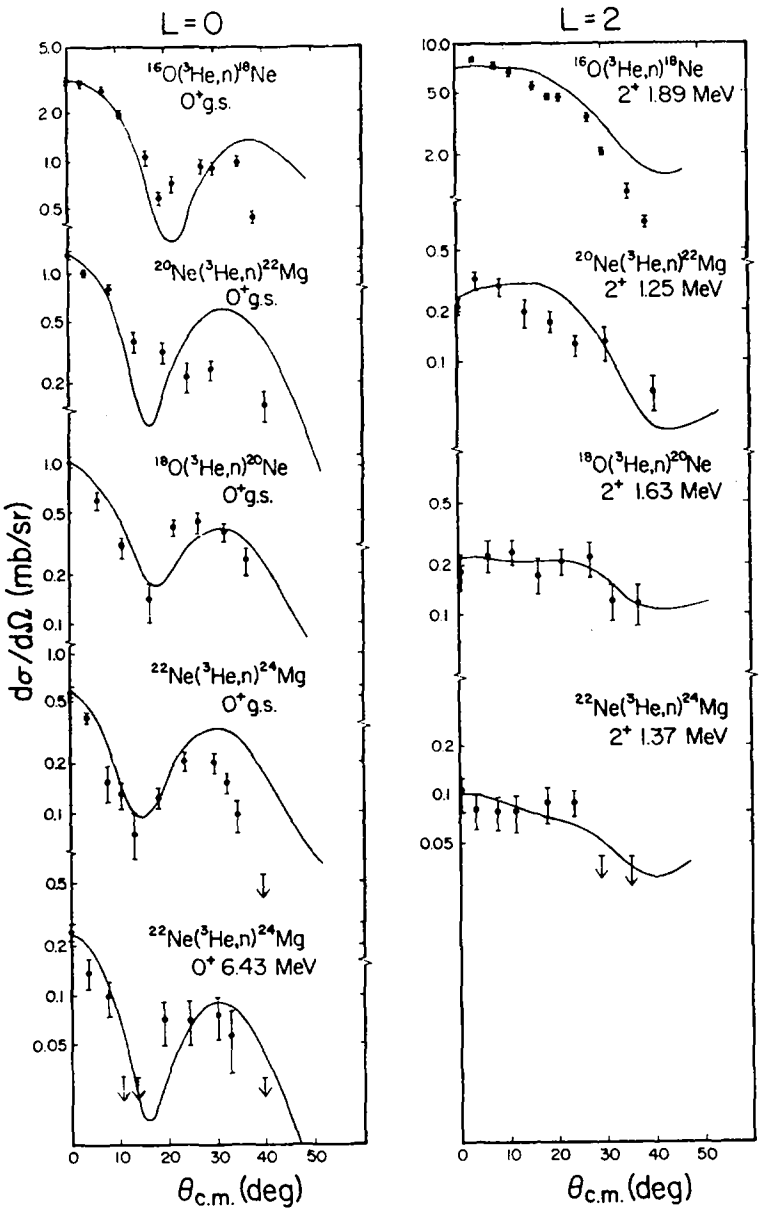

Fig. 2. Measured $L = 0$ and $L = 2$ angular distributions and DWBA calculations.

3. Results

In time-of-flight spectroscopy the overall energy resolution depends on many factors including the energy of the emitted neutrons. For this reason the resolution

varied from target to target as the Q-value for the reaction changed. For example, for the lowest Q-value (-3.20 MeV for the $^{16}O(^3He, n)^{18}Ne$ reaction) the width of the ground-state peak was 120 keV FWHM. This width was primarily determined by the target thickness and energy straggling of the beam in the entrance window. For the highest Q-value reaction ($+13.12$ MeV for $^{18}O(^3He, n)^{20}Ne$) the resolution was determined by the 1.5 ns time width of the beam bursts. For the ground-state transition this resolution was 300 keV FWHM. Fig. 1 shows 0° spectra from these two reactions.

Angular distributions were obtained over the range 0° to 45° lab angle for all g.s. to g.s. and g.s. to 2_1^+ transitions, as well as for a few other strong resolved states. As has been seen in other two-nucleon transfer reactions with light ions [3-5], $L = 0$ transitions exhibit a pronounced forward peaked diffraction structure while higher L-transfers are relatively flat and featureless.

4. Comparison with theory

The data were analyzed using the two-nucleon transfer option of the zero-range DWBA code DWUCK4 [ref. [6])]. Appropriate optical model parameters were taken from the literature [7]). The transferred protons were bound in the residual nucleus in a Woods-Saxon well with one-half of the two-proton separation energy. The data and DWBA fits for the $L = 0$ and $L = 2$ transitions are shown in fig. 2.

4.1. SHELL-MODEL SPECTROSCOPIC AMPLITUDES

Shell-model wave functions and the resulting (^{3}He, n) spectroscopic amplitudes have been calculated by Wildenthal and Nann [8]) for many of the transitions measured in this work. These amplitudes and the resulting cross sections are listed in table 1 and compared with the experimental results. In all cases the peak cross sections are given relative to the 0° peak of the 0^+ g.s. to 0^+ g.s. transition for the particular target. Note that, as might be expected, the calculations are farthest off for the case with the largest number of valence particles, namely $^{22}Ne(^3He, n)^{24}Mg$.

TABLE 1

Shell-model predictions compared to experimental results

Reaction	Final state	σ_{rel}	
		calc	exp
$^{16}O(^3He, n)^{18}Ne$	2^+ 1.89 MeV	0.76	1.8 ±0.2
$^{20}Ne(^3He, n)^{22}Mg$	2^+ 1.25 MeV	0.30	0.24±0.04
$^{18}O(^3He, n)^{20}Ne$	2^+ 1.63 MeV	0.14	0.23±0.05
$^{22}Ne(^3He, n)^{24}Mg$	2^+ 1.37 MeV	0.05	0.18±0.03
	0^+ 6.43 MeV	0.15	0.43±0.06

$\sigma_{rel} \equiv$ (peak cross section for given state)/(peak cross section for 0^+ g.s.).

Data are available for the reaction ^{16}O(t, p)^{18}O done with 10 MeV tritons [9]). In the spirit of this shell-model analysis, this reaction is spectroscopically identical to the ^{16}O(^{3}He, n)^{18}Ne reaction. In particular the g.s. to g.s. and g.s. to 2_1^+ (1.98 MeV) transitions can be analyzed using the same spectroscopic amplitudes that were used in the two-proton transfer analysis to the analog states in ^{18}Ne. The value of σ_{rel} (as defined in table 1) is calculated to be 0.15 for the 2^+ state at 1.98 MeV compared to an observed σ_{rel} of 0.37. The ratio of the experimental σ_{rel} to the calculated σ_{rel} is 2.3 for both the (^{3}He, n) and the (t, p) reactions to the first 2^+ state, indicating that the differences between the two reactions are well described by the DWBA analyses.

In general, the shell-model spectroscopic amplitudes provide reasonable agreement with the data. The sensitivity of the calculations is perhaps best demonstrated by an example. Assuming that a calculation for the ^{22}Ne(^{3}He, n)^{24}Mg $L = 0$ g.s. to g.s. cross section gives a result of 1.0 (arbitrary units) for a pure $(1d_{\frac{3}{2}})^2$ transition, a pure $(2s_{\frac{1}{2}})^2$ calculation would then give 3.9. A 50/50 mix of $(1d_{\frac{3}{2}})^2$ and $(2s_{\frac{1}{2}})^2$ would give 3.3 or 0.4 for constructive or destructive coherence, respectively. A similar but somewhat weaker effect is observed in comparing a $(1d)^2$ $L = 2$ to a (2s1d) $L = 2$ transition. The calculations are not sensitive to changes from a $1d_{\frac{3}{2}}$ to a $1d_{\frac{5}{2}}$ component.

4.2. SU(3) SPECTROSCOPIC AMPLITUDES FOR STATES IN ^{20}Ne

Of the four reactions measured in this study, possibly the most interesting one spectroscopically is ^{18}O(^{3}He, n)^{20}Ne. This is because of a question about the structure of one of the 0^+ states in ^{20}Ne. The 0^+ states are known to be strongly excited via (^{3}He, n) reactions, and identification of an $L = 0$ transition can be made unambiguously from its angular distribution. Furthermore, the selectivity of the reaction makes it a good probe for 0^+ states at excitations where the high density of states limits the usefulness of single-nucleon transfer reactions. In the case of ^{20}Ne, Arima and Strottman [10]) have proposed the following configurations for the first three 0^+ states, $(2s1d)^4$ for the ground state and 6.72 MeV state and $(1p)^{-4}$ $(2s1d)^8$ for the 7.2 MeV state. The fourth 0^+ at approximately 8.3 MeV is thought to be either $(2s1d)^2(2p1f)^2$ or $(2p1f)^4$. If the ^{18}O ground state is considered to be primarily a $(2s1d)^2$ structure, then adding two protons via the (^{3}He, n) reaction can lead directly only to $(2s1d)^4$ or $(2s1d)^2(2p1f)^2$ states in ^{20}Ne. From the 0° spectrum shown in fig. 1, it can be seen that none of the three excited 0^+ states is strongly excited. The state expected at 8.3 MeV is known to have a large width ($\approx$ 800 keV) [11]). Assuming this width, an upper limit on the 0° cross section to this state can be set at 250 μb/sr or about 25 % of the ground-state strength. Cross sections to the other two 0^+ states (which have much smaller widths) are less than 50 μb/sr. The 6.72 MeV state is the orthogonal $(2s1d)^4$ partner to the ground-state $(2s1d)^4$ configuration. While the ground-state configuration leads to constructive $L = 0$ coherence, the excited state will have destructive coherence and, therefore,

a much smaller cross section. A shell-model spectroscopic amplitude for this state is, in fact, available from the same calculations used to generate the amplitudes in table 1. When this amplitude is used, the resulting σ_{rel} is 0.0016, which is consistent with the data.

The low cross sections for the other two 0^+ states might be qualitatively explained as follows. The absence of the state at 7.2 MeV is consistent with its $(1p)^{-4}(2s1d)^8$ description. The lack of strength for the 8.3 MeV state may imply that it is primarily an $(fp)^4$ configuration.

In order to investigate this last possibility, the spectroscopic amplitude for the $(1s2d)^2(2p1f)^2$ configuration should be calculated. A model which has the capability of such a calculation is the SU(3) strong-coupling formalism.

If SU(3) wave functions are available for the target and the final state, then generating spectroscopic amplitudes is a straightforward process. The procedure for generating few nucleon spectroscopic amplitudes has recently been outlined by Hecht and Braunschweig [12]). In the same article they give many of the reduced matrix elements which are necessary for calculating spectroscopic amplitudes in the mass region of the 2s1d shell. When the SU(3) spectroscopic amplitude is obtained, it can be transformed to *L-S* coupling [13]) and then to *j-j* coupling suitable for use in DWUCK. For the (^{3}He, n) reaction on a 0^+ target, only the terms with $T = 1$, $M_T = -1$, and $S = 0$ contribute to the spectroscopic amplitude.

Arima and Strottman have calculated many SU(3) wave functions for the mass region $A = 18$ to $A = 21$ [ref. [14])]. This compilation shows that the ground state and first 2^+ state in ^{20}Ne are dominated by the configuration of highest SU(3) symmetry for four particles in the 2s1d shell, namely (80). This symmetry accounts for 78 % of the ground-state wave function and 81 % of the 2_1^+ wave function. Similarly, in ^{18}O the ground state is 65 % (40).

In view of these results, as a lowest order approximation, only the (80) components of the ^{20}Ne ground state and 1.63 MeV 2^+ state were considered. The only coupling which can result in this final symmetry is a (40) ^{18}O target with a (40) for the transferred proton pair. The spectroscopic amplitudes for these two states were calculated and used in DWUCK. Using the notation of table 1 again, the σ_{rel} for the 2^+ was found to be 0.20 compared to a measured σ_{rel} of 0.23 ± 0.05. Thus the lowest-order SU(3) predictions for these two states are consistent with the data.

In the context of SU(3) strong coupling, a possible structure for the 1^- state at 5.79 MeV would be a $1\hbar\omega$ excitation leading to a state with (90) symmetry. Ichimura *et al.* [15]) have shown that such a state must be a mixture of a 4p state and a 1h5p state with amplitudes of $\sqrt{\frac{2}{5}}$ and $\sqrt{\frac{3}{5}}$, respectively. This mixing is necessary to construct a state without spurious c.m. motion. If we assume that ^{18}O has a closed ^{16}O core, then the 1h5p configuration will be spectroscopically inert. The 4p configuration consists of three (2s1d) particles coupled to (60) and then coupled to a single (30) (2p1f) particle. The spectroscopic amplitude calculated with this part of the (90) 1^- state leads to a σ_{rel} of 0.61, which is to be

compared with the observed σ_{rel} of 0.26 ± 0.05. The agreement is not as good as for the 2_1^+ state, but it is of a quality comparable to the shell-model calculations presented earlier for this region.

For the 0^+ state at 8.3 MeV, a $2\hbar\omega$ (10, 0) excitation is considered. Here the situation is more complicated; Hecht and Braunschweig [12]) have pointed out that there are seven shell-model configurations which must be considered in a $2\hbar\omega$ excitation. However, only two of these configurations are of the 4p type which would be spectroscopically active in the (^{3}He, n) reaction as treated here. One of these is a $(2s1d)^2(2p1f)^2$; the other is a $(2s1d)^3(3s2d1g)^1$. If it is assumed that the 0^+ state at 8.3 MeV is of (10, 0) character without spurious content or (3s2d1g) content, then the amplitude for the $(2s1d)^2(2p1f)^2$ component is 0.52. If the $(2s1d)^2(2p1f)^2$ component of a nonspurious state is maximized, the amplitude can be increased to 0.61, but this requires a destructively coherent admixture of the $(2s1d)^3(3s2d1g)^1$ configuration with an amplitude of 0.49. Again, these are the results of Hecht and Braunschweig.

Spectroscopic amplitudes for the $(2s1d)^2(2p1f)^2$ state free of (3s2d1g) excitation and the mixed state result in σ_{rel} values of 0.31 and 0.71, respectively. The mixed configuration gives a larger cross section, despite the destructive interference between the two configurations. This is mainly due to a very large contribution from the $(2s_{\frac{1}{2}}3s_{\frac{1}{2}})$ part of the $(2s1d)^3(3s2d1g)^1$. Since experimentally only an upper limit of 0.25 can be set for σ_{rel}, both results must be considered compatible with the data, given the uncertainty of this lowest order approach. The present data and analyses are not then able to rule out a $(2s1d)^2(2p1f)^2$ structure for the 0^+ state at 8.3 MeV.

5. Conclusions

It has been seen that current shell-model spectroscopic amplitudes are capable of qualitatively describing the (^{3}He, n) transfer data presented. Also, the SU(3) strong-coupling model produces reasonable agreement for the states observed in ^{20}Ne. Given the limitations of a DWBA analysis, it may be that the agreement found for both models is as good as should be expected. Other work in the (2s1d) shell has shown that coupled-channel effects may be considerable in two-nucleon transfer reactions. For example, in a recent article by Olsen *et al.* [16]), a CCBA analysis of the ^{22}Ne(p, t)^{20}Ne resulted in a significant change in both the shape and magnitude of calculated angular distributions. In their work they find that the $L = 2$ transition to the first-excited state is increased by a factor of five. In view of this result and CCBA treatments of other two-nucleon transfer data, it is natural to consider doing a CCBA analysis of this data as well. Such calculations would then provide a more stringent test of the spectroscopic amplitudes.

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