Levels in $^{28}$Si via the $^{24}$Mg($^{3}$He, $n$) reaction

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The $^{24}$Mg($^{3}$He, $n$)$^{28}$Si reaction at $E_{n} = 15$ MeV has been studied. Relative strengths to excited states in $^{28}$Si are determined from a distorted-wave Born-approximation analysis of the data. The ratios $R(y' - 1)/R(y' - 0)$ for the levels $2', 4'$ states suggest degeneracy with predictions based on pure $S_{0}$ symmetry. When compared with results from the $^{35}$Mg($^{3}$He, $n$)$^{39}$K a consistent picture for the structure of the 0.0 0', 1.0 0', 2.0', 4.02 0', and 6.69 0' MeV levels in $^{28}$Si is suggested.

NUCLEAR REACTIONS $^{24}$Mg($^{3}$He, $n$) $E = 15$ MeV: measured $R(y' - 1)/R(y' - 0) = 0.55$; extracted strength with DWBA, compared with $S_{0}$ predictions.

I. INTRODUCTION

The low-lying levels of $^{28}$Si have been studied by a variety of experimental techniques and have been the focus of numerous theoretical investigations. Here we present results of a $^{24}$Mg($^{3}$He, $n$) study to some of those levels. Differential cross sections were measured for 15 MeV incident He ions on $^{24}$Mg, and strengths relative to that for the ground state were extracted. These strengths are compared with theoretical results deduced from a simple pure symmetry $S_{0}$ picture for the 0' ground state of $^{28}$Si and the 0' ground state, 2', (1.76 MeV) and 4' (4.62 MeV) states in $^{35}$K. A comparison with $^{35}$Mg($^{3}$He, n) results suggests a consistent picture for the structure of the levels studied.

II. EXPERIMENTAL DETAILS AND RESULTS

The University of Rochester beam testing and data acquisition systems have been described in detail in a recent paper. The thickness of the enriched (99.22) $^{24}$Mg target used in the present experiment was 0.5 mg/cm$^2$. A neutron time-of-flight spectrum is shown in Fig. 1, from which it can be seen that the levels in $^{28}$Si at 0.0 MeV (0') and 1.78 MeV (2') are clearly resolved. The 0' level at 4.62 MeV is not clearly resolved from the 4', 4.63 MeV level; nonetheless, the forward angle dominance of 0' levels makes a reliable strength assignment for that level feasible. The same is true for the 0' level at 6.69 MeV, even though it is not resolved at all angles from the 2', 6.88 MeV level. However, determination of the strengths of the 4', 4.62 MeV and 2', 6.88 MeV levels depends on the accurate representation of the 0' angular distributions by the distorted wave Born approximation (DWBA); clearly this introduces sizable uncertainties for these unresolved levels having nonzero spin. The 0', 2' level at 10.39 MeV also dominates any unresolved levels of forward angles, thus allowing a strength determination for this level. The data for these levels and their DWBA representations are shown in Fig. 2. The relative strengths of the levels were obtained from DWBA calculations assuming the transfer of an (ST) = (01) cluster and normalizing to 1.0 for the ground state. The optical model parameters used in the calculations are parameter set C from Greiner et al. for $^{3}$He and those of Bacchetti and Greenlees for the neutron and bound state well geometry. The neutron surface imaginary potential was increased by 5 MeV from the values in Ref. 6. This resulted in greatly improved fits to the ground state and 2', 1.78 MeV angular distributions. The strengths resulting from the ($^{3}$He, n) DWBA calculations are listed in Table 1, along with the relative strengths in the same $^{28}$Si levels resulting from the $^{35}$Mg($^{3}$He, n) experiment.

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III. THEORETICAL DISCUSSION

The reaction was considered to proceed from the ground state of $^{24}$Mg, with dominant symmetry ($\pi\nu)$? $\frac{1}{2}^-$ ($\lambda\sigma$) $J^{\pi}$=$\frac{1}{2}^-$ $\left(\frac{1}{2}^+\right)$, to states in $^{36}$Si, with symmetry ($\pi\nu\sigma$)? $\frac{1}{2}^-$ $\left(\frac{1}{2}^+\right)$ $J^{\pi}$=$\frac{1}{2}^-$ $\left(\frac{1}{2}^+\right)$, $\frac{3}{2}^-$ $\left(\frac{3}{2}^+\right)$, $\frac{5}{2}^-$ $\left(\frac{5}{2}^+\right)$. The expected strengths under these assumptions are those given under the columns labeled SJ in Table I. This description of the $^{24}$Mg ground state is consistent with the $^{24}$Mg($p$, $\gamma$) data. In particular, the observed favoring of the $J^{\pi}$=$\frac{1}{2}^+$ $(2.34$ MeV) over the $J^{\pi}$=$\frac{3}{2}^+$ $(1.81$ MeV), in that reaction is unique to the ($\lambda\nu$)? $(40)$ assignment for the $^{24}$Mg ground state. (The dominant SJ's; structures of the $^{24}$Mg and $^{36}$Si ground states $\left[\frac{1}{2}^+\right]$ ($\nu\sigma$)? $(41)$ and $\left[\frac{3}{2}^+\right]$ ($\nu\sigma$)? $(42)$, respectively, for the interaction of $^{24}$Mg have been determined via large shell-model calculations, as discussed in Ref. 1.) Furthermore, the $^{24}$Mg($d$, $\gamma$) results assigned the ($\lambda\nu$)? $(40)$ assignment. Since the other possiblities, ($\lambda\nu$)? $(10,2)$, has little strength (none in the pure symmetry limit, since $(01)\times(10,2)$ from the $J^{\pi}$=$\frac{1}{2}^+$ ground state of $^{24}$Mg $(\nu\sigma)$? $(60)$, as determined in Ref. 10), that level is presumably dominated by the $(10,2)$ configuration.

Predicted strengths are, in general, sensitive to symmetry admixtures in the target and final nuclear states. For $^{24}$Mg($He$, $p$) $\gamma$, however, the effect of such admixtures is expected to be small. The spin-isospin values associated with the leading symmetries of the target ($^{24}$Mg) $(\lambda\nu)$? $(44)$ $(\nu\sigma)$? $(44)$ $(\lambda\nu\sigma)$? $(47)$ $(\nu\sigma)$? $(00)$, together with the $(\nu\sigma)$? $(01)$ character of the transferred pair of protons, allow only the large dominant component in the $^{24}$Mg ground state to couple with the large dominant component in the final states of $^{36}$Si, and small components to couple

![Graph 1](image1)

**FIG. 1.** Spectrum for the $^{24}$Mg($He$, $p$) $\gamma$ reaction at $E_{He}$ = 5.0 keV. Neutron groups are labeled to correspond to the excitation energies of the $^{24}$Mg residual nuclear states. The time calibration is 0.4 nsec per channel.

![Graph 2](image2)

**FIG. 2.** Differential cross section for several $^{36}$Si states populated in the $^{24}$Mg($He$, $p$) $\gamma$ reaction. For the raw measured groups, the dashed curves are DWBA representations of the separate states; the solid curves are their sum.
TABLE I. Experimental and theoretical strengths of reactions populating \( ^{24} \)Mg levels.

<table>
<thead>
<tr>
<th>( E_x ) (MeV)</th>
<th>( J^\pi )</th>
<th>( g_{\pi} )</th>
<th>( g_{\nu} )</th>
<th>( g_{\pi,\nu} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>0^+</td>
<td>0.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>1.18</td>
<td>2^+</td>
<td>0.18</td>
<td>0.16</td>
<td>0.21</td>
</tr>
<tr>
<td>4.09</td>
<td>1^+</td>
<td>0.04</td>
<td>0.17</td>
<td>0.10</td>
</tr>
<tr>
<td>4.96</td>
<td>0^+</td>
<td>0.30</td>
<td>0.25</td>
<td>0.30</td>
</tr>
<tr>
<td>5.49</td>
<td>0^+</td>
<td>0.15</td>
<td>0.20</td>
<td>1.00</td>
</tr>
<tr>
<td>6.66</td>
<td>3^+</td>
<td>2.14</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>9.16</td>
<td>0^+</td>
<td>0.00</td>
<td>0.94</td>
<td>0.04</td>
</tr>
</tbody>
</table>

only with small components. Connections between large and small components are forbidden in low- \( L \) order. The effects of symmetry admixtures enter therefore as products of small numbers. In addition, the (48) = (0,12) transfer estimates 32% of the total \( \Sigma \omega (L) = (0,12) \) summed strength. \( 2^+ \)

These observations lend credibility to the pure \( \omega \) limit, particularly for the strong \( 2^+ \) to \( 0^+ \) and \( 1^+ \) to \( 0^+ \) transfers. It is to be emphasized that the \( ^{12} \)Mg(\( \pi \),\( \pi \)) \( ^{12} \)Mg process is unique in this selectivity.

Transfer strengths for \( ^{12} \)Mg on other targets, be they good \( \omega \), nuclei or not, will in general be more sensitive to \( \omega \) asymmetry admixtures, as large to small connections are not ruled out and the normal-state strength is not so fully concentrated in a single \( \omega \) channel.

IV. COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS

From Table I it can be seen that the observed relative \( \Gamma(\pi,\pi) \) \( 0^+ \) (MeV) to \( 2^+ \) (1.76 MeV) transition strength is weak both experimentally (0.15) and theoretically (0.13). Although the agreement between theory and experiment is not as good for the \( 4.08 \) MeV state, the theoretical prediction of a weak two proton transfer to it is confirmed experimentally.

The leading spatial symmetry \( (J^\pi = (44)) \) for \( \omega \) has two additional \( 0^+ \) states from the fundamental \( \omega \) symmetries (12, 0) and (06). However, two proton transfer from the \( (10,0) \) to \( ^{12} \)Mg to the \( (12,0) \) is prohibited and the \( (06,0) \) transfer is down in strength from the \( (44,0) \) by a factor of 20. Although the observed strength to the \( 0^+ \) (4.69 MeV) level exceeds these pure symmetry limits, the weakness of the transition to that state supports its identification as predominantly (06) or (12, 0). The configuration of the \( 0^+ \) (4.69 MeV) level is probably quite complicated, as is discussed below.

The qualitative disagreement between theory and experiment is probably caused by admixtures which become significant when the dominant configurations do not support strong two-proton transfer. Mixing within the \( (J^\pi = (44)) \) symmetry class is probably not the explanation since, as mentioned above, two-body interactions allowed non-direct couplings between the \( \omega \) of \( (\pi,\nu) \) representations. Contributions from \( \omega \) 's in other symmetry classes could account for the observed \( \omega \) strength, but this too seems unlikely since the \( (44,0) \) (\( \pi,\nu \)) admixed configuration completely dominates the \( \omega \) -orb picture. A more likely alternative is the influence of particle-hole admixed configurations.

The influence of such admixtures is seen most prominently in the \( 0^+ \) (4.69 MeV) level. In \( (\pi,\nu) \) scattering \( \omega \) on \( ^{12} \)Mg this level to levels \( 0^+ \) to \( 10^+ \) times more strongly than the \( 0^+ \) level at 6.69 MeV. Since all transitions within a major oscillator shell are forbidden, particle-hole admixed configurations must play a significant role. Indeed this explains the failure of the no-model \( \omega \) as well as its importance in non-\( \omega \) scattering.uck calculations \( \omega \), to account for the structure of the \( 4.69 \) MeV level. If a pure \( \omega \) configuration is assumed for the ground state of \( ^{12} \)Mg, a consistent picture requires the \( 0^+ \) level at 0.66 MeV to contain appreciable \( \omega \) admixtures; to give the strong \( \omega \) (\( \pi,\nu \)) results which are accessible via a 2-particle transfer \( \omega \) (3^+), for the strong \( \omega \) (\( 0^+ \) transition), but which are not accessible via 2-proton transfer \( \omega \) (3^+) for the weak \( \omega \) (\( 4^+ \) transition). In contrast to this, the \( 0^+ \) (4.69 MeV) level is well described by components of the (\( 0^+ \) to \( 0^+ \) transition) and \( \pi \) admixture which yields essentially zero \( \omega \) strength.

It should be noted that compound nuclear contributions could be significant at the energy at which the present experiment was performed. The work of Green et al. \( \omega \) used a similar energy to the compound system of a similar nucleus \( \pi \) versus \( \omega \). The work in the present paper gives some feeling for the level of this contribution. None of the cross sections which they interpret as being due to compound nuclear effects exceeds about \( 10 \) \( \omega \)-sr. Furthermore the DWBA representation of the experimental cross section (\( \pi,\nu \)) cross section to the \( 1^+ \) level at 1.76 MeV suggests that compound nuclear contributions could not be made above that amount. Absorption of such contributions at a level at \( \pi \) of \( 10 \) \( \omega \)-sr would have a pronounced effect only on the experimentally determined strength of the \( 4^+ \) level at 4.64 MeV. Subtraction of about that amount from the cross section in that level would reduce that strength by about a factor of 2, which would bring theory and experiment into better agreement.
V. SUMMARY

Comparison of the results of the $^7$Li($^4$He, $n$), the $^7$Li($e$, $e'$), and the $^7$Li($^4$He, $d$) experiments and the SH predictions for three yields a consistent picture for the $^8$Si levels studied. The SH configurations predicted to be the dominant case for several of these levels give the correct qualitative description of the two proton and a transfer reactions. This comparison also suggests, for the Si$^8$ level at 5.68 MeV, a complex structure having quite specific properties with respect to the ($e$, $e'$), ($^4$He, $n$), and ($^4$He, $d$) reactions.

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**Calculations were performed with code CODEC, F. D. Evans, Univ. of Colorado Report, 1969 (unpublished).