Comparison of alpha spectroscopic factors on $^{24,26}$Mg: The $(^{14}$N, $^{10}$B) reaction

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Cross sections for states populated in the $^{24,26}$Mg$^{(14}$N, $^{10}$B)$^{28}$Si and $^{26}$Mg$^{(14}$N, $^{10}$B)$^{30}$Si reactions at 83 MeV were measured. Equal strengths for population of $^{28}$Si and $^{30}$Si ground states were observed, in contrast to $(^{16}$O, $^{12}$C) and $(^{12}$C, $^9$Be) reactions, but in agreement with $(^{6}$Li, d) results and with theoretical predictions.

**NUCLEAR REACTIONS**

$^{24}$Mg $(^{14}$N,$^{10}$B), $^{26}$Mg $(^{14}$N,$^{10}$B), $E = 83$ MeV;

measured $\sigma(\theta)$.

I. INTRODUCTION

Several measurements of alpha-spectroscopic factors between the ground states of $^{24}$Mg-$^{28}$Si and $^{26}$Mg-$^{30}$Si have been carried out in the past few years with widely varying results. Measurements of the ratio of spectroscopic factors via the $(\alpha,2\alpha)$ reactions are in good agreement with shell model predictions, but in poor agreement with $(^{12}$C, $^{8}$Be) (Ref. 3) and $(^{16}$O, $^{12}$C) (Ref. 4) reactions. Unpublished results for $^{26}$Mg$(^6$Li,d)$^{30}$Si at $E_{\text{Li}} = 36$ MeV observe the ground state spectroscopic factor (and peak cross section) to be nearly equal to that from the $^{26}$Mg$(^6$Li,d)$^{28}$Si reaction at the same incident energy — a result which is in good agreement with the shell model predictions. In order to try to pin down this discrepancy and, in particular, to look for substantive problems in the description of the different reactions as one-step direct alpha transfer, we have investigated the relative ground-state yields to $^{28}$Si and $^{30}$Si via the $(^{14}$N,$^{10}$B) reaction on $^{24,26}$Mg. The $^{26}$Mg$(^{14}$N,$^{10}$B)$^{30}$Si reaction has been shown to be adequately described by distorted wave Born approximation (DWBA) calculations at 70 MeV, giving an indication that the reaction mechanism is direct. An earlier study of the relative ground state yields for the two reactions at 70 MeV proved inconclusive due to insufficient statistics.

II. EXPERIMENTAL PROCEDURE AND RESULTS

Beam currents of up to 1.5 $\mu$A of 83 MeV $^{14}$N were obtained from the Texas A&M 88 inch cyclotron and were used to bombard $\sim 100 \mu$g/cm$^2$ targets of isotopically enriched (>$99\%$) $^{24}$Mg and $^{26}$Mg on thin carbon backings. Reaction products were observed in the focal plane of an Enge split-pole spectrograph using a 1.2 m detector with mass and charge identification derived from energy loss information and particle rigidity. Transfer reaction cross sections were measured at 8°, 9°, and 10°. The $(^{12}$C,$^{14}$N,$^{10}$B)$^{16}$O reaction was used for calibration. The backing on the Mg targets provided reference peaks since the cross sections are a factor of 10 larger than for either Mg isotope. Unfortunately, the mass resolution was insufficient to completely resolve $^{10}$B from $^{11}$B. This did not prove a problem with the $^{24}$Mg target, where the $^{11}$B yields were less than half those for $^{10}$B. However, this introduced large backgounds with the $^{26}$Mg target which produced $^{11}$B's at a rate ten times that of the $^{10}$B's. The large leak-through of $^{11}$B's resulted in considerable uncertainty in yields for the $^{26}$Mg target and prohibited extraction of yields for $^{30}$Si excited states.

Relative cross sections were obtained by using the dead time corrected charge integration. Repeated runs showed a reproducibility of better than 3%. The products of target thickness and solid angle needed for calculating absolute cross sections were obtained by measuring elastic scattering cross sections and simultaneously fitting the normalization and the optical model parameters with the code ECIS. Different parameter sets were compared to establish the uncertainties of the procedure. The overall normalization is estimated to have an uncer-
tainty of ±40%, although the uncertainty in the cross section for 28Si relative to 30Si is 25%, since possible errors in the optical model normalization largely cancel.

Levels in 28Si were observed up to an excitation energy of ~12 MeV. However, the simultaneous population of 10B levels and 28Si levels and the many levels populated in 16O allowed extraction of yields for only the 28Si 2+ level at 1.78 MeV and the 10B 1+ (0.72 MeV) built on the 28Si 2+ level.

The cross sections for 24,26Mg(14N,10B)28,30Si ground state transitions are shown on the left hand side of Fig. 1, and the cross sections for the 1.78 (2+) and the 28Si(2+)-10B(1+) levels are to the right. Error bars represent uncertainties arising from background subtraction, statistics, and charge integration. The absolute cross sections for the 26Mg(14N,10B) transitions are consistent with the excitation function systematics of Ref. 7.

III. DISCUSSION

Table I lists the ratios of cross sections (or ratios of spectroscopic factors) for several reaction systems on 24,26Mg, together with the present data. Since there is little difference in the Q values or angular momentum matching between the reactions on 24Mg and 26Mg, the dynamics of the two reactions should be the same if they are direct; thus ratios of cross sections should correspond to ratios of spectroscopic factors. It is seen that only the (6Li,d) and the (14N,10B) reactions have ratios as predicted by theory¹ and consistent with the (α,2α) work.² Recent 28Si(p,pa)32Mg work supports both the (α,2α) and (6Li,d) work on 24Mg. The (12C,3Be) and (18O,12C) reactions seem to be the only ones in disagreement. One possible explanation is very different angular momentum mismatches inhibiting the reactions. Table I, however, shows there is no correlation between mismatch and ratios of cross sections, although the (6Li,d) and (14N,10B) reactions are more mismatched than the other channels.

We thus find the (α,2α), (p,pa), (6Li,d), and (14N,10B) data to be consistent with each other and with theory. The (12C,3Be) and (18O,12C) are in disagreement with everything else. We are left with a choice between two possibilities: (1) the first four reactions are direct and the last two are not, and (2) none of the reactions are predominantly direct. The latter choice is somewhat implausible based simply on the agreement of the results for the four reactions. However, a careful examination of the evidence for or against the reactions being direct is needed. Such an examination for the four heavy ion studies follows.

At 70 MeV reasonable DWBA fits to the 26Mg(14N,10B)30Si angular distributions were obtained,⁷ while compound nucleus, Hauser-Feshbach (HF) calculations underpredicted the forward angle between

TABLE I. Cross section ratios for 24,26Mg reactions.

<table>
<thead>
<tr>
<th>Reactions</th>
<th>E&lt;sub&gt;lab&lt;/sub&gt; (MeV)</th>
<th>dσ/dΩ&lt;sub&gt;26Mg&lt;/sub&gt;</th>
<th>dσ/dΩ&lt;sub&gt;24Mg&lt;/sub&gt;</th>
<th>Δl</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>18O,12C</td>
<td>42</td>
<td>0.029</td>
<td>0.229</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>12C,3Be</td>
<td>50</td>
<td>&lt;0.02&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.02</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>6Li,d</td>
<td>65</td>
<td>&lt;0.1&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>14N,10B</td>
<td>83</td>
<td>1.0±0.3</td>
<td>1.0±0.3</td>
<td>5, 6</td>
<td></td>
</tr>
<tr>
<td>Theory&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
<td>0.88±0.31</td>
<td>0.88±0.31</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>The authors of Ref. 3 report that the ground state of 30Si was not observed at any energy or angle. The 50 MeV ratio is that of the strongest state observed. The 65 MeV 30Si state is the lowest cross section observed (assumed upper limit).

<sup>b</sup>Ratio of spectroscopic factors.
cross sections by two orders of magnitude. Semi-
classical analysis of the \(^{16}\)O\(^{14}\)N,\(^{10}\)B\(^{20}\)Ne reaction at
155 MeV also presents evidence for a direct
mechanism.\(^{14}\) Only in the \(^{12}\)O\(^{14}\)N,\(^{10}\)B\(^{16}\)O reaction at
53 MeV were good fits obtained with HF calcula-
tions.\(^{10}\) The presence of many \(^{10}\)B excited states
from both the Mg targets and the \(^{12}\)C backing
prevented identification of \(T=1\) states, the pre-

cence of which would be indicative of multistep
processes.

There is considerable evidence that the \((^{6}\text{Li},d)\)
re-
action proceeds by single step transfer on many nu-
clii in the mass range \(20\text{–}40\).\(^{5,15}\) Only in the
\(^{16}\)O\(^{6}\text{Li},d\(^{20}\)Ne reactions is there some evidence for
compound nuclear and multistep processes. At 32
MeV, HF calculations for the ground state transition
are 20 times too small at forward angles, but
are in good agreement at backward angles, although
the complete angular distribution is very poorly
described\(^{16}\) by the HF calculations. Multistep calcu-
lations produced only marginally better fits to the
data than the DWBA.\(^{17}\) Only at 20 MeV were the
HF calculated strengths at forward angles below the
experimental points by a factor of 4.\(^{18}\)

Good DWBA fits have been observed for the
\((^{12}\text{C},^{8}\text{Be})\) reactions on \(^{24}\)Mg at 50 MeV,\(^{3}\) on
\(^{40}\)Ca at
45 MeV,\(^{19}\) and on \(^{28}\)Si at 42 MeV.\(^{20}\) Additionally,
the excitation function for the \(^{28}\)Si\(^{(12}\text{C},^{8}\text{Be})^{12}\)S
ground state transition does not exhibit any reso-
nancelike structure in the range \(23 \leq E_{\text{c.m.}} \leq 29\)
MeV.\(^{20}\) Therefore, there is evidence that \(^{(12}\text{C},^{8}\text{Be})\)
is direct, with no data to the contrary. At 56 MeV the
\(^{24}\text{Mg}^{(16}\text{O},^{12}\text{C})^{28}\text{Si}\) reaction is well
described by the DWBA calculations.\(^{21}\) In the
energy range \(40 \leq E_{\text{lab}} \leq 80\) MeV many successful
DWBA and Legendre polynomial fits have been
made.\(^{22,23}\) However, it is well known that the
\(^{24}\text{Mg}^{(16}\text{O},^{12}\text{C})^{28}\text{Si}\) shows strong resonance features\(^{22}\)
over this 40 MeV bombarding energy range. It is
possible that some enhancement of the cross section

from the \(^{24}\)Mg target compared to \(^{26}\)Mg has oc-
curred because of this resonance behavior, thereby
invalidating any comparison of spectroscopic fac-
tors for \(^{(16}\text{O},^{12}\text{C})\) on Mg isotopes. In a study of
\(^{(16}\text{O},^{12}\text{C})\) on \(^{28}\)Si, Berg et al.\(^{24}\) observed that the re-
action does not populate a \(T=1\) state which is not
accessible \textit{via} a direct \textquotedblleft alpha-cluster\textquotedblright; transfer, indicat-
ing the reaction is direct.

It would seem that there is considerable evidence
that all the heavy ion \(\alpha\)-transfer reactions discussed
are essentially single step processes on at least some
\(sd\)-shell nuclei and that evidence for competing
mechanisms is scarce, with the exception of the
\(^{24}\text{Mg}^{(16}\text{O},^{12}\text{C})^{28}\text{Si}\) reaction. However, the cross sec-
tions for \(^{(12}\text{C},^{8}\text{Be})\) and \(^{(16}\text{O},^{12}\text{C})\) on \(^{26}\)Mg are small,
on the order of \(1\text{–}10\) \(\mu\text{b/sr}\), and represent the ma-

jor inconsistency between the other reactions and
between the theory. With such small cross sections
the possibility of reaction mechanisms contributing
differently to each reaction is more likely and
makes a detailed comparison between these chan-
dles difficult. The agreement of the \(^{(14}\text{N},^{10}\text{B})\) and
\((^{6}\text{Li},d)\) results with light ion work suggests that
these channels proceed \textit{via} a single step mechanism
and that \(^{(16}\text{O},^{12}\text{C})\) and \(^{(12}\text{C},^{8}\text{Be})\) reactions have
contributions from other mechanisms, at least on the
Mg isotopes.

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