We have measured inclusive data for mass, kinetic energy and angular distributions from the $^4\text{He} + ^{28}\text{Si}$ reaction at 117.4 and 198.5 MeV, or $E/A = 29$ and $50$ MeV/nucleon. An understanding of such intermediate-energy light-ion interactions is important to studies of cosmic-ray related phenomena associated with space-radiation effects and nuclear astrophysics.

Cosmic-ray nuclei represent an important source of bit upset generation in microelectronic devices. An essential ingredient for any attempt to account for these radiation-induced errors is the availability of reliable doubly differential cross-section information, $d^2\sigma/d\Omega dE$, for cosmic-ray-induced reactions in the material of interest, primarily silicon and oxygen. Of particular concern in evaluating radiation effects is the possibility that energetic heavy recoil fragments may enhance the magnitude of radiation effects due to their high ionization density, proportional to $AZ^2$ of the fragment. The large excess of energetic heavy fragments at forward angles (relative to theoretical predictions) observed in these studies, as well as for the $p + ^{27}\text{Al}$ system,$^1$ indicate that heavy recoils may be a significant contributor to error generation in silicon chips exposed to cosmic-ray fluxes.

Three problems of astrophysical interest are also addressed by these data. The first relates to the origin of galactic cosmic rays (GCR). Measurements$^2$ of the isotopic composition of galactic cosmic rays reveal a significant enrichment of neutron-excess Ne and Mg isotopes relative to their interstellar medium (ISM) ratios. This observation suggests that GCR propagation may be associated with an $r$-process-like environment. However, in order to test such theories, it is essential to understand the modification to the primary source flux due to nuclear reactions which occur during transport through the interstellar medium. Corrections for these processes depend on an accurate knowledge of cross sections for reactions between heavy cosmic-ray primaries (such as $^{28}\text{Si}$) with hydrogen and helium (the dominant components of the interstellar medium).

In Table I isotopic ratios for the stable Ne and Mg isotopes are compared with the cross-section ratios for these data and for the 180-MeV $p + ^{27}\text{Al}$ reaction.$^1$ The data demonstrate that in these spallation processes, mass numbers $A = 24 - 26$ (Mg isotopes on a cosmic-ray time scale, except for $^{26}\text{Al}$) and $A = 20 - 22$ (Ne isotopes) are populated with roughly equal probability. Thus one would expect enrichment of neutron-excess species relative to solar system abundances in the spectrum of neon and magnesium isotopes formed in the spallation of Si primaries in the cosmic-ray flux. Similarly, for mass numbers
A = 16 – 18 (oxygen) enhanced production is observed for the neutron-excess isotopes; however, at this level contributions from the spallation of $^{20}\text{Ne}$ and $^{24}\text{Mg}$ primaries also becomes important. Thus, the observation of enriched ratios for neutron excess isotopes in the cosmic-ray flux relative to solar system material is at least in part a consequence of spallation reactions experienced by any primary flux in passing through the interstellar medium. Quantitative evidence for anomalies in the cosmic-ray isotopic composition can only be understood after correction for these spallative processes.

A second similar application of these data relates to the abundances of secondary nuclei produced in meteorites by GCR-induced spallation reactions during the meteorite lifetime. These measured cross sections, in conjunction with isotope ratios observed for a given meteorite, can be used to infer information on its exposure geometry and the history of GCR fluxes.

A third astrophysical problem of related interest is the nucleosynthesis of the elements lithium, beryllium, and boron (LiBeB). The abundances of the nuclides $^6\text{Li}$, $^9\text{Be}$, $^{10}\text{B}$, and $^{11}\text{B}$ can be understood as primarily due to reactions of galactic-cosmic-ray H and He with He and CNO nuclei in the interstellar medium ($\text{CNO} = \text{carbon, nitrogen, and oxygen}$). One open question concerning this model is the possible contribution of heavier target species in the interstellar medium (e.g., Ne, Mg, and Si spallation) to the production of LiBeB. Since the relative abundances of these target-source elements are smaller than for CNO ($C/N/O/Ne/Mg/Si = 0.61/0.13/1.00/0.14/0.06/0.06$), the heavier species can only be important if the formation cross sections for LiBeB are significantly higher than for CNO. The cross-section results for LiBeB listed in Table I are slightly lower for Si than for CNO targets at these energies. This suggests that the high energy cross sections for $^{20}\text{Ne}$ and $^{24}\text{Mg}$, the other two major contributors to GCR synthesis of LiBeB, are comparable. Inclusion of these $^4\text{He}+^{28}\text{Si}$ results and those of Ref. 1 into the GCR calculations of Walker, et al., serves to increase the absolute production rates of $^6,^7\text{Li}$, $^7\text{Be}$, and $^{10,11}\text{B}$ by about 2-4% and to have little effect on the isotope ratios. Thus, the contribution of species heavier than CNO to the LiBeB formation in galactic cosmic-ray interactions with the interstellar medium appears to be small and does not significantly perturb the existing scenario for LiBeB nucleosynthesis.

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**TABLE I.**

Isotope number ratios of neon and magnesium isotopes in ISM and GCR\(^2\) compared with cross section ratios for corresponding mass numbers in the p+\(^{27}\)Al reaction\(^1\) and these data.

<table>
<thead>
<tr>
<th></th>
<th>(^{20})Ne : (^{21})Ne : (^{22})Ne</th>
<th>(^{24})Mg : (^{25})Mg : (^{26})Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISM</td>
<td>1.0 : 0.024 : 0.073</td>
<td>1.0 : 0.13 : 0.14</td>
</tr>
<tr>
<td>GCR</td>
<td>1.0 : 0.25 : 0.67</td>
<td>1.0 : 0.28 : 0.30</td>
</tr>
<tr>
<td>180 MeV p + (^{27})Al</td>
<td>1.0 : 1.12 : 1.03</td>
<td>1.0 : 1.13 : 1.40</td>
</tr>
<tr>
<td>198.5 MeV (^4)He + (^{28})Si</td>
<td>1.0 : 0.55 : 1.50</td>
<td>1.0 : 0.94 : 0.85</td>
</tr>
</tbody>
</table>