ISOTOPIC FRACTIONATION OF SILICON IN ALLENDE INCLUSIONS.
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Epstein and Yeh (1977) measured the isotopic abundances of silicon in several meteorites, and in inclusions and separated minerals from the Allende meteorite, and made the following observations:

1. The variation in \( \delta^{30}\text{Si} \) in the ordinary chondrites is small, ranging from 0 to -15.0 relative to the Rose Quartz standard.

2. The variation in \( \delta^{30}\text{Si} \) in the Allende samples was much larger, ranging from -1.6\% to +2.6\%. The relationship between \( \delta^{29}\text{Si} \) and \( \delta^{30}\text{Si} \) was consistent with a mass-dependent fractionation process, and no nuclear effects were evident.

3. There was no obvious relationship between the \( \delta^{30}\text{Si} \) values and the \( \delta^{18}\text{O} \) values of the same materials.

In the present work, silicon isotope analyses were made of three differentiated meteorites: Nakhla (rakhlite), Eagle Station (an unusual pallasite), and Weekeroo Station (type II E iron). Six Allende inclusions were also measured: one fine-grained Ca-Al-rich inclusion and five coarse-grained type A and type B inclusions. All of the Allende samples have large \( 16\text{O} \) excesses. In addition, one of the type B inclusions was sample C1, which had previously been shown to have isotopic compositions for oxygen (Clayton and Mayeda, 1977) and magnesium (Wasserburg et al., 1977) which are exceptional, even for Allende inclusions. The mass spectrometric analyses were done on SiF\(_4\) samples which were by-products of the BrF\(_5\) reactions used to produce \( \text{O}_2 \) for oxygen isotope analysis. The \( \delta^{28}\text{Si} \) and \( \delta^{29}\text{Si} \) data are given in Table 1 and are plotted in Figs. 1 and 2.

The natural terrestrial samples show very small departures from the pegmatite quartz standard. The tank SiF\(_4\) sample has been substantially fractionated isotopically, presumably during some stage of its industrial synthesis and purification. It shows clearly the expected 2:1 relationship between the \( \delta^{32}\text{Si}/\delta^{30}\text{Si} \) fractionation and the \( \delta^{28}\text{Si}/\delta^{30}\text{Si} \) fractionation.

The three differentiated meteorites have isotopic compositions indistinguishable from the terrestrial standard. It appears that these three differentiated meteorites have \( \delta^{30}\text{Si} \) values identical with terrestrial igneous rocks and slightly greater (by about 0.5\%) than ordinary chondrites (Epstein and Yeh, 1977). This point is discussed further by Epstein and Yeh (1978).

The "normal" silicon isotopic composition of Eagle Station is especially noteworthy, since this unusual pallasite has a large \( 16\text{O} \) excess (Clayton et al., 1976). There is no evidence of a nuclear isotope anomaly in silicon in the Eagle Station olivine. Rees and Thode (1977) found no evidence for a nuclear anomaly in sulfur in Eagle Station sulfides.

Five of the Allende inclusions exhibit the same pattern observed by Epstein and Yeh (1977): an apparent mass-fractionation array extending to both positive and negative \( \delta \)-values. Nuclear anomalies, if present, must be very small. However, the isotopic variations due to mass-fractionation may be useful in determining the origins of the inclusions. In the samples reported here, all of the coarse-grained inclusions, both type A and type B, have positive \( \delta \)-values. The single fine-grained inclusion has a negative value.
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It is not clear whether this same distinction is true for the samples of Epstein and Yeh (1977), but there is a suggestion that it may be, since most of their samples with negative δ-values have small oxygen anomalies, and are thus unlike the type B coarse-grained inclusions (Clayton et al., 1977).

It is very interesting that the materials believed to form at high temperatures in the solar nebula (Grossman, 1972) exhibit a much larger range of isotopic composition than the ordinary chondrites. If the Allende inclusions formed by condensation from the vapor, the silicon isotopic compositions should be controlled by the fractionation between gaseous SiO and the condensing silicates. An estimate of the magnitude of this fractionation factor can be made from the vibrational frequencies of the SiO molecule (Herzberg, 1950) and of the SiO⁻ ions in crystals (Piques-Ledent and Tarte, 1973). Lower limits for the $^{28}\text{Si}/^{30}\text{Si}$ fractionation are 1.7% at 1500K and 2.7% at 1200K, with $^{30}\text{Si}$ enriched in the solid phases. (Fractionation between various silicates is negligible at these temperatures (Epstein and Taylor, 1971; Epstein and Yeh, 1977)). Thus the observed $^{30}\text{Si}$-enrichments in the coarse-grained inclusions are consistent with their formation as condensates from a nebular gas with $\delta^{30}\text{Si} \approx 0\%$. If the fine-grained inclusions are also nebular condensates (Grossman and Ganapathy, 1976), they must have formed from a gas depleted in $^{30}\text{Si}$ by at least 4-5%, presumably by prior condensation of the coarse-grained inclusions. This scenario has been advanced previously to account for the fractionated rare-earth patterns in fine-grained inclusions (Boynton, 1975; Grossman and Ganapathy, 1976).

Allende inclusion Cl exhibits a ten-fold larger heavy-isotope enrichment than the other coarse-grained inclusions. This is apparently a large mass-fractionation effect. Its magnitude of 12%/mass unit is comparable to the 15%/mass unit for oxygen (Clayton and Mayeda, 1977) and 30%/mass unit for magnesium (Wasserburg et al., 1977) on the same sample. Mass-fractionation of calcium isotopes in this inclusion is very much smaller (0.3%/mass unit) (Lee et al., 1978). Apparently oxygen, magnesium and silicon in this inclusion have undergone some very extensive mass-fractionation, probably in the vapor phase, whereas the calcium, being more refractory, was predominantly in solid phases and avoided fractionation. Besides having large mass-fractionation effects for several elements, inclusion Cl also has nuclear isotopic anomalies in O (Clayton and Mayeda (1977), Mg, Ca (Lee et al., 1978) and Ba (McCulloch and Wasserburg, 1978). In Fig. 2, the data point for silicon in Cl lies slightly above the mass-fractionation line, suggesting the possibility of a small excess of $^{28}\text{Si}$ (or deficiency of $^{29}\text{Si}$ or $^{30}\text{Si}$).

REFERENCES
S. Epstein and H.W. Yeh (1978) Lunar Science IX.

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Table 1

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>$\delta^{30}$Si (%)</th>
<th>$\delta^{29}$Si (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reagent SiF$_3$ (Matheson)</td>
<td>+1.8</td>
<td>+0.9</td>
</tr>
<tr>
<td>Icelandic basalt (L22)</td>
<td>-0.1</td>
<td>+0.1</td>
</tr>
<tr>
<td>Lake Magadi Chert</td>
<td>+0.3</td>
<td>+0.1</td>
</tr>
<tr>
<td>Nakhla diopside</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Weekeroo Station plagioclase</td>
<td>0.0</td>
<td>-0.1</td>
</tr>
<tr>
<td>Weekeroo Station augite</td>
<td>0.0</td>
<td>-0.1</td>
</tr>
<tr>
<td>Eagle Station olivine</td>
<td>-0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Allende samples:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1 7 (type A, whole rock)</td>
<td>+2.5</td>
<td>+1.2</td>
</tr>
<tr>
<td>A1 13 (type B, whole rock)</td>
<td>+2.9</td>
<td>+1.3</td>
</tr>
<tr>
<td>A1 15 (type B, whole rock)</td>
<td>+1.7</td>
<td>+0.8</td>
</tr>
<tr>
<td>A1 3 54 (type B, pyroxene)</td>
<td>+1.8</td>
<td>+0.9</td>
</tr>
<tr>
<td>A1 NO 8-11 (pink, fine-grained)</td>
<td>-0.6</td>
<td>-0.3</td>
</tr>
<tr>
<td>CIS2 (type B, whole-rock)</td>
<td>+23.4</td>
<td>+12.5</td>
</tr>
</tbody>
</table>

Fig. 1. $\delta^{30}$Si vs. $\delta^{29}$Si for terrestrial and meteoritic samples. Line is a mass-fractionation reference line through the origin.

Fig. 2. Expanded $\delta^{30}$Si vs. $\delta^{29}$Si plot to show position of the highly fractionated sample, Cl. Same reference line as Fig. 1.