Short-lived chlorine-36 in a Ca- and Al-rich inclusion from the Ningqiang carbonaceous chondrite

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Excesses of sulfur-36 in sodalite, a chlorine-rich mineral, in a calcium- and aluminum-rich inclusion from the Ningqiang carbonaceous chondrite linearly correlate with chlorine/sulfur ratios, providing direct evidence for the presence of short-lived chlorine-36 (with a half-life of 0.3 million years) in the early solar system. The best inferred (36Cl/35Cl)0 ratios of the sodalite are ~5 × 10^{-6}. Different from other short-lived radionuclides, chlorine-36 was introduced into the inclusion by solid-gas reaction during secondary alteration. The alteration reaction probably took place at least 1.5 million years after the first formation of the inclusion, based on the correlated study of the 26Al-26Mg system of the relict primary minerals and the alteration assemblages, from which we inferred an initial ratio of (36Cl/35Cl)0 = ∼1.6 × 10^-4 at the time when calcium- and aluminum-rich inclusions formed. This discovery supports a supernova origin of short-lived nuclides [Cameron, A. G. W., Hoeflich, P., Myers, P. C. & Clayton, D. D. (1995) Astrophys. J. 447, L53; Wasserburg, G. J., Gallino, R. & Busso, M. (1998) Astrophys. J. 500, L189–L193], but presents a serious challenge for local irradiation models [Shu, F. H., Shang, H., Glassgold, A. E. & Lee, T. (1997) Science 277, 1475–1479; Gounelle, M., Shu, F. H., Shang, H., Glassgold, A. E., Rehm, K. E. & Lee, T. (2001) Astrophys. J. 548, 1051–1070]. Furthermore, the short-lived 36Cl may serve as a unique fine-scale chronometer for volatile-rock interaction in the early solar system because of its close association with aqueous and/or anhydrous alteration processes.

Short-lived, now extinct, radionuclides have been detected in primitive meteorites (1). They have been intensively studied and are still subjects of ongoing great interest for broad scientific audiences, because short-lived radionuclides may serve as the only available fine-scale chronometers to trace processes in the early solar system (1, 2), and their relative abundance can constrain the local galactic environment of solar system formation (3–6). However, the origin of short-lived radionuclides is a long-standing issue. One scenario holds that the short-lived radionuclides originated in stellar sources like supernovae (3, 7) or asymptotic giant branch stars (5, 6) in close proximity to the forming solar system. According to such a stellar origin, short-lived radionuclides were injected homogeneously in the solar nebula, hence they may be used as chronometers. This idea is supported by the measurement of U-Pb absolute ages of Ca- and Al-rich inclusions (CAIs) and chondrules with a ~1-million year (My) resolution (8), which yields a time interval between formation of CAIs and chondrules similar to that inferred by many 26Al-26Mg measurements, although a recent study reported that chondrule formation began contemporaneously with the formation of CAIs (9). On the other hand, the same short-lived radionuclides may be produced locally by intense irradiation of nebular materials by the proto-sun (10–12). The predictions of local irradiation models (4, 13) are compatible with the observed abundance of some nuclides (e.g., 39Be, 26Al, 41Ca, and 53Mn). According to local irradiation models, the systematically different initial (26Al/27Al), ratios between CAIs and chondrules are related to their different distances from the proto-sun, bearing no temporal significance.

Chlorine-36 has a half-life of 0.3 My and decays to either 36Ar (98.1%, β−) or 36S (1.9%, e and β+) (14), hence it can be detected by measuring the excess of 36Ar or 36S. A previous study reported the excess of 36Ar in matrix of the Efremovka carbonaceous chondrite (15), which was attributed to the decay of short-lived 36Cl. In this study, we provide direct evidence for the existence of live 36Cl in primitive meteorites based on excess of 36S and its correlation with Cl/S ratios of the samples. The suitable samples for this purpose are sodalite (Na8Al6Si6O24Cl2) in CAIs, because this mineral is Cl-rich (~7.5 wt%) and CAIs are the oldest assemblages of the solar system (16, 17).

Methods

Because only 1.9% 36Cl decays to 36S, the excess 36S [(36S/34S)*] can be calculated in the following relationship:

\[ \frac{(36S/34S)_d}{(36S/34S)_s} = \frac{(36S/34S)_d - (36S/34S)_s}{(36S/34S)_s} = 0.019 \times \frac{(36Cl/35Cl)_0}{(36Cl/35Cl)_s}, \]

where (36S/34S)_m and (36S/34S)_s are the measured and initial (or normal) S isotopic ratios at the time of closure. The inferred (36Cl/35Cl)_s ratio can be calculated from Eq. 1.

In secondary ion MS analysis, (36S/34S)* in a sample is detected by measuring its S isotopes relative to standards. S isotopic data are reported as delta values, defined as:

\[ \Delta(3S) = \left( \frac{(3S/34S)_m}{(3S/34S)_s} - 1 \right) \times 1,000 \]

and

\[ \Delta(36S) = \left( \frac{(36S/34S)_m}{(36S/34S)_s} - 1 \right) \times 1,000, \]

where m indicates measured ratios and s indicates standard’s normal S isotope ratios. Because of its high abundance, 32S is not used here as the reference isotope. The fractionation-corrected isotopic anomaly in 36S is then calculated from the linear “law”:

\[ \delta(36S) = \Delta(36S) + 2 \Delta(33S). \]

Sulfur isotopes (33S, 34S, and 35S) and 35Cl of the samples were analyzed by using the Cameca ims-6f ion microprobe at Arizona State University. A small (<10 μm) Cs+ primary beam of <0.1 nA at 10 keV size was used. Secondary ions were accelerated to ~9 keV and collected with an electron multiplier, and dead-time correction was applied to the data. Transfer lenses were tuned for a 75-μm imaged field to increase the secondary ion transmission. Depending on the phase being analyzed, each measurement ran 30–200 cycles through the mass sequence, 33S, 34S, 35Cl, 36Cl.

Abbreviations: CAI, Ca- and Al-rich inclusion; My, million years.

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with integration times set to 3, 1, 1, and 30 s, respectively. Even with the instrumental conditions set up to allow the highest possible transmission of secondary ions, a long collecting time was still required to achieve reasonable statistical precision because of the low count rates of the S isotopes in sodalite. Hydride and other molecular interferences to the S isotopes were eliminated under high mass resolution conditions with a mass resolving power \( m/\Delta m \) of \( \approx 4,300 \). Relative to the sulfur isotope standard, Canyon Diablo troilite, troilite (FeS), and djerfisherite \([(K,Na)_{6}(Fe,Ni,Cu)_{25}S_{26}Cl]\) in the Qingzhen enstatite chondrite should have normal sulfur isotope composition within the precision of the ion microprobe. Therefore, they were used repeatedly as standards to check instrumental mass fractionation (IMF) and verify that no \(^{36}\text{S} \) anomaly exists in their measurements. For both standards and samples, IMF was internally corrected by using \(^{33}\text{S}/^{34}\text{S} \) according to the linear law. Because there are no suitable silicate standards, the relative sensitivity factor of \(^{35}\text{Cl}/^{34}\text{S} \) \( \approx 0.6 \) used throughout this study was determined from djerfisherite in Qingzhen. This may introduce a slight uncertainty in the slopes of the lines, but does not significantly affect the results.

Because sodalite is a secondary phase replacing primary minerals of CAIs during alteration processes, a combined study of \(^{26}\text{Al}/^{26}\text{Mg} \) systems of individual minerals of the CAI was carried out to determine the time interval between formation and alteration of the CAI. The measurements of magnesium isotopes were carried out by using the same ion microprobe with a \(-12.5 \) keV \( \text{O}^- \) primary beam of \(<0.4 \) nA for different mineral phases, including melilite (a solid solution of \( \text{Ca}_2\text{MgSi}_2\text{O}_7-\text{Ca}_2\text{Al}_2\text{Si}_3\text{O}_9 \)), plagioclase, and sodalite. Positive secondary ions were accelerated to \(+9 \) keV and collected with an energy band-pass of \( \approx 50 \) eV, an imaged field of \( \approx 75 \) \( \mu \text{m} \), and a mass resolving power of \( \approx 3,500 \). The relative sensitivity factors of \( \text{Al}/\text{Mg} \) were determined by using terrestrial standards of melilite and plagioclase.

Results

Three CAIs from the Ningqiang carbonaceous chondrite and two EH3 enstatite chondrites (EET 87746 and ALH 77295) were
Table 1. Sulfur isotopic compositions and Cl/S ratios

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$^{35}$Cl/$^{34}$S, ±2σ</th>
<th>$^{36}$S/$^{34}$S × 10$^3$, ±2σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sod-1a</td>
<td>2,905 ± 217</td>
<td>3.81 ± 0.38</td>
</tr>
<tr>
<td>Sod-1b</td>
<td>4,287 ± 210</td>
<td>4.09 ± 0.58</td>
</tr>
<tr>
<td>Sod-1c</td>
<td>7,031 ± 385</td>
<td>4.33 ± 0.60</td>
</tr>
<tr>
<td>Sod-1d</td>
<td>6,289 ± 435</td>
<td>4.48 ± 0.46</td>
</tr>
<tr>
<td>av. Tr-1</td>
<td>&lt;0.01</td>
<td>3.434 ± 0.003</td>
</tr>
<tr>
<td>av. Dj-1</td>
<td>0.75 ± 0.01</td>
<td>3.420 ± 0.002</td>
</tr>
<tr>
<td>Sod-2a</td>
<td>26,872 ± 2493</td>
<td>5.64 ± 1.15</td>
</tr>
<tr>
<td>Sod-2b</td>
<td>10,031 ± 1045</td>
<td>4.84 ± 1.00</td>
</tr>
<tr>
<td>Sod-2c</td>
<td>22,942 ± 1475</td>
<td>5.59 ± 0.98</td>
</tr>
<tr>
<td>Sod-2d</td>
<td>24,977 ± 1946</td>
<td>5.72 ± 0.94</td>
</tr>
<tr>
<td>Sod-2e</td>
<td>38,533 ± 3777</td>
<td>7.37 ± 1.19</td>
</tr>
<tr>
<td>Sod-2f</td>
<td>32,931 ± 2936</td>
<td>7.12 ± 1.54</td>
</tr>
<tr>
<td>av. Tr-2</td>
<td>&lt;0.01</td>
<td>3.436 ± 0.013</td>
</tr>
<tr>
<td>Sod-3a</td>
<td>10,141 ± 637</td>
<td>5.70 ± 0.94</td>
</tr>
<tr>
<td>Sod-3b</td>
<td>13,151 ± 800</td>
<td>6.17 ± 0.78</td>
</tr>
<tr>
<td>Sod-3c</td>
<td>7,924 ± 447</td>
<td>5.63 ± 0.85</td>
</tr>
<tr>
<td>Sod-3d</td>
<td>7,816 ± 332</td>
<td>6.11 ± 0.73</td>
</tr>
<tr>
<td>Sod-3e</td>
<td>9,142 ± 426</td>
<td>4.52 ± 0.73</td>
</tr>
<tr>
<td>Sod-3f</td>
<td>5,894 ± 372</td>
<td>3.93 ± 0.75</td>
</tr>
<tr>
<td>av. Tr-3</td>
<td>&lt;0.01</td>
<td>3.436 ± 0.002</td>
</tr>
<tr>
<td>A_sod-1a</td>
<td>18 ± 4</td>
<td>3.57 ± 0.09</td>
</tr>
<tr>
<td>Sod-3a</td>
<td>19,958 ± 1,198</td>
<td>6.33 ± 1.19</td>
</tr>
<tr>
<td>Sod-3b</td>
<td>36,306 ± 3,490</td>
<td>6.92 ± 1.29</td>
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<tr>
<td>Sod-3c</td>
<td>49,896 ± 2,506</td>
<td>7.36 ± 0.94</td>
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<tr>
<td>Sod-3d</td>
<td>57,486 ± 4,797</td>
<td>7.51 ± 1.59</td>
</tr>
<tr>
<td>Sod-3e</td>
<td>52,159 ± 4,215</td>
<td>8.34 ± 1.39</td>
</tr>
<tr>
<td>Sod-3f</td>
<td>44,581 ± 3,808</td>
<td>8.39 ± 1.67</td>
</tr>
<tr>
<td>av. Tr-3</td>
<td>&lt;0.01</td>
<td>3.431 ± 0.003</td>
</tr>
</tbody>
</table>

For all sodalite-rich alteration assemblages in the Ningqiang CAI mantle, the sulfur isotopic compositions are given as averages (av.).

Except for one analysis (A_sod-1a) of sodalite (Sod) in ALH 77295, others are in the Ningqiang CAI alteration assemblages as shown in Table 1. Studies of sodalite-rich alteration assemblages in the Ningqiang CAI show clear 26Mg excesses that linearly correlate with the $^{27}$Al/$^{24}$Mg values of the minerals (Fig. 3a), indicating in situ decay of $^{26}$Al.

The inferred (26Al/27Al)$_o$ ratio (±2σ) is (5.1 ± 1.4) × 10$^{-6}$, consistent with previous observations in the CAI alteration assemblages (18) and identical to the canonical (26Al/27Al)$_o$ value (5 × 10$^{-5}$) (19). However, neither anorthite nor the sodalite-rich assemblages in the CAI mantle show resolvable 26Mg excess, possibly because of the low 36S concentration of sodalite. The inferred (26Al/27Al)$_o$ ratio of the sodalite-rich assemblages is 0.7 × 10$^{-5}$ (Fig. 3b). Assuming the (26Al/27Al)$_o$ ratios of melilite and sodalite reflect a temporal difference, then sodalite formed ≥ 2 My after the formation of melilite.

Discussion

Because of the high Cl concentration of sodalite, 36Cl may be cosmonogenically produced by reaction of 33Cl(n,γ)36Cl during cosmic-ray exposure of the meteorite. However, the cosmonogenic 36Cl can be ignored according to the noble gas isotopic data. If there had been cosmonogenic 36Cl, we would have an excess of 36Ar from its decay. This excess would increase the 36Ar/39Ar ratio that is used to calculate cosmonogenic 36Ar concentration. An increase in 36Ar/39Ar ratio causes the cosmonogenic 36Ar to be too low if we use a trapped 36Ar/39Ar ratio of 5.32. That means the cosmic-ray exposure (CRE) age calculated from cosmonogenic 36Ar will be lower than that from 4He and 21Ne. However, this is not the case: the CRE ages of the Ningqiang meteorite based on 36Ar, 4He, and 21Ne are 43.5 ± 5.3, 43.4 ± 5.4, and 39.6 ± 4.0 My, respectively (20). Similarly, the estimated cosmonogenic 36Ar component decayed from the cosmonogenic 36Cl in the Efremovka matrix is also very low, <3% of the excess 36Ar from decay of short-lived 36Cl (15).

The inferred (36Cl/35Cl)$_o$ ratios of (5–11) × 10$^{-6}$ for the Ningqiang CAI alteration assemblages are four to eight times higher than a previous estimate (1.4 ± 0.2) × 10$^{-6}$, which was derived from measurements of 36Ar excess in the matrix of Efremovka (15). There are several possible explanations for the difference. First, the vast majority (94–96%) of 36Ar in meteorites is a mixture of a trapped component, a spallation component, and the decay of cosmonogenic 36Cl. Estimation of 36Ar excess from the decay of short-lived 36Cl hence highly depends on accurate determination and subtraction of these components. A recent study of cosmic-ray production of noble gases in meteorites showed a large variation of 36Ar/36Ar ratios caused by experimental artifact, requiring reassessment for the entire reported 36Ar excess (21). Thus, it is likely that the previous report of 36Cl decay products was inaccurate.

Second, the difference may be related to partial loss of gaseous 36Ar during mild thermal metamorphism in the asteroidal body. The partial loss of 36Ar in Ningqiang would be consistent with its significantly lower gas retention ages (40K–39Ar age of 4,260 ± 70 My and U/Th-4He age of 4,170 ± 160 My, in comparison with the chondrite formation age of 4.56 My) (20). Although Efremovka may have had a different parent body from that of Ningqiang, it probably lost some 36Ar as well, because both meteorites are carbonaceous chondrites and experienced comparable mild thermal metamorphism (with the same petrographic type of 3) in their parent bodies. In contrast, little sulfur was lost during the same metamorphism event. Third, the different 36Cl/35Cl ratios of the Efremovka matrix and the Ningqiang sodalite may be caused by their distinct cosmic-ray exposure histories. However, as discussed above, the cosmonogenic 36Cl is negligible. Finally, it is possible that the difference may represent a time interval of 0.6–1.2 My (i.e., two to four times of the half-life of 36Cl) between the alteration of the CAI and the formation of Efremovka matrix, with assumption of homogeneous distribution of 36Cl in the nebula.
first formed, the time interval between the formation and alteration of the Ningqiang CAI is required. Such a time interval ≥2 My was determined based on the canonical 

(\textsubscript{26}Al/\textsubscript{27}Al)\textsubscript{0} ratio and the maximum inferred (\textsubscript{26}Al/\textsubscript{27}Al)\textsubscript{0} ratio of the anorthite and sodalite-rich assemblages. However, the lack of \textsubscript{26}Mg excesses in the anorthite and the sodalite-rich

Fig. 2. Sulfur isotopic compositions of four sodalite-rich assemblages of the CAI (NQJ11#1) from the Ningqiang meteorite. All four analyses show clear excess of \textsubscript{34}S that linearly correlates with the Cl/S ratio, indicating in situ decay of \textsubscript{36}Cl in the assemblages. Error bars are 2 \(\sigma\). The inferred (\textsubscript{36}Cl/\textsubscript{35}Cl)\textsubscript{0} ratios of the assemblages at the time of alteration are determined from the slopes of the best-fit correlation lines and are calibrated in proportion to the decay of \textsubscript{36}Cl to \textsubscript{36}S.

Fig. 3. Mg isotopic compositions and Al/Mg ratios of the same CAI. (a) Melilite in the unaltered crust of the inclusion shows clear \textsubscript{26}Mg excess that correlates with the Al/Mg ratios. Spinel and Ca-pyroxene occur in the crust. The inferred (\textsubscript{26}Al/\textsubscript{27}Al)\textsubscript{0} ratio is determined from the slope of the best-fit line of the analyses. Error bars are 2 \(\sigma\). (b) Anorthite and the sodalite-rich alteration assemblage show no significant \textsubscript{26}Mg excess. The dashed line refers to a (\textsubscript{26}Al/\textsubscript{27}Al)\textsubscript{0} ratio of 0.7 \times 10\textsuperscript{-5}, the upper limit; the dot horizontal line refers to the normal \textsubscript{26}Mg/\textsubscript{24}Mg ratio of 0.139. Error bars are 2 \(\sigma\). The analysis data are given in Table 2, which is published as supporting information on the PNAS web site.
assemblages may be partially caused by metamorphism that occurred much later on the parent body of Ningqiang. The 26Al-26Mg systematics of plagioclase in a plagioclase- and fassaite-rich (type C) inclusion and plagioclase- and olivine-rich inclusions from the same meteorite also show little 26Mg excess (23). In accordance with self-diffusion rates of Mg in anorthite, it takes <2 My to homogenize Mg isotopes of the anorthite layers (<10 μm, in width) in the CAI at 500°C (23). Therefore, the (26Al/27Al) ratios in anorthite or sodalite might reflect redistribution of Mg isotopes during metamorphism on the parent body. However, the 36Cl-35S system may not be significantly disturbed by the same event, because there are no S-bearing minerals surrounding the sodalite-rich assemblages. Assuming NQ1-1#1 was an unmelted CAI that endured the same heating event that produced type C inclusions (22), a time interval of 1.5 My between the formation of the unaftered crust of NQ1-1#1 and the heating event can be estimated according to the canonical value and the maximum (26Al/27Al) ratio of type C inclusions (∼1 × 10−5) (19, §§). The same time difference (1.5 My) can be referred to as the minimum interval between the formation and alteration of the Ningqiang CAI. Using this time difference and the best inferred (36Cl/35Cl)i ratio of ∼5 × 10−6 of sodalite, the initial (36Cl/35Cl)i ratio at the time when CAIs formed is then deduced to be ∼1.6 × 10−4.

The initial (36Cl/35Cl)i value can be used to constrain the source of short-lived radionuclides and the setting of solar system formation. Wassenburg et al. (5) assumed that the solar system formation was triggered by explosion of a nearby supernova, and 36Cl and other short-lived radionuclides were injected into the protosolar nebula. The predicted initial (36Cl/35Cl)i, ratios of the solar nebula range from 3 × 10−6 to 2 × 10−4 (3), with consideration of a dilution factor for the supernova material to force a canonical (26Al/27Al)i ratio and by using the yields of massive stars reported in ref. 24. The predictions are consistent with the initial (36Cl/35Cl)i, ratio of ∼1.6 × 10−4 estimated in this study. Recent calculations report somewhat higher yields of 36Cl/35Cl related to 26Al/27Al for massive stars (25). The new data may enhance the initial (36Cl/35Cl)i, values, but are still consistent with our observations. On the other hand, 36Cl might be synthesized in a nearby low-mass asymptotic giant branch star instead of a supernova. However, a low-mass asymptotic giant branch star source predicted much lower initial (36Cl/35Cl)i, ratios (∼7.85 × 10−7 to 2.4 × 10−4) (5, 6).

Alternatively, local irradiation models predict an upper limit of 36Cl/35Cl,i = 1.3 × 10−4 (4). Although the predicted value is consistent with the observation from this study, the volatile nature of chlorine and the observation of 36Cl in sodalite probably are not compatible with local irradiation models. According to the model by Shu et al. (10, 11), intense irradiation of the proto-sun evaporated Mg-Fe-silicate dust balls to form CAIs and simultaneously produced short-lived radionuclides (e.g., 36Cl, 26Al, and 41Ca) through the bombardment of CAI materials by energetic particles. After their formation, short-lived radionuclides bearing CAIs were ejected to distant locations where chondrites accreted. Sodalite, a volatile-rich (Na and Cl) alteration product, could not form together with the CAI primary minerals during the intense irradiation near the proto-sun. Instead, it almost certainly formed in the chondrite-accreting locations in the nebula and/or the asteroidal bodies. Therefore, in the local irradiation model, 36Cl itself would have to be produced in a gaseous phase close to the proto-sun by intense irradiation, and then a mechanism to transport the gaseous 36Cl, coupled with solids, from the CAI-forming region to distant chondrite-accreting regions must be invoked. Finally, the transported gaseous 36Cl would have to be incorporated into alteration assemblages through solid-gas reaction. However, the transported gaseous 36Cl must have been much diluted before it was incorporated into the alteration assemblages. Furthermore, according to the local irradiation model (10), gases and small particles would be thrown into interstellar space with finite escape speeds, decoupled from the large CAIs that fell back to the disk. Therefore, the observation of 36Cl in this study presents a serious challenge to local irradiation models.

CAIs and chondrules in carbonaceous chondrites are commonly altered to produce sodalite and other secondary minerals (17). However, where the alteration took place, in the nebula or the asteroidal bodies, is a highly controversial issue. One approach is to determine ages of sodalite and other alteration products. The I-Xe (half-life of 129I, 15.7 My) data of Allende sodalite-rich samples suggest an apparent closure time of 5 My after Murchison magnetite (26), marginally longer that the predicted lifetime of the solar nebula. However, the long closure age may be caused by partial loss of gaseous 129Xe during thermal metamorphism in the parent body. Other data on Al-Mg systems of sodalite suggest the time intervals of several My after formation of CAI primary minerals (19, §§, §5), but they also may be explained by diffusion of normal Mg isotopes from common surrounding Mg-rich phases as discussed above. 36Cl has a shorter half-life than those of 26Al and 129I, and discovery of the short-lived 36Cl in sodalite favors for a short interval (e.g., a few half-lives of 36Cl), otherwise it would have decayed and little can be detected. This short time interval favors a nebular origin of sodalite in the Ningqiang CAI, consistent with petrography and mineral chemistry (22).

Conclusions

Sodalite-rich alteration assemblages in a Ningqiang CAI show clear excess of 36Cl that linearly correlates with Cl/S ratios of the assemblages, providing direct evidence for the presence of short-lived 36Cl in the early solar system. The best inferred (36Cl/35Cl)i ratio of sodalite is 5 × 10−6. Combined with the 26Al-26Mg systems of the individual minerals and petrographic settings of the CAI, the initial (36Cl/35Cl)i ratio of the solar nebula is determined to be ∼1.6 × 10−4.

The presence of 36Cl in the sodalite-rich alteration assemblages of the Ningqiang CAI and the initial (36Cl/35Cl)i, ratio are consistent with a supernova source of short-lived radionuclides, whereas a low-mass asymptotic giant branch star source predicts a much lower (36Cl/35Cl)i, ratio. Although 36Cl can be produced by local irradiation of the proto-sun, its volatile nature and occurrence in alteration assemblages of CAIs present a serious challenge for local irradiation models.

Unlike other short-lived radionuclides (e.g., 26Al and 41Ca), chlorine is closely associated with secondary alteration in CAIs, chondrules, and matrix. 36Cl may serve as a unique fine-scale chronometer, especially for volatile-rock reactions in the nebula and/or on asteroidal bodies. The discovery of 36Cl in sodalite favors a short time interval after formation of CAI primary minerals, consistent with a nebular origin of the alteration in the Ningqiang CAI.

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