



## Acid-susceptive material as a host phase of argon-rich noble gas in the carbonaceous chondrite Ningqiang

Tomoki NAKAMURA,<sup>1\*</sup> Michael ZOLENSKY,<sup>2</sup> Minoru SEKIYA,<sup>1</sup> Ryuji OKAZAKI,<sup>3</sup> and Keisuke NAGAO<sup>3</sup>

<sup>1</sup>Department of Earth and Planetary Sciences, Faculty of Sciences, Kyushu University, Hakozaki, Fukuoka 812–8581, Japan

<sup>2</sup>Mail code ST, NASA Johnson Space Center, Houston, Texas 77058, USA

<sup>3</sup>Laboratory for Earthquake Chemistry, Graduate School of Science, University of Tokyo, Hongo, Bunkyo, Tokyo 113–0033, Japan

\*Corresponding author. E-mail address: [tomoki@geo.kyushu-u.ac.jp](mailto:tomoki@geo.kyushu-u.ac.jp)

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**Abstract**—A fine-grained dark inclusion in the Ningqiang carbonaceous chondrite consists of relatively pristine solar nebular materials and has high concentrations of heavy primordial rare gases. Trapped <sup>36</sup>Ar concentration amounts to  $6 \times 10^{-6}$  cc STP/g, which is higher than that of Ningqiang host by a factor of three. Light HF-HCl etching of the dark inclusion removed 86, 73, and 64% of the primordial <sup>36</sup>Ar, <sup>84</sup>Kr, and <sup>132</sup>Xe, respectively. Thus, the majority of the noble gases in this inclusion are located in very acid-susceptive material. Based on the elemental composition, the noble gases lost from the dark inclusion during the acid-treatments are Ar-rich, and the noble gases remaining in the inclusion are Q and HL gases. Transmission electron microscopy showed that the acid treatments removed thin Si, Mg, and Fe-rich amorphous rims present around small olivine and pyroxene grains in the dark inclusion, suggesting that the Ar-rich gases reside in the amorphous layers. A possible origin of the Ar-rich gases is the acquisition of noble-gas ions with a composition fractionated relative to solar abundance favoring the heavy elements by the effect of incomplete ionization under plasma conditions at 8000 K electron temperature.

### INTRODUCTION

Noble gases in meteorites are key elements elucidating the formation of the early solar system. Various isotopic anomalies associated with nucleosynthesis in stars and supernova have been identified from the noble gases in carbon minerals (e.g., Lewis et al. 1987) in primitive chondritic meteorites. Primordial noble gases, which were incorporated into meteorites during their formation, include He and Ne that were found to reside mainly in interstellar diamonds (Lewis et al. 1987). They also include Ar, Kr, and Xe that are sited mainly in phase Q (Lewis, Srinivasan, and Anders 1975), still unidentified but probably absorption-sites on carbonaceous material.

The third component is Ar-rich noble gas, or so-called “sub-solar” noble gas, that is characterized by the enrichment of Ar and Kr relative to Xe and Q gas (Wacker and Malti 1983). But, the composition of Ar-rich noble gas has not been well-defined: <sup>36</sup>Ar/<sup>84</sup>Kr and <sup>84</sup>Kr/<sup>132</sup>Xe ratios are variable between meteorites and thus have no endmember composition, unlike Q and solar gases. Therefore, the origin of Ar-rich noble gas remains unknown. Ar-rich noble gas is commonly contained in enstatite chondrites (Crabb and

Anders 1982; Patzer and Schultz 2002) and major host phases were found to be silicate minerals (Crabb and Anders 1982; Wacker and Malti 1983). However, it is unclear where in the silicates the Ar-rich noble gases are located and how they were incorporated into them. Recently, Ar-rich gas was found in chondrules (Okazaki et al. 2001) and also in phase Q (Busemann, Baur, and Wieler 2002) in enstatite chondrites. In this paper, we report the discovery of Ar-rich noble gas and its host phases in a chondrule-free fine-grained dark inclusion (hereafter “DI”) in the Ningqiang carbonaceous chondrite.

Ningqiang is an ungrouped carbonaceous chondrite with some petrologic, oxygen isotopic, and thermoluminescence similarities to the oxidized CV3 chondrites (e.g., Rubin et al. 1988). It contains ferromagnesian chondrules, calcium-aluminum-rich inclusions, and DIs in fayalitic olivine matrix. A large DI (5 mm across), which we have examined for mineralogy (Zolensky et al. 2003) and noble gases, consists of micron-sized olivine and pyroxene grains rimmed by amorphous materials with major-element compositions similar to underlying crystalline grains. The DI also contains lath-like crystals of Ca-rich pyroxene that appear to be primitive nebular condensate. These mineralogical features

indicate that the DI is highly primitive solar nebular material (Zolensky et al. 2003).

### SAMPLE PREPARATION AND ANALYTICAL PROCEDURES

A petrologically and mineralogically characterized fine-grained DI in Ningqiang (Zolensky et al. 2003) and Ningqiang host material, chipped out from the same meteorite piece that contains DI, were analyzed for noble gases. 2.7 mg of the fine-grained DI, 0.6 mg of HF/HCl-treated DI, 4.9 mg of host material, and 2.6 mg of HF/HCl-treated host were measured by the total melting. Noble gases were extracted in a Mo crucible at 1850°C for 20 min, purified in low-blank stainless tubes using Ti-Zr getters, separated into He-Ne, Ar, Kr-Xe fractions, and analyzed by noble-gas mass spectrometers (modified MM5400) at University of Tokyo and Kyushu University. The mass spectrometers at the two institutes are the same. When noble gases were analyzed, the complete separation of Ar from Kr was not possible and small amounts of Ar were retained in the Kr-Xe fraction. We thus analyzed Ar in the Kr-Xe fraction and added it to Ar in the Ar fraction to have total Ar concentrations and isotopic ratios. In the same way, Kr in the Ar fraction was added to Kr in the Kr-Xe fraction.

A stepped heating analysis was also performed on a 12.6 mg chip of Ningqiang host sample. 20 min heating at 700, 1000, 1300, and 1850°C released noble gases that were analyzed in the same way as the total melting analysis. Sensitivities and mass discriminations of the mass spectrometer were calibrated by measuring known amounts of atmospheric noble gases and He standard gas that was prepared by mixing known amounts of  $^3\text{He}$  and  $^4\text{He}$ . Blanks of the mass spectrometer at 1850°C, so called “hot blanks,” were measured in between sample analyses and average blank levels of  $^4\text{He}$ ,  $^{20}\text{Ne}$ ,  $^{36}\text{Ar}$ ,  $^{84}\text{Kr}$ , and  $^{132}\text{Xe}$  were  $5 \times 10^{-10}$ ,  $1 \times 10^{-12}$ ,  $3 \times 10^{-12}$ ,  $5 \times 10^{-14}$ , and  $1 \times 10^{-14}$  cm<sup>3</sup> STP, respectively, which constitute less than 1% of the noble gases from the samples. We assumed that the trapped Ne component is Ne-A, because the Ne isotope data of the DI and host are plotted close to a tie line connecting Ne-A and Ne-cosmogenic. The  $^{21}\text{Ne}/^{22}\text{Ne}$  and  $^{38}\text{Ar}/^{36}\text{Ar}$  ratios were used as a measure for the proportion of primordial and cosmogenic components in neon and argon, respectively. The primordial ratios were assumed to be 0.024 and 0.188 (Ne-A and Ar-A; Black 1972) and the cosmogenic ratios were 0.9 and 1.5 for  $^{21}\text{Ne}/^{22}\text{Ne}$  and  $^{38}\text{Ar}/^{36}\text{Ar}$ , respectively.

To identify host phases of the primordial noble gases, light acid-treatments were performed on the DI and host material. A 2.7 mg chip of the fine-grained DI was treated in 1 cc hot acid solution, a mixture of HF: HCl: H<sub>2</sub>O = 1: 1: 4, for 6 min. This technique is typically used for the release of surface-correlated noble gases such as solar wind from minerals (Rao et al. 1991). The treatment was carried out in an ultrasonic bath to facilitate

the reaction between the DI and the solution. After the treatment, the solution was diluted by cold ethanol to stop the reaction and centrifuged to separate solid residues from the solvent. The dilution process was repeated 5 times to wash away the acid solvent completely. Then, the solid residues were dried and weighed. The treatments reduced the mass of the DI down to 44% of the initial weight. The same process was applied for a 10.9 mg chip of Ningqiang host and reduced the mass to 65% of the initial weight. The acid-treated samples were used in parts for transmission electron microscopy (TEM) and in parts for noble gas analysis. The acid-treated Ningqiang samples were embedded in epoxy, microtomed, and observed with a JEOL 2000 TEM using the same procedures as that employed in the companion study describing the amorphous rims (Zolensky et al. 2003).

### RESULTS AND DISCUSSION

The results of the noble gas analysis of the fine-grained DI and the Ningqiang host material are shown in Table 1. Concentrations and isotope ratios of noble gas in the host is comparable to the published data (Eugster et al. 1993; Scherer and Schultz 2000). The DI is very rich in trapped rare gases: primordial  $^{36}\text{Ar}$  concentration is  $6 \times 10^{-6}$  cc STP/g, which is higher than that of the Ningqiang host by a factor of three. Meteorites with such high concentrations of trapped  $^{36}\text{Ar}$  are usually regolith breccias that have been exposed to the solar wind on the surface of parent asteroids (Wieler et al. 1989). However, the Ningqiang DI is depleted in light elements: the  $(^{20}\text{Ne}/^{36}\text{Ar})_{\text{trap}}$  ratio is 0.026. This ratio is too low to indicate solar noble gases because the  $^{20}\text{Ne}/^{36}\text{Ar}$  of the Sun is 40 (Anders and Grevesse 1989). The  $^{36}\text{Ar}/^{132}\text{Xe}$  and  $^{84}\text{Kr}/^{132}\text{Xe}$  ratios are 316 and 1.8, respectively, which are again too low for solar wind, but higher than those of Q gas in phase Q (90 and 1.0, respectively) (Wieler et al. 1991). The elemental composition, therefore, indicates that the noble gases in the DI are mixtures of Q and Ar-rich noble gases. The Ningqiang host also contains Ar-rich noble gas, but the  $^{36}\text{Ar}/^{132}\text{Xe}$  ratio is higher in the DI (316) than in the host (213).

A detailed mineralogical survey indicates that the DI appears to be very pristine nebular material, because fine-grained olivine and pyroxene grains in the DI are rimmed by thin layers of Mg, Fe, and Si-rich amorphous material that are very susceptible to the secondary alteration on the meteorite parent body such as aqueous alteration and weak thermal metamorphism (Zolensky et al. 2003). Thus, the noble gases in this DI must still represent the primitive noble gas composition in this meteorite.

Light acid etching using a HF/HCl solution has markedly reduced the noble gas concentrations both in the DI and the host (Table 1). On average, 86%, 74%, and 64% of the trapped  $^{36}\text{Ar}$ ,  $^{84}\text{Kr}$ , and  $^{132}\text{Xe}$ , respectively, and a lesser proportion (41%) of the trapped  $^{20}\text{Ne}$  were lost during the treatment (Fig. 1). The acid treatment removed 56% in weight from the fine-

Table 1. Noble gas compositions of DI and host of the Ningqiang carbonaceous chondrite.

DI	$^4\text{He}$	$^3\text{He}/^4\text{He}$	$^{20}\text{Ne}$	$^{20}\text{Ne}/^{22}\text{Ne}$	$^{21}\text{Ne}/^{22}\text{Ne}$	$^{36}\text{Ar}$	$^{38}\text{Ar}/^{36}\text{Ar}$	$^{40}\text{Ar}/^{36}\text{Ar}$	$^{84}\text{Kr}$	$^{132}\text{Xe}$
Untreated	40900	0.0162	224	1.860	0.761	5990	0.1888	0.987	33.5	18.9
2.7 mg		$\pm 0.0001$		$\pm 0.007$	$\pm 0.003$		$\pm 0.0003$	$\pm 0.001$		
Acid treated <sup>a</sup>	19085	0.00850	121	2.804	0.644	831	0.1866	2.93	9.1	6.9
0.6 mg <sup>b</sup>		$\pm 0.00001$		$\pm 0.021$	$\pm 0.002$		$\pm 0.0002$	$\pm 0.01$		
Host										
Untreated	21700	0.0297	145	1.329	0.829	2080	0.1940	15.54	14.4	9.7
4.9 mg		$\pm 0.0002$		$\pm 0.004$	$\pm 0.004$		$\pm 0.0002$	$\pm 0.05$		
Acid treated <sup>a</sup>	10465	0.0283	85	1.324	0.836	260	0.1950	6.74	3.6	3.4
2.6 mg <sup>c</sup>		$\pm 0.0001$		$\pm 0.003$	$\pm 0.003$		$\pm 0.0002$	$\pm 0.02$		
Host (12.6 mg)										
700°C	18500	0.0270	47.3	1.333	0.787	51.4	0.2497	532.9	0.74	0.46
		$\pm 0.0001$		$\pm 0.001$	$\pm 0.003$		$\pm 0.0003$	$\pm 0.3$		
1000°C	6850	0.0151	63.4	1.698	0.770	1370	0.1900	12.65	7.50	4.50
		$\pm 0.0001$		$\pm 0.002$	$\pm 0.003$		$\pm 0.0002$	$\pm 0.05$		
1300°C	1850	0.0132	39.5	1.337	0.818	880	0.1928	4.11	6.44	5.07
		$\pm 0.0001$		$\pm 0.003$	$\pm 0.004$		$\pm 0.0002$	$\pm 0.02$		
1850°C	320	0.0311	10.8	0.880	0.871	31.8	0.2186	14.86	0.36	0.35
		$\pm 0.0002$		$\pm 0.003$	$\pm 0.004$		$\pm 0.00025$	$\pm 0.06$		
Total	27500	0.0232	161	1.447	0.794	2330	0.1959	30.8	15.0	10.4

<sup>a</sup>Concentrations normalized to the weight before the acid treatment.

<sup>b</sup>2.7 mg of DI was acid treated and 1.2 mg was recovered (thus, 1.5 mg was dissolved in acid). 0.6 out of 1.2 mg was used for noble gas analysis, and the remainder was used for TEM observation.

<sup>c</sup>10.9 mg of Ningqiang host was acid-treated, and 7.1 mg was recovered. 2.6 out of 7.1 mg was used for noble gas analysis.

grained DI that consists mainly of olivine and pyroxene with a grain size of approximately 1  $\mu\text{m}$  (Zolensky et al. 2003). 56% weight loss corresponds to the removal of approximately 0.1  $\mu\text{m}$  surface layers from the 1  $\mu\text{m}$  silicate grains. In the case of the Ningqiang host, which consists mainly of silicates coarser than those of the DI (Zolensky et al. 2003), 35% in weight was lost by the etching. This also indicates that the acid solution attacked only surfaces of material that are easily susceptible to acid. The results indicate that major fractions of the trapped heavy noble gases in the Ningqiang meteorite are located in material very susceptible to acid treatment, like implanted solar noble gases in some meteorites (Rao et al. 1991), but unlike Q gas in phase Q, which is very resistant to acid treatment (Wieler et al. 1991).

The noble gas elemental ratios also greatly changed during the acid treatment (Table 1). The  $^{36}\text{Ar}/^{132}\text{Xe}$  and  $^{84}\text{Kr}/^{132}\text{Xe}$  ratios were lowered, while  $^{20}\text{Ne}/^{132}\text{Xe}$  was increased, indicating that the noble gases lost from the samples are depleted in Ne but enriched in Ar and Kr relative to those in untreated samples. Calculated  $(^{20}\text{Ne})_{\text{trap}}/^{132}\text{Xe}$ ,  $(^{36}\text{Ar})_{\text{trap}}/^{132}\text{Xe}$ , and  $^{84}\text{Kr}/^{132}\text{Xe}$  ratios of the noble gases lost from the samples during acid treatments are 4.4, 429, and 2.0 for the DI and 5.4, 278, and 1.7 for the host, respectively (Fig. 2). On the contrary, the ratios of the noble gases remaining in the samples are 15.0, 120, and 1.3 for the DI and 11.3, 76, and 1.1 for the host, respectively (Fig. 2). In this calculation, we used the  $(^{20}\text{Ne})_{\text{trap}}$  and  $(^{36}\text{Ar})_{\text{trap}}$  concentrations corrected for cosmogenic Ne and Ar, respectively. When compared with various types of primordial noble gases, the noble gases lost from the Ningqiang samples are similar to Ar-rich noble gases

in enstatite chondrites (Crabb and Anders 1982; Okazaki 1999; Patzer and Schultz 2002) and ureilites (Göbel, Ott, and Begemann 1978; Wacker 1986; Goodrich et al. 1987), while those remaining in the samples are close to Q gas (Wieler et al. 1991; Busemann, Baur, and Wieler 2000) (Fig. 3). The  $(^{20}\text{Ne})_{\text{trap}}/^{132}\text{Xe}$  ratios of noble gases remaining in the samples (11–15) are high relative to those of Q gas ( $[^{20}\text{Ne}/^{132}\text{Xe}]_{\text{Q}} = 3.2$  from Busemann, Baur, and Wieler 2000), suggesting that the remaining  $(^{20}\text{Ne})_{\text{trap}}$  consists of Q and HL gases. These results indicate that Ar-rich noble gases were selectively removed from the Ningqiang samples by the light acid treatment, and Q and HL gases were retained in the samples.

The krypton and xenon isotopic ratios of the acid-untreated and acid-treated samples are essentially similar and show no significant differences, except for a depletion of radiogenic  $^{129}\text{Xe}$  in the acid-treated samples (Table 2). This suggests that the Ar-rich gases in Ningqiang have Kr and Xe compositions similar to the gases in the acid-resistant sites. The decrease of the  $^3\text{He}/^4\text{He}$  ratios during the etching (Table 1) can be ascribed to selective dissolution of the materials rich in cosmogenic noble gas with high  $^3\text{He}/^4\text{He}$  ratios. The increase of the  $^{40}\text{Ar}/^{36}\text{Ar}$  ratios indicates that the materials rich in primordial  $^{36}\text{Ar}$  with low  $^{40}\text{Ar}/^{36}\text{Ar}$  ratios are dissolved more easily than the materials rich in radiogenic  $^{40}\text{Ar}$  with high  $^{40}\text{Ar}/^{36}\text{Ar}$  ratios. To determine precise isotopic ratios of noble gases removed from the samples, in situ closed-system stepped etching analysis is needed (cf., Wieler et al. 1991; Busemann, Baur, and Wieler 2002).

Ar-rich gases in some enstatite and ordinary chondrites are known to reside in silicate phases soluble in HF/HCl,

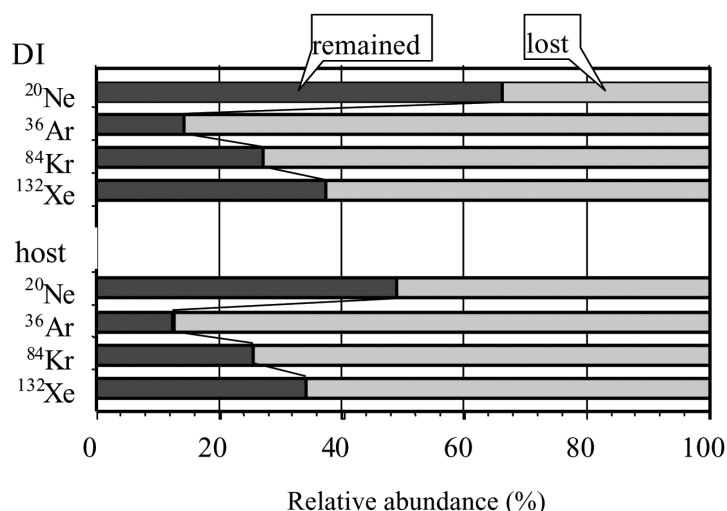


Fig. 1. Relative abundances of the trapped noble gases remaining in and lost from the DI and host during the light acid treatments. More than 60% of  $(^{36}\text{Ar})_{\text{trap}}$ ,  $^{84}\text{Kr}$ , and  $^{132}\text{Xe}$  were lost by the treatment. The relative abundances of  $^{20}\text{Ne}$  to  $^{132}\text{Xe}$  are similar in the DI and the host.

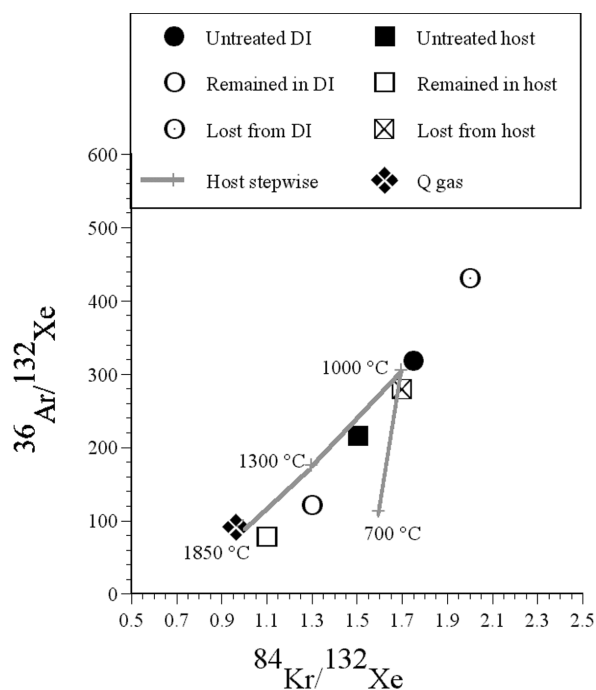


Fig. 2. Changes of elemental ratios during the light-acid etching and stepped pyrolysis. During the acid treatment, both DI and host of Ningqiang show a decrease of  $(^{36}\text{Ar})_{\text{trap}}/^{132}\text{Xe}$  and  $^{84}\text{Kr}/^{132}\text{Xe}$  ratios and thus the noble gases that were removed during the treatment have high elemental ratios. The results of stepped pyrolysis show that the noble gases with high elemental ratios (Ar-rich gas) are released mainly at  $1000^\circ\text{C}$ , while those with low ratios (Q gas) are released at temperatures higher than  $1300^\circ\text{C}$ .

which was discovered by the complete dissolution of bulk meteorites (Schelhaas, Ott, and Begemann 1990; Wacker and Malti 1983; Crabb and Anders 1982). Our results show that the host phases of the Ar-rich gases in carbonaceous chondrites are very susceptible to HF/HCl solution. Based on

the  $^{36}\text{Ar}/^{132}\text{Xe}$  ratios in the stepped heating analysis of the Ningqiang host sample (Table 1), the release of the Ar-rich noble gases peaked at  $1000^\circ\text{C}$ , while that of Q gas peaked at  $1300^\circ\text{C}$ , indicating that the former is located at sites less retentive against heating than the latter. In addition, transmission electron microscopy of the acid-treated DI shows that the amorphous material ubiquitously present around silicate grains in the DI (Zolensky et al. 2003) was completely lost during the light acid treatment. TEM characterization of untreated DI samples shows that the amorphous rims were  $0.1\ \mu\text{m}$  in thickness on average (Zolensky et al. 2003). This corresponds to the thickness of material removed by the acid treatment, as estimated from the weight loss during the treatment as shown above. All the clues suggest that the most probable trapping sites of the Ar-rich gases in Ningqiang are the amorphous rims around the silicate grains.

We suggest that the most pristine material in the solar system contains high concentrations of Ar-rich noble gases like the DI of Ningqiang. The enrichment of primordial noble gases in DIs was also described in the Krymka LL 3.1 chondrite by Vogel et al. (2001). The subsequent secondary alteration processes on the meteorite parent asteroid, such as aqueous alteration and thermal metamorphism, released the Ar-rich noble gases located in the weak trapping sites and left gases located in more resistant sites such as Q gas in phase Q (Lewis, Srinivasan, and Anders 1975) and HL gases in diamonds (Lewis et al. 1987). In fact, Q and HL gases are dominant and Ar-rich gas is minor in carbonaceous chondrites that experienced extensive aqueous alteration, such as CM and CI chondrites (e.g., Nakamura, Nagao, and Takaoka 1999a; Nakamura et al. 1999b). In such meteorites, the Q gas composition itself is also affected by the aqueous alteration (Busemann, Baur, and Wieler 2000).

When the Ar-rich noble gases in the Ningqiang DI are compared with those in enstatite chondrites (e.g., Crabb and

Table 2. Kr and Xe isotopic compositions of the Ningqiang carbonaceous chondrite determined by total-melting and step-heating analysis.<sup>a</sup>

DI	78/84	80/84	82/84	83/84	86/84	124/132	126/132	128/132	129/132	130/132	131/132	134/132	136/132
Untreated	0.0062 ±0.0001	0.0398 ±0.0003	0.2016 ±0.0006	0.2023 ±0.0005	0.3108 ±0.0009	0.0046 ±0.0002	0.0041 ±0.0001	0.0821 ±0.0008	1.101 ±0.007	0.1616 ±0.0008	0.8191 ±0.0023	0.3850 ±0.0012	0.3257 ±0.0012
Acid treated	0.0062 ±0.0001	0.0398 ±0.0004	0.2016 ±0.0010	0.2010 ±0.0014	0.3092 ±0.0025	0.0047 ±0.0002	0.0040 ±0.0002	0.0830 ±0.0009	1.062 ±0.007	0.1632 ±0.0011	0.8214 ±0.0049	0.3894 ±0.0021	0.3310 ±0.0018
Host													
Untreated	0.0062 ±0.0001	0.0410 ±0.0003	0.2064 ±0.0011	0.2067 ±0.0010	0.3197 ±0.0010	0.0048 ±0.0002	0.0043 ±0.0002	0.0865 ±0.0010	1.222 ±0.007	0.1680 ±0.0015	0.8271 ±0.0040	0.3914 ±0.0025	0.3308 ±0.0026
Acid treated	0.0060 ±0.0002	0.0398 ±0.0005	0.2026 ±0.0010	0.2026 ±0.0015	0.3108 ±0.0015	0.0046 ±0.0002	0.0040 ±0.0002	0.0826 ±0.0009	1.050 ±0.006	0.1624 ±0.0013	0.8183 ±0.0047	0.3865 ±0.0019	0.3274 ±0.0019
Host													
700°C	0.0064 ±0.0001	0.0451 ±0.0003	0.2050 ±0.0011	0.2038 ±0.0005	0.3105 ±0.0003	0.0047 ±0.0002	0.0041 ±0.0002	0.0816 ±0.0009	1.201 ±0.009	0.1602 ±0.0011	0.8146 ±0.0043	0.4045 ±0.0021	0.3574 ±0.0030
1000°C	0.0061 ±0.0001	0.0402 ±0.0004	0.2017 ±0.0006	0.2021 ±0.0005	0.3106 ±0.0005	0.0046 ±0.0002	0.0042 ±0.0001	0.0825 ±0.0009	1.324 ±0.008	0.1622 ±0.0007	0.8193 ±0.0023	0.3839 ±0.0009	0.3241 ±0.0008
1300°C	0.0062 ±0.0001	0.0401 ±0.0004	0.2019 ±0.0006	0.2022 ±0.0007	0.3107 ±0.0010	0.0045 ±0.0002	0.0042 ±0.0001	0.0820 ±0.0008	1.250 ±0.008	0.1618 ±0.0007	0.8189 ±0.0020	0.3813 ±0.0009	0.3208 ±0.0007
1850°C	0.0066 ±0.0003	0.0408 ±0.0010	0.2035 ±0.0029	0.2051 ±0.0024	0.3120 ±0.0025	0.0047 ±0.0002	0.0041 ±0.0002	0.0822 ±0.0011	1.235 ±0.008	0.1625 ±0.0015	0.8209 ±0.0070	0.3835 ±0.0019	0.3244 ±0.0026
Total	0.0062	0.0405	0.2025	0.2028	0.3115	0.0046	0.0042	0.0820	1.2768	0.1616	0.8174	0.3828	0.3234
Q	0.0060	0.0394	0.2018	0.2018	0.3095	0.0046	0.0041	0.0822	1.0420	0.1619	0.8185	0.3780	0.3164
HL	0.0042	0.0305	0.1590	0.1989	0.3623	0.0083	0.0056	0.0905	1.0560	0.1542	0.8457	0.6356	0.6991
Atmosphere	0.0061	0.0396	0.2022	0.2014	0.3052	0.0035	0.0033	0.0714	0.9830	0.1514	0.7890	0.3879	0.3294

<sup>a</sup> Isotopic ratios of Q, HL, and Atmosphere are from Busemann, Baur, and Wieler (2000), Huss and Lewis (1994), and Basford et al. (1973), respectively.

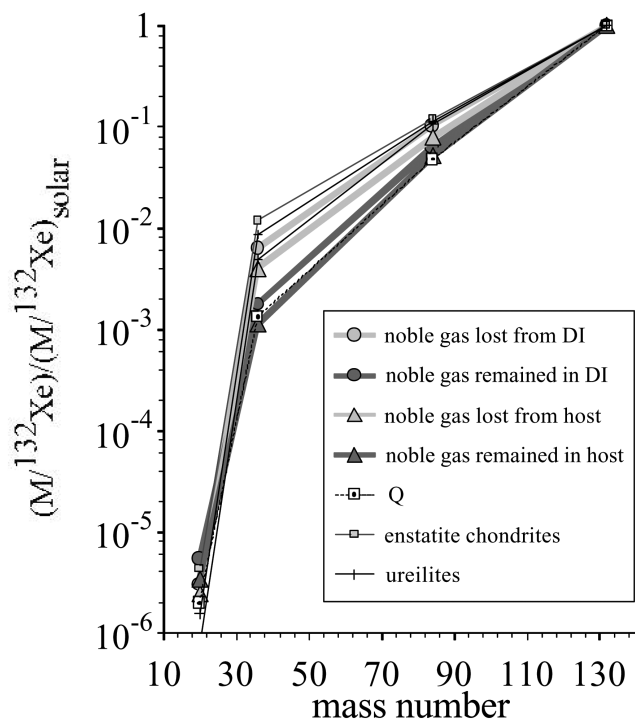


Fig. 3. The elemental abundance patterns of primordial noble gases lost from or remaining in the samples during acid treatments. The abundance patterns of the gases lost are similar to those of ureilites (Göbel, Ott, and Begemann 1978; Wacker 1986; Goodrich et al. 1987) and enstatite chondrites (Okazaki 1999). The patterns of the gases remained are roughly similar to that of Q gas.

Anders 1981; Okazaki 1999) and ureilites (e.g., Wacker 1986), the  $^{36}\text{Ar}/^{132}\text{Xe}$  elemental ratio of the DI (429) is again similar to that of most enstatite chondrites ( $\sim 1000$ ) and ureilites ( $\sim 600$ ), except for some enstatite chondrites such as South Oman (2700). But the host phases and the release temperatures in the stepped pyrolysis are quite different from each other: the hosts are amorphous rims for the DI, diamonds for ureilites (Göbel, Ott, and Begemann 1978), and enstatites for enstatite chondrites (Crabb and Anders 1982). The release temperature reflects the difference in host phases: up to  $1000^\circ\text{C}$  for the DI, which is lower than the temperature, above  $1200^\circ\text{C}$ , for enstatite chondrites and ureilites (Okazaki 1999; Göbel, Ott, and Begemann 1978).

A possible origin of the Ar-rich noble gases in Ningqiang is the acquisition of noble gas ions with a composition fractionated relative to solar abundance favoring the heavy elements by the effect of incomplete ionization by high-temperature electrons under plasma conditions (Elwert 1952; Jokipii 1964). The elemental ratios of the Ar-rich noble gases in both the Ningqiang DI and host plot on the fractionation line with an electron temperature of  $8000\text{ K}$  (Fig. 4). Thus, the silicate grains in Ningqiang could have trapped such fractionated noble gas ions. Trapping of unfractionated solar wind and subsequent diffusive loss of light noble gases (Okazaki et al. 2001) cannot be applied for the case of the Ningqiang DI, because the noble gas isotope ratios indicate that signatures of solar wind are absent in the DI and the survival of amorphous silicates indicates that the DI has not experienced high temperature processes like chondrule formation.

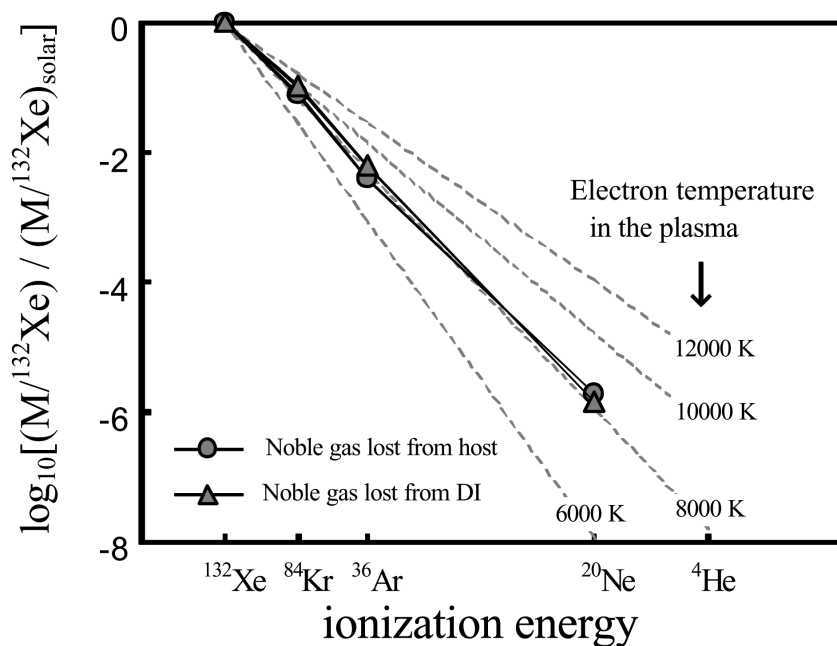


Fig. 4. A diagram showing the ionization degree of noble gases with solar composition, as a function of ionization energy. The abundance of noble gases is normalized to that of solar abundance. When electrons in the plasma are at  $8000\text{ K}$ , the electron bombardment ionizes most of Xe and parts of Ne, resulting in the elemental fractionation of noble gases. The elemental abundance of noble gases lost from the DI and the host lies on the fractionation line at  $8000\text{ K}$  electron temperature.

A naive idea to explain the fractionation is that there had been a gas of 8000 K at the spouting point of the ancient solar wind or the T Tauri disk wind. In such regions, only ionized gases were magnetically accelerated to become keV wind and were then implanted into micron-sized dust grains. Assuming thermal equilibrium at 8000 K, the ionization rates of the rare gases are calculated from Saha's equation (Clayton 1968):  $n_1 n_e / n_0 = 1.8 \times 10^{14} \text{ m}^{-3}$  for Ne,  $8.3 \times 10^{17} \text{ m}^{-3}$  for Ar,  $1.0 \times 10^{19} \text{ m}^{-3}$  for Kr, and  $1.6 \times 10^{20} \text{ m}^{-3}$  for Xe, where  $n_1$  is the ion number density,  $n_e$  is the electron number density, and  $n_0$  is the number density of the neutral atoms. In order to reproduce the trend of Fig. 4,  $n_1/n_0$  must be smaller than unity for all rare gas elements from Ne to Xe. Thus, the electron density must be on the order of  $10^{21} \text{ m}^{-3}$  or larger. The mean collision time of a neutral hydrogen atom and an ionized rare gas atom is on the order of  $10^{-1} \text{ s}$  or smaller in such a dense gas, and the separation of ions from neutral atoms is rare.

## CONCLUSIONS

A series of noble gas analyses showed that a fine-grained DI in the Ningqiang carbonaceous chondrite is rich in Ar-rich noble gas. The light HF-HCl etching of the DI removed the Ar-rich noble gas, together with thin Si, Mg, and Fe-rich amorphous rims around fine-grained silicates. Thus, we proposed that the Ar-rich noble gas in the DI is located in the amorphous rims that are very susceptible to acid. The  $(^{20}\text{Ne})_{\text{trap}}/^{132}\text{Xe}$ ,  $(^{36}\text{Ar})_{\text{trap}}/^{132}\text{Xe}$ , and  $^{84}\text{Kr}/^{132}\text{Xe}$  ratios of the Ar-rich noble gas in the DI are estimated to be 4.4, 429, and 2.0, which are in the range observed for enstatite chondrites and ureilites. Noble gas ions, formed by the incomplete ionization in a hot region of the solar nebula, have been accelerated to keV wind and implanted into fine silicate grains, which results in the formation of amorphous rims and the enrichment of the Ar-rich noble gas in the rims.

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