

Noble gas study of the Saratov L4 chondrite

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Abstract—We have determined the elemental abundances and the isotopic compositions of noble gases in a bulk sample and an HF/HCl residue of the Saratov (L4) chondrite using stepwise heating. The Ar, Kr, and Xe concentrations in the HF/HCl residue are two orders of magnitude higher than those in the bulk sample, while He and Ne concentrations from both are comparable. The residue contains only a portion of the trapped heavy noble gases in Saratov; $40 \pm 9\%$ for ^{36}Ar , $58 \pm 12\%$ for ^{84}Kr , and $48 \pm 10\%$ for ^{132}Xe , respectively. The heavy noble gas elemental pattern in the dissolved fraction is similar to that in the residue but has high release temperatures. Xenon isotopic ratios of the HF/HCl residue indicate that there is no Xe-HL in Saratov, but Ne isotopic ratios in the HF/HCl residue lie on a straight line connecting the cosmogenic component and a composition between Ne-Q and Ne-HL. This implies that the Ne isotopic composition of Q has been changed by incorporating Ne-HL (Huss et al. 1996) or by being mass fractionated during the thermal metamorphism. However, it is most likely that the Ne-Q in Saratov is intrinsically different from this component in other meteorites. The evidence of this is a lack of correlation between the isotopic ratio of Ne-Q and petrologic types of meteorites (Busemann et al. 2000). A neutron capture effect was observed in the Kr isotopes, and this process also affected the $^{128}\text{Xe}/^{132}\text{Xe}$ ratio. The ^3He and ^{21}Ne exposure ages for the bulk sample are 33 and 35 Ma, respectively.

INTRODUCTION

Primitive chondrites have trapped noble gas components with distinct isotopic compositions. Lewis et al. (1975) dissolved the Allende meteorite with acids and discovered that trapped noble gases resided in an HF–HCl residue that by mass comprised <1% of the bulk meteorite. The subsequent chemical treatment showed that large amounts of heavier noble gases (Ar, Kr, and Xe) were released from the HF/HCl residue by oxidation with HNO_3 (Lewis et al. 1975). The dissolved portion was <0.1% of the bulk meteorite. The released gases are elementally fractionated being highly enriched in heavier noble gases compared with gases of solar composition. These gases (referred to as Q-gases) are observed in many primitive chondrites. The chemical structure of phase Q is not clear although it is known that the Q phase is carbonaceous (Reynolds et al. 1978; Ott et al. 1981). Phase Q is the main carrier of the

primordial Ar, Kr, and Xe, and the manner by which it was acquired and the processes that subsequently alter it likely reflect processes occurring in the early solar system and on parent bodies. Accordingly, it is important to examine the nature of Q in a variety of meteorites, including metamorphosed meteorites.

Phase Q and carriers of other noble gas components were lost in varying degrees by thermal metamorphism in meteorite parent bodies. Although abundances of phase Q, presolar diamond (carrier of HL gases), and SiC (carrier of Ne–E(H) and Xe–S) decrease with increasing petrologic sub-type among the type 3 ordinary chondrites, SiC and presolar diamonds are more susceptible to loss by thermal metamorphism (Huss et al. 1996); SiC is more readily destroyed than presolar diamond (Huss et al. 1996). Thermal metamorphism also changes elemental compositions of Q gases. In many chondrites, the higher petrologic subtypes of type 3 have lower $(^{22}\text{Ne}/^{132}\text{Xe})_{\text{Q}}$ and

$(^{36}\text{Ar}/^{132}\text{Xe})_{\text{Q}}$ ratios (Busemann et al. 2000). This suggests that lighter gases were preferentially lost during thermal metamorphism. Busemann et al. (2000) argues that there are two carrier phases “Q1” and “Q2,” each containing different proportions of light and heavy noble gases and that these phases have different susceptibility to thermal alteration. However, the peak release temperatures of all five noble gases are similar in many chondrites, indicating a single component for phase Q (Huss et al. 1996). The correlation between the petrologic type and the elemental ratios also implies that a common Q component is present in all the chondrites (Huss et al. 1996).

In this study, we measure elemental abundances and isotopic compositions of noble gases in the bulk and the HF/HCl-resistant residue of the Saratov (L4) chondrite. Presolar diamonds are not detected in ordinary chondrites of petrologic type >3.8 (Alexander et al. 1990; Huss 1990). It is likely that diamond is completely absent while Q survived thermal metamorphism in petrologic type 4. If this is the case, we will be able to determine the elemental abundances and isotopic compositions of those Q gases in Saratov that survived thermal metamorphism without having to correct for the HL noble gases found in diamond. To date, noble gas investigations of phase Q have performed mainly on type 3 primitive chondrites. Noble gas studies of equilibrated (type 4, 5, and 6) ordinary chondrites have been carried out for LL chondrites (Alaerts et al. 1979) and H chondrites (Moniot 1980), but in both cases the residues were measured in a single step extraction. The aim of this study is to examine how phase Q and Q gases were modified in chondrites of higher petrologic type.

SAMPLE PREPARATION AND EXPERIMENTAL PROCEDURE

Saratov fell in Saratov province, Russia, on September 6, 1918, and its recovered weight is 328 kg (Grady 2000). It is classified as a L4 ordinary chondrite. Saratov contains abundant chondrules, ranging in size from less than a millimeter to over a centimeter, and contains metal (mainly troilite and FeNi phases) in addition to chondrules and matrix (Herd et al. 2004). Its shock stage is low (S1–S2) and it is unweathered.

We prepared an original residue (HF/HCl-resistant residue) of the L4 Saratov using HF/HCl treatment described by Lewis et al. (1975). After crushing, the sample was dissolved with seven alternating cycles of 10 M HF – 1 M HCl and 6 M HCl (1 day each). Then CS_2 was used to remove elemental sulfur. The yield of the residue was 0.76 wt% (estimated error of 20%) of the bulk chondrite after these treatments. The HF/HCl

dissolution generally dissolves $>99\%$ of the mass in most chondrites; the yield for Saratov is consistent with those in LL chondrites for petrologic type of 3–6 where the yield increases from 0.3% to 0.9% as petrologic type increases (Alaerts et al. 1979). A bulk sample of the Saratov chondrite was also prepared for comparison.

The elemental abundances and the isotopic ratios of noble gases in the original HF/HCl residue and the bulk sample were measured by stepwise heating at 600, 800, 1000, 1200, 1400, and 1600 °C. Samples were dropped in a Mo crucible with a Ta heater and heated for 20 min at each temperature step. The extracted gases were purified by two Ti–Zr getters at 700 °C. The purified noble gases were separated from each other using a cryogenic cold trap and were then admitted to a sector-type mass spectrometer (VG5400, Osaka University, Osaka, Japan) with two collectors: a Faraday for ^4He and ^{40}Ar analyses and an electron multiplier with a pulse counting system for other isotopes. Activated charcoal was used to remove residual Ar in the line for the He and Ne measurements. We calculated the sensitivities and mass discrimination factors by analyzing pipetted atmospheric noble gases. Sensitivity uncertainties are about 5%. These errors include uncertainties in the volumes of the standard air pipette and statistical errors of the measurement. All data were blank corrected using procedural blanks. Procedural blanks were measured at 1000 and 1600 °C. The 1000 °C blank was used to correct 600, 800, and 1000 °C extractions, and the 1600 °C blank was used for the 1200, 1400, and 1600 °C extractions. The gas concentrations in the procedural blanks at 1600 °C are: $^4\text{He} = 1.1$ to 1.3×10^{-9} , $^{22}\text{Ne} = 9.7$ to 36×10^{-14} , $^{36}\text{Ar} = 1.1$ to 2.7×10^{-11} , $^{84}\text{Kr} = 1.4$ to 11×10^{-12} , and $^{132}\text{Xe} = 1.9$ to 4.1×10^{-13} cm^3 STP. The uncertainty in the blank concentrations was taken to be 100%. The blank corrections were negligible for all extractions of the bulk sample and the residue with the exception of the 1600 °C extraction for the residue. For example, the ^{132}Xe blank correction for the 1600 °C fraction of the residue was 7%.

RESULTS

Tables 1–3 list the noble gas concentrations and isotopic ratios of the bulk and the HF/HCl residue of the L4 Saratov chondrite.

Elemental Abundance

Figure 1 shows the total elemental concentrations in the bulk and the HF/HCl residue. The Ar, Kr, and Xe concentrations in the residue sample are two orders of

Table 1. Concentration and isotopic ratio of He, Ne, and Ar in Saratov.

Sample	Temp. (°C)	(^4He) 10^{-6} cm^3		(^{22}Ne) 10^{-8} cm^3		(^{36}Ar) 10^{-8} cm^3		$^{38}\text{Ar}/^{36}\text{Ar}$	$^{40}\text{Ar}/^{36}\text{Ar}$
		STP/g	$^3\text{He}/^4\text{He} \times 10^{-4}$	STP/g	$^{20}\text{Ne}/^{22}\text{Ne}$	STP/g	$^{21}\text{Ne}/^{22}\text{Ne}$		
Saratov bulk (248.7 mg)	600	15.2	205.3 ± 6.9	1.82	0.717 ± 0.011	0.770 ± 0.008	0.386	0.3079 ± 0.0011	4211 ± 86
	800	3.04	188.5 ± 6.0	1.78	0.788 ± 0.008	0.853 ± 0.007	0.0945	0.4919 ± 0.0014	4284 ± 89
	1000	1.86	202.7 ± 6.5	1.92	0.793 ± 0.009	0.875 ± 0.008	0.242	0.4200 ± 0.0015	1377 ± 28
	1200	1.20	231.1 ± 7.4	1.61	0.794 ± 0.012	0.877 ± 0.007	1.31	0.3016 ± 0.0008	1765 ± 36
	1400	0.394	256.1 ± 8.2	1.70	0.870 ± 0.010	0.890 ± 0.007	3.25	0.2698 ± 0.0006	334.3 ± 6.8
	1600	0.0949	523.1 ± 16.6	1.47	0.845 ± 0.009	0.905 ± 0.007	1.48	0.2555 ± 0.0007	171.4 ± 3.5
Total		21.8	206.5 ± 4.9	10.3	0.799 ± 0.004	0.859 ± 0.003	6.77	0.2835 ± 0.0004	889.0 ± 9.3
Saratov residue (3.63 mg)	600	17.6	132.0 ± 3.2	0.844	2.075 ± 0.090	0.750 ± 0.012	29.4	0.1875 ± 0.0004	20.8 ± 0.3
	800	1.97	140.3 ± 4.4	1.57	0.885 ± 0.050	0.847 ± 0.008	7.39	0.1887 ± 0.0005	0.1 ± 0.05
	1000	1.47	135.1 ± 2.5	1.59	1.375 ± 0.050	0.795 ± 0.010	25.9	0.1897 ± 0.0004	0.4 ± 0.01
	1200	3.05	32.4 ± 0.5	1.31	5.415 ± 0.074	0.441 ± 0.006	167	0.1925 ± 0.0004	<0.4
	1400	1.60	13.1 ± 0.2	0.707	5.873 ± 0.113	0.377 ± 0.010	103	0.1977 ± 0.0004	<0.7
	1600	0.0389	38.0 ± 2.6	0.0722	1.685 ± 1.237	0.789 ± 0.109	1.93	0.2141 ± 0.0008	<33.1
Total		25.7	113.5 ± 2.2	6.10	2.739 ± 0.034	0.678 ± 0.004	335	0.1934 ± 0.0002	9.9 ± 0.1 ^a
Q ^b		1.53	(1.23–1.59)		10.70	0.0294		0.1890	
HL ^c		1.70			(10.05–10.70)	(0.0291–0.0321)		(0.18727 ± 0.00070)	
Air		0.014			8.50	0.036		0.2270	<0.08
					9.80	0.029		0.188	295.5

The elemental concentrations are listed as upper limits without blank correction in case that the errors exceed 100%.

^aThe total of $^{40}\text{Ar}/^{36}\text{Ar}$ ratios is the sum of 600–800 °C fractions.

^bWieler et al. (1992). This is the Murchison Q. Helium and Ne isotopic ratios for carbonaceous and ordinary chondrites have a range (Busemann et al. 2000). The values in parentheses are from Busemann et al. (2000).

^cHuss and Lewis (1994). This HL component of Ne (Ne – HL) is actually Ne-A2 (Ne-HL + P3) (Huss et al. 1996).

Table 2. Concentrations and isotopic ratios of Kr in Saratov.

Sample	Temp. *(°C)	[⁸⁴ Kr] 10 ⁻¹⁰ cm ³ STP/g	⁷⁸ Kr/ ⁸⁴ Kr	⁸⁰ Kr/ ⁸⁴ Kr	⁸² Kr/ ⁸⁴ Kr	⁸³ Kr/ ⁸⁴ Kr	⁸⁶ Kr/ ⁸⁴ Kr
Saratov bulk (248.7 mg)	600	0.885	0.0066 ± 0.0002	0.0824 ± 0.0007	0.2134 ± 0.0016	0.2055 ± 0.0015	0.3070 ± 0.0016
	800	0.129	0.0068 ± 0.0009	0.3465 ± 0.0062	0.3266 ± 0.0049	0.2135 ± 0.0041	0.2997 ± 0.0050
	1000	0.254	0.0065 ± 0.0004	0.1742 ± 0.0016	0.2497 ± 0.0040	0.2157 ± 0.0033	0.2950 ± 0.0037
	1200	1.57	0.0065 ± 0.0001	0.1120 ± 0.0015	0.2288 ± 0.0015	0.2085 ± 0.0009	0.3118 ± 0.0016
	1400	2.71	0.0068 ± 0.0001	0.0621 ± 0.0005	0.2164 ± 0.0012	0.2094 ± 0.0008	0.3142 ± 0.0010
	1600	1.31	0.0062 ± 0.0002	0.0485 ± 0.0005	0.2074 ± 0.0013	0.2051 ± 0.0015	0.3069 ± 0.0013
	Total	6.86	0.0066 ± 0.0001	0.0831 ± 0.0004	0.2205 ± 0.0007	0.2082 ± 0.0005	0.3104 ± 0.0006
Saratov residue (3.63 mg)	600	48.7	0.0063 ± 0.0003	0.0405 ± 0.0010	0.2025 ± 0.0019	0.1999 ± 0.0020	0.3003 ± 0.0034
	800	11.3	0.0053 ± 0.0008	0.0382 ± 0.0014	0.2082 ± 0.0052	0.2025 ± 0.0053	0.2980 ± 0.0063
	1000	39.8	0.0062 ± 0.0002	0.0379 ± 0.0006	0.1999 ± 0.0023	0.1995 ± 0.0035	0.3120 ± 0.0021
	1200	261	0.0059 ± 0.0001	0.0392 ± 0.0005	0.2055 ± 0.0006	0.2044 ± 0.0009	0.3107 ± 0.0013
	1400	157	0.0059 ± 0.0001	0.0390 ± 0.0005	0.2038 ± 0.0010	0.2020 ± 0.0010	0.3137 ± 0.0018
	1600	3.24	0.0058 ± 0.0014	0.0363 ± 0.0047	0.2081 ± 0.0176	0.2172 ± 0.0161	0.3105 ± 0.0198
	Total	521	0.0060 ± 0.0001	0.0391 ± 0.0003	0.2044 ± 0.0005	0.2029 ± 0.0006	0.3104 ± 0.0010
Q ^a			0.00603	0.03937	0.2018	0.2018	0.3095
HL ^b			0.0043	0.0308	0.1600	0.1993	0.3603
Air			0.006087	0.03960	0.20217	0.20136	0.30524

^aBusemann et al. (2000).

^bHuss and Lewis (1994).

magnitude higher than those in the bulk sample, whereas the He and the Ne concentrations are similar in the two samples (Fig. 1). This suggests that the heavy noble gases are mainly in the residue.

The Ar, Kr, and Xe concentrations in the HF/HCl residue of Saratov are low compared with those of L3 ordinary chondrites (Huss et al. 1996). Those concentrations of Saratov (L4) are about 40–60% of those of Julesburg (L3.6), suggesting that the noble gas concentrations were affected by thermal metamorphism. The He and Ne in bulk ordinary chondrites are mainly cosmogenic (and radiogenic for ⁴He). The fractions of the He and Ne retained in the residue are low compared to those in the bulk. This is the case for Saratov.

Figure 2 shows the release curves of ⁴He, ³He, ²²Ne, ³⁶Ar, ⁸⁴Kr, and ¹³²Xe. The released fraction is normalized to the total bulk concentration for both bulk and the residue sample. For ⁴He, ³He, and ²²Ne, the fractions of the gases in the residue are small so for display they have been multiplied by a factor of 100 in Fig. 2. The He in the bulk and the residue samples are dominated by a cosmogenic component. To examine how much radiogenic ⁴He is present, we compare the release pattern of ⁴He to that of ³He, which is exclusively cosmogenic (Fig. 2). As there is no systematic difference between the ³He and ⁴He release patterns we cannot resolve the radiogenic component from the cosmogenic component. The Ne in the bulk sample is predominantly cosmogenic. Figure 3 shows the trapped and the cosmogenic components in the

residue. We assumed the ²¹Ne/²²Ne ratio of the trapped component is 0.029 (air) and that of the cosmogenic component is 0.847 (that of 800 °C fraction of the residue). Of the total amount of ²²Ne in the residue, about 20% is cosmogenic. The peak release temperature of the cosmogenic component is 1200 °C, but for the trapped component it is 800–1000 °C (Fig. 3).

The residue is not concentrated in He and Ne; however, the residue carries much of the ³⁶Ar, ⁸⁴Kr, and ¹³²Xe (Fig. 2). Cosmogenic and radiogenic components are also predominant in Ar, especially in the bulk Saratov. We resolved Ar into cosmogenic and trapped components. We calculated the cosmogenic ³⁶Ar amounts on the assumption that the ³⁶Ar is a mixture of trapped ((³⁶Ar/³⁸Ar)_{atm} = 5.32) and cosmogenic ((³⁶Ar/³⁸Ar)_c = 0.68) (Schultz et al. 1991). The cosmogenic ³⁶Ar is only 0.4% of the total ³⁶Ar in the residue, and 7% in the bulk. The release patterns of the cosmogenic and the trapped ³⁶Ar in the bulk sample are shown in Fig. 3. Their release curves are similar and the main release peaks are at 1400 °C for both components.

The bulk sample releases significant amounts of the heavy gases (³⁶Ar, ⁸⁴Kr, and ¹³²Xe) at 1400 °C, while the chemical residue releases them at 1200 °C; the typical release temperature of Q gas (Huss et al. 1996) (Fig. 2).

The concentrations of heavy noble gases and their release temperatures in the residue indicate that the heavy noble gases are trapped in phase Q, the carrier of

Table 3. Concentrations and isotopic ratios of Xe in Saratov.

Sample	Temp. (°C)	^{132}Xe 10^{-10} cm^3 STP/g	$^{124}\text{Xe}/^{132}\text{Xe}$	$^{126}\text{Xe}/^{132}\text{Xe}$	$^{128}\text{Xe}/^{132}\text{Xe}$	$^{129}\text{Xe}/^{132}\text{Xe}$	$^{130}\text{Xe}/^{132}\text{Xe}$	$^{131}\text{Xe}/^{132}\text{Xe}$	$^{134}\text{Xe}/^{132}\text{Xe}$	$^{136}\text{Xe}/^{132}\text{Xe}$
Saratov bulk (248.7 mg)	600	0.692	0.0042 ±0.0004	0.0038 ±0.0003	0.0762 ±0.0012	1.0602 ±0.0103	0.1573 ±0.0019	0.8063 ±0.0045	0.3822 ±0.0059	0.3160 ±0.0040
	800	0.205	0.0043 ±0.0005	0.0048 ±0.0004	0.0797 ±0.0019	1.3813 ±0.0167	0.1562 ±0.0032	0.8164 ±0.0094	0.3782 ±0.0075	0.3190 ±0.0073
	1000	0.392	0.0047 ±0.0003	0.0042 ±0.0002	0.0822 ±0.0016	1.7373 ±0.0207	0.1549 ±0.0014	0.8236 ±0.0051	0.3875 ±0.0057	0.3228 ±0.0047
	1200	3.11	0.0047 ±0.0001	0.0041 ±0.0002	0.0831 ±0.0010	1.4061 ±0.0120	0.1606 ±0.0012	0.8207 ±0.0041	0.3782 ±0.0041	0.3166 ±0.0037
	1400	7.59	0.0045 ±0.0001	0.0041 ±0.0001	0.0849 ±0.0009	1.2080 ±0.0102	0.1631 ±0.0012	0.8186 ±0.0033	0.3790 ±0.0042	0.3209 ±0.0037
	1600	4.83	0.0044 ±0.0001	0.0042 ±0.0001	0.0828 ±0.0009	1.1765 ±0.0103	0.1627 ±0.0011	0.8239 ±0.0033	0.3854 ±0.0043	0.3226 ±0.0037
	Total	16.8	0.0045 ±0.0001	0.0041 ±0.0001	0.0835 ±0.0005	1.2440 ±0.0060	0.1620 ±0.0007	0.8201 ±0.0020	0.3810 ±0.0024	0.3204 ±0.0021
Saratov residue (3.63 mg)	600	62.7	0.0049 ±0.0003	0.0042 ±0.0002	0.0806 ±0.0013	1.1045 ±0.0089	0.1584 ±0.0021	0.8075 ±0.0036	0.3735 ±0.0027	0.3160 ±0.0036
	800	18.4	0.0040 ±0.0004	0.0038 ±0.0003	0.0827 ±0.0012	1.0865 ±0.0106	0.1591 ±0.0033	0.8255 ±0.0105	0.3712 ±0.0077	0.3072 ±0.0068
	1000	75.1	0.0048 ±0.0003	0.0043 ±0.0002	0.0795 ±0.0008	1.0684 ±0.0046	0.1599 ±0.0018	0.8258 ±0.0044	0.3806 ±0.0030	0.3133 ±0.0030
	1200	559	0.0045 ±0.0002	0.0042 ±0.0001	0.0829 ±0.0004	1.0474 ±0.0029	0.1622 ±0.0014	0.8231 ±0.0018	0.3811 ±0.0017	0.3160 ±0.0013
	1400	337	0.0049 ±0.0002	0.0042 ±0.0002	0.0825 ±0.0006	1.0417 ±0.0042	0.1608 ±0.0013	0.8236 ±0.0028	0.3806 ±0.0019	0.3173 ±0.0017
	1600	7.16	0.0052 ±0.0008	0.0038 ±0.0008	0.0804 ±0.0050	1.0387 ±0.0191	0.1650 ±0.0071	0.8088 ±0.0201	0.3593 ±0.0144	0.2960 ±0.0093
	Total	1060	0.0047 ±0.0001	0.0042 ±0.0001	0.0823 ±0.0003	1.0510 ±0.0021	0.1613 ±0.0009	0.8225 ±0.0014	0.3801 ±0.0011	0.3159 ±0.0009
Q ^a		0.00455	0.004057	0.0822	1.042	0.1619	0.8185	0.3780	0.3164	
HL ^b		0.00842	0.00569	0.0905	1.056	0.1544	0.8442	0.6361	0.7000	
Air		0.003537	0.003300	0.07136	0.9832	0.1514	0.7890	0.3879	0.3294	

^aBusemann et al. (2000).^bHuss and Lewis (1994).

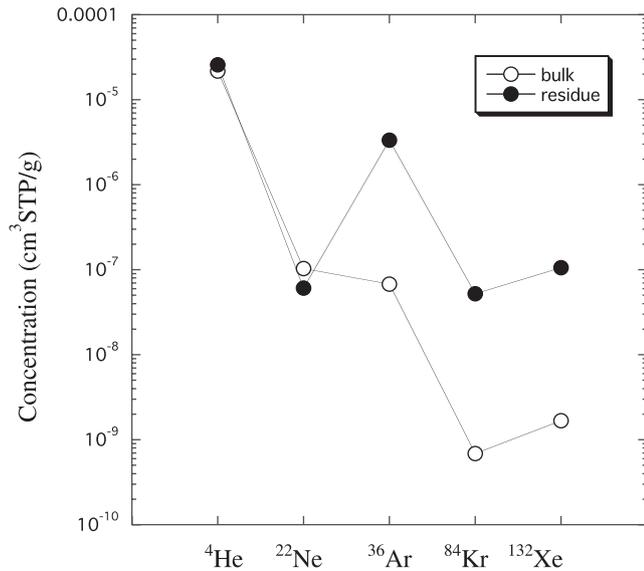


Fig. 1. Comparison of the total elemental concentrations of noble gases in the bulk sample (open circle) and the HF/HCl residue (closed circle) of L4 Saratov.

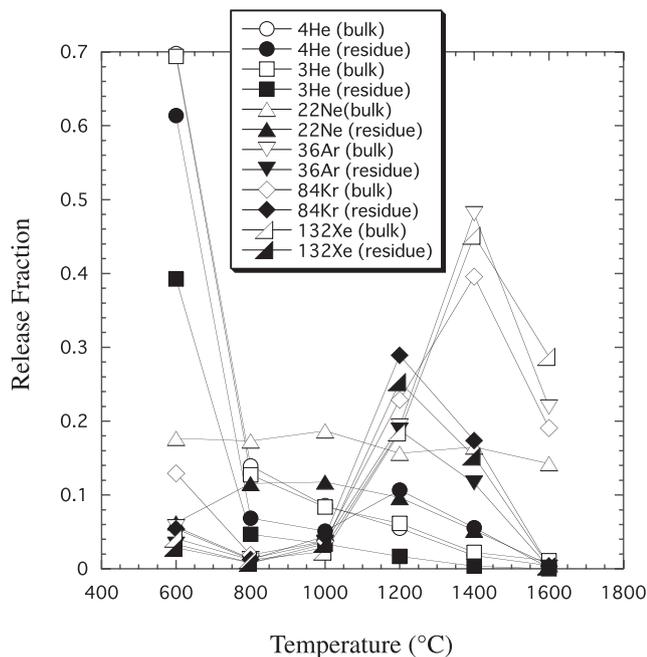


Fig. 2. Release profiles of ^4He , ^3He , ^{22}Ne , ^{36}Ar , ^{84}Kr , and ^{132}Xe in the bulk (open symbol) and the HF/HCl residue (closed symbol) of L4 Saratov. All release fractions of both the bulk and the HF/HCl residue are normalized to the total gas amounts in the bulk sample. The released fractions of He and Ne of the residue are very small and are multiplied by 100.

heavy noble gases in the HF/HCl residue in most primitive chondrites (e.g., Huss et al. 1996). Table 4 shows the elemental concentrations of heavy noble gases, their ratios in the bulk sample, the residue, and

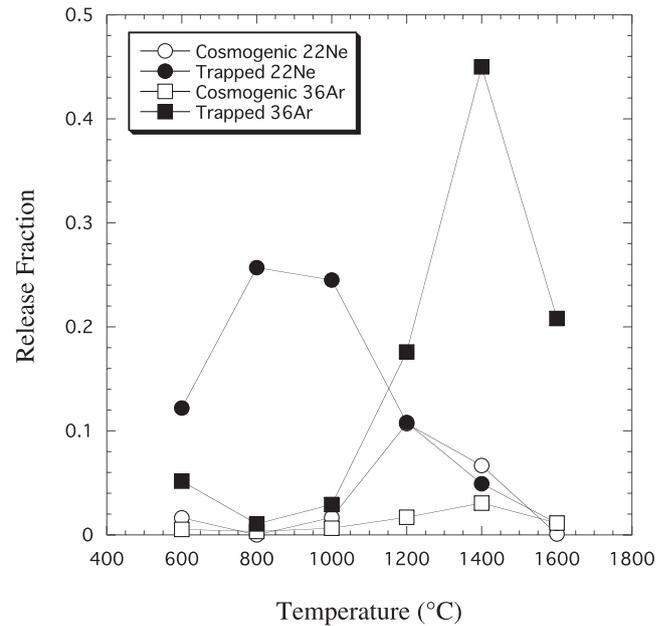


Fig. 3. Release profile of the cosmogenic ^{22}Ne (open circle) and the trapped ^{22}Ne (closed circle) of the HF/HCl residue. The release fractions are normalized to the total amount of ^{22}Ne in the residue. We assumed the $^{21}\text{Ne}/^{22}\text{Ne}$ ratio of the trapped component as 0.029 (air) and that of the cosmogenic component as 0.847 (the value of the 800 °C fraction). The cosmogenic ^{36}Ar (open square) and the trapped ^{36}Ar (closed square) of the bulk sample are also plotted. A cosmogenic component was calculated from the $^{36}\text{Ar}/^{38}\text{Ar}$ ratio on the assumption that the Ar is a mixture of trapped ($(^{36}\text{Ar}/^{38}\text{Ar})_{\text{atm}} = 5.32$) and cosmogenic component ($(^{36}\text{Ar}/^{38}\text{Ar})_{\text{c}} = 0.68$) (Schultz et al. 1991). The release fractions of ^{36}Ar are to the total amount in the bulk.

the fraction dissolved during the chemical procedure. The ^{36}Ar concentrations were corrected for the cosmogenic contributions, although the correction is small (7% of the bulk and 0.4% for the residue, respectively). No cosmogenic corrections were made for the ^{84}Kr and ^{132}Xe . The residue contains $40 \pm 9\%$, $58 \pm 12\%$, and $48 \pm 10\%$ of the trapped ^{36}Ar , ^{84}Kr , and ^{132}Xe of that found in the bulk. These values are low compared with residues from type 3 carbonaceous chondrites and generally account for more than 80% of Xe (e.g. Huss et al. 1996). About 95% of all ^{132}Xe is associated with phase Q in the bulk Orgueil CI chondrite (no thermal metamorphism) (Ott 2002). Saratov follows the trend that chemical residues in higher petrologic types contain a smaller fraction of the gas relative to lower petrologic grades (Alaerts et al. 1979; Moniot 1980; Schelhaas et al. 1990). Evidently, there are carrier phase other than phase Q in meteorites of higher petrologic types. Our measurements indicate that $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios in the bulk, the residue, and the dissolved fraction are similar. $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios in the Saratov residue

Table 4. A comparison of the trapped ^{36}Ar , ^{84}Kr , and ^{132}Xe concentrations in the Saratov bulk, the HF/HCl residue, and the dissolved fraction during the chemical leaching.

Sample	^{36}Ar ^a 10 ⁻⁸ cm ³ STP/g	^{84}Kr 10 ⁻¹⁰ cm ³ STP/g	^{132}Xe 10 ⁻¹⁰ cm ³ STP/g	$^{36}\text{Ar}/^{132}\text{Xe}$	$^{84}\text{Kr}/^{132}\text{Xe}$
Bulk	6.27	6.86	16.8	37 ± 3	0.41 ± 0.03
Residue	334	521	1060	31 ± 2	0.49 ± 0.03
Dissolved fraction	3.76 ± 0.61	2.92 ± 0.89	8.8 ± 1.9	43 ± 11	0.33 ± 0.12
Q ^b				76 ± 7	0.81 ± 0.05
HL ^b				50 ± 20	0.48 ± 0.04
Subsolar ^b				2660 ± 376	5.86 ± 0.84
Solar wind ^c				10000–17000	4.7–9.0
Air				1340	28

The errors of noble gas concentrations in the bulk and the residue are 5% although we do not list the error in the table. We calculated the errors of the elemental concentrations in the dissolved fraction and their elemental ratios from these 5% errors and the 20% error of the residue yield.

^aThe ^{36}Ar concentrations in the bulk and the residue are those of the trapped component. The calculation was carried out on the assumption that ^{36}Ar is a mixture of the trapped ($^{36}\text{Ar}/^{38}\text{Ar}$ ratio = 0.532) and the cosmogenic component ($^{36}\text{Ar}/^{38}\text{Ar}$ ratio = 0.68) (Schultz et al. 1991).

^bFrom table 2 in Ott (2002).

^cWieler and Baur (1995).

are low compared with those in typical phase Q (Table 4). These values are even lower than those of H and L chondrites of higher petrologic types (≥ 3.6). We interpret the low ratios as indicative of selective Ar loss during thermal metamorphism (Busemann et al. 2000). The $^{36}\text{Ar}/^{132}\text{Xe}$ ratio in the dissolved fraction is lower than the canonical subsolar component observed in E-chondrites (Crabb and Anders 1981, 1982), making it unlikely that the dissolved gases are subsolar (c.f. Table 4). The solar $^{36}\text{Ar}/^{132}\text{Xe}$ is even higher than the subsolar component (Wieler and Baur 1995), so it cannot be the source of the gases in the dissolved fraction. The noble gases in the dissolved fraction are highly fractionated, being enriched in heavy noble gases and have similar elemental abundance ratios as those found in the phase Q in Saratov. Silicate may be one of the carriers of this component. It is conceivable that the gases released from phase Q during thermal metamorphism might be tightly retrapped in silicate.

The mass yield of the HF/HCl residue (0.76 wt%) and the ^3He concentrations of the samples indicate that more than 99% of the cosmogenic ^3He was lost during the HF/HCl treatment. Likewise, 98% of cosmogenic ^{38}Ar and more than 99% of radiogenic ^{40}Ar were lost during dissolution. Cosmogenic and radiogenic components were homogeneously distributed in the bulk sample.

Isotopic Ratios of Kr and Xe

The $^{80}\text{Kr}/^{84}\text{Kr}$ (Table 2) is high for bulk Saratov; the Kr in the 800 °C fraction (about 0.35) is about an order of magnitude higher than the ratios seen in Q and air (about 0.04), and the $^{82}\text{Kr}/^{84}\text{Kr}$ at this temperature

fraction is high. Figure 4 shows the Kr data, the Kr data form a linear array with a slope of 3. This corresponds to production by neutron capture on Br (Murty and Marti 1987). The 800 °C fraction lies to the right of this line and may indicate the presence of spallation. The slope of this line depends on the neutron energy and varies from 2.6 to 3.5 for neutron energies < 300 eV (Marti et al. 1966). All temperature steps from the bulk sample have contributions from neutron capture. The HF/HCl residue plots near Q and air.

Figure 5 illustrates the cosmogenic Kr isotopes. ^{78}Kr is produced exclusively by spallation, while ^{83}Kr is produced by spallation, neutron capture on ^{82}Se (Murty and Marti 1987), and U fission. The Kr from the HF/HCl residue are distributed around Q and air, whereas all the extractions from bulk samples show $^{78}\text{Kr}/^{84}\text{Kr}$ and $^{83}\text{Kr}/^{84}\text{Kr}$ ratios slightly higher than the ratios of Q, indicating a small contribution of spallation and neutron capture.

There is no Kr-HL in any of the extractions (Figs. 4 and 5), indicating that thermal metamorphism destroyed presolar diamonds (the host phase of HL gases). The $^{86}\text{Kr}/^{84}\text{Kr}$ ratios of the total bulk and the total HF/HCl residue are 0.310, identical to that of Q (Table 2).

Xe-Q and Xe-HL can be seen in Fig. 6. Many extractions from both the bulk and the HF/HCl residue are located near Q. The 1000 and 1600 °C extractions from the bulk sample fall on the right side of the data point of Q, but their positions are still on the left side of air. This could plausibly be either due to a small contribution of air or HL (or may within error still correspond to pure Xe-Q). The 800 and 1600 °C extractions from the HF/HCl residue are on the left

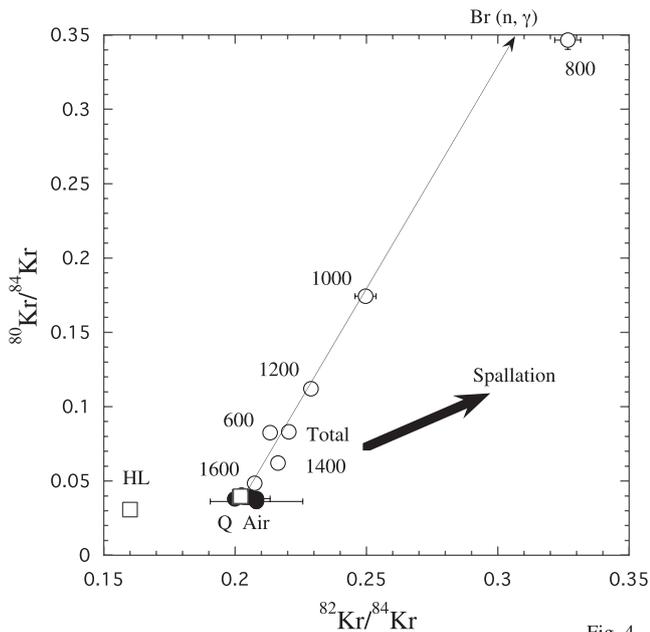


Fig. 4

Fig. 4. Three isotope plot showing $^{80}\text{Kr}/^{84}\text{Kr}$ versus $^{82}\text{Kr}/^{84}\text{Kr}$ of the bulk sample (open circle) and the HF/HCl residue (closed circle). The numerical values are the extraction temperatures of the stepwise heating. The data source of Q is from Busemann et al. (2000) and HL from Huss and Lewis (1994). There is no effect of Kr-HL for both samples and data points of the HF/HCl residue show no effect of cosmogenic nor neutron capture reaction. The thin arrow shows the isotopic shift by the neutron capture reaction of $\text{Br}(n, \gamma)$ (Murty and Marti 1987), and the thick arrow indicates that due to spallation (Marti et al. 1966).

side of Q. We cannot eliminate the possibility of small contributions of solar Xe and/or Xe-S. The carrier of Xe-S (SiC) is even more susceptible to thermal alteration than the carrier phase of Xe-HL (presolar diamond) (Huss et al. 1996), so it is likely that Xe-S has been lost.

In Fig. 7, the contributions from Q, HL, and air form a triangle. The Xe in the temperature fractions from bulk Saratov indicate a mixture of Q and air. The air contribution is most noticeable at the low temperature steps. This could indicate adsorbed atmospheric Xe. Owing to the uncertainty of the measurements we cannot unequivocally state that there is no Xe-HL, however, it is masked by Q.

Iodine-derived ^{129}Xe is largely removed from the HF/HCl residue, but the 600 and 800 °C extractions show some contribution of radiogenic ^{129}Xe (Fig. 8). This is probably due to the readsorption of ^{129}Xe during the chemical treatment. Readsorption of radiogenic ^{129}Xe was previously reported by Srinivasan et al. (1977) in the chemical residue, but it is not obtained upon physical separation of a Q-rich phase (Matsuda et al. 1999). This Xe may have resided in

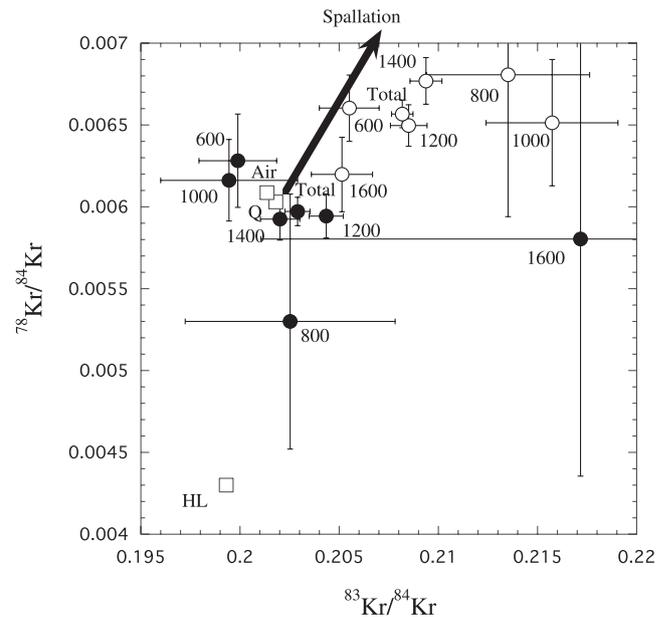


Fig. 5. Three isotope plot showing $^{78}\text{Kr}/^{84}\text{Kr}$ versus $^{83}\text{Kr}/^{84}\text{Kr}$. The symbols and the data sources are the same as those in Fig. 4. The arrow shows the direction to the product by spallation reaction (Marti et al. 1966). The bulk sample shows the effects of spallation and the neutron capture reaction.

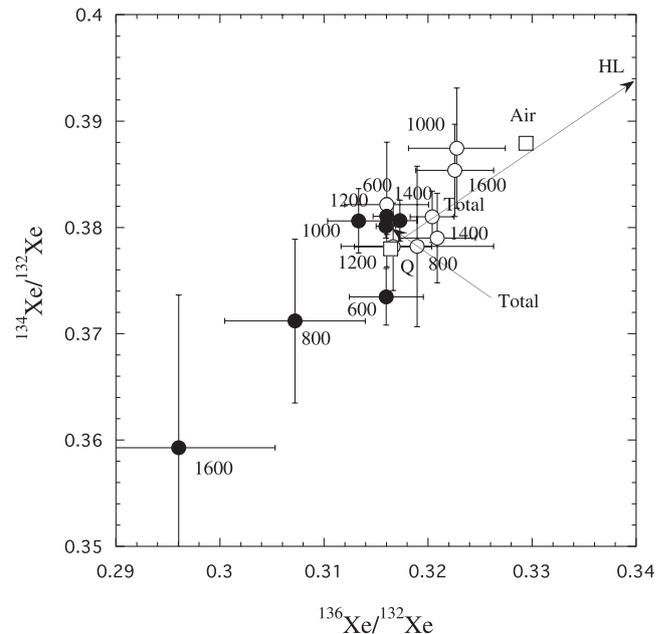


Fig. 6. Three isotope plot showing $^{134}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$. The symbols and the data sources are the same as those in Fig. 4.

sodalite, which was dissolved, the Xe then being readsorbed on the surface of the HF/HCl residue (Srinivasan et al. 1977).

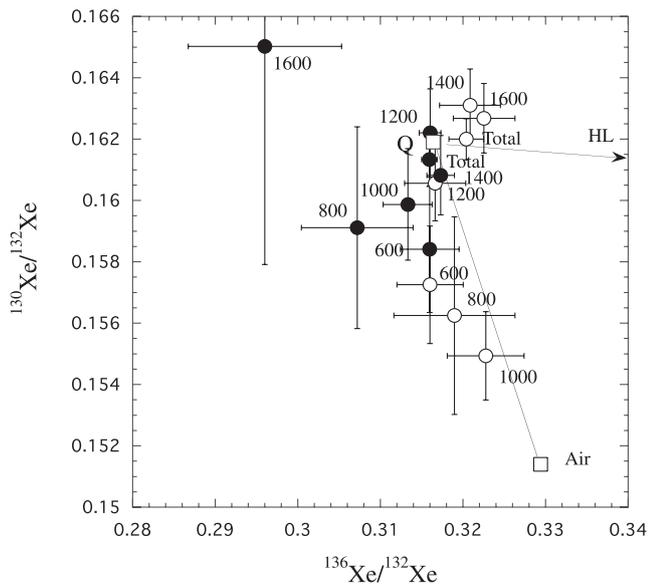


Fig. 7. Three isotope plot showing $^{130}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$. The symbols and the data sources are the same as those in Fig. 4.

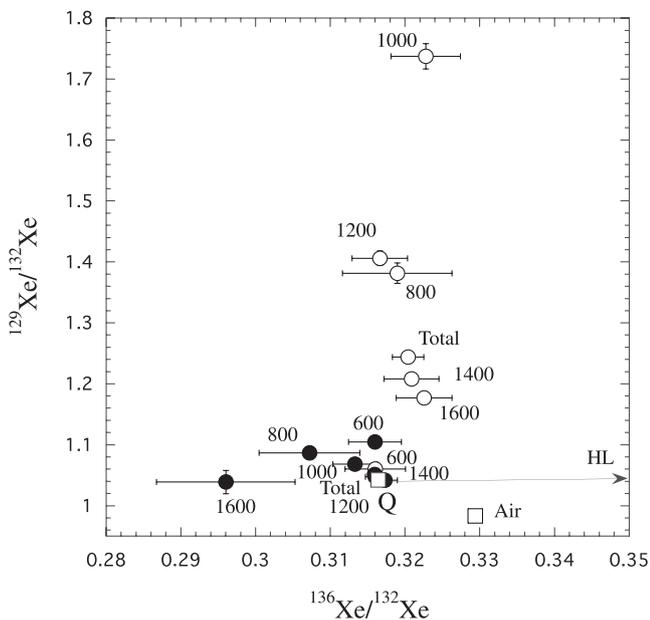


Fig. 8. Three isotope plot showing $^{129}\text{Xe}/^{132}\text{Xe}$ versus $^{136}\text{Xe}/^{132}\text{Xe}$. The symbols and the data sources are the same as those in Fig. 4. The data points of the bulk sample show the contribution of radiogenic ^{129}Xe . The low temperature fractions of the HF/HCl seem to show the effect of the readsorption of radiogenic ^{129}Xe during the chemical treatment.

The Xe isotopic ratios of the total for both bulk and the HF/HCl residue agree well with Q ratios (Table 3), especially, the extractions at 1200 and

1400 °C, the temperature where Xe-Q is released. This suggests that the isotopic composition of Xe-Q was not altered by thermal metamorphism. The total ^{132}Xe abundance (about $1.1 \times 10^{-7} \text{ cm}^3 \text{ STP/g}$) in the HF/HCl residue is 24–41% of that found in residues from primitive ordinary chondrites (LL3.0–LL3.1) (Huss et al. 1996). The Xe-Q abundance evidently decreases upon thermal metamorphism but the isotopic ratios of this component have not been altered. The ^{132}Xe concentration in Saratov is lower than that of Julesburg (L3.6), indicating a continuous trend of decreasing Xe-Q with increasing petrologic type for chondrites of subgroup 3 (Huss et al. 1996) to type 4.

DISCUSSION

Exposure Ages of Saratov

The ^3He and ^{21}Ne exposure ages for the bulk sample are 33 and 35 Ma, respectively. We used production rates of 1.59 and 0.271 in units of $10^{-8} \text{ cm}^3 \text{ STP/g per Ma}$, respectively (Eugster 1988). The production rates are corrected for shielding using the measured $^{22}\text{Ne}/^{21}\text{Ne}$ ratio of 1.16. For this calculation, we assumed that all the ^3He and ^{21}Ne are cosmogenic in the bulk sample. The cosmogenic age distribution of L chondrites peaks at 40 Ma with a minimum in the exposure age distribution of L chondrites around 30–35 Ma (Marti and Graf 1992). The ^3He and ^{21}Ne exposure ages of Saratov are this region. We assumed that the Ar is a mixture of trapped ($^{36}\text{Ar}/^{38}\text{Ar}_{\text{atm}} = 5.32$) and cosmogenic component ($^{36}\text{Ar}/^{38}\text{Ar}_{\text{c}} = 0.68$) (Schultz et al. 1991). The cosmogenic ^{38}Ar concentration is $0.740 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$. Using the equations of Eugster (1988) we obtained a production rate of $0.0426 \times 10^{-8} \text{ cm}^3 \text{ STP/g per Ma}$, yielding an ^{38}Ar exposure age of 17 Ma, about a half the ^3He and ^{21}Ne exposure ages. This discrepancy may be due to uncertainty of the production rates and/or an inhomogeneity in target element concentrations. Another possibility is an overcorrection of the trapped component. Part of the trapped ^{36}Ar might have been produced by the capture of thermal neutrons on ^{35}Cl . However, the amount of ^{36}Ar produced by this reaction, as judged from the neutron-produced ^{80}Kr , is negligible. ^{38}Ar exposure ages lower than ^{21}Ne exposure ages are also reported in achondrites (Welten et al. 1997), where the differences are greater than a factor of two. Welten et al. (1997) concludes that it is primarily due to the uncertainties of the shielding correction for the production rates. A lack of target element chemistry also may contribute to the problem. Schultz et al. (1991) used the production rates of ^3He and ^{21}Ne given by Eugster (1988). For ^{38}Ar ,

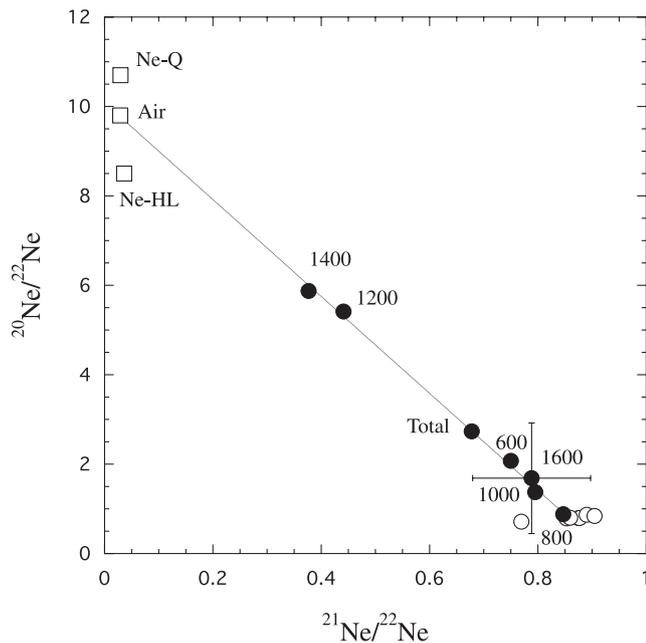


Fig. 9. Three isotope plot showing $^{20}\text{Ne}/^{22}\text{Ne}$ versus $^{21}\text{Ne}/^{22}\text{Ne}$ for the bulk sample (open circle) and the HF/HCl residue (closed circle). The numerical values are the extraction temperatures ($^{\circ}\text{C}$) of the stepwise heating (only shown for the HF/HCl residue). The data source of Murchison Q is from Wieler et al. (1992) and HL from Huss and Lewis (1994).

Schultz et al. (1991) used a production rate 13% lower than that proposed by Eugster (1988) for H chondrites.

On the Ne-Q

Neon extractions lie very well on a straight line (Fig. 9), indicating two component mixing in Saratov. The regression line in Fig. 9 is obtained using least squares and includes all extractions for the HF/HCl residue. One end-member is cosmogenic Ne, the other is close to air but the data indicate a component other than air. The trapped Ne was released at 1200 and 1400 $^{\circ}\text{C}$. These temperatures are too high to represent release temperatures of physically adsorbed air. If the end-member is air, low temperature fractions should have been more enriched in air because of the weak interaction due to physical adsorption; so it is unlikely that the end-member is atmospheric. As Xe is present in the Q phase in the HF/HCl residue, it is reasonable to infer that the end-member is Ne-Q. However, the best fit line does not intersect the composition of Ne-Q. Similar behavior was observed in the residues of Julesburg (L3.6) and Abee (EH4) (Huss et al. 1996).

The first possibility is that the low $^{20}\text{Ne}/^{22}\text{Ne}$ ratio in the residue may be due to an addition of Ne-HL to Ne-Q. However, the release temperature of Ne-HL is

about 800 $^{\circ}\text{C}$ while that of Ne-Q is 1200 $^{\circ}\text{C}$. If Ne-Q and Ne-HL are contained in distinct carriers, the Ne data of these HF/HCl residue should be scattered in the triangle bound by three end-members (cosmogenic component, Ne-Q, and Ne-HL) in a Ne three isotope plot. Huss et al. (1996) proposed that a fraction of the Ne-HL was captured by the Q-phase during thermal metamorphism. The $^{20}\text{Ne}/^{22}\text{Ne}$ ratios of the modified Ne-Q component reported by these authors are about 10.6 and 9.6 (assuming $^{21}\text{Ne}/^{22}\text{Ne} = 0.035$) for Julesburg and Abee, respectively. The intersection of the regression line and the line connecting Ne-Q and Ne-HL for Saratov is $^{21}\text{Ne}/^{22}\text{Ne} = 0.0320$ and $^{20}\text{Ne}/^{22}\text{Ne} = 9.84 \pm 0.18$. There is no Xe-HL in the HF/HCl residue of Saratov, so, it is puzzling why only Ne-HL was captured in phase Q. Similar observation have been made for graphite nodules in the Canyon Diablo iron meteorite (Matsuda et al. 2005). They reported that only Ne-HL was observed as a trapped component for Ne, even when Xe-HL was absent and only Xe-Q was observed. This has been attributed to loss of Xe-HL during thermal metamorphism. It is likely that Ne-HL was present in spite of the absence of Xe-HL because the Ne concentration is much larger than the Xe concentration in the presolar diamond, the carrier of HL gases.

The second possibility is that the trapped Ne was mass fractionated. The loss of light Ne during thermal metamorphism would leave reservoir of isotopically heavy Ne. We derived the Ne isotopic ratios ($^{21}\text{Ne}/^{22}\text{Ne} = 0.0283$ and $^{20}\text{Ne}/^{22}\text{Ne} = 9.88$) as the crossing point of the regression line and the mass fractionation line starting from Ne-Q. If Rayleigh fractionation is the main mechanism for the isotopic fractionation the residual amount of Ne should be about 20% of the original. This would move the ratio from 10.7 (the $^{20}\text{Ne}/^{22}\text{Ne}$ ratio of Murchison Ne-Q; Wieler et al. 1992) to 9.88. The ^{22}Ne -Q abundance is estimated to be about $1.3 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$ in the HF/HCl residue of Saratov. This value is much lower than the ^{22}Ne -Q concentrations (about $1.0 \times 10^{-7} \text{ cm}^3 \text{ STP/g}$) of L3.5 Mezö Madaras and is comparable with that (about $1.2 \times 10^{-8} \text{ cm}^3 \text{ STP/g}$) of L3.6 Julesburg (Huss et al. 1996). However, ^{22}Ne -Q concentrations vary among meteorites, and the value in Saratov (L4) is higher than those LL3.4 and H3.7 chondrites of lower petrologic types (Table 8 in Busemann et al. 2000). Evidently, there is no correlation between the ^{22}Ne -Q amounts and the petrologic types.

Busemann et al. (2000) reported that there are two groups of $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{Q}}$ ratio of 10.67 ± 0.18 (Allende, Murchison, Dimmitt, Grosnaja, and Chainpur) and 10.11 ± 0.04 (Dhajala, Lancé, and Cold Bokkeveld) and concluded that there is no correlation between the

$(^{20}\text{Ne}/^{22}\text{Ne})_{\text{Q}}$ ratio and the metamorphic grade and that low $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{Q}}$ ratios do not depend on thermal alteration. They also suggested the possibility that $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{Q}}$ ratios consisted of high and low $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{Q}}$ ratios in different proportions in individual chondrite because there is a variation of $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{Q}}$ ratios (10.13–10.36) even in a single meteorite Lancé (Busemann et al. 2000). Close inspection of Fig. 9 shows that individual points slightly deviate from the best fit line. Because all data points are rather close to the cosmogenic end-member, the extrapolation of the composition of the trapped end-member thus has a large uncertainty. If we extrapolate each individual data point separately from the cosmogenic component and calculate the intersection with the line connecting Ne-Q and Ne-HL, we obtain a similar (or even larger) variation of the $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{Q}}$ ratios compared to that (approximately ± 0.1) in Lancé (Busemann et al. 2000).

In any case, our obtained value (9.84 ± 0.18) of the $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{Q}}$ ratio obtained from the two components mixing model is lower than 10.11 ± 0.04 (for Dhajala, Lancé, and Cold Bokkeveld by Busemann et al. 2000) but agrees well with the value of 9.6 obtained for EH4 Abee (Huss et al. 1996). There may be more variability of $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{Q}}$ ratios than so far assumed and unknown processes might have occurred to modify Ne-Q in the early solar system. Considering that there is no correlation between the $(^{20}\text{N}/^{22}\text{Ne})_{\text{Q}}$ ratios and petrologic types of meteorite, it seems reasonable to think that Ne-Q with variable composition existed before the noble gases were incorporated in meteorites and that the thermal metamorphism is not related with the variation of $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{Q}}$.

On the Neutron Capture Effect

Neutron capture has substantially altered the Kr isotopic composition of the bulk sample (Table 2, Fig. 4). The $^{80}\text{Kr}/^{84}\text{Kr}$ ratio of the 800 °C fraction of the bulk sample is about an order of magnitude higher than values previously reported in ordinary chondrites (e.g., Alaerts et al. 1979; Moniot 1980). The relevant reaction is $^{79}\text{Br}(\text{n}, \gamma\beta)^{80}\text{Kr}$. The ^{80}Kr amount produced by neutron capture is calculated to be $3.0 \times 10^{-11} \text{ cm}^3$ STP (Table 2). Using the Kr data, we can also calculate neutron capture contributions on ^{36}Ar and ^{128}Xe .

Argon-36 is produced by the reaction $^{35}\text{Cl}(\text{n}, \gamma\beta)^{36}\text{Ar}$. The $^{35}\text{Cl}/^{79}\text{Br}$ ratio in Saratov is not known, so we used the solar abundance ratio of 478 (Anders and Grevesse 1989). This value is about two times higher than the estimated value of 222 for Dimmitt (H3.4) (Moniot 1980). Using the resonance integral (0.6

barns for ^{35}Cl and 110 barns for ^{79}Br) proposed by Marti et al. (1966) where the neutron energy of 30–300 eV produces most of ^{80}Kr , we obtain the concentration of neutron-produced ^{36}Ar as $7.8 \times 10^{-11} \text{ cm}^3$ STP. The concentration of ^{36}Ar in the bulk Saratov is $6.77 \times 10^{-8} \text{ cm}^3$ STP, so that produced by neutron capture is only about 0.1%, a negligible contribution.

Xenon-128 is produced by the reaction of $^{127}\text{I}(\text{n}, \gamma\beta)^{128}\text{Xe}$. The solar abundance ratio $^{127}\text{I}/^{79}\text{Br}$ is 0.150 (Anders and Grevesse 1989). Again, neutrons in the 30–300 eV range are expected to produce most of the ^{80}Kr and the ^{128}Xe (Marti et al. 1966). Using the resonance integral (130 barns for ^{127}I and 110 barns for ^{79}Br), we obtain a ^{128}Xe concentration as $5.3 \times 10^{-12} \text{ cm}^3$ STP for the neutron-produced component. This represents about 4% of the total ^{128}Xe amount ($1.4 \times 10^{-10} \text{ cm}^3$ STP) in bulk Saratov. The slightly elevated $^{128}\text{Xe}/^{132}\text{Xe}$ ratio (0.0835 ± 0.0005) of the total bulk sample may be attributed to this effect. The excess ^{128}Xe amount calculated from the Q ratio (0.0822) is $2.1 \times 10^{-12} \text{ cm}^3$ STP, an amount compatible with the above estimated amount.

SUMMARY

1. The yield of the HF/HCl resistant residue in Saratov is 0.76%. The yield for Saratov is compatible with those in LL chondrites for petrologic type of 3–6 where the yield increases from 0.3% to 0.9% as petrologic type increases (Alaerts et al. 1979).
2. The Ar, Kr, and Xe concentrations in the original residue are two orders of magnitude higher than those in the bulk sample, whereas He and Ne concentrations are similar in the two samples. Our measurements indicate that the residue carries about a half of the heavy noble gases in the bulk sample. The $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios in the bulk, the residue and the dissolved fraction are very similar and are low compared with those in typical phase Q, indicating the loss of lighter noble gases due to thermal metamorphism. It is also conceivable that the gases released from phase Q during thermal metamorphism might be tightly retrapped in silicate.
3. The He, Ne, and Ar of the bulk sample are predominantly cosmogenic. The corresponding ^3He and ^{21}Ne exposure ages are 33 and 35 Ma, respectively, although ^{38}Ar exposure age gives low value of 17 Ma.
4. The isotopic ratios of Kr-Q and Xe-Q in the Saratov are, within errors, the same as the values determined from primitive chondrites, indicating

that that thermal metamorphism does not affect the isotopic compositions of Kr and Xe. We observed that the elemental abundance of the heavy noble gases was altered. Meanwhile, Ne-Q in Saratov shows a very low $^{20}\text{Ne}/^{22}\text{Ne}$ ratio, suggesting that thermal metamorphism may affect the Ne-Q by incorporating Ne-HL or by mass fractionation. Alternatively, the low $^{20}\text{Ne}/^{22}\text{Ne}$ ratio of Saratov Ne-Q may indicate that the isotopic ratio of Ne-Q is not homogeneous in our solar system.

5. Neutron capture effects are observed in the Kr isotopes in the bulk sample. Neutron-capture also produced a slightly elevated $^{128}\text{Xe}/^{132}\text{Xe}$ ratio.

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REFERENCES

- Alaerts L., Lewis R. S., and Anders E. 1979. Isotopic anomalies of noble gases in meteorites and their origins—III. LL-chondrites. *Geochimica et Cosmochimica Acta* 43:1399–1415.
- Alexander C. M. O'D., Arden J. W., Ash R. D., and Pillinger C. T. 1990. Presolar components in the ordinary chondrites. *Earth and Planetary Science Letters* 99:220–229.
- Anders E. and Grevesse N. 1989. Abundances of the elements: Meteoritic and solar. *Geochimica et Cosmochimica Acta* 53:197–214.
- Busemann H., Baur H., and Wieler R. 2000. Primordial noble gases in “phase Q” in carbonaceous and ordinary chondrites studied by closed-system stepped etching. *Meteoritics & Planetary Science* 35:949–973.
- Crabb J. and Anders E. 1981. Noble gases in E-chondrites. *Geochimica et Cosmochimica Acta* 45:2443–2464.
- Crabb J. and Anders E. 1982. On the siting of noble gases in E-chondrites. *Geochimica et Cosmochimica Acta* 46:2351–2361.
- Eugster O. 1988. Cosmic-ray production rates for ^3He , ^{21}Ne , ^{38}Ar , ^{83}Kr , and ^{126}Xe in chondrites based on ^{81}Kr -Kr exposure ages. *Geochimica et Cosmochimica Acta* 52:1649–1662.
- Grady M. M. 2000. *Catalogue of meteorites*, 5th ed. Cambridge, UK: Cambridge University Press. 689 p.
- Herd R. K., Hunt P. A., Venance K. E., and Killgore M. B. 2004. Preliminary mineralogical data from the Saratov (L4) primitive ordinary chondrite (abstract #2070). 35th Lunar and Planetary Science Conference. CD-ROM.
- Huss G. R. 1990. Ubiquitous interstellar diamond and SiC in primitive chondrites: Abundances reflect metamorphism. *Nature* 347:159–162.
- Huss G. R. and Lewis R. S. 1994. Noble gases in presolar diamonds I: Three distinct components and their implications for diamond origins. *Meteoritics* 29:791–810.
- Huss G. R., Lewis R. S., and Hemkin S. 1996. The “normal planetary” noble gas component in primitive chondrites: Compositions, carrier, and metamorphic history. *Geochimica et Cosmochimica Acta* 60:3311–3340.
- Lewis R. S., Srinivasan B., and Anders E. 1975. Host phase of a strange xenon component in Allende. *Science* 190:1251–1262.
- Marti K. and Graf T. 1992. Cosmic-ray exposure history of ordinary chondrites. *Annual Review of Earth and Planetary Sciences* 20:221–243.
- Marti K., Eberhardt P., and Geiss J. 1966. Spallation, fission, and neutron capture anomalies in meteoritic krypton and xenon. *Zeitschrift für Naturforschung* 21a:398–413.
- Matsuda J., Amari S., and Nagao K. 1999. Purely physical separation of a small fraction of the Allende meteorite that is highly enriched in noble gases. *Meteoritics & Planetary Science* 34:129–136.
- Matsuda J., Namba M., Maruoka T., Matsumoto T., and Kurat G. 2005. Primordial noble gases in a graphite-metal inclusion from the Canyon Diablo IAB iron meteorite and their implications. *Meteoritics & Planetary Science* 40:431–443.
- Moniot R. K. 1980. Noble-gas-rich separates from ordinary chondrites. *Geochimica et Cosmochimica Acta* 44:253–271.
- Murty S. V. S. and Marti K. 1987. Nucleogenic noble gas component in Cape York iron meteorite. *Geochimica et Cosmochimica Acta* 51:163–172.
- Ott U. 2002. Noble gases in meteorites—Trapped components. In *Noble gases*, edited by Porcelli D., 2002. Reviews in Mineralogy and Geochemistry, vol. 47: pp. 71–101.
- Ott U., Mack R. and Chang S. 1981. Noble-gas-rich separates from the Allende meteorite. *Geochimica et Cosmochimica Acta* 45:1751–1788.
- Reynolds J. H., Frick U., Neil J. M., and Phinney D. L. 1978. Rare-gas-rich separates from carbonaceous chondrites. *Geochimica et Cosmochimica Acta* 42:1775–1797.
- Schelhaas N., Ott U., and Begemann F. 1990. Trapped noble gases in unequilibrated ordinary chondrites. *Geochimica et Cosmochimica Acta* 54:2869–2882.
- Schultz L., Weber H. W., and Begemann F. 1991. Noble gases in H-chondrites and potential differences between Antarctic and non-Antarctic meteorites. *Geochimica et Cosmochimica Acta* 55:59–66.
- Srinivasan B., Gros J., and Anders E. 1977. Noble gases in separated meteoritic minerals: Murchison (C2), Ornans (C3), Karoonda (C5), and Abee (E4). *Journal of Geophysical Research* 82:762–778.
- Welten K. C., Lindner L., van der Borg K., Loeken T., Scherer P., and Schultz L. 1997. Cosmic-ray exposure ages of diogenites and the recent collisional history of the howardite, eucrite and diogenite parent body/bodies. *Meteoritics & Planetary Science* 32:891–902.
- Wieler R. and Baur H. 1995. Fractionation of Xe, Kr, and Ar in the solar corpuscular radiation deduced by closed system etching of lunar soils. *The Astrophysical Journal* 453:987–997.
- Wieler R., Anders E., Baur H., Lewis R. S., and Signer P. 1992. Characterisation of Q-gases and other noble gas components in the Murchison meteorite. *Geochimica et Cosmochimica Acta* 56:2907–2921.