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## ORIGIN OF ISOTOPIC FRACTIONATION OF TERRESTRIAL XENON

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**Abstract:** By taking account of a size distribution of planetesimals, we show that noble gases gravitationally trapped by planetesimals in the solar nebula can explain the isotopic fractionation of terrestrial Xe relative to Xe in primitive meteorites, leaving Kr and other lighter noble gases almost unfractionated. However, this model is not successful in explaining noble gas elemental abundances in the Earth.

### 1. Introduction

Isotopic composition of terrestrial Xe (not only atmospheric Xe, but also Xe in mantle-derived materials) is severely fractionated (about 3.5% per atomic mass unit) relative to that in primitive meteorites, whereas surface correlated Xe in lunar soil (SUCOR Xe), which approximates the solar Xe, has almost identical isotopic composition to that in primitive meteorites (*cf.* OZIMA and PODOSEK, 1983). Moreover, it seems to be a rule rather than an exception that Xe in the mantle-derived materials is characterized by excess  $^{129}\text{Xe}$  due to the decay of  $^{129}\text{I}$  ( $T_{1/2} = 16$  Ma) relative to the atmospheric Xe (*e.g.*, PHINNEY *et al.*, 1978; STAUDACHER and ALLEGRE, 1982). This observation strongly suggests that isotopic fractionation of terrestrial Xe must have occurred at a very early stage of the Earth's accretion, say, before the decay of  $^{129}\text{I}$ .

In contrast to Xe, isotopic composition of Kr is almost identical among terrestrial materials, meteorites and SUCOR (BASFORD *et al.*, 1973). Therefore, to explain the isotopic fractionation of terrestrial Xe, one needs a special mechanism which could cause severe isotopic fractionation only in Xe, the heaviest noble gas, leaving Kr (and other lighter noble gases) almost unfractionated.

### 2. The Planetesimal-Type Noble Gases

As a possible mechanism of origin of isotopic fractionation of terrestrial Xe, OZIMA and NAKAZAWA (1980) proposed gravitational trapping of noble gases by planetesimals in the solar nebula. According to their theory, the enrichment factor  $\alpha_i$ , the ratio of the amount of a noble gas atom  $i$  gravitationally trapped by planetesimals to that when gravity is not taken into account, is expressed as,

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$$\alpha_i = 3 \exp(A\mu_i) \int_0^1 x^2 \exp(-A\mu_i x^2) dx,$$

$$A \equiv (m_H/kT)(2\pi/3)\rho_s GR^2,$$

$$x \equiv r/R,$$
(1)

where  $k$  is Boltzmann's constant,  $T$  the absolute temperature,  $\mu_i$  the atomic weight of the noble gas  $i$ ,  $m_H$  the mass of hydrogen atom,  $R$  the radius of the planetesimal and  $\rho_s$  the density of the planetesimal. Because the enrichment factor  $\alpha_i$  increases exponentially with an atomic weight, isotopic fractionation becomes larger in a heavier noble gas element than in a lighter one. OZIMA and NAKAZAWA (1980) showed that isotopic fractionation is the largest in Xe among all noble gas elements and that observed isotopic fractionation of terrestrial Xe could be approximately explained by Xe gravitationally trapped by a planetesimal of about 600 km in radius. However, there remains a problem in their theory that gravitationally trapped Kr also should show non-negligible isotopic fractionation when the planetesimal becomes large enough to produce Xe isotopic fractionation, which is contrast to the observation.

### 3. A Size Distribution of Planetesimals

We worked to circumvent the above difficulty by taking account of a size distribution of planetesimals. The radius of planetesimals around the Earth's orbit was estimated to be about a few km (*e.g.*, HAYASHI *et al.*, 1985) when they were formed by fragmentation of a dust layer due to gravitational instability at the ecliptic plane in the solar nebula. Planetesimals then collided with each other to form larger planetesimals. The size distribution of planetesimals growing in the solar nebula was simulated by NAKAGAWA *et al.* (1983). Although the size distribution could not be expressed by a simple function, they showed that it could be approximated by an exponential function of the radius of a planetesimal for larger bodies than a typical size of the growing planetesimals (for smaller bodies, the size distribution is proportional to  $R^{-9/2}$ ). Because the noble gas amount trapped in planetesimals becomes significant for large-sized planetesimals, we may approximate the size distribution of planetesimals by a "Γ distribution",

$$N(R) \simeq (R/R_0) \exp(-R/R_0),$$
(2)

where  $R_0$  is the radius at the maximum of  $N(R)$  (the mode of the radius). Planetesimals growing in the solar nebula continued to trap noble gases gravitationally from ambient nebula gases. The Earth was then formed by accretion of planetesimals of various sizes containing various amounts of noble gases. Therefore, noble gases trapped by the Earth would be a mixture of those gravitationally trapped by earth-accreting planetesimals of various sizes.

### 4. Isotopic Fractionations of Noble Gases in the Earth-Accreting Planetesimals

The enrichment factor for a mixture of noble gases in the earth-accreting planetesimals which have the size distribution (eq. 2) is expressed as,

$$\bar{\alpha}_i = \int_0^{R_{\max}} \alpha_i N(R) R^3 dR / \int_0^{R_{\max}} N(R) R^3 dR, \quad (3)$$

where  $R_{\max}$  is the maximum radius of the planetesimals.

Isotopic fractionation is conventionally expressed in terms of  $\delta$ -values relative to the solar isotopic composition. In the case of Xe,  $\delta_i$  will be defined as

$$\delta_i \equiv \{({}^i\text{Xe}/{}^{130}\text{Xe})/({}^i\text{Xe}/{}^{130}\text{Xe})_{\text{solar}} - 1\} \times 1000, \quad (4)$$

$\delta_i$  is then expressed in terms of  $\bar{\alpha}_i$  defined in eq. 3,

$$\delta_i = (\bar{\alpha}_i / \bar{\alpha}_{130} - 1) \times 1000. \quad (5)$$

Table 1. Isotopic fractionation ( $\delta_i$  in per mil) for noble gases in planetesimals which have a size distribution with various  $R_{\max}$ . We also assumed  $R_0=30$  km (the mode of the radius of planetesimals).

$R_{\max}$ (km)	$\delta_i$				
	${}^4\text{He}$	${}^{20}\text{Ne}$	${}^{36}\text{Ar}$	${}^{84}\text{Kr}$	${}^{130}\text{Xe}$
300	3.7	3.8	4.0	4.4	4.9
600	4.1	4.4	4.7	6.1	9.1
900	4.1	4.4	4.7	6.3	14.9
1080	4.1	4.4	4.7	6.3	35.2
1200	4.1	4.4	4.7	6.4	100.7
$R$ (single planetesimal) <sup>a</sup>					
730	—	10	20	30	40

<sup>a</sup> OZIMA and NAKAZAWA (1980).

Table 1 shows  $\delta_i$  per atomic mass unit for various  $R_{\max}$  in the case of  $R_0=30$  km. The  $\delta_i$  for a single planetesimal (OZIMA and NAKAZAWA, 1980) is also listed for comparison. As the  $R_{\max}$  becomes large,  $\delta_i$  is enhanced significantly only in the case of Xe. Consequently, compared with the case of planetesimals of the same size, difference of  $\delta_i$  between Kr and Xe becomes very large when a size distribution of planetesimals is taken into account. For  $R_{\max}=1080$  km, Xe isotopic fractionation amounts to the observed value in terrestrial Xe (about 3.5‰/AMU), while Kr isotopic fractionation is only 0.6‰/AMU. Moreover, if we choose smaller  $R_0$  and larger  $R_{\max}$ , the difference of  $\delta_i$  between Kr and Xe becomes still larger, for example, we obtain Kr isotopic fractionation of 0.4‰/AMU for  $R_0=25$  km and  $R_{\max}=1500$  km, 0.2‰/AMU for  $R_0=20$  km and  $R_{\max}=2100$  km, with Xe isotopic fractionation of about 3.5‰/AMU. EBERHARDT *et al.* (1972) reported isotopic fractionation of terrestrial Kr relative to solar Kr in the opposite direction (−0.4‰/AMU). It is impossible for this model to explain such a Kr fractionation in the opposite direction. However, BASFORD *et al.* (1973) observed two principal isotopic fractionations in solar Kr, the first closely resembling the terrestrial Kr within  $10^{-3}$  at all isotopes and the second apparently fractionated with respect to the terrestrial isotopic composition by about −0.25‰/AMU, which is smaller than that observed by EBERHARDT *et al.* (1972). It seems that the fractionation of terrestrial Kr relative to solar Kr is not well established and needs further confirmation.

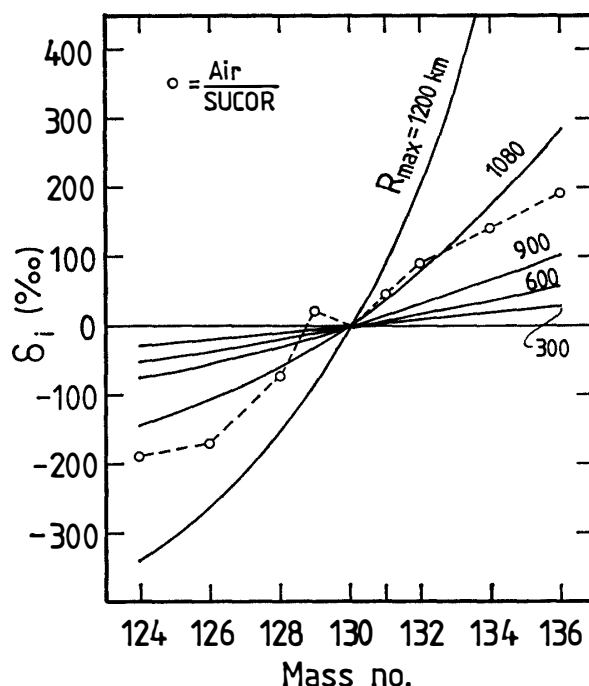


Fig. 1. Isotopic fractionation pattern for Xe in planetesimals which have a size distribution. Lines indicate the fractionation patterns for planetesimals with various  $R_{\max}$  in the case of  $R_0=30$  km. An isotopic fractionation pattern for Air Xe relative to SUCOR Xe (PODOSEK *et al.*, 1971), which is regarded to be close to the solar Xe composition, is also shown for comparison.

Isotopic fractionation lines calculated for various  $R_{\max}$  are shown in Fig. 1. An isotopic fractionation pattern for Air Xe relative to SUCOR Xe, which is regarded to be close to the solar Xe composition, is also shown for comparison.  $^{129}\text{Xe}$  excess in Air Xe can be attributed to a contribution of  $^{129}\text{I}$  decay. In addition, although there seems to be a difference of the isotopic fractionation pattern between Air Xe and the planetesimal-type Xe in heavy Xe isotopes ( $^{134}\text{Xe}$  and  $^{136}\text{Xe}$ ), it may be explained by a lunar fission component in SUCOR Xe, that is, SUCOR Xe cannot be directly identified with the solar Xe, but may contain a heavy Xe component such as a lunar fission component implanted on the grain surface by ion pumping processes (PODOSEK *et al.*, 1971). From the difference of isotopic fractionation pattern between Air Xe and Xe predicted by this model, we could estimate that the fission component in SUCOR Xe amount to  $(10 \pm 5)\%$  of total  $^{136}\text{Xe}$ .

In the above argument, we assumed that noble gases in planetesimals are in gravitational diffusion equilibrium. The time constant for heavy noble gases within a planetesimal of a radius of  $R$  is of the order of  $R^2/(4 \times 10^{10})\text{y}$  ( $R$  in cm) (OZIMA and NAKAZAWA, 1980), for example,  $R=2000$  km ( $2 \times 10^8$  cm) gives the time constant of  $10^6$  y. On the other hand, NAKAGAWA *et al.* (1983) showed by numerical calculations that the maximum size of planetesimals growing in the solar nebula exceeds  $R=2000$  km within the order of  $10^6$  y. Hence, it is plausible that the noble gases in a planetesimal with a radius up to a few thousand kilometers are nearly in gravitational diffusion equilibrium.

### 5. Elemental Fractionations of Noble Gases in the Earth-Accreting Planetesimals

In Table 2, we show enrichment factor  $\bar{\alpha}_1$  for various  $R_{\max}$  in the case of  $R_0 = 30$  km. The enrichment factor for a single planetesimal (OZIMA and NAKAZAWA, 1980) is also listed for comparison. By taking account of a size distribution of planetesimals, noble gas elemental fractionations become much smaller than that for a single planetesimal; the values of enrichment factor become only 2–4 for  $^{130}\text{Xe}$ , whereas those in single planetesimals of the same sizes are  $10^3$ – $10^4$ . Consequently, if we take the same values of porosity of planetesimals and nebular conditions as those used by OZIMA and NAKAZAWA (1980), the total amount of heavy noble gases contained in the earth-accreting planetesimals is too small to account for heavy noble gas abundances in the Earth, by about two orders of magnitude in Ar, about three orders of magnitude in Kr and Xe, whereas total Ne amount in the earth-accreting planetesimals is about the same order of magnitude as that in the Earth. Thus, this model is not successful in explaining both absolute and relative elemental abundances of noble gases in the Earth.

Table 2. Enrichment factor  $\bar{\alpha}_1$  for noble gases in planetesimals which have a size distribution with various  $R_{\max}$ . We also assumed  $R_0 = 30$  km.

$R_{\max}$ (km)	$\bar{\alpha}_1$				
	$^4\text{He}$	$^{20}\text{Ne}$	$^{36}\text{Ar}$	$^{84}\text{Kr}$	$^{130}\text{Xe}$
300	1.01	1.07	1.15	1.40	1.73
600	1.02	1.09	1.17	1.51	2.11
900	1.02	1.09	1.17	1.51	2.27
1080	1.02	1.09	1.17	1.51	2.62
1200	1.02	1.09	1.17	1.51	4.01
$R$ (single planetesimal) <sup>a</sup>					
730	1.08	2.10	4.34	67.3	$1.46 \times 10^3$
Air/Solar (normalized to $^{20}\text{Ne} \equiv 1$ ) <sup>b</sup>	—	$\equiv 1.00$	61.5	$3.8 \times 10^3$	$3.0 \times 10^3$

<sup>a</sup> OZIMA and NAKAZAWA (1980). <sup>b</sup> OZIMA and PODOSEK (1983).

### 6. Conclusion

We have reconsidered the gravitational segregation model proposed by OZIMA and NAKAZAWA (1980) by taking account of a size distribution of planetesimals growing in the solar nebula, and found that the difference of isotopic fractionation factor  $\delta_i$  between Kr and Xe becomes very large compared with that in a single planetesimal; when Xe isotopic fractionation amounts to that observed in terrestrial Xe (3.5‰/AMU), Kr is left almost unfractionated (less than 0.6‰/AMU). However, this model is not successful in explaining noble gas elemental abundances in the Earth. A more complicated model will be needed to explain both isotopic and elemental abundances of noble gases in the Earth.

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