

The isotopic composition of the primordial noble gas in the early solar system and its implications on solar oxygen isotopic composition. Ozima M¹, Yamada A¹, and Podosek F.A.². 1. Earth and Planetary Sciences, University of Tokyo, Tokyo 113-0033, Japan, ezz03651@nifty.ne.jp, 2. Department of Earth and Planetary Science, Washington University, St Louis, USA.

Introduction: The latest report of GENESIS project [1, 2] gave a convincing isotopic composition of oxygen in bulk solar wind sample collected on a concentrator, but correction for putative isotopic fractionation between SW and the Sun is still needed to conclude the solar oxygen isotopic composition. Although a model-dependent and somehow circular argument on a fractionation process was suggested in GENESIS report with the use of noble gas isotope as a reference [1, 2], an independent examination of the isotopic fractionation is urgent. Here, we studied noble gas isotopic fractionation between SW and the Sun, and conclude that the isotopic fractionations is almost two times larger than those adopted in the GENESIS oxygen isotopic data correction. Therefore, the isotopic fractionation concluded in this work, if applied to the GENESIS SW oxygen isotopic data, suggests that indigenous solar oxygen isotopic composition would be much closer to the terrestrial oxygen composition. Below we first discuss the primordial noble gas isotopic composition, which is used as a common reference in correcting for SW-Solar isotopic fractionation.

Primordial noble gas isotopic composition: Two major noble gas components are widely recognized in the early solar system, namely SW noble gas and Q noble gas in primitive meteorites. They are characterized by ubiquitous occurrence and by very uniform isotopic composition. Since Q-noble gas has much smaller ³He/⁴He, which is characteristic to pre-D burning He in the solar system [3], we conclude that Q-noble gas must predate SW noble gas. Figure 1 shows a schematic view of He isotopic evolution in the early solar system.

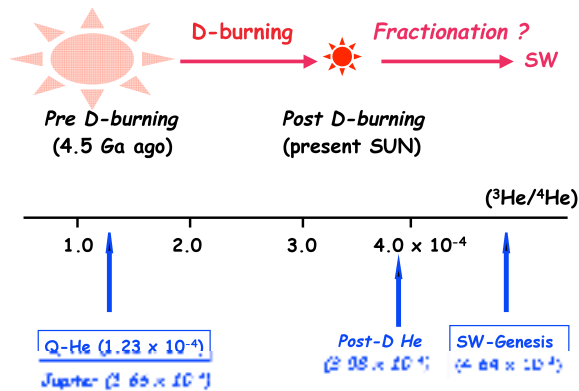


Figure 1. Helium isotopic evolution in the early solar system.

The current Solar He (Post D-burning He) consists of the primordial ³He and of D-converted ³He (D + p → ³He). The difference between the post-D He and Genesis SW-He then corresponds to isotopic fractionation between the Solar- and SW-He.

Noble gases isotopic fractionation in SW: In Figure 2, we plotted SW-noble gas isotopic ratios relative to Q-noble gas (SW/Q) against $(m_j/m_i)^{1/2}$, where m_j, m_i are mass number of isotope i, j . The approximate linear array of data points shows that the isotopic compositions of Q- and SW-noble gases are related to each other by a mass dependent fractionation factor $(m_j/m_i)^{1/2}$, commonly observed in a kinetic process such as Rayleigh distillation. Therefore, from this fractionation relation and from the seniority of Q-gas to SW noble gas, we conclude that SW noble gas was fractionated from Q noble gas. Next we discuss the origin of this characteristic fractionation factor.

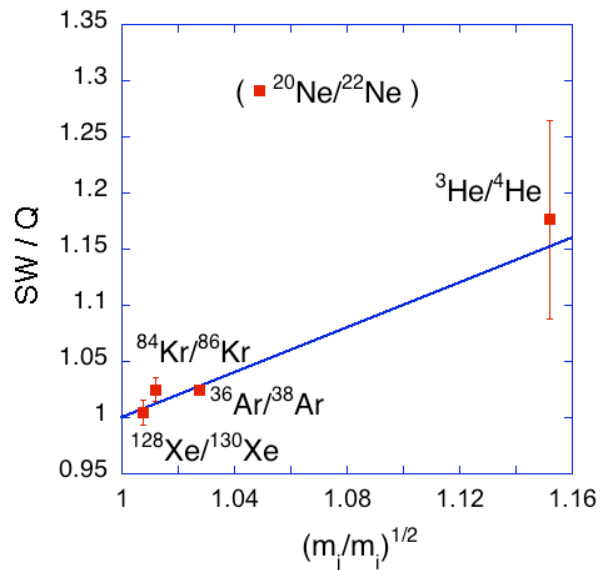


Figure 2. Noble gas isotopic ratios of SW relative to Q-noble gas is plotted against the square root of mass ratio. The approximate linear correlation line supports that SW-noble gases are fractionated from Q-noble gas with a fractionation factor proportional to $(m_j/m_i)^{1/2}$. Here, Ne ratio is discarded, because Q-Ne cannot be uniquely defined [4].

From an assumption on the conservation of ions in a stationary flow of plasma (SW), a relation $n_i V r^2 = \text{constant}$ (n_i : the number density of ion 'i', V : the bulk velocity of plasma, r : radial distance from the Sun) can be deduced [5]. On the basis of this relation, Bodemer and Bochsler [6] derived an expression for an isotopic fractionation of minor ions in SW,

$$\text{fractionation factor } (x, y) = v_x(r_b)/v_y(r_b) \quad (1)$$

,where x, y stand for a respective isotope and $v_x(r_b), v_y(r_b)$ indicate velocity of ions at radial distance r_b from the Sun, and a suffix b indicates an arbitrarily chosen reference point in the lower solar atmosphere. Assuming homogeneous temperature and concentration gradients in SW, Bodemer and Bochsler [6] solved a momentum equation to obtain

$v_x(r_b)/v_y(r_b)$ of ions, and deduced an approximate expression for isotopic fractionation known as Coulomb drag fractionation. However, since r_b is not clearly specified, it is difficult to judge the validity of the model. Below we propose an alternative process analogous to Rayleigh distillation-like mass dependent isotopic fractionation, which is inferred from Figure 2.

Extensive ionization of atoms takes place above the transition zone in the solar atmosphere. Once trapped into a magnetic flux, ions are essentially conserved within a magnetic flux. We assume that velocity ratio $v_x(r_b)/v_y(r_b)$ in eq. 1, may be more appropriately defined just below the transition layer or in the chromosphere, where atoms are neutral. We also assume a Boltzmann velocity distribution for both atoms and ions in this region, namely velocity is proportional to $(kT/m)^{1/2}$. Therefore, we have that $v_x(r)/v_y(r)$ in eq. 1 is proportional to $(m_y/m_x)^{1/2}$, in accordance with the empirical result inferred from Figure 2.

We note that the process is analogous to putative thermal escape of ions from the terrestrial ionosphere (Jeans escape), since number density and temperature are roughly similar both in the terrestrial ionosphere and in the transition zone in the solar atmosphere. The crucial difference between them is the gravitational force acting on ions, about 27 times larger in the Sun than in the Earth. However, owing to SW electrostatic field, gravitational force on ions in the solar atmosphere is largely cancelled to facilitate radial escape of ions [6].

Discussions : With the use of currently available observational data on D/H [7], H/He [8], we can further constrain the magnitude of noble gas isotopic fractionation between the SW and the Sun (Table 1). In Table 1, we also compare the magnitude of noble gas isotopic fractionation, which was used as a reference to correct the experimentally determined GENESIS SW oxygen isotopic composition to infer the solar isotopic composition [2].

	Rayleigh	This work	GENESIS
$^3\text{He}/^4\text{He}$	~ 15 %	~ 16 %	
$^{20}\text{Ne}/^{22}\text{Ne}$	~ 5.0	na	~ 3.0 %
$^{36}\text{Ar}/^{38}\text{Ar}$	~ 2.7	~ 3.0	~ 1.6
$^{84}\text{Kr}/^{86}\text{Kr}$	~ 1.2	~ 2.3	
$^{128}\text{Xe}/^{130}\text{Xe}$	~ 0.8	~ 0.6	

Table 1 Isotopic fractionation of noble gases relative to the solar ratios. Rayleigh: an isotopic fractionation factor is proportional to $1/(m_i/m_j)^{1/2}$, Genesis: (imperfect Coulomb drag isotopic fractionation [1]).

If fractionation factors for noble gases between SW and the Sun (*cf.* This work in Table 1) were applied to the GENESIS bulk SW oxygen isotope, oxygen isotopic compositions in the Sun would be further shifted to heavier isotopes along a terrestrial fractionation line well beyond the CAI point in an oxygen three isotope plot (e.g. Figure 4 in [2]), but they would come closer to the Earth composition,

although still requires some mass-independent isotopic fractionation to coincide with the Earth component

So far our argument concerned with mass-dependent type isotopic fractionation. This is reasonable in the case of noble gas, since the isotopic fractionation occurs through a kinetic process, which is essentially dependent on mass only. However, since the solar chromosphere is known to contain a substantial amount of CO molecule as deduced from IR absorption line in the solar radiation ($\text{CO}/\text{C} \sim 0.2\text{-}0.3$ [9]), mass-independent isotopic fractionation may also need to be considered in correcting oxygen isotopic fractionation between SW and the Sun. The photo-dissociation of CO [10] or the self-shielding of CO may be viable possibility.

Conclusions:

1. The average noble gas isotopic composition in the early solar system is represented by Q-noble gases, from which SW-noble gas was fractionated.
2. Noble gas isotopes in SW is mass-dependently fractionated relative to Q-noble gas with a fractionation factor inverse proportional to a square root of mass ratio of isotope. We suggest the characteristic fractionation factor is attributable to the Rayleigh distillation type fractionation.
3. If the noble gas isotopic fractionation factor concluded in this work were applied to the Genesis SW oxygen data, the corrected oxygen isotopic composition becomes much closer to the terrestrial composition than those suggested in the latest Genesis report [1, 2].
4. In the lower solar atmosphere below a transition layer, a substantial fraction of oxygen is likely to exist as CO rather than O, there could be mass-independent isotopic fractionation beside a mass-dependent fractionation inferred from noble gases [1, 2].

[1] Heber V. et al. (2011) *LPSXLII*, Abstract #2789. [2] McKeegan et al. (2011) *Science*, 332, 1528-1531. [3] Geiss J. and Reeves H. (1972) *Astronomy and Astrophysics*, 18, 126-132. [4] Busemann H. et al., (2000) *Meteoritics & Planetary Science*, 35, 949-973. [5] Geiss J. et al. (1970) *Solar Physics*, 12, 458-483. [6] Bodemer R. and Bochsler P. (2000) *J. G. R 105*, NO, A1, 47-60. [7] Linsky J.L. et al., (2006) *Astrophysical J.*, 647:1106-1124. [8] Basu S. and Antia H.M., (2004) *Astrophysical J.*, 606:L85-L88, 2004. [9] Asplund M. et al., (2009) *Ann. Rev. Astron. Astrophys.*, 47, 481-522. [10] Yamada A. et al. (2011) Abstract, Meteoritical Soc. Meeting, Greenwich, UK.