Origin of Mo isotope dichotomy between carbonaceous chondrites and non-carbonaceous meteorites

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The existence of nucleosynthetic isotope anomalies for refractory heavy elements in bulk meteorites evidently points to the heterogeneous distribution of dust grains with distinct isotopic compositions in the early solar nebula. Molybdenum is a promising element for the study of nucleosynthetic isotope anomalies in meteorites; previous studies found that bulk meteorites and their constituents including CAIs, chondrules, and presolar materials had nucleosynthetic isotope variations for Mo [1-6]. Recently, Warren [7] discovered isotopic dichotomy for O, Ti, and Cr between carbonaceous chondrites (CCs) and non-carbonaceous meteorites (NCs: ordinary, enstatite, and rumuruti chondrites, differentiated meteorites). Budde et al. [2] suggested that Mo isotopic compositions for CCs and their components could be discriminated from those of NCs. However, highly precise Mo isotopic data for NCs are limited so far because of analytical difficulties. In this study, we provide high precision Mo isotope data for NCs measured with N-TIMS to better understand the origin of source materials for NCs that represent the materials existed in the inner part of the early Solar System.

Molybdenum isotope analyses for nineteen NC samples from ten meteorite groups (ordinary chondrites: H, LL; rumuruti chondrites; irons: IIAB, IIE, IIIAB, IVA, IVB, ungrouped) have been made in this study. The meteorite samples were dissolved with HF–HNO_3 and HCl–HNO_3. Molybdenum was purified by employing two-stage chemical separation technique [8]. Molybdenum isotope analysis was performed with N-TIMS using TRITON *plus* (Thermo Fischer Scientific Inc., Bremen) installed at Tokyo Institute of Technology [9].

The extent of Mo isotope anomalies for NCs is clearly discriminated from that of CCs. Most importantly, the data points for NCs defined a positive linear correlation on the μ^{94}Mo–μ^{95}Mo diagram passing through the origin (i.e., Earth's composition), whereas those for CCs deviate from the Earth–NCs correlation line. An exception is that IVB irons and ungrouped irons (Chinga) have Mo isotopic compositions similar to CCs, presumably indicating that the parent bodies for these irons have formed under the physical condition (e.g., fO_2) similar to those of CC parent bodies [10-11]. Our observation suggests the existence of contributor which produced Mo isootpic difference between NCs and CCs. A possible carrier phase that involved in this difference is the type X presolar SiC enriched in ^{95}Mo and ^{97}Mo [6], although a dominant contributor of Mo isotope anomalies are considered to be the mainstream SiC [3].

Based on the data presented here, we propose that the observed Mo isotopic dichotomy has been formed across the formation region of meteorite parent bodies by the time when parent bodies of irons have accreted. The accretion of iron parent bodies for NCs (IIAB, IIAB, and IVA) and for presumed CCs (IVB) occurred within 0.3 Myr after CAI formation in the basis of the Hf–W system along with the S contents in irons [12]. The early formation of the two reservoirs regarding Mo isotope anomalies could be associated with the dramatic migration of giant planets that ultimately disturbed the composition of asteroid belt [13]. Therefore, determination of the timing of giant planet formation is crucial to decode the origin of Mo isotope dichotomy.

* $\mu^{i}\mathrm{Mo} = [(^{i}\mathrm{Mo}^{96}\mathrm{Mo})_{sample}(^{i}\mathrm{Mo}^{96}\mathrm{Mo})_{std} - 1] \times 10^{6}$

reference: [1] Burkhardt et al. (2011) *EPSL*, **312**, 390. [2] Budde et al. (2016) *EPSL*, **454**, 293. [3] Nicolussi et al. (1998a) *GCA*, **62**, 1093. [4] Nicolussi et al. (1998b) *ApJ*, **504**, 492. [5] Savina et al. (2007) *LPSC*, **38**, #2231. [6] Pellin et al. (2006) *LPSC*, **37**, #2041. [7] Warren (2011) *EPSL*, **311**, 93. [8] Nagai and Yokoyama (2014) *Anal. Chem.*, **86**, 4856. [9] Nagai and Yokoyama (2016) *JAAS*, **31**, 948. [10] Campbell and Humayun (2005) *GCA*, **69**, 4733. [11] Walker et al. (2008) *GCA*, **72**, 2198. [12] Kruijer et al. (2014) *Science*, **344**, 1150. [13] Walsh et al. (2011) *Nature*, **475**, 206.

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