ON THE ISSUE OF MOLYBDENUM ISOTOPIC ANOMALIES IN METEORITES: IS IT STILL "FUN"?

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Introduction: Since B^2FH (1957) and AGWC (1957) [1,2], heavy elements beyond the Fe group are known to be produced via two major nucleosynthetic paths; one is through the rapid neutron addition (r-process), usually associated with extremely neutron rich environments in supernova explosions. The second is through slow neutron addition (s-process), normally associated with AGB stars, where neutron density is not as high and the rate of neutron addition is slower than the rate of beta decay. By definition, the isotopic abundance pattern in the r-process is expected to be enriched for un-shielded nuclides, while nuclides shielded from free beta decay are deficient in r-process and enriched in s-process components. Thus in a reservoir representing mixtures of these nucleosynthetic processes such as the solar nebula, the isolated components are expected to be complimentary to each other in their isotopic abundance patterns.

Recent Mo isotope measurements in meteorites beautifully illustrate this theory (Fig.1). Similar observations have been made for other elements (e.g. Nd, Sm, Ba, and Xe; see [4] for review) primarily in the so called FUN inclusions ("Fractionated and Unknown Nuclear effects), while the new measurements were made in the "not so FUN" bulk carbonaceous chondrites as well as in CAIs [3]. The extension of such observations to Mo and Zr [3,5,6,7] represent advancement of new analytical capabilities. More stunning observations are expected in the near future. There are already indications of endemic Ru isotopic anomalies in iron meteorites and in Allende [8] as well as planet wide ^{54}Cr anomalies in the HED parent body [9], distinct from the Earth-Moon system and the bulk chondrites.

However, the Mo isotopic anomalies have also generated confusion, highlighted by a recent publication [10]. The issue centered around the terminology (definition of "bulk" rock vs. leachate) and whether the choice of isotope pair used to correct instrumental mass fractionation could generate artificial isotopic anomalies or not. The doubt cast by [10] about our Mo isotope work, as well as the recent works of several others, hinders the use of valid data and proper interpretation by cosmochemists and astrophysicists. This contribution is intended to clarify these issues through open discussions.

Normalization issue: To suggest that a simple choice of isotopic ratio for normalization could generate or erase non-linear isotopic anomalies is incorrect. The practice of normalization is merely to correct for a largely linear instrumental mass discrimination of light versus heavy isotopes. Non-linear isotopic anomalies are preserved regardless of choice of isotopic ratio (pairs) for normalization. The isotopic data are simply transformed. It is just another way of looking at the same data. If there exist interference on any of the isotopes used for normalization, then an apparent anomaly can be produced.

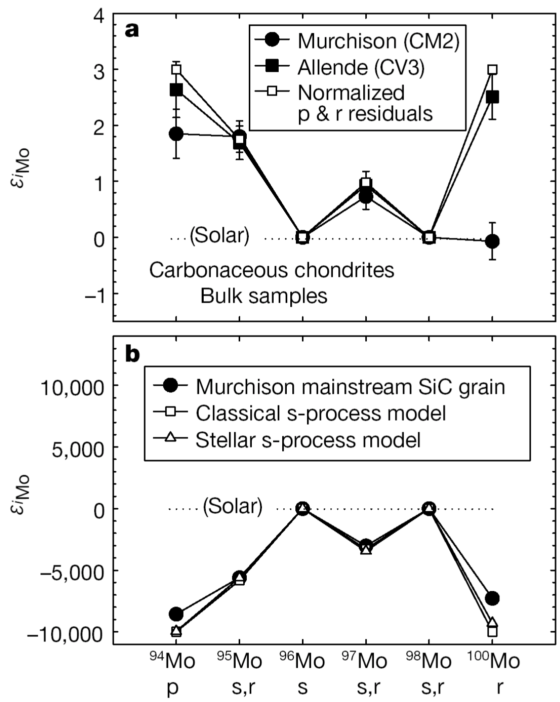

Fig. 1 Mo isotope anomalies in carbonaceous chondrites and a CAI compared with pre-solar SiC grain data and theoretical models (reproduced from Fig. 1 of Yin et al. [3]).

There is a very good reason why Mo isotope ratios in meteorites are best referenced to ^{96}Mo. This is independent of the isotopic ratios chosen for mass fractionation correction: either using ^{92}Mo/^{98}Mo or ^{96}Mo/^{98}Mo. The reason for choosing ^{96}Mo as denominator is that ^{96}Mo is the only Mo isotope with one unique nucleosynthetic origin (s-process only isotope). The rest of Mo isotopes are all of mixtures of multiple origins (r-, s-, and p-processes). Choosing ^{96}Mo as the reference isotope makes the identification of excess or deficit of other nucleosynthetic components easy relative to the s-process. The choice of a better reference isotope to make identification of certain components easier is a common practice in Xenology.

We have re-plotted Becker and Walker data [10], both with their normalization (Fig. 2) and by re-normalizing to $^{98}Mo/^{96}Mo$ (Fig.3) and in both cases with ^{96}Mo as reference isotope. This is very similar to what Yin et al. [3] have observed (Fig. 1, normalized to $^{96}Mo/^{98}Mo$). No matter how one looks at the data, we have to conclude that Becker and Walker have observed Mo isotopic anomalies similar to those of Yin et al. [3]. It is perplexing how Fig. 2 and 3 lead Becker and Walker [10] to conclude that "bulk Allende shows no evidence for significant enrichment in the p- and r-process isotopes, relative to pure s-process ^{96}Mo"?

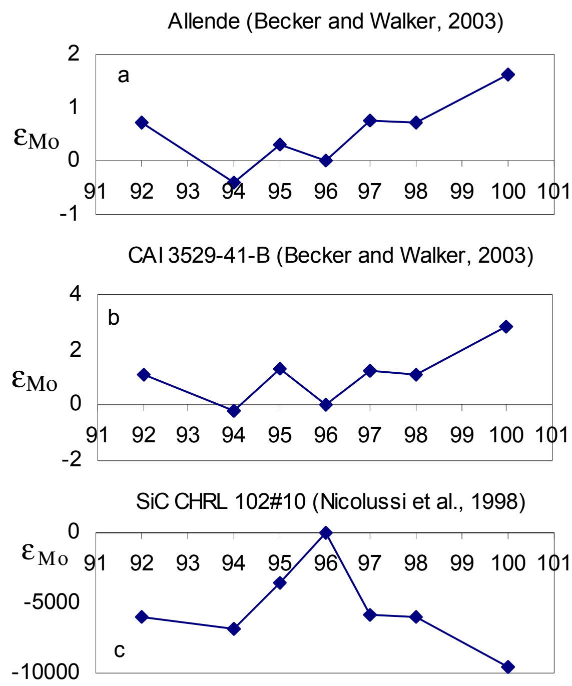

Fig. 2 Mo data for Bulk Allende and CAI from [10] normalized to $^{92}Mo/^{98}Mo$.

Concluding Remarks: The choice of terrestrial Mo isotopic composition as reference value is arbitrary. There is no *a priori* reason to expect the bulk isotopic composition of any material in the solar system is perfectly identical to that of the silicate Earth. Any imbalance between r- and s-process in any given reservoir at more than 1/10000 level is then expected to reveal its isotopic difference from the terrestrial value. This is especially true if multiple supernova sources are providing spikes of extinct radionuclides to the solar nebula leading to its final collapse. In this view, anomalies are the norm rather than exception, and results such as [3] provide a tool to study the scale and extent of heterogeneity in the solar system.

Thirty years after the discovery of oxygen isotope anomalies and other FUN anomalies, we are still on the difficult journey to walk out from the persistent mind set of Suess' hot, gaseous, well mixed nebula; the remnants of this idea creep into all discussions of meteorites and the early solar system. May the discovery of isotope anomalies at the bulk planetary scales mark the beginning of an end of the homogeneous nebula notion! The fun is just starting.

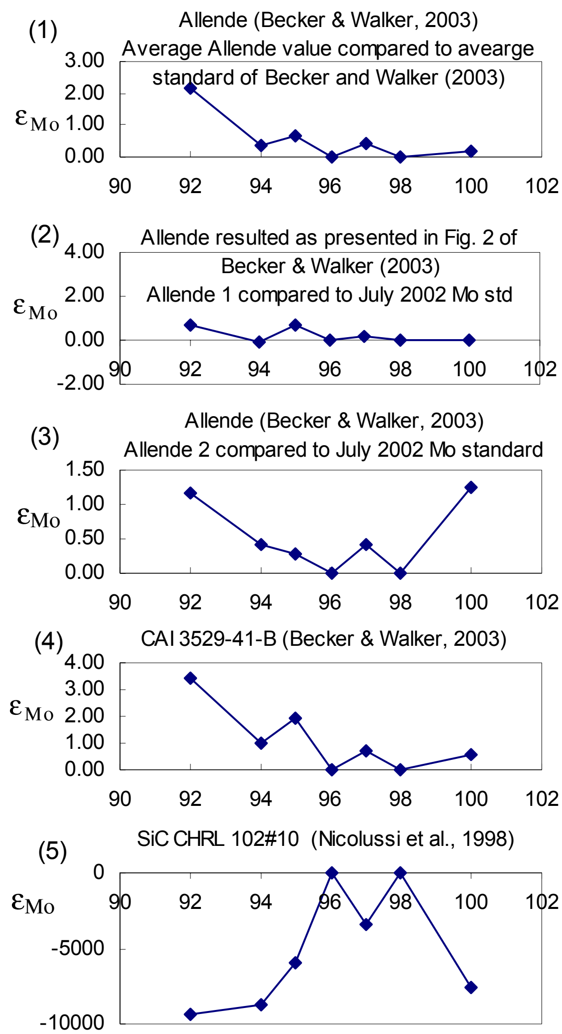

Fig. 3 Mo isotope data of [10] normalized to $^{96}Mo/^{98}Mo$. We note that only panel 2 is presented in [10] as an Earth-like Mo isotopic composition in their bulk Allende measurement.

References: [1] Burbidge et al. (1957) *Rev. Mod. Phys. 29,* 547-650. [2] Cameron A.G.W. (1957) *CRL-41 Atomic Energy of Canada Limited, 454,* 161pp. [3] Yin et al. (2002) Nature 415, 881-883. [4] Zinner E. (1997) AIP 3-26. [5] Yin et al. (2000) LPSC XXXI, 1920. [6] Yin et al. (2001) LPSC XXXII, 2128. [7] Nicolussi et al. (1998) *GCA*, 62, 1093-1104. [8] Chen J. H. et al. (2003) LPSC XXXIV 1789. [9] Trinquier A. et al. (2003) *GRA, 5,* 05916. [10] Becker H. and Walker R. (2003) Nature 425, 152-155.