INITIAL ABUNDANCE OF ^{60}FE IN THE INNER SOLAR SYSTEM: EVIDENCE FROM DIFFERENTIATED ASTEROIDS.

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Introduction: Among the short-lived radionuclides that may have been present in the early Solar System (ESS), ^{60}Fe is particularly important as a potential tracer for late injection of material from a nearby stellar source, since it is not produced efficiently by other means (such as by energetic particle irradiation). Furthermore, if present in sufficient abundance, it may have served as a significant heat source (along with ^{26}Al) for early planetesimal differentiation. At present, there is debate regarding the initial abundance of ^{60}Fe in the ESS, which has been estimated primarily based on analyses of two classes of meteoritic materials: 1) within components of unequilibrated chondrites, and 2) minerals and bulk samples of differentiated meteorites. Estimates of the Solar System initial ^{60}Fe/^{56}Fe based on analyses of chondritic components (particularly chondrules) are discussed in [1]. Here we review the evidence based on analyses of differentiated meteorites, and the implications for the initial ^{60}Fe abundance.

The first evidence for live ^{60}Fe in the ESS: Eucrites (1990s). The first unambiguous evidence for the presence of live ^{60}Fe in the ESS was reported in the eucrite Chervony Kut (CK) [2]. In this work, it was shown that mineral separates, leachates, and bulk samples of CK (analyzed by TIMS) had excesses in ^{60}Ni (~2-50 ε units relative to a terrestrial standard). While the Fe-Ni systematics in mineral separates and leachates appeared to be disturbed, three bulk samples defined an isochron relationship with a slope corresponding to a ^{60}Fe/^{56}Fe ratio ~3.9×10^{-9}, interpreted to be the value at the time of CK crystallization. This isochron also yielded a resolvably positive initial ^{60}Ni/^{58}Ni ratio (3.2 ± 0.9 ε units), which the authors suggested as having resulted from early Fe/Ni fractionation in the mantle source of the eucrite parent body (EPB) due to core formation. Since no absolute age determination exists for CK, these authors assumed that eucrite formation occurred ~10 My after Allende refractrory inclusions, and estimated a Solar System initial ^{60}Fe/^{56}Fe ~$1\text{-}2 \times 10^{-6}$ (assuming a ^{60}Fe half-life of ~1.5 My) [2].

This initial study was followed by a report of Fe-Ni systematics in the Juvinas (JUV) eucrite [3]. As was the case for CK, Fe-Ni systematics in leachates of JUV bulk samples appeared to be disturbed although bulk samples (unleached and leached) defined an isochron corresponding to a ^{60}Fe/^{56}Fe ratio ~4.3×10^{-10}, an order of magnitude lower than that obtained for CK. Taken at face value, this implied that JUV crystallized ~4.7 My after CK, which appeared to be consistent with the higher initial ^{60}Ni/^{58}Ni ratio (5.9 ± 0.8 ε units) determined for JUV. However, Mn-Cr systematics in CK and JUV indicate a formation time difference of only ~1.1 My between these two eucites [4]. Therefore, this suggested that either the closure temperatures for the Fe-Ni and Mn-Cr systems in these samples were different, or the Fe-Ni system was disturbed.

Investigations following the advent of MC-ICPMS: Achondrites and iron meteorites (2005-2008). More than a decade following the initial detection of radiogenic ^{60}Ni excesses in eucrites by TIMS [2,3], analytical advances in MC-ICPMS made it possible to measure Ni isotopes with sub-ε precision. Similar to the previous TIMS studies, the initial MC-ICPMS analyses of eucrites also indicated disturbance of the Fe-Ni system on the mineral scale due to thermal metamorphism [5]. While subsequent MC-ICPMS investigations of iron meteorites and achondrites have claimed improvements in the precision of Ni isotope measurements over previous studies, they have also yielded conflicting results suggesting that some analytical challenges may still remain to be resolved with ultrahigh-precision isotope ratio measurements of Ni isotopes. Specifically, several studies found no resolvable effects in ^{60}Ni (from the decay of ^{60}Fe) in metal of iron meteorites [6-8]. The most precise of these analyses [8] placed an upperlimit on the Solar System initial ^{60}Fe/^{56}Fe ratio of $<6 \times 10^{-7}$ assuming a delay of ~2 My between formation of refractory inclusions and metal-silicate differentiation in the iron meteorite parent bodies (and a half-life for ^{60}Fe of ~1.5 My).

In contrast, another study found uniform ^{60}Ni deficits (~25 ppm) in bulk samples of a variety of differentiated meteorites (including iron meteorites, pallasites, ureilites and angrites) relative to terrestrial materials and chondrites [9]. This was interpreted to imply that the earliest planetesimals accreted in the absence of live ^{60}Fe, which was subsequently injected ~1 My after the formation of the Solar System from a nearby stellar source. Yet another subsequent report found small but variable effects in ^{60}Ni in bulk samples of iron meteorites and chondrites [10]; however, estimated upper limits on the Solar System initial ^{60}Fe/^{56}Fe ratio were consistent with that proposed by [8]. A recent high precision study [11] has shown that while the results of

[9] were likely affected by an interference at mass 61, other previous data [8,10] are largely consistent with each other within their respective analytical precisions.

The latest findings: Angrites and eucrites (2010-present). More recent investigations (also conducted using MC-ICPMS) have focused on Fe-Ni systematics in the angrites and eucrites. In particular, Quitté et al. [12] reported Fe-Ni analyses of mineral separates and bulk samples of two quenched angrites (D'Orbigny and Sahara 99555), and one plutonic angrite (NWA 2999). They estimated $^{60}Fe/^{56}Fe$ ratios of ~2-4 × 10^{-9} at the time of crystallization of the two quenched angrites, that are thought to have formed contemporaneously [13,14] (the slopes of the isochrons for these two samples were consistent within the reported uncertainities). Furthermore, they also suggested that the bulk samples of these angrites defined a whole-rock Fe-Ni isochron (analogous to the whole-rock Mn-Cr isochron for the angrites reported by [15]) corresponding to a $^{60}Fe/^{56}Fe$ ratio of ~3 × 10^{-9} at the time of major Fe/Ni fractionation in their mantle sources. Finally, based on these and other analyses of additional meteoritic materials (including ureilites), it was suggested that ^{60}Fe was heterogeously distributed in the early Solar System.

More recently, we have undertaken MC-ICPMS analyses of bulk samples and mineral separates of various eucrites and angrites, preliminary results of which are reported by [16-19]. Here we report the results of Fe-Ni analyses of bulk samples of five eucritic meteorites, which define a single isochron corresponding to a $^{60}Fe/^{56}Fe$ ratio of (3.5 ± 0.5) × 10^{-9} and an initial $^{60}Ni/^{58}Ni$ ratio that is indistinguishable from the terrestrial value (i.e., $\varepsilon^{60}Ni_0$ = –0.10 ± 0.16). This whole-rock Fe-Ni isochron is thought to represent the timing of major Fe/Ni fractionation in the EPB. Assuming that mantle differentiaton on the EPB occurred 3.5 ± 1.3 Ma after the beginning of the Solar System, as inferred from comparison of the slope of the Mn-Cr HED whole-rock isochron [4] with initial $^{53}Mn/^{55}Mn$ ratio for the Solar System [20], an initial Solar System $^{60}Fe/^{56}Fe$ ratio of (0.9 ± 0.5) × 10^{-8} is estimated (assuming the recently re-determined ^{60}Fe half-life of 2.6 Ma [21]). It is noteworthy that the slope of the Fe-Ni whole-rock isochron for eucrites is identical to that defined by CK bulk samples [2], as would be expected given the similarity of the slopes of the Mn-Cr whole-rock isochron for the HEDs and the Mn-Cr internal isochron for CK [4]. However, the positive initial $^{60}Ni/^{58}Ni$ ratio for the CK Fe-Ni isochron (3.2 ± 0.9 ε) does not agree with that of the eucrite Fe-Ni whole-rock isochron (–0.10 ± 0.16 ε). The cause of this apparent discrepancy remains to be investigated.

We also report here an internal isochron, based on two mineral separates and two whole-rock fractions of the D'Orbigny angrite, that yields a $^{60}Fe/^{56}Fe$ ratio = (4.3 ± 1.7) × 10^{-9} and $\varepsilon^{60}Ni_0$ = -0.28 ± 0.34 at the time of last equilibration of Ni isotopes in this sample. These values agree with those reported for this meteorite by [12], but are more precisely defined. Assuming that D'Orbigny formed ~4-5 Ma after CAIs ([22-24]), initial $^{60}Fe/^{56}Fe$ ratios in the range of (1.2 ± 0.5) × 10^{-8} to (1.6 ± 0.6) × 10^{-8} are estimated, which is in agreement with that based on the Fe-Ni whole-rock isochron for eucrites discussed above. These latest estimates of the initial Solar System $^{60}Fe/^{56}Fe$ are similar to, or lower than, the values inferred for the ISM (~10^{-8} to ~10^{-7}) from closed-box GCE models and measurements of ^{60}Fe gamma ray emissions (e.g., [25,26] and references therein); if open-box models (that better explain the metallicity of G-dwarfs in the galaxy) are considered (e.g., [27,28]), $^{60}Fe/^{56}Fe$ ratios ~3 times higher are estimated for the ISM. Therefore, our estimated initial values obviate the need for late injection of ^{60}Fe into the protoplanetary disk from a nearby stellar source.

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