LOW ABUNDANCE AND HOMOGENEOUS DISTRIBUTION OF ^{60}FE IN THE EARLY SOLAR SYSTEM.

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Introduction: Iron-60 is particularly important as it can help establish early solar system chronology and its abundance provides critical constraints on the astrophysical context of solar system formation. However, the initial $^{60}Fe/^{56}Fe$ ratio at solar system birth, corresponding to the formation of Ca-Al-rich inclusions (CAIs) in meteorites, is uncertain. The first evidence for ^{60}Fe in solar system material was found in the form of excess ^{60}Ni in eucrites [1,2]. However, the closure time for the ^{60}Fe-^{60}Ni system in these meteorites was unknown, hindering a reliable estimate of the initial $^{60}Fe/^{56}Fe$ ratio at solar system birth. Subsequent studies have yielded widely variable initial $^{60}Fe/^{56}Fe$ ratio estimates. *In situ* measurements of chondrites (undifferentiated meteorites) by secondary ion mass spectrometry (SIMS) have given elevated $^{60}Fe/^{56}Fe$ ratios of around $\sim 6\times10^{-7}$ [3-7], while measurements of differentiated achondrites by multi-collector inductively coupled plasma mass spectrometry (MC-ICPMS) or thermal ionization mass spectrometry (TIMS) have given much lower ratios of $\sim 2\times10^{-8}$ [8-10]. The reason for this discrepancy is unknown but could be due to heterogeneous distribution of ^{60}Fe [8].

In this study we analyzed Fe-Ni systematics in achondrites (HED and angrites) and chondritic components (LL, ungrouped ordinary, and CB chondrites) using a ThermoScientific Neptune MC-ICPMS at the University of Chicago in order to solve the issue of the initial abundance of ^{60}Fe and of its distribution in different early-formed parent bodies, which is significant to assess the plausibility of the scenario of supernova-triggered solar system formation [11,12].

Results: Terrestrial rock standards passed through the same column chemistry as meteoritic samples have normal Ni isotopic ratios, attesting to the accuracy of the measurements.

(1)Achondrites.

Two groups of achondrites, ureilites and aubrites, did not yield any detectable ^{60}Ni excess because these samples have low Fe/Ni ratios.

In HED meteorites, Fe/Ni fractionation between bulk samples was produced by magma ocean differentiation. We measured 6 bulk non-cumulate eucrites (Camel Donga, Béréba, Pasamonte, Stannern, Juvinas, Ibitira) and 3 diogenites (Tatahouine, Johnstown, Shalka), which define a bulk rock isochron of slope $^{60}Fe/^{56}Fe = (3.20\pm0.29)\times10^{-9}$. According to ^{53}Mn-^{53}Cr systematics, mantle differentiation in the HED parent body took place 4.1±1.1 Myr after CAI formation [13,14]. Bulk rock isochrons are little susceptible to thermal disturbances, so one can safely use the time interval inferred from ^{53}Mn-^{53}Cr systematics to back-calculate a $(^{60}Fe/^{56}Fe)_0$ ratio at the time of CAI formation of $(0.95\pm0.30)\times10^{-8}$.

Eight bulk angrites were analyzed (NWA2999, NWA6291, NWA1670, NWA4590, NWA4801, Angra dos Reis, Sahara 99555, D'Orbigny), several of which show resolvable ^{60}Ni excesses linearly correlated with $^{56}Fe/^{58}Ni$ ratios. Data from plutonic angrites (Angra dos Reis, NWA4590, NWA4801) are scattered, possibly reflecting the protracted magmatic history of the angrite parent-body [15,16]. With this caveat, we calculate a $^{60}Fe/^{56}Fe$ ratio of $(2.62\pm1.02)\times10^{-9}$ at the time of core formation/global silicate differentiation in the angrite parent-body (APB), which is comparable to values reported by independent studies on similar samples [8,10]. Using the time interval between CAI and global silicate differentiation in the angrite parent-body from ^{53}Mn-^{53}Cr systematics (5.3±1.0 Myr) [14,17], an initial $(^{60}Fe/^{56}Fe)_0$ ratio at the time of CAI formation of $(1.05\pm0.50)\times10^{-8}$ is estimated.

We have also measured the Ni isotopic composition in mineral separates from the D'Orbigny meteorite. This angrite has a quenched texture indicative of rapid cooling [15] and several chronometers point to early crystallization, which must have occurred 5.6±1.0 Myr after CAI [14,18]. The data points define an internal isochron of slope $^{60}Fe/^{56}Fe= (3.20\pm0.53)\times10^{-9}$, from which we can back calculate the $(^{60}Fe/^{56}Fe)_0$ ratio at the time of CAI formation of $(1.38\pm0.43)\times10^{-8}$.

(2)Chondritic components.

The initial ratios obtained from HEDs and angrites are identical to one another, but are much lower than the initial ratio inferred from in situ measurements of chondrite components. To elucidate the cause of this discrepancy, we have measured the Ni isotopic compositions of chondrules and mineral separates from CB chondrite Gujba, as well as three ordinary chondrites Semarkona (LL 3.0), NWA 5717 (ungrouped 3.05), and Chainpur (LL 3.4) that have experienced minimal thermal metamorphism.

Chondrules from Semarkona and NWA 5717 are expected to show little disturbance in ^{60}Fe-^{60}Ni systematics [4,7]. The analyzed chondrules were from a larger batch of dissolved chondrules and were selected based on their elevated Fe/Ni ratios. A barely resolvable positive correlation between $\varepsilon^{60}Ni$ and Fe/Ni ratio was found in chondrules and mineral separates from unequilibrated ordinary chondrites (UOC), corresponding to a $^{60}Fe/^{56}Fe$ ratio of $(1.52\pm0.97)\times10^{-8}$ at chondrule formation (Fig.1A). The timing of formation of these objects is not precisely known but most chondrules in ordinary chondrites were formed 2.3±1.1 Myr after CAI [19]. This translates into an initial $^{60}Fe/^{56}Fe$ ratio at CAI formation of $(2.3\pm1.6)\times10^{-8}$ in the region of the protoplanetary disk where ordinary chondrites formed. CB chondrites are thought to have formed 5.7±1.3 Myr after solar system formation from a vapor-melt plume produced by a large impact between asteroids [20,21]. Despite the large spread in Fe/Ni ratios of Gujba chondrules, no excess ^{60}Ni was found corresponding to an upper-limit on the $^{60}Fe/^{56}Fe$ ratio of $<3.2\times10^{-9}$ at the time of CB chondrule formation (Fig.1B). This constrains the $^{60}Fe/^{56}Fe$ ratio at CAI formation to $<1.4\times10^{-8}$.

The values derived from chondrite measurements agree with the initial $^{60}Fe/^{56}Fe$ ratio inferred from angrite and eucrite data but are inconsistent with the high initial $^{60}Fe/^{56}Fe$ ratio inferred from SIMS data in similar chondrites. While the Fe/Ni ratios of the components studied here are much lower than those studied by *in situ* methods, our precision is superior and we should have detected excess ^{60}Ni of +3.7 ε-unit if the initial $^{60}Fe/^{56}Fe$ ratio at CAI formation was $\sim6\times10^{-7}$. Thus, our results indicate that different regions of the protoplanetary disk incorporated the same amounts of ^{60}Fe ($^{60}Fe/^{56}Fe = 1.08\pm0.21\times10^{-8}$).

(3) Iron-58 distribution.

A further way to examine the question of the homogeneity of ^{60}Fe in the early solar system is to measure the isotopic abundance of ^{58}Fe [22]. Indeed, in core-collapse supernovae, these two neutron-rich isotopes are produced by neutron-capture reactions on pre-existing Fe isotopes, therefore any heterogeneity in ^{60}Fe should be accompanied by ^{58}Fe isotope anomalies. If chondrites formed from a reservoir with $(^{60}Fe/^{56}Fe)_0\sim6\times10^{-7}$ while achondrites formed from a reservoir with $(^{60}Fe/^{56}Fe)_0\sim1\times10^{-8}$, the latter group of meteorites should deficits in ^{58}Fe of -3 ε-unit or more relative to chondrites [22]. We have measured at high precision the abundance of ^{58}Fe in most samples analyzed for ^{60}Ni, and failed to detect any variation in this isotope between different meteorite group. This supports the view that achondrites and chondrites shared the same initial $^{60}Fe/^{56}Fe$ ratio.

Analysis of γ-ray emissions from the galactic plane give a present $^{60}Fe/^{56}Fe$ ratio in the ISM at present as $(1.36\pm0.67)\times10^{-7}$ [23,24]. This value is ~10 times higher than the ratio measured in meteorites. Thus, the low abundance of ^{60}Fe documented here could have simply been inherited from abundances present in the interstellar medium (ISM) that made the solar system.

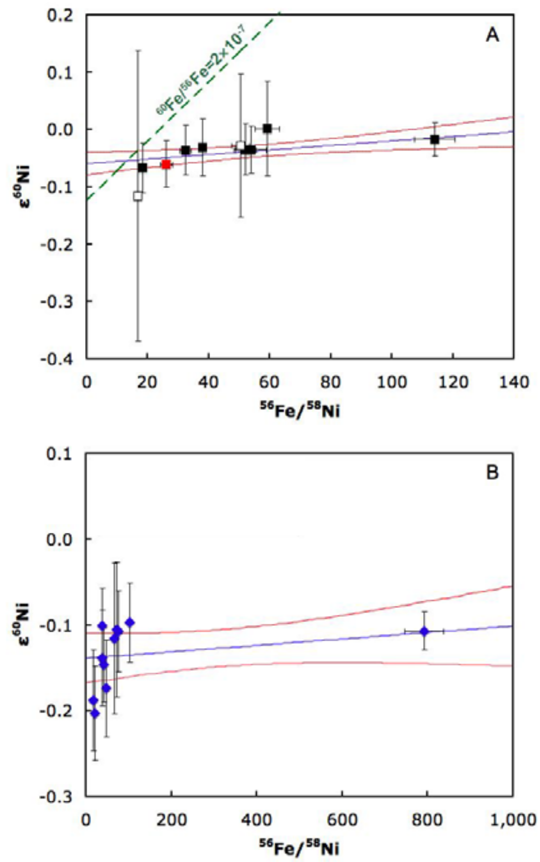

Figure 1A: Fe-Ni systematics in NWA5717 (black squares), Semarkona chondrules (open squares) and Chainpur (red square). B: Fe-Ni systematics in Gujba chondrules.

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