IRON-60 INJECTION IN THE PROTOSOLAR NEBULA: HOW EARLY AND HOW WELL MIXED? N. Dauphas[1], D.L. Cook[2], A. Sacarabany[1], C. Fröhlich[3], A.M. Davis[1], M. Wadhwa[4], A. Pourmand[1], T. Rauscher[5], and R. Gallino[6], [1]Origins Laboratory, Department of the Geophysical Sciences and Enrico Fermi Institute, The University of Chicago, Chicago IL 60637, USA, dauphas@uchicago.edu, [2]Department of Chemistry and Chemical Biology, Rutgers University, Piscataway, NJ 08854, USA, [3]Department of Astronomy and Astrophysics, Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637, USA, [4]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA, [5]Departement für Physik, Universität Basel, CH-4056 Basel, Switzerland, [6]Dipartimento di Fisica Generale dell'Universita' di Torino, 10125 Torino, Italy.

Introduction: Among extinct radioactivities, ^{60}Fe ($t_{1/2}$=1.49 My, decay product ^{60}Ni) plays a key role as a tracer of the astrophysical setting of solar system formation, a high-resolution chronometer, and a possible heat source in planetesimals [1-6]. Although the presence of ^{60}Fe in the Early Solar System (ESS) was established almost two decades ago [1,2], important progress has been made recently in estimating its initial abundance [5-8]. The present best estimate of the ^{60}Fe/^{56}Fe ratio at the time of condensation of the first solids in the ESS is 5 to 10×10^{-7}, based on *in situ* analyses of chondrule pyroxenes with elevated Fe/Ni ratios [6]. A major difficulty with ^{60}Fe-^{60}Ni systematics is the question of the ^{60}Fe distribution in the protosolar nebula. Several groups have analyzed Ni isotopes in iron meteorites and have found normal isotopic compositions within uncertainties [9-12]. However, Bizzarro *et al.* reported uniform deficits of 0.25 ε in ^{60}Ni in iron meteorites [13]. They interpreted these deficits as evidence that iron meteorite parent bodies accreted before ^{60}Fe was injected into the ESS by supernova dust [14]. They also reported ^{62}Ni deficits that they ascribed to incomplete mixing of the products of stellar nucleosynthesis.

If ^{60}Fe was injected late or was not well mixed in the protosolar nebula, then one would expect meteorites to show ^{60}Ni deficits (from lack of ^{60}Fe decay) and collateral effects on other neutron-rich isotopes of Fe and Ni coproduced with ^{60}Fe in both core-collapse supernovae (cc-SN) and AGB-stars. Here, we show that iron meteorites have Fe and Ni isotopic compositions identical to Earth and chondrites, thus demonstrating that ^{60}Fe was homogeneously distributed in the solar nebula at the 10 % level.

Material and methods: For Fe isotope analyses, we used aliquots of the samples Coahuila (IIAB), Santa Luzia (IIAB), Casas Grandes (IIIAB), Henbury (IIIAB), Molong (PMG) and Bishunpur (LL3.1, metal) dissolved by Cook *et al.* [9]. The protocol used for separation of Fe is described in ref. 15. The Fe isotopic analyses were performed on a Thermo Neptune MC-ICPMS at the University of Chicago in high-resolution mode on peak shoulders to avoid argide interferences on ^{54}Fe (^{40}Ar^{14}N), ^{56}Fe (^{40}Ar^{16}O), ^{57}Fe (^{40}Ar^{16}O^{1}H), and ^{58}Fe (^{40}Ar^{18}O). Mass fractionation was corrected by internal normalization to a fixed ^{57}Fe/^{54}Fe ratio using the exponential law. Mass-fractionation-corrected isotopic ratios are reported in ε-unit, $\varepsilon^{i}\text{Fe}=[(^{i}\text{Fe}/^{54}\text{Fe})/(^{i}\text{Fe}/^{54}\text{Fe})_{\text{IRMM014}}-1]\times10^{4}$, where IRMM-014 is a reference material representative of the terrestrial Fe composition. For Ni isotope analyses, we used aliquots of purified solutions previously analyzed by Cook et al. [9]. High resolution was also used to resolve interferences on ^{57}Fe (^{40}Ar^{16}O^{1}H, used for correction of ^{58}Fe isobaric interference on ^{58}Ni) and ^{58}Ni (^{40}Ar^{18}O). Two internal normalization schemes are reported in the literature (^{62}Ni/^{58}Ni [9-11] or ^{61}Ni/^{58}Ni [1,13]). Both normalizations were used to compute ε-values, $\varepsilon^{i}\text{Ni}=[(^{i}\text{Ni}/^{58}\text{Ni})/(^{i}\text{Ni}/^{58}\text{Ni})_{\text{SRM986}}-1]\times10^{4}$, where SRM-986 is a reference material representative of the terrestrial Ni composition. We report the most precise published measurements of the low abundance neutron-rich isotopes ^{58}Fe (±0.3 ε) and ^{64}Ni (±0.2 ε).

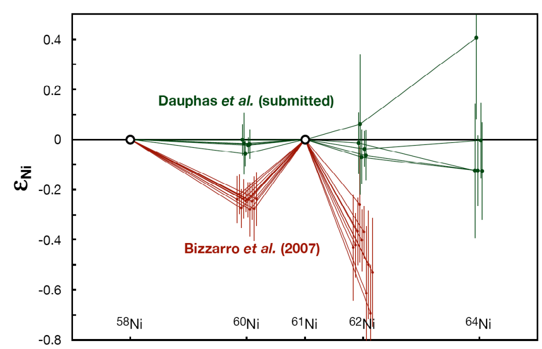

Fig. 1. Comparison between Ni data from this study and ref. 13 for differentiated meteorites (identical notation and internal normalization scheme were used). Because of its low abundance and the presence of a ^{64}Zn interference, ^{64}Ni data were not reported in ref. 13.

Results and discussion: As shown in Fig. 1, we did not detect any of the isotopic anomalies reported in ref. 13. The discrepancy is not due to differences in sampling (meteorites of the same type were analyzed in ref. 13 and this study) or the choice of the ratio used for correcting mass-dependent fractionation (the ^{61}Ni/^{58}Ni ratio was used in both ref. 13 and this study;

Fig. 1). If ^{60}Fe was heterogeneously distributed in the solar nebula, one would expect to see $\varepsilon^{60}Ni$ deficits in a hypothetical reservoir free of ^{60}Fe relative to chondrites. For $(^{60}Fe/^{56}Fe)_0=5\times10^{-7}$, the predicted $\varepsilon^{60}Ni$ effect is ~-0.3. Our high-precision measurements rule out the presence of such a deficit. The dispersion of less than ±0.05 around 0 in $\varepsilon^{60}Ni$ (using $^{62}Ni/^{58}Ni$ normalization) limits the possible heterogeneity of ^{60}Fe to less than ~15 %. This is consistent with the homogeneity of ^{26}Al in the accretion region of meteorite parent bodies [16] as well as dynamical simulations, which show that passive tracers are mixed in the nebula at the 10 % level on time-scales of a few thousand years [17].

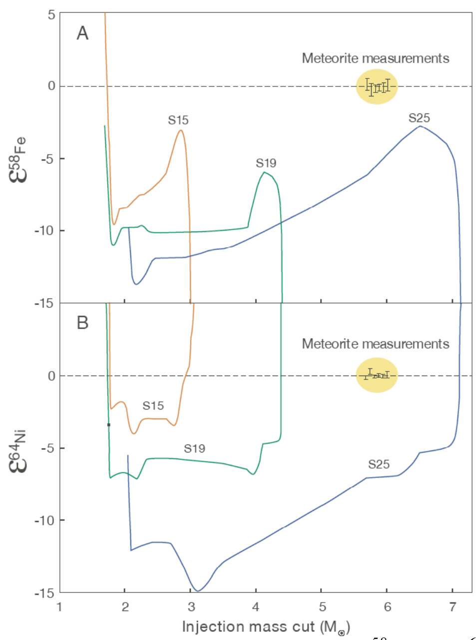

Fig. 2. Comparison between measured ^{58}Fe and ^{64}Ni isotopic compositions in meteoritic metal with predicted collateral isotopic effects if ^{60}Fe from a cc-SN was heterogeneously distributed in the ESS (see ref. 22 for definition of the injection mass cut).

Another means of investigating whether ^{60}Fe was heterogeneously distributed in the ESS is to search for collateral anomalies in other isotopes of Fe and Ni [18, 19]. Iron-58 is particularly useful because it is co-produced with ^{60}Fe by neutron-capture reactions in cc-SN and AGBs (possible nucleosynthetic sites for short-lived radioactivities) and cannot be chemically decoupled from ^{60}Fe during injection. We have computed expected collateral $\varepsilon^{58}Fe$ effects resulting from heterogeneous distribution of ^{60}Fe. Yields from 15, 19, and 25 $M_\odot$ cc-SN [20] and a 3 $M_\odot$ initial mass star with solar metallicity and standard ^{13}C-pocket [21] were used. For cc-SN injection, the predicted deficit on $\varepsilon^{58}Fe$ is -3 or more, depending on the injection mass cut [22]. For AGB injection, the predicted deficit on $\varepsilon^{58}Fe$ is -133. Such effects are inconsistent with $\varepsilon^{58}Fe$ measured in meteorites, which are all within ±0.3 of the terrestrial and chondritic value. This provides compelling evidence against delayed injection or incomplete mixing of ^{60}Fe in the ESS. The dispersion of ±0.3 in $\varepsilon^{58}Fe$ only allows for a heterogeneity of less than ~10 % in the initial $^{60}Fe/^{56}Fe$ ratio (if this ratio is 5×10^{-7}). A similar calculation for collateral effects on ^{64}Ni (in that case, one must make the reasonable assumption that ^{60}Fe and ^{64}Ni were not decoupled during injection) predicts ^{64}Ni deficits of -2 or lower for cc-SN injection and -125 for AGB injection. This contradicts measurements, which show normal $\varepsilon^{64}Ni$ within ±0.2. This also limits the possible heterogeneity of the $^{60}Fe/^{56}Fe$ ratio to within 10 %.

Conclusion: Iron and nickel isotopic analyses of meteorites indicate that ^{60}Fe must have been injected into the protosolar nebula and mixed at the 10 % level before formation of planetary bodies. Otherwise, ^{60}Ni deficits (from lack of ^{60}Fe decay) and collateral isotope effects on neutron-rich isotopes of Fe and Ni (co-produced with ^{60}Fe in AGB and/or cc-SN) would be present. Our measurements agree with results of dynamical modeling, showing that passive tracers are rapidly mixed in a turbulent nebula [17].

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