^{60}Fe-^{60}Ni SYSTEMS IN FERROMAGNESIAN CHONDRULES IN LEAST EQUILIBRATED ORDINARY CHONDRITES.
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Introduction: Iron-60, which decays to ^{60}Ni with a half-life of 1.49 Myr, is one of the now-extinct short-lived radionuclides in the solar system, and is produced efficiently only in stars. Because the estimated abundance of ^{60}Fe in the early solar system [1-3] cannot be explained by its steady-state abundance in the interstellar medium, its presence in the early solar system indicates that stellar nucleosynthesis shortly before or soon after the solar system formation contributed to the inventory of short-lived radionuclides. It is thus important to determine the initial abundance of ^{60}Fe in the early solar system in order to evaluate a stellar source(s), which brought short-lived radionuclides to the early solar system, and a birth environment of the solar system.

Clear evidence of the presence of ^{60}Fe has been found in sulfides and pyroxene-rich chondrules in least equilibrated ordinary chondrites [1-3]. However, sulfides are susceptible to mild thermal metamorphism or aqueous alteration on the parent body, so that the initial abundance of ^{60}Fe in the solar system has been only loosely constrained. Because silicates are much less susceptible to later disturbance on the parent body of unequilibrated chondrites, [3] analyzed ^{60}Fe-^{60}Ni systems in ferromagnesian pyroxene-rich chondrules from Semarkona (LL3.0) and Bishunpur (LL3.1) to estimate the initial abundance of ^{60}Fe in the solar system. The obtained $(^{60}Fe/^{56}Fe)_0$ ratios range from $(2.2 \pm 1.0) \times 10^{-7}$ to $(3.7 \pm 1.9) \times 10^{-7}$, but it has not been clear if there is a variation of $(^{60}Fe/^{56}Fe)_0$ within ferromagnesian chondrules, which might be related to duration of chondrule forming events, because only four rare pyroxene-rich cryptocrystalline chondrules have been so far analyzed.

In this study, in order to obtain more data on ^{60}Fe-^{60}Ni systems of ferromagnesian chondrules, we analyzed seven ferromagnesian porphyritic- and barred-chondrules from least equilibrated ordinary chondrites, Semarkona and Bishunpur.

Nickel isotopic analyses: We selected four FeO-rich chondrules from Semarkona (porphyritic olivine-, barred olivine-, porphyritic olivine-pyroxene-, and barred pyroxene chondrules) and three FeO-rich chondrules from Bishunpur (a barred pyroxene-chondrule and two porphyritic olivine-pyroxene-chondrules).

Nickel isotopic analyses of chondrules were carried out using the Cameca imf-1280 ion microprobe at University of Hawai'i at Manoa. A focused, 15-30 μm, 3-5 nA, primary O^- beam was rastered over a 20 x 20 μm square on samples and standards. The secondary mass spectrometer was operated at 10 kV with a 50 eV energy window and a mass resolving power of ~5000, sufficient to resolve all interferences except for hydrides. In order to cancel shifts of the energy distribution, sample voltage offset was adjusted during the measurement. Secondary ions ($^{57}Fe^+$, $^{60}Ni^+$, $^{61}Ni^+$ and $^{62}Ni^+$) were counted on an electron multiplier for 0.3, 3, 15 and 5 seconds in each cycle. Each spot was measured for two hours. Contributions of interferences of hydrides and molecular ions of oxides ($^{44}Ca^{16}O$, $^{45}Sc^{16}O$, and $^{46}Ti^{16}O$) to count rates of nickel isotopes were confirmed to be <1‰. Data are corrected for electron multiplier background (0.002 cps) and dead-time (29.5 ns). The sensitivity correction for the Fe/Ni elemental ratio was done using San Calros olivine and terrestrial hypersthene. Instrumental mass fractionation for the measured $^{60}Ni/^{61}Ni$ was corrected internally using $^{62}Ni/^{61}Ni$.

Results: Chondrule SMK1-5 is an FeO-rich porphyritic olivine-pyroxene chondrule from Semarkona (~500 μm in diameter), containing a large low-Ca pyroxene phenocryst (~400 μm x ~250 μm). The $^{56}Fe/^{61}Ni$ ratio of phenocrysts range from ~10^5 to 10^6. It shows marginal excesses of ^{60}Ni and its $(^{60}Fe/^{56}Fe)_0$ ratio is estimated to be $(3.2 \pm 1.6) \times 10^{-7}$ (Fig. 1a).

Chondrule SMK1-6 is an FeO-rich porphyritic olivine chondrule from Semarkona (~1200 μm in diameter). The $^{56}Fe/^{61}Ni$ ratios of most of olivine phenocrysts are ~1.5×10^5, which is ~10 times smaller than the highest $^{56}Fe/^{61}Ni$ ratio obtained in low-Ca pyroxene. It shows no resolvable excess of ^{60}Ni (Fig. 1b).

Chondrule SMK3-2 is a ~500-μm-sized FeO-rich barred olivine chondrule from Semarkona. The highest $^{56}Fe/^{61}Ni$ ratio obtained for olivine bars is ~1.5×10^5. Its $(^{60}Fe/^{56}Fe)_0$ ratio is estimated to be $(2.7 \pm 2.7) \times 10^{-7}$, and it is not clear if there is an excess of ^{60}Ni in this chondrule.

Chondrule SMK3-6 is a ~1500-μm-sized FeO-rich barred pyroxene chondrule with olivine phenocrysts from Semarkona, with an inferred $(^{60}Fe/^{56}Fe)_0$ ratio of $(1.7 \pm 1.1) \times 10^{-7}$. The $^{56}Fe/^{61}Ni$ ratios in most of phenocrysts are within a range of $(4\text{-}7) \times 10^5$.

Chondrule BIS-1is an FeO-rich porphyritic olivine-pyroxene chondrule from Bishunpur (~500 μm in diameter). It does not show resolvable excesses of ^{60}Ni.

The $^{56}Fe/^{61}Ni$ ratio of phenocrysts range from ~10^5 to ~1.4 x 10^6.

Chondrule BIS-32 is an FeO-rich porphyritic olivine-pyroxene chondrule from Bishunpur with marginal excesses of ^{60}Ni (~900 µm in diameter). The $^{56}Fe/^{61}Ni$ ratio of phenocrysts range from ~3 x 10^5 to ~1.4 x 10^6. Its $(^{60}Fe/^{56}Fe)_0$ ratio is estimated to be (1.9 ± 1.1) x 10^{-7} (Fig. 1c).

Chondrule BIS-38 is an elongated FeO-rich barred pyroxene chondrule (~800 µm x ~400 µm). The $^{56}Fe/^{61}Ni$ ratio of phenocrysts range from ~10^5 to ~2 x 10^6. The highest $^{56}Fe/^{61}Ni$ ratio of ~2 x 10^6 is consistent with those obtained from other pyroxene-rich chondrules [3]. The $(^{60}Fe/^{56}Fe)_0$ ratio is estimated to be (1.2 ± 0.9) x 10^{-7} for this chondrule.

Discussion: Four out of 7 ferromagnesian chondrules, which are not cryptocrystalline pyroxene-rich chondrules measured in [3], show excesses of ^{60}Ni. The estimated $(^{60}Fe/^{56}Fe)_0$ ratios of the four chondrules range from (1.2 ± 0.9) x 10^{-7} to (3.2 ± 1.6) x 10^{-7}. Considering that $(^{60}Fe/^{56}Fe)_0$ ratios have large uncertainties, the range of $(^{60}Fe/^{56}Fe)_0$ ratios in this study seems to be consistent with that reported in [3].

Three chondrules show little or no excess of ^{60}Ni, two of which are olivine-rich ferromagnesian chondrules (SMK1-6 and SMK3-2). The following reasons may be considered for the lack of ^{60}Ni excess in olivine-rich chondrules; (1) olivine grains tend to contain more Ni than low-Ca pyroxene (Fig. 1b), which made it difficult to detect small excesses of ^{61}Ni, (2) diffusion rates of Fe and Ni in olivine would be ~~much~~ higher than those in low-Ca pyroxene [4-6], so that the ^{60}Fe-^{60}Ni systems in olivine grains may have been disturbed even by very weak thermal metamorphism on the parent body, (3) ^{60}Fe was present heterogeneously in the early solar system, and olivine-rich chondrules somehow did not contain ^{60}Fe in their precursor materials, or (4) ^{60}Fe was injected in the chondrule-forming epoch [7], and some chondrules formed before the injection of ^{60}Fe.

More data from chondrules is surely needed to determine the $(^{60}Fe/^{56}Fe)_0$ ratio and its variation during the chondrule-forming epoch, but the present study showed that ^{60}Fe was present not only in rare cryptocrystalline pyroxene-rich chondrules, but in more common ferromagnesian porphyritic- and barred-chondrules as well.

References: [1] Tachibana S. and Huss G. R. (2003) *Ap. J. 588,* L41-L44. [2] Mostefauoi S. et al. (2005) *Ap. J. 625,* 271-277. [3] Tachibana S. et al. (2006) *Ap. J. 639,* L87-L90. [4] Ganguly J. and Tazzoli V. (1994) *Am. Min. 79,* 930-937. [5] Morioka M. (1981) *GCA 45,* 1573-1580. [6] Chakraborty S. (1997) *JGR 102,* 12317-12331. [7] Bizzarro M. et al. (2006) *Meteorit. Planet. Sci. 41,* A5217.

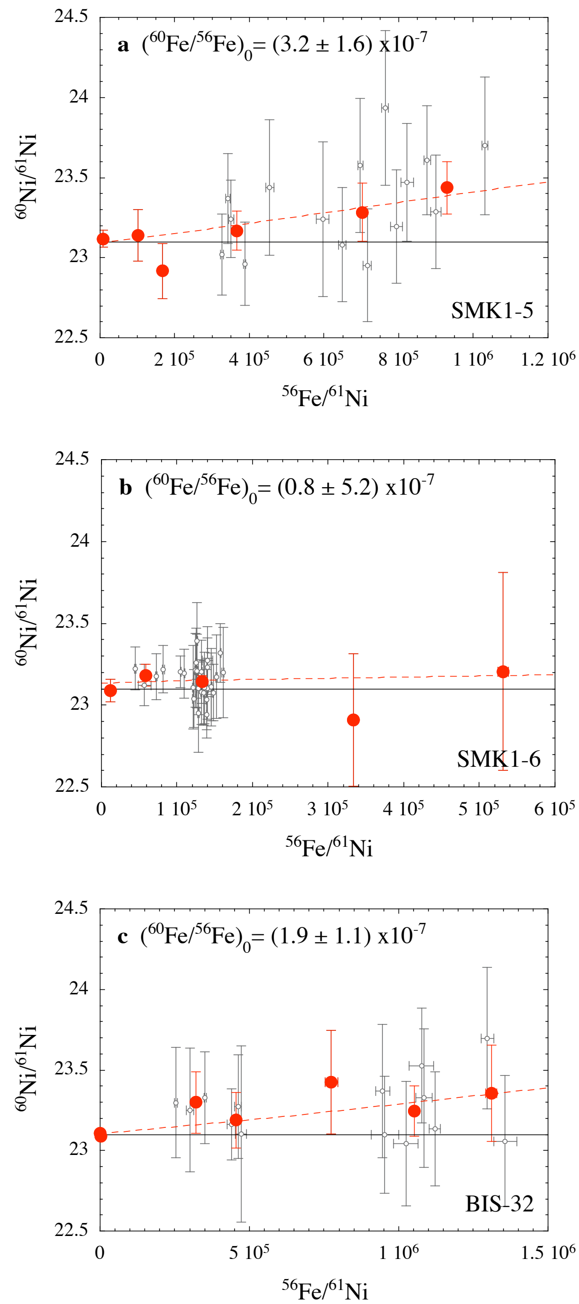

Figure 1. Isochron diagrams of FeO-rich chondrules from Semarkona (LL3.0) and Bishunpur (LL3.1). Individual two-hour measurements (open circles) and weighted means of individual points with similar Fe/Ni ratios (red circles) are plotted. (a) An FeO-rich porphyritic olivine-pyroxene chondrule SMK1-5 from Semarkona. (b) An FeO-rich porphyritic olivine chondrule SMK1-6 from Semarkona. (c) An FeO-rich porphyritic olivine-pyroxene chondrule BIS-32 from Bishunpur.