THE ABUNDANCES OF IRON-60 IN PYROXENE CHONDRULES FROM UNEQUILIBRATED ORDINARY CHONDRITES. S. Tachibana[1], G. R. Huss[2], N. T. Kita[3], H. Shimoda[4] and Y. Morishita[4], [1]Dept. of Earth and Planet. Sci., Univ. of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, Japan (tachi@eps.s.u-tokyo.ac.jp), [2]Dept. of Geological Sci. and Center for Meteorite Studies, Arizona State Univ., Box 871404, Tempe AZ 85287-1404, USA, [3]Dept. of Geology and Geophysics, Univ. of Wisconsin, Madison, 1215 W. Dayton St., Madison, WI 53706-1692, USA, [4]Inst. of Geology and Geoinfo., the Geological Survey of Japan, AIST, Tsukuba, Ibaraki 305-8567, Japan.

Introduction: In recent years, clear evidence that ^{60}Fe was present in the early solar system has been found in sulfides, magnetite, and silicates from unequilibrated ordinary and enstatite chondrites [1-5]. Iron-60 decays to ^{60}Ni with a half-life of 1.5 million years. Because it is produced in stars much more efficiently than by energetic-particle irradiation, its presence in the early solar system indicates that stellar nucleosynthesis contributed to the inventory of short-lived radionuclides. Initial ratios, (^{60}Fe/^{56}Fe)$_0$, inferred for chondritic materials range from ~1x10^{-7} to >1x10^{-6} and are significantly higher than the steady-state value in interstellar medium (~2.6x10^{-8} [6]). Thus, stellar production of ^{60}Fe shortly before the solar system formation is required, suggesting a setting such as the Orion nebula, where cluster star formation occurs [7]. However, many details remain to be worked out, not the least of which is to establish a reliable estimate of (^{60}Fe/^{56}Fe)$_0$ for the solar system.

Current estimates of (^{60}Fe/^{56}Fe)$_0$ for the solar system are based primarily on sulfides from unequilibrated ordinary chondrites ((^{60}Fe/^{56}Fe)$_0$=1 x10^{-7}-1.8x10^{-7} for sulfides from Bishunpur and Krymka (LL3.1) [1]; (^{60}Fe/^{56}Fe)$_0$=1x10^{-6} for sulfides from Semarkona (LL3.0) [2, 5]). Sulfides are easily disturbed by mild thermal metamorphism [3]. Magnetite and many of the sulfides in Semarkona are the products of aqueous alteration on the parent body [8]. Silicates are less susceptible to thermal and aqueous processes, and are apparently unaltered in Semarkona and only slightly altered in Bishunpur [9]. Therefore, following up on [4], we report ^{60}Fe-^{60}Ni data for three more pyroxene chondrules from Semarkona and Bishunpur.

Experimental: Thin sections of Semarkona and Bishunpur were examined by SEM-EDS at ASU to identify chondrules with FeO-rich silicates. Because Ni contents in silicates suitable for this study are way below the detection limit of EDS, Fe/Ni ratios of chondrule silicates were checked using the ASU Cameca ims-6f ion microprobe. Preliminary Ni-isotope measurements were also made, following the analytical procedure of [4]. We selected three pyroxene-rich chondrules with Fe/Ni elemental ratios up to ~30,000 and hints of ^{60}Ni excesses for detailed isotopic analysis using the Cameca imf-1270 ion microprobe at the Geological Survey of Japan. We also re-measured the pyroxene-rich chondrule reported last year [4]. A Kohler-illuminated, 15-μm, 1 nA, primary O_2^- beam was used to sputter the samples. The secondary mass spectrometer was operated at 10 kV with a 50 eV energy window and a mass resolving power (MRP) of ~4500. Secondary ions (^{57}Fe$^+$, ^{60}Ni$^+$, ^{61}Ni$^+$ and ^{62}Ni$^+$) were counted on an electron multiplier. Although the MRP of 4500 is insufficient to resolve interferences from hydrides and molecular ions of oxides (^{44}Ca^{16}O, ^{45}Sc^{16}O, and ^{46}Ti^{16}O), the contributions of such interferences were confirmed to be ≤1‰. San Carlos olivine and basalt glasses (KL2-G and ML3B-G) were used to determine the Fe/Ni sensitivity factor; (Fe/Ni)$_{true}$/(Fe/Ni)$_{meas}$ = 0.73-0.78 for San Carlos olivine, 0.70-0.72 for KL2-G, and ~0.77 for ML3B-G. Instrumental mass fractionation for the measured ^{60}Ni/^{61}Ni was corrected internally using ^{62}Ni/^{61}Ni.

Results: Excesses of ^{60}Ni were clearly observed in all of the chondrules. Chondrule SMK1-4 is the fine-grained radiating pyroxene chondrule from Semarkona for which data were reported last year [4]. In the isochron plot in [4], data were shown as weighted means of several analyses. These data and our new data, where each data point represents a single spot, are plotted in Fig. 1a. Excesses of ^{60}Ni are correlated with ^{56}Fe/^{61}Ni, and the (^{60}Fe/^{56}Fe)$_0$ inferred for SMK1-4 from the new data, (2.5±0.8)x10^{-7}, agrees well with that obtained in [4] (Fig.1a). Combined data gives (^{60}Fe/^{56}Fe)$_0$ of (2.7±0.7)x10^{-7}. Chondrule SMK2-1 is also a fine-grained radiating pyroxene chondrule from Semarkona that resembles to SMK2-4. Its ^{60}Ni excesses also correlate with ^{56}Fe/^{61}Ni, and the inferred initial (^{60}Fe/^{56}Fe)$_0$ is (1.9±1.3)x10^{-7} (Fig.1b). Chondrule SMK2-4, a barred pyroxene chondrule from Semarkona with Fe-rich olivine grains between bars, also shows excesses of ^{60}Ni and its inferred (^{60}Fe/^{56}Fe)$_0$ is (3.4±2.1)x10^{-7} (Fig.1c). Chondrule BIS-21, an irregular-shaped fine-grained pyroxene chondrule from Bishunpur, gives an inferred initial (^{60}Fe/^{56}Fe)$_0$ of (5.1±2.5)x10^{-7} (Fig.1d).

Discussion: There is now clear evidence from sulfides, magnetite, and silicates that ^{60}Fe was present in the chondrite-forming region. However, it is not clear what the ^{60}Fe/^{56}Fe ratio was in that region because different minerals give quite different initial ratios. Interpreted in terms of formation times, differences of an order of magnitude in initial ratio correspond to a difference in formation time of 4.5-5.0 million years for components in a single meteorite. Such a large range of formation times seems to be inconsistent with nebula timescales.

Semarkona and Bishunpur are the least metamorphosed ordinary chondrites and have experienced metamorphic temperatures no higher than ~260ºC and ~300°C, respectively [10-12]. Although there are no data on Fe and Ni diffusion in low-Ca pyroxene at low temperatures, if we extrapolate Fe-Mg diffusion rates [13] to low temperatures, no cation diffusion is expected in pyroxene on the parent body. Magnetite should also be quite resistant to diffusion at these temperatures [14], but diffusion of Fe and Ni in sulfides may occur [15]. The sulfides in Semarkona may well have been produced in part or altered by aqueous alteration [8].

The following interpretation seems to explain the data. The chondrules formed in a nebular reservoir in which $^{60}Fe/^{56}Fe$ was 2-5x10^{-7}. Differences exhibited by the chondrules suggest either an extended period of chondrule formation or a slightly heterogeneous ^{60}Fe reservoir, but the data are not currently precise enough to address this issue. Chondrules and other materials accreted to form chondrite parent bodies. In Semarkona, aqueous alteration took place, producing secondary, Ni-rich sulfides and magnetite. Because magnetite excludes Ni almost quantitatively when it forms, the Fe-Ni system would have been reset and the initial ratio for the magnetite (~1.4x10^{-7}, [5]) should reflect the time of aqueous alteration, ~0.5-2.0 million years after chondrule formation. The sulfides retained Ni from the parent phases (probably sulfides), but lost Fe, so the sulfides were disturbed but not reset. Thus, sulfides cannot be used to infer either time differences or the initial $^{60}Fe/^{56}Fe$ ratio in the early solar system. If the chondrules in Semarkona and Bishunpur are undisturbed, and if they experienced last-melting events 1-2 million years after CAIs, as suggested by ^{26}Al data [e.g., 16], then the $^{60}Fe/^{56}Fe$ ratio at the time the CAIs formed was between 5x10^{-7} and 1x10^{-6}.

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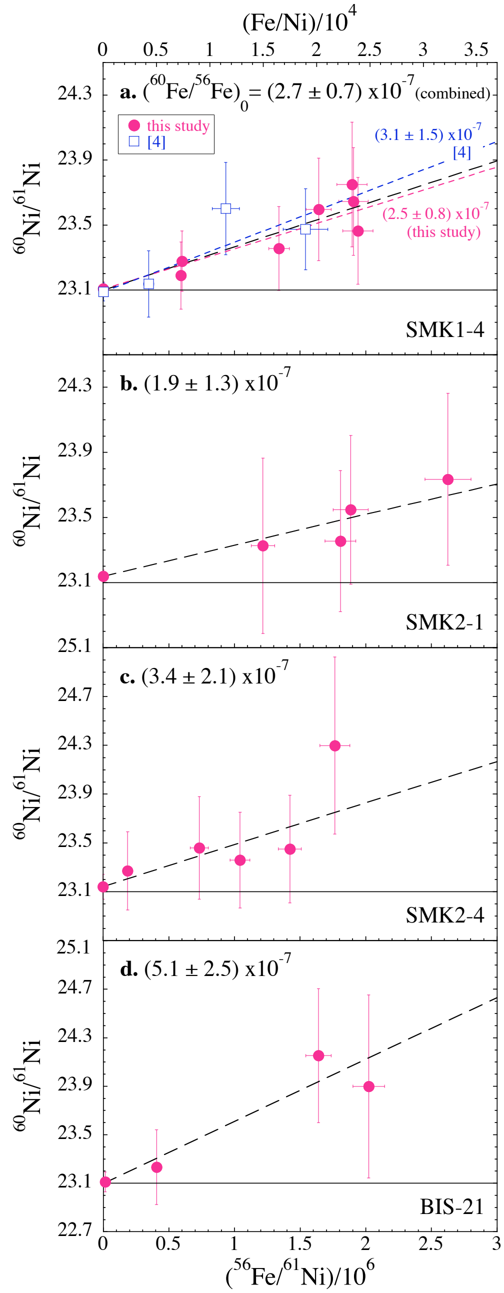

Fig. 1. Isochron diagrams for pyroxene chondrules. $(^{60}Fe/^{56}Fe)_0$ for each chondrule is shown. Data in [4] for SMK1-4 are also plotted.