EVIDENCE FOR LIVE IRON-60 IN SEMARKONA AND CHERVONY KUT: A NANOSIMS STUDY.
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Introduction: One of the most debated subjects in meteoritics is the time scale of events that occurred during the early history of the solar system. Chronometers based on short lived nuclides, such as ^{26}Al, ^{53}Mn, ^{60}Fe, ^{107}Pd, ^{129}I, ^{146}Sm, were extensively studied during the last decades. Some of them were shown to afford chronological resolutions on the order of a few Ma to less than one Ma [e.g. 1,2]. This considerably helped resolving the sequence of events that occurred since the formation of the first solid objects. Considering the high iron and aluminum contents of meteorites, special attention was devoted to ^{60}Fe and ^{26}Al, as they would have been the most powerful heat sources for inducing planetary melting and differentiation. The search for ^{60}Ni isotopic anomalies produced by the decay of short lived ^{60}Fe ($T_{½}$ = 1.5 Ma) had been successful in the eucrite Chervony Kut [3]. Correlated with the Fe/Ni ratio, ^{60}Ni excesses were found for several bulk samples. A large 5‰ excess was measured in a "troilite", which, however, does not follow the trend of the bulk samples. While this evidence shows that ^{60}Fe was alive in the early solar system, the apparent mobility of Ni between the major phases of this meteorite limits the usefulness of the Fe-Ni system as a chronometer. In this report we present an *in situ* NanoSIMS study of the Fe-Ni system in iron sulfides in the Chervony Kut (CK) eucrite and in the Semarkona (LL3.0) ordinary chondrite. We chose CK to perform a follow-up study on a micro-scale on this highly Ni depleted planetary differentiate [4]. Semarkona was selected because it is a highly unequilibrated chondrite where a disturbance of the Fe-Ni system during parent body processing is assumed to be minimal.

Petrography: Optical microscopy studies of polished sections of Semarkona (USNM 1805-2) and CK meteorites are a prerequisite for selecting suitable mineral species and their grains in different petrographic settings for the Fe-Ni isotopic measurements with the NanoSIMS. Among the preferred phases in Semarkona are grains of troilite. We avoided grains in contact with Fe-Ni metal because of possible disturbance of the Fe-Ni isotope system that could have resulted from preferential Ni diffusion from troilite to the neighboring metal during cooling in the parent asteroid. Selected troilite in three different locations (#d1, #d2, and #e1) in the matrix are polycrystalline aggregates and are found to have high Fe/Ni ratios. They are all metal-free and occur more or less associated with silicates and/or minor magnetite. Their presence together in aggregates indicates that they are primary and their compaction probably took place before parent body accretion. In Chervony Kut, pyrhotite in two distinct petrographic settings are clearly distinguished by optical microscopy. The first type of pyrhotite (Pyr-1) is predominant. The grains are variable in shape (from spherical to elongated) and size (from <1µm to ~100µm). These grains coexist with pyroxene, plagioclase, and glass, and in some cases with titanomagnetite. The round edges of the Pyr-1 grains are suggestive of extensive processing. The second type of pyrhotite (Pyr-2) is present as veins exclusively in a mesostasis enclave and is very rare. We found it in only one location. Contrary to Pyr-1, Pyr-2 is jointly associated with titanomagnetite, and this is the sole occasion where some of the titanomagnetites are also present as veins. For isotopic measurements, we selected 14 Pyr-1 grains and 2 Pyr-2 veins. In addition, two pyroxene grains in the CK matrix coexisting with Pyr 1 grains were found to have Fe/Ni ratios high enough for potential ^{60}Ni excesses to be resolved.

Analytical Technique: The Fe and Ni isotopes in troilite, pyrhotite and pyroxene were measured with the Cameca NanoSIMS-50 ion microprobe at the Max-Planck-Institute for Chemistry. Positive secondary ions of ^{54}Fe, ^{60}Ni, and ^{62}Ni were measured in a multidetection mode at a mass resolution m/Δm of 4000. Using high current conditions (~ 1nA on the sample surface), primary ion beam of O^- was focused into spots of 1 to 5 µm in size on the samples. The instrumental mass fractionation for ^{60}Ni/^{62}Ni ratios was corrected using external standards. For the Semarkona measurements we used as standards Ni-rich phases in the sample itself in the same areas as the selected troilites. For CK, we used an Fe-Ni-rich standard. The reproducibility of the ^{60}Ni/^{62}Ni measurements on the standards was ≈ 5‰. A synthetic FeS standard was used to determine the sensitivity factor ($\varepsilon(Fe^+)/\varepsilon(Ni^+)$ =1.7±0.1) for Fe/Ni ratios. The integration time for each measurement was set depending on the size of the measured area and on the Ni contents of the measured phase. In most cases, to avoid cratering effect problems, the measurements did not exceed ~1 hour.

Results and discussion: In Semarkona, the elemental Fe/Ni ratio in troilite varies from ~100 to 9000. ^{60}Ni excesses were found in all three troilite aggregates, with a maximum δ^{60}Ni of 46±15 (2σ) in #e1.

Figure1 displays the relative excesses expressed in δ-units (1 part in 10^{-3}) as a function of the ^{56}Fe/^{58}Ni ratio of Semarkona troilite. Each data point comprises the results of one to six measurements on the same troilite grain. The diagram shows a common trend for the three troilite aggregates - a clear correlation is seen between ^{60}Ni excesses and $^{56}Fe/^{58}Ni$ ratios. The best-fit line through the data yields an inferred $^{60}Fe/^{56}Fe$ ratio of (7.5 ± 2.6) x 10^{-7} (2σ error). The non-zero intercept of this line is probably due to matrix effects and needs a further investigation.

The correlation in Fig.1 gives clear evidence for live ^{60}Fe in Semarkona. From this measurement the resulting $^{60}Fe/^{56}Fe$ ratio is much higher than previously estimated for the initial solar system value [3] and approaches that inferred from a CAI (1.6x10^{-6}) by [5]. In terms of a chronological interpretation, assuming a homogeneous distribution of ^{60}Fe in the early solar system this preliminary value from the troilite in Semarkona corresponds to a difference of only one half life of ^{60}Fe.

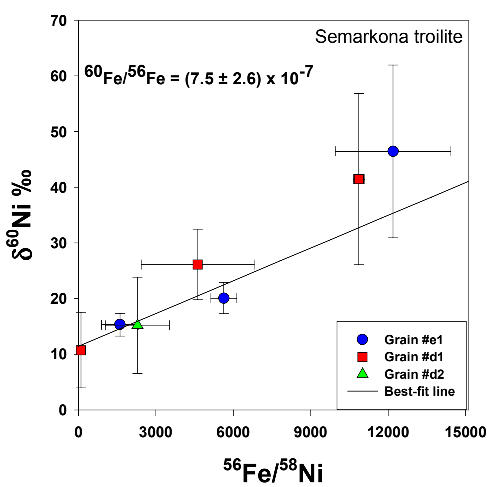

Figure 1. $\delta^{60}Ni$ as a function of $^{56}Fe/^{58}Ni$ for three troilite aggregates in the Semarkona matrix. ^{56}Fe and ^{58}Ni are calculated from measured ^{54}Fe and ^{60}Ni. Errors are 2σ.

Elemental Fe/Ni ratios in CK are between 3x10^4 and 13x10^4 in pyrhotite and up to around 6x10^5 in pyroxene. These high ratios are not surprising, since CK is known to have a bulk Ni content of only a few ppm. Figure 2 shows the results for CK pyrhotite and pyroxene. Each data point in the diagram is an average of 2 to 13 measurements in individual grains having similar Fe/Ni ratios. Here again, ^{60}Ni excesses are found in pyrhotite and also in pyroxene. The $\delta^{60}Ni$ varies from 22±16‰ (2σ) in Pyr-1 to an extremely high value of 1775 ± 250 ‰ in Pyr-2 veins. The data for Pyr-2 are the result of four measurements taken from two distinct grains. This is the highest excess ever reported for ^{60}Ni.

Figure 2 shows no clear correlation between the ^{60}Ni excess and Fe/Ni ratio in Pyr-1 and Pyroxene. Nevertheless, a forced fit-line through the origin gives a $^{60}Fe/^{56}Fe$ ratio of (7.8 ± 4.2) x 10^{-8} (dashed line in Fig. 2), which is significantly higher than that of the bulk CK samples [3]. Interestingly, however, the value of 5‰ excess obtained in [3] on a "troilite" grain falls exactly on this line. On the other hand, the present data set does not allow a plausible explanation for the extreme excess encountered in Pyr-2. Additional measurements are in progress in an attempt to clarify this ambiguity.

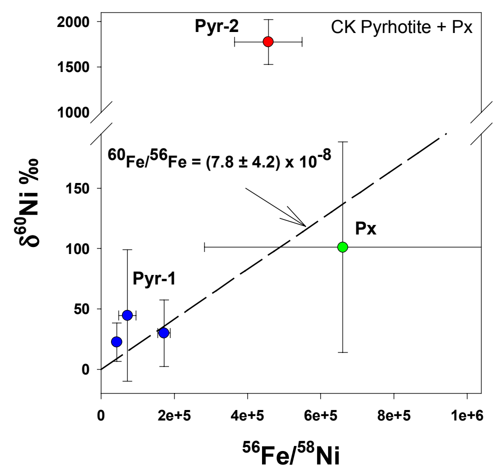

Figure 2. $\delta^{60}Ni$ as a function of $^{56}Fe/^{58}Ni$ for pyrhotite and pyroxene in the Chervony Kut eucrite. ^{56}Fe and ^{58}Ni are calculated from measured ^{54}Fe and ^{60}Ni. Errors are 2σ.

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