Evidence for Live Iron-60 in Meteorites

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Early solar system evolution

Nucleosynthesis

First solid objects

Production + injection of short lived radionuclides ($T_{1/2} \sim 1$ to $\sim 100$ million years): time interval (condition: already present at the time of solids formation) $\Rightarrow$ METEORITES
Short lived radionuclides

- **Some chronometers for dating events during early Solar System history:**
  - $^{53}\text{Mn}$, $^{26}\text{Al}$: time resolution $< 1$ Ma (e.g. Lugmair & Shukolyukov 1998; Mostefaoui et al 2002).

- **Heat sources for planetary differentiation:**
  - $^{26}\text{Al}$: established $\Rightarrow (T_{1/2} = 0.7$ My).
  - $^{60}\text{Fe}$: $(T_{1/2} = 1.5$ My); not much explored (phases with high Fe/Ni rare, analytical limitations).

$^{60}\text{Fe}$-$^{60}\text{Ni}$ isochron in Chervony Kut (eucrite); in “troilite”: $^{60}\text{Ni}$-excess up to 5‰ $\Rightarrow$ live $^{60}\text{Fe}$ in the early solar system (Shukolyukov & Lugmair 1993).
1- To what extent can the Fe-Ni system be considered a reliable chronometer?

2- Was $^{60}\text{Fe}$ a potential heat source inducing planetary melting & differentiation? To what extent?
Principle

\[ \alpha, \beta, \gamma \]

\[ \text{Closed system (crystallization):} \]

\[ P_0 : \text{quantity of parent element at time } t = 0 \]

\[ P(t) = P_0 e^{-\lambda t} \]

\[ T_{1/2} = \frac{\ln 2}{\lambda} \]

\[ D_0 : \text{quantity of daughter element at time } t = 0 \]

\[ P_0 + D_0 = P + D \]
$^{60}\text{Ni} = (^{60}\text{Ni})_{\text{Init}} + (^{60}\text{Ni}^*)$

$^{60}\text{Fe}$ \rightarrow $^{60}\text{Ni}^*$

half-life: $T_{1/2} = 1.5\text{Ma}$

$(^{60}\text{Ni}/^{58}\text{Ni})_{\text{Now}} = (^{60}\text{Ni}/^{58}\text{Ni})_{\text{Init}} + (^{56}\text{Fe}/^{56}\text{Fe})_{\text{Init}} \times (^{56}\text{Fe}/^{58}\text{Ni})_{\text{Now}}$

$\delta^{60}\text{Ni} \%$

NanoSIMS 0.38218

NanoSIMS
\[
\frac{^{60}\text{Fe}^{/^{56}\text{Fe}}}{\text{phase}} = \left( \frac{^{60}\text{Fe}^{/^{56}\text{Fe}}}{\text{CAIs}} \right) x \ e^{-\Delta t \times \ln(2)/1.5}
\]

\[
\Delta t = \left[ \frac{1.5}{\ln(2)} \right] \times \ln\left( \frac{\left( ^{60}\text{Fe}^{/^{56}\text{Fe}} \right)_{\text{CAIs}}}{\left( ^{60}\text{Fe}^{/^{56}\text{Fe}} \right)_{\text{phase}}} \right)
\]
This work: NanoSIMS study of Fe-Ni isotopes

- Chervony Kut (eucrite):
  - Known to have $^{60}\text{Ni}$-excesses (Shukolyukov & Lugmair 1993)
  - Its lithology was the result of planetary differentiation
    (analyzed phases: pyrrhotite, pyroxene)

- Semarkona (LL3.0):
  - Highly primitive chondrite (Fe-Ni system undisturbed)
  - Possibility for a better estimate of initial solar system $^{60}\text{Fe}/^{56}\text{Fe}$.
    (analyzed phases: troilite, magnetite)
Pyrrhotite in Chervony Kut

Two types:
- **Pyr-1**: round shape; abundant
- **Pyr-2**: veins; in a shock-melt pocket; rare
Troilite-bearing assemblages in Semarkona

- **Metal-associated troilite**
  - Metal
  - Troilite
  - Magnetite

- **Metal-free troilite**
  - Matrix
  - Troilite

**High Fe/Ni**
NanoSIMS-50

Characteristics:

- High lateral resolution: 50nm (Cs⁺), 150nm (O⁻)
- High transmission: high ratio of detected/produced ions
- Multi-detection: simultaneous measurement of up to 6 isotopes
NanoSIMS conditions

- **Primary ions**: O\(^{-}\)
- **Ion intensity on sample**: 0.5-1nA
- **Spot size**: ~1-2\(\mu\)m
- **Analyzed isotopes**: \(^{54}\text{Fe}, \, ^{60}\text{Ni}, \, ^{62}\text{Ni} \) (Multi-detection)
- **Mass Resolution**: 4500
- **Standards**: Synth. Fe-Ni alloy; Ni-rich phases on sample;
  St. Carlos oliv.; NBS glass; Synth. troilite.
NanoSIMS ion images of $^{54}\text{Fe}^+$ and $^{60}\text{Ni}^+$ of a troilite assemblage in Semarkona.
NanoSIMS results for metal-free troilite in the matrix of Semarkona

$^{60}\text{Fe}/^{56}\text{Fe} = (1.08 \pm 0.18) \times 10^{-6}$

Errors: 2 sigma

Metal-free troilite formed ~1 Ma after CAIs

$^{60}\text{Fe}/^{56}\text{Fe} = 1.6 \times 10^{-6}$ (CAIs) (Birck and Lugmair, 1988)
NanoSIMS results for magnetite in Semarkona

$^{56}\text{Fe}/^{58}\text{Ni}$

$^{60}\text{Fe}/^{56}\text{Fe} = (1.08 \pm 0.18) \times 10^{-6}$

$^{60}\text{Fe}/^{56}\text{Fe} = (0.14 \pm 0.09) \times 10^{-6}$

Magnetite formation:
At least
~ 4 Ma after troilite

Magnetite: Secondary phase

$\delta^{60}\text{Ni} \%$

Errors: 2 sigma

Magnetite formation: at least ~ 4 Ma after troilite

Magnetite: Secondary phase
60Fe: potential heat source for planetary melting and differentiation.
Proportions of total energies due to decay of $^{60}$Fe and $^{26}$Al

Asteroid core formation

Time (Ma)

Energy (%)
NanoSIMS results for pyrrhotite and pyroxene in Chervony Kut

\[ \delta^{60}\text{Ni} = 1780 \pm 250 \, \text{‰} \]

Pyrrhotite Pyr-2

\[ \frac{^{60}\text{Fe}}{^{56}\text{Fe}} = \left(8.6 \pm 4.2\right) \times 10^{-8} \]

Errors: 2 sigma
Summary

- **Metal-free troilite in Semarkona (LL3.0):** resolvable $^{60}$Ni-excesses, $\delta^{60}\text{Ni}_{\text{max}} \sim +100\%\text{oo}$. 

- **The correlation of $\delta^{60}\text{Ni}$ with Fe/Ni:** live $^{60}$Fe in the early solar system (S.S.), $^{60}\text{Fe}/^{56}\text{Fe}_{\text{init}} = 1.08\pm0.18\times10^{-6}$.  
  * The troilites formed $\sim1$Ma after CAIs (assuming homog. dist. & $1.6\times10^{-6}$ in SS).
  * $^{60}$Fe produced in Supernova & injected into the S.S. shortly before or at its birth.
  * $^{60}$Fe a heat source for planetary melting and differentiation, + early volcanic activities.

- **In the Chervony Kut eucrite:** resolvable $^{60}$Ni-excesses detected in pyroxene and in two types of pyrrhotite (Pyr-1 & Pyr-2).

- **Pyr-2 veins:** an extreme excess in $^{60}$Ni ($\delta^{60}\text{Ni}$ of $\sim+1780\%\text{oo}$), no obvious explanation. More data are needed...