NanoSIMS, the new tool of choice: 
$^{26}\text{Al}, \, ^{44}\text{Ti}, \, ^{49}\text{V}, \, ^{53}\text{Mn}, \, ^{60}\text{Fe}, \, \text{and more}$

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Astronomy with Radioactivities IV
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NanoSIMS 50

• Commercial ion microprobe from Cameca with significant input on instrument design from research groups at Washington University, St. Louis, and MPI für Chemie, Mainz

• Installation at Washington University in February 2001 and at MPI für Chemie in May 2001

• Instrumental features:
  – High lateral resolution (down to 50 nm for Cs\(^+\) primary ions)
  – High sensitivity for secondary ions (30x higher for O as compared to IMS3f ion microprobe)
  – Simultaneous detection of up to 6 isotopes
The Early Solar System

I. Extinct radioactivities: Early Solar System history
II. Stardust: Stellar astrophysics
## I. Extinct radioactivities: Early Solar System history

<table>
<thead>
<tr>
<th>nuclide</th>
<th>$T_{1/2}$</th>
<th>occurrence</th>
<th>reference nucl.</th>
<th>$\sim$ ratio</th>
<th>pref. process</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^7$Be</td>
<td>53 d</td>
<td>CAIs</td>
<td>$^9$Be</td>
<td>up to $10^{-2}$</td>
<td>spallation</td>
</tr>
<tr>
<td>$^{10}$Be</td>
<td>1.5 Ma</td>
<td>CAIs</td>
<td>$^9$Be</td>
<td>$10^{-3}$</td>
<td>spallation</td>
</tr>
<tr>
<td>$^{26}$Al</td>
<td>0.7 Ma</td>
<td>mostly CAI</td>
<td>$^{27}$Al</td>
<td>$5 \times 10^{-5}$</td>
<td>H burn.</td>
</tr>
<tr>
<td>$^{36}$Cl(?)</td>
<td>0.3 Ma</td>
<td>carb. chondr.</td>
<td>$^{35}$Cl</td>
<td>$1.4 \times 10^{-6}$</td>
<td>s (?)</td>
</tr>
<tr>
<td>$^{41}$Ca</td>
<td>0.1 Ma</td>
<td>CAI</td>
<td>$^{40}$Ca</td>
<td>$1.5 \times 10^{-8}$</td>
<td>s (?)</td>
</tr>
<tr>
<td>$^{53}$Mn</td>
<td>3.7 Ma</td>
<td>widespread</td>
<td>$^{55}$Mn</td>
<td>$1-2 \times 10^{-5}$</td>
<td>NSE, Si burn., spall.</td>
</tr>
<tr>
<td>$^{60}$Fe</td>
<td>1.5 Ma</td>
<td>HED meta</td>
<td>$^{56}$Fe</td>
<td>$4 \times 10^{-9}$</td>
<td>s, n-rich NSE</td>
</tr>
<tr>
<td>$^{92}$Nb</td>
<td>36 Ma</td>
<td>widespread</td>
<td>$^{93}$Nb</td>
<td>$2 \times 10^{-5}$</td>
<td>p</td>
</tr>
<tr>
<td>$^{107}$Pd</td>
<td>6.5 Ma</td>
<td>iron met.</td>
<td>$^{108}$Pd</td>
<td>$2 \times 10^{-5}$</td>
<td>s,r</td>
</tr>
<tr>
<td>$^{129}$I</td>
<td>16 Ma</td>
<td>widespread</td>
<td>$^{127}$I</td>
<td>$1 \times 10^{-4}$</td>
<td>r</td>
</tr>
<tr>
<td>$^{146}$Sm</td>
<td>103 Ma</td>
<td>widespread</td>
<td>$^{144}$Sm</td>
<td>$7 \times 10^{-3}$</td>
<td>p</td>
</tr>
<tr>
<td>$^{182}$Hf</td>
<td>9 Ma</td>
<td>widespread</td>
<td>$^{180}$Hf</td>
<td>$1 \times 10^{-4}$</td>
<td>r</td>
</tr>
<tr>
<td>$^{244}$Pu</td>
<td>81 Ma</td>
<td>widespread</td>
<td>$^{238}$U</td>
<td>$7 \times 10^{-3}$</td>
<td>r</td>
</tr>
</tbody>
</table>
Extinct $^{26}$Al in ordinary chondrites (I)

- In-situ study of Mg-Al-isotopic systematics in plagioclase in Ste. Marguerite and Forest Vale ordinary chondrites
- High Al/Mg makes plagioclase suitable samples for the search of now extinct $^{26}$Al ($T_{1/2} = 0.7$ My)
- Location of grains by automatic EDX imaging
- Small beam diameter allows to exclude abundant small pyroxene inclusions from analyses
Extinct $^{26}$Al in ordinary chondrites (II)

- High Al/Mg ratios of up to 15,000
- Measurement errors of several permil
- Excesses in $^{26}$Mg of up to 2% relative to solar Mg
- Correlation line with slope $1.6 \times 10^{-7}$ ($\Delta T_{\text{CAI}} = 6$ My)
- $^{26}$Al widely distributed in the early solar system
Extinct $^{53}$Mn in Orgueil carbonates (I)

- Study of Mn-Cr isotopic systematics in separated carbonates from Orgueil
- High Mn/Cr makes carbonates suitable samples for the search of now extinct $^{53}$Mn ($T_{1/2} = 3.7$ My)
- Information about aqueous activity on parent body
- Mineralogy:
  - Breunnerite ($\text{Mg(Fe,Mn)(CO}_3)_2$)
  - Dolomite ($\text{CaMg(CO}_3)_2$)
- Small beam diameter allows to exclude Cr-rich inclusions from analyses
Extinct $^{53}\text{Mn}$ in Orgueil carbonates (II)

- Large $^{55}\text{Mn}/^{52}\text{Cr}$ ratios of up to 50,000
- Large $^{53}\text{Cr}$ excesses with $^{53}\text{Cr}/^{52}\text{Cr}$ ratios of up to 2.3x solar
- Breunnerite and dolomite form slightly different isochrons ($\Delta T = 1$ My)
- Bulk Orgueil ($^{53}\text{Mn}/^{55}\text{Mn}$)$_0$ $\leq 2 \times 10^{-5}$, i.e., $\Delta T \leq 10$ My; early aqueous activity on Orgueil parent body
Extinct $^{60}$Fe in Semarkona troilite (I)

- Study of Fe-Ni isotopic systematics in metal-free troilite grains in Semarkona
- High Fe/Ni makes troilites suitable samples for the search of now extinct $^{60}$Fe ($T_{1/2} = 1.5$ My)
- Questions to be addressed:
  - Time of troilite formation
  - Was $^{60}$Fe a potential heat source for planetary melting?
Extinct $^{60}$Fe in Semarkona troilite (II)

- Large $^{56}$Fe/$^{58}$Ni ratios of up to 30,000
- $^{60}$Ni excesses of up to 10%
- Fe-Ni data plot on an isochron with $(^{60}$Fe/$^{56}$Fe)$_0 = 1.1 \times 10^{-6}$
- In CAIs, $^{60}$Fe/$^{56}$Fe = $1.6 \times 10^{-6}$ (Birck and Lugmair, 1988), i.e., troilite formed $\approx 1$ My after CAIs
- With $(^{60}$Fe/$^{56}$Fe)$_0 > 10^{-6}$, $^{60}$Fe must be considered a significant heat source for planetary melting
II. Stardust: Stellar astrophysics

Presolar SiC X grains

- SiC X grains are a rare type of presolar SiC
- Isotopic signatures: Excesses in $^{12}\text{C}$ (most grains), $^{15}\text{N}$, and $^{28}\text{Si}$, large amounts of $^{26}\text{Al}$ and presence of $^{44}\text{Ti}$ (some grains)
- Type II SN are the most likely stellar sources
Si, $^{44}$Ti, and $^{49}$V in Type II SN

- The isotopic signatures of X grains point to deep mixing in SN ejecta
- $^{28}$Si excesses require contribution from inner Si/S zone
- Presence of radiogenic $^{44}$Ca (from decay of $^{44}$Ti, $T_{1/2} = 60$ a) and $^{49}$Ti (from decay of $^{49}$V, $T_{1/2} = 330$ d) expected in X grains
44Ti in presolar SiC X grains (I)

- 37 X grains studied with NanoSIMS for Si- and Ca-Ti-isotopic compositions
- All X grains have lower than solar $^{40}\text{Ca}/^{28}\text{Si}$
- 7 X grains show large excesses in $^{44}\text{Ca}$ ($^{44}\text{Ca}/^{40}\text{Ca}$ is up to $\approx 6x$ solar) that can be attributed to the decay of 44Ti
$^{44}\text{Ti}$ in presolar SiC X grains (II)

- Inferred initial $^{44}\text{Ti}/^{48}\text{Ti}$ ratios of up to 0.3
- Negative correlation between $^{29}\text{Si}/^{28}\text{Si}$ and $^{44}\text{Ti}/^{48}\text{Ti}$
$^{44}\text{Ti}$ in presolar SiC X grains (III)
Spatial Distribution

localized, correlated with $^{48}\text{Ti}$
49V in presolar SiC X grains (I)

- 7 X grains studied for Ti-V-isotopic compositions
- All X grains exhibit enrichments in 49Ti
- Except for 47Ti there is a good agreement between the X grain data and the predictions from a SN mixing model
49V in presolar SiC X grains (II)

- V/Ti varies by 3x
- 49Ti/48Ti correlates with V/Ti: Evidence for extinct 49V
- Good match between grain data and SN model predictions
- Grain formation several months after SN explosion
The NanoSIMS 50 is a new type of SIMS that opens new research windows in planetary sciences and astrophysics (spatial resolution, sensitivity !)

First NanoSIMS studies:
- Search for the decay products of short-lived radioactive nuclides (\(^{26}\)Al, \(^{53}\)Mn, \(^{60}\)Fe) in meteorites
- Investigation of isotopic homogeneity in \(\mu\)m-sized presolar SiC and Al\(_2\)O\(_3\) grains
- Search for now extinct \(^{44}\)Ti and \(^{49}\)V in presolar SN grains
- In-situ search for presolar oxides/silicates in meteoritic thin sections (Thursday !)