Low energy particle production of short-lived nuclides in the early solar system

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Background: Short-lived nuclides

• Source: Stellar nucleosynthesis vs. Irradiation

• Stellar sources: AGB, Novae, Supernovae
  \(^{26}\text{Al}(0.74\text{Ma}),^{41}\text{Ca}(0.1\text{Ma}),^{60}\text{Fe}(1.5\text{Ma}),^{53}\text{Mn}(3.7\text{Ma})\)

• \(^{10}\text{Be} (t_{1/2} = 1.5\text{Ma})\) : Pure Spallation product
Interesting Problem

- Do energetic particle interactions also contribute to the inventory of some of the other short-lived nuclides (e.g., $^{26}$Al, $^{41}$Ca, $^{53}$Mn) in the early solar system?

- Samples (Hibonite, CaAl$_{12}$O$_{19}$) devoid of $^{26}$Al and $^{41}$Ca were analysed.

  $^{26}$Al/$^{27}$Al$^{\text{upper lmt.}} = 2 \times 10^{-6}$
  $^{41}$Ca/$^{40}$Ca$^{\text{upper lmt.}} = 3 \times 10^{-9}$

  $^{26}$Al/$^{27}$Al$^{\text{cannonical}} = 5 \times 10^{-5}$
  $^{41}$Ca/$^{40}$Ca$^{\text{cannonical}} = 1.4 \times 10^{-8}$

Marhas et al. 2002
Samples: Murchison (CM) Hibonites
\textbf{Be-B systematics: Hibonite}

\begin{itemize}
\item \textbf{CH B7}
\[ \left( \frac{^{10}\text{Be}}{^{9}\text{Be}} \right)_{i} = (8.04 \pm 2.37) \times 10^{-4} \]

\item \textbf{CH C1}
\[ \left( \frac{^{10}\text{Be}}{^{9}\text{Be}} \right)_{i} = (1.47 \pm 1.46) \times 10^{-3} \]

\item \textbf{SH 7}
\[ \left( \frac{^{10}\text{Be}}{^{9}\text{Be}} \right)_{i} = (2.8 \pm 1.7) \times 10^{-4} \]

\item \textbf{CH C4}
\[ \left( \frac{^{10}\text{Be}}{^{9}\text{Be}} \right)_{i} = (8.0 \pm 3.3) \times 10^{-4} \]
\end{itemize}
$^{26}\text{Al} - ^{10}\text{Be}$ Correlation

All CV CAIs (Type A / Type B) + FUN inclusions + CM hibonite

$^{26}\text{Al}/^{27}\text{Al}$$_{\text{initial}}$ very low to Canonical

$^{10}\text{Be}/^{9}\text{Be}$$_{\text{initial}}$ $4 \times 10^{-4}$ - $1.5 \times 10^{-3}$

$^{26}\text{Al}$ and $^{10}\text{Be}$ are decoupled different sources
Energetic Particle Interactions: Source of $^{10}$Be

- Trapped Galactic Cosmic Rays  
  (Desch et al., LPSC, 2003)

- R-process jets (supernova)  

- Low-energy irradiation of Protosolar Cloud  
  (Ramaty et al, 1995; Bloemen et al., 1999)

- Local Production by SEP: conventional / X-wind  
  (Shu et al., 1994, Goswami et al., 2001; Marhas et al., 2003)
SOURCE OF SHORT LIVED NUCLIDES: Interaction with Solar Energetic Particles (SEP)
Calculations

Production $P_i = \sum_j \int F(E) N_j \sigma (j \rightarrow i, E) \, dE$

Input parameters

- Incident Flux $F = \text{flux of SEP}$
  - $dN \propto E^{-\gamma} \, dE \quad [\gamma = 2 \ldots 5]$
  - $dN \propto \exp(-R/R_0) \, dR \quad [R_0 = 50 \ldots 400]$

  $\alpha/p \text{ in SEP} : 0.1$

- $N = \text{number of target particles}$

  Target composition : Solar

- Flux normalisation used:
  
  $dN/dE_{E>10\text{MeV}} = 100 \text{ protons cm}^{-2} \text{ sec}^{-1}$
Energy Cross Section for $^{26}$Al and $^{41}$Ca

Ramaty et al., 1996
Approach

1. Obtain Secondary energy spectra
   \[ \frac{dN}{dE} = KE^{-\gamma} \quad R = CE^\beta \]
   Flux at depth \( x \), \( \frac{dN}{dE_x} = KE^{\beta-1} (E^\beta + E_x^\beta)^{(1-\beta-g)/\beta} \)

2. Production rate as a function of depth for different grain size \( P(r,x) \)

3. Average production rate as a function of grain size
   \[ P(r) = \int [P(x) \frac{4\pi (\rho-x)^2}{\rho^2} \ dx] / \rho^2 \]

4. Ensemble average production rates using size distribution:
   \( \frac{dn}{dr} = C.r^{-\beta} \)
   \[ \text{Total Production} = \int_{r_{\text{min}}}^{r_{\text{max}}} \frac{dn}{dr} P(r) \ dr \]
Solar energetic particle interactions: Result-I

\[
\frac{^{10}\text{Be}}{^{9}\text{Be}} = 1 \times 10^{-3} \\
\frac{^{26}\text{Al}}{^{27}\text{Al}} = 5 \times 10^{-5} \\
\frac{^{41}\text{Ca}}{^{40}\text{Ca}} = 1.4 \times 10^{-8}
\]
Solar energetic particle interactions: Result-II
Solar energetic particle interactions: Result-III

\[ \frac{dN}{dE} = KE^{-\gamma} \quad (\gamma=2) \]
Results and Conclusions

- SEP irradiation of nebular material appears plausible
- Flatter spectra \( [\gamma=2] \) accounts for the observed presence of \(^{10}\text{Be}\) and \(^{26}\text{Al},^{41}\text{Ca}\) below detection limit.
  \[\text{effective irradiation dose } \sim 2 \times 10^{18} \text{ protons/cm}^2\]
- Very little contribution towards \(^{53}\text{Mn}\) inventory
- A stellar source is most plausible for \(^{41}\text{Ca}\) and \(^{26}\text{Al}\)
- A short time scale for protosolar cloud collapse; suggest a triggered origin of the solar system