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“Element Genesis -Solving the Mystery”

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- NuPECC’s use for PANS (Public Awareness of Nuclear Science) Project
- Creative Excellence Award at U.S. Int. Film Festival (2003)
- If you are interested in, please visit www.rarf.riken.go.jp/video/
$^{44}$Ti Radioactivity in Young SNRs:
Cas A and SN 1987A

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Workshop on Astronomy with Radioactivities IV
and MeV Gamma-Ray, Kloster Seeon, Germany
5/27/03
$^{44}\text{Ti}$ Decay

- **Half-Life**: $t_{1/2} \approx 60$ y
- **E-Capture (99.3%)**: $Q_{EC} = 119$ keV
- **$78$ keV**: $\gamma$-ray
- **$68$ keV**: $\gamma$-ray

**Pure Electron-Capture-Decay!**

(First-forbidden $0^+ \rightarrow 0^-$ EC)

- Argonne*
- Jerusalem*
- Torino*
- Notre Dame
- NIST
- LBNL†

- RIKEN 2000*

<table>
<thead>
<tr>
<th>Decay Type</th>
<th>Source</th>
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<tbody>
<tr>
<td>$\beta^+$-decay</td>
<td>$^{44}\text{Sc}$</td>
</tr>
<tr>
<td>$\gamma$-ray</td>
<td>$1.157$ MeV (100%)</td>
</tr>
<tr>
<td>$\gamma$-ray</td>
<td>$78$ keV</td>
</tr>
<tr>
<td>$\gamma$-ray</td>
<td>$68$ keV</td>
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- † used two mixed sources
- * used the same source
- # used 78, 68 keV lines

**Half-Life of Neutral $^{44}\text{Ti}$ (yrs)**

- $60 \pm 1$ (1σ)

**Note:**

- $^{44}\text{Ca}$
- $^{44}\text{Sc}$
- $^{44}\text{Ti}$
Decay rate of highly ionized $^{44}\text{Ti}$

Atomic Electron Binding Energies

- K electrons (1S$_{1/2}$) ..... 6.6 keV
- L$_{I}$ electrons (2S$_{1/2}$) ..... 1.6 keV
- L$_{II}$ electrons (2P$_{1/2}$) ..... 1.6 keV
- L$_{III}$ electrons (2P$_{3/2}$) ..... 1.6 keV

*Theoretically calculated for non-relativistic electrons & point-charge nucleus (simple estimate)
### Activity Change by Ionization: Linear Analysis

\[
A = N_0 \lambda \ e^{-\lambda t}
\]

\[
\frac{\Delta A}{A} = (1 - \lambda t) \frac{\Delta \lambda}{\lambda}
\]

<table>
<thead>
<tr>
<th></th>
<th>$^{44}$Ti</th>
<th>Ti$^{21+}$</th>
<th>Ti$^{20+}$</th>
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</thead>
<tbody>
<tr>
<td>$\Delta A/A$</td>
<td>-0.46</td>
<td>-0.1</td>
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<tr>
<td></td>
<td>$\sim 50%$</td>
<td>10%</td>
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<td>Reduction!</td>
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<tr>
<td>$\Delta A/A$</td>
<td>+1.5</td>
<td>+0.32</td>
<td></td>
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<tr>
<td></td>
<td>factor 2.5</td>
<td>30%</td>
<td></td>
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<td>Enhance!</td>
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- **87a**
- **Cas A**
- **Always Negative**
Element map of Cas A

(Chandra X-ray Obs.)

Red: K shell lines of O, Ne, Mg
Green: K shell lines of Si
Blue: K shell lines of Fe, Ca, Ar, S

Hughes et al. 2000

Age ~320 y
d~3.4+0.3-0.1 kpc
t_{1/2}=60+-3 yrs (3\sigma)
Discrepancy between theory and observation

Yield derived from observed values

Rauscher, Heger, Hoffman & Woosley 2002

Schönfelder et al. 2000

Iyudin et al. 97

\gamma\text{-ray photon Flux} (10^{-5}\text{ cm}^{-2}\text{s}^{-1})

44\,^{\text{Ti}}\text{ Ti Yield} (10^{-4}\text{M}_\odot)
SNR Model: McKee & Truelove 95 + Clumpy Structure + recent X-ray obs.
Updated from: Y.M. 01; Y.M., Takahashi, Janka, Hillebrandt & Diehl 99

\[ T_e(r,t), n_e(r,t) \]

320 shells

\[ n_{H0} \sim 13 \text{ cm}^{-3} \]

\[ M_{ej} \sim 2 \text{ M}_\odot \]

\[ E_{ej} \sim (1-3) \times 10^{51} \text{ erg} \]

\[ \alpha_{clp} \sim 5-20 \]

Willingale et al. 2002a, b

Y.MOTIZUKI, Workshop on Astronomy with Radioactivities VII, 5/27/03
Microphysics

- Electron capture decay
- Ionization, Recombination
- non-thermal equilibrium \( T_e \neq T_i \)
- No collisional (ionization) equilibrium
- shocked clump temperature
- non-adiabatic effects by ionization / recombination
Activity Evolution with Ionization

$\frac{\text{Activity}^\text{ion}}{\text{Activity}^\text{neutral}}$

$t = 400 \text{ y}$

$2M_\odot$, $15 \text{ cm}^{-3}$, $2 \times 10^{51} \text{ erg}$, 10

$R_{\text{rejecta_max}}$
Chandra X-ray Observation of Cas A, Willingale et al. 2002

flux distribution of Fe-K

radius arc seconds

blast-shock here

North -->

West -->
The Present $^{44}$Ti Activity in Cas A

Cas A, the present (320 y)

averaged act. ratio=2

$2M_\odot, 15 \text{cm}^{-3}, 2 \times 10^{51} \text{erg}, 10$

$\frac{\text{(Activity)_{ion}}}{\text{(Activity)_{neutral}}}$ vs $r/R_{\text{ejecta}_{\text{max}}}$
Real Initial Mass

\[ t_{\text{lab}} \sim 60 \text{ y} \]

\[ t = 0 \]

explosion

the present

\[ M_{0}^{\text{real}} = M_{0}^{\text{neut}} / \sqrt{A} \]
Coincidence between theory and observation?

Motizuki 2003 in preparation

Rauscher, Heger, Hoffman & Woosley 2002

Yield derived from observed values (No ionization)

Ionization \( A = 2.0 \)

\( \gamma \)-ray photon Flux \( (10^{-5} \text{cm}^{-2} \text{s}^{-1}) \)

Yield derived from observed values (No ionization)

Vink et al. 2001

Schönfelder et al. 2000

Motizuki 2003 in preparation
Summary : $^{44}\text{Ti}$ in Cas A

- $^{44}\text{Ti}$ yield derived from observed $\gamma$-ray flux with $t_{1/2}$ of $\sim 60$ yrs may not necessarily mean the real initial mass.

- The real initial mass is most likely smaller than the "observed" value by a factor 1.5 - 2, due to retardation of the decay caused by the reverse shock.

Bolometric light curve for SN 1987A

“upper limit case”

$(0.67 - 1.7) \times 10^{-4} M_\odot$

for $t_{1/2} = 60 \pm 3\sigma (3\sigma)$

& $D = 48.6$ kpc

Collision to the inner ring

Log [Luminosity (erg/s)]

Motizuki, Kumagai, & Nomoto 2003 in preparation
Detectability of $^{44}$Ti radioactivity from SN 1987A

"upper limit case for 2003"

- 68, 78 keV lines
  - Astro-E2 (HXD)
    - $3 \times 10^{-5}$ for 100 ks obs.
  - NeXT (To be launched in 2010)
    - $\sim 10^{-6} [\text{cts/cm}^2/\text{s}]$

- Internal conversion
  - 68 keV flux: 8% reduction from 78 keV flux
  - Valid for Cas A, too!

Thanks to prof. P. Leleux for SPI data
Summary: $^{44}\text{Ti}$ in SN1987A

- With 2-week observation-time, it would be difficult for SPI to detect $^{44}\text{Ti}$ activity.
- If $^{44}\text{Ti}$ is ionized even partially to H-like state due to the collision, the detection becomes more difficult. Activity may decrease with time according as ionization proceeds.
- Detectability of 68 and 78 keV lines with future X-ray missions.