Actinides and the Sources of Cosmic Rays

B. Pfeiffer\textsuperscript{a}, K.-L. Kratz\textsuperscript{a}, R.E. Lingenfelter\textsuperscript{b}, and J.C. Higdon\textsuperscript{c}

\textsuperscript{a} Institut für Kernchemie, Universität Mainz, Deutschland
\textsuperscript{b} CASS, Univ. of California San Diego, La Jolla, USA
\textsuperscript{c} W.M. Keck Science Center, Claremont, USA

- Introduction
- R-process calculations
- Predictions for actinides
- Future perspectives
Early Discoveries

• Ionisation of air was attributed to natural radioactivity in the soil
• No decrease on top of Eiffel tower
• In 1912, Hess measured increase up to 5 km: cosmic origin
• Dependance on geographical latitude: particles

First high energy physics laboratory
• 1929: Skobelzyn observes cosmic rays in a cloud chamber
• 1932: antimatter - positron
• 1937: myon
• 1947: $\pi$-Meson

• Recently neutrino oscillations

Nobel award 1936

V.F. Hess

C.D. Anderson
Composition of extraterrestrial matter
Old and new observables

Optical spectroscopy: Bunsen/Kirchhoff
Birth of astrophysics 1863: 9 elements detected in Aldebaran and Betelgeuse

• Spectroscopy of ultra-metal-poor Halo stars
  Interstellar matter (ISM) 13 Gy ago

• Elemental and isotopic composition of meteorites
  Interstellar Medium 4.6 Gy ago

• Pre-solar grains in meteorites and high atmosphere
  ISM prior to formation of Solar system

• Ultra-heavy component of cosmic rays
  Recent nucleosynthesis events

• STARDUST at comet 81P/Wild 2 (Jan. 2004)
Ultra-metal-poor Halo stars
Th-U cosmochronometer

• Th-U chronometer ideal for dating of solar system.
• Lower limit for age of the Universe requires models of Galactic chemical evolution.

• High-resolution optical spectroscopy of ultra-metal-poor, very old Halo red giants stars opens new perspectives:
  • One (or few) nucleosynthesis events seeded ISM.
  • Scaled solar system r-process abundances for $56 \leq Z \leq 79$.
  • Radioactive dating requires „production ratios“.
  • Th/U ratio (hopefully) less affected by extrapolations of nuclear structure

Abundances in BD+17°3248
Acceleration of Cosmic Rays

1949 E. Fermi:
- acceleration by SN shock fronts
- protons up to „knee“ at $10^{15}$ eV

Highest energies:
- AGN (Cen A, M87)
- $\gamma$-ray burster
- new particles, physics?

Still far more energetic than man-made particles
Knee, ankle, toe

- Shock-accelerated ions: $E \sim 4 \times 10^{14}$ eV
  Excess due to 1 SN in 1000 ly 100000 yrs ago?
- Parallax of Pulsar PSR B0656+14 950 Ly (VLBA)
  100,000 year old Monogem SN-remnant possible source of excess ions from „knee“ to „ankle“
- Hess-particles in „toe“ of extra-galactic origin

Mono(ceros)Gem(ini) SN-remnant with ROSAT

Excess from knee to ankle

Composition
Sources and acceleration mechanisms for heavy nuclei

Origin of GCR nuclei remains mysterious

• Chromospheres of sun-like stars?
  Overabundance of easily ionisable elements;
  abundance as ions accelerated by solar flares

• Dust grains and gas?
  SN shocks accelerate ions sputtered from dust grains;
  refractory elements should be overabundant

Difficult to distinguish
Refractory elements (easy to ionize) condense into grains,
volatile ones (often difficult to ionize) stay in gas phase
Pb, easy to ionize yet volatile, could help to disentangle
Flux of heavy nuclei („metals“)

The flux of heavy elements is decreasing steeply from about 1 per m² sr sec in the iron group to below 1 per m² sr day for neutron-capture elements.

- Iron group elements can be detected with balloon-flown instruments as TIGER (up to 38 days in Antarctica).
- Pt-group elements and actinides require measurement periods of years as glass-etch detectors on MIR (TREK).
Nuclear physics input data

Data for extremely neutron-rich nuclei, mostly out of reach of actual experimental techniques:
- nuclear masses
- $\beta$-decay properties: $T_{1/2}$, $P_n$, $\beta$-delayed fission
- $(n,\gamma)$, $(\gamma,n)$, $n$-induced fission

Approximation to full network calculations already give insights in decisive data:
- „canonical“ $r$-process
  - $(n,\gamma) \leftrightarrow (\gamma,n)$ equilibrium („waiting-point“)
  - $\beta$-flow equilibrium
  - Fe seed nuclei
  - $Y(Z) \cdot \lambda_\beta = \text{const.}$
  - In the simplest case, $S_n$ and $T_{1/2}$ (by given neutron number and temperature) are sufficient
Importance of **experimental** data

- The r-process abundances of the actinides depend also on nuclear-structure data at the **magic neutron-numbers**, nuclei which act as **bottle-necks** for the matter flow.
- Up to present, only neutron-rich nuclei with N=50 and 82 could be observed.
- Future RIB-facilities hopefully will make N=126 accessible for experiments.
Importance of **selectivity** in production and detection

Low production yields demand imperatively **high-selectivity** in separation and detection:

- Z-selective resonance-ionization laser ion-sources
- isobar separation
- „neutron-converter“ to suppress proton-rich isobars
- multifold-coincidence methods at multi-detector arrays
- projectile-fragmentation, TOF techniques

![Laser excitation scheme for Cd](image1)

![Laser ion-source + converter](image2)

Fig. 1: Beta-delayed neutron decay curves for the neutron-rich isotope $^{115}$In, after correction for β-decay activities and neutron background.
R-process „waiting-point“ nucleus $^{130}$Cd: N=82 shell-quenching

Nuclear-physics „surprises“
- high excitation energy of $1^+$ level
- high $Q_\beta$ -value of 8.34 MeV

Comparison with mass models

Additional selectivity from hyperfine splitting

• Solid line:
  - HF-splitting of the $\pi g_{9/2}$ configuration
• Dashed line:
  - $\pi p_{1/2}$ component

Laser ion source
• Laser set to off-center frequency $g_{9/2}$ ground-state decay
• Laser on central frequency
  Indication of isomeric decay
Progenitors of the Actinides

After freeze-out, the extremely neutron-rich nuclei undergo $\beta$, $\beta$-del. n-, $\beta$-del. fission-, sp. fission decay
• New attempt to include $\beta$-del. fission decay by Schatz et al.
• Extended studies underway

Progress in mass modeling required:
• Production ratios even of close-lying nuclides as $^{232}\text{Th}$ and $^{238}\text{U}$ differ considerably when applying different mass models.
Fit to solar r-process isotopic abundances obtained as superposition of 16 \( n_n \)-components. There is also a good fit to the r-process Pb and Bi contributions after summing up the \( \alpha \)-decay chains of heavier nuclei.

Observed neutron-capture elemental abundances in an ultra-metal-poor halo-star (squares) compared to scaled solar values (dots) and our calculated r-abundances (full line).
In old Halo stars only $^{232}$Th and in a few cases $^{238}$U have survived. Cosmic rays propagate for some tens of million years until they are destroyed by spallation/fission or are scattered out of the Galaxis.

„Short-lived“ actinides could be observed if the sources of the cosmic rays

- lie close to the Solar System and
- they are freshly synthesized.

<p>| Table 1. Half-lives and expected r-process yields of the long-lived actinides |
|-------------------------------|------------------|-------------------|</p>
<table>
<thead>
<tr>
<th>Element</th>
<th>Half-life ($\times 10^6$ yr)</th>
<th>r-process yield ([Th]=1.0) (Pfeiffer et al., 1997)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}$Th</td>
<td>14 100</td>
<td>1.0</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>704</td>
<td>0.94</td>
</tr>
<tr>
<td>$^{236}$U</td>
<td>23</td>
<td>0.68</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>4 470</td>
<td>1.26</td>
</tr>
<tr>
<td>$^{244}$Pu</td>
<td>81</td>
<td>0.59</td>
</tr>
<tr>
<td>$^{247}$Cm</td>
<td>15.6</td>
<td>1.06</td>
</tr>
</tbody>
</table>
Abundance predictions for actinides

The predictions on the left are based on our calculations from 1997, whereas the right ones were calculated by Goriely and Arnould 2001. The right figure is based on one single SN event, whereas the left one assumes a uniform synthesis model in the frame of the superbubble concept.
Local Superbubble: Gould´s Belt

Cosmic rays propagate in a huge volume (about 1 kpc) of rarefied ISM. The outer expanding shell is marked by star-forming regions with young, hot OB associations (Gould´s Belt, Linblad Ring). The expansion is fuelled by recent SN explosions (over some ten million years).

*The Sun does not belong to this structure. It just passes through.*

In this close-up scheme of our Galactic neighbourhood (500 pc), the outer edge of the Linblad Ring is shown in the lower left corner. The region is dominated by a multitude of expanding shells of hot gases enclosing bubbles of rarefied ISM (~0.06 atoms/cm³ instead of mean value ~0.5).
The Local Bubble

• The local bubble (120 pc) is attributed to a SN about 34,000 years ago at a distance of 60 pc.
• The Geminga (γ-ray) pulsar (actually 100 pc distant) is a candidate for the remnant.

• The cosmic-ray enriched shock-front might have passed Earth 40,000 years ago leading to enhanced levels of Be-10 and C-14.
• But, this can also be explained by the significantly reduced terrestrial magnetic field: Laschamp event 41.5 - 36 kyr BP.
Mean actinide abundance ratios from r-process yields of core collapse supernovae in their accumulating ejecta averaged over various time intervals, assuming a constant supernova rate during those intervals. The typical cosmic-ray acceleration time span in the supernova-active cores of superbubbles of roughly 50 Myr is indicated by the dashed line (SB).

Superbubble core metallicity

In the cores of superbubbles, SNe are concentrated in space (about 1 kpc) and time (about 40 Myr). Freshly synthesized matter of high metallicity is deluted into old ISM with metallicity slightly higher than the Solar system value.

<table>
<thead>
<tr>
<th>Ratio</th>
<th>ISM origin</th>
<th>90% ISM + 10% fresh</th>
<th>freshly synthesized (Pfeiffer et al., 1997)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Act/Pt-group (×0.01)</td>
<td>1.85 ± 0.18</td>
<td>2.13 ± 0.19</td>
<td>4.63 ± 0.23</td>
</tr>
<tr>
<td>Th/Pt-group (×0.01)</td>
<td>1.28 ± 0.15</td>
<td>1.23 ± 0.19</td>
<td>0.83 ± 0.12</td>
</tr>
<tr>
<td>U/Th</td>
<td>0.45 ± 0.09</td>
<td>0.62 ± 0.12</td>
<td>2.88 ± 0.47</td>
</tr>
<tr>
<td>Pu/Pt-group (×0.01)</td>
<td>&lt; 2.3</td>
<td>4.0 ± 2.3</td>
<td>59 ± 14</td>
</tr>
<tr>
<td>Cm/Pt-group (×0.01)</td>
<td>&lt; 2.3</td>
<td>7.2 ± 3.2</td>
<td>106 ± 21</td>
</tr>
</tbody>
</table>

Expected cosmic-ray actinide abundance ratios as a function of superbubble core metallicity. Also indicated are the estimated U/Th and Actinide/PtGroup(75< Z<79) ratios in the present interstellar medium and in the supernova-enriched protosolar material.
UHCR measurements

Elemental abundances of UHCR were measured with track-etch detectors (as TREK on MIR):
Pt-group and Pb

Actinide nuclei:
• TREK: 6 nuclei (Z>88)  
  actinide/P-group = 0.034(18)
• UHCRE on LDEF: 30 nuclei  
  actinide/Pt-group = 0.028(8)

Predicted value in superbubble model:  
actinide/Pt-group = 0.027(5)

Etch pit in glass detector
Fe-60 in Deep-Sea Sediments

• An excess of $^{60}\text{Fe}$ has been detected in 2 to 5 Myr old deep-sea sediments.

• The upper Scorpius subgroup of the Sco-Cen OB association passed 40 pc from the Solar system about 2 Myr ago when several SNe exploded in this group.

• Up till now, no detection of $^{244}\text{Pu}$

• Some speculate that these close SNe might have had an influence on the development of early hominides at the Pliocene-Pleistocene transition.

• Others discuss relations between flux of CR and climate.
Future developments

• r-process calculations
  - inclusion of termination of r-process by fission
  - fission barriers, rates, mass distributions
  - dynamical network calculations

• cosmic-ray propagation
  - inhomogeneous matter distribution

• cosmic-ray experiments
  - fission track detectors: ECCO, on ISS?
  - ultra-long duration balloon flights: TIGER
  - dedicated satellites: Heavy Nuclei Explorer Mission

• interstellar matter
  - marine sediments: $^{60}\text{Fe}$, $^{244}\text{Pu}$?
  - sampling of stardust by high-flying air planes
  - Stardust probe: comet 81P/Wild-2