VERA – THE VIENNA ENVIRONMENTAL RESEARCH ACCELERATOR

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Attoagrams and Zeptomoles – Nuclear Physics with Utmost Sensitivity

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THE AUSTRALOPITHECUS 2-3 MYR AGO ...
Signatures of a Nearby Supernova

Nearby Supernova (SN II): < 100 pc \((10^{18} \text{m})\), rate \(\sim 0.3 - 10 \text{ (Ma)}^{-1}\)

WHERE to look for:
- ice core
- sediments
- deep sea crusts

\(^{26}\text{Al}, ^{60}\text{Fe}, ^{182}\text{Hf}, ^{244}\text{Pu}, \ldots\)

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SUPERNOVA-SIGNATURES IN DEEP-SEA SEDIMENTS

Cruise: Eltanin
Location: Indian Ocean
Depth: 4200 m

Courtesy of Google Maps (map) and www.navsource.org (ship).
Recent near-Earth supernovae probed by global deposition of interstellar radioactive $^{60}$Fe


The locations of recent supernovae near the Sun from modelling $^{60}$Fe transport

D. Breitschwerdt$^1$, J. Feige$^1$, M. M. Schulreich$^1$, M. A. de. Avillez$^{1,2}$, C. Dettbarn$^3$ & B. Fuchs$^3$
Voyage to SUPERHEAVY Island

Picture: Dusan Petricic
http://www.jinr.ru/
Search for SHE nuclides in Nature

Positive evidence from ICP-SF-MS:
Marinov et al., Jerusalem, 2007, 2009, 2010

Upper limits from AMS:
Lachner et al., Munich, 2008
Dellinger et al., VERA, 2010, 2011
Ludwig et al., Munich 2012

211,213,217,218\text{Th}: (1-10) \times 10^{-11}, <8 \times 10^{-15}

Summary of SHE searches in:
, 
Neutron Capture Cross Section of Unstable $^{63}\text{Ni}$: Implications for Stellar Nucleosynthesis

C. Lederer,1,2

In summary, we measured the energy-dependent $^{63}\text{Ni}(n, \gamma)$ cross section at the n_TOF facility providing the first experimental results for MACSs at stellar neutron energies. The MACSs ranging from $kT = 5$–100 keV exhibit total uncertainties of 20%–22% and are about a factor of 2 higher than the theoretical prediction of the KADoNiS compilation. Our results improve one of the main nuclear uncertainties affecting theoretical predictions for the abundances of $^{63}\text{Cu}$, $^{64}\text{Ni}$, and $^{64}\text{Zn}$ in $s$-process rich ejecta of core collapse supernovae. Furthermore, these results are a fundamental step to constrain the contribution from explosive nucleosynthesis to these species.
Preparation of an $^{55}$Fe-AMS-Standard & Precise measurement of the neutron capture cross-section $^{54}$Fe(n,$\gamma$)$^{55}$Fe

Kathi Buczak
**Basic principle**

**Neutron Capture Cross Section Measurement**

Activity measurement of the fluence monitor $^{197}$Au

$$\Phi = \frac{N_{^{198}Au}}{\sigma_{n,\gamma} N_{^{197}Au}} = \frac{A_{^{198}Au}(t_{irr,E})}{\sigma_{n,\gamma} N_{^{197}Au}} \cdot \frac{T_{irr}}{(1 - e^{-\lambda T_{irr}})}$$

with

$$A_{^{198}Au}(t_{irr,E}) = \frac{n(t_{MA})}{\varepsilon_\lambda p_\lambda} \cdot e^{\lambda T_w}$$

$^{198}$Au:

- $T_{1/2} = 2.69$ d
- $E_\gamma = 412$ keV
- $P_\gamma = 96\%$
- $\varepsilon_\gamma = 0.97\%$

$\sigma_{^{54}Fe(n,\gamma)} = \frac{N_{^{55}Fe}}{\Phi_n}$
Research is centered around a facility for Accelerator Mass Spectrometry (AMS) "VERA" Vienna Environmental Research Accelerator

"... detect long-lived radioisotopes all across the nuclear chart with utmost sensitivity $10^{-12}$ ... $10^{-16}$, i.e., at natural levels"
ACCELERATOR MASS SPECTROMETRY AMS

... a mass-spectrometric technique to measure long-lived radioisotopes, e.g., $^{10}\text{Be}$, $^{14}\text{C}$, $^{26}\text{Al}$, ... , $^{236}\text{U}$, $^{244}\text{Pu}$ at natural abundance levels $10^{-12} \ldots 10^{-16}$ g/g.
...exploring our world atom-by-atom
Conventional (low-energy) Mass Spectrometry

Stable isotope ratios from $\sim 1$ to $10^{-6}$
e.g. $\frac{^{13}\text{C}}{^{12}\text{C}} = 1.1 \times 10^{-2}$
Conventional (low-energy) Mass Spectrometry
Stable isotope ratios from \(~1\) to \(10^{-6}\)
e.g. \(^{13}\text{C}/^{12}\text{C} = 1.1 \times 10^{-2}\)

Accelerator Mass Spectrometry
Radioisotope ratios from \(10^{-12}\) to \(10^{-16}\)
e.g. \(^{14}\text{C}/^{12}\text{C} = 1.2 \times 10^{-12}\)
Accelerator Mass Spectrometry for “all“ isotopes: \(^{10}\text{Be},^{14}\text{C},^{26}\text{Al},^{36}\text{Cl},^{41}\text{Ca},^{55}\text{Fe},^{182}\text{Hf},^{210}\text{Pb},^{210}\text{Bi},^{236}\text{U},^{239-244}\text{Pu},\text{SHE},(\text{H}_2)^-,\text{(LiF}_3)^-,\ldots\)
Accelerator Mass Spectrometry (AMS) for “all” isotopes: \(^{10}\text{Be}, {^{14}\text{C}}, {^{26}\text{Al}}, {^{36}\text{Cl}}, {^{41}\text{Ca}}, {^{55}\text{Fe}}, {^{182}\text{Hf}}, {^{210}\text{Pb}}, {^{210}\text{Bi}}, {^{236}\text{U}}, {^{239-244}\text{Pu}}, \text{SHE}, (\text{H}_2)^-, (^{43}\text{Ca}^{19}\text{F}_4)^{-}, \ldots$

**Negative-Ion Sources**

**NEGATIVE-ION SOURCES**

**Cs-Beam Sputter Source for Negative Ions**

**Source 1**
- 40 Samples
- 75 kV Preacceleration
- Insertable Faraday Cup
- Electrostatic Analyzer
  - \(E/q=90 \text{ keV} \)
  - \(r=0.300 \text{ m}\)
- Beam Switch
- Magnetic Quadrupole Doublet
- Multi Beam Switcher

**Source 2**
- 40 Samples
- 75 kV Focus
- Insertable Faraday Cup
- Einzel Lens
- Beam Profile Monitor
- \(x/y\)-Steerer
- 75 kV Focus

**Stripping and Molecule Dissociation**

**+3 MV Tandem Accelerator**

- Wienfilter
  - \(\varepsilon x B = 35 \text{ kV/cm} \times 0.4 \text{ T}\)
- Magnetic Quadrupole Triplet
- Gas + Foil Stripper
- Charging Chain
- Einzel Lens
- Zooming Quadrupole Triplets
- \(x/y\)-Steerer

**Heavy Isotope Detection**

**Detector area**

**VERA**

Vienna Environmental Research Accelerator

1996: 1\(^{st}\) operation
2001: 1\(^{st}\) upgrade
2007: 2\(^{nd}\) upgrade

**Positive-Ion Mass Spectrometer (MeV)**

**Additional Elements**

- Ion Production and Detection
- Electrostatic Components
- Magnetic Components
- Beamline

**Stable Isotope Measurement**

- \(^{12}\text{C}^3+, {^{13}\text{C}^3+}\}
- Offset Faraday Cups
- Beam Profile Monitor
- \(14\text{C}^3+, \ldots\)
- \(15\text{C}^3+, \ldots\)
- Offset Faraday Cups
- Accelerator Mass Spectrometry (AMS) 43CaF4
**Tandem Accelerator in AMS**

... provides sufficient energy [MeV] to break up molecular ions in the stripping process, & to help identify atomic ions, e.g. by M, E and ΔE(Z).
Mass($^{14}$C$^-$) $\approx$ Mass($^{12}$CH$_2$-)
AMS: $\text{Mass}(^{14}\text{C}^+) \neq \text{Mass}(^{12}\text{C}^+), \text{Mass}(^{1}\text{H}^+)$
zeptomole
\[ 1 \times 10^{-21} \times 6.02 \times 10^{23} \approx 600 \]

attogram \( 10^{-18} g \)
\[ 100 \text{ zmol} \ ^{14}\text{C} \approx \]
\[ 100 \times 600 \times 14 \times 1.66 \times 10^{-24} \approx 1 \text{ ag} \]
... provides sufficient energy [MeV] to break up molecular ions in the stripping process, & to help identify atomic ions, e.g. by M, E and ΔE(Z).
Setup to stop stable isobar $^{10}_5\text{B}$

- Foil stack with 13 SiN–foils: 5 mm x 5 mm x $1000 \text{ nm}$
- Window–SiN–foil: 5 mm x 5 mm x $100 \text{ nm}$
**Simulations to identify background**

**Molecules**
- $^9$BeH$^2^+$ *from $^9$Be$^{16}$OH$^-$
- $^{25}$Mg$^{5^+}$ *from $^{25}$MgH$^-$
- $^{15}$N$^{3^+}$ *from $^{15}$N$^9$BeH$_2^-$

**Nuclear reactions**
- $^4$He, $^7$Be *from p($^{10}$B,α)$^7$Be
- $^{12}$C *from p($^{15}$N, α)$^{12}$C
**Standard** (measured 4 minutes) 
irradiated at TU-Vienna

$^{10}\text{Be}/^{9}\text{Be} = (1.72\pm0.05) \times 10^{-12}$

**Blank** (measured 60 minutes)

$^{10}\text{Be}/^{9}\text{Be} = (7.1 \pm 1.7) \times 10^{-16}$
... at $10^{-12}$...$10^{-16}$ there are

almost all stable nuclides in sample &

huge amounts of molecules at almost all masses from ion source.
236U as an Oceanic Tracer

Not only spatially resolved...

...but also temporally resolved archives in corals

(Sakaguchi et al., 2012)

(Winkler et al., EPSL2012)
Magnetic rigidity $\frac{p}{q}$

Electric rigidity $\frac{E}{q}$

$E = \frac{p^2}{2m}$

E.g. $^{238}\text{U}^{5+}$ with all possible energies
$E = \frac{p^2}{2m}$

Suppression $10^4$

Magnetic rigidity $p/q$

Electric rigidity $E/q$

Magnet

E.g. $^{236}\text{U}^{5+}$

E.g. $^{238}\text{U}^{5+}$

No suppression
HIGH-RESOLUTION FILTERS

Electric rigidity $E/q$

Magnetic rigidity $p/q$

$E = \frac{p^2}{(2m)}$

Suppression $10^4$

Suppression $10^8$

e.g. $^{238}\text{U}^{5+}$

e.g. $^{236}\text{U}^{5+}$

ESA
HIGH RESOLUTION FILTERS

Electric rigidity $E/q$

Magnetic rigidity $p/q$

velocity $v = 2E/p$
e.g. $^{236}\text{U}/^{238}\text{U} \approx 10^{-13}$
e.g. $^{236}\text{U}/^{238}\text{U} \approx 10^{-13} \rightarrow 10^{-17}$
Voyage to SUPERHEAVY Island

Picture: Dusan Petricic
http://www.jinr.ru/
HOW ABSENCE OF EVIDENCE BECOMES EVIDENCE OF ABSENCE

Voyage to SUPERHEAVY Island

Picture: Dusan Petricic
http://www.jinr.ru/
Search for Eka-Th in natural thorianite

Thoria (ThO$_2$) pebble found in Morocco

+ Ag powder (1:1)

≈ 400 nA ThO$_2^-$ out of source


- additional targets of commercial ThO$_2$ powder (Merck)
- targets from Th solution used by Marinov et al.

Franz DELLINGER, AMS of Actinides and the Search for Superheavy Elements
$^{197}\text{Au}^{126}\text{Te}^-$ (m=323) to tune le-side for $^{292}\text{Eka-ThO}_2^-$ (m=324)

$^{126}\text{Te}^{3+}$ to tune the he-side for $^{292}\text{Eka-Th}^7^+$

197 Au$^{126}$Te$^-$ (m=323) to tune le-side for 292 Eka-ThO$^-_2$ (m=324)

126 Te$^{3+}$ to tune the he-side for 292 Eka-Th$^7^+$
Franz DELLINGER, AMS of Actinides and the Search for Superheavy Elements
Result of the first beamtime (141 runs):
Result of the first beamtime (141 runs):

Typical measurement sequence of one single run:

- current setup (~20 s)
- reference ion 1 (~20 s)
- reference ion 2 (~20 s)
- reference ion 3 (~20 s)
- SHE isotope 1 (~200 s)
- SHE isotope 2 (~200 s)
- SHE isotope 3 (~200 s)
- SHE isotope 4 (~200 s)
- current setup (~20 s)

~ 1000 s per run
Composite Spectrum of the first beamtime (141 runs):

3 reference ion setups: $^{238}\text{U}^{6+}$, $^{208}\text{Pb}^{5+}$ and $^{167}\text{Er}^{4+}$
(measured in separate setups)

no event detected within SHE bin
Search for neutron-deficient Th isotopes (first 59 runs):
Pile-up suppression by pulse width (first 59 runs)
Nucleosynthesis of the elements

Heavy elements (A > 56) are produced by the s-process (~50%) and the r-process (~50%).
• Half-life: 8.9 Myr [1]

• Production expected in supernova

\[ \frac{^{182}\text{Hf}}{^{180}\text{Hf}} \leq 10^{-12} \]

AMS Isotopes: $T_{1/2} = 10^4 \ldots 10^8$ a

Routine at VERA
Very large AMS required

(some more actinides not shown)
AMS Isotopes: $T_{1/2} = 10^4 \ldots 10^8$ a

Routine at VERA

Very large AMS required

Laser + AMS

(some more actinides not shown)
Resonant Ionization for Ion Production and Isomer Separation

Negative Ion Laser Photodetachment in Cooler / Trap

Collinear Fast Ion / Atom Beam - Laser Interaction

Trapped / Cooled Ion - Laser Interaction

Trapped / Cooled Atom - Laser Interaction
ACCELERATOR MASS SPECTROMETRY

Negative-ion source

Electrostatic + magnetic mass separation

Acceleration

"Stripping": Molecule destruction Charge change 1- to q+

Acceleration

Ion current measurement

Electrostatic + magnetic mass separation

Rare ion identification and counting

Isobar separation
ACCELERATOR MASS SPECTROMETRY

1. Negative-ion source
2. Electrostatic + magnetic mass separation
3. Acceleration
4. "Stripping": Molecule destruction Charge change 1- to q+
5. Acceleration
6. Ion current measurement
7. Electrostatic + magnetic mass separation
8. Rare ion identification and counting
9. Isobar separation
"No chance for injection, no need for rejection"
**Isobar suppression by photodetachment in a gas-filled rf quadrupole ion guide**

Y. Liu, J. R. Beene, C. C. Havener, and J. F. Liang  
*Physics Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831-6368*

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Nd:YAG Laser at 1064 nm  
Power ~ 3 W  
He pressure ~ 6x10^{-2} mbar


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EA 0.663 eV  
EA 1.157 eV
RFQ ion cooler

RF quadrupole structure consists of four cylindrical rods. A small longitudinal field is created by separate guide electrodes. Length of RFQ region: 80cm

Typical values:
- $U_{RF}$: 200V
- $f_{RF}$: 0.5-5MHz
- $U_{DC}$: 0V
- $U_{guide}$: −150V
Laser interaction:
unwanted isobar neutralized, isotope of interest unchanged
Suppression of $^{26}\text{Mg}^-$ from $^{26}\text{Al}^-$

<table>
<thead>
<tr>
<th>Species</th>
<th>EA (eV)</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{AlO}^-$</td>
<td>2.600</td>
<td>477</td>
</tr>
<tr>
<td>$\text{MgO}^-$</td>
<td>1.630</td>
<td>760</td>
</tr>
</tbody>
</table>

Suppression of $^{60}\text{Ni}^-$ from $^{60}\text{Fe}$

<table>
<thead>
<tr>
<th>Species</th>
<th>EA (eV)</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni$^-$</td>
<td>1.157</td>
<td>1071</td>
</tr>
<tr>
<td>Fe$^-$</td>
<td>0.151</td>
<td>8211</td>
</tr>
<tr>
<td>FeH$^-$</td>
<td>0.934</td>
<td>1327</td>
</tr>
<tr>
<td>Ni H$^-$</td>
<td>0.481</td>
<td>2578</td>
</tr>
</tbody>
</table>

Suppression of WF$_5^-$ from HfF$_5^-$ for AMS of $^{182}\text{Hf}$

Theor. EA’s WF$_5^-$ 3.9 eV, HfF$_5^-$ 8.8 eV.

Exp. detachment @ 266 nm WF$_5^-$ 100 higher than HfF$_5^-$.

[Leopold et al., IJMS (2014) 359]
Mass selected negative ion beams within mass 1 ... ~300 u at energies up to 30 keV from a sputtering ion source.
Ion cooler with HV-cage

- Negative ion beam
- Laser beam