New Measurement of the $^{93}$Zr(n,$\gamma$) Cross Section and the Zr and Nb Abundances in Stardust Grains from AGB Stars

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The monoisotopic element Nb is produced mostly by the s process via the decay of the long-living radioactive nucleus $^{93}\text{Zr}$ ($T_{1/2}=1.5$ million years), which is on the main s-process path.

Roberto Gallino would remind me to say that: Nb can be used to discriminate between *intrinsically* and *extrinsically* AGB stars, similarly but opposite to Tc: *intrinsically* AGB stars will have low Nb, while *extrinsically* AGB stars will have high Nb.
The s process in AGB stars

- Proton diffusion
- $^{13}$C($\alpha$,n)$^{16}$O
- $^{22}$Ne($\alpha$,n)$^{25}$Mg

- Base of convective envelope
- Convective pulse
- He - C intershell

- Mass: $10^{-4}$
- Log H: 0.7

- Neutron density
- Time

- C-O core
- H-burning shell
- He-burning shell
• **We model the s process in AGB stars** with a nucleosynthesis network of 320 nuclear species from H to Bi and 2,336 nuclear reactions with rates from the USA Joint Institute for Nuclear Astrophysics (JINA) database.

• **The post-processing code** activates nuclear reactions in the star on the basis of the information on the temperature, density, and convective velocity provided by the stellar structure models.

• **Nuclear burning and convective mixing** are both included in the equations of the abundance changes and thus solved simultaneously.

• The equations that describe the changes in the abundances are solved using an implicit method where a large matrix of $320^2$ is solved.

• The runs take from days to weeks depending on the stellar mass.

**Neutron-capture cross sections along the s-process path are fundamental input physics for the models!**
The n_TOF facility at CERN

somewhere around here
The CERN n_TOF Facility

n_TOF
200m Tunnel

Sample
n-beam

Proton Beam
20GeV/c
7x10^{12} ppp

Booster
14 GeV

Linac
50 MeV

PS 20GeV

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Some specifications:

<table>
<thead>
<tr>
<th>n_TOF features</th>
<th>Use in astrophysics</th>
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<tbody>
<tr>
<td>broad neutron energy</td>
<td>neutron capture cross sections for s-process studies (1 eV – 1 MeV)</td>
</tr>
<tr>
<td>high instantaneous flux</td>
<td>small capture cross sections</td>
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<tr>
<td></td>
<td>small sample quantities (isotopically enriched samples)</td>
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<td></td>
<td>radioactive samples (low intrinsic background)</td>
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<td></td>
<td>resonance dominated cross sections</td>
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<tr>
<td></td>
<td>accurate cross section measurements</td>
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<tr>
<td></td>
<td>even for large $s_{el}/s_{capture}$</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>proton beam momentum</th>
<th>20 GeV/c</th>
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<tbody>
<tr>
<td>intensity (dedicated mode)</td>
<td>$7 \times 10^{12}$ protons/pulse</td>
</tr>
<tr>
<td>repetition frequency</td>
<td>1 pulse/2.4s</td>
</tr>
<tr>
<td>pulse width</td>
<td>6 ns (rms)</td>
</tr>
<tr>
<td>n/p</td>
<td>300</td>
</tr>
<tr>
<td>lead target dimensions</td>
<td>80x80x60 cm$^3$</td>
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<tr>
<td>cooling &amp; moderation material</td>
<td>H$_2$O</td>
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<tr>
<td>moderator thickness in the exit face</td>
<td>5 cm</td>
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$^{93}\text{Zr}(n,\gamma)$

- The preliminary n_TOF estimate is 43% lower than given by the pioneering experiment by Macklin (1985), and outside the previously given 20% $2\sigma$ error bar.

- n_TOF allows for a strong reduction of the background induced by neutrons scattered by the sample and captured in the materials constituting the experimental setup.

- For $^{93}\text{Zr}$ it was possible to extract n_TOF information only below 8 keV of incident neutron energy. To complement n_TOF data at higher energies we scaled the evaluation given by the JENDL calculations at high energy by the same factor extracted in the n_TOF measured range.
A lower $^{93}\text{Zr}(n,\gamma)$ value means that more $^{93}\text{Zr}$ is produced. After radiogenic decay of $^{93}\text{Zr}$ more Nb will result.

The final result is $\sim50\%$ more Nb!
What are stardust grains

They are *microscopic meteoritic* dust

Allende meteorite
(Mexico, 1969)
Carbonaceous chondrite

Matrix:
amalgam of amorphous material and crystals of very small dimensions

size ~ 1 µm

Chondrules
size ~ 1 mm

Stellar grains
Stardust grains are tiny specks of stars

Stardust grains were
✓ born around ancient stars,
✓ ejected into the interstellar medium,
✓ preserved during the formation of the solar system, and
✓ trapped inside primitive meteorites from where they are now extracted and analysed.
Elemental Nb and Zr abundances in stardust silicon carbide (SiC) grains

Most stardust SiC grains extracted from primitive meteorites originated from carbon-rich AGB stars. Their isotopic compositions show the clear signature of the s process.

Chemically, Zr and Nb are very similar: they are both very refractory elements. This means that they condense from gas into solid at high temperatures. So, they should be both present in SiC.

Actually, $^{93}\text{Zr}$ was still alive at the time the grains condensed in the source AGB stars, so most Nb in SiC would have derived from the decay of $^{93}\text{Zr}$ inside the grains!
Kashiv et al. (2010) used synchrotron X-ray fluorescence to measure the abundances of Zr and Nb in single SiC.

As compared to AGB s-process predictions, the grains confirm that $^{93}\text{Zr}$ condensed in the grains and then turned into Nb.

But, the data are generally to the left of the prediction lines…
Elemental Nb and Zr abundances in SiC

1. To explain the mismatch Kashiv et al. (2010) assumed depletion of Zr before SiC grain condensation.

2. For example Zr can form ZrC at higher temperatures, thus before SiC form in a cooling gas.

3. However, the problem with this scenario is that Nb should have done exactly the same: form NbC before SiC.

4. Kashiv et al. (2010) suggest that perhaps condensation of NbC was too slow because there is 4-6 times less Nb than Zr in AGB envelope? Or perhaps the data are somewhat contaminated by solar Nb (and not by solar Zr)?
With the new $^{93}\text{Zr}(n,\gamma)$ cross section the prediction lines seem to cover the data better.
Equal loss of Zr and Nd would move the data along this line

80% of Zr removed from the gas

Selective contamination?

90% of Nb removed from the gas

Equal loss of Zr and Nd would move the data along this line
Low mass AGB stars do not produce Zr and Nb in solar proportions, they make more Nb than Zr, relatively.

According to Galactic chemical evolution models of Travaglio et al. (2004) the s-process AGB contribution to solar is of the order of 70% in this atomic region.

Where the rest come from we do not know, Light Elements Primary Process – LEPP (Montes et al. 2007). Whatever LEPP is, it should make more Zr than Nb, relatively.
Summary and Conclusions

• The new n_TOF $^{93}\text{Zr}(n,\gamma)$ cross section is 43% lower than the previous estimate.
• This results in higher production of $^{93}\text{Nb}$, the radiogenic daughter of $^{93}\text{Zr}$ and the only isotope of Nb, of up to 50%.
• It provides a better match of the elemental abundances of Zr and Nb measured in single stardust SiC grains.
• Grains that are $2\sigma$ outside the model predictions, could be explain by selective contamination and/or selective removal of Zr or Nb from the gas. Is this feasible?
• Using the new cross section it is predicted that LEPP should make more Zr than Nb.