Search for Neutron Antineutron Oscillations at Super Kamiokande I

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- a neutron oscillates into an antineutron

Oxygen 16

\( n \)

time \( 10^{33} \) years
• the antineutron annihilates with another nucleon → pions

time \sim 5 \times 10^{-24} \text{ seconds}
the pions traverse and interact with the residual nucleus

• time $\sim 2 \times 10^{-23}$ seconds
the residual nucleus de-excites and/or breaks up.

time $<< 1 \times 10^{-8}$ seconds
Outline

• R - Nuclear Suppression Factor
• Signal MC
• Detector
• Background – Atmospheric Neutrinos
• Analysis
• Future
Oscillation Suppression in Nuclei
Neutron Antineutron Oscillations

Two State non relativistic Schrödinger's Equation

\[
\begin{pmatrix}
\frac{p^2}{2m} + \Delta E \\ \varepsilon \\ \varepsilon \\ \frac{p^2}{2m} - \Delta E
\end{pmatrix}
\begin{pmatrix}
\frac{E}{n} \\ \frac{\varepsilon}{n}
\end{pmatrix} = E
\begin{pmatrix}
\frac{E}{n} \\ \frac{\varepsilon}{n}
\end{pmatrix}
\]

where \( \Delta E \) represents differing responses of n and \( \bar{n} \) to the environment: Earth’s magnetic field, Surrounding nuclear medium etc.

if \( \Delta E \ll \varepsilon \)

Free oscillation probability = \( \varepsilon^2 t^2 \)
Oscillations in Nuclei

\[
\left( \frac{p^2}{2m} + U_n - E \right) n = -\varepsilon \, n_{\text{bar}} \approx 0
\]

\[
\left( \frac{p^2}{2m} + U_{n_{\text{bar}}} + i W_{n_{\text{bar}}} - E \right) n_{\text{bar}} = -\varepsilon \, n
\]

1) Adjust \( E \) to make \( n \) square normalizable.

2) Adjust \( n_{\text{bar}}/n \)

Taken from antiproton-nucleus scattering experiments.

The problem is we only have data near the nuclear surface.

if these are dissimilar the curvature blows up
n and nbar wavefunctions
(based roughly on Dover. For qualitative illustration only)

\[ \int_{-\infty}^{\infty} \psi_n(x) \psi_{\overline{n}}(x) dx \]

roughly follows shape of \(|n|^2\)

\[ \frac{1}{\tau} = \Gamma = -2 \int d^3x |\overline{n}(x)|^2 W(x) \]

from previous page \( \frac{1}{\tau} = \frac{n \propto \varepsilon \propto \frac{1}{\tau_{\text{free}}}}{\tau_{\text{free}}} \)

so we can define \( R = \frac{\tau}{\tau_{\text{free}}^2} \)

* in our current analysis the annihilation location is based on \(|n|^2\)
Some calculations of $R$

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Potential</th>
<th>$R$</th>
<th>$R_\text{O}/R_\text{Fe}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dover</td>
<td>1983</td>
<td>249+i107</td>
<td>1.2</td>
<td>.71</td>
</tr>
<tr>
<td>Dover</td>
<td>1983</td>
<td>107+i222</td>
<td>.8</td>
<td>.71</td>
</tr>
<tr>
<td>Alberico</td>
<td>1991</td>
<td>Various</td>
<td>1.7-2.6</td>
<td>?</td>
</tr>
<tr>
<td>Hufner</td>
<td>1998</td>
<td>40+i40</td>
<td>.69</td>
<td>1.11</td>
</tr>
<tr>
<td>Hufner</td>
<td>1998</td>
<td>200+i40</td>
<td>3.6</td>
<td>.92</td>
</tr>
</tbody>
</table>

We use the most conservative values $3.6 \times 10^{23}$ sec$^{-1}$ for comparing with $\tau_\text{free}$ and .71 when comparing with $\tau_\text{free}$. From previously shown potential uncertainty.
Signal MC
Fermi Momentum / Quasi-Invariant Mass

• annihilating antineutron and nucleon are in energy eigenstates.

• Fermi momentum can be taken from scattering data (should match the Fourier Transform of the wavefunctions)

• quasi-invariant mass  \( m^2 = E^2 - p_F^2 \)

• During roughly 10% of the events, the matter nucleon will be interacting with another nucleon during the annihilation – giving a smaller invariant mass – Yamazaki Phys Lett B 453 (not implemented yet)

However, we aren’t very sensitive to these effects, setting the Fermi momentum to zero only changes our efficiency by ~10%

Leads to <4.2% uncertainty in final efficiency
## Branching Fractions

### n pbar annihilations (from pbar deuterium data)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Tegid’s Memo</th>
<th>Our Analysis</th>
<th>Bettini (1967)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^0$</td>
<td>0%</td>
<td>1%(±1.0)</td>
<td>≤ 0.7%</td>
</tr>
<tr>
<td>$\pi^+\pi^0\pi^0$</td>
<td>9%</td>
<td>8%(±1.2)</td>
<td></td>
</tr>
<tr>
<td>$\pi^+\pi^0\pi^0\pi^0$</td>
<td>10%</td>
<td>10%(±1.2)</td>
<td>16.4 ± 0.5%</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^0$</td>
<td>22%</td>
<td>22%(±1.8)</td>
<td>21.8 ± 2.2%*</td>
</tr>
<tr>
<td>$\pi^+\pi^0\pi^0\pi^0$</td>
<td>36%</td>
<td>36%(±1.8)</td>
<td>59.7 ± 1.2%</td>
</tr>
<tr>
<td>$2\pi^+\pi^-\omega$</td>
<td>*</td>
<td>16%(±4)</td>
<td>12.0 ± 3.0%*</td>
</tr>
<tr>
<td>$3\pi^+2\pi^0$</td>
<td>23%</td>
<td>7%(±4)</td>
<td>23.4 ± 0.7%</td>
</tr>
<tr>
<td>$4\pi^+3\pi^-m\pi^0$</td>
<td>0%</td>
<td>0%</td>
<td>0.39 ± 0.07%</td>
</tr>
<tr>
<td>$\pi^+\pi^+\pi^-$</td>
<td>0%</td>
<td>0%</td>
<td>1.57 ± 0.21%</td>
</tr>
</tbody>
</table>

### p pbar annihilations (use isospin invariance)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^-$</td>
<td>0%</td>
<td>2%(±.4)</td>
<td>0.33 ± 0.48%</td>
<td>0.32 ± 0.03%</td>
</tr>
<tr>
<td>$\pi^0\pi^0$</td>
<td>0%</td>
<td>1.52%(±.4)</td>
<td>3.20 ± 0.50%</td>
<td></td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^0$</td>
<td>10%</td>
<td>6.48%(±.7)</td>
<td>5.4 ± 0.7%</td>
<td>7.8 ± 0.9%</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^0\pi^0$</td>
<td>11%</td>
<td>11%(±1.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2\pi^+2\pi$</td>
<td>7%</td>
<td>7%(±1.4)</td>
<td>5.4 ± 0.3%</td>
<td>5.8 ± 0.3%</td>
</tr>
<tr>
<td>$2\pi^+2\pi^0\pi^0$</td>
<td>22%</td>
<td>24%(±3.4)</td>
<td>22.6 ± 0.7%</td>
<td>18.7 ± 0.9%</td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^0\pi^0\pi^0$</td>
<td>*</td>
<td>10%(±0.9)</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>$\pi^+\pi^-\omega$</td>
<td>*</td>
<td>10%(±0.9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2\pi^+2\pi^0\pi^0\pi^0$</td>
<td>20%</td>
<td>10%(±0.9)</td>
<td>21.3 ± 1.1%</td>
<td></td>
</tr>
<tr>
<td>$3\pi^+3\pi^-m\pi^0$</td>
<td>0%</td>
<td>0%</td>
<td>1.7 ± 0.2%</td>
<td>1.9 ± 0.2%</td>
</tr>
<tr>
<td>$3\pi^+3\pi^+\pi^-$</td>
<td>0%</td>
<td>0%</td>
<td>1.7 ± 0.2%</td>
<td>1.6 ± 0.3%</td>
</tr>
</tbody>
</table>

Decays are according to phase space (Genbod)

**more recent ppbar BF’s**

astro-ph/0005419
kaons 7%
eta 3%
won’t change our results

**Leads to 5.2% uncertainty in final efficiency**
Pion (and Omega) Propagation

- Pions propagate through the residual nucleus in .2 fm steps.
- Total pion-nucleus cross section is taken from scattering experiments and distributed throughout the residual nucleus according to the nuclear density.
- Cross section peak due to $\Delta(1232)$.

25% of pions absorbed, 25% scattered, 2.2 charged, 1.3 neutral pions escape.

Leads to 12.5% uncertainty in final efficiency.
Fermi Momentum / Pauli Blocking

- Nucleons of the residual nucleus are assigned a fermi momentum.
- For a fermi gas of local density $\rho$
  \[ p_{\text{max}} \propto \rho^{\frac{1}{3}} \]
- Reactions that would result in a final state momentum $> p_{\text{max}}$ are not allowed – Pauli Blocking
Nuclear De-excitation / Break-up

**Gamma rays** - P 3/2 holes will decay with the emission of a 6 MeV gamma – but this overlaps the rest of our signal.

In events with a pion interaction we currently create nuclear fragments (p n d He etc.) that statistically match inclusive multiplicities from antiproton-nucleus data.

**Cherenkov Light** - some proton fragments will be above threshold, but the amount of light is insignificant compared to the pion contribution.

**Neutron decay** – another analysis group is working on a special trigger for neutron decay. However it is not clear that a background DIS atmospheric neutrino event would break up differently than a signal nucleus, so a more sophisticated break-up model is probably not worth the effort for this analysis.
Detector

- 22.5 Kton Fiducial
- 2,700 m water equivalent overburden
- 11,146 inner PMTs
- 1,885 outer PMTs
- SK1  4.1 yr (this analysis)
- SK2  ~ 2 yr (1/2 PMTs)
- SK3  ~ 1 yr
- 2.2 nsec timing
- Can see 4.5 MeV neutrinos
Cherenkov Rings

π or μ losing 2 MeV/cm to ionization

in water ionization = bremsstrahlung at ~93 MeV
Ring Reconstruction

1) Place vertex at point which time of flight is equal to all hit PMTs. Resolution ~30 cm

2) For each PMT plot all possible track directions which could have resulted in a 42 degree Cherenkov angle photon hitting the tube. Look for overlaps.

3) Reconstruct entire length of track (~1 meter for our events.)
Track Momentum/Event Energy

- The track momentum is determined from the total number of photo-electrons seen near the ring (70 degree $\frac{1}{2}$ angle for single ring events)

- In single ring events the momentum resolution is $(2.5/\sqrt{\text{GeV}} + .5)\%$ for electrons. and 3% for muons

- “Visible Energy” for an event is defined as the energy of an electromagnetic shower giving the number of photo-electrons we see.
Background
Atmospheric Neutrinos
## Selected background events

<table>
<thead>
<tr>
<th></th>
<th>$\nu_\mu$</th>
<th></th>
<th></th>
<th>Anti-$\nu_\mu$</th>
<th></th>
<th></th>
<th>Anti-$\bar{\nu}_e$</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Q.E.</strong></td>
<td>11 (2.0%)</td>
<td></td>
<td></td>
<td>0 (0%)</td>
<td></td>
<td></td>
<td>0 (0%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CC 1pi</strong></td>
<td>50 (9.6%)</td>
<td></td>
<td></td>
<td>10 (1.9%)</td>
<td>47 (9.0%)</td>
<td></td>
<td>7 (1.3%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CC Mpi</strong></td>
<td>101 (19.4%)</td>
<td></td>
<td></td>
<td>10 (1.9%)</td>
<td>103 (19.8%)</td>
<td></td>
<td>9 (1.7%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CC K,eta</strong></td>
<td>6 (1.2%)</td>
<td></td>
<td></td>
<td>6 (1.1%)</td>
<td></td>
<td></td>
<td>8 (1.5%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NC 1pi</strong></td>
<td></td>
<td>17 (3.3%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NC mpi</strong></td>
<td></td>
<td></td>
<td>125 (24.0%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NC K,eta</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 (0.4%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NC elastic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 (0.2%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Atmospheric $\nu$

Lepton

W or Z

pion

nucleon

nucleon
Background Signatures

Invariant mass different from $n+n\bar{n} \sim 1800$ MeV

Large final state total momentum

Smaller number of rings
Smaller number of $\pi \rightarrow \mu \rightarrow e$

Large fraction of energy in a single ring

Atmospheric $\nu$ → $W$ or $Z$ → nucleon

Lepton → $\pi$ → pion

$nucleon \rightarrow W$ or $Z$ \rightarrow $nucleon$
\[ \nu_e + n \rightarrow e^- + p + \pi^+ + \pi^- + \pi^0 \]
Background Direction and Energy

from oscillation analysis

background more likely to come from above
(we are currently not using this)
Neutrino flux is our largest systematic. It leads to 20% uncertainty in final background rate.
Neutrino cross sections

Cross section in multi-pion events leads to 3.4% uncertainty in final background rate
Multiple pions production models

- For hadronic mass $1.4 < W < 2.0$ GeV, we fit Koba, Nielsen, Olesen (KNO) scaling to experimental pion multiplicities and forward/backward asymmetries from BECB and Gargamelle.
- For $W > 2.0$ we use Jetset.

Model dependence leads to 15.5% uncertainty in final background rate.
Analysis
# Reduction to “Fully Contained” Data Sample

<table>
<thead>
<tr>
<th>Step</th>
<th>Data</th>
<th>FC MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>1.9G</td>
<td>100%</td>
</tr>
<tr>
<td>200 PE within 300 nsec, &lt;1/2 of PE in one PMT, &lt;25 Outer Detector (OD) hits, &gt;.1 msec since last event.</td>
<td>302K</td>
<td>99.94</td>
</tr>
<tr>
<td>&lt;10 OD hits aligned with an inner muon track. &gt;50 PMT hits within 50 nsec after TOF (eliminates low energy events)</td>
<td>67K</td>
<td>99.83</td>
</tr>
<tr>
<td>Elimination of Flashing PMTs -Broad timing distributions eliminated. Hit patterns similar to earlier events removed.</td>
<td>27K</td>
<td>99.17</td>
</tr>
<tr>
<td>&lt;10 OD hits in any 200 nsec window in the last 9 μs. (removes muons which drop below Cherenkov threshold inside the detector then decay.</td>
<td>24K</td>
<td>97.59</td>
</tr>
<tr>
<td>Within fiducial volume (2m from wall). Visible Energy &gt;30 MeV</td>
<td>12K</td>
<td>97.59</td>
</tr>
</tbody>
</table>
Cuts

Red – atmospheric $\nu$ MC
Black – signal MC
Dotted - data

Number of Rings

Total momentum(MeV/c) after Ring,Evis cut

Visible energy(MeV/c) after Ring cut

Invariant mass(MeV/C$^2$) after Ring,Evis cut
High energy leptons from charged current events

The shapes of the distributions are not very different.

→ cannot use for reduction.
## Systematic uncertainties in the efficiency

<table>
<thead>
<tr>
<th></th>
<th>error</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Detection efficiency</strong></td>
<td>14.9 %</td>
<td></td>
</tr>
<tr>
<td>Fermi momentum</td>
<td>20% of $P_f$</td>
<td>&lt;4.2%</td>
</tr>
<tr>
<td>Annihilation branching ratio</td>
<td>Baltay(’66), Bettini(’67)</td>
<td>5.2%</td>
</tr>
<tr>
<td>(model dependence)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-uniformity of detector gain</td>
<td>+/-1.2% of $P_{tot}$</td>
<td>4.0%</td>
</tr>
<tr>
<td>Energy scale</td>
<td>+/-2.5% of $e_{vis}$</td>
<td>1.7%</td>
</tr>
<tr>
<td>Ring counting</td>
<td></td>
<td>0.6%</td>
</tr>
<tr>
<td>Nuclear propagation (model dependence)</td>
<td>NEUT</td>
<td>1.7%</td>
</tr>
<tr>
<td>Nuclear propagation (cross section)</td>
<td>Elastic 20%, Charge ex 30%, Abs 25%, Pi prod 30%</td>
<td>12.5%</td>
</tr>
<tr>
<td><strong>Exposure</strong></td>
<td>&lt;3.2%</td>
<td></td>
</tr>
<tr>
<td>Detector livetime</td>
<td></td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td></td>
<td>3.2%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>&lt;15.2%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>error</td>
<td>Uncertainty</td>
</tr>
<tr>
<td>--------------------------------------</td>
<td>------------------</td>
<td>-------------</td>
</tr>
<tr>
<td><strong>Neutrino cross section</strong></td>
<td>18%</td>
<td></td>
</tr>
<tr>
<td>$M_A$ in quasi-elastic and single-pi</td>
<td>$10%$ in $M_A$</td>
<td>4.4%</td>
</tr>
<tr>
<td>Quasi elastic scattering (model dependence)</td>
<td>$1\sigma = \text{Fermi-gas vs. Oset}$</td>
<td>- %</td>
</tr>
<tr>
<td>Quasi elastic scattering (cross section)</td>
<td>$10%$</td>
<td>0.4%</td>
</tr>
<tr>
<td>single-pion production (cross section)</td>
<td>$10%$</td>
<td>2.8%</td>
</tr>
<tr>
<td>multi-pion production (model dependence)</td>
<td>$1\sigma = \text{w/ vs. w/o Bodek}$</td>
<td>15.5%</td>
</tr>
<tr>
<td>multi-pion production (cross section)</td>
<td>$5%$</td>
<td>3.4%</td>
</tr>
<tr>
<td>coherent pion production (cross section)</td>
<td>$30%$</td>
<td>0.1%</td>
</tr>
<tr>
<td>NC/(CC) ratio</td>
<td>$20%$</td>
<td>6.2%</td>
</tr>
<tr>
<td>Nuclear effect in 16O (mean free path)</td>
<td>$30%$</td>
<td>2.7%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>32.1%</strong></td>
<td></td>
</tr>
</tbody>
</table>
Result

efficiency = 10.4% ± 1.6%
number of neutrons = 6.02 x 10^{33}
SK-I livetime = 4.077 years
observed candidates = 20
expected background = 21.31 ± 6.84
Bayesian statistics

Official Result 90% CL
1.77 x 10^{32} years

with R=3.6 x 10^{23} this corresponds to \( \tau_{\text{free}} = 1.25 \times 10^8 \) seconds
compared to .87 x 10^8 at Grenoble

Frequentist result = 2.45 x 10^{32} years

Frequentist result
without systematics= 4.45 10^{32} years
(as in previous experiments)
Bayes vs Frequentist

with no systematic errors we have ...

Frequentist $CL = 1 - e^{-(b+s)} \sum_{n=0}^{n_0} \frac{(b+s)^n}{n!}$

Bayes $CL = 1 - \frac{e^{-(b+s)} \sum_{n=0}^{n_0} \frac{(b+s)^n}{n!}}{e^{-b} \sum_{n=0}^{n_0} \frac{(b)^n}{n!}}$

$s =$ signal limit
$b =$ expected background
$n =$ selected data events

$\sim 1/2$
Previous Results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Year</th>
<th>Exposure ($10^{32}$ neutron-yr)</th>
<th>Efficiency</th>
<th>Data</th>
<th>BG</th>
<th>Signal Limit</th>
<th>Frequentist Limit no systematics ($10^{32}$yr)</th>
<th>Start point</th>
<th>Absorption cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>SuperK I</td>
<td>2006</td>
<td>245</td>
<td>.104</td>
<td>20</td>
<td>21.3</td>
<td>5.7</td>
<td>4.45</td>
<td>Volume</td>
<td>Linear</td>
</tr>
<tr>
<td>Sudan II *</td>
<td>2002</td>
<td>2.15</td>
<td>.18</td>
<td>5</td>
<td>2.5</td>
<td>5.5</td>
<td>.72 (.84)*</td>
<td>Vol. (Dov.)</td>
<td>Linear</td>
</tr>
<tr>
<td>Frejus *</td>
<td>1990</td>
<td>5</td>
<td>.30</td>
<td>0</td>
<td>2.1</td>
<td>2.3</td>
<td>.65*</td>
<td>Volume</td>
<td>Linear</td>
</tr>
<tr>
<td>Kamiokande</td>
<td>1986</td>
<td>3</td>
<td>.33</td>
<td>0</td>
<td>1.2</td>
<td>2.3</td>
<td>.43</td>
<td>Dover</td>
<td>Linear</td>
</tr>
<tr>
<td>IMB</td>
<td>1983</td>
<td>3.2</td>
<td>.14</td>
<td>0</td>
<td>0</td>
<td>2.3</td>
<td>.17</td>
<td>Dover</td>
<td>Density$^2$</td>
</tr>
</tbody>
</table>

*Iron experiments have an additional suppression of $\sim$1/.71 not included here (see slides 11 and 43)
Future
Future Results

- Predicted MC results for cuts resulting in different efficiencies.
- Frequentist result with systematic errors
- Upward fluctuations correspond to seeing one less event in the data.
- Future SK limit $\sim 6 \times 10^{32}$ years
Efficiency Correlations with “R”

\[ \tau^2_{\text{free}} = \frac{\text{Exposure}}{\text{Signal limit}} \left( \frac{E_s + 3E_p}{R_s + 3R_p} \right) \]

if we consider correlations
we have …

plugging in Dover
\( R_s = 1.21 \quad R_p = 0.82 \times 10^{23} \)

and a guess from this plot \( \rightarrow \)
\( E_s = 0.06 \quad E_p = 0.12 \)

gives us 7% higher \( \tau^2_{\text{free}} \)
Should absorption cross section scale like the nuclear density squared?

Absorption is a three body reaction, so IMB (1983) distributed the Oxygen-pion absorption cross section according to the nuclear density squared. No one has done this since then. Looks like it will result in a 5-10% improvement.
Conclusions

• Official Result $\tau = 1.77 \times 10^{32}$ years (Bayes, including systematic errors)

• Improvement of 4.4 times over previous measurement of $\tau_{\text{nuclei}}$ (When duplicating their procedure of using frequentist statistics without any systematic errors and $R_O/R_{Fe} = .71$)

• 44% better than Grenoble $\tau_{\text{free}}$ (Bayes, $R = 3.6 \times 10^{23}$)