Neutrino Physics with Cold Atoms

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Collaborators include Dr. Mark Raizen, Dr. Joshua Klein, Dr. Francis Robicheaux, and Julia Majors
Neutrino Physics with Cold Atoms

What can we learn about neutrinos?

Tritium β-decay:
Has long been a probe of neutrino properties

Atomic Physics:
Recently developed general methods of slowing & cooling

Cold $^3$H source
Neutrino Mass

Maki-Nakagawa-Sakata matrix

\[
\begin{pmatrix}
\nu_e \\ 
\nu_\mu \\ 
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\times
\begin{pmatrix}
\nu_1 \\ 
\nu_2 \\ 
\nu_3
\end{pmatrix}
\]

The probability of flavor change depends on the mass differences between states, not on absolute masses

\[
P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta) \sin^2(1.27\Delta m^2 L/E)
\]

Oscillations only provide a lower limit on the \(\nu\)-mass scale!

\[
m_3 \geq \text{sqrt}(|\Delta m_{\text{atm}}^2|) \sim (0.04 - 0.07 \text{ eV})
\]

\[
\Delta m_{21}^2 = \Delta m_{\text{sol}}^2 = 8.0 \times 10^{-5} \text{ eV}^2 \quad \text{(KamLAND)}
\]

\[
\Delta m_{31}^2 \approx \Delta m_{32}^2 = \Delta m_{\text{atm}}^2 = 2.4 \times 10^{-3} \text{ eV}^2 \quad \text{(Super-K)}
\]
Experimental options

Neutrinoless Double Beta Decay Experiments

- Neutrino emitted at one beta decay vertex has to be absorbed by the second decay vertex as an antineutrino

\[ m_\nu = \sum |U_{ek}|^2 e^{i\alpha_k} m_k \]

- CUORE plans to reach a limit of 20-50 meV on neutrino mass

- Only possible if neutrinos are massive and Majorana, meaning they are their own antiparticles

- Double beta decay experiments actually measure:  

Majorana CP-phases are unknown \( \Rightarrow \) cancellations could occur
Experimental options

Tritium beta decay

\[ ^3\text{H} \rightarrow ^3\text{He}^+ + e^- + \bar{\nu}_e \]

Half life: \( t_{1/2} = 12.3 \) years
Endpoint energy: \( E_0 = 18.6 \text{ keV} \)

Figure: Osipowicz, A. et al. (KATRIN), arXiv:hep-ex/0109033
Tritium beta decay

Electron energy spectrum of tritium $\beta$ decay:

$$N(E) = \frac{dN}{dE} = K \times F(E,Z) \times p_e \times E_e \times p_v \times E_v$$

$$= K \times F(E,Z) \times p \times W \times \sqrt{(E_0 - E)^2 - m_v^2} \times (E_0 - E)$$

- $m_v^2$ = “mass” of the $\bar{\nu}_e = \sum |U_{ei}|^2 m_i^2$
- $W$ = electron total energy
- $E_0$ = endpoint energy = 18.6 keV
- $F(Z,E)$ = Fermi function, accounting for Coulomb interaction of the outgoing electron in the final state
- $K = G_F^2 \left( \frac{m_e^5}{2\pi^3} \right) \cos^2 \theta_C |M|^2$
**Previous Experiments**

**Troitsk**

\[ m_v^2 = -1.0 \pm 3.0 \pm 2.5 \text{ eV}^2 \]
\[ m_v \leq 2.5 \text{ eV (95\% CL)} \]

Source = Windowless gaseous T\(^2\)

**Mainz**

\[ m_v^2 = -1.6 \pm 2.5 \pm 2.1 \text{ eV}^2 \]
\[ m_v \leq 2.2 \text{ eV (95\% CL)} \]

Source = Quench condensed T\(^2\) film on graphite

**Limiting Factors:**

- Statistics
- Scattering in source
- Backgrounds
- Energy resolution
- Electronic final state effects
- Tritium source uncertainties
Current Experiments

KATRIN

- Scaled-up version of Troitsk experiment
- Low background of $< 10^{-2}$ counts/s is required
- Plans to reach a neutrino mass sensitivity of 0.2 eV after 5-6 years of data taking

- Windowless Gaseous Tritium Source is a 10m long cylinder (80x stronger source)
- Main spectrometer is 23m long and 10m in diameter (4x better energy resolution)
Current Experiments

KATRIN

Monte Carlo spectra:
- Run time = 3 years
- $\Delta E = 1$ eV
- WGTS column density = $5 \times 10^{17}/\text{cm}^2$
- Final state effects included
- Analysis window = 5 eV below endpoint

Is there another approach to directly measuring $m_\nu$?
Magnetic Slowing of Atoms

Slowing and trapping cold atomic tritium would create a new kind of source for tritium $\beta$-decay.

- Supersonic nozzle $\rightarrow$ beam of atoms moving at $\sim 400$ m/s
- Temperature of beam is very cold ($\sim 50$ mK in co-moving frame)
- Tritium can be entrained into the beam and then slowed for trapping

Magnetic Slowing of Atoms

Use pulsed magnetic fields to decelerate tritium atoms

- Zeeman effect: $\Delta E = -\mu \cdot B$
- Low-field seekers are repelled in high field regions and lose kinetic energy

Supersonic beam
Magnetic Slowing of Atoms

Use pulsed magnetic fields to decelerate tritium atoms

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Magnetic Slowing of Atoms

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- Low-field seekers are repelled in high field regions and lose kinetic energy

Can we further cool tritium once we’ve trapped it?

Laser cooling: Highly effective but limited to a small group of atoms

- 1997 Nobel Prize: Chu, Cohen-Tannoudji, Phillips
- Repeated scattering of photons reduces atomic momentum
- Requires a cycling transition
- Hydrogen cannot be laser cooled

Is there a more general cooling method?
Single Photon Cooling

Thought-experiment by Maxwell (1867)
Entropy reduced without expenditure of work

2nd law is saved by information carrying entropy

Szilard (1929)
- Demon makes a measurement
- Information entropy

Demon’s jobs:
- Measure $r$, $p$
- Operate gate

Single-photon cooling realizes Maxwell’s demon:
“Demon” discriminates coldest atoms and releases this info in a single scattered photon
Single Photon Cooling

Goal: Transfer atoms from a magnetic to an optical trap via emission of a single photon

- Slowly translate 1-way barrier so that you catch atoms at their classical turning points
- A spontaneous Raman emission could be such a 1-way barrier
- This cooling technique has been demonstrated on $^{87}$Rb


Correlation between position and momentum for $v_{\text{atom}}$ and $v_{\text{demon}}$

$\sigma > \sigma_{\text{min}}$

\begin{align*}
10^{-1} \text{ cm s}^{-1} & \quad 10^2 \text{ cm s}^{-1}
\end{align*}
Single Photon Cooling

Allows creation of a tritium source with ~μK temperature

- “Demon” = gravito-optical trap + resonant pump beam
- Approach classical turning points slowly from the left
- If final state has weaker or opposite magnetic coupling, atom is trapped in optical trap

\[ U = \mu_B g_F m_F |B| + mgz \]
Experimental options

A low-density source of trapped atoms allows the ion to escape as well as the $\beta$.

$$^{3}\text{H} \rightarrow ^{3}\text{He}^+ + e^- + \bar{\nu}_e$$

Source density $< 10^{15}$ atoms/cm$^3$
Source column density $< 10^{13}$ atoms/cm$^2$

Figure: Osipowicz, A. et al. (KATRIN), arXiv:hep-ex/0109033
Tritium $\beta$-Decay

Direct reconstruction of the neutrino mass!

$$m^2 = (W - E_{\text{ion}} - E_{\beta})^2 - (p_{x_{\text{ion}}} + p_{x_{\beta}})^2 - (p_{y_{\text{ion}}} + p_{y_{\beta}})^2 - (p_{z_{\text{ion}}} + p_{z_{\beta}})^2$$

- Thin source allows ion detection!
- Don’t have to rely only on beta spectrum
- Coincidence measurement $\Rightarrow$ low backgrounds
- Atomic tritium $\Rightarrow$ well-known final state corrections
Direct reconstruction of the neutrino mass!

$m_{\nu}^2 = (W - E_{\text{ion}} - E_\beta)^2 - (p_{x\text{ion}} + p_{x\beta})^2 - (p_{y\text{ion}} + p_{y\beta})^2 - (p_{z\text{ion}} + p_{z\beta})^2$

Ion detector = Microchannel Plate

- $\theta$ and $\phi$ of ion
- TOF for ion

$E_{\text{ion}}$ reconstructed from energy conservation

$\beta$ detector: hemispherical analyzer + optical lattice of Rydberg atoms

$E_\beta$ $p_{x\beta}$ $p_{y\beta}$

(p_{z\beta} reconstructed from energy conservation)
How do we measure the β’s momentum?

1) Slow β down to < 900 eV after leaving source
2) Cross section for passing β to excite atom from 53s to 53p is: $0.36 \times 10^{-9}$ cm$^2$
3) When spectrometer detects the β, the 53s atoms are optically de-excited using STIRAP
4) 100 V/cm is ramped to ionize the 53p atoms
5) MCP detects the ionized Rydberg atoms, giving us a 1D track projection of the β’s path
What about background events?

- Collisions ➔ Solved by putting the atoms in an optical lattice
- Blackbody radiation ➔ Solved by surrounding the lattice with a wire mesh whose spacing is small compared to microwave wavelength
- Additionally ➔ Atoms can be periodically cycled between the ground state and the n=53s state to avoid accumulating 53p backgrounds
Tritium β-Decay

Use Rydberg atoms to measure β momentum non-invasively:

Lattice Specifications:
- Density of Rydberg atoms \( \sim 10^{11} \) atoms/cm\(^3\)
- Optical lattice size: 10 cm x 10 cm x 1 cm
- β excites an atom within \( \sim 5 \) microns as it transverses lattice
- Lattice positioned 2 m from the tritium source
- Momentum resolution varies from 40 meV/c to 2.7 eV/c

This non-invasive method may find other applications in the detection of low-energy β’s.
Tritium β-Decay

What about the opening angle uncertainty?

\[ \tilde{p}_v \cdot \tilde{p}_v = m_v^2 \quad \tilde{p}_v + \tilde{p}_{\text{ion}} + \tilde{p}_\beta = \tilde{p}_{3\text{H}} \]

\[ m_v^2 = \tilde{p}_v \cdot \tilde{p}_v = (\tilde{p}_{3\text{H}} - \tilde{p}_{\text{ion}} - \tilde{p}_\beta) \cdot (\tilde{p}_{3\text{H}} - \tilde{p}_{\text{ion}} - \tilde{p}_\beta) \]

\[ m_v^2 = W^2 - 2WE_{\text{ion}} - 2WE_\beta + m_{\text{ion}}^2 + m_\beta^2 + 2|p_{\text{ion}}||p_\beta|\cos\theta \]

\[ \delta\theta \frac{\partial m_v^2}{\partial \theta} = -2|p_{\text{ion}}||p_\beta|\sin\theta \quad \sim \delta\theta \sin(\theta)10^{10} \text{ (eV/c)}^2 \]

How do we avert disaster?

- Opening angle is almost \( \pi \), which makes \( \sin\theta \) small
- The uncertainty of the mean goes like \( 1/N^{1/2} \)
- \( \delta\theta\sin(\theta)10^{10} \text{ (eV/c)}^2 = 10^{-5}(\sin(\pi-10^{-4}))10^{10} \text{ (eV/c)}^2 = 10 \text{ (eV/c)}^2 \)
Tritium $\beta$-Decay

Detector smearings of $m_\nu^2$ peak:

a) No Smearing
b) $\beta$ Energy Resolution
c) Ion's MCP binning
d) Ion's MCP timing
e) $\beta$ Momentum Resolution
f) Initial tritium temperature
**Tritium β-Decay**

ROOT simulation: based on kinematics (no particle tracking)

<table>
<thead>
<tr>
<th>What’s in the simulation?</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>• atomic tritium source is 100μm diameter sphere</td>
<td>• Electron momentum resolution of 40 meV/c to 2.7 eV/c</td>
</tr>
<tr>
<td>• Tritium source atoms at 1μK with a Gaussian momentum smear of width mkT</td>
<td>• Geometrical acceptance for the β limited by optical lattice of Rydberg atoms 10 x 10 x 1 cm placed 2m from source</td>
</tr>
<tr>
<td>• Electron TOF Gaussian smear of 20ps</td>
<td>• MCP: 2 micron binning, 44% geometrical acceptance, 15 x 15 cm, placed 5m from source</td>
</tr>
<tr>
<td>• Electron energy resolution of 5 meV</td>
<td>• Ion TOF Gaussian smear of 20ps</td>
</tr>
<tr>
<td>• Final state effects: ground state 70%, 1\textsuperscript{st} excited state 30%</td>
<td>• Gravity correction for the ion ~0.5 microns</td>
</tr>
<tr>
<td>• 1 year assumed runtime</td>
<td></td>
</tr>
</tbody>
</table>
Background test:
• Randomize MCP hits
• Randomize ion TOF
• Leave beta unchanged

$10^{-5}$ background rejection, not including $\beta$-coincidence
Coincidence time $\sim 3$ ms

Magnitude of $p_\nu$ is increased 2-3 times, while $E_\nu$ changes only slightly $\rightarrow m_\nu$ always reconstructs extremely negative for background events
Tritium $\beta$-Decay

- Fit utilizes data up to $500\text{eV}$ away from the endpoint energy
- Minuit log-likelihood fit using 2D probability density functions (pdf)
- Find $m_\nu$ by interpolating between pdfs of different neutrino masses

Statistics gained by moving far from the endpoint improve precision on $m_\nu$ even though the spread in reconstructed mass gets broader.
### Tritium β-Decay

Results of a pull distribution of the neutrino mass fit results are consistent with a normal Gaussian.

<table>
<thead>
<tr>
<th>Assumed $m_\nu$ (eV)</th>
<th>Fit $m_\nu$</th>
<th>(+) error</th>
<th>(-) error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.239</td>
<td>0.174</td>
<td>0.153</td>
</tr>
<tr>
<td>0.4</td>
<td>0.354</td>
<td>0.166</td>
<td>0.150</td>
</tr>
<tr>
<td>0.6</td>
<td>0.690</td>
<td>0.270</td>
<td>0.203</td>
</tr>
<tr>
<td>0.8</td>
<td>0.794</td>
<td>0.247</td>
<td>0.215</td>
</tr>
<tr>
<td>1.0</td>
<td>0.813</td>
<td>0.246</td>
<td>0.207</td>
</tr>
<tr>
<td>5.0</td>
<td>5.188</td>
<td>0.402</td>
<td>0.378</td>
</tr>
</tbody>
</table>
Tritium $\beta$-Decay

What are the strengths of this technique?

- Extremely thin source $\rightarrow$ low scattering
- Atomic tritium $\rightarrow$ simpler final state effects
- $\beta$ coincidence $\rightarrow$ low backgrounds
- Direct $m_\nu$ reconstruction & $\beta$-spectrum
- Trap lifetimes of 5-10 minutes with cryogenic cold fingers and chamber bake-out
- Optical lattice of Rydberg atoms could be placed to aid in distinguishing sources for reconstruction

Trapping $2 \times 10^{13}$ tritium atoms:

- Stack sources along a line by repeated launching & trapping
- Trap lifetimes of 5-10 minutes with cryogenic cold fingers and chamber bake-out
- Valid for Dirac and Majorana neutrinos

Results of fit to simulated data in which $m_\nu=0.4$ eV

- $m_\nu = 0.473^{+3.72}_{-1.35}$ eV
- $m_\nu = 0.425^{+0.585}_{-0.438}$ eV
- $m_\nu = 0.354^{+0.166}_{-0.150}$ eV

fit results for neutrino mass (eV)

number of beta decays

$10^{10}$ $10^{11}$ $10^{12}$
Conclusions

Slowing and trapping cold $^3$H atoms $\rightarrow$ Fundamentally new way of measuring $m_\nu$

• General slowing, trapping, & cooling methods present new opportunities
• Working towards the first atomic source ever utilized in tritium beta decay
• Rydberg atoms offer an innovative non-invasive momentum measurement technique
• Our proposed experiment could compete with KATRIN’s goal of limiting $m_\nu < 0.2$ eV

Special Thanks

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Neutrino Mass

• Are neutrino masses hierarchical or degenerate?
• Are neutrinos Dirac or Majorana particles?
• Why are neutrino masses so relatively small?

![Diagram showing mass hierarchy and oscillation](image)

- Increasing Mass: 100,000 X mass of electron
- Neutrinos vs. Quarks
- Charged leptons

**Hierarchical Scenarios**

**Degenerate Scenarios**

- $\Delta m^2_{\text{solar}}$
- $\Delta m^2_{\text{atmos}}$

- $m_{\nu_e}$, $m_{\nu_\mu}$, $m_{\nu_\tau}$
Neutrino Mass

Cosmology

- Neutrinos = hot dark matter in the early universe

- Energy density parameter $\Omega$ of the universe:
  Experimental limits: $\Omega_\nu = 0.003 - 0.25$

- Fits for $m_\nu$ depend sensitively on other cosmological parameters

WMAP data has been fit with cosmological models that estimate $\sum m_\nu \leq 0.6 \text{ eV}$
Experimental options

Tritium beta decay

What about neutrino mixing?

\[ N(E) = \frac{dN}{dE} = K \times F(E,Z) \times p \times E \times \sqrt{(E_0 - E)^2 - m^2} \times (E_0 - E) \]

\[ |U_{ei}|^2 = |\langle \nu_e | \nu_i \rangle|^2 \]

\[ m_\nu^2 = \text{“mass” of the electron (anti-)neutrino} = \sum |U_{ei}|^2 m_i^2 \]

The measured neutrino mass from tritium beta decay would fix the absolute neutrino mass scale in a degenerate model.

Double beta decay experiments actually measure: \[ m_\nu = \left| \sum |U_{ek}|^2 e^{i\alpha_k} m_k \right| \]

Majorana CP-phases are unknown \(\Rightarrow\) cancellations could occur.
Previous Experiments

ITEP
- $T_2$ in complex molecule
- magn. spectrometer (Tret'yakov)
- $m_V = 17-40 \text{ eV}$

Los Alamos
- gaseous $T_2$ - source
- magn. spectrometer (Tret'yakov)
- $m_V = < 9.3 \text{ eV}$

Tokio
- $T$ - source
- magn. spectrometer (Tret'yakov)
- $m_V = < 13.1 \text{ eV}$

Livermore
- gaseous $T_2$ - source
- magn. spectrometer (Tret'yakov)
- $m_V = < 7.0 \text{ eV}$

Zürich
- $T_2$ - source impl. on carrier
- magn. spectrometer (Tret'yakov)
- $m_V = < 11.7 \text{ eV}$

Troitsk (1994-today)
- gaseous $T_2$ - source
- electrostat. spectrometer
- $m_V = < 2.5 \text{ eV}$

Mainz (1994-today)
- frozen $T_2$ - source
- electrostat. spectrometer
- $m_V = < 2.2 \text{ eV}$
Previous Experiments

Troitsk and Mainz

- Obtained $m_\nu$ by fitting the beta spectrum
- Parameters were $m_\nu$, endpoint energy, background, and normalization
Previous Experiments

Troitsk and Mainz: $m_\nu < 2.2$ eV

Limiting Factors:

- Statistics
- Scattering in source
- Backgrounds
- Energy resolution
- Electronic final state effects
- Tritium source uncertainties
Previous Experiments

Troitsk & Mainz breakthrough technology: MAC-E-Filter

Guiding by magnetic fields (magnetic adiabatic collimation)

$$\Delta \Omega \sim 2 \pi$$

Electric (retarding-) field:

analysis of electron energies (electrostatic filter)

integral transmission: $E > U_0$

$$\mathbf{F} = (\mathbf{\mu} \cdot \mathbf{v}) \mathbf{B} + q \mathbf{E}$$

$$\mathbf{\mu} = \frac{E_{\perp}}{B} = \text{const}$$

Adiabatic motion

Adiabatic transformation $E_{\perp} \rightarrow E_{\parallel}$
KATRIN

- Factor of 4 improvement in energy resolution over Troitsk and Mainz
- Increased $T_2$ source strength (factor 80)
- Low background of $10^{-2}$ counts/s or less is required
- Reduced inelastic scattering events to 2% of signal rate by looking only at the last 25 eV below the endpoint
- Pre-spectrometer rejects all electrons except those close to the endpoint, reducing the count rate to $\sim 1000$/s

Sensitivity (90% CL)
$m_\nu < 0.2$ eV

Discovery (95% CL)
$m_\nu < 0.35$ eV
## Current Experiments

### KATRIN:
Karlsruhe Tritium Neutrino Experiment

- External $\beta$-source ($^3$H)
- $^3$H endpoint = 18.6 keV
- $^3$H half-life = 12.3 years
- Energy: electrostatic spectrometer
  - Measures kinetic energy of $\beta$
  - Narrow interval close to $E_o$
  - Integrated $\beta$-energy spectrum
  - Integral design, size limits
  - $\Delta E_{\text{expected}} = 0.93$ eV

### MARE:
Microcalorimeter Arrays for a Rhenium Experiment

- $\beta$-source = detector ($^{187}$Re)
- $^{187}$Re endpoint = 2.6 keV
- $^{187}$Re half-life = $5 \times 10^{10}$ years
- Energy: single crystal bolometer
  - Measure entire decay energy
  - Measure entire spectrum
  - Differential $\beta$-energy spectrum
  - Modular size, expandable
  - $\Delta E_{\text{expected}} \approx 5$ eV (FWHM)

---

Is there another approach to directly measuring $m_\nu$?
Single Photon Cooling

Allows creation of a tritium source with ~μK temperature

- “Demon” = gravito-optical trap + resonant pump beam
- Approach classical turning points slowly from the left
- If final state has weaker or opposite magnetic coupling, atom is trapped in optical trap

\[ U = \mu_B g_F m_F |B| + mgz \]
Tritium β-Decay: 3-Body

PHOIBOS hemispherical analyzer 225 HV

- 15 keV energy
- Small geometrical acceptance
- Potential calibration source: $^{83\text{m}}$Kr conversion electron with energy of 17.8 keV and width of 2.7 eV
Tritium β-Decay: 3-Body

Burle 2-micron MCP detector

- Detects position and time-of-flight (TOF)
- 2 micron holes spaced 3 microns center-to-center
- 350 ps pulse width resolution

We need:
- 2-10 μm spacing
- ~20ps timing
- Large area: ~ 1m wide x 20cm tall
Boundstate $\beta$-Decay: 2-Body

$^3\text{H} \rightarrow ^3\text{He} + \nu_e$

$\nu_{\text{Recoil}} = \left[ \frac{(M_{^3\text{H}} - M_{^3\text{He}})^2 - (m_{\nu} c^2)^2}{M_{^3\text{He}} c} \right]^{1/2}$

- Measure $^3\text{He}$ recoil velocity
- 0.69% of all $^3\text{H}$ decays are boundstate
- 3% of boundstate He$^3$ atoms are in an excited state and emit a 706.52nm photon
Boundstate $\beta$-Decay: 2-Body

$^3\text{H} \rightarrow ^3\text{He} + \nu_e$

$$v_{\text{Recoil}} = \left[ \frac{(M_{^3\text{H}} - M_{^3\text{He}})^2 - (m_{\nu} c^2)^2}{M_{^3\text{He}} c} \right]^{1/2}$$

- Measure $^3\text{He}$ recoil velocity
- 0.69% of all $^3\text{H}$ decays are boundstate
- 3% of boundstate $\text{He}^3$ atoms are in an excited state and emit a 706.52nm photon

Detect photon from $^3\text{He}$ atom & $^3\text{He}$ TOF to MCP
Boundstate $\beta$-Decay: 2-Body

Boundstate beta decay does not currently offer a competitive limit on $m_\nu$.

- Given sufficient statistics, the fit is very accurate
- But even with $10^{13}$ decays, the 90%CL is only 8.8eV

Simulation $m_\nu=20\text{eV}$, Fit $m_\nu=19.6\text{eV}$
Mössbauer Neutrinos: 1-Body

Ordinary Mossbauer effect: photons emitted recoillessly by one nucleus can be resonantly absorbed by another nucleus of the same type.

Nuclei must be bound in a lattice for significant recoilless emission or absorption.
Mössbauer Neutrinos: 1-Body

\[ \nu\text{'s emitted recoillessly from boundstate decay of } ^3\text{H can be resonantly absorbed by } ^3\text{He} \]

\[ ^3\text{H} \rightarrow ^3\text{He} + \bar{\nu}_e \]

Boundstate tritium beta decay:

Reverse tritium beta decay:

\[ \bar{\nu}_e + ^3\text{He} \rightarrow ^3\text{H} \]
Mössbauer Neutrinos: 1-Body

Debye temperature = temperature of a crystal's highest normal mode of vibration

\[ f_{	ext{recoilless}} = \exp\left\{ \frac{-E^2}{2Mc^2} \times \frac{3}{2k_B \theta_D} \right\} \]

where \( \theta_D \) is the Debye temperature

We can get a very high Debye temperature by going to high pressures

![Debye Temperature vs. Pressure for solid He3](image-url)
Mössbauer Neutrinos: 1-Body

- High pressures raise the Debye temperature, which increases $f_{\text{recoilless}}$
- Volume not likely to exceed $0.004\text{cm}^3$

2 Diamond Anvil Cells placed ~1-4cm apart

$^3\text{He}$ detector @10GPa
$V = 0.004\text{cm}^3$

$T_2$ source @10GPa
Source ~29Cu
Mössbauer Neutrinos: 1-Body

Tuning the pressure allows us to align emission & absorption peaks!

\[ \sigma_{\text{resonant}} = 4.18 \times 10^{-41} g_o^2 \rho (E_{\text{res}}) / \sqrt{\tau} \approx 10^{-32} \text{cm}^2 \]

(assuming linewidth \( \sim 10^{-12} \text{eV} \))

- Linewidth dominated by inhomogeneous broadening (impurities, lattice defects, etc.)
- Narrow linewidth implies we must be able to tune energy shifts to observe resonance
- Very cold temperatures reduce Doppler shifts
- Isomer shift (from changes in atomic radius) can be canceled by zero-point energy shift:

\[ \Delta E/E = \left( \frac{9k_B}{16Mc^2} \right) (\theta_{\text{emitter}} - \theta_{\text{absorber}}) \]
Mössbauer Neutrinos: 1-Body

We estimate a Debye temperature of ~700K
Simulation results: ~31755 events per week

Event rate vs. Pressure (assuming a DAC volume of 0.004cm$^3$)

Debye temp = 900 K
Mössbauer Neutrinos: 1-Body

But how do you detect the tritium in the helium-3 absorber?

- Magnetic slowing enables trace element detection so we can actually detect the $^3$H in the $^3$He absorber! (~1/1000 detection efficiency)

Physics motivation:
- $\theta_{13}$ measurement from rates taken at distances 1cm-10m

\[ P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E) \]

A large L is unnecessary if E=18.6keV