The **Stability of the Proton** continues to be one of the biggest questions in Particle Physics

- Tests a fundamental, but unexplained conservation law
- Hallmark of Grand Unified Theories
- Extension of the idea of running coupling constants
- Broad connection with theory at many levels: strings, extra dimensions, etc.
- Explores a region forever inaccessible to accelerators
- If SUSY is not found at LHC, may be only way to search for it for foreseeable future
- **What are limiting factors?**
Proton Decay: Is Normal Matter Stable?

Three of the four forces of nature are thought to become similar in strength at very high energies – far above any conceivable accelerator.

Simple unification theory ruled out by data – proton decay is an effective way to test such theories.

\[ \tau \approx \frac{M_X^4}{\alpha^2 M_p^5} \]

\[ \tau(e^+\pi^0) = 4.5 \times 10^{29 \pm 1.7} \text{ years (predicted)} \]

>1.3 \times 10^{34} \text{ years (PRD 85 112001)}
\[ \alpha_s(Q) \]

\[ Q \text{ [GeV]} \]

- **Deep Inelastic Scattering**
- **e^+e^- Annihilation**
- **Hadron Collisions**
- **Heavy Quarkonia**

\[ \alpha_s(M_Z) = 0.1189 \pm 0.0010 \]

- **QCD**
New theories (e.g. SUSY) can push up unification scale

Example of a possible proton decay through supersymmetric particles.

Observation of virtual processes like proton decay is our only known way to access physics at these energies

Unification scale pushed up...

\[ \tau(e^+\pi^0) \approx 10^{35-38} \text{ years} \]

...But new decay modes now predicted
$P \rightarrow e^+ \pi^0$ in Water Cherenkov

0.260 Mton-years exposure (M.Shiozawa, TAUP2013)

...but expected atmospheric neutrino background is 0.7 events measurements done by the K2K experiment. This mode will be background limited in future detectors.
WATCHMAN competitive with other direct K+ detection experiments
Expected Backgrounds for $p \rightarrow e^+\pi^0$

<table>
<thead>
<tr>
<th>Calculated:</th>
<th>$2.1 \pm 0.9 \text{ ev/Mton/yr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured*</td>
<td>$1.63 \pm 0.42/-0.33 \text{ stat} \pm 0.45/-0.51 \text{ syst.} \text{ ev/Mton/yr}$</td>
</tr>
</tbody>
</table>

- Super-Kamiokande currently has **NO** candidates at 0.141 Mton-yr
- A 0.2 Mton detector would have $\sim 3$ background events after 10 years. 9 events for 0.56 Mton. Background limitations will enter.

**Can this be improved?**

Efficiency dominated by nuclear effects. Background dominated by resolution.

<table>
<thead>
<tr>
<th>Detector</th>
<th>$\varepsilon x B_{\text{meson}}$</th>
<th>$\text{BKG (}/\text{Mtonyr})$</th>
<th>$\text{BG (/yr)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMB3</td>
<td>0.48</td>
<td>26</td>
<td>0.087</td>
</tr>
<tr>
<td>KAM-I</td>
<td>0.53</td>
<td>$&lt;15$</td>
<td>$&lt;0.015$</td>
</tr>
<tr>
<td>KAM-II</td>
<td>0.45</td>
<td>$&lt;8$</td>
<td>$&lt;0.008$</td>
</tr>
<tr>
<td>Super-K</td>
<td>0.44</td>
<td>2.1</td>
<td>0.047</td>
</tr>
</tbody>
</table>

*PRL 102:141801 (2009)
• background is from atmospheric neutrino interactions
• Estimate that this is dominated by CC (81%), with 51% of these 1+ pion production (PRL 102, 2009)
• How many background events will have one or more neutrons, either from initial interaction, FSI in nucleus, or nuclear de-excitation?
• Discussions ongoing about a low-energy neutrino beam experiment.
Addition of Gadolinium

Tests with Super-Kamiokande have shown that neutron tagging via gadolinium in the water is feasible. LBNE Case Study document details the increased light collection needed for LBNE. Roughly a factor of two is desirable to achieve good efficiency.

Cosmological and galactic SN, DAEDALUS, proton decay, solar neutrinos, possible beam event tagging?
Will Proton Decay Result in Neutrons?

FIG. 1. Deexcitation scheme of a proton hole produced by proton decay ($p \rightarrow x$) in $^{16}$O. $N$ and $Z$ stand for neutron and proton shells, respectively. $p^*$ and $n^*$ are protons and neutrons emitted into the continuum region.

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Neutrons from Proton Decay in Water

• 2/10 of protons are free protons. No neutrons.
• 2/10 of protons are in $P_{1/2}$ shell. If they decay nucleus is already in the ground state. No neutrons
• 4/10 of protons are in $P_{3/2}$ shell. If they decay then a $P_{1/2}$ proton will drop down, giving a 6 MeV gamma. No neutrons. (Ejiri gives 94% B.R. for this)
• ~80% of proton decays should give neutrons only indirectly from FSI. (such FSI usually makes them undetectable anyway) This is fairly model independent. Ejiri's more detailed estimate gives 81%
• Similar numbers for neutron decay.
Note: Proton Decay in water makes No Neutrons

- 2/10 of protons are free protons. No neutrons.
- 2/10 of protons are in $P_{1/2}$ shell. If they decay nucleus is already in the ground state. No neutrons
- 4/10 of protons are in $P_{3/2}$ shell. If they decay then a $P_{1/2}$ proton will drop down, giving a 6 MeV gamma. No neutrons.
- ~80% of proton decays should give neutrons only indirectly from FSI. Detailed calculation gives 81% (Eijiri, PRC 48, 1993)
- ATMOSPHERIC NEUTRINO EVENTS THAT MIMIC PROTON DECAY CAN BE REJECTED BY NEUTRON TAGGING

R.Svoboda, 3 March 2014
The prompt 6.32 MeV gamma ray branching ratio of 41% comes from a study of de-excitation of 15-N following a proton decay. This same study predicts inclusive neutron de-excitation branching ratio of \( \sim 8\% \). Most proton decays should not have neutrons.

\[
0.08 \times 0.8 = 6.4\%
\]

### Table I

<table>
<thead>
<tr>
<th>Hole</th>
<th>Residual</th>
<th>States</th>
<th>((k))</th>
<th>(E_\gamma)</th>
<th>(E_p)</th>
<th>(E_n)</th>
<th>(B(k))</th>
</tr>
</thead>
<tbody>
<tr>
<td>((p_{1/2})_p^{-1})</td>
<td>g.s.</td>
<td>(1^+)</td>
<td>15-N</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.25</td>
</tr>
<tr>
<td>((p_{3/2})_p^{-1})</td>
<td></td>
<td>(3^+)</td>
<td>15-N</td>
<td>6.32</td>
<td>0</td>
<td>0</td>
<td>0.41</td>
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<tr>
<td>((s_{1/2})_p^{-1})</td>
<td>g.s.</td>
<td>(1^+)</td>
<td>14-N</td>
<td>0</td>
<td>0</td>
<td>(\sim 20)</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2^+)</td>
<td>14-N</td>
<td>7.03</td>
<td>0</td>
<td>(\sim 13)</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>g.s.</td>
<td>(3/2^-)</td>
<td>13-C</td>
<td>0</td>
<td>1.6</td>
<td>(\sim 11)</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>g.s.</td>
<td>(0^+)</td>
<td>14-C</td>
<td>0</td>
<td>(\sim 21)</td>
<td>0</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>g.s.</td>
<td>(1/2^-)</td>
<td>13-C</td>
<td>0</td>
<td>(\sim 11)</td>
<td>(\sim 2)</td>
<td>0.03</td>
</tr>
<tr>
<td>((j)_p^{-1}) others</td>
<td>many states</td>
<td>(\leq 3-4)</td>
<td>(\leq 3-4)</td>
<td>(\leq 3-4)</td>
<td>(\leq 3-4)</td>
<td>(\leq 3-4)</td>
<td>0.16</td>
</tr>
<tr>
<td>((p_{1/2})_n^{-1})</td>
<td>g.s.</td>
<td>(1^-)</td>
<td>12-O</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.25</td>
</tr>
<tr>
<td>((p_{3/2})_n^{-1})</td>
<td></td>
<td>(3^-)</td>
<td>12-O</td>
<td>6.18</td>
<td>0</td>
<td>0</td>
<td>0.44</td>
</tr>
<tr>
<td>((s_{1/2})_n^{-1})</td>
<td>g.s.</td>
<td>(1^+)</td>
<td>14-N</td>
<td>0</td>
<td>(\sim 24)</td>
<td>0</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2^+)</td>
<td>14-N</td>
<td>7.03</td>
<td>(\sim 17)</td>
<td>0</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>g.s.</td>
<td>(3/2^-)</td>
<td>13-C</td>
<td>0</td>
<td>(\sim 14.5+1.6)</td>
<td>0</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>g.s.</td>
<td>(0^+)</td>
<td>14-O</td>
<td>0</td>
<td>0</td>
<td>(\sim 18)</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>g.s.</td>
<td>(1^-)</td>
<td>13-N</td>
<td>0</td>
<td>2.0</td>
<td>(\sim 11.5)</td>
<td>0.02</td>
</tr>
<tr>
<td>((j)_n^{-1}) others</td>
<td>many states</td>
<td>(\leq 3-4)</td>
<td>(\leq 3-4)</td>
<td>(\leq 3-4)</td>
<td>(\leq 3-4)</td>
<td>(\leq 3-4)</td>
<td>0.22</td>
</tr>
</tbody>
</table>
...But Do Atmospheric Neutrino Interactions Have Neutrons?

- Direct neutron production via CC-QE
- FSI scattering in nucleus \((p,n), (\pi,n)\)
- Nuclear de-excitation with neutron emission
- Secondary production in water. E.g. \(\pi^-\) capture and \((p,n)\) interactions
- Difficult calculation, but estimates are that there should be 1-3 neutrons on average per event. What is the actual number? Can we measure it for relevant neutrino energies?
Effects of Atmospheric Neutrino Background Rejection on $p \rightarrow e^+\pi^0$ sensitivity

0.5 Megaton with neutron tagging (rejects 90% of atmospheric neutrinos)

0.5 Megaton with background

Super-K with background
$p \rightarrow \bar{\nu}K^+$


<table>
<thead>
<tr>
<th>Mode</th>
<th>eff × B.R.</th>
<th>Background (/Mton/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \mu \nu$</td>
<td>36.0%</td>
<td>2000</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu \nu + \gamma$</td>
<td>7.2%</td>
<td>1.7</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0$</td>
<td>6.2%</td>
<td>4.7</td>
</tr>
</tbody>
</table>

R.Svoboda, 3 March 2014
$\nu K^+$ in Water Cherenkov

E.Kearns, ISOUP 2013

<table>
<thead>
<tr>
<th>$\gamma$-tag and $\pi^+\pi^0$</th>
<th>SK1</th>
<th>(20% coverage) SK2</th>
<th>SK3</th>
<th>(new electronics) SK4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>15.7 %</td>
<td>13.0 %</td>
<td>15.8 %</td>
<td>18.9 %</td>
</tr>
<tr>
<td>Background rate (/100 kty)</td>
<td>0.3</td>
<td>0.6</td>
<td>0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

New efficiencies and background rates after analysis improvement
Super-K Preliminary 2013: No candidates, 260 kton yr (SK 1+2+3+4):

$p \rightarrow \nu K^+$  $\tau/B > 5.9 \times 10^{33}$ years, 90\%CL
Technique first invented by R.Svoboda (TAUP 2003)

Only a small amount of WbLS is needed to see the 105 MeV K+
Hyper-Kamiokande

(ISODAR @ WATCHMAN)

(Mike's talk)

CHIPS

LOI FNAL PAC

WATCHMAN

ANNE