Experimental Status and Future Prospect of the Proton Decay Searches

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http://nngroup.physics.sunysb.edu/nngroup/pub/whitepaper.ps
Einstein’s Dream: Unification of All Particle Interactions

Standard Model (SM) = Unified Electro-weak theory + QCD (not a truly unified theory)

Can all the forces in nature be unified in one form?
Mr. Radioactive, I think protons decay.

You cannot be serious! You must be more desperate than I was.
Sometime in Early 1970’s...
Pati-Salam Model of Grand Unification

Prof. Salam, my GUT feeling is that protons must decay.

I don’t think so. Experimental results indicate otherwise. Let me think about it…

Some months later…

My GUT feels the same. Let’s publish it.
SU(5) by Georgi and Glashow (1974)
Decay mechanisms

dominated by the dimension=6 op. gauge boson mediated decays

\[ p \begin{cases} 
  d & \quad X \\
  u & \quad \bar{u} \\
  u & \\
  u & \quad \bar{u} \\
  d & \quad Y \\
  u & \\
  \end{cases} \rightarrow e^+ + \bar{u} + d + e^+ \\
\]

\( (X^{\pm 4/3}, Y^{\pm 1/3} : \text{new gauge bosons}) \)

Predictions

\[ B(p \rightarrow e^+ X^0) = 4 \times 10^{29\pm1.7} \text{ years}, \quad B(p \rightarrow e^+ X^0) \geq 40 \sim 60\% \]

\[ B(p \rightarrow e^+ X^0) > 1.2 \times 10^{33} \text{ yrs (IMB (+Frejus) Lower Limit @90\% C.L.)} \]

\[ 5.4 \times 10^{33} \text{ yrs (current SuperK Lower Limit @90\% C.L.)} \]

\( \Rightarrow \) Complete exclusion of minimal SU(5) model
Current Status

- So far, no evidence for proton decay
- However, there are tantalizing hints for unification
  - Small but finite neutrino mass
    - see-saw mechanism?
  - Convergence of the running coupling constants
    - Especially with supersymmetry

$$M_{\text{GUT}} = 10^{16} \sim 2 \times 10^{16} \text{ GeV (??)}$$
SUSY GUTs

- Current SuperK limit \( \Gamma_B (p \rightarrow nK) > 2.3 \times 10^{33} \) yrs (new)

- Many models may have been already ruled out!
  - Especially MSSM SU(5) is considered to be ruled out (Murayama et al.)
  - Proton decay limits provide most stringent restrictions to SUSY (recall R-parity conservation)

- Some say SUSY-SO(10) models are also in trouble.

- But…

Discovery is around the corner!
Summary Proton Decay Search Results

\( p \rightarrow e^+ \pi^0 \)
\( p \rightarrow \mu^+ \pi^0 \)
\( p \rightarrow \nu \pi^+ \)
\( p \rightarrow e^+ \eta \)
\( p \rightarrow \mu^+ \eta \)
\( p \rightarrow e^+ \rho^0 \)
\( p \rightarrow \mu^+ \rho^0 \)
\( p \rightarrow \nu \rho^+ \)
\( p \rightarrow e^+ \omega \)
\( p \rightarrow \mu^+ \omega \)
\( p \rightarrow e^+ K^0 \)
\( p \rightarrow \mu^+ K^0 \)
\( p \rightarrow \nu K^+ \)
\( p \rightarrow e^+ K^- (892)^0 \)
\( p \rightarrow \nu K^- (892)^+ \)

Unification Day Oct. 15, 2004
What now?
Can we build Next generation Nucleon decay and Neutrino (NNN) detectors to continue our quest for proton decay and unification?

Strong theoretical motivations and interests can help us realize the goal as it did in the 1970’s
1998 Neutrino Revolution and Physics Goals for NNN Experiments

- Neutrino Oscillations
  - Super-Kamiokande+Atm exps
  - +SNO+Solar exps

- Non-zero Neutrino Mass
- See-saw Mechanism

- Grand Unification
- Proton Decay
- Large Underground Detectors

- Non-zero Neutrino Mixing

- Lepton Mixing Matrix
  - K2K, MINOS, CNGS, JHF-->SK
  - Superbeams, (Betabeams)

- LMA solution, $\sin^2 \theta_{13} \neq 0$

- CP Violation in Lepton Sector
  - Superbeam, Neutrino Factories

- Lepto-Genesis
  - Matter-antimatter Asymmetry in the Universe

- Majorana Phase CPV?
Current Proposals and Ideas

- Water Cherenkov Detectors
  - 3-M, Hyper-Kamiokande, Mton-Frejus, UNO

- Liquid Argon Detectors
  - 100kton-Europe, LANDD

- Liquid Scintillator Detectors
  - LENA (a la SciPIO)

- Magnetized Iron Detectors
  - INO (India-based Neutrino Observatory: a la MONOLITH)

  - Focused on atmospheric neutrinos detection
A Water Cherenkov Detector optimized for:
• Light attenuation length limit
• PMT pressure limit
• Cost (built-in staging)

UNO Collaboration
99 Physicists
40 Institutions
7 Countries

UNO Detector Conceptual Design

Total Vol: 650 kton
Fid. Vol: 440 kton (20xSuperK)
# of 20” PMTs: 56,000
# of 8” PMTs: 14,900

Only optical separation
Hyper-Kamiokande Current Design

2 detectors with 5 modules each
2 X (48m × 50m × 250m),
Total (Fiducial) vol. = 1 (0.54) Mton
20% photocathode coverage

DUE?
1Mton Class WC Detector at Fréjus

- Considered in conjunction with an ambitious CERN “Physics with a MMW proton source” initiative
- Window of opportunity with the planned new safety tunnel construction
- Variety of detector design is considered
UNO/NNN Physics Goals

- Nucleon decay
- Supernova Neutrinos
- Supernova Relic Neutrinos
- Atmospheric Neutrinos
- Astrophysical Neutrino sources
- Super-beam (+Beta-beam)
- Solar Neutrinos

- Multi-purpose detector with comprehensive physics programs for astrophysics, nuclear physics and particle physics
- Synergy between accelerator physics and non-accelerator physics
UNO Proton Decay Sensitivity

We need to update this figure.

One of the motivations of this Workshop.

Fermion mass correlated
MSSM SO(10) - BPW
MSSM SO(10) - generic
Extra dimension at GUT scale
Andromeda Galaxy

Supernova Reach
~ 1 Mpc
(local group of galaxies)

Supernova Rate
~ 1/10 or 15 yrs
Galactic Supernova

Approximately 140,000 events in UNO, ~1/30 years
- msec timing structure of the flux
- Determination of core collapse mechanism
- Possible Observation of Birth of a Black Hole!

An example of unstable Eq. Of State
Pons et al., PRL 86, 5223 (2001)

Beacom, Boyd and Mezzacappa
PRL 85, 3568 (2000)

$m_{\nu_e} = 1.8$ eV
# SuperK SNR Search Limits

<table>
<thead>
<tr>
<th>Theory Model</th>
<th>SK SRN Rate Limit (Efficiency Corrected)</th>
<th>SK SRN Flux Limit (18 MeV &lt; (E_e) &lt; 82 MeV)</th>
<th>SK SRN Flux Limit (Full Spectrum)</th>
<th>Predicted SRN Flux (Full Spectrum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galaxy evolution (Totani et al., 1996)</td>
<td>3.2 (\frac{\text{events}}{\text{year}}) 22.5 kton</td>
<td>&lt; 1.2 (\frac{\overline{V}_e}{\text{cm}^2 \text{sec}})</td>
<td>&lt; 130 (\frac{\overline{V}_e}{\text{cm}^2 \text{sec}})</td>
<td>44 (\frac{\overline{V}_e}{\text{cm}^2 \text{sec}})</td>
</tr>
<tr>
<td>Heavy metal abundance (Kaplinghat et al., 2000)</td>
<td>3.0 (\frac{\text{events}}{\text{year}}) 22.5 kton</td>
<td>&lt; 1.2 (\frac{\overline{V}_e}{\text{cm}^2 \text{sec}})</td>
<td>&lt; 29 (\frac{\overline{V}_e}{\text{cm}^2 \text{sec}})</td>
<td>&lt; 54 (\frac{\overline{V}_e}{\text{cm}^2 \text{sec}})</td>
</tr>
<tr>
<td>Constant supernova rate (Totani et al., 1996)</td>
<td>3.4 (\frac{\text{events}}{\text{year}}) 22.5 kton</td>
<td>&lt; 1.2 (\frac{\overline{V}_e}{\text{cm}^2 \text{sec}})</td>
<td>&lt; 20 (\frac{\overline{V}_e}{\text{cm}^2 \text{sec}})</td>
<td>52 (\frac{\overline{V}_e}{\text{cm}^2 \text{sec}})</td>
</tr>
<tr>
<td>LMA neutrino oscillation (Ando et al., 2002)</td>
<td>3.5 (\frac{\text{events}}{\text{year}}) 22.5 kton</td>
<td>&lt; 1.2 (\frac{\overline{V}_e}{\text{cm}^2 \text{sec}})</td>
<td>&lt; 31 (\frac{\overline{V}_e}{\text{cm}^2 \text{sec}})</td>
<td>11 (\frac{\overline{V}_e}{\text{cm}^2 \text{sec}})</td>
</tr>
</tbody>
</table>


UNO at 4000 mwe can rule out all models within 3~5 years or discover SNR

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Chang Kee Jung
UNO as a Distant Detector for a Superbeam Experiment

- Water Cherenkov detector is a natural fit for a superbeam LBL neutrino oscillation experiments
- CPV along with many other crucial oscillation parameters could be measured with a UNO scale detector at various baselines
  - CERN Fréjus study (130 km, 4MW proton beam)
  - J-PARK Kamioka study (295 km, 4MW proton beam)
  - BNL Western sites study (2000 - 4000 km, 1MW proton beam)

an elegant idea

provides a crucial LBL superbeam exp. option for UNO
DUSEL/UNO at Henderson Initiative
Envisioned Mission of DUSEL

- Deep Underground Physics Experiments
  - Dark matter search experiments
  - Neutrino-less double beta decay experiments
  - Low energy solar neutrino experiments
- Very Large Scale Physics Experiments
  - Proton decay experiment
  - Long baseline neutrino superbeam experiment
  - Supernova observatory
- Variety of Geo-science
  - Geology, geo-engineering, biology, chemistry, hydrology, etc.
- Low Background Counting Facility (National Security)
- Outreach
Henderson Mine, Empire, Colorado
The Best Location (Empire, Colorado)

- Excellent Access
  - Near an international airport
  - Near a major highway

- Excellent Environment
  - Near major universities
  - Near a major city
  - Strong community support
  - Friendly and enthusiastic mining company
  - Near many resorts with conference facilities
• One of the largest mining operation with large modern shafts
• Large capacity high speed conveyor system
• Existing tailing site and all necessary environmental permits
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Mining Area
Harrison Mt.
~12,300’
possible UNO site
~1,800’

High speed conveyor
Possible Depths for UNO at Henderson

Elevation

Harrison Mt.

Red Mt.

Optimal Depth for UNO

.5% Straight - 4,800' deep

15% Ramp - 5,100' deep
A.4.1 Proton Decay

If protons decay, their lifetimes are long, so proton decay experiments require massive detectors. A worldwide collaboration has begun to develop the design for a next-generation proton decay experiment. Such a detector should be at least an order of magnitude larger than Super Kamiokande. A next-generation experiment would extend the search for proton decay into the regime favored by unified theories.

Current thinking favors the use of a large water Cherenkov detector, as in the UNO approach. The detector would be situated underground to reduce cosmic-ray backgrounds. A large water Cherenkov detector could simultaneously serve as the long-baseline target for an accelerator neutrino beam. It would also expand our ability to observe neutrinos from supernovae.

Present estimates suggest a price of about $650M for such a detector. Given its strong science program, and assuming that an affordable design can be reached, we believe it likely that a large proton decay detector will be proposed somewhere in the world, and that U.S. physicists will participate in its construction and utilization. The R&D effort should be completed over the next several years. A decision might be made near the middle of the decade, perhaps in conjunction with a decision on a neutrino superbeam facility.
### HEP Facilities Summary Table

<table>
<thead>
<tr>
<th>Project</th>
<th>Type</th>
<th>Physics</th>
<th>Cost</th>
<th>Scientific Potential</th>
<th>Proposed Facility</th>
<th>State of Readiness</th>
<th>Possible Time Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Collider</td>
<td>Facility</td>
<td>Energy Frontier</td>
<td>$5B – $7B</td>
<td>Absolutely Central</td>
<td>Absolutely Central</td>
<td>R&amp;D</td>
<td>2015 Operation</td>
</tr>
<tr>
<td>LHC Luminosity Upgrade</td>
<td>Facility</td>
<td>Energy Frontier</td>
<td>$150M (US Part)</td>
<td>Absolutely Central</td>
<td>Absolutely Central</td>
<td>R&amp;D</td>
<td>2014 Operation</td>
</tr>
<tr>
<td>LHC Energy Upgrade</td>
<td>Facility</td>
<td>Energy Frontier</td>
<td>Unknown</td>
<td>Don't Know Enough Yet</td>
<td>Don't Know Enough Yet</td>
<td>R&amp;D</td>
<td>Decision in Next Decade</td>
</tr>
<tr>
<td>SNAP</td>
<td>Experiment</td>
<td>Cosmology</td>
<td>$400M – $600M</td>
<td>Absolutely Central</td>
<td>Absolutely Central</td>
<td>R&amp;D</td>
<td>2009 Launch</td>
</tr>
<tr>
<td>BTEV</td>
<td>Experiment</td>
<td>Quark Physics</td>
<td>$120M</td>
<td>Important</td>
<td>Important</td>
<td>Ready for Decision on Construction</td>
<td>2008 Operation</td>
</tr>
<tr>
<td>CKM</td>
<td>Experiment</td>
<td>Quark Physics</td>
<td>$100M</td>
<td>Important</td>
<td>Important</td>
<td>Ready for Decision on Construction</td>
<td>2008 Operation</td>
</tr>
<tr>
<td>Super-B Factory</td>
<td>Facility</td>
<td>Quark Physics</td>
<td>Unknown</td>
<td>Don't Know Enough Yet</td>
<td>Don't Know Enough Yet</td>
<td>R&amp;D</td>
<td>Decision Later This Decade</td>
</tr>
<tr>
<td>Double-Beta Decay</td>
<td>Experiment</td>
<td>Neutrino Physics</td>
<td>$100M</td>
<td>Absolutely Central</td>
<td>Don't Know Enough Yet</td>
<td>R&amp;D</td>
<td>2005 Prototype</td>
</tr>
<tr>
<td>Off-Axis Neutrino Detector</td>
<td>Experiment</td>
<td>Neutrino Physics</td>
<td>$120M</td>
<td>Important</td>
<td>Important</td>
<td>Project Engineering and Design</td>
<td>2010 Operation</td>
</tr>
<tr>
<td>Neutrino Super Beam</td>
<td>Facility</td>
<td>Neutrino Physics</td>
<td>$250M – $500M (Accelerator and Beam Only)</td>
<td>Absolutely Central</td>
<td>Don't Know Enough Yet</td>
<td>Project Engineering and Design</td>
<td>Decision Later This Decade</td>
</tr>
<tr>
<td><strong>Underground Detector</strong></td>
<td>Facility</td>
<td>Neutrino Physics and Proton Decay</td>
<td>$500M</td>
<td>Absolutely Central</td>
<td>Don't Know Enough Yet</td>
<td>R&amp;D</td>
<td>Decision Later This Decade</td>
</tr>
<tr>
<td>Neutrino Factory</td>
<td>Facility</td>
<td>Neutrino Physics</td>
<td>Unknown</td>
<td>Don't Know Enough Yet</td>
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<td>R&amp;D</td>
<td>Decision in Next Decade</td>
</tr>
</tbody>
</table>

- Released in April 2004
- Response to CPU report
- Coordinated by NSTC
- Intragency Working Group
  - DOE, NASA, NSF, OMB, OSTP
- Summary of Recommendations
  - Ready for Immediate Investment and Directions Known
    - Dark Energy
    - Dark Matter, Neutrinos and Proton Decay
    - Gravity
Conclusions

- NNN detectors with LBL neutrino beams tackle some of the most important physics questions today with potential of major discoveries
  - Rich physics program comparable to LHC/LC

- If built, they will provide a comprehensive nucleon decay and neutrino physics program for the world science community for the 21st century
  - Despite the phenomenal scientific success achieved by the neutrino experiments during the last decade, we do not have any major experiments approved that go beyond 10 years from now
    - Long lead time for large experiments
    - In order to sustain our community, we must plan ahead
    - Strong support from the theoretical physics community is crucial

- Intersection of interests from HEP, NP and AP communities; and international community (Europe, Japan and USA)
  - A well organized international effort with common physics goals and strong mutual support can bring a successful experiment somewhere in the world
The End