What is unification?

Planetary Motion  Falling Bodies  Fast Particles  Electric Current  Magnetism  Atoms  Nuclei  Quarks  
Gravity  Special Relativity  Electromagnetism  Quantum Mechanics  Weak Force  Strong Force  
General Relativity  

QED: Quantum Electrodynamics  
The Standard Model  Electroweak Theory  QCD: Quantum Chromodynamics  

QCD: Quantum Chromodynamics  

Better Electroweak Theory  

GUTS: Grand Unified Theories  

(String?) Theory of Everything  

Dark Matter  

Dark Energy
100 EeV Cosmic Ray

\[ E_{cm} = \sqrt{2EM} \]
\[ E \sim \sqrt{10^{20}} \text{ eV} \times 1 \text{ GeV} \]
\[ E \sim 10^6 \text{ GeV} \]

Enrico Fermi's Globatron

\[ p = 0.3 \text{ B}[T] \text{ r}[m] \]
\[ p \sim 100 \text{ T} \times 10^6 \text{ m} \]
\[ E \sim 10^8 \text{ GeV} \]
only way to probe the grand unification scale is by virtual particle exchange

propagator $\sim 1/M^2$

$\Gamma(A \rightarrow BC) = \frac{1}{\tau} \approx \frac{\left| \langle BC | A \rangle \right|^2 |\vec{p}_B|}{m_A^2} \approx \frac{\alpha^2 m_p^5}{M_X^4}$

Proton (nucleon) decay turns out to be one of the most useful systems.
In the Standard Model, proton decay is forbidden by Conservation of Baryon Number

**Origins:** baryon number conservation formulated by: Weyl (1929), Stueckelberg (1938), Wigner (1949), Lee & Yang (1950) to explain stability of matter.

**Phenomenological limits (1950’s):**
M. Goldhaber observes that life requires $\tau > 10^{16}$ years.
Isotope abundance requires $\tau > 10^{23}$ years.

**Sakharov Conditions (1966):**
Matter-Antimatter asymmetry requires baryon number non-conservation.
Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group $SU(5)$.

It makes just one easily testable prediction, $\sin^2 \theta_w = \frac{3}{8}$. It also predicts that the proton decays—but with an unknown and adjustable rate.

Other work of this era:

Pati and Salam: Is Baryon Number Conserved? PRL 31, 661 (1973)

Georgi, Quinn, and Weinberg: PRL 33, 451 (1974) proton lifetime $\sim 6 \times 10^{31}$ years.
Assume SU(3)⊗SU(2)⊗U(1) is part of a larger symmetry group E.g. SU(5)

Consequences:
- Single (unified) coupling
- Charge quantization: \(Q_d = Q_e / 3\), \(Q_u = -2Q_d\) \(\Rightarrow Q_p = -Q_e\)
- New gauge interactions (X, Y bosons) \(\Rightarrow\) proton decay
- Other predictions of SU(5):
  - magnetic monopoles, value of weak mixing angle (3/8 not so good), massless neutrinos (oops!)
or SO(10)

or E_6 or Flipped SU(5) or G_2\times 4 or ... 

and would you like SUSY with that?
Gauge Coupling Unification

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

\[ \tau(e^+\pi^0) = 4.5 \times 10^{29\pm1.7} \text{ years (predicted)} \]
How can we find proton decay if protons live for $10^{30}$ years?

- watch 1 proton for $10^{31}$ years
  - or
  - watch $10^{32}$ protons (~kton) for a month
  - or
  - something in between
Morton Salt Mine, Ohio
610 meters deep – 1570 mwe
3.3 kton (fiducial volume)
2000 PMTs, 4% coverage
935 events in 851 live-days
no proton decay found
\[ \tau(e^+\pi^0) > 5.5 \times 10^{32} \text{ years (1990)} \]

similar results from Kamiokande (1 kton)
both saw SN 1987a, both uncovered atmospheric neutrino anomaly
Kamiokande measured solar neutrinos
Problems solved by SUSY ...

Unification scale pushed up...

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

Rapid proton decay:
Dimension = 4 operators
e.g. $U^cD^cD^c$ and $QLD^c$
$M_{squark} \sim 1$ TeV
proton lifetime $\sim 1$ second
that’s OK – saved by R-parity

Dimension = 5 operators
e.g. $QQQL$
proton lifetime $\sim 10^{29\text{-}35}$ years
something new to look for!

dimension counting: powers of $(\text{mass})^D$ for each field
fermion $D = 3/2$, boson $D = 1$, Lagrangian terms must be $D=4$
Many Other GUTs Beyond This Simple Story

<table>
<thead>
<tr>
<th>Model</th>
<th>Ref.</th>
<th>Modes</th>
<th>$\tau_N$ (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal $SU(5)$</td>
<td>Georgi, Glashow [2]</td>
<td>$p \rightarrow e^+\pi^0$</td>
<td>$10^{30} - 10^{31}$</td>
</tr>
<tr>
<td>Minimal SUSY $SU(5)$</td>
<td>Dimopoulos, Georgi [11], Sakai [12]</td>
<td>$p \rightarrow \bar{\nu}K^+$</td>
<td>$10^{28} - 10^{32}$</td>
</tr>
<tr>
<td></td>
<td>Lifetime Calculations: Hisano, Murayama, Yanagida [13]</td>
<td>$n \rightarrow \bar{\nu}K^0$</td>
<td></td>
</tr>
<tr>
<td>SUGRA $SU(5)$</td>
<td>Nath, Arnowitt [14, 15]</td>
<td>$p \rightarrow \bar{\nu}K^+$</td>
<td>$10^{32} - 10^{34}$</td>
</tr>
<tr>
<td>SUSY $SO(10)$ with anomalous flavor $U(1)$</td>
<td>Shafi, Tavartkiladze [16]</td>
<td>$p \rightarrow \bar{\nu}K^+$</td>
<td>$10^{32} - 10^{35}$</td>
</tr>
<tr>
<td>SUSY $SO(10)$ MSSM (std. $d = 5$)</td>
<td>Lucas, Raby [17], Pati [18]</td>
<td>$n \rightarrow \bar{\nu}K^0$</td>
<td>$10^{33} - 10^{34}$</td>
</tr>
<tr>
<td>SUSY $SO(10)$ ESSM (std. $d = 5$)</td>
<td>Pati [18]</td>
<td>$p \rightarrow \bar{\nu}K^+$</td>
<td>$10^{28} - 10^{33}$</td>
</tr>
<tr>
<td>SUSY $SO(10)$/G(224) MSSM or ESSM (new $d = 5$)</td>
<td>Babu, Pati, Wilczek [19, 20, 21], Pati [18]</td>
<td>$p \rightarrow \bar{\nu}K^+$</td>
<td>$\leq 2 \times 10^{34}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p \rightarrow \mu^+K^0$</td>
<td>$B \sim (1 - 50)%$</td>
</tr>
<tr>
<td>SUSY $SU(5)$ or $SO(10)$ MSSM ($d = 6$)</td>
<td>Pati [18]</td>
<td>$p \rightarrow e^+\pi^0$</td>
<td>$\sim 10^{34.9\pm1}$</td>
</tr>
<tr>
<td>Flipped $SU(5)$ in CMSSM</td>
<td>Ellis, Nanopoulos and Wlaker[22]</td>
<td>$p \rightarrow e^+\mu^+\pi^0$</td>
<td>$10^{35} - 10^{36}$</td>
</tr>
<tr>
<td>Split $SU(5)$ SUSY</td>
<td>Arkani-Hamed, et. al. [23]</td>
<td>$p \rightarrow e^+\pi^0$</td>
<td>$10^{35} - 10^{37}$</td>
</tr>
<tr>
<td>$SU(5)$ in 5 dimensions</td>
<td>Hebecker, March-Russell[24]</td>
<td>$p \rightarrow \mu^+K^0$</td>
<td>$10^{34} - 10^{35}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p \rightarrow e^+\pi^0$</td>
<td></td>
</tr>
<tr>
<td>$SU(5)$ in 5 dimensions option II</td>
<td>Alciati et.al.[25]</td>
<td>$p \rightarrow \bar{\nu}K^+$</td>
<td>$10^{36} - 10^{39}$</td>
</tr>
<tr>
<td>GUT-like models from</td>
<td>Klebanov, Witten[26]</td>
<td>$p \rightarrow e^+\pi^0$</td>
<td>$\sim 10^{36}$</td>
</tr>
<tr>
<td>Type IIA string with D6-branes</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE I: Summary of the expected nucleon lifetime in different theoretical models.

A. Bueno et al. hep-ph/0701101

Uncertainties in the predictions:

Nuclear matrix elements updated w. lQCD, still: x10 uncertainty in lifetime

SUSY masses: $\sim x100$ uncertainty in lifetime
Modes beyond $e^+\pi^0, K^+\nu$
and other antilepton + meson decays

\[
p \rightarrow \mu^-\pi^+K^+ \quad B + L
\]

\[
n \rightarrow \bar{n} \quad \Delta B = 2, \ \text{TeV} < \text{scale} < \text{GUT}
\]

\[
pp \rightarrow K^+K^+ \quad \lambda''_{uds} < 10^{-8}
\]

\[
p \rightarrow e^-\pi^+\pi^+\nu \nu \quad \text{6 dimensions}
\]

\[
n \rightarrow \nu \nu \nu \quad \text{invisible}
\]

\[
p \rightarrow e^+\gamma \quad \text{radiative}
\]

there is plenty to keep us busy ...
Proportional to fiducial mass

- Soudan 1
- Soudan 2
- Kamiokande
- IMB
- Frejus
- NUSEX
- KGF

Tracking calorimeters

Water Čerenkov detectors

Super-K

Soudan 2

π⁺

K⁺

π⁰
Antilepton + meson

\[ p \rightarrow e^+ \pi^0 \]
\[ n \rightarrow e^+ \pi^- \]
\[ p \rightarrow \mu^+ \pi^0 \]
\[ n \rightarrow \mu^+ \pi^- \]
\[ p \rightarrow \nu \pi^+ \]
\[ n \rightarrow \nu \pi^- \]
\[ p \rightarrow e^+ \eta \]
\[ p \rightarrow \mu^+ \eta \]
\[ n \rightarrow \nu \eta \]
\[ p \rightarrow e^+ \rho^0 \]
\[ n \rightarrow e^+ \rho^- \]
\[ p \rightarrow \mu^+ \rho^0 \]
\[ n \rightarrow \mu^+ \rho^- \]
\[ p \rightarrow \nu \rho^+ \]
\[ n \rightarrow \nu \rho^0 \]
\[ p \rightarrow e^+ \omega \]
\[ p \rightarrow \mu^+ \omega \]
\[ n \rightarrow \nu \omega \]
\[ p \rightarrow e^+ K^0 \]
\[ n \rightarrow e^+ K^- \]
\[ p \rightarrow \mu^+ K^0 \]
\[ n \rightarrow \mu^+ K^- \]
\[ p \rightarrow \nu K^+ \]
\[ n \rightarrow \nu K^- \]
\[ p \rightarrow \nu K^{(892)}^+ \]
\[ p \rightarrow \nu K^{(892)}^0 \]
\[ n \rightarrow \nu K^{(892)}^0 \]
Super-Kamiokande

22.5 kton fiducial volume
$7.5 \times 10^{33} p + 6 \times 10^{33} n$

SK-I: 1996 - 2001
11146 50-cm inner PMTs, 40% coverage
1885 20-cm outer PMTs

SK-II: Jan 2003 - Oct 2005
Recovery from accident
5182 50-cm inner PMTs
Acrylic + FRP protective
Outer detector fully restored

SK-III: May 2006 - August 2008
Restored 40% coverage
Outer detector segmented (top | barrel | bottom)

SK-IV: September 2008 -
SK-IV Replace all electronics – 2008
T2K beam – late 2009
Add gadolinium - 201?
(1) proton decay MC
(2) atmospheric neutrino MC

Reduction
no OD activity
remove flashing PMTs etc.

Reconstruction
ergy, vertex, ring counting,
particle identification, muon decay etc.

Final analysis
Good event criteria

Data
Monte Carlo

1e6 evts/day

vertex

$\Delta t_i$

$\Delta t_{i}$

electron shower

muon
• Fully contained
• Fiducial volume
• 2 or 3 rings
• All rings are EM showers
• \( \pi^0 \) mass 85-185 MeV/\( c^2 \)
• No \( \mu \)-decay electrons
• Mass range 800-1050 MeV/\( c^2 \)
• Net momentum < 250 MeV/\( c \)
Example event: \((p \rightarrow \mu^+\pi^0)\)
Sit at reconstructed vertex and adjust $\Delta t$.
Look forward/backward in two hemispheres.
Proton Decay Signal Prediction (Monte Carlo)

- Effective mass in $^{16}\text{O}$
- Correlation with other nucleons
- Fermi motion – by shell
- Initial position (Woods-Saxon)
- Nuclear de-excitation $\gamma$
- Pion-nuclear interactions
  - Elastic Scattering
  - Charge Exchange
  - Absorption

efficiency $\sim 44\%$
main source of inefficiency:
$\pi^0$ absorption in $^{16}\text{O}$ nucleus

Free protons (hydrogen)
Background: Atmospheric Neutrinos

\[ \nu_e \]

\[ \pi^0 \]

\[ p \rightarrow e^+ + \nu_e + \pi^0 \]
Atmospheric Neutrino Background (Monte Carlo)

- Flux \(E, \text{flavor}\)
- Cross sections:
  - quasielastic
  - \(1-\pi, \text{multi-}\pi\)
  - DIS
- Pauli blocking
- Intranuclear scattering
- \(\nu\) oscillations
Direct measurement of proton decay background using K2K neutrino beam (1KT near detector)

$e^+\pi^0$ BG = $1.63^{+0.42}_{-0.33}$ (stat) $^{+0.45}_{-0.51}$ (sys.) evts/Mt·yr
\[ p \rightarrow e^+ \pi^0 \]

**Search Results: Super-K DATA**

<table>
<thead>
<tr>
<th></th>
<th>SK-I</th>
<th>SK-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection efficiency</td>
<td>44.6%±19%</td>
<td>43.6±19%</td>
</tr>
<tr>
<td>Background estimate</td>
<td>0.30±0.04±0.11</td>
<td>0.34±0.05±0.12</td>
</tr>
<tr>
<td>Exposure</td>
<td>1489.2 d (91.6 kt·yr)</td>
<td>798.6 d (49.1 kt·yr)</td>
</tr>
<tr>
<td>Data</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Setting a limit

a simple calculation of the rate if we measured something:

\[
\frac{\tau}{B} = \frac{\lambda \varepsilon}{n - b}
\]

- \( n \) = number of observed events
- \( b \) = expected number of background events
- \( \lambda \) = exposure = \( N_{\text{proton}} \cdot \Delta t \)
- \( \varepsilon \) = efficiency

\[
\frac{\tau}{B} = \frac{\lambda \varepsilon}{S_{90}}
\]

\( S_{90} = \frac{\int_0^{S_{90}} P_{\text{poiss.}}(n, x + b) dx}{\int_0^{\infty} P_{\text{poiss.}}(n, x + b) dx} \)

\[\tau / B > 8.9 \times 10^{33} \text{ years}\]

a simple calculation of a 90% CL limit, but...
does not take into account \( n=0 \) properly (see F&C)
and does not take into account systematic uncertainty

treatment of limit using Bayes theorem to incorporate systematic uncertainty:

\[
P(\Gamma \mid n) = \iiint e^{-\Gamma \lambda \varepsilon + b} \frac{(\Gamma \lambda \varepsilon + b)^n}{n!} P(\Gamma) P(\lambda) P(\varepsilon) P(b) d\Gamma d\lambda d\varepsilon db
\]

\[\tau / B(e^+\pi^0) > 8.2 \times 10^{33} \text{ years}\]
\[ p \rightarrow K^+ \nu \]

Nuclear interaction is negligible
Kaon momentum is 340 MeV/c: is below Cherenkov threshold
essentially a search for kaon decay at rest

\[ K^+ \rightarrow \pi^+ \pi^0 \quad 21\% \]
\[ K^+ \rightarrow \mu^+ \nu_\mu \quad 65\% \]
Gamma Tag Single Muon Search:

\[ \text{BR} \times \epsilon = 8.6 \pm 20_{\text{sys}} \% \]

Background = 0.7 events (±59%)
Limits in context with theory

- Soudan
- Frejus
- Kamiokande
- IMB
- Super-K I+II

\[ p \rightarrow e^+ \pi^0 \]
Minimal SU(5)

\[ p \rightarrow e^+ \pi^0 \] predictions

\[ p \rightarrow e^+ K^0 \]
Minimal SUSY SU(5)

\[ p \rightarrow \mu^+ K^0 \]
SUGRA SU(5)

\[ n \rightarrow \bar{\nu} K^0 \]
SUSY SU(5) with additional U(1) flavor symmetry

\[ p \rightarrow \bar{\nu} K^+ \]
Various SUSY SO(10)

\[ p \rightarrow \bar{\nu} K^+ \] predictions

\[ \tau/B \text{ (years)} \]
Thinking Big(ger)

2 detectors 48m x 50m x 250 m
1 Mton total mass
The Next Generation?

Fiducial Mass

- IMB
- Frejus
- Soudan 2
- Kamiokande
- Super-K
- Hyper-K A
- Hyper-K B
- Icarus T600
- 500 kt WC
- 300 kt WC
- 200 kt WC
- 100 kt WC
- 100 kt LAr
- 5 kt LAr

Liquid Argon Time Projection Chamber

Charge yield \( \sim 6000 \) electrons/mm 
\( (\sim 1 \, fC/mm) \)

Charge readout planes: \( Q \)

UV Scintillation Light: \( L \)

Light yield \( \sim 5000 \, \gamma/mm \)

Drift direction

\( E_{\text{drift}} \)

Pixel size \( \sim \) mm

dE/dx

no Cherenkov threshold
$p ightarrow \bar{\nu} K^+$
$p \rightarrow e^{+}\pi^{0}$

Lifetime Sensitivity (90% CL)

- SK3/4
- SK2
- SK1

$10^{32}$ $10^{33}$ $10^{34}$ $10^{35}$

Year

- 1995
- 2000
- 2005
- 2010
- 2015
- 2020
- 2025
- 2030
- 2035
- 2040

Efficiency = 0.45
BG = 0.2 evts/100 kty
Nobs = Nbg
p → K⁺ν

### Lifetime Sensitivity (90% CL)

- **SK1**
- **SK 3/4**
- **LAr 5kt**
- **Icarus T600**
- **+100 kton LAr**
- **300 kton WC**
- **200 kton WC**
- **100 kton WC**

#### Parameters:
- **WC efficiency = 0.14**
- **LAr efficiency = 0.98**
- **BG = 1.2 evts/100 kty**
- **BG = 0.1 evts/100 kty**
- **Nobs = Nbg**
Many people think proton decay is important...

**EPP2010 (2005)**
Action Item 5: A Staged Neutrino and Proton Decay Research Program

**HEP Future Facilities Roadmap (2003)**
Scientific potential: “absolutely central”. Specific Facility: “Don’t know enough yet”.

**NRC– Committee on the Physics of the Universe**
#8 Are protons unstable?

#3. What is the lifetime of the proton and how do we understand it?

#9. What indeed is the lifetime of the nucleus of the neutral hydrogen atom?
What does it take to get a new megaton-class detector started?

- firm theoretical predictions are unlikely
- discovery of SUSY at the LHC would help
- perhaps a candidate or two from Super-K?
- real progress in reducing costs (PMTs = $$$$)
- demonstrated feasibility of multi-kt LAr TPC
- a funded next generation neutrino beam