Proton decay

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Outline

- Baryon number violation in the Standard Model
- Grand unification and proton decay
- Non-supersymmetric grand unification
- SUSY/SUGRA grand unification
- Proton decay in Extra dimension models
- String/D-brane models/quantum gravity
- Overview of proton lifetimes in unification models
- Prospects/Conclusions

Physics Reports
"Proton decay in Grand Unified Theories, in Strings and in Branes", PN, PF Perez, Vol. 441, Nos5-6, April, 2007.

Mass scales

- Electroweak scale

$$G_F^{-1/2} \simeq 250\text{GeV}$$

LHC will probe this scale.

- The intermediate scale M_{RR} which enters in Type I See-Saw mechanism to generate tiny masses for **neutrinos**

$$M_{RR} \simeq 10^{12-14}\ \text{GeV}$$

- The scale M_G associated with unification of gauge coupling constants (in SUSY), which also enters in **nucleon stability**.

$$M_G \simeq 2 \times 10^{16}\ \ \text{GeV}$$

- The Planck scale M_{Pl} associated with gravity

$$M_{Pl} = (8\pi G_N)^{-1/2} \simeq 2.4 \times 10^{18}\ \text{GeV}$$

Thus the study of neutrino masses and nucleon stability is a probe of high scale physics beyond the reach of any current or future accelerator.

Baryon number violation in the Standard Model

The SM has a $U(1)_B$ global symmetry at the classical level which implies stability of the proton, which, however, is broken at the quantum level by anomalies

$$\partial_\mu J^\mu_B = \frac{n_f g^2}{16\pi^2} Tr F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \mathrm{t'Hooft(1976)}$$

The B-violating effective operator induced by the instanton processes is (i is gen index)

$$O_{eff} = c(\frac{1}{M_W})^{14} e^{-\frac{2\pi}{\alpha_2}} \prod_{i=1}^{3} (\ \epsilon_{\alpha\beta\gamma}\ Q^i_{\alpha L}\ Q^i_{\beta L}\ Q^i_{\gamma L}\ L^i_L)$$

The above implies $\Delta B = \Delta L = 3$ interactions. The front factor gives a rate

$$\mathrm{Rate} \sim |e^{-\frac{2\pi}{\alpha_2}}|^2 \sim 10^{-173}$$

which is highly suppressed irrespective of other particulars.

Grand unification and proton decay

Grand Unification - brief history

- Quark-lepton unification
  Pati, Salam (1974)

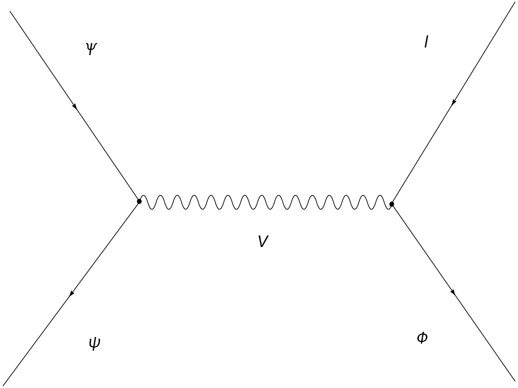
- Non-supersymmetrc grand unification
  SU(5) grand unification
  Georgi, Glashow (1975)
  SO(10) grand unification
  Georgi (1975); Fritzch, Minkowski (1975)

- Supersymmetric grand unification
  Dimopoulos, Georgi (1981)
  N. Sakai (1981)

- Supergravity grand unification (SUGRA)
  Arnowitt, Chamseddine, PN (1982)
  Soft breaking in mSUGRA: $\boldsymbol{m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sign}\mu}$

Proton decay in non-supersymmetric grand unification

- Proton decay via vector lepto-quarks
- Proton decay via scalar lepto-quarks
- $d = 6$ operators for proton decay with $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariance.



$B\&L$ violating dim 6 operators from exchange of lepto-quark gauge bosons

$d = 6$ operators for proton decay with $SU(3) \times SU(2) \times U(1)_Y$ invariance

Weinberg, Wilczek & Zee (1979)

$$\mathcal{O}_I^{B-L} = C_1^2 \, \epsilon_{ijk} \, \epsilon_{\alpha\beta} \, \overline{u^C_{iaL}} \, \gamma^\mu \, Q_{j\alpha a_L} \, \overline{e^C_{b\;L}} \, \gamma_\mu \, Q_{k\beta b_L}$$

$$\mathcal{O}_{II}^{B-L} = C_1^2 \, \epsilon_{ijk} \, \epsilon_{\alpha\beta} \, \overline{u^C_{iaL}} \, \gamma^\mu \, Q_{j\alpha a_L} \, \overline{d^C_{kbL}} \, \gamma_\mu \, L_{\beta b_L}$$

$$\mathcal{O}_{III}^{B-L} = C_2^2 \, \epsilon_{ijk} \, \epsilon_{\alpha\beta} \, \overline{d^C_{iaL}} \, \gamma^\mu \, Q_{j\beta a_L} \, \overline{u^C_{kbL}} \, \gamma_\mu \, L_{\alpha bL}$$

$$\mathcal{O}_{IV}^{B-L} = C_2^2 \, \epsilon_{ijk} \, \epsilon_{\alpha\beta} \, \overline{d^C_{iaL}} \, \gamma^\mu \, Q_{j\beta a_L} \, \overline{\nu^C_{b\;L}} \, \gamma_\mu \, Q_{k\alpha bL}$$

$$C_{1,2} = g_{GUT}/\sqrt{2} M_{(X,Y),(X',Y')}$$

$$Q_L = (u_L, d_L), L_L = (\nu_L, e_L); a, b = 1, 2, 3(\text{gens})$$

$$\alpha, \beta = 4, 5(SU(2)); i, j, k = 1, 2, 3(\text{color})$$

Proton decay via exchange of vector lepto-quarks

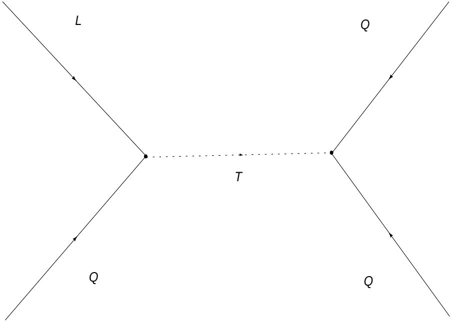
$$\Gamma_p \approx \alpha_{GUT}^2 \frac{m_p^5}{M_V^4}$$

The current experimental limit $\tau(p \to \pi^0 e^+) \; > \; 1.6 \times 10^{33}$ y implies a very rough lower bound on the superheavy gauge boson masses of

$$M_V \; > \; (1.6 - 3.2) \times 10^{15} \;\; \mathrm{GeV}$$

$$\alpha_{GUT} = 1/50 - 1/25.$$

- Thus the existence of proton stability at current levels implies the existence of a very high scale, much closer to the Planck scale than the weak scale.



$B\&L$ violating dim 6 operators via exchange of scalar lepto-quarks (T)

$$\Gamma_p \approx |Y_u Y_d|^2 \; \frac{m_p^5}{M_T^4}$$

$\tau(p \to \pi^0 e^+) \; > \; 1.6 \times 10^{33}$ y gives $M_T \; > \; 3 \times 10^{11} \mathrm{GeV}$.
The above implies that we need a doublet-triplet splitting.

Proton decay in SUSY/SUGRA grand unification

- SUSY/SUGRA
- Dim 4 and Dim 5 B&L violating operators
- p stability in SUSY/SUGRA GUT models

SUSY/SUGRA: Looking back

- An explanation of EWSB via RG
- Precision LEP data & gauge coupling unification
- A heavy top
- $b - \tau$ unification
- BNL result on $a_\mu = (g_\mu - 2)/2$

$$a_\mu^{exp} = 116592080(63) \times 10^{-11}$$

From Hagiwara et.al., hep-ph/0611102v3

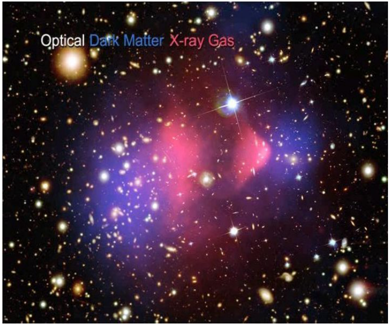
$$a_\mu^{SM} = 116591802(53) \times 10^{-11}$$

$$\Delta a_\mu = 27.8(8.2) \times 10^{-10} \;\; 3.4\sigma \;\; \text{discrepancy}$$

Prediction in SUGRA model in early eighties: TC Yuan, Arnowitt, Chamseddine, PN; Kosower, Krauss, Sakai

- Dark matter

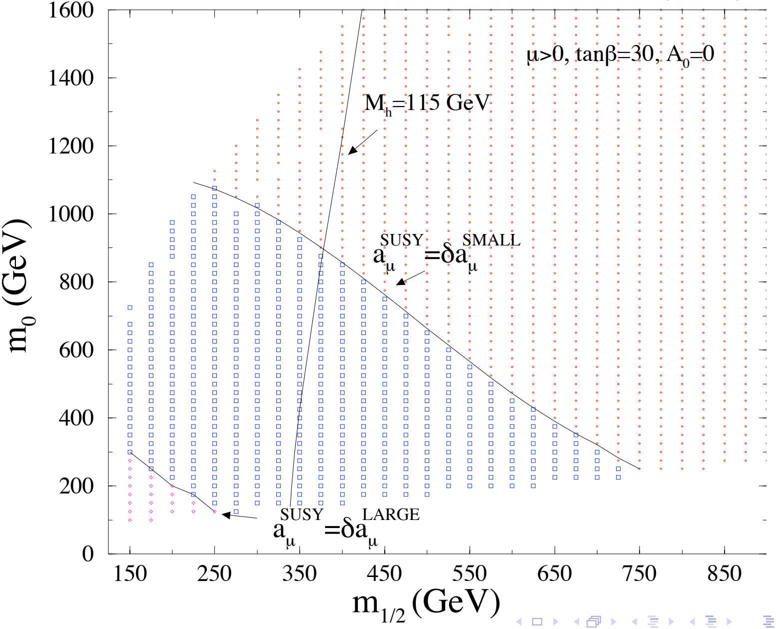
Direct evidence for dark matter: Neutralinos? gravitinos? .. or ?. Need direct lab experiment such as CDMS to check.



Looking forward: Missing link- Sparticles

If the BNL experiment holds up, i.e., a $\boldsymbol{3.4\sigma}$ discrepancy is present, then within SUSY/SUGRA it is predicted that some of the **sparticles** have an upper bound and **must be seen at the LHC.**

Sparticle mass upper limits: Chattopadhyay, PN (2001)



Dim 4 and Dim 5 B&L violating operators

- B&L violating dim 4 operators can appear in SUSY

$$QLD^C, U^C D^C D^C, LLE^C, LH$$

These may be suppressed by the constraint of R parity.

- B&L violating dim 5 operators (Weinberg; Sakai, Yanagida).

$$LLLL : C_{ikl}(Q_i.Q_i)(Q_k.L_l)/M_T$$

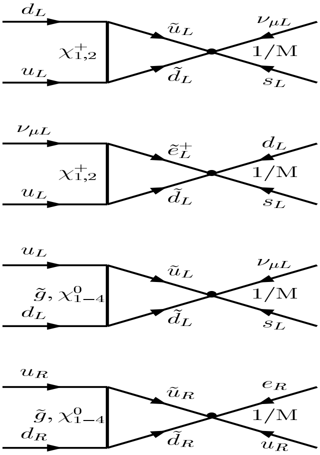
$$RRRR : C'_{ijkl} u_i^C e_j^C u_k^C d_l^C / M_T$$

Dressing loops convert dim 5 to dim 6 operators involving quarks and leptons. Further, the quark -lepton lagrangian is converted to the one involving mesons and baryons using effective lagrangian techniques. These give rise to decay modes

$$p \rightarrow \bar{\nu}_{e,\mu,\tau} K^+,\ \nu_{e,\mu,\tau}\pi,\ \nu_{e,\mu,\tau}\eta,\ \mu\pi,\ eK,\ \mu K, ..$$

SUSY scale enters via dressings of dim 5

Arnowitt, Chamseddine, PN; Hisano, Murayama, Yanagida; Ellis, Nanop, Rudaz,..



SUSY GUT Models

- SU(5) models
  - Minimal model ruled out: Murayama, Pierce (2002)
  - Non-minimal: Planck slop, additional Higgs/particles
- E(6) models:
  - Typically too many exotics.
- SO(10) models
  - These are phenomenologically the most successful of the grand unified models.
- Considerable literature in this area

  Ellis, Nanop, Rudas; Arnowitt, PN; Hisano, Murayama, Yanagida; Dermisek, Mafi, Rabi; Bajc, Perez, Senjanovic, .. Anderson, Hall, Dimopoulos, Raby; Babu, Pati, Wilczek; Aulakh, Senjanovic; Lucas, Raby; Dutta, Mimura, Mohapatra PN, Syed; Fukuyama; Wiesenfeldt, Barr, Shafi,

Specific SO(10) models and their Higgs structures

- $\mathbf{45}$-plet to break $SO(10)$ in $B-L$ direction, $\mathbf{16}+\overline{\mathbf{16}}$ to break $B-L$, and two $\mathbf{10}$-plets to break EW symmetry. Babu, Pati, Wilczek
  - Natural doublet-triplet splitting
  - Small desirable correction to α_3 from heavy thresholds
  - Detailed analysis of textures, neutrino oscillations, proton decay.
    $\tau(p \to e^+\pi^0) = 5 \times 10^{34\pm1} y$
    $\tau(p \to \bar{\nu}K^+) = (1/3-2) \times 10^{34} y$.
- Higgs structure: $\mathbf{10}, \mathbf{120}, \overline{\mathbf{126}}, \mathbf{210}$. Dutta, Mimura, Mohapatra
  - Detailed analysis of quark-lepton textures, with a suppressed proton decay from dimension five operators.

A new path to SO(10) unfication

Quite remarkably it is possible to completely break $SO(10)$ with a single $\mathbf{144}$ which under $SU(5) \times U(1)$ decomposes as

$$\mathbf{144} = \bar{\mathbf{5}}_{\mathbf{3}} + \mathbf{5}_{\mathbf{7}} + \mathbf{10}_{-\mathbf{1}} + \mathbf{15}_{-\mathbf{1}} + \mathbf{24}_{-\mathbf{5}} + \mathbf{40}_{-\mathbf{1}} + \overline{\mathbf{45}}_{-\mathbf{3}}$$

Since the 24-plet has a $U(1)$ charge a VEV formation for $\mathbf{24}$ leads to (Babu, Gogoladze, PN, Syed (2005))

$$SO(10) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_{em}$$

Proton stability can be achieved by a cancellation among the contributions from the $\mathbf{5}(\bar{\mathbf{5}})$ and from $\mathbf{45}(\overline{\mathbf{45}})$.
$\tau(p \rightarrow \bar{\nu} K^+) > 3 \times 10^{33}$ y.
PN, Syed (2007)

Proton stability in SUSY/SUGRA GUTs

- Nature and strength of $B\&L$ violating interactions at the GUT scale.
- Nature of soft breaking which enters in the dressing loop diagrams.
- Constraints on gauge coupling unification which constrain the heavy thresholds and the Higgsino triplet mass.
- $b-\tau$ unification, $g_\mu - 2$, and $b \rightarrow s\gamma$.
- Quark-lepton textures.
- Dark matter constraint
- Planck slop corrections.
- Gravitational warping effects
- Accuracy of effective lagrangian approximation which converts operators such as $QQQL$ and $U^C U^C D^C E^C$ into lagrangian for mesons + baryons.

Proton Decay in Extra Dimension Models

- **5D models**
- **6D models**
- **Universal Extra Dimension (UED) models**

Extra dim GUTs

Basic idea: Kawamura

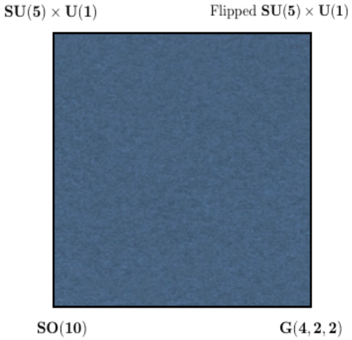
Multiplets can be split by choice of different orbifold parities.

6-D constructions

Hall, Nomura, Smith

Buchmuller, Covi, Emmanuel-Costa, Weisenfeldt (BCEW); ...

A 6-D model: Compactification on $R^4 \times T^2/Z_2 \times Z_2' \times Z_2''$



6D model continued (BCEW)

gen 1 is on $SU(5) \times U(1)$ brane
gen 2 on flipped $SU(5) \times U(1)$ brane
gen 3 on $SU(4)_C \times SU(2)_L \times SU(2)_R$ brane.

There are additional assumptions regarding the Higgs structure of the theory.

$$BR(\pi^0 e^+) = (71 - 75)\%, \quad BR(\bar{\nu}\pi^+) = (19 - 23)\%,$$

$$BR(\mu^+\pi^0) = (4 - 5)\%.$$

$$\tau(p \to e^+\pi^0) = 1 \times 10^{35}(\frac{0.01\mathrm{GeV}^3}{\alpha})^2(\frac{M_C}{2 \times 10^{16}})^4 y.$$

With default values of α, M_C: $\tau(p \to e^+\pi^0) \simeq 1 \times 10^{35}\mathrm{y}$ within reach of the next generation of proton decay experiments.

P decay in universal extra dimension (UED) models: 6D case

Applequist, Dobrescu, Ponton, Yee

- The SM particles are charged under the $U(1)$ arising from the extra dims x_4 and x_5. A discrete Z_8 symmetry survives which allows only very high dim B&L violating operators such as $(\bar{\nu}_L d_R)^2(\bar{l}_L d_R) + ...$

  P decay modes: $\pi^+\pi^+e^-\nu\nu,\ \pi^+\pi^+\mu^-\nu\nu, ...$

- As estimate of proton decay into these modes is then

$$\tau(p \to \pi\pi l\nu\nu) \simeq 10^{35}\mathrm{y}.f_{17}^2(\frac{M_C}{0.5TeV})^{12}(\frac{\Lambda}{5M_C})^{22}$$

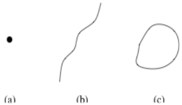
  Lifetime very sensitive to small changes in M_C and Λ.

  Current exp limit on $p \to \pi^+\pi^+e^-$: $\tau_p > 3 \times 10^{31}\mathrm{y}.$

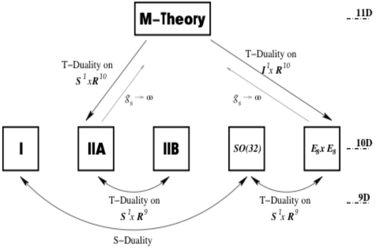
p decay in string theory

- **Old heterotic string models**
- **D -brane models**

String Theory



- Five string theories connected by dualities
- All from one - the M theory.



Proton decay in old 3 gen Hererotic Calabi-Yau Models

In $E_8 \times E_8$ heterotic strings $10D \longrightarrow M_4 \times K$ where K is the CY manifold. An interesting case is the manifold $CP^3 \times CP^3/Z_3$. The zero modes of K are given by the Hodge numbers $h_{2,1} = 9$, $h_{1,1} = 6$. The gauge group E_6 is broken by Wilson lines to give

$$E_6 \rightarrow SU(3)_C \times SU(3)_L \times SU(3)_R$$

Spectrum

$$L = (l, H, H', e^C, \nu^C, N),\ Q = (q, D),\ Q^C = (u^C, d^C, D^C)$$

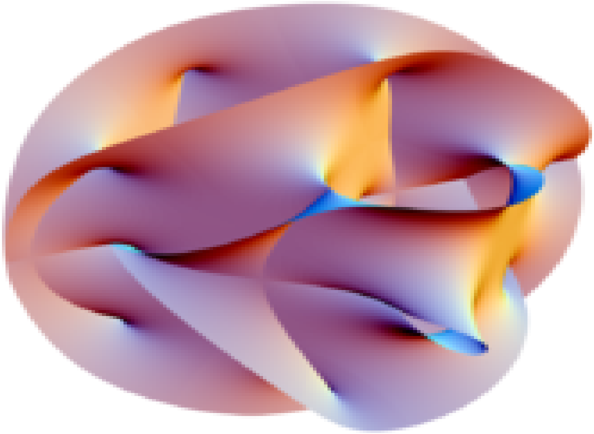
The D^C exchange gives for the dominant mode $\bar{\nu}K^+$

$$\tau(p \rightarrow \bar{\nu}_\mu K^+) \sim 10^{34-35} y.$$

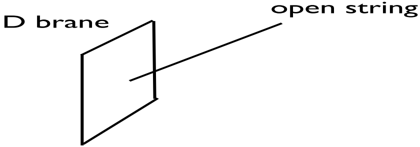
Arnowitt, PN; Greene, Miron, Ross

Compactification of heterotic $E_8 \times E_8$ on Calabi-Yau manifold.

The fig below: Calabi-Yau manifold projection in 3D

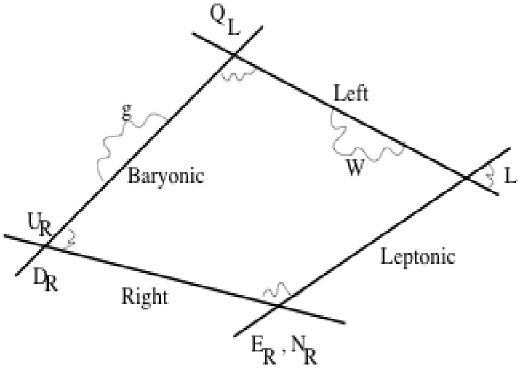


Intersecting D branes



A stack of n D branes give a
gauge group U(n)

Intersecting D branes



Proton decay in D brane models

Klebanov-Witten (2003) investigate proton decay on SU(5) GUT like models in Type IIA orientifolds with D6-branes. KW find

$$\tau_{string}(p \to e^+\pi^0) = \tau_{GUT}(p \to e^+\pi^0) C_{st} \frac{M_G^4}{M_X^4}$$

C_{st} is the string enhancement factor estimated as $C_{st} \simeq 0.5 - 1.2$. Using $M_G = M_X$, $\tau_{GUT} = 1.6 \times 10^{36}$y one finds

$$\tau_{string} = (0.8 - 1.9) \times 10^{36}\mathrm{y}.$$

In this model $p \to e_R^+\pi^0$ is suppressed relative to $p \to e_L^+\pi^0$.

p decay via Quantum gravity effects

Proton decay from black hole and worm hole effects

Hawking, Page, Pope; Ellis, Hagelin, Nanop, Tamvakis; Gilbert; Adams, Laughlin, Mbonye, Perry, ..

Quantum gravity does not conserve baryon number and hence can catalize p decay by exchange of mini black holes (BH) and wormhole effects.

$$q + q \rightarrow \bar{q} + l$$

The effects can be simulated by 4-Fermi interactions suppressed by an effective scale M_{QG}. Proton decay lifetime from such a process is

$$\tau_p \approx 10^{36}\mathrm{y} \left(\frac{M_{QG}}{10^{16}\mathrm{GeV}} \right)^4$$

With $M_{QG} = M_{Pl}$ this leads to $\tau_p \sim 10^{45}$ y, beyond experimental reach but controls the ultimate fate of the universe.

Overview of proton decay lifetimes in unification models

Theoretical lifetime limits on $p \to e^+\pi^0$ mode

Lifetime estimates for $p \to e^+\pi^0$ for various models

Ref	Model	Lifetime estimate in ys
LMPR	Non-SUSY GUTs	10^{33-38}
DP	SU(5)	$\sim 10^{37}$
JH	SUSY GUTs	1.6×10^{36}
JCP	SUSY-SO(10)	$\sim 5 \times 10^{35\pm1}$
HM-R	5D models	$\sim 4 \times 10^{36}$
KR	5D -SO(10)	$\sim 7 \times 10^{33\pm2}$
BCEW	6D models	$\sim 5 \times 10^{34\pm1}$
KW	D-brane models	$(0.8 - 1.9) \times 10^{36}$
PR	Black holes, worm holes	$\sim 10^{45}$

Proton lifetime estimates for $p \longrightarrow \bar{\nu} K^+$ for various models

	Model	Lifetime/ys
BPS, EW, DMN	SUSY SU5)	$\sim \mathbf{10^{34}}$
BPW	SUSY SO(10)	$\mathbf{(1/3-2) \times 10^{34}}$
LR	SUSY SO(10)	$\mathbf{(6.6 - 3 \times 10^2) \times 10^{33}}$
DMM, NS	SUSY GUTs	$\geq \mathbf{(2-3) \times 10^{33}}$
AN	Calabi-Yau Strings	$\sim \mathbf{10^{34-35}}$

Proton lifetime estimates for unconventional modes

Ref	Mode	Model	Lifetime/ys
ADPY	$p \longrightarrow \pi^+ \pi^+ l^- \nu \nu$	UED -6D	$\geq \mathbf{10^{35}}$
PR	$p(n) \longrightarrow \gamma + e^+(\bar{\nu})$	SUSY GUTs	$> \mathbf{10^{38 \pm 1}}$

Abbreviations used in Table

(AN) Arnowitt, Nath (1989)

(BPW): Babu, Pati, Wilczek (2000).

(BGNS): Babu, Gogoladze, Nath, Syed (2005)

(BF-PS): Bajc, Filieviez-Perez, Senjanovic (2002)

(DMN): Dasgupta, Mamales, Nath (1995)

(DF-P): Dorsner, Fileviez-Perez (2005,2006)

(DMM): Dutta, Mimura, Mohapatra (2004)

(E-CW): Emmanuel-Costa, Wiesenfeldt (2003)

(KW) Klebanov, Witten (2003)

(LMPR): Lee, Mohapatra, Parida, Rani (1995)

(LR): Lucas, Raby (1997)

(MP): Murayama, Pierce (2002)

(NS): Nath, Syed (2001, 2007)

Abbreviations used in Tables

(JCP): Pati, Berkeley Conf (2007)

(ADPY): Appelquist, Dobrescu, Ponton, Yee (2001)

(BCEW): Buchmuller, Covi, Emmunuel-Costa, Wiesenfeldt (04)

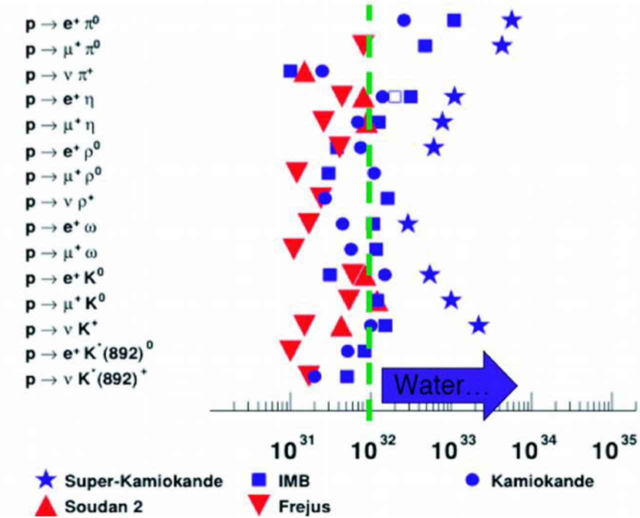
(HM-R): Hebecker, March-Russel (2002)

(KR): Kim, Raby (2003)

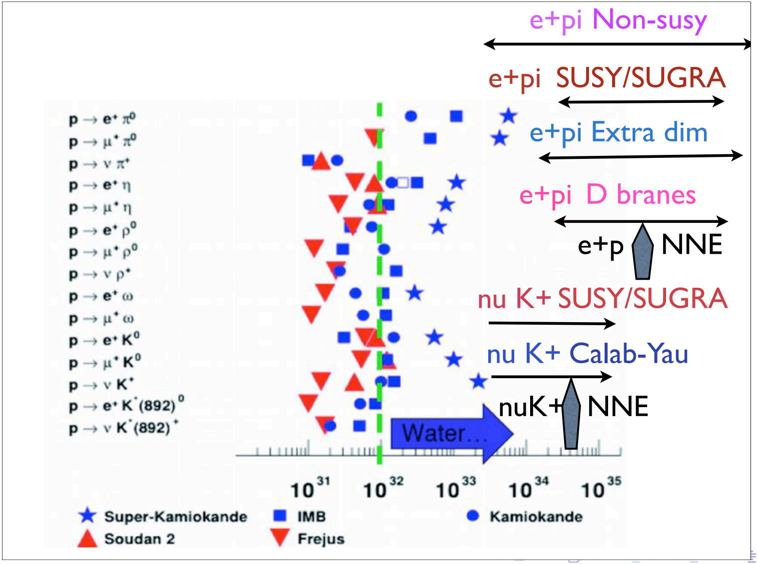
(KS): Kovalenko, Schmidt (2003)

(PR): Physics Reports: Nath, Perez (2007)

Current nucleon stability limits



Theory vs Next generation Nucleon stability Experiments (NNE)



Conclusion/prospects

- The next generation nucleon stability experiments (NNE) will either discover proton decay or eliminate a very significant portion of the space of unified models.
- The LHC will hopefully provide us with concrete evidence and measurement of sparticle spectra leading to improved proton lifetime predictions.
- Proton stability experiments should continue as they probe the nature of fundamental interactions at extremely short distances which the accelerators can never hope to reach.