Proton decay

Tommy Ohlsson

Department of Physics, KTH Royal Institute of Technology, Stockholm, Sweden

Neutrino 2022, Seoul, Republic of Korea – June 4, 2022

Speaking from Stockholm, Sweden @ Virtual Seoul

Outline

This is an overview and review talk on *proton decay*, covering both *experimental results* and *theoretical models* including their predictions.

This is an overview and review talk on *proton decay*, covering both *experimental results* and *theoretical models* including their predictions.

Outline

This talk is organized as follows:

- What is proton decay?
- History of proton decay (including results by experiments)
- Proton decay in theory (in basic GUTs)
- Estimates of proton lifetime
- Proton decay in non-SUSY GUTs [e.g. $\mathrm{SU}(5)$ and $\mathrm{SO}(10)$]
- Future experiments
- Summary & Outlook

What is proton decay?

Proton decay

- In particle physics, *proton decay* is a hypothetical form of particle decay in which protons decay into lighter subatomic particles.
- Examples of potential decay channels are:
  - $p \to e^+ + \pi^0, \quad p \to \mu^+ + \pi^0 \quad$ (canonical examples)
  - $p \to \overline{\nu} + \pi^+, \quad p \to \mu^+ + K^0, \quad p \to \overline{\nu} + K^+, \quad \ldots$

What is proton decay?

Proton decay

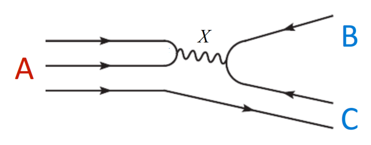
- In particle physics, *proton decay* is a hypothetical form of particle decay in which protons decay into lighter subatomic particles.
- Examples of potential decay channels are:
  - $p \to e^+ + \pi^0, \quad p \to \mu^+ + \pi^0$ (canonical examples)
  - $p \to \overline{\nu} + \pi^+, \quad p \to \mu^+ + K^0, \quad p \to \overline{\nu} + K^+, \quad \ldots$

Not proton decay

- Positron emission (or β^+ decay): $p \to n + e^+ + \nu_e$
- Electron capture: $p + e^- \to n + \nu_e$

Positron emission (or electron capture) is **not** *proton decay*, since protons interact with other subatomic particles inside nuclei or atoms.

How to calculate lifetime in theory



- Assuming $M_X \gg m_A$, the Feynman amplitude can be approximated by an effective four-fermion interaction:

$$\langle BC|A\rangle \simeq g \cdot \frac{1}{M_X^2} \cdot g = \frac{g^2}{M_X^2} \propto \frac{\alpha}{M_X^2}, \qquad \alpha \equiv \frac{g^2}{4\pi}$$

- A rough estimate of the total decay width:

$$\Gamma(A \to BC) \simeq |\langle BC|A\rangle|^2 m_A^5 \propto \frac{\alpha^2}{M_X^4} m_A^5$$

- Thus, on dimensional grounds, the lifetime is given by

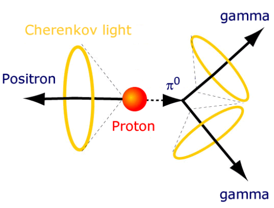
$$\tau_A \equiv \frac{1}{\Gamma(A \to BC)} \propto \frac{M_X^4}{\alpha^2 m_A^5}.$$

How to measure proton decay in experiments

- For example, the decay channel $p \to e^+ + \pi^0$ could be searched for in the following process:

$$p \longrightarrow e^+ + \pi^0 \\ \qquad\qquad \hookrightarrow \gamma + \gamma$$

- In a water-Cherenkov detector, the two photons would be detected as two rings and the positron would also produce a third ring by Cherenkov radiation. Thus, the signal would be measured through **three rings**.



Background: Atmospheric neutrinos

How does an event look like in the proton decay channel $p \to e^+ + \pi^0$?

- Signal: $\boxed{p \to e^+ + \pi^0 \to e^+ + \gamma + \gamma}$

  $\because$ **3 rings**, where 1 ring comes from e^+ and 2 rings come from $\pi^0 \to \gamma + \gamma$.

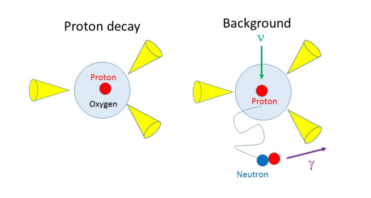
- Major background: $\boxed{\nu_e + p \to e^- + n + \pi^0 \to e^- + n + \gamma + \gamma}$

  [Atmospheric neutrinos: $\pi^+ \to \mu^+ + \nu_\mu, \quad \mu^+ \to e^+ + \overline{\nu_\mu} + \nu_e$]

  Atmospheric neutrino events **mimic** "proton decay" events!

  A neutron n does not produce a ring, but it is sometimes captured by a proton p followed by delayed gamma ray emission γ.

  $\because$ **3 rings** + gamma ray emission



There are some experiments that have been searching for proton decay.

There are some experiments that have been searching for proton decay.

Past experiments

- Water-Cherenkov detectors:
  - IMB (Ohio, USA; 1982–1991)
  - KamiokaNDE (Kamioka Nucleon Decay Experiment, Gifu, Japan; 1983–1985, 1985–1990, 1990–1995)
- Iron-tracking calorimeters:
  - NUSEX (Nucleon Stability Experiment, Mont-Blanc, France; 1982–1983): a candidate event in the $p \to \mu^+ + K^0$ channel
  - Fréjus (Fréjus, France; 1984–1988)
  - Soudan (Minnesota, USA; 1981–1982, 1989–2001): a candidate event in the $p \to \overline{\nu} + K^+$ channel

History of proton decay

There are some experiments that have been searching for proton decay.

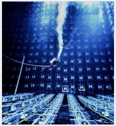
Past experiments

- Water-Cherenkov detectors:
  - IMB (Ohio, USA; 1982–1991)
  - KamiokaNDE (Kamioka Nucleon Decay Experiment, Gifu, Japan; 1983–1985, 1985–1990, 1990–1995)
- Iron-tracking calorimeters:
  - NUSEX (Nucleon Stability Experiment, Mont-Blanc, France; 1982–1983): a candidate event in the $p \to \mu^+ + K^0$ channel
  - Fréjus (Fréjus, France; 1984–1988)
  - Soudan (Minnesota, USA; 1981–1982, 1989–2001): a candidate event in the $p \to \overline{\nu} + K^+$ channel

Operating experiment

- Super-Kamiokande (water-Cherenkov detector, Gifu, Japan; 1996–now)

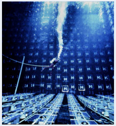
IMB



- 3.3 kton (fiducial vol.), 2 000 PMTs (4 %)
- No proton decay have been found.
- $\tau(p \to e^+\pi^0) > 5.5 \cdot 10^{32}$ years (1990)

History of proton decay – water-Cherenkov detectors

IMB



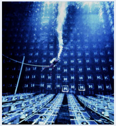
- 3.3 kton (fiducial vol.), 2 000 PMTs (4 %)
- No proton decay have been found.
- $\tau(p \to e^+\pi^0) > 5.5 \cdot 10^{32}$ years (1990)

KamiokaNDE

- 0.88 kton (fiducial vol.), 948 PMTs (20 %)
- No proton decay have been found.
- $\tau(p \to e^+\pi^0) > 2.6 \cdot 10^{32}$ years (1989)

History of proton decay – water-Cherenkov detectors

IMB

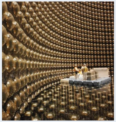


- 3.3 kton (fiducial vol.), 2 000 PMTs (4 %)
- No proton decay have been found.
- $\tau(p \to e^+\pi^0) > 5.5 \cdot 10^{32}$ years (1990)

KamiokaNDE

- 0.88 kton (fiducial vol.), 948 PMTs (20 %)
- No proton decay have been found.
- $\tau(p \to e^+\pi^0) > 2.6 \cdot 10^{32}$ years (1989)

Super-Kamiokande (SK)



- 22.5 kton (fiducial vol.), 11 146 PMTs (40 %)
- No proton decay have been found.
- Still operating!

Results on proton decay by Super-Kamiokande

PHYSICAL REVIEW D **102,** 112011 (2020)

Search for proton decay via $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$ with an enlarged fiducial volume in Super-Kamiokande I-IV

arXiv:2010.16098 [hep-ex]

Results on proton decay by Super-Kamiokande

PHYSICAL REVIEW D **102**, 112011 (2020)

Search for proton decay via $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$ with an enlarged fiducial volume in Super-Kamiokande I-IV

arXiv:2010.16098 [hep-ex]

- $p \to e^+ + \pi^0$ channel: **no** candidate events have been found.

$$\boxed{\tau/B(p \to e^+\pi^0) > 2.4 \cdot 10^{34}\ \text{years} \quad @\ 90\ \%\ \text{C.L.}}$$

Results on proton decay by Super-Kamiokande

PHYSICAL REVIEW D **102,** 112011 (2020)

Search for proton decay via $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$ with an enlarged fiducial volume in Super-Kamiokande I-IV

arXiv:2010.16098 [hep-ex]

- $p \to e^+ + \pi^0$ channel: **no** candidate events have been found.

$$\boxed{\tau/B(p \to e^+\pi^0) > 2.4 \cdot 10^{34} \text{ years} \quad @ \ 90\ \%\ \text{C.L.}}$$

- $p \to \mu^+ + \pi^0$ channel: **one** candidate event remains.

$$\boxed{\tau/B(p \to \mu^+\pi^0) > 1.6 \cdot 10^{34} \text{ years} \quad @ \ 90\ \%\ \text{C.L.}}$$

Results on proton decay by Super-Kamiokande

PHYSICAL REVIEW D **102,** 112011 (2020)

Search for proton decay via $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$ with an enlarged fiducial volume in Super-Kamiokande I-IV

arXiv:2010.16098 [hep-ex]

- $p \to e^+ + \pi^0$ channel: **no** candidate events have been found.

$$\boxed{\tau/B(p \to e^+\pi^0) > 2.4 \cdot 10^{34} \text{ years} \quad @\ 90\ \%\ \text{C.L.}}$$

- $p \to \mu^+ + \pi^0$ channel: **one** candidate event remains.

$$\boxed{\tau/B(p \to \mu^+\pi^0) > 1.6 \cdot 10^{34} \text{ years} \quad @\ 90\ \%\ \text{C.L.}}$$

- Earlier results by SK (proton lifetime [years] @ 90 % C.L.):

2001.08011 [hep-ex]	$\tau/B(p \to 3\ell) > 0.92 \cdot 10^{34}$	
1610.03597 [hep-ex]	$\tau/B(p \to e^+\pi^0) > 1.6 \cdot 10^{34}$	$\tau/B(p \to \mu^+\pi^0) > 7.7 \cdot 10^{33}$
1408.1195 [hep-ex]	$\tau/B(p \to \overline{\nu}K^+) > 5.9 \cdot 10^{33}$	
1205.6538 [hep-ex]	$\tau/B(p \to \mu^+K^0) > 1.6 \cdot 10^{33}$	Poster by R. Matsumoto: $> 3.6 \cdot 10^{33}$
0903.0676 [hep-ex]	$\tau/B(p \to e^+\pi^0) > 8.2 \cdot 10^{33}$	$\tau/B(p \to \mu^+\pi^0) > 6.6 \cdot 10^{33}$
hep-ex/9904020 [hep-ex]	$\tau/B(p \to \overline{\nu}K^+) > 6.7 \cdot 10^{32}$	
hep-ex/9806014 [hep-ex]	$\tau/B(p \to e^+\pi^0) > 1.6 \cdot 10^{33}$	

Results on proton decay by Super-Kamiokande – background

PHYSICAL REVIEW D **102,** 112011 (2020)

Search for proton decay via $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$ with an enlarged fiducial volume in Super-Kamiokande I-IV

arXiv:2010.16098 [hep-ex]

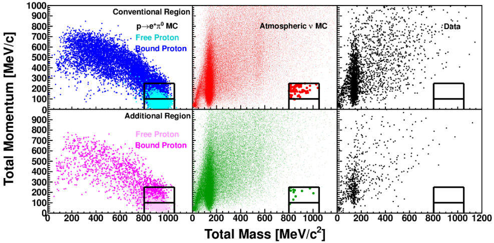


FIG. 8. Reconstructed total mass shown against the total momentum distributions for $p \to e^+\pi^0$ after all cuts except those on these variables. The top plots correspond to the conventional and the bottom plots correspond to the additional fiducial volume. The left panels show the signal MC (SK-I to -IV are combined), where lighter colors show free protons and dark colors show bound protons. The middle panels show the 2000 year-equivalent atmospheric neutrino MC. The right panels show all the combined data SK-I to -IV. The black box shows the signal region and for the middle panels the markers in the signal region have been enlarged for visibility.

The Standard Model

- In the Standard Model (SM), baryon number B and lepton number L are conserved.
- For example, the decay channel $p \to e^+ + \pi^0$ is forbidden in the SM, since both B and L are not conserved:

$$\boxed{\begin{array}{rccccc} & p & \to & e^+ & + & \pi^0 \\ B: & 1 & \neq & 0 & + & 0 \\ L: & 0 & \neq & -1 & + & 0 \\ B-L: & 1 & = & 1 & + & 0 \end{array}}$$

- In fact, the proton p is **stable** in the SM:

$$\Gamma(p \to \cdots) = 0 \quad \Longrightarrow \quad \tau_p \to \infty$$

In the SM (with minimal particle content), B and L are conserved due to *gauge invariance* and *renormalizability* which ensure that B and L are global symmetries of the theory. [Nanopoulos (1973); Weinberg (1973)]

In the SM (with minimal particle content), B and L are conserved due to *gauge invariance* and *renormalizability* which ensure that B and L are global symmetries of the theory. [Nanopoulos (1973); Weinberg (1973)]

The SM at the non-renormalizable level

There are at least **two** obvious possibilities for violation of B and L:

1. The particle content of the SM is enlarged.
2. The gauge group $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$ of the SM is extended.

This leads to effective operators that can cause violation of B and L which are non-renormalizable and have dimensions $d > 4$ as well as coupling constants with dimensions $[M^{4-d}]$.

Effective operators $d > 4$ in the SM (at the non-renorm. level)

- Dimension $d = 5$: The *Weinberg operator* is the only operator, which can be formally written as [Weinberg (1979)]

$$\mathcal{L}_5 \sim \frac{1}{M}(H\ell)(H\ell).$$

  This operator has $\Delta B = 0$ and $\Delta L = 2$ and gives rise to Majorana neutrino masses. See talk on *Theoretical models of neutrino masses* by F. Feruglio.

- Dimension $d = 6$: Four-fermion operators can be schematically written as [Weinberg (1979); Wilczek & Zee (1979); Abbott & Wise (1980)]

$$\mathcal{L}_6 \sim \frac{1}{M^2} qqq\ell + \mathrm{h.c.}$$

  These operators have $\Delta B = 1$ and $\Delta L = 1$, but $\Delta(B - L) = 0$, which means that they violate $B + L$ but conserve $B - L$.
  All dimension-six operators lead to two-body proton decay!

- Dimension $d \geq 7$: These operators are naturally suppressed with respect to dimension-six operators.

In 1967, the hypothesis of proton decay was formulated by Sakharov. Three necessary conditions for baryon asymmetry (*i.e.* generation of a non-zero baryon number in the initially matter-antimatter symmetric Universe) were proposed [Sakharov (1967)]. The three *Sakharov conditions* are:

1. Baryon number violation $\Delta B \neq 0$
2. C- and CP-violation
3. Interactions out of thermal equilibrium

Proton decay in theory

In 1967, the hypothesis of proton decay was formulated by Sakharov. Three necessary conditions for baryon asymmetry (*i.e.* generation of a non-zero baryon number in the initially matter-antimatter symmetric Universe) were proposed [Sakharov (1967)]. The three *Sakharov conditions* are:

1. Baryon number violation $\Delta B \neq 0$
2. C- and CP-violation
3. Interactions out of thermal equilibrium

Beyond the SM

Only physics beyond the SM can connect higher-dimensional effective operators with other physical phenomena and thus be testable.

- The best candidate: **Grand unified theories (GUTs)**
- Other candidates: quantum tunneling, quantum gravity, extra dimensions, string theory, ...
- Problem: There is a plethora of many different GUTs!

Proton decay in theory

In general, GUTs predict exotic interactions through their additional gauge bosons and scalars, which can mediate proton decay. The gauge boson-mediated proton decay can be observed in the covariant derivative of the fermions in which gauge bosons couple to both quarks and leptons. Therefore, they are called *leptoquark* gauge bosons and can convert quarks to leptons, and vice versa. The leptoquark gauge and scalar bosons violate B. These leptoquark gauge bosons can be integrated out, and thus, effective dimension-six operators are produced that describe proton decay.

Proton decay in theory

In general, GUTs predict exotic interactions through their additional gauge bosons and scalars, which can mediate proton decay. The gauge boson-mediated proton decay can be observed in the covariant derivative of the fermions in which gauge bosons couple to both quarks and leptons. Therefore, they are called *leptoquark* gauge bosons and can convert quarks to leptons, and vice versa. The leptoquark gauge and scalar bosons violate B. These leptoquark gauge bosons can be integrated out, and thus, effective dimension-six operators are produced that describe proton decay.

Model dependence of GUTs

- Proton decay is a generic prediction of GUTs, but there is some model dependence in the allowed effective operators, depending on which couplings are present in the given GUT.
- There is a difference in GUTs with or without supersymmetry (SUSY). In addition to dimension-six operators, SUSY allows for dimension-five and dimension-four operators that may lead to faster proton decay.

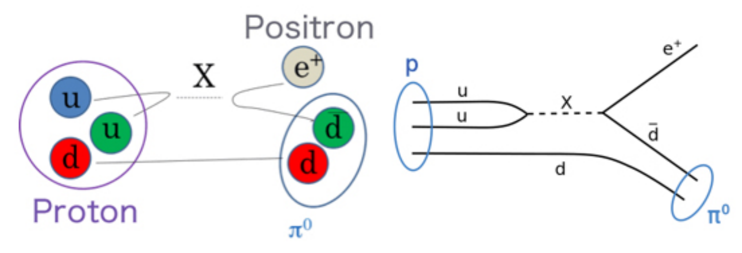
Proton decay operators in GUTs

- Dimension-six operators: All of the dimension-six proton decay operators violate **both** B and L but not $B - L$.
    1. The exchange of leptoquark gauge bosons (denoted X or Y) with masses M_{GUT} can lead to some operators suppressed by $1/M_{\mathrm{GUT}}^2$.
    2. The exchange of triplet Higgs with mass m_H can lead to all of the operators suppressed by $1/m_H^2$.
- Dimension-five operators: In SUSY GUTs, it is also possible to have dimension-five proton decay operators. In this case, the operators are suppressed by $(MM_{\mathrm{SUSY}})^{-1}$, where M is the mass of the exchange particle and M_{SUSY} is the mass scale of the superpartners.
- Dimension-four operators: In SUSY GUTs with the absence of R-parity, it is also possible to have dimension-four proton decay operators. In this case, the operators are suppressed by $1/M_{\mathrm{SUSY}}^2$ which gives rise to proton decay that is normally too fast.

Proton decay in GUTs

In GUTs, since all dimension-six proton decay operators conserve $B - L$, a *proton* **always** decays into an *antilepton*.

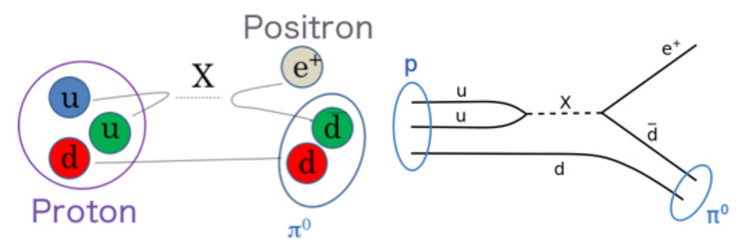
A generic example of proton decay in GUTs is: $\boxed{p \longrightarrow e^{+} + \pi^{0}}$



Proton decay in GUTs

In GUTs, since all dimension-six proton decay operators conserve $B - L$, a *proton* **always** decays into an *antilepton*.

A generic example of proton decay in GUTs is: $\boxed{p \longrightarrow e^+ + \pi^0}$



A rough estimate of the proton lifetime with a GUT-scale gauge boson mediator (like X) is:

$$\boxed{\tau_p \propto \frac{M_{\mathrm{GUT}}^4}{\alpha_{\mathrm{GUT}}^2 m_p^5}}$$

Proton decay in theory

- A long proton lifetime requires a combination of a large mass scale M_{GUT} and a small coupling constant α_{GUT}, since $\tau_p \propto M_{\mathrm{GUT}}^4/\alpha_{\mathrm{GUT}}^2$.
- There is a stronger dependence on M_{GUT} than on α_{GUT}.

$\because$ Non-observation of proton decay $\Rightarrow$ Lower bound on M_{GUT}

Proton decay in theory

- A long proton lifetime requires a combination of a large mass scale M_{GUT} and a small coupling constant α_{GUT}, since $\tau_p \propto M_{\mathrm{GUT}}^4/\alpha_{\mathrm{GUT}}^2$.
- There is a stronger dependence on M_{GUT} than on α_{GUT}.

$\because$ Non-observation of proton decay $\Rightarrow$ Lower bound on M_{GUT}

A more precise estimate of proton lifetime in GUTs

1. Proton contains physical quark mass states $\to$ Yukawa mixing factor included
2. Proton @ $M \simeq 1$ GeV, operators @ $M \simeq M_{\mathrm{GUT}}$ $\to$ renormalization factor included
3. Projection of proton state onto meson state $\to$ hadronic matrix element included

The proton decay width for $p \to e^+ + \pi^0$ [Nath & Fileviez-Pérez (2007)]:

$$\Gamma(p \to e^+\pi^0) \simeq \frac{\pi m_p}{4 f_\pi^2} \frac{\alpha_{\mathrm{GUT}}^2}{M_{\mathrm{GUT}}^4} F_q R^2 \alpha_H^2$$

A generic estimate for proton lifetime in GUTs:

$$\boxed{\tau(p \to e^+\pi^0) \simeq 7.47 \cdot 10^{35} \left(\frac{M_{\mathrm{GUT}}}{10^{16}\ \mathrm{GeV}}\right)^4 \left(\frac{0.03}{\alpha_{\mathrm{GUT}}}\right)^2 \text{ years}}$$

Upper bounds on proton lifetime in GUTs

- Assume only dimension-six operators, since other operators can be set to zero in searching for upper bounds.
- Assume proton lifetime induced by superheavy gauge bosons X.

Upper bound on proton lifetime for any GUT with or without SUSY [see e.g. Doršner & Fileviez-Pérez (2005); Nath & Fileviez-Pérez (2007)]:

$$\boxed{\tau_p \lesssim 6.0 \cdot 10^{39} \frac{1}{\alpha_{\mathrm{GUT}}^2} \left(\frac{M_X}{10^{16}\ \mathrm{GeV}} \right)^4 \left(\frac{0.003\ \mathrm{GeV}^3}{\alpha_{\mathrm{ChPT}}} \right)^2 \text{ years}}$$

Proton decay in basic GUTs

Upper bounds on proton lifetime in GUTs

- Assume only dimension-six operators, since other operators can be set to zero in searching for upper bounds.
- Assume proton lifetime induced by superheavy gauge bosons X.

Upper bound on proton lifetime for any GUT with or without SUSY [see e.g. Doršner & Fileviez-Pérez (2005); Nath & Fileviez-Pérez (2007)]:

$$\boxed{\tau_p \lesssim 6.0 \cdot 10^{39} \frac{1}{\alpha_{\mathrm{GUT}}^2} \left(\frac{M_X}{10^{16}\ \mathrm{GeV}} \right)^4 \left(\frac{0.003\ \mathrm{GeV}^3}{\alpha_{\mathrm{ChPT}}} \right)^2 \ \mathrm{years}}$$

In minimal non-SUSY $\mathrm{SU}(5)$, the upper bound is

$$\tau_p \lesssim 1.4 \cdot 10^{36}\ \text{years}. \quad (@\ M_X = 2 \cdot 10^{14}\ \mathrm{GeV},\ \alpha_{\mathrm{GUT}} = 1/39)$$

$$\boxed{\because\ \text{Non-SUSY GUTs are still allowed.}}$$

In realistic minimal non-SUSY GUTs, $\tau_p \lesssim 10^{36}$ years.

However, minimal SUSY $\mathrm{SU}(5)$ is, or at least very close to be, ruled out.

Unified Theories and Baryon Number in the Universe, KEK (1979)

Theorists, these days, actually seem to be convinced of the existence of proton decay, but the predicted life time is $\sim 10^{35}$yr, too stable to be observed by the present-day technology, yet a very challenging problem from experimentarists' point of view,

[Y. Watanabe, *Trying to measure the proton's life time*]

Predicted proton lifetimes

An incomplete list of models:

Model class	Lifetime [years]	Ruled out?
Minimal $\mathrm{SU}(5)$ [Georgi & Glashow (1974)]	$10^{30} - 10^{31}$	yes
Minimal SUSY $\mathrm{SU}(5)$ [Dimopoulos & Georgi; Sakai & Yanagida]	$10^{28} - 10^{34}$	yes
SUGRA $\mathrm{SU}(5)$ [Nath, Chamseddine & Arnowitt (1985)]	$10^{32} - 10^{34}$	yes
SUSY (MSSM/ESSM) $\mathrm{SO}(10)/G(224)$ [Babu, Pati & Wilczek]	$2 \cdot 10^{34}$	yes
SUSY (MSSM/ESSM, $d = 5$) $\mathrm{SO}(10)$ [Lucas & Raby; Pati]	$10^{32} - 10^{35}$	partially
SUSY $\mathrm{SO}(10) + \mathrm{U}(1)_{\mathrm{fl}}$ [Shafi & Tavartkiladze (2000)]	$10^{32} - 10^{35}$	partially
SUSY ($d = 5$) $\mathrm{SU}(5)$ – option I [Hebecker & March-Russell (2002)]	$10^{34} - 10^{35}$	partially
SUSY (MSSM, $d = 6$) $\mathrm{SU}(5)$ or $\mathrm{SO}(10)$ [Pati (2003)]	$\sim 10^{34.9 \pm 1}$	partially
Minimal non-SUSY $\mathrm{SU}(5)$ [Doršner & Fileviez-Pérez (2005)]	$10^{31} - 10^{38}$	partially
Minimal non-SUSY $\mathrm{SO}(10)$	$\boxed{???}$	no
SUSY (CMSSM) Flipped $\mathrm{SU}(5)$ [Ellis, Nanopoulos & Walker (2002)]	$10^{35} - 10^{36}$	no
GUT-like models from string theory [Klebanov & Witten (2003)]	$\sim 10^{36}$	no
Split SUSY $\mathrm{SU}(5)$ [Arkani-Hamed *et al.* (2005)]	$10^{35} - 10^{37}$	no
SUSY ($d = 5$) $\mathrm{SU}(5)$ – option II [Alciati *et al.* (2005)]	$10^{36} - 10^{39}$	no

This list is an updated version of the one presented in `hep-ph/0701101`.

Minimal non-SUSY $\mathrm{SU}(5)$ 1712.06526 [hep-ph]; 1911.05738 [hep-ph]

Non-SUSY $\mathrm{SU}(5) \times \mathrm{U}(1)_{\mathrm{PQ}} \longrightarrow \mathcal{G}_{\mathrm{SM}}$ @ GUT scale

- Boucenna & Shafi (2018):
  - unification @ $M_{\mathrm{GUT}} \approx 10^{16}$ GeV
  - $8 \cdot 10^{34}$ years $\lesssim \tau_p \lesssim 3 \cdot 10^{35}$ years, axions constitute dark matter
- Fileviez-Pérez, Murgui & Plascencia (2020):
  - unification @ $M_{\mathrm{GUT}} \in (1.12, 10.45) \cdot 10^{15}$ GeV
  - 10^{34} years $\lesssim \tau_p \lesssim 10^{38}$ years, axions constitute dark matter

Proton decay in non-SUSY GUTs

Minimal non-SUSY $\mathrm{SU}(5)$ 1712.06526 [hep-ph]; 1911.05738 [hep-ph]

Non-SUSY $\mathrm{SU}(5) \times \mathrm{U}(1)_{\mathrm{PQ}} \longrightarrow \mathcal{G}_{\mathrm{SM}}$ @ GUT scale

- Boucenna & Shafi (2018):
  - unification @ $M_{\mathrm{GUT}} \approx 10^{16}$ GeV
  - $8 \cdot 10^{34}$ years $\lesssim \tau_p \lesssim 3 \cdot 10^{35}$ years, axions constitute dark matter
- Fileviez-Pérez, Murgui & Plascencia (2020):
  - unification @ $M_{\mathrm{GUT}} \in (1.12, 10.45) \cdot 10^{15}$ GeV
  - 10^{34} years $\lesssim \tau_p \lesssim 10^{38}$ years, axions constitute dark matter

Minimal non-SUSY $\mathrm{SO}(10)$ hep-ph/9404238

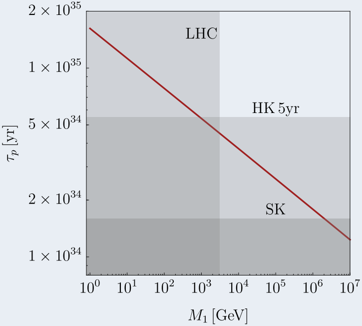
Minimal non-SUSY $\mathrm{SO}(10) \longrightarrow \mathcal{G} \longrightarrow \mathcal{G}_{\mathrm{SM}}$, $\quad \tau_p = \tau(p \to e^+\pi^0)$

Model A ($\mathcal{G} = G_{422D}$):	$\tau_p = 1.44 \cdot 10^{32.1\pm0.7}$ years	ruled out
Model B ($\mathcal{G} = G_{422}$):	$\tau_p = 1.44 \cdot 10^{37.4\pm0.7}$ years	allowed
Model C ($\mathcal{G} = G_{3221D}$):	$\tau_p = 1.44 \cdot 10^{34.2\pm0.7}$ years	partially
Model D ($\mathcal{G} = G_{3221}$):	$\tau_p = 1.44 \cdot 10^{37.7\pm0.7}$ years	allowed

[Lee, Mohapatra, Parida & Rani, Phys. Rev. D **51**, 229 (1995)]

Minimal non-SUSY $\mathrm{SO}(10) \times \mathrm{U}(1)_{\mathrm{PQ}}$ 1812.10548 [hep-ph]

- Minimal non-SUSY SO(10): $\mathrm{SO}(10) \times \mathrm{U}(1)_{\mathrm{PQ}} \longrightarrow \mathcal{G}_{\mathrm{SM}}$
- Two color-octet scalar multiplets of $\mathbf{210}_H$: $S_1 = (\mathbf{8}, \mathbf{1}, 1)$ and $S_2 = (\mathbf{8}, \mathbf{3}, 0)$
- Precise gauge coupling unification if $M_1 \leq M_2 \leq M_{\mathrm{GUT}}$:
  $M_1 \simeq 3.10 \cdot 10^3$ GeV, $M_2 \simeq 2.34 \cdot 10^8$ GeV, and $M_{\mathrm{GUT}} \simeq 4.51 \cdot 10^{15}$ GeV

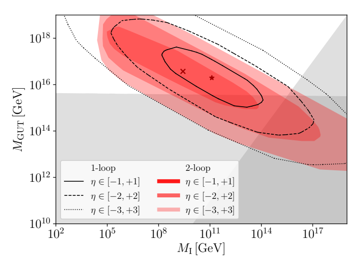


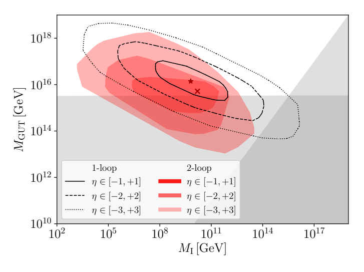
- Current bounds on M_1 from LHC ($M_1 > 3.1 \cdot 10^3$ GeV) and SK ($M_1 < 1.6 \cdot 10^5$ GeV) $\Rightarrow$ $\boxed{\tau_p \in (2.4, 4.5) \cdot 10^{34} \text{ years}}$
- If HK reaches $\tau_p > 5.5 \cdot 10^{34}$ years in five-years of running, then this model would be strongly disfavored.

[Boucenna, Ohlsson & Pernow, Phys. Lett. B **792**, 251 (2019)]

Minimal non-SUSY SO(10) with one intermediate scale 1911.11411 [hep-ph]

- Minimal non-SUSY SO(10) with one intermediate gauge group: seven groups are analysed and two are allowed by proton decay.
- RG running @ two-loop level. Threshold corrections are taken into account.





PS $= \mathrm{SU}(4)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$

- The Pati–Salam model as intermediate group.
- $\boxed{\tau_p \simeq 1.2 \cdot 10^{38} \text{ years}}$

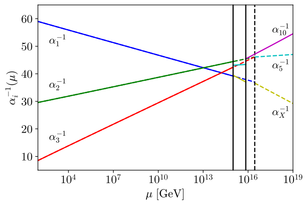
$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$

- The left-right model as intermediate group.
- $\boxed{\tau_p \simeq 9.4 \cdot 10^{34} \text{ years}}$

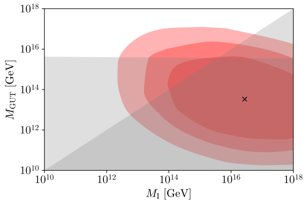
[Meloni, Ohlsson & Pernow, Eur. Phys. J. C **80**, 840 (2020)]

Minimal non-SUSY SO(10) with SU(5) as an intermediate scale 2006.13936 [hep-ph]

- Minimal non-SUSY SO(10) with flipped $\mathrm{SU}(5) \times \mathrm{U}(1)$ as intermediate gauge group: $\mathrm{SO}(10) \longrightarrow \mathrm{SU}(5) \times \mathrm{U}(1) \longrightarrow \mathcal{G}_{\mathrm{SM}}$
- This model does not achieve unification if threshold corrections are not taken into account: $\eta_i = \ln(M_{S_i}/M_{m \to n})$



unification



flipped $\mathrm{SU}(5) \times \mathrm{U}(1)_X$

- $M_I \simeq 10^{15}$ GeV, $M_{\mathrm{GUT}} \simeq 7 \cdot 10^{15}$ GeV

- Threshold corrections are needed in order to achieve unification and allow proton decay: $\boxed{\eta_i \in [-4, 4]}$ ("middle" red color)

[Ohlsson, Pernow & Sönnerlind, Eur. Phys. J. C **80**, 1089 (2020)]

In the last five years: 2017–now

Proton decay in $\mathrm{SU}(5)$ GUTs

- Lee & Mohapatra [1611.05478]: non-SUSY $\mathrm{SU}(5) \times \mathrm{SU}(5)$, $\tau_{p \to e^+ \pi^0} \simeq 6.2 \cdot 10^{34}$ years
- Fornal & Grinstein [1706.08535]: $\mathrm{SU}(5)$, stable proton
- Rehman, Shafi & Zubair [1804.02493]: SUSY flipped $\mathrm{SU}(5)$, $\tau_p \sim 10^{36}$ years
- Haba, Mimura & Yamada [1812.08521]: non-SUSY $\mathrm{SU}(5)$
- Ellis *et al.* [2003.03285]: SUSY (flipped) $\mathrm{SU}(5)$
- Mehmood, Rehman & Shafi [2010.01665]: SUSY flipped $\mathrm{SU}(5) \times \mathrm{U}(1)_R$
- Babu, Gogoladze & Un [2012.14411]: minimal SUSY $\mathrm{SU}(5)$, $\tau_{p \to \overline{\nu} K^+} \lesssim 10^{35}$ years
- Doršner, Džaferović-Mašić & Saad [2105.01678]: realistic mini. non-SUSY $\mathrm{SU}(5)$
- Evans & Yanagida [2109.12505]: minimal SUSY (CMSSM, $d = 5$) $\mathrm{SU}(5)$
- Haba & Yamada [2110.01198]: SUSY ($d = 5$) flipped $\mathrm{SU}(5)$
- Ellis *et al.* [2110.06833]: SUSY flipped $\mathrm{SU}(5)$, $\tau_p \gtrsim 10^{36}$ years

In the last five years: 2017–now

Proton decay in $\mathrm{SU}(5)$ GUTs

- Lee & Mohapatra [1611.05478]: non-SUSY $\mathrm{SU}(5) \times \mathrm{SU}(5)$, $\tau_{p \to e^+ \pi^0} \simeq 6.2 \cdot 10^{34}$ years
- Fornal & Grinstein [1706.08535]: $\mathrm{SU}(5)$, stable proton
- Rehman, Shafi & Zubair [1804.02493]: SUSY flipped $\mathrm{SU}(5)$, $\tau_p \sim 10^{36}$ years
- Haba, Mimura & Yamada [1812.08521]: non-SUSY $\mathrm{SU}(5)$
- Ellis *et al.* [2003.03285]: SUSY (flipped) $\mathrm{SU}(5)$
- Mehmood, Rehman & Shafi [2010.01665]: SUSY flipped $\mathrm{SU}(5) \times \mathrm{U}(1)_R$
- Babu, Gogoladze & Un [2012.14411]: minimal SUSY $\mathrm{SU}(5)$, $\tau_{p \to \overline{\nu} K^+} \lesssim 10^{35}$ years
- Doršner, Džaferović-Mašić & Saad [2105.01678]: realistic mini. non-SUSY $\mathrm{SU}(5)$
- Evans & Yanagida [2109.12505]: minimal SUSY (CMSSM, $d = 5$) $\mathrm{SU}(5)$
- Haba & Yamada [2110.01198]: SUSY ($d = 5$) flipped $\mathrm{SU}(5)$
- Ellis *et al.* [2110.06833]: SUSY flipped $\mathrm{SU}(5)$, $\tau_p \gtrsim 10^{36}$ years

SUSY flipped $\mathrm{SU}(5)$ seems to be popular!

In the last five years: 2017–now

Proton decay in $\mathrm{SO}(10)$ GUTs

- Babu, Bajc & Saad [1612.04329]: minimal non-SUSY $\mathrm{SO}(10) \to$ PS
- Mohapatra & Severson [1805.05776]: SUSY $\mathrm{SO}(10)$
- Babu, Fukuyama, Khan & Saad [1812.11695]: SUSY $\mathrm{SO}(10) \times \mathrm{U}(1)_{\mathrm{PQ}}$, $\tau_{p \to e^+ \pi^0} \simeq 9 \cdot 10^{34}$ years
- Haba, Mimura & Yamada [1904.11697]: SUSY $\mathrm{SO}(10)$
- Chakraborty, Parida & Sahoo [1906.05601]: minimal non-SUSY $\mathrm{SO}(10)$
- Hamada *et al.* [2001.05235]: non-SUSY $\mathrm{SO}(10) \to$ LR
- King, Pascoli, Turner & Zhou [2106.15634]: non-SUSY $\mathrm{SO}(10)$ with all possible intermediate scales

In the last five years: 2017–now

Proton decay in $\mathrm{SO}(10)$ GUTs

- Babu, Bajc & Saad [1612.04329]: minimal non-SUSY $\mathrm{SO}(10) \to$ PS
- Mohapatra & Severson [1805.05776]: SUSY $\mathrm{SO}(10)$
- Babu, Fukuyama, Khan & Saad [1812.11695]: SUSY $\mathrm{SO}(10) \times \mathrm{U}(1)_{\mathrm{PQ}}$, $\tau_{p \to e^+ \pi^0} \simeq 9 \cdot 10^{34}$ years
- Haba, Mimura & Yamada [1904.11697]: SUSY $\mathrm{SO}(10)$
- Chakraborty, Parida & Sahoo [1906.05601]: minimal non-SUSY $\mathrm{SO}(10)$
- Hamada *et al.* [2001.05235]: non-SUSY $\mathrm{SO}(10) \to$ LR
- King, Pascoli, Turner & Zhou [2106.15634]: non-SUSY $\mathrm{SO}(10)$ with all possible intermediate scales

Non-SUSY $\mathrm{SO}(10)$ seems to be popular!

JUNO (Jiangmen, China; under construction, data taking in 2023)

- 20 kton liquid scintillator detector
- Possibility to search for proton decay

Future experiments

JUNO (Jiangmen, China; under construction, data taking in 2023)

- 20 kton liquid scintillator detector
- Possibility to search for proton decay

Hyper-Kamiokande (Gifu, Japan; under construction, data taking in 2027)

- 188 kton water-Cherenkov detector ($\sim 8 \times$ SK)
- To search for proton decay is among the main objectives.

Future experiments

JUNO (Jiangmen, China; under construction, data taking in 2023)

- 20 kton liquid scintillator detector
- Possibility to search for proton decay

Hyper-Kamiokande (Gifu, Japan; under construction, data taking in 2027)

- 188 kton water-Cherenkov detector ($\sim 8 \times$ SK)
- To search for proton decay is among the main objectives.

DUNE (Illinois & South Dakota, USA)

- 68 kton liquid Argon detector
- Possibility to search for proton decay

Future experiments

JUNO (Jiangmen, China; under construction, data taking in 2023)

- 20 kton liquid scintillator detector
- Possibility to search for proton decay

Hyper-Kamiokande (Gifu, Japan; under construction, data taking in 2027)

- 188 kton water-Cherenkov detector ($\sim 8 \times$ SK)
- To search for proton decay is among the main objectives.

DUNE (Illinois & South Dakota, USA)

- 68 kton liquid Argon detector
- Possibility to search for proton decay

ESSnuSB (Sweden)

- 0.5 Mton water-Cherenkov detector ($\sim 20 \times$ SK)
- Excellent opportunity to search for proton decay

- There are <u>many</u> different available GUTs:

  minimal/non-minimal, SUSY/non-SUSY, $\mathrm{SU}(5)/\mathrm{SO}(10)/\ldots$

  I have not been able to review them all.
- Personally, I believe that GUTs without SUSY seem to be more viable than those with SUSY.
- Minimal non-SUSY $\mathrm{SO}(10)$ GUTs are allowed and seem prosperous.
- Any reasonable and testable model must be able to survive the present experimental limits on proton decay.
- Future experiments with huge detectors will increase the lower bound on proton lifetime, but may eventually also detect proton decay!

Thank you for your attention!

Thank you for your attention!

Posters on proton decay @ Neutrino 2022

- Morgan Askins, *Search for Invisible Modes of Nucleon Decay with the SNO+ Extended Water Data*
- Wan-Lei Guo, *Exploring neutrinos from proton decays catalyzed by GUT monopoles in the Sun*
- Yuhang Guo, *Simulation Study of Proton Decay in JUNO*
- Ryo Matsumoto, *Search for proton decay into muon and neutral Kaon in Super-Kamiokande*
- Vivek Sharma, *Search for Invisible Tri-nucleon decay in* ^{130}*Te with CUORE*