GUTS, Unification & Proton Decay

"Protons Are Not Forever"

Dimitri Nanopoulos 1978 Talk

William J. Marciano

October 29, 2015

NNN2015 Workshop

BROOKHAVEN NATIONAL LABORATORY

Maurice Goldhaber (1911-2011)
Proton Decay Pioneer & Champion
Reines, Cowan & Goldhaber (1954)…IMB, SK

the Bulletin

BROOKHAVEN
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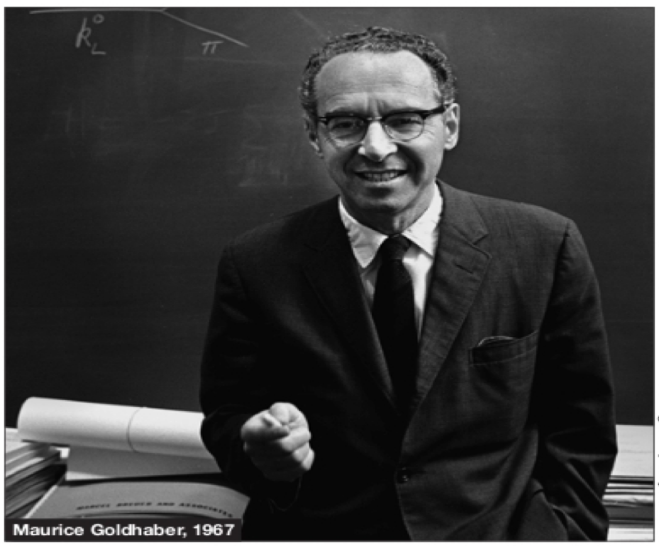
Former BNL Director Maurice Goldhaber Turns 100

On Monday, April 18, BNL will celebrate the 100th birthday of Distinguished Scientist Emeritus Maurice Goldhaber, a highly honored physicist and former BNL Director whose long and extremely productive career has won him many awards, including the Tom W. Bonner Prize in Nuclear Physics in 1971, the J. Robert Oppenheimer Memorial Prize in 1982, the National Medal of Science in 1983, the Wolf Prize in Physics in 1991, and the Enrico Fermi Award in 1999.

Born in Austria, Goldhaber earned his Ph.D. in physics at the University of Cambridge in 1936. Two years earlier, in 1934, with James Chadwick from the Cavendish Laboratory at Cambridge, he had been the first to measure accurately the mass of the subatomic particle known as the neutron, showing that it was not a compound of a proton and an electron as was believed at the time, but a new particle.



Maurice Goldhaber, 1967

Doug Humphrey 10-338-67

Goldhaber's research in the fields of nuclear physics and

ample: while on an experiment on proton decay, which would

Birthday Wishes to Maurice

From Sam Aronson, BNL
We'll celebrate a wonderful milestone n Monday, April 18 — the 100th birthday of former BNL Director Maurice Goldhaber, a Distinguished Scientist Emeritus whose outstanding contributions to science and to Brookhaven Lab have been honored throughout his career. He is also a valued friend of many, known for his sparkling wit and appreciated for his courtesy to all. Happy birthday, Maurice, from all of us.

From Nicholas Samios, BNL
Maurice Goldhaber is one of the great physicists of the twentieth century. His physics interests are global, from the neutron to the periodic table of nuclei, to the neutrino and all its complexity and then back to the stability of the proton. He is a human physics google. His essence can be encapsulated by his elegant proposition for measuring the helicity of the neutrino, accomplished with A.W. Sunyar and L. Grodzins. It required his encyclopedic knowledge of esoteric nuclei and complete command of the complex physics involved. Without Maurice it may not have been done even up to today. A most productive and imaginative physicist.

From Peter Bond, BNL
Maurice: I fondly recall our various interactions over the years which began with my visit to BNL in 1972 and your graciously taking me to dinner with Trudy, the Sunyars and the Sprouses at the Bellport Inn. While in the early years we didn't have many occasions to talk, I began to learn about what an extraordinary scientist you were. One of the greatest compliments I heard about your science was from Nobel Prize

Irvine-Michigan-Brookhaven (IMB) (1979-1989)

Einstein LoSecco

Smith Wuest Sinclair Learned Cortez

Bratton Sobel Van der Velde Goldhaber Reines Sulak

1974: A Great Year For Unification

1974 Classics

- ***Pati & Salam:***

  Lepton Number as the Fourth Color

  3846 Citations

- ***Georgi & Glashow:***

  Unity of All Elementary Particle Forces

  4013 Citations

- ***Georgi, Quinn & Weinberg:***

  Hierarchy of Interactions in Unified Gauge Theories

  1672 Citations

Natural Consequence – Proton Decay!

Grand Unified Theories: <u>SU(5),</u> SO(10), E_6…

$g^0_3 = g^0_2 = g^0_1 = g^0_{GUT}$ For $SU(3)_c x SU(2)_L x U(1)_Y$

$\sin^2\theta^0_W = 3/8$

<u>Quarks & Leptons</u>: 3 Mixed Families

10 + 5* + 1 of SU(5), 16 of SO(10), 27 of E_6…

Provide a natural extension of the Standard Model

<u>Explain</u>: Charge-Color Quantization, quark-lepton unification…

Easily include (suggest) supersymmetry

Superstring connection

<u>Part of the Particle Physics Vernacular</u>

GUT Symmetry Breaking

SU(5)➔SU(3)$_c$xSU(2)$_L$xU(1)$_Y$ by 24 Higgs plet

12 of 24 gauge boson **($X^{\pm 4/3}$,$Y^{\pm 1/3}$)$_i$** color triplet get

very large masses **M_X=M_Y=M_{GUT}**, violate B & L (converve B-L)

Mediate proton decay eg. **p➔$e^+\pi^0$, $e^+\rho^0$… n➔$e^+\pi^-$, $e^+\rho^-$…**

SU(3)$_c$xSU(2)$_L$xU(1)$_Y$ ➔SU(3)$_c$xU(1)$_{em}$ by 5 + 45 Higgs

Doublet components break EW symmetry

Color Triplets mediate proton decay: **p➔K^+v, $K^0\mu^+$, $\mu^+\pi^0$…**

(Enhanced p➔K^+v from dim. 5 SUSY operators)

In **SO(10) & E_6**, a second **($X'^{\pm 2/3}$,$Y'^{-/+1/3}$)$_i$** color gauge triplet

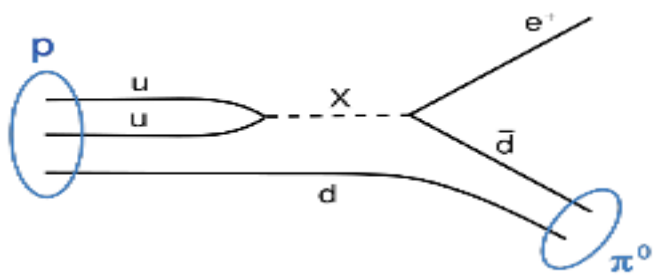
can also mediate proton decay (generally increases **p➔$e^+\pi^0$)**

All proton decay mediators must be very heavy ≥O(10^{16}GeV)

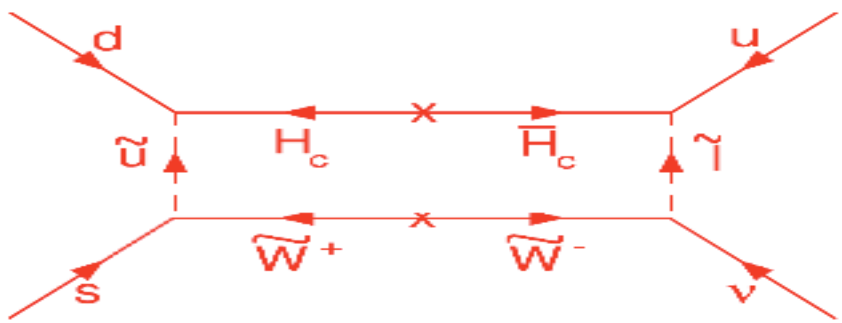
Baryon Number Violation Overview

from K.S. Babu (INT 2015)

$p \longrightarrow e^+\pi^0$



Supersymmetric nucleon decay mode



Sakai, Yanagida (1982)
Weinberg (1982)

$p \longrightarrow \bar{\nu} K^+$

Other exotic scalar multiplets: 10 + 15 + 50* of SU(5) (contained in 126 of SO(10))*

Can give rise to: ΔL=2 & ΔB=2 Interactions at much lower scales

ΔB=2 effects probed by proton decay exps (pn➔pions)

ΔB=2 Neutron-antineutron oscillations (Are neutrons majorana?)

Baryon analog of

ΔL=2 Majorana neutrino masses

Neutrinoless double beta decay **nn➔ppe$^+$e$^+$**

ΔB=ΔL=2 Double proton decay **pp➔e$^+$e$^+$ or μ$^+$μ$^+$**

(Also, ΔB=ΔL=1, pp➔pe$^+$ etc.)

Very interesting but wide range of predictions

.

Coupling Unification

Current Values: $\alpha_3(m_Z)=0.1185(6)$

$\alpha_2(m_Z)=0.0338(1)$

$\alpha_1(m_Z)=0.0170(1)$

Come together but do *not* quite unify without an intermediate mass scale(s): m_{susy}, m_R SO(10), m_{scalar}…

Predict $\sin^2\theta_W(m_Z)\approx 0.233$

Generic SUSY GUT ➔ $\mathbf{M_X \approx (1TeV/m_{susy})^{2/15} x 10^{16} GeV}$

(G. Senjanovic & WJM 1982)

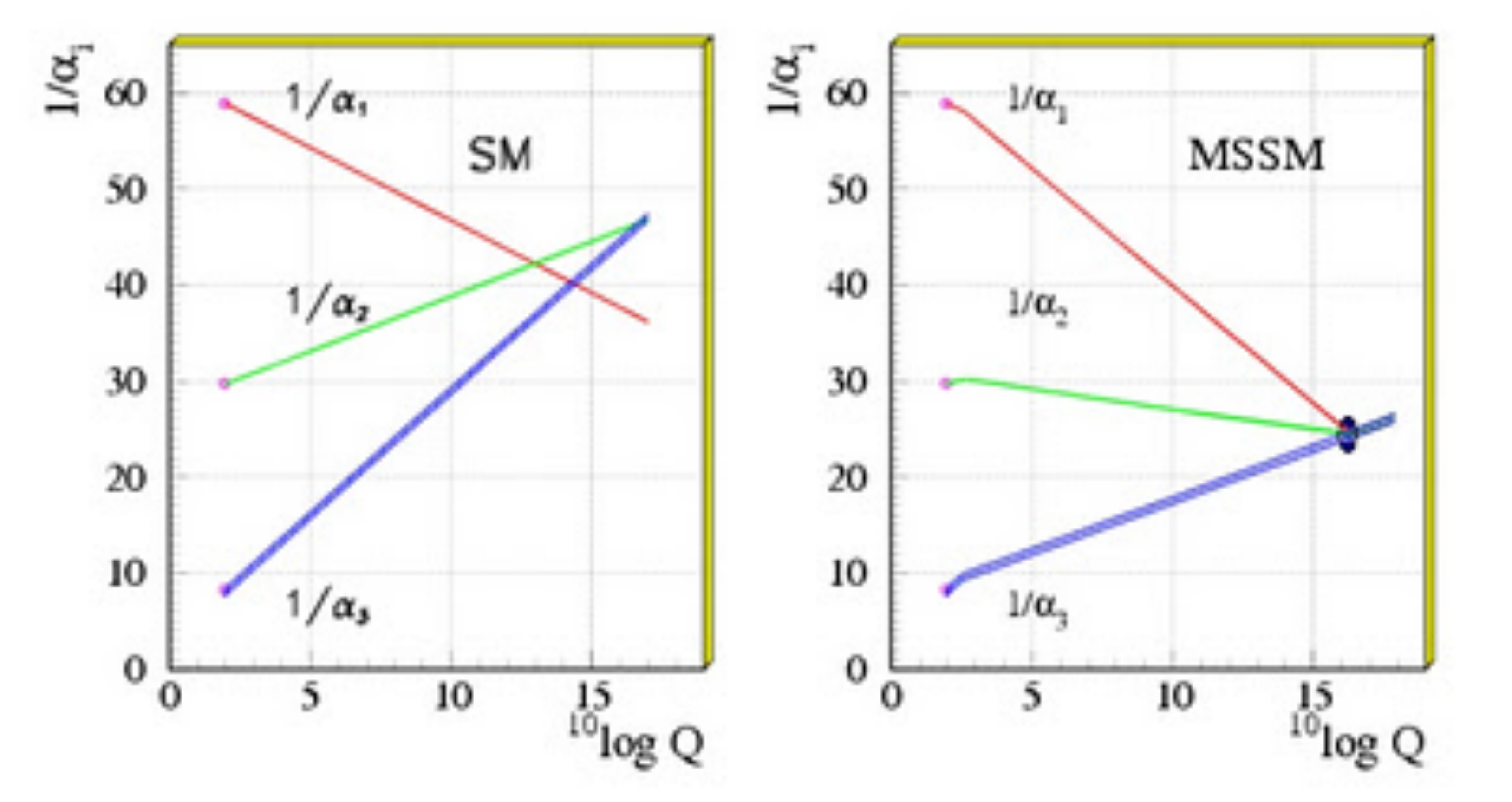
Proton Partial Lifetime:

$\boldsymbol{\tau(p \rightarrow e^+\pi^0)} \approx (1TeV/m_{susy})^{8/15} x 10^{35\pm1} yr$

Uncertainties: Matrix Elements (Lattice), $\alpha_3(m_Z)$, mass splittings…

SUSY GUT Unification

S. Raby PDG



LHC/ Proton Decay Complementarity

Current experimental "hint" of SUSY?

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 276(63)(49) \times 10^{-11}$ (3.5σ)

suggests *$m_{susy} \approx 100\text{-}500$GeV*

some tension with LHC $m_{susy} \geq 1$ TeV (squarks & gluinos)

SUSY GUTS "prefer" heavier $m_{susy} \approx 3\text{-}10$TeV

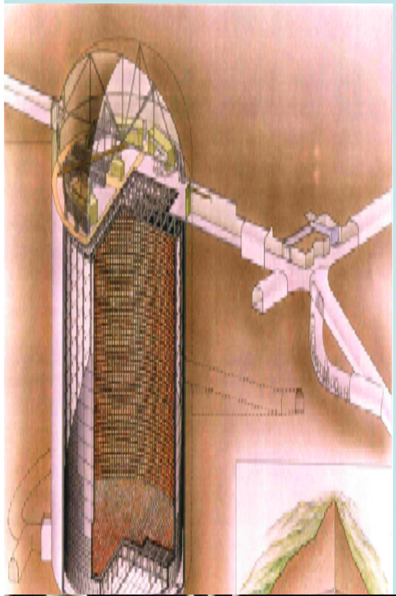
Heavier m_{susy} → shorter $\tau(p \to e^+\pi^0) \approx (1\text{TeV}/m_{susy})^{8/15} \times 10^{35\pm1}$yr

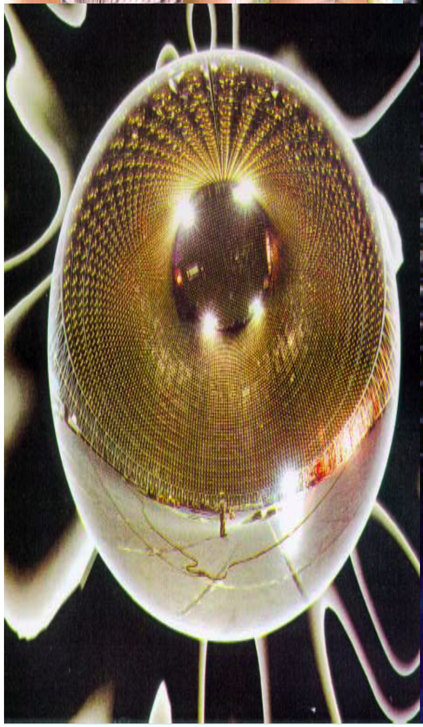
Heavier m_{susy} makes $p \to e^+\pi^0$ easier to observe!

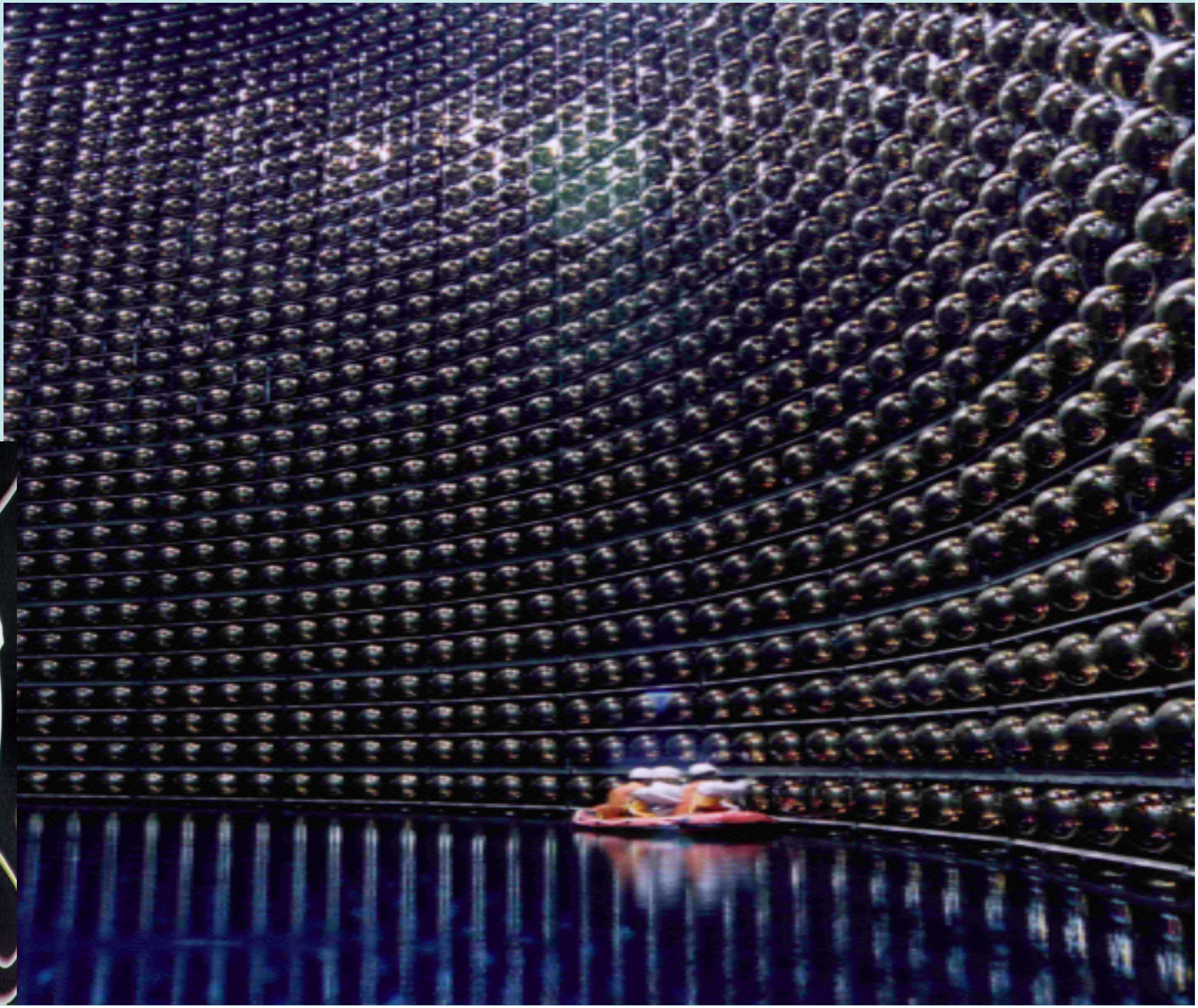
but it makes direct SUSY at the LHC less likely

Together They Squeeze SUSY

SUPER KAMIOKANDE







SuperK 2012 Partial Lifetime Bounds

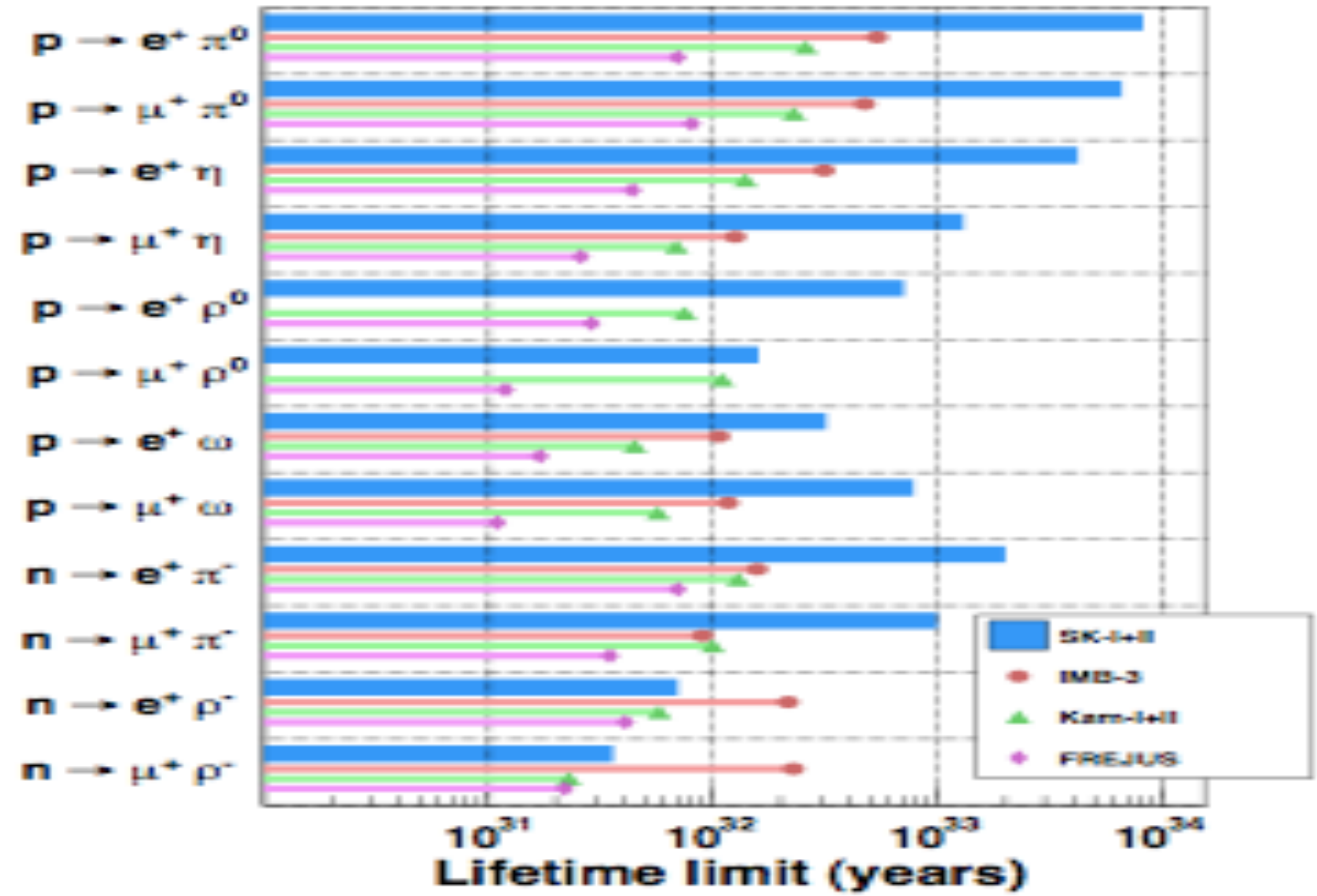


FIG. 18. Explored ranges and lower limits (at 90% confidence level) of nucleon partial lifetime with the results of the previous experiments; IMB-3 [4], KAMIOKANDE-I+II [5] and FREJUS [43].

Some Current SuperK Bounds

SuperK 22.5Kton Fiducial Vol. H_2O Cerenkov

Bounds on ***many*** p & n decay modes (2012PRD)

$\tau(p \rightarrow e^+\pi^0) > 8\times10^{33}$yr (${m_X} > 5\times10^{15}$GeV)

$\tau(n \rightarrow e^+\pi^-) > 2\times10^{33}$yr

$\tau(p \rightarrow K^+\nu) > 5.9\times10^{33}$yr (2014 update!)

Reaching asymptotic capabilities **$\tau(p \rightarrow e^+\pi^0) \sim 2\times10^{34}$yr**

$\tau(p \rightarrow K^+\nu) \sim 9\times10^{33}$yr

goals for future detectors (HyperK at 10yrs.)

$\tau(p \rightarrow e^+\pi^0) > 1.3\times10^{35}$yr ($m_X \geq 10^{16}$GeV)

$\tau(p \rightarrow K^+\nu) > 2.5\times10^{34}$yr!!

Also probe neutron-antineutron osc. ($\tau_{nnbar} > 10^9$sec)

Double proton decay $pp \rightarrow e^+e^+$, nn→pions…

Dark Matter Catalysis of proton decay $p+d \rightarrow e^+$+anti d

Future proton decay detectors

Given the SuperK bounds, the next generation water cerenkov detector should be at least 10x larger, i.e. ≥200Kton (Fiducial)

A future LArgon detector should have **$\tau(p \rightarrow K^+ \nu) > 3 \times 10^{34}$yr** sensitivity, i.e. fiducial mass ≥40Kton

Those requirements are well matched to future neutrino Oscillation experiments designed to measure CP violation (differences between neutrinos and antineutrinos)

Japan HyperK: 25xSK H_2O, > Megawatt p, (off axis ν's), 10yrs
USA DUNE: 40 Kton LAr, 1-2 Megawatt p, (WBB ν's), 10yrs

LArgon vs Water Detector Capabilities

LArgon represents superior detector capabilities

Water Cerenkov: Mature, Cheap, Proven Technology

LArgon Advantages/Kton

DUNE ν (on-axis): 6 to 1 (larger acceptance)

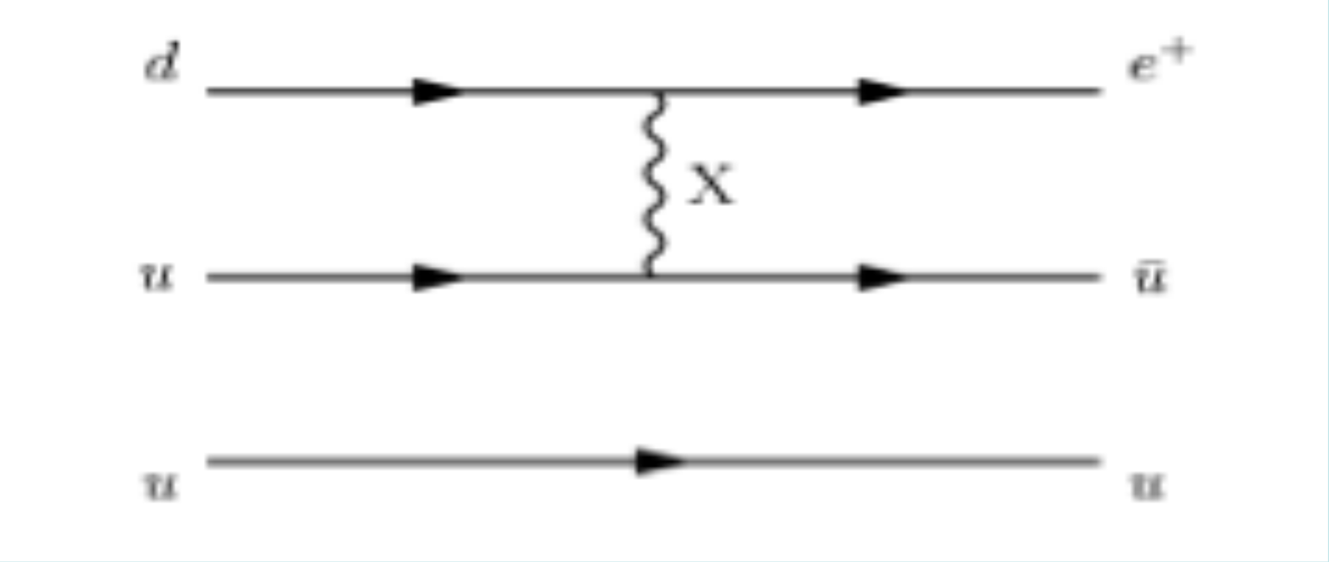
40Kton LAr ~ 240Kton H_2O

Super Nova ν LArgon (more interesting cross-sections)

Proton Decay $p \rightarrow K^+\nu$ Acceptance/Backgrounds

What about $p \rightarrow e^+\pi^0$? (m_{GUT} determination-unification)

($X^{\pm 4/3}$, $Y^{\pm 1/3}$) Mediated Proton Decay



$p \rightarrow e^+\pi^0$, $e^+\omega$ or $\rho^0 \ldots \pi^+\nu$..

Similarly, $n \rightarrow e^+\pi^-$ (via $Y^{\pm 1/3}$)

Isospin: $\Gamma(n \rightarrow e^+\pi^-) = 2\Gamma(p \rightarrow e^+\pi^0)$

$\Gamma(p \rightarrow \pi^+\nu) = 2\Gamma(n \rightarrow \pi^0\nu)$

SU(5) Expectations

proton lifetime ≈ bound neutron lifetime (±10-20%)

Br(**p→e$^+\pi^0$) ≈ 0.35**

Br(**p→e$^+\omega$ or ρ^0) ≈ 0.35 (multi-pion final states)**

Br(**p→$\pi^+\nu$) ≈ 0.15**

Br(**p→**ρ^+**ν, e$^+\eta$, μ^+K^0…) ≈ 0.15**

Br(**n→e$^+\pi^-$) ≈ 0.70 (factor of 2 larger than p→e$^+\pi^0$)**

Br(**n→$\pi^0\nu$) ≈ 0.07**

.

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Water Cherenkov ≈ 45% p→e$^+\pi^0$ acceptance

≈ 19% n→e$^+\pi^-$ acceptance

The "Perfect" Proton Decay Detector

Compare with SuperK $p \rightarrow e^+\pi^0$ Performance

- 100% p & n decays Acceptance (No Backgrounds)

$2_{p+n} x 2_{Accept} x 3_{all\ modes.}$ = 12 x SuperK! ($p \rightarrow e^+\pi^0$)

No Perfect Detector

LArgon is about as good as it gets

Realistic Assessment: ~3-4 (better?) Advantage/Kton

(Comparison Depends on H_2O Backgrounds)

Super-K Approaching v back.

LArgon Efficiencies

LArgon$\approx$ 45% p$\rightarrow$e$^+\pi^0$ acceptance

$\approx$ 45% n$\rightarrow$e$^+\pi^-$ acceptance

Earth's Atm. Ar(18p,22n) Radiogenic

$\Gamma(n\rightarrow e^+\pi^-)=2\Gamma(p\rightarrow e^+\pi^0)$

Should be considered together: BR(Ar$\rightarrow$e$^+\pi^0/\pi^-$ +N')

(Includes pion charge exchange in the nucleus)

Roughly 3-4xBR(p$\rightarrow$e$^+\pi^0$) in LAr

Can one do even better?

Neutrino Backgrounds Less Important in LAr?

How to compare H_2O & LArgon p➔$e^+\pi^0$ Capabilities

SuperK starting to hit neutrino backgrounds ➔$(MT)^{1/2}$ sensitivity

Compare ***p➔$e^+\pi^0$ 500Kton H_2O running for <u>30 years</u>***

With p➔$e^+\pi^0$ + n➔$e^+\pi^-$ in 40 Kton LArgon running for <u>30 years</u>

(Naively enhanced by factor of (3-4)

With neutrino background included:

Water reaches **$\tau(p \to e^+\pi^0) > 1\text{-}2\times10^{35}$yr factor of 10 better than current**

LArgon reaches **$\tau(p \to e^+\pi^0) > 0.4\times10^{35}$yr combine with *n➔$e^+\pi^-$ effectively***

$>1.2\times10^{35}$yr (do even better?)

<u>Very Roughly-Equal/Complementary Capabilities</u>

Neutrino Background & p/n decays in LArgon – Need Study

Analyze decays together

Acceptance Cuts

Conclusion

The search for proton decay remains very well motivated by GUTS. Unique direct window to ***10^{16}GeV***. A $p \rightarrow e^+\pi^0$ discovery would have revolutionary implications.

Next generation of underground detectors candidates

HyperK (25x**SuperK**) & DUNE (40Kton LAr)

H_2O & LAr Competitive & Complementary Potential

Primary Exp. Goal: CP violation in neutrino oscillations

Proton Decay has Similar Detector Requirements (Fortuitous)

Dark Matter, neutron-antineutron, double nucleon decay…

Start as soon as possible

He who hesitates is lost!

Remember Super Nova Neutrinos are Coming!