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lecture cource on

Astroparticle physics

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8 Proton decay

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General

- General conservation laws – valid in all fields of physics – do not prevent proton of decaying
  - energy, electric charge and (linear and angular) momentum
- Free neutron is unstable: $n \longrightarrow p + e^- + \nu$ ($\tau_n \approx 12$ min)
- Electron is stable: it is the lightest charged particle
- An average human body consists of $\sim 10^{29}$ protons
  - proton decay is a high-energy phenomena $\Longrightarrow$ it would destroy thousands of molecules
  - if $\tau_p \ll 10^{30}$ years $\Longrightarrow$ people would die on cancer in the age of teen-age or young adults
- Proton decay would perhaps be the most significant results of the future large-volume next-generation detectors (LAGUNA, Hyper-K, UNO, ...)
  - unique test of GUTs

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Motivation – GUT – Grand Unified Theories

- Postulated at the first time 1974
- The Grand Unified Theories (GUTs) aim to unify electromagnetic, weak and strong interactions at high energies (or small distances)
  - 10^{15} GeV
  - experimental verification difficult $\Longleftarrow$ proton decay
- Predicts that proton is unstable
  - two quarks in a proton transform into a lepton and an antiquark
  - baryon and lepton number violation
- Simplest of the GUTs – minimal SU(5)
  - the dominant decay mode is $p \longrightarrow e^+ + \pi^0$ with $\tau_p \sim 10^{31}$ years, but this has already been ruled out by SK and others
- Supersymmetric GUTs (SUSY GUTs)
  - baryon and lepton number violation (but conserve $B - L$)
  - make lifetime longer and increase possible decay channels
  - for $p \longrightarrow e^+ + \pi^0$, $\tau_p \sim 5 \times 10^{35\pm1}$ years (WC)
  - for $p \longrightarrow K^+ + \nu$, the dominant SUSY-GUT decay channel $\tau_p \sim (0.3 - 3) \times 10^{34}$ years (LSCI)

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GUT – Grand Unified Theories

- In standard model, proton decay is not allowed
  - more a coincidence than a general principle
  - a bound neutron is stable against all decay modes
  - proton decay allowed in (mnay) standard model extensions
- In GUTs – if baryon number conservation is violated, neutron can also decay
  - the lifetime of a bound neutron would be comparable to the lifetime of a proton
  - they would have different decay modes
- Theoretical predictions have large deviations
  - no clear picture yet
  - large range of predicted τ_p and several possible decay channels
  - some models already ruled out be experiments
- The physics of proton decay could also be linked to the excess of matter over antimatter in the Universe
  - baryon number violation – baryogenesis

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Experiments – General

- water Cerenkov detector – H_2O
  liquid scintillation detector – $C_{16}H_{18}$ (PXE)
  - the free protons (two in H of water and 18 in H of PXE) and eight oxygen- and 6×16 carbon-protons are assumed to decay with equal probability
- For the case of a free proton in hydrogen, the momenta of the decay particles (e^+, π^0) or (μ^+, π^0) or $(K^+, \bar{\nu})$, or ... are uniquely determined by two-particle kinematics
- For the bound protons (in oxygen and carbon), the decay-particle momenta are no longer determined by simple two-particle kinematics. (Small) corrections from
  - the Fermi motion of the protons (Fermi momentum, ∼250 MeV/c for p in ^{12}C)
  - the nuclear binding energy ($m_p^* = m_p - E_\mathrm{b}$)
  - the meson–nuclear interaction (in O and C)

  should be considered

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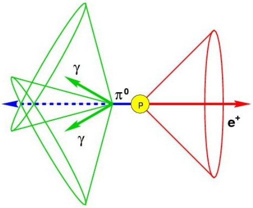
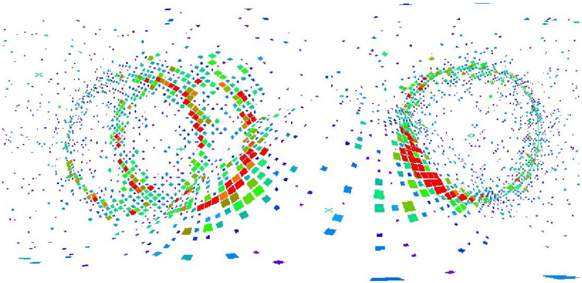
Experiments – proton decay in water Cerenkov – channel: $p \longrightarrow e^+ + \pi^0$





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The IMB experiment (Irvine–Michigan–Brookhaven) – 1

- C. McGrew *et al.*, PRD**59** (1999) 052004
  "Search for nucleon decay using the IMB-3 detector"
- University of California (Irvine), University of Michigan, Brookhaven National Laboratory
  - the IMB-1 detector detected neutrinos from SN1987A and was the first experiment dedicated to the proton decay
- The IMB-3 detector situated
  - at the Fairport salt mine, Ohio, operated by Morton International
  - at depth 1900 feet (∼600 m) (⟶muon rate: $R_\mu \approx 3$ Hz)
- Tank
  - dimensions: 17 m × 17.5 m × 23 m (∼cubic)
  - filled with ultrapure H_2O of 2.5×10^6 gallons (≈10 milj. litres)
  - 2048 8-inch PMTs
- Fiducial mass (IMB-3): 3.3 kton

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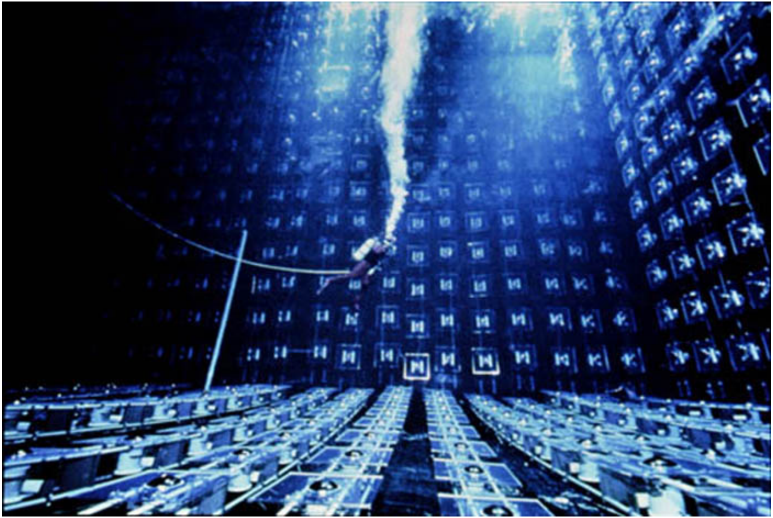
The IMB experiment (Irvine–Michigan–Brookhaven) – 2



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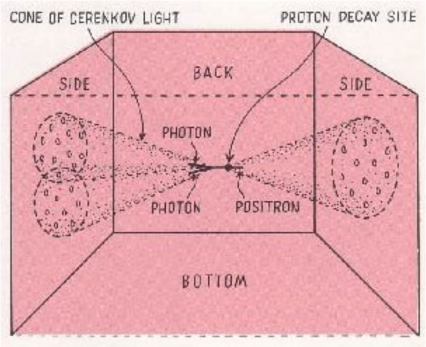
The IMB experiment (Irvine–Michigan–Brookhaven) – 3

- 851 days of exposure
  - 7.6 kton·year ($\sim 4.6 \times 10^{33}$ nucleon·yr)
  - 935 contained events observed
- Looked for 44 different modes of nucleon decay
  - 18 for neutron and 26 for proton decay
- Saw no evidence for nucleon decay
  - IMB-1 & IMB-3 : $p \longrightarrow \pi^0 + e^+ \; (\longrightarrow \gamma + \gamma + e^+)$: $\tau_p > 8.5 \times 10^{32}$ yr



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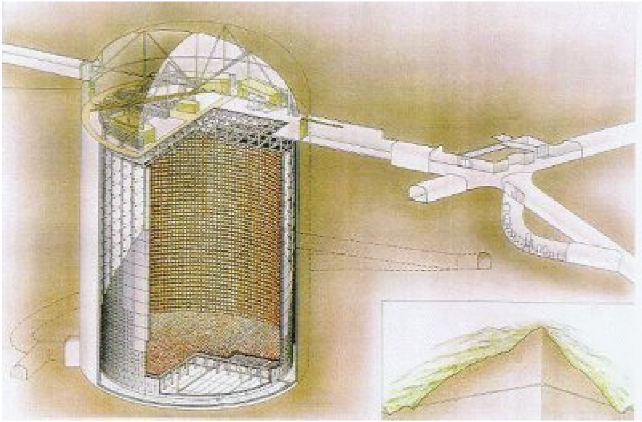
Proton decay in SK – 1

- Super-Kamiokande is a 50 kton water Cerenkov detector
  - at Kamioka Observatory, Japan
  - depth 1 km



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Proton decay in SK – 2

- H. Nishino *et al.*, PRL**102** (2009) 141801
  "Search for Proton Decay via $p \to e^+ + \pi^0$ and $p \to \mu^+ + \pi^0$ in a Large Water Cherenkov Detector"
- SK-I and SK-II
  - SK-I : April 2006 – September 2001 (11146 20-inch PMTs)
  - SK-II : October 2002 – October 2005 (5182 20-inch PMTs)
  - SK-III was completed in June 2006 (when all the PMTs were reinstalled)
- Data from 91.7 kton·yr (SK-I) and 49.2 kton·yr (SK-II)
  - 1489 and 798 live days, respectively
- Results: no proton decays were observed
  - $p \to e^+ + \pi^0 \implies \tau_p > 8.2 \times 10^{33}$ yr (prev $\tau_p > 1.6 \times 10^{33}$ yr, SK)
  - $p \to \mu^+ + \pi^0 \implies \tau_p > 6.6 \times 10^{33}$ yr (prev $\tau_p > 4.7 \times 10^{32}$ yr, IMB)
- SK-III – already three years of data collected
  - predicted by theory: $\tau_p \sim 5 \times 10^{35\pm1}$ years

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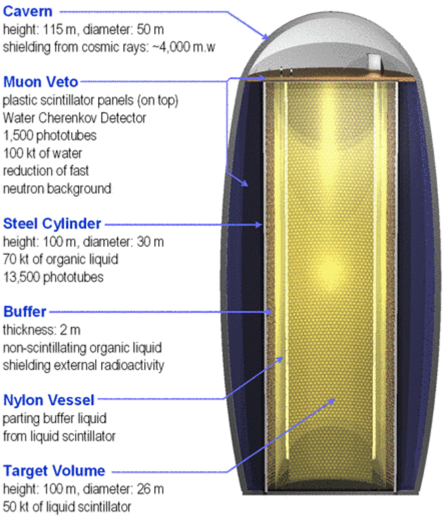
Next generation detectors – LENA – 1



vertical design is favourable in terms of rock pressure and buoyancy forces

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Next generation detectors – LENA – 2

- T. Marrodán Undagoitia *et al.*, Phys. Rev. D 72 (2005) 075014
  "Search for the proton decay $p \rightarrow K^+ + \bar{\nu}$ in the large liquid ..."
- In LENA, the proton decay would be observed via (SUSY-GUT favoured channel) $p \longrightarrow K^+ + \bar{\nu}$
  - $K^+ \longrightarrow \mu^+ + \bar{\nu}_\mu$ (63 %), $\tau_K = 12.8$ ns
    $\longrightarrow \pi^0 + \pi^+$ (21 %)
  - clear double-peak structure from kaon and its decay
    $\sim$257 MeV (K+μ) and $\sim$459 MeV (K+π)
  - time and position correlations, PSA
- The current limit for τ_p from SK: $\tau_p = 2.3 \times 10^{33}$ yr (not newest)
  - LENA would see 40 proton-decay events in 10 years
    with 1 background event
- If no event is seen in 10 years (500 kton·yr) ☞ $\tau_p > 4 \times 10^{34}$ yr
  - already above the predicted range of $\tau_p \sim (0.3 - 3) \times 10^{34}$ years
- The main background source is atmospheric neutrinos (ν_μ)
  - can be rejected by $\sim$70% by rise-time cut (PSA)