Proton Decay and Neutrino Oscillations

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The ICARUS R&D Programme

- Bubble chambers have played a fundamental role in particle physics
  - non-biased images, three diemnsions, high resolution
- Because of the high density of the liquid medium, bubble chambers can combine target and detector functions (ideal in search for rare events contained in sensitive volume)
- However, bubble chambers are triggered blindly, are slow and data analysis are fastidious. Hence, they were replaced by electronic detectors, for which, because of the low density of the gaseous medium used, detector and target functions had to be separated
- The ideal detector for rare events search, such as proton decays or neutrino interactions, could be a high resolution liquid detector equipped with an electronic readout (an electronic bubble chamber)
- The ICARUS R&D programme has shown that it is possible to build an ionization chamber (TPC), using a very large liquid argon volume which is
  - continuously sensitive
  - self-triggering
  - able to provide three-dimentional images of ionizing events
  - able to identify particles (dE/dX vs range) and their direction

- Such a detector is also an excellent calorimeter with high granularity and resolution

LAr doping with TMG

- No degradation of the electron lifetime
- drift velocity, space resolution unchanged
- Linearization of the charge yield
- Increase of the free charge also for m.i.p.
- Linearization of the charge yield
  (from muons and protons stopping)
- Energy resolution

  S/N improved by the full conversion of the deexcitation UV photons to electrons

- Particle recognition

  dE/dx vs range measurement improved by linearization of dQ/dx

ICARUS at the Gran Sasso Laboratory

The ICARUS Physics Programme

- proton decay
- atmospheric neutrinos
- long baseline neutrinos (with a neutrino beam from CERN or Serpukhov)
- solar neutrinos

- supernova or any unexpected source of neutrinos

Proton decay and other rare deacys

- There are two ways to probe the structure of matter at very short range
  - The direct way, by increasing the energy (LHC)
  - The indirect way, looking for very rare events which involve transitions through very high potential barriers;

    The study of proton decay the only experimental access to Gran Unification. New large underground detectors in preparation (Superkamiokande, ICARUS) will extend the search to lifetimes of 10^{34} years.

    The study of double β-decay very rare process, could yield surprises with neutrinos.
- Proton decay is a priority field
  - Unification of the electro-weak and the strong coupling constants within SUSY with particle spectrum with masses og the order 10^2 to 10^3 GeV.
  - In SUSY GUT proton decay is controlled by both GUT physics and Plank scale physics.

"either LEP200 will observe a chargino or ICARUS will observe proton decay in the $p \rightarrow \bar{\nu} K^+$ channel, assuming a sensitivy up to 10^{34} years".

UNIFICATION OF FORCES?

SUSY 2nd order

Neutrinos

- The most exciting sector of the lepton world is perhaps that of the neutrinos! We now know from LEP that there are only three types of neutrinos, associated to e, μ and τ.

- Do they have a mass?
  - $m_{\nu_e} < 7.2$ eV (Double β-decay)
  - $m_{\nu_\mu} < 270$ KeV
  - $m_{\nu_\tau} < 31$ MeV
- If yes, can they mix as in the quarks sectors?
- Do they constitute the bulk of dark matter? COBE result suggest $m_{\nu_x} \sim 7$ eV
- The example of SO(10) minimal SUSY GUT the recent LEP precision data are consistent with Unification scale $M_X = n1.6 \times 10^{16\pm0.4}$GeV and SUSY symmetry breaking scale ≤ 1 TeV
  If $M_N = M_X$

  $m_{\nu_e} = (0.05)\frac{m_u^2}{M_N} < 2 \times 10^{-11}$ eV

  $m_{\nu_\mu} = (0.09)\frac{m_c^2}{M_N} = 6 \times 10^{-9} \div 4 \times 10^{-6}$ eV

  $m_{\nu_\tau} = (0.38)\frac{m_t^2}{M_N} = 0.00011 \div 0.87$ eV

  The uncertainties are due mainly to the errors on M_N and m_{top}. In this scenario the masses are too small to play an important cosmological role, such as providing the matter needed to close our Universe.
- The non-Supersymmetric SO(10) GUT there are two levels of symmetry breaking
  - (1) at the GUT scale $M_X = 9.6 \times 10^{10\pm0.4}$GeV down to a Left-Right symmetric model
  - (2) at an intermediate energy scale $M_R = 1.5 \times 10^{10\pm0.3}$ GeV down to the Standard Model. $M_N = (0.01 \div 1)M_R = (7.5 \times 10^7 \div 3 \times 10^{10}$GeV.

$$m_{\nu_e} = (0.05)\frac{m_u^2}{M_N} < 2 \times 10^{-5} \text{ eV}$$

$$m_{\nu_\mu} = (0.07)\frac{m_c^2}{M_N} = 5 \times 10^{-3} \div 2.2 \text{ eV}$$

$$m_{\nu_\tau} = (0.18)\frac{m_t^2}{M_N} = 60 \div 10^5 \text{ eV}$$

Note that the cosmological upper limit for $m_{\nu_\tau} is \sim$ 40 eV! In this type of model the τ neutrino may be cosmologically important. Smaller neutrino masses can be obtained if the intermediate scale is increased.

- The feature to retain is a definite mass hierarchy $m_{\nu_e} m_{\nu_\mu} m_{\nu_\tau} = m_u^2 m_c^2 m_t^2$

Mixing of Neutrino Species

- Although there is no compelling reason why neutrino families should mix like quarks do, it is very likely that if neutrinos have mass, ‘some’ mixing occurs also in the neutrino sector. The weak eigenstates, ν_e and ν_μ, are linear combinations of the mass eigenstates ν_1 and ν_2

  $$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} cos(\theta) & sin(\theta) \\ -sin(\theta) & cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- There is also no known reason why neutrino mixing parameters should emulate the quark Cabibbo-Kobayashi-Maskawa matrix, but if they do

  $sin^2 2\theta_{e\mu} = 0.19; \quad sin^2 2\theta_{\mu\tau} = 0.004 \div 0.012; \quad sin^2 2\theta_{e\tau} = 1.6 \times 10^{-5} \div 2 \times 10^{-4}$

  J. Ellis, J.L.Lopes & D.V.Nanopoulos (CERN-TH 6569/92) have shown a possible example of such a scenario in the context of flipped SU(5).

- The actual angles are probably going to be quite a bit smaller than those for quarks! However, if the texture of the neutrino mixing matrix follows the one for quarks, then on rather general grounds one expects a natural hierarchy between mixing angles

  $$\theta_{\mu\tau} \sim \theta_{e\mu}^2 \quad \textbf{and} \quad \theta_{e\tau} \sim \theta_{e\mu}^3 \Rightarrow \theta_{e\tau} << \theta_{\mu\tau} << \theta_{e\mu}$$

- Conclusion for the elementary particle physics point of view masses and angles are likely to be very small but to have a definite hierarchy between them. This is probably a very valuable hint

  $$m_{\nu_e} m_{\nu_\mu} m_{\nu_\tau} = m_u^2 m_c^2 m_t^2$$

Neutrino Masses and Cosmology

- Our confidence in nucleosynthesis has gained credibility now that its indication of 3 or 4 neutrino families has been vindicated by the LEP result $N_\nu = 3.04 \pm 0,04$. However, the amount of baryonic matter inferred by nucleosynthesis is by far too low to close the Universe.

- Many cosmologists believe that $\Omega = 1$ to high accuracy s required by the inflation hypothesis ($\Omega \equiv \bar{\rho}/\rho_c; \quad \rho_c = 3H_0^2/8\pi G = 1.879 \times 10_{-29} h^2 g/cm^3; \quad H_0 = h \times 100 kms_{-1}/Mpc; \quad 0.4 < h, 1$).

- If $\Omega = 1$ and $\Omega_{visible} < 0.01$, a large amount of additional "dark" matter must exist.

- The COBE observations on the large-scale structure of the early Universe combined with observations at smaller scale, suggest that both 'hot' (HDM) and 'cold' (CDM) components must be present with a possible sharing $\Omega_{HDM} \sim 0.3$ and $\Omega_{CMD} \sim 0.7$. Among the HDM candidates, neutrinos seem to be the most credible option, while for CDM several possibilities exist including SUSY photinos, exotic massive partilces, baryonic matte (MACHO), etc.

- Therefore a very plausible cosmological hypothesis is that neutrinos constitute a major fraction of matter. Because of the mass hierarchy, one neutrino species dominates entirely and the closure condition for the Universe is simply $m_{\nu_\tau} = 91.5 \Omega_\nu h^2$ (eV) which sets a definite window for m_{ν_τ}, the heaviest of the types of neutrinos 3 eV $\leq m_{\nu_\tau} \leq$ 40 eV.

- Experimental challenge How can we experimentally determine such a neutrino mass?

STATUS OF EXPERIMENTAL NEUTRINO DATA

- It is intriguing that a cosmological constraint (COBI) for closing the universe gives
$$m_{\nu_\tau} \approx 91.5 \Omega_\nu h^2 (eV) \approx 7 \div 28 eV$$

- If the texture of the CKM-neutrino matrix follows the one for quarks (not obvious it should)

$$\theta_{\mu\tau} \approx \theta_{e\mu}^2 \qquad \textbf{and} \qquad \theta_{e\mu} \approx \theta_{e\mu}^3 \Rightarrow sin^2(2\theta_{\mu\tau}) \approx 10^{-4}$$

$$\Delta m^2 \approx m_{\nu_{mu}} \approx 10^{-5} eV^2 \Rightarrow m_{\nu_\tau} \approx m_{\nu_\mu} \times \{\frac{m_t}{m_C}\}^2 \approx 30eV$$

- In general in many GUT's quadratic (linear) see-saw mechanisms generate masses

$$m_\nu \propto \frac{m_{u,c,t}^2}{m_{GUT}} \quad \Rightarrow \quad m_{\nu_e} m_{\nu_\mu} m_{nu_\tau} = m_u^2 m_c^2 m_t^2$$

- Hint from the data that neutrinos may have a mass and may mix as quarks do.

Atmospheric Neutrino Studies

- 1200 events per year per 5 kt module in 4π steradians.
- Matter effects and discrimination between neutrinos and antineutrinos included
  - In neutrino interactions, recoiling proton is associated to the μ^- or e^- lepton in final state.
  - In antineutrino interactions, single lepton with some nuclear activity from neutron interactions.
  - Also, different capture-to-deacy ratio for μ^+ and μ^- in argon.

FUTURE ATMOSPHERIC NEUTRINO EXPERIMENTS EVENT RATES (PER YEAR) COMPARED TO PRESENT KAMIOKANDE

$\nu + \bar{\nu}$	KAMIOKANDE I & II (contained events)	SUPERKAMIOKANDE (scaled from KAM I, II)	ICARUS 4π srad (C.C. o assuming no oscillation no acceptance correctio
ELECTRON - LIKE (single track)	159	700 (0.1-1.33 GeV/c)	360 (0.06 → few GeV)
μ - LIKE (single track)	151	680 (0.2-1.5 GeV/c)	500 (0.130 → few GeV)
MULTI-TRACK EVENTS	146	660	380
TOTAL	456	2,000	1,240

Neutrino Beams for Long Baseline Neutrino Oscillations

- Neutrino Beam from CERN
    - 450 GeV, 3×10^{13} protons per SPS cycle, cycle time 6.9 seconds, 4×10^{19} protons per year. $(\nu_\mu \rightarrow \nu_\tau)$
    - 120 GeV, the cycle time is only 3.6 seconds, 8.3×10^{19} protons per year. $(\nu_\mu \rightarrow \nu_e)$
- Possibility a neutrino beam from UNK, 2200 km away from the Gran Sasso Laboratory (600 GeV protons).

Solar neutrinos

- Reactions used for the direct observation of solar neutrinos from the ^8B
    - $\nu_X + e^- \rightarrow \nu_X + e^-$ for which 2,700 events/year/module are predicted in the electron elastic channel assuming the SSM rate and an efficiency of 65% for $E_e > 5$ MeV.
    - $\nu_e +^{40} Ar \rightarrow^{40} K + e^-$, a superallowed Fermi transition to the isobaric analog 4.38 MeV level, followed by $9^{40}K + 1$ or $2\gamma\,[2MeV]$) for which the SSM predicts about 3,000 events/year/module (Fermi transition only) for a detection efficiency of 80% and $E_e > 5$ MeV. Gamow-Teller transitions to a 2.29 MeV level could add 5000 events/year/module.
- The distinctive properties of the recoil electron energy spectrum together with the detection of photons associated with the ^{40}K decay allow one to measure the ratio R of elastic electron scattering to absorption cross-sections. This ratio provides a direct measurement of the fraction of ν_e's which converted to ν_μ's or ν_τ's through oscillations.
- With two years of data and $E_e > 5$ MeV, ICARUS could detect a neutrino oscillation probability of 20% or larger (R¿1.15; 90% C.L.).

Conclusion

- The new detector technology developed by the ICARUS Collaboration (electronic bubble chamber) opens an important new physics programme
    - Study of matter stability
    - Neutrino studies atmospheric neutrinos, long baseline neutrinos from CERN or Serpukhov, solar neutrinos
    - Astrophysical and cosmological studies
- This programme should lead to a test of GUTs and perhaps also Supersymmetry. Fundamental progress should be achieved in our knowledge of neutrino properties
- The ICARUS expriment will benefit from a favourable time window between LEP and LHC programmes.