IC/81/135

INTERNATIONAL CENTRE FOR
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INTERNATIONAL
ATOMIC ENERGY
AGENCY

UNITED NATIONS
EDUCATIONAL,
SCIENTIFIC
AND CULTURAL
ORGANIZATION

1981 MIRAMARE-TRIESTE

IC/81/135

International Atomic Energy Agency
and
United Nations Educational Scientific and Cultural Organization
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

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MIRAMARE - TRIESTE
August 1981

* Introductory remarks, Proton Decay Session, EPS Conference on High Energy Physics, Lisbon, 14th July, 1981. To be published in the Proceedings.

This session was planned when the organisers heard of the progress of the Indo-Japanese experiment on proton's possible instability. The session will include a report on this and also on other experiments, presently being readied for observations during this year.

It is particularly gratifying to me that Professor Sreekantan, Director of the Tata Institute, Bombay will speak on the Kolar Gold Field Experiment. In November 1973, Professor M.G.K. Menon – then Director of the Tata Institute – and I were attending a United Nations meeting in Geneva. In the summer[1] Pati and I had extended an earlier suggestion[2] of placing quarks and leptons in the same multiplet of a unifying symmetry $SU_C(4)$ to a *gauging* of this symmetry. This gave as gauge-particles lepto-quarks, which couple to (B-L). Since no massless gauge mesons carrying such a quantum number were known, we had been forced to break the symmetry spontaneously ($\Delta(B-L) \neq 0$) in order to give masses to lepto-quarks. This meant that the price of gauging quark-lepton symmetry was proton-decay.

Since proton stability is a notion for which our experimental colleagues like Goldhaber and Reines had been principally responsible, we were naturally very keen to interest experimental groups to test this stability more stringently. One of the first converts (in November 1973) was Menon, who persuaded the Indo-Japanese group to build a dedicated experiment at Kolar Gold Fields. It is good therefore that this group is reporting the first few candidate-events for proton decay, as Professor Sreekantan will tell us.

With a true theoretician's extrapolation I shall proceed by assuming that proton decay does occur; my main purpose in these remarks is to re-emphasise that, potentially, proton decay offers one of the most important, and for some purposes, an absolutely unique window on high energy physics. Thus I wish to emphasise the long-term aspects of this experiment, in particular its potential:

(1) For Investigation of High Mass Scales, inaccessible elsewhere in Physics.

(2) For Distinguishing between Preonic versus Grand Unifying Models of quarks and leptons.

(3) And finally, for discovering which Grand Unifying Symmetry (if any) may be operative: is it for example Georgi-Glashow $SU(5)$ or $SO(10)$ or the maximal $SU(16)$, which gauges all possible quantum numbers, that can be associated with the sixteen members $(q, \ell, \bar{q}, \bar{\ell})_L$ of each family.

Mass Scales in Proton Decay

It can be shown that proton decays may be classified into four categories, with the following associated mass scales:

Decay Mode	Mass Scale Involved and its Accessibility[3]
(1) $P \to 3\bar{\ell}$ ($\Delta B = \frac{\Delta L}{3}$) (example, $P \to e^+ + \bar{\nu} + \bar{\nu} + \pi^0$) (2) $P \to 3\ell$ ($\Delta B = -\frac{\Delta L}{3}$) (example, $N \to e^- + \nu + \nu + \pi^+$)	$10^4 - 10^5$ GEV This mass-scale is also explored in:- (a) $N - \bar{N}$ oscillation experiments presently being mounted; (b) Highest-energy Cosmic Rays (200 events/year at 10^5 GEV 3000 events/year at 10^4 GEV); (c) 10^4 GEV may become available with a super-conducting P-P or P-$\bar{P}$ collider which may be installed in the 27KM tunnel to be built for LEP in Geneva. But this may not happen until 2000 A.D. (d) For reference, note that $\mu \to e + \gamma$ at present levels of accuracy probes down to 10^5 GEV.

(3) $P \rightarrow \bar{\ell}$ $\Delta B = -\Delta L$ (example $N \rightarrow e^- + \pi^+$)	$10^8 - 10^{10}$ GEV Even with a laser accelerator of a future design such energies will need an accelerator at least 5000 KM long.
(4) $P \rightarrow \bar{\ell}$ $\Delta B = \Delta L$ (example $P \rightarrow e^+ + \pi^0$)	$10^{14} - 10^{15}$ GEV Accessible only in early cosmology when the Universe was 10^{-37} secs. from the big bang.

Clearly proton decay experiments provide a unique window on high mass scales*. Where do these mass scales come from? These were first encountered in the context of Grand Unifying theories:

Decay Mode	Mass Scale	Electro-nuclear (Grand) Unifying Models
$\Delta B = \Delta L$	$10^{14} - 10^{15}$ GEV	As emphasised by Weinberg and Pati (VPI Conference 1980), this follows from grand unifying models G which involve just one mass descent from $G \rightarrow SU(3) \times SU(2) \times U(1)$. This includes[4] SU(5), SO(10) and SU(16); the predicted $\tau_p \approx 10^{31 \pm 1.5}$ years.
$\Delta B = -\Delta L$ $\Delta B = \pm \frac{1}{3}\Delta L$	$10^8 - 10^{10}$ GEV $10^4 - 10^5$ GEV	A number of electro-nuclear models motivate these decays either through gauge (V) or scalar Higgs (S) exchanges. One particular unified treatment is given by the maximal[5] SU(16).

An alternative dimensional derivation of these mass scales which does not rely on any particular Grand Unifying Model is given by Weinberg[6] (and for $\Delta B = \Delta L$ case by Wilczek and Zee[7]). Assuming $SU(3) \times SU(2) \times U(1)$, and only "light" particles (q, ℓ), $(W^{\pm}, Z^0, \gamma)$, ϕ_{Higgs} one can easily compute the form and dimension (d) of typical Lagrangians for proton decay:-

$\Delta B = \Delta L$	$L_{eff} \propto$	$\frac{1}{M^2}$	$q\,q\,q\,\ell$	$d = 6$
$\Delta B = -\Delta L$	$\propto$	$\frac{1}{M'^3}$	$q\,q\,q\,\bar{\ell}\,\phi$	$d = 7$
$\Delta B = -\frac{\Delta L}{3}$	$\propto$	$\frac{1}{M''^6}$	$q\,q\,q\,\bar{\ell}\bar{\ell}\bar{\ell}\,\phi$	$d = 10$
$\Delta B = +\frac{\Delta L}{3}$	$\propto$	$\frac{1}{M'''^7}$	$q\,q\,q\,\ell\ell\ell\,\phi^2$	$d = 11$

* To be sure the value of $\sin^2\theta$ does provide a second window for high mass scales, but unlike proton decay where one is studying the vast numbers of decay modes and their implications for the underlying dynamics, $\sin^2\theta$ is just one parameter.

The empirical lower limit on proton life gives the masses M, M', M'', M''' in the ranges already indicated.

The important experimental questions which now arise are the following:-

(1) Can the four modes listed above co-exist; are there selection rules; what are the relative rates?

(2) Can they co-exist together with $N - \bar{N}$ oscillations ($\Delta B = 2$) at the present level of experimentation?[10]

The answers differ; depending on the assumptions made.

Spontaneous Versus Explicit Symmetry Breaking

One of the major theoretical sources of contrasting selection rules is explicit versus spontaneous breaking of baryon and lepton numbers.

Assuming that baryon-number is explicitly broken, Weinberg[6], for example, would permit only two out of 4 modes listed above to co-exist – $\Delta B = \Delta L$ and one other mode – but no $N - \bar{N}$ oscillations. In the maximal SU(16) gauge model, where baryon-number violation is spontaneous[5], all modes of decay may simultaneously occur, together with $N - \bar{N}$ oscillations.

This contrast can be traced back to the second motivation (besides the gauge unification of leptons and quarks) for baryon-decay viz the observed baryon asymmetry of the Universe. This was first remarked upon by Weinberg[8] in his 1964 Brandeis Lectures, and independently elaborated by Sakharov[8] in 1967 (Sakharov actually considered the decay mode $\Delta B = + \frac{\Delta L}{3}$ $(P \rightarrow 3\bar{\ell})$; this line of work remained unknown until it was rediscovered in the context of electro-nuclear grand unification[9] in 1978.)

The point about explicit versus spontaneous symmetry breaking is that with explicit breaking a rise in temperature does not – unlike the case for spontaneous breaking – obliterate the decays themselves. In SU(5) or SO(10) gauge theories for example where the baryon-violating current is of the form $(q\,q + \bar{q}\,\bar{\ell})$, the gauge-boson may indeed make a transition to masslessness with rising temperature, but the decay does not stop. In contrast in the maximal SU(16) theory where there are two distinct gauge mesons, one coupling to $(q\,q)$ and the other to $(\bar{q}\,\bar{\ell})$, the decay occurs through a spontaneously induced mixing of these two types of gauge bosons. Beyond the transition temperature, the mixing is obliterated and with it also the baryon-decay mode. The successive proton decay modes $\Delta B = \Delta L$ with mass scale $10^{14} - 10^{15}$ GEV, $\Delta B = -\Delta L$ with $10^{8} - 10^{10}$ GEV, and $\Delta B = \pm \frac{\Delta L}{3}$ and $\Delta B = 2$ $(N - \bar{N}$ oscillations) with mass scales $10^{4} - 10^{5}$ GEV, occur at different epochs in the evolving history of the expanding universe. The requirement that the baryon asymmetry due to the earlier mode does not get washed out when the transition temperature corresponding to the next decay mode is reached leads to different selection rules, depending on the two scenarios of explicit versus spontaneous breaking of symmetries. Clearly, it is essential that we have experimental information on the frequency of all the modes listed.

Preons versus Grand Unified Theories

Are quarks and leptons elementary up to the mass scales indicated, or are all or some of them composites of preons? Does the preonic hypothesis entail its own selection rules? The answer is yes:

Examples: The composite model of Harari and Saiberg[11] predicts only $\Delta(B-L) \neq 0$ decays; the "hyperunification" model of Kim[12] (where (d_R, e_L, ν_L)'s are composite and other quarks and leptons elementary), predicts that nucleon decays produce only charged anti-leptons (e^+) and that their polarisation is 100%. This is in contrast to non-composite models[13] where the degree and universality of polarisation (for e's and μ's) depends on whether the basic couplings of elementary quarks and leptons is gauge vector (V) or Higgs (S). Note that in some preonic models the mass scale for nucleon decays can be as low[14] as .5–1 TEV.

In this context, another distinction between V and S couplings is provided by the expected predominance of ρ and η mesons among the nucleon two-body decay products[15] for the mode $\Delta B = \Delta L$, for the scalar (S) case.

Which Gauge Theory?

Thus far we have talked of distinctions, which essentially are independent of which (if any) unifying gauge model there may be. To decide which gauge theory is operative, one can devise tests; some, which have been suggested are the following[16]:–

$$(1+\gamma^2)\,\Gamma(P \rightarrow \pi^+ \bar{\nu}) = \Gamma(P \rightarrow \pi^0 \ell^+) = \tfrac{1}{2}\,\Gamma(N \rightarrow \pi^- e^+)$$
$$= (1+\gamma^2)\,\Gamma(N \rightarrow \pi^0 \bar{\nu})$$
$$\Gamma(P \rightarrow e^+ + \text{anything}) = (1+\gamma^2)\,\Gamma(N \rightarrow \bar{\nu})$$

r = 2 Tree level SU(5) (plus renormalization corrections which have been evaluated)

r = 0 For SO(10), with the assumption that nucleon decay is mediated by bosons which are not in SU(5).

r = 1 SU(2) x SU(2) x U(1) in the first approximation, if this is the electroweak theory much below 10^{15} GEV.

It is important to stress once again that as a rule the larger symmetry, for example SU(16), may give the results of its subgroups SO(10) or SU(5), and SO(10) may give the results of SU(5) depending on the chain of symmetry breaking adopted. The converse, however, is not true.

I hope I have convinced you that the proton decay experiment must be looked upon as a continuing long-range experiment. I hope I have convinced the enterprising experimenters to contemplate acquiring long term leases for occupancy of the Kolar Gold Fields or the Mont Blanc tunnel. I hope I have convinced you that new groups should feel encouraged and that generous funding should be provided for these experiments. Since I see Professor Schopper in front of me, I hope he will kindly take note of this last remark.

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