PHYSICS WITH 100-1000 TeV ACCELERATORS

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I INTRODUCTION

There is no question but that unless our community takes urgent heed, there is the danger that high energy accelerators may become extinct, in a matter of thirty years or so.

Consider the case of CERN, representing European High Energy Physics. With LEP, to be completed around 1987 with centre-of-mass energy $\approx \frac{1}{7}$ TeV, CERN will have acquired a tunnel of 27 Km. circumference. One may expect to install in this tunnel a proton ring which by the year 2,000 may provide ep, $p\bar{p}$ and pp centre-of-mass energies up to 10 TeV, assuming the availability of 5 T magnets, and 20 TeV for magnets of 10 T. But this may be the end: this is because high energy accelerators have become like dinosaurs: large, energy- and site-intensive, precious and impersonal. What makes the situation worse is that, except for stochastic cooling, no new ideas have been worked out for thirty years in accelerator building.

Contrast this with the expectations of the theorists, so far as energy ranges are concerned. Up to 1965, we were content with Yukawa's legacy of m_π and Regge slope ($\approx$ 1/1000 TeV) as energy units. After that date we graduated hesitantly to thinking of the $(\frac{1}{10} - \frac{1}{5})$ TeV range of the electroweak theory. This energy range (and beyond) has now been experimentally realized with the $\frac{1}{2}$ TeV of the $p\bar{p}$ collider. Around 1974, with dramatic suddenness, came the realization that the $SU_c(3)$, $SU_L(2)$ and U(1) gauge forces, if extrapolated in energy, using renormalization group ideas, would carry us to 10^{11} TeV. And then in 1976, with supergravity and the possibility it offers of unification of gravity with other forces, the Planck energy $m_P \approx 10^{16}$ TeV came to be accepted as the "natural" scale for particle physics[1]).

This catalogue of high energies is depressing for prospects of accelerator building. Even more demoralizing is the theoretical conjecture which some of us are responsible for: there may be no new physics between $\frac{1}{10}$ TeV and 10^{11} TeV - the desert syndrome.

Let us examine this syndrome. It is a consequence of three assumptions: 1) that there are no gauge forces except the known $SU_c(3)$, $SU_L(2)$ and U(1) between the presently accessible 1/10 TeV and an upper energy Λ_0; 2) that no new particles will be discovered in this range, which might upset the relation $\sin^1\theta_W(\Lambda_0) = \frac{3}{8}$ satisfied for the known quarks and leptons; 3) and that the Higgs particles and the Higgs forces responsible for spontaneous symmetry breaking represent no new physics. With these three assumptions, renormalization group extrapolation shows that the effective couplings of the three gauge forces $SU_c(3)$, $SU_L(2)$ and U(1) converge to the same value at the same (unification) energy Λ_0 and further that this Λ_0, is high, of the order of $\approx 10^{11}$ TeV. To put it irreverently, assume that there is a desert of new physics up to Λ_0 - and by new physics imply new gauge forces - then the theory will oblige by showing that this assumption can be self-consistently upheld, with the desert stretching even up to $\Lambda_0 \approx 10^{11}$ TeV.

Clearly, one may question the basic assumptions. To motivate this questioning and to define the intermediate energy scale at which new physics may be discovered (and at which the next generation of accelerators may be aimed) one should examine critically the conventional grand unification ideas [i.e. the minimal SU(5) or SO(10) or E_6 or the maximal SU(16) which incorporate SU(3) x SU(2) x U(1)]. It is well known that all these theories are uniformly embarrassed by the following difficulties: i) the profusion of the Higgs sector and parameters associated with it; ii) the existence of three - apparently similar - families and iii) the theoretical problem of hierarchies, i.e. the theoretical inconsistency, in a perturbative context, of having just two scales in the theory ($\frac{1}{10}$ TeV and 10^{11} TeV), so widely separated from each other. It is these weaknesses and their amelioration which provide us with clues to new physics and possible intermediate energies for the new accelerator to explore.

Consider these three weaknesses in turn.

The Higgs sector

The Higgs sector of the gauge theories is at once an embarrassment as well as a source of richness in physics. Embarrassment: because each

Higgs particle introduces into the theory, on the average, at least 5 new undetermined parameters. Richness: because, with these Higgs particles is associated most of the experimentally exciting physics to be expected: neutrino masses, axions, $N-\bar{N}$, $H-\bar{H}$ oscillations, proton decays into leptons (as contrasted to anti-leptons), cosmological early Universe scenarios. To take a concrete example, the minimal SU(5) which started life with just two Higgs (a $\underline{5}$ and a $\underline{24}$) and with just ten Higgs parameters, has recently been supplemented with ($\underset{\sim}{5}$, $\underset{\sim}{10}$, $\underset{\sim}{15}$, $\underset{\sim}{45}$, $\underset{\sim}{50}$ and $\underset{\sim}{75}$) of Higgs, to accord to it the desirable richness of testable physical phenomena at diverse intermediate, i.e. between $\frac{1}{10}$ and 10^{11} TeV, energy scales[2]). Clearly there is a lot of physics here.

For this richness, one must however pay a price. How can one compute these parameters from some fundamental theory? One answer, favoured for the last three years, was to consider these Higgs as composites, dynamically held together by a new type of gauge force - called the technicolour force with an associated (confinement) scale of around 1 TeV. The technicolour gauge force would then force us to abandon assumption 1) above; i.e. that there are no other gauge forces except those represented by SU(3), SU(2) and U(1).

This idea of technicolour has recently run into difficulties with flavour-changing neutral currents, only to be replaced by the hypothesis that all presently known particles, quarks, leptons, Higgs, as well as the gauge particles may be composites of a next level of elementary entities - the preons. The force which binds preons together replaced the technicolour force. In this picture quarks and leptons would have inverse radii between 10 and 100 TeV. I would like to suggest that the next generation of accelerators should aim at this possible preonic level of structure i.e. energies in excess of 100 TeV where quark and leptonic form factors may be expected to show experimentally. The preon hypothesis would also resolve the second embarrassment of grand unified theories: the existence of three apparently "identical" families of quarks and leptons. Just as the quark hypothesis resolved the difficulty posed by "identical" families of hadrons (of the eight-fold way) being considered as elementary entities, likewise preons would resolve the problem of "identical" quark and leptonic families by treating them as composites.

It is relevant in this context to remark that the present indirect experiments on lepton sizes give 10-100 TeV as the inverse radii of these particles. These are experiments related to the following processes :

<u>Experiment</u>	<u>Radii</u>
$(g-2)_{e,\mu}$	- $(1\ \text{TeV})^{-1}$
$\mu \to e + \mu$	- $(10\text{-}100\ \text{TeV})^{-1}$
$K \to e + \mu$	- $(10\text{-}100\ \text{TeV})^{-1}$
e/μ universality	- $(100\ \text{TeV})^{-1}$
e/τ universality	- $(\text{TeV})^{-1}$

(These estimated radii are somewhat model dependent).

To resolve the third problem of grand unified theories - i.e. the hierarchy problem - there has been the recent suggestion of a postulated Fermi-Bose symmetry. Such a symmetry (supersymmetry) may have a characteristic breaking scale associated with it, which may range anywhere between a few TeV to 10^8 TeV. Even for the upper end of this scale, the indirect effects of supersymmetry may manifest themselves much earlier. In fact there are suggestions that the preonic hypothesis may be combined with supersymmetry; supersymmetry may manifest itself at the preonic (or the pre-preonic) level.

From global supersymmetry, one makes a natural transition to gauged supersymmetry, i.e. to supergravity theory with its characteristic spin $\frac{3}{2}$ gravitinos, accompanying the gravitons. Recently, there have been exciting suggestions of supergravity playing an important role in the breaking of symmetries at all levels with masses of gravitinos possibly being in the W,Z range. This may imply an influence of supergravity theory earlier than anyone anticipated, even in the $\bar{p}p$ collider range.

My summary conclusions are as follows:

1 Do not ask theorists at which energy to aim for the next generation of high energy accelerators. Aim at the highest possible. One may recall the cautionary story of Lord Kelvin who (reviewing what his generation had accomplished in the nineteenth century) remarked in his address to the British Association for the Advancement of Sciences: "There is nothing new to be discovered in physics now; all that remains is more and more precise measurement". This happened to be the same year when (subsequent to Lord Kelvin's speech) J J Thomson announced the discovery of the electron!

2 The chief limitation to achieving higher energies for accelerators, I believe, is the present rather low value for the gradients of accelerating fields, which range no higher than tens of GeV/km. With proposed collective laser accelerators (e.g. employing gratings or laser-plasma beat wave concepts) higher gradients may possibly be achieved even up to 100 TeV/km. It is essential that these ideas are pursued with vigour, with young theorists and experimentalists in multi-disciplinary teams to be constituted and generously funded, at the (indigent) universities by the (richer) national accelerator laboratories in Europe, USA, USSR and Japan. Clearly, accelerator physics is a multi-disciplinary subject with inputs from laser, plasma and high energy physics. For experimentation, collaborations between national and international laboratories in these diverse fields will need to be built up actively with the big accelerator laboratories taking the lead in forging these.

3 Between the first and second decades of the next century, I would suggest that the community should set itself as a modest target the design, installation and the operation of a 100-1000 TeV (centre-of-mass) accelerator.

4 And finally, I would like to remind you that the ultimate accelerator will perhaps consist of electromagnetic bottles of monopoles of 10^{13} TeV mass culled from iron ore concentrations heated above Curie temperature, as suggested by Cline at the recent Venice conference.

I shall now briefly elaborate on the points made above. The plan of the talk will be as follows:

a) a brief review of the standard model,

b) grand unified theories and a critique of the reasoning leading to the desert syndrome,

c) the richness implied by a realistic set of Higgs particles,

d) the richness implied by supersymmetry and supergravity theories,

e) composite models of Higgs particles and the richness implied by preonic models.

II A BRIEF REVIEW OF THE STANDARD MODEL

At present 39 two-component fermions are known, which appear to be grouped into three families of quarks and leptons:

Table I

Family	Quarks	Leptons
Electron (e)	$\begin{pmatrix} u \\ d \end{pmatrix}_L, u_R, d_R$	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, e_R$
Muon (μ)	$\begin{pmatrix} c \\ s \end{pmatrix}_L, c_R, s_R$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \mu_R$
Tauon (τ)	$\begin{pmatrix} t \\ b \end{pmatrix}_L, t_R, b_R$	$\begin{pmatrix} \nu_\tau \\ \nu \end{pmatrix}_L, \tau_R$

Each quark comes in three colours: red, yellow and blue. In the tau family, the top quark (t) is conjectural. With it included the third family - like the first two - would correspond to the $(\underset{\sim}{3},\underset{\sim}{2},\underset{\sim}{1})_L + (1,2,1)_L + (3,1,2)_R + (1,1,1)_R$ representation of $SU(3)\big|_{colour} \times SU(2)_L \times U_{L+R}(1)$ group. Each family would then contain 15 two-component objects.

The forces between quarks and leptons are the gauge forces corresponding to the symmetry-group $SU_c(3) \times SU_L(2) \times U(1)$, represented by eight gluons (g), and the four electroweak gauge particles ($W^{\pm}, Z^0, \gamma$). There are three coupling parameters: α_c corresponding to the strong colour forces, and ($\alpha/\sin^2\theta$, $\alpha/\cos^2\theta$) corresponding to the $SU_L(2)$ and U(1) electroweak forces (α is the fine structure constant). In addition to these, there is a (single) neutral Higgs particle, whose (Yukawa) couplings with fermions are proportional to their masses. The (renormalizable) Lagrangian corresponding to this standard model contains 26 parameters (masses of fermions, their mixings, Higgs mass, its couplings, etc.) which, so far as this model is concerned, must be determined from experiment. The partial unification of the electromagnetic and weak forces implied by the model, however, predicts that (ignoring radiative corrections), $M_W = M_Z \cos\theta = (\pi\alpha/\sqrt{2}\, G_F)^{\frac{1}{2}}/\sin\theta$, where G_F is the weak Fermi constant. As is well known, the model has strong indirect support from νN, $\bar{\nu}N$, νe, $\bar{\nu}e$, ed and the present (40 GeV) e^+e^- experiments. However its direct predictions (concerning $W^{\pm}$, Z^0 masses and their interactions) will be tested at the $p\bar{p}$ collider and at LEP and SLC.

The existence of the three families (apparently identical replications of each other) and the unknown mass and interaction parameters of the Higgs particle, pose two of the problems of the standard model. To emphasize the riches to be expected, even for this model, it has been shown (by Grisaru and Schnitzer) that if the Higgs mass happens to exceed 300 GeV, one may expect Regge recurrences of $W^{\pm}$, Z^0 and γ to occur for masses beyond 2-4 TeV. I must confess however that this scenario is not the one which theorists like, because it makes the Higgs sector a "strong sector" - not amenable to perturbation calculations. Such recurrences would occur also if Higgs mass is < 300 GeV but then their location would be at much higher energies.

III GRAND UNIFICATION AND THE DESERT

Is there an internal symmetry group of which both quarks and leptons are representations and which contains $SU_c(3) \times SU_L(2) \times U(1)$? The first