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INTERNATIONAL CENTRE FOR
THEORETICAL PHYSICS

PHYSICS WITH 100-1000 TeV ACCELERATORS

Abdus Salam

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Abdus Salam
International Centre for Theoretical Physics, Trieste, Italy,
and
Imperial College, London, England.

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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 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 hesitantly we graduated 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 $\frac{1}{2}$ 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 *).

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.

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*) True enough, after 1979, with the work of Cremmer and Julia and the revival of Kaluza-Klein higher dimensional theories, there has been a slight remission downwards by more than an order of magnitude in energy scales as emphasized by Freund. We believe, for example, that already at a lower energy $\frac{e}{2\pi} m_{Planck}$, of the order of a mere 10^{15} TeV, space-time will have blossomed from four to eleven dimensions. Thus before Planck energies are reached, we may have a totally new regime to deal with.

Let us examine this syndrome. It is a consequence of three assumptions: 1) assume 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) assume that no new particles will be discovered in this range, which might upset the relation $\sin^2\theta_W(\Lambda_0) = \frac{3}{8}$ satisfied for the known quarks and leptons; 3) assume 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) × SU(2) × 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 5 and a 24) and with just ten Higgs parameters, has recently been supplemented with (5, 10, 15, 45, 50 and 75) of Higgs, to accord to it the desirable richness of testable physical phenomena at diverse intermediate (between $\frac{1}{10}$ and 10^{11} TeV) energy scales *). 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 techni-colour force with an associated (confinement) scale of around 1 TeV. The techni-colour 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 techni-colour 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 replaces the techni-colour 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 variety of indirect experiments on lepton sizes give 10-100 TeV as the inverse radii of these particles. These are experiments related to the following processeses:

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*) An intermediate energy scale (not available within SU(5)) is the one associated with the breakdown of the left-right symmetry (V+A currents and predicted existence of W_R) characteristic of all grand-unifying theories, except SU(5). Such a breakdown may manifest itself anywhere between $\frac{1}{3}$ and 1000 TeV.

Experiment	Radii
$(g-2)_{e,\mu}$ -	$(1\ \text{TeV})^{-1}$
$\mu \to e + \mu$ -	$(10\text{-}100\ \text{TeV})^{-1}$
$K \to e + \mu$ -	$(10\text{-}100\ \text{TeV})^{-1}$
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 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 at 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 Advancemenet 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, are the present rather low values for 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-disiplinary 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)	$\begin{pmatrix} u \\ d \end{pmatrix}_L, u_R, d_R$	$\begin{pmatrix} \nu_c \\ e \end{pmatrix}_L, e_R$
Muon (μ)	$\begin{pmatrix} c \\ s \end{pmatrix}_L, c_R, s_R$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \mu_R$
Taon (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 taon 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), $M_W = M_Z \cos\theta = (\pi\alpha/\sqrt{2}\, G_F)^{1/2}/\sin\theta$, 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 group suggested (with Pati) was the non-Abelian $SU_c(4) \times SU_L(2) \times SU_R(2)$ with two (rather than three) coupling constants and with inbuilt left-right symmetry of the electroweak and with $SU_c(4)$ of colour. This $SU_c(4)$ contains

$[SU_c(3) \times U_{B-L}(1)]$ as a subgroup *) and combines quarks and leptons of each *family* (B and L are the baryon and lepton numbers) *into one multiplet* $(\underset{\sim}{4},\underset{\sim}{2},\underset{\sim}{2})$ consisting of $\underset{\sim}{16}$ (rather than $\underset{\sim}{15}$) two-component fermions (i.e. in addition to ν_L, ν_R's also exist). This was the first suggestion of quark-lepton unification. The second suggestion (with one coupling constant) is the postulated symmetry SU(5). Here the $\underset{\sim}{15}$ quarks and leptons of one family are united in a $\underset{\sim}{5} + \underset{\sim}{\overline{10}}$ of SU(5). There is also the symmetry group SO(10) which can contain both $SU_c(4) \times SU_L(2) \times SU_R(2)$ as well as SU(5) and which describes one single family of $\underset{\sim}{16}$ fermions. The maximal gauge group with $\underset{\sim}{16}$ fermions per family but with a vastly larger number of gauge mesons is SU(16) of which SO(10) would be a subgroup.

Consider the SU(5) grand unifying model. With two Higgs multiplets (a $\underset{\sim}{24}$ and a $\underset{\sim}{5}$) spontaneous symmetry breaking at the tree diagram level will induce the following chain of symmetries:

$$SU(5) \underset{\underset{\sim}{24}}{\rightarrow} SU_c(3) \times SU_L(2) \times U(1) \underset{\underset{\sim}{5}}{\rightarrow} SU_c(3) \times U_{em}(1) \quad .$$

The second breaking $(SU_c(3) \times SU_L(2) \times U(1) \underset{\underset{\sim}{5}}{\rightarrow} SU_c(3) \times U_{em}(1))$ is assumed to occur at m_W. What is the scale (the so-called grand unification scale) of the first breaking $SU(5) \times SU_c(3) \times SU_L(2) \times U(1)$? This upper scale will determine ths stretch of the desert.

To illustrate the ideas involved, consider just the unification of the electroweak sector of the theory $SU_L(2) \times U(1)$, starting with two couplings $\alpha/\sin^2\theta$ and $\alpha/\cos^2\theta$ (both evaluated by experiments involving *energy and momentum transfers of order* m_W) *into a non-Abelian unifying* symmetry G, which need not be specified. In this scenario the symmetry G is assumed to break down to SU(2) × U(1), around M_U through the Higgs mechanism. Now the renormalization group tells us that both α and $\sin^2\theta$ are functions of energy; that $\alpha/\sin^2\theta$ decreases logarithmically with energy and $\alpha/\cos^2\theta$ increases with it. M_U is the energy where the two curves will meet.

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*) As was noted almost immediately after $SU_c(4)$ was postulated, one could consider breaking (B-L) (around 10^5 GeV) and mediate proton decays into three leptons. The breakdown of $SU_c(4)$ into $SU_c(3) \times U_{B-L}(1)$ could also give rise to monopoles of "light"mass ($\approx 10^6$ GeV) which future accelerators may produce.

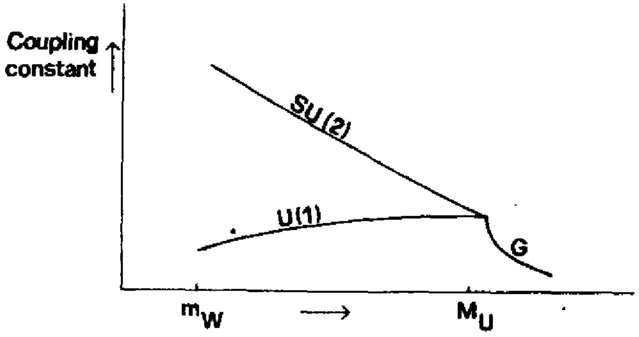

Fig.1

In Fig.1 are plotted the evolution curves of the two coupling constants. Ignoring contributions from the Higgs particles, these curves meet at M_U given by the formula

$$\ln \frac{M_U}{m_W} = \frac{3}{\alpha(m_W)} \quad \frac{\sin^2\theta(M_U) - \sin^2\theta(m_W)}{\cos^2\theta(M_U)} \quad . \qquad (1)$$

To compute M_U we now make two assumptions: 1) There are no new gauge forces to interrupt the evolution curves for the coupling constants shown in Fig.1 and 2) that we have some theoretical criterion for determining $\sin^2\theta(M_U)$ at the upper energy M_U - assuming that we know $\sin^2\theta(m_W)$ evaluated at the lower scale m_W from experiment.

Now it can be shown that at the upper scale M_U,

$$\sin^2\theta(M_U) = \frac{9\ N_q + 3\ N_\ell}{20N_q + 12N_\ell}$$

where N_q and N_ℓ are the numbers of the fundamental quark and leptonic SU(2) doublets with masses below M_U (assuming that these are the only types of SU(2) multiplets which can exist and that each of the three colours counts once). For the known families, it happens that $N_q = N_\ell$ *), thus $\sin^2\theta(M_U) = \frac{3}{8}$, if no other types of multiplets are discovered to upset this.

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*) $N_q = N_\ell$ can be theoretically motivated by the demand for axial anomaly cancellation between quarks and leptons. If however one admits the possibility of the existence of mirror fermions, coupling with (V+A) currents to $W^\pm$ and Z^0 (and one can give arguments that such fermions *must appear below 300 GeV or so, if they exist at all) then there is no* anomaly and no necessity for $N_q = N_\ell$.

Using (1) with $\sin^2\theta(M_U) = \frac{3}{8}$ as input, and with an empirical value of $\sin^2\theta(m_W) = 0.23$, one would obtain for the unifying mass $M_U \approx 1.3 \times 10^{13}$ GeV. This is a high value for the unifying mass.

To obtain it, we made several assumptions: (1) that there is a desert of new gauge forces up to the mass scale M_U; (2) that there is a desert of intermediate mass scales which the Higgs particles may introduce and (3) that there is a desert of new fermions right up to the (large) mass M_U, such as may shift $\sin^2\theta(M_U)$ from its (unrenormalized) value $\frac{3}{8}$. Making these extrapolations from what we know from experiments below 40 GeV, up to the energy scale M_U, we find that our theory tells us that the desert of new gauge forces, the desert of new Higgs and the desert of new "unconventional" fermions should stretch all the way up to inordinately high energy scales $M_U \sim 10^{13}$ GeV.

To take one counter example of new types of forces which may invalidate this scenario, even within the context of uniting just $SU_L(2) \times U(1)$, remark that we have ignored the very likely experimental possibility that three-family-universality may not hold up to M_U ($\approx 10^{13}$ GeV). Let us relax this assumption; assume this universality is a low-energy phenomenon, i.e. that it holds only up to a mass scale $M < M_U$. Assume that the starting symmetry is $G_e \times G_\mu \times G_\tau$ with a $e \rightarrow \mu \rightarrow \tau$ discrete symmetry built in to guarantee a unique coupling constant and that each G_i $(i = e,\mu,\tau)$ breaks to $[SU(2) \times U(1)]_i$ at M_i. There is the lower breaking stage (which restores e,μ,τ universality) and the emergence of the diagonal-sum symmetry $[SU(2) \times U(1)]^{e+\mu+\tau}$ at the scale M. For this simple scenario, one can now show that the analogue of formula (1) reads:

$$\ell n \, \frac{M_e M_\mu M_\tau}{M^2 m_W} = \frac{3\pi}{\alpha(m_W)} \, \frac{\sin^2\theta(M) - \sin^2\theta(m_W)}{\cos^2\theta(M)} \quad .$$

Assume that M, the scale up to which e,μ universality may hold maybe as high as 10^5 GeV, though we are far less certain of e,μ universality empirically. Now, even with $\sin^2\theta(M) = \frac{3}{8}$, we obtain M_e, M_μ, M_τ as low as 10^8 GeV for the case of three families. The "desert" has shrunk from 10^{13} GeV to 10^8 GeV. If the number of families increased to four, the "desert" would shrink still further and stretch only between $M = 10^5$ and 10^6 GeV. Such is the sensitivity of logarithmic functions to (small) changes of inputs!

The conclusion we arrive at is that the stretch and the extent of the desert is crucially dependent on the assumption made. In particular, the simplest assumption of a breakdown of family universality can shrink the desert

drastically. The same would happen if $N_q \neq N_\ell$: i.e. whenever the numbers of (left-handed) quark and leptonic doublets differed from each other; this could be the case if mirror fermions exist. Such theoretical extrapolations from present experience (no breakdown of universality, no mirrors) are aesthetically motivated. These however drastically affect the stretch of the desert simply because the renormalization group formulae which we use involve logarithms of masses.

I have so far been speaking about uniting the electroweak forces SU(2) and U(1) with two coupling paremerts into one (non-Abelian) structure with one coupling parameter. One could carry out a similar analysis if we wish to unite SU(3) of colour together with $SU(2) \times U(1)$ into a (non-Abelian) symmetry with one coupling parameter - for example the symmetry SU(5) for each family. Here there are three evolution curves for the three couplings, and the demand that all three meet for the same M_U can apparently be met, with $M_U \sim 10^{14}$ GeV and $\sin^2\theta(m_W) \approx 0.21 - 0.23$ provided $\alpha_{colour}(m_W)$ is assumed to be of the order of $\approx \frac{1}{10}$.

Once again, if we did not entertain family universality holding right up to M_U (i.e. we assume the symmetry is $SU_e(5) \times SU_\mu(5) \times SU_\tau(5)$ which breaks at a lower energy to $SU(5)\big|_{e+\mu+\tau}$), the stretch of the desert can tumble down drastically (for example to 10^8 GeV or lower). Another possible symmetry which incorporates the three families is the symmetry $[SU(6)]^4$. This symmetry would predict new leptons in each family ($\sin^2\theta(M_U) = \frac{9}{28}$ instead of $\frac{3}{8}$) and also give $M_U \approx 10^8$ GeV (besides $\sin^2\theta(m_W) \approx 0.23$).

Clearly the determination of up to which energies e,μ,τ universality holds, becomes a parameter of crucial importance for determining the stretch of the "desert".

In the next section we consider the relaxing of the assumption about there being a desert of Higgs particles.

IV. THE RICHNESS ASSOCIATED WITH HIGGS PARTICLES

1. Gauge theories have been surmised to resolve some of the outstanding puzzles of early cosmology - for example the problem of baryon-antibaryon asymmetry, and the problem of nucleation of galaxies. Likewise these theories may account for masses for neutrinos , and the may lead to neutron-antineutron oscillations. It is important to realize that this richness of physics comes associated with Higgs particles, a multitude of which must be introduced into the theory to bring about specific varieties of spontaneous symmetry breaking. The minimal Higgs structures associated with SU(3) × SU(2) × U(1) (one Higgs) or with the minimal SU(5) (two Higgs multiplets) are insufficient. Thus an important future experimental task is to test the phenomena predicted and to explore the energy regimes where such Higgs might be operative.

Consider for definiteness the grand unifying model SU(5). The minimal Higgs structure consists of a $\underset{\sim}{24}$ and a $\underset{\sim}{5}$. The $\underset{\sim}{24}$ breaks SU(5) into SU(3) × SU(2) × U(1) around $M_U \sim 10^{14}$ GeV, while the $\underset{\sim}{5}$ breaks SU(2) × U(1) to $U_{em}(1)$ around 10^2 GeV. Let us leave aside for the next section the hierarchy problem - i.e. the problem that if such a breaking is arranged through an appropriate choice of the Higgs parameters in a tree approximation, there is no "natural" way in which the radiative corrections can be made to respect and preserve this large ratio of around $10^{12} \simeq M_U/m_W$ for higher radiative corrections in a perturbative context, except possibly through an invocation of supersummetry (and its own complicated Higgs structure). In this section we shall simply wish to list those Higgs which have been postulated from time to time to explain away old puzzles or to predict new physics.

Table II

SU(5) representation	Raison for introducing
$\underset{\sim}{24}$ or $\underset{\sim}{75}$	To break SU(5) → SU(3) × SU(2) × U(1) with associated energy scale $\approx 10^{14}$ GeV
$\underset{\sim}{5}$	To break SU(2) × U(1) → $U_{em}(1)$ $\approx 10^2$ GeV $\Big\}$ minimal SU(5)
$\underset{\sim}{45}$	SU(5) used for all three families, predicts the successful relation $\frac{m_\tau}{m_\mu} \approx \frac{m_c}{m_s}$, but by the same token gives the distastrous relation $\frac{m_\mu}{m_e} \approx \frac{m_s}{m_d}$ (wrong by a factor of 20 or so Need $\underset{\sim}{45}$ to avoid this problem.
$\underset{\sim}{15}$	To give ν_L a mass.
More $\underset{\sim}{5}$'s or $\underset{\sim}{45}$'s	SU(5) (or any other grand unifying theory) gives an explanation of baryon-asymmetry. For minimal SU(5), however the predicted value is $\frac{n_B}{n_\gamma} \sim 10^{-15}$-$10^{-16}$ as against the empirical $\sim 10^{-11}$. To correct this, need extra $\underset{\sim}{5}$'s or $\underset{\sim}{45}$'s.
Complex $\underset{\sim}{5}$	To motivate the axion mechanism and thereby avoid strong CP problem in SU(5).
Complex $\underset{\sim}{10}$	The axion mechanism, as a rule, brings with it the domain wall problem; such domains would make it hard to understand the isotropy of 3°K radiation.*)
Further complex Higgs	To generate strings which produce density perturbations, which may nucleate galaxies
$\underset{\sim}{10}$, $\underset{\sim}{15}$ or $\underset{\sim}{50}$ or both	For neutron-antineutron oscillations and for $\Delta(B-L) = 0$ processes like $P + P \rightarrow e^+ + e^+$. (For $n \longleftrightarrow \bar{n}$ with $\tau_{n-\bar{n}} \sim 10^7$ secs, need Higgs of mass $\sim 10^5$ GeV.) Also need these multiplets for (B-L) violation.

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*) In an inflationary universe scenario these problems may take on a different complexion.

A similar proliferation of Higgs is necessary in SO(10) where the minimal set of $\underset{\sim}{45}$, $\underset{\sim}{126}$ plus $\underset{\sim}{10}$ needs supplementation with complex $\underset{\sim}{10}$ or $\underset{\sim}{120}$ to avoid undesirable family mass relations like $m_\mu/m_e \simeq m_s/m_d$ as well as a complexification of $\underset{\sim}{126}$, $\underset{\sim}{45}$ and $\underset{\sim}{10}$ to cope with the cosmological problems mentioned in the SU(5) context. The SO(10) model admits also of (V+A) currents and contains W_R as well as ν_R, with the possibility of an intermediate mass scale in the 10^6-10^7 GeV range. These and other grand unifying models (like SU(16)) which admit of possible $\Delta(B-L) \neq 0$ baryon decays into (1) three leptons (or three antileptons) or (2) into a lepton (as contrasted with the $\Delta(B-L) = 0$ decay baryon → antilepton, mediated in the minimal SU(5) by massive gauge particles) need Higgs in the mass ranges 10^5-10^6 GeV and 10^8-10^9 GeV, respectively *).

2. What are the allowed mass ranges for the Higgs I have mentioned? This is naturally what the accelerator-builder will want to know. In this context, Marciano at the Paris Conference in July 1982, presented the following constraints for an enlarged SU(5) model for those Higgs ($\underset{\sim}{5}$, $\underset{\sim}{10}$, $\underset{\sim}{15}$, $\underset{\sim}{45}$, $\underset{\sim}{50}$) which may couple to fermions.

$$\begin{array}{lll} \underline{SU(5)} & & \underline{SU(3)\times SU(2)\times U(1)\ \text{content}} \\ \underset{\sim}{5} & = & \underbrace{(1,2,1)}_{\phi_1} + \underbrace{(3,1,-2/3)}_{\phi_2} \quad (P \to \mu^+K^0, \bar{\nu}_\mu K^+ \ \ldots \ \text{imply } m_2 > 10^{10}\ \text{GeV}) \end{array}$$

$$\left.\begin{array}{ll} \underset{\sim}{10} & \underbrace{(1,1,2)}_{\phi_3} + \underbrace{(3,1,-4/3)}_{\phi_4} + \underbrace{(3,2,1/3)}_{\phi_5} \\ & \\ \underset{\sim}{15} & \underbrace{(1,3,2)}_{\phi_6} + \underbrace{(3,3,1/3)}_{\phi_7} + \underbrace{(6,1,-4/3)}_{\phi_8} \end{array}\right\} \begin{array}{l} \text{B-L violation} \\ \text{neutrino mass} \\ n\text{-}\bar{n}\ \text{oscillation} \end{array}$$

$$\begin{array}{ll} \underset{\sim}{45} & \underbrace{(1,2,1)}_{\phi_1} + \underbrace{(3,1,-2/3)}_{\phi_{10}} + \underbrace{(3,3,-2/3)}_{\phi_{11}} + \underbrace{(\bar{3},1,8/3)}_{\phi_{12}} + \underbrace{(\bar{3},2,-7/3)}_{\phi_{13}} \\ & \qquad + \underbrace{(\bar{6},1,-2/3)}_{\phi_{14}} + \underbrace{(8,2,1)}_{\phi_{15}} \\ & \\ \underset{\sim}{50} & \underbrace{(1,1,-4)}_{\phi_{16}} + \underbrace{(3,1,-2/3)}_{\phi_{16}} + \underbrace{(\bar{3},2,-7/3)}_{\phi_{18}} + \underbrace{(6,1,8/3)}_{\phi_{19}} \\ & \qquad + \underbrace{(\bar{6},3,-2/3)}_{\phi_{20}} + \underbrace{(8,2,1)}_{\phi_{21}} \end{array}$$

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*) It is important to remark that a rare process like proton → three leptons - rare below 10^5 GeV - would become "normal", beyond the transition energy $\gg 10^5$ GeV.

One can show (from proton decay considerations) that m_2, m_{10}, m_{11}, m_{12}, $m_{17} \gg 10^{10}$ GeV. For the others (which mediate D^0-$\bar{D}^0$, B-$\bar{B}^0$, n-$\bar{n}$, H-$\bar{H}$ oscillations, neutrino mass and other rare processes) the deviations for the computed $\sin^2\theta(M_U)$ and τ_{proton} from the minimal SU(5) predictions provide the following constraints:

$$\sin^2\theta(m_W) = 0.210 - \frac{\alpha(m_W)}{36\pi}\,\ell n\left[\frac{m_W^2\, m_5^4\, m_6^7\, m_7^4\, m_9^2\, m_{11}^{24}\, m_{20}^{33}}{m_2^2\, m_3\, m_4^3\, m_8^{11}\, m_{10}^2\, m_{12}^7\, m_{14}^9\, m_{15}^4\, m_{16}^4\, m_{17}^2\, m_{18}^4\, m_{19}^{19}\, m_{21}^4}\right]$$

$$\tau_P = 1 \times 10^{30}\ \text{years} \times \left(\frac{m_W\ \ m_3\, m_6^5\, m_9\, m_{11}^3\, m_{12}^4\, m_{13}^7\, m_{16}^4\, m_{18}^7\, m_{19}^4}{m_2\, m_5\, m_7\, m_8^4\, m_{10}\, m_{14}^6\, m_{15}^8\, m_{17}\, m_{20}^6\, m_{21}^8}\right)^{2/33} .$$

Clearly these are not too restrictive constraints.

3. Another rich source of new fermions, new Higgs and new physics, which has been speculated upon arises from the desire to remove the family degeneracy, inherent in family groups like SU(5) and SO(10).

One assumes that there exist trival unifying symmetries like SU(7) incorporating two of the known families (besides many new fermions), or SU(11) incorporating all the three families or SO(14) incorporating two of the known plus two mirror families or SO(10) × SO(10) or SU(5) × SU(5), etc. One then starts over again with new Higgs to mediate the breaking of these symmetries, and to push the unwanted fermions to higher unobserved masses. The variety of such symmetries and their fermionic and suggested Higgs content is so large that it would be pointless to list them here. Such symmetries would of course give rise to flavour changing neutral currents whose strength may be expected to be $\approx 1/M_F^2$, which is the characteristic mass scale at which these tribal symmetries break down to the simpler family symmetries like SU(5) or SO(10). Particularly relevant in this context would be the precise rate of determination of rare decays like $K_L \to \mu^+e^-$, etc., which can of course be undertaken at present accelerators, though their cross-sections would have "normal" rates beyond the "transition" energies of the relevant Higgs.

V. RICHNESS ASSOCIATED WITH SUPERSYMMETRY

Besides the family problem, the most troublesome problem for grand unification ideas is the hierarchy problem - the "naturalness" of large numbers like $M_U/m_W \sim 10^{12}$ in a perturbative context. Supersymmetry has been suggested as a way out of this but even without this to commend it, supersymmetry - and its promise of richess of physics - must be taken very seriously.

Supersymmetry - the symmetry between fermions and bosons - is an incredible symmetry. It could have been discovered at any time subsequent to 1935 after the canons of quantum theory of fields had been established. However, even in 1971 when it was first conceived of in the USSR, its existence went unnoticed and its significance missed. The situation persisted till the symmetry was rediscovered in 1973. And even thereafter, though one recognized quite early its elegance, the freedom of supersymmetric Lagrangians from field-theoretic infinities, and the remarkable positivity of supersymmetric Hamiltonians, the fact that there is no direct evidence for its existence at the low energies hitherto available has meant its being somewhat ignored hitherto.

The hierarchy problem arises because there is no mechanism in ordinary theories by which a spin-zero Higgs which starts life with a small mass ($\lesssim 100$ GeV) can protect itself from acquiring mass of the order of 10^{14} GeV(through its interactions with other Higgs which are needed by the theory with large (10^{14} GeV) mass). Thus radiative corrections destroy any hierarchy with which we may start. There is however a protective mechanism for fermions - chirality. So why not tie all bosons with corresponding fermions through supersymmetry? Thus in a supersymmetric SU(5) we may "protect" a $\underset{\sim}{5}$ and a $\underset{\sim}{\overline{10}}$ of Higgs by placing them in the same supersymmetric multiplets as the $\underset{\sim}{5}$ and $\underset{\sim}{\overline{10}}$ of the fermions. Remember the doublet in the $\underset{\sim}{5}$-fold of Higgs was needed (around 100 GeV) to act as the familiar Higgs of SU(3) x SU(2) x U(1).

Unfortunately things are not all that simple. We do want, for example, the triplet contained inside the $\underset{\sim}{5}$-fold of Higgs to be as massive as 10^{14} GeV so as not to enhance proton decay rate. These conflicting phenomenological requirements (of a light doublet versus a heavy triplet inside the same $\underset{\sim}{5}$) can be met - as a rule by the standard device of doubling everything (if one $\underset{\sim}{5}$-fold does not work, take two) - but this needs a careful adjustment of parameters.

For normal renormalizable field theories, radiative corrections destroy such careful adjustments, but amazingly enough, not for supersymmetric theories, where they are stable. As a rule, after the adjustments and the doublings of the multiplets the final supersymmetric grand unifying theories which emerge are baroque affairs. Presumably, with experience, this will be set right.

But the major question which remains open in this: What is the scale of supersymmetry breaking m_S? It turns out that there are two theoretical choices. One is ≈ 1 TeV and the other is much higher around $m_S = (m_W m_{Planck})^{1/2}$. $\approx 10^{10}$-10^{11} GeV. But even for the higher scale m_S one must emphasize that there is a promise of experimental signatures for lower than TeV energies, since the supersymmetric partners in such models can acquire masses differing by $(\frac{\alpha}{\pi})^n m_S$.

What are the signatures? All quarks and leptons have scalar partners "squarks" and "sleptons"; all gauge particles have fermion partners, gluinos ($\tilde{g}$), photinos $\tilde{\gamma}$, W-inos, Z-inos, etc. For supersymmetry breaking in the TeV range, the photinos may be expected below a few GeV and gluinos around 30 GeV. Present experimental analyses place only meagre limits on the $m_{\tilde{g}} \gtrsim 2$ GeV, $m_{sleptons} \gtrsim 16$ GeV.

So much for global supersymmetry. However, supersymmetry like all symmetries can be gauged, and the gauge particles turn out to be the graviton and its fermionic partner of spin $\frac{3}{2}$ - the gravitino. Clearly, if we wish to unite gravity with other forces, a gauging of supersymmetric grand unifying models is one way to accomplish this. As we shall see, in the next section, the ultimate expression of this line of thought is the self-gauged "N = 8 extended supergravity theory" which possesses a unique multiplet (with a unique self-coupling) consisting of one graviton, eight gravitinos, twenty-eight vector mesons, fifty-six spin $\frac{1}{2}$ two-component objects and seventy scalars. Can this multiplet and its self-interaction accomodate all known particles, their symmetries, and their interactions? The answer turns out to be NO; we shall examine this further in the next section on preons.

Let us for the moment be content with the humbler version of supergravity, where a supersymmetric grand unifying model like SU(5) interacts with the simplest version N = 1 of a supergravity multiplet, consisting of one graviton and one gravitino. What mass does the gravitino acquire on account of supersymmetry breaking? A simple way to compute this is to observe that in such a theory a cosmological constant arises which can be made to acquire its empirically determined value of "zero" by giving the gravitino a mass of $\approx m_S^2/m_{Planck}$. This could be as small as $\approx 10^{-16}$ GeV or as large as $\approx m_W$ (or larger) depending on at what energy (m_S) supersymmetry breaks. Since the helicity $\frac{1}{2}$ component of the gravitino has been shown by Fayet to have an effective interaction of strength E^2/m_S^2 for the lower value of gravitono mass (in the electron-volt range) its coupling could be large; on the other hand, with the higher scale for m_S, there is the exciting possibility that (the spin $\frac{3}{2}$) gravitono pair production (with gravitinos of mass $\gtrsim m_W$) may provide an important search-project for the $p\bar{p}$ collider or for the higher energy accelerators. One must emphasize that we are still very far from a standard and favoured supergravity or even a supersymmetric model. My purpose in mentioning these ideas is merely to emphasize the richness which these prospects promise.

VI. THE NEXT LEVELS OF STRUCTURE; PREONS, PRE-PREONS.

As repeatedly emphasized already, the most mysterious aspect of present day phenomenology is the existence of apparently "similar" recurrences of families of fifteen two-component quarks and leptons. Whenever such recurrences have shown themselves to occur in the past, we have eventually uncovered a new layer of elementarity. Will this happen again, before the onset of the energy scale $M_U \approx 10^{14}$ GeV. Do quarks and leptons possess radii much larger than $(M_U)^{-1}$? The present limits on leptonic radii are only in the (10 TeV - 100 TeV)$^{-1}$ range, the precise values depending on the definition adopted. Clearly this will be one of the most beckoning tasks for experimental searches in the near future, to determine quark and lepton structure.

The simplest "preonic" model is the one which associates light fundamental entities, one each with four colours (c = red, yellow, blue and B-L), and one each with four flavours (f = up-left, down-left, up-right and down-right). If the four chromons (c) are spin-zero and four flavons (f) are spin $\frac{1}{2}$, there may even exist a supersymmetric version of the preonic theory with four basic supersymmetric multiplets, where supersymmetry breaking is synonymous with the emergence of colour and flavour quantum number and "composite" symmetries $SU_c(4) \times SU_L(2) \times SU_R(2)$.

The family distinctions can be built into the theory in diverse ways; one of the simplest (in a non-supersymmetric version of preonic theory) is to postulate three familons in addition to chromons and flavons, one for each family. If familons are (analogoue) dyons carrying (analogue) electric and magnetic charges (e,g) and chromons and flavons carry charges (-e,0) and (0,-g)(with $eg/4\pi = n/2$), the binding force could be an (analogue) magneto-electric U(1) force. Quarks, leptons, Higgs and SU(4) x SU(2) x SU(2) gauge particles would then be the uncharged composites of flavons, chromons and familons.

There are of course other versions of the preonic models. In one of these the unbroken SU(3) of colour and U(1) of electromagnetism are accorded a privileged status as truly fundamental forces with "elementary" gauge particles associated with them, while the $W^{\pm}$, Z^0 of the electro-weak force are composites. The "elementary" preonic fermions are assumed to be $(3,\bar{3})_{L,R}$ and $(3,3)_{L,R}$ of a $SU(3)_{\text{hyper- colour}} \times SU(3)_{\text{colour}} \times U(1) \times U(1)$ with the new strong hyper-colour gauge force binding the preons together. The family distinctions are brought in, through varying the numbers of preonic pairs in the composites.

Finally, there is the supergravity preonic model which treats the unique N = 8 supergravity multiplet as referring to preons rather than to quarks, leptons and Higgs, etc. *) I shall not describe this version of the theory in any further detail except to remark that the model may accomodate (a chiral) SU(5) grand unifying theory, though the question of whether the three families do indeed emerge as composites is not fully settled. However it is clear that if this preonic model is the correct one, the quark and leptonic radii are not likely to be larger than inverse Planck mass $\approx (10^{19}\text{ GeV})^{-1}$.

In the preonic context, an important question is to state criteria which guarantee that if preons are (chirally protected) massless fermions, the composites are massless as well. 't Hooft has attempted to formulate such criteria in terms of anomaly-matching of preonic multiplets with the expected mutliplets of composite bound states. These criteria have proved

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*) If it is assumed that the N = 8 supergravity theory describes physical quarks and leptons and physical gauge particles, the maximal classifying group cannot be larger than the vectorial $SU_{\text{colour}}(4) \times U_{L+R}(1)$. The $SU(4)_{\text{colour}}$ may break into $SU_c(3) \times U(1)_{B-L}$. For this picture $W^{\pm}$, Z^0 must in any case be treated as composites; so must the muon, the taon and the b-quark. It seems preferable therefore to treat all the objects in the multiplet on par as preons and to make all the known particles as composites of these.

difficult for realistic models *) to satisfy and have led 't Hooft to suggest that a high degree of complexity in particle spectrum seems unavoidable. Stated differently, there may be an unending chain of "elementary" structures, quarks, preons, pre-preons,... associated with an unending chain of gauge groups SU(3), SU(4), SU(5),..., SU(N), where $N \to \infty$ on a linear energy scale. Presumably with this scenario never will the (accelerator) physicist be at a loss for new discoveries!

Contrast this with the view advocated by some of us that the preon, pre-preon,... chain may end "monotheistically" with one unique multiplet of one unique symmetry. I have mentioned N = 8 supergravity preonic theory in this context. There is a uniquer supersymmetry, the N = 4 supersymmetry with the particle types $\underset{\sim}{1}$ vector particle, $\underset{\sim}{\text{four}}$ (Majorana) fermions and $\underset{\sim}{\text{six}}$ (real) scalars, all in the adjoint representation of a non-Abelian symmetry group **) (like SU(2)). This theory has been shown to have no infinities whatsoever - even when the fermions and scalars are (N = 2 supersymmetrically) massive. And it may be the only theory in particle physics to exhibit this finiteness. Furthermore, Grisaru and Schnitzer have shown that a Reggeization of this theory could lead to a set of composites - none other than the N = 8 preons mentioned above, while Osborn **) has shown that the theory also possesses solitonic solutions which form a dual multiplet (of one vector, four fermionic and six bosonic triplets of SU(2)) which in its turn describes magnetic monopoles. (Since there is no renormalization of charge, there is no problem of whether it is the unrenormalized electric (e) and magnetic charges (g) or the renormalized ones which satisfy the Dirac condition $eg/4\pi = n/2$. In this dyonic form, is this the ultimate pre-preonic multiplet of which preons and then

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*) One simple model (due to Albright, Schremp and Schremp) where a part of these criteria are met contains preons $(\underline{3},\underline{6},\underline{1})_L$ and $(\underline{3},\underline{1},\underline{6})_R$ of $[SU(3)_{\text{hyper-colour}} \times SU_L(6) \times SU_R(6) \times U_{L+R}(1)]$ symmetry with $(\underline{1},\underline{6},\underline{15})$ and $(\underline{1},\underline{\overline{15}},\underline{\overline{16}})$ of composite quarks and leptons. A notable prediction of this model (shared also by the simplest flavon-chromon model) is the lack of universality of taon-couplings with e, μ couplings (e.g. $e^+e^- \to \tau^+\tau^-$ should exhibit vanishing charge asymmetry).

**) The internal symmetry SU(P) may not be unique, except possibly for the case when we wish this spectrum to represent dyons when $p = 2$ is the simplest choice.

quarks and leptons are composed? An important experimental question will be: what are the mass parameters associated with this multiplet? *)

VII. CONCLUDING REMARKS

High energy physics is an intoxicating subject - every generation has felt that it has nearly scaled the truth, and perhaps after the ideas it has espoused have been worked out, there will be a desert of basic principles. And every generation has been proved wrong in the past.

I have concentrated in this lecture on the physics riches which we can now perceive may be in store for future accelerator physics. These concern the physics associated with Higgs in grand unifying theories, physics associated with supersymmetry and with preonic ideas. I have not spoken of the dimly-perceived prospects — like those arising out of extra space-time dimensions and the Kaluza-Klein theories which live on them. Such ideas are intimately related to the prospects of supergravity theories, particularly the N = 8 theory whose most natural formulation is in terms of compactified eleven-dimensional space-time, and will presumably become relevant at much higher energies.

What physics is likely to be associated with the extra dimensions? Do they hold the secret of the charge concept? **) What is the topology of

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*) This same N = 4 supersymmetric theory in four space-time dimensions can also be looked upon as a compactified N = 1 supersymmetry in ten space-time dimensions. In this elegant form, there is a unique internal symmetry group which can be married to it - the E_8 symmetry group. A grand unified theory based on these ideas has been worked out recently by D. Olive and P. West, Imperial College, preprint (1982).

**) In this half century, in the science of biology, the analogue of our universal gauge principle was found in 1953 with the discovery of the double helix. However, this has not obscured from the biologist the fact that far from being the "end of molecular biology" this was only a beginning. "Something quite essential is missing in our basic understanding of life and we have not the slightest idea about the nature of lacunae in our knowledge", "The End of Molecular Biology" by A. Sibatani, Trends in Biochemical Sciences, Vol.4, No.7 (Elsevier, 1979). I believe the same applies to particle physics with the unsolved problem of the nature of charge.

these compactified spaces; What is their likely relationship to the cosmology of the early Universe? What is the likely resolution of the unseasonably large cosmological constant such theories appear to support.. As Nahm has stressed, are we likely to discover a new principle (perhaps with low energy experimentation) like the equivalence principle, in the context of an empirically vanishing cosmological constant. As I said these are dimly perceived questions at present. But before we grow too wildly speculative, we need experimental direction. And the amazing aspect of the interaction of theory and experiment is that even one well-conceived experiment can be the decisive pointer to give direction to our speculations. We are here to-day to ensure that experiment and theory do not get out of phase in this regard.