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Particle physics today

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ABSTRACT. — A review of particle physics (today) is attempted in this paper.

RÉSUMÉ. — Cet article tente de faire une revue de la physique actuelle des particules.

I. OVERVIEW OF PARTICLE PHYSICS

In the past, Particle Physics was driven by a troika which consisted of (1) Theory, (2) Experiment, and (3) Accelerator and Detection-Devices technology. To this troika have been added two more horses. Particle Physics is now synonymous with (4) Early cosmology (from 10^{-43} sec. up to the end of the first three minutes of the Universe's life) and (5) it is strongly interacting with Pure Mathematics. One may recall Res Jost who made the statement (towards the end of the 1950's) that all the mathematics which a particle physicist needed to know was a rudimentary knowledge of Latin and Greek alphabets so that one can populate ones' equations with indices. This is no longer true today.

The situation in this regard has changed so drastically that a theoretical particle physicist must now know algebraic geometry, topology, Riemann surface theory, index theorems and the like. More mathematics that one knows, the deeper the insights one may aspire for.

In the last decade or so, in particle physics, we are experiencing an age of great synthesis and of great vitality. At the same time, this is an age of great danger for the future of the subject in the sense that we need higher

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and higher accelerator energies, and more costly non-accelerator and passive underground experiments (which take a greater injection of funds as well as longer experimentation times), for discovering new phenomena or for testing the truth or the inadequacy of theoretical concepts. This is in contrast to the time when I started research (late forties and early fifties) when we had ever-increasing quantities of undigested experimental data, and theoretical vignettes of great beauty and power, but little *coherent* corpus of concepts.

II. THREE TYPES OF IDEAS

We shall divide our remarks into three topics: A) Ideas which have been tested or will soon be tested with accelerators which are in existence or presently being constructed; B) Theoretical ideas whose time has not yet come (so far as the availability of accelerators to test them goes), but hopefully the situation may change before the year 2 000 AD; and C) Passive, non-accelerator experiments which have tested — but not conclusively so far — some of the theories of the 1970's. To give a brief summary, consider each of these three topics in turn.

A) *Ideas which have been tested or will soon be tested.* These include *i*) the standard model based on the symmetry group $SU_c(3) \times SU_L(2) \times U(1)$, with which there is no discrepancy known at the present time.

ii) Light Higgs which may be discovered soon at SLC or at LEP.

iii) The fourth family which may be easily incorporated into the standard model.

iv) Preons of which quarks may be made up. (Light preons (if they exist) may be discovered at HERA (after 1991) and may fetch a new slant on the family problem, and on the problem of quark elementarity).

v) $N=1$ supergravity for «light» supersymmetric particles below 100 GeV.

B) *Theoretical ideas whose time has not yet come (from supersymmetry to the Theory of Everything [T. O. E.]);* basically because accelerators to test them are not yet commissioned. These ideas include *i*) $N = 1$ supersymmetry and $N = 1$ supergravity. (The lower limit for supersymmetric partners for presently known particles appears to be rising and may now be as large as 50 GeV.) Persuasive theoretical arguments would lead us to expect that supersymmetric partners of quarks and leptons may exist below 1 TeV. To find these (if they are more massive than 100 GeV), we shall need LHC (large hadron collider in the LEP tunnel), or SSC (superconducting supercollider being considered in the USA), or an e^+e^- collider with centre of mass energy in the TeV range. *ii*) The same remark goes for heavy Higgs.

Other ideas in this category which also need higher energies are

iii) Right-handed weak currents. *iv*) The massive axial colour gluons in an $SU_V(3) \times SU_A(3)$ extension of the strong interaction sector of the standard model. *v*) The mirror quarks needed to cancel the axial-colour SU(3) anomaly (or other heavy quark multiplets needed for the same purpose) and *vi*) Superstrings. (The axial colour gluons interfering with vector gluons may give the simplest explanation of the spin dependence of scattering of polarised protons as well as of the left-right asymmetry observed by Krisch and collaborators in *pp* scattering up to 30 GeV.)
There is no dearth of theoretical ideas to test.

C) *The set of ideas for which non-accelerator and passive underground experiments have been, or should be, mounted (these ideas mainly refer to grand unified theories, neutrino masses and astro-particle physics).* These are mostly concerned with neutrino physics and the grand unification of electroweak and strong forces in their multifarious ramifications and include *i*) Proton decays. *ii*) Dark and shadow matter. *iii*) Neutrino masses and possible oscillations. *iv*) Solar neutrino problem. *v*) Neutrino astrophysics with supernova and *vi*) double β-decay.

Let us now consider in more detail each of these topics in turn.

III. IDEAS WHICH HAVE BEEN TESTED OR WILL SOON BE TESTED

While we are discussing the availability of future accelerators, one must remember the following.

1) For the circular accelerators, the bending magnet may be improved by Superconductivity Technology, but the real limitation is due to synchrotron radiation $\alpha(E^4)$. The cost and size of the accelerator increase as E^2.

2) For linear accelerators, the highest *Electric Field* gradients achievable with to-day's technology, are at most around 1/10 GV per metre (*). Twenty years hence (when, for example, we may have mastered the technology of laser beat-wave plasma accelerators) this gradient may go up by a factor of 1 000-i. e. 1/10 TV per metre. This may mean that a 30 km long accelerator would produce centre of mass Energy $(\sqrt{s}) \simeq 10^4$ TeV.

(*) To be crazy, an accelerator around the moon may generate 10^6 TeV; an accelerator around the earth—as Fermi once conceived—may be capable of $\sqrt{s} = 10^7$ TeV, while an accelerator extending from earth to the sun would be capable of $\sqrt{s} \simeq 10^{11}$ TeV (with $E \simeq 1/10$ TV/metre). In the same crazy strain, for an accelerator to be capable of generating $\sqrt{s} \simeq 10^{16}$ TeV (the theoretically favoured, Planck Energy) one would need 10 light years.

3) Chen and Noble have shown that if one can use longitudinal electron plasma waves in a metal, the electron density is of the order of 10^{22} cm^3 (versus normal plasma densities of the order of 10^{14}-10^{18} cm^3) and we gain a factor of $\sqrt{n} \simeq 10^2$-10^3 (with the maximum energy limited to 10^5 TeV, on account of channeling radiation).

4) Similar estimates have been made by T. Tajima and M. Cavenago, who have considered the crystal X-ray accelerators.

Clearly one must eventually fall back on the highest energy cosmic rays —to study, for example, the likes of the recently discovered high energy muon signals in the Nusex (Mont-Blanc) and Soudan I experiments. These muons (produced in the atmosphere), can apparently be traced back to a cosmological accelerator associated with Cygnus X3—an X-ray source discovered in 1966, some 37 thousand light years distant from us, which has a duty cycle of 4.8 hours and an integrated luminosity of 10^5 suns.

From the muon signals, recent Kiel, Nusex and Soudan experiments have claimed that Cygnus X-3 beaming to us high-energy radiation of neutral variety. If this experimental evidence is taken at its face value, how is the radiation beamed at us by Cygnus X3 generated? Cygnus X-3 has been called the HERA of the sky. One speculative idea is that the Cygnus system may consist of a binary star—a conventional main sequence star plus a pulsar or a black-hole. Matter from the conventional star accretes around the compact pulsar or the black hole, forming a disc. The protons thus accelerated go into a beam dump, wherein is created the mysterious radiation, which hits our atmosphere and makes the observed muons. The secondary beams from this dump will contain photons and neutrinos ($P \to w^0 \to \gamma$ and $P \to w^+ \to \nu$).

A new generation of cosmic ray experiments can measure photoproduction for γ-energies exceeding 100 TeV, using tagged photon beams emitted by cosmic accelerators. It has been estimated that Cygnus X-3 could emit as many as 10^5 photons/km^2/year with energies exceeding 100 TeV.

According to Halzen, « These experiments, although motivated by astronomy, should be of interest to particle physics as they are unlikely to be ever performed with accelerators in the early future. They also avoid the classical pitfalls of present cosmic ray experiments in this energy range as *i*) they can achieve reasonable statistics with good signal/noise, *ii*) they use a beam of known composition (i. e. photons) and *iii*) they observe showers whose development in the air is dictated by QED and therefore calculable so that unusual phenomena can be unambiguously interpreted as new physics. They can at the least, provide us with a first look at the energy regime probed by future supercolliders ».

Are there likely to be available more intense and more energetic sources than Cygnus X-3 in the sky ?

IV. THE STANDARD MODEL, AND ROLE OF FERMI MASS OF 300 GeV

1. The standard model of to-day's particle physics describes three replicated families of quarks and leptons. The first family consists of the so-called up and down quarks (u_L, d_L) and (u_R, d_R) quarks (L and R stand for left and right « chirality » of spin 1/2 particles). Each quark comes in three colours: red, yellow and blue. There are, in addition, 3 colourless leptons (e_L, v_L) and e_R. Thus this family has 12 quarks and 3 leptons (altogether 15 two-component objects).

The second family has charm and strange quarks (c, s) (replacing the up and down (u, d) quarks) while the electron and its neutrino are replaced by the muon and its neutrino. Like the first family, there are 15 two-component objects. The third family likewise consists of top and bottom (t, b) quarks plus the tauon and its neutrino.

In addition to these $45 = 3 \times 15$ [spin 1/2 two-component] objects there are the 12 Yang-Mills-Shaw gauge spin 1 mediators corresponding to the symmetry $SU_c(3) \times SU_L(2) \times U(1)$—the photon γ, $W^{\pm}$, Z^0 and light gluons. Nine of these (γ and eight gluons) are massless. In addition, there should be at least one physical spin-zero Higgs H^0 giving a total minimum of 118 degrees ($118 = 3 \times 15 \times 2 + 9 \times 2 + 3 \times 3 + 1$) of freedom for the particles in the standard model. All particles except the top quark and the Higgs in this list have been discovered and their masses and spins determined. In this context it is worth remarking that CERN data from $Sp\bar{p}S$ have confirmed *the theoretical (ree diagram) expectation* of $W^{\pm}$, Z^0 masses to within 1 %. Experiments give 81.8 ± 1.5 GeV for $W^{\pm}$ and 92.6 ± 1.7 GeV for Z^0 masses. The model is semi-unified in the sense that although the γ and Z^0 mix, the magnitude of the mixing is expressed as a parameter ($\sin^2 \theta$) in the theory to be fixed by experiment. The unification happens on Fermi mass scales which, according to the standard cosmological model, occurred when the Universe was 10^{-12} secs. old. Before this phase transition occurred, there were three fundamental forces (electroweak, strong and gravitational). Afterwards, the electroweak force separated into electromagnetism and the weak nuclear force, with $W^{\pm}$ and Z^0 being massive.

2. Family mixing of quarks (and leptons).

The quarks families can mix. A measure of the mixing is provided by the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix V with experimentally determined matrix elements.

If $V_{ud} = \text{Cos}\ \theta\ \text{Cos}\ \beta$, and $V_{tb} = \text{Cos}\ \beta\ \text{Cos}\ \gamma$, then $\theta = (12.74 \pm .11)^0$,

$\beta=(0\pm.43)^0$, $\gamma=(2.72\pm.038)^0$. Note that, $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=1.0014$ which is in good accord with the prediction of unity for this number. « This must be considered a significant triumph for the standard model one-loop radiative corrections, since without these corrections unitarity would be violated ». (Marciano, Berkeley Conference, Summer 1986.) As we shall see later, the major problem within the standard model is to find a theoretical basis for the CKM matrix.

3. The limits on the Fourth Family.

A lower bound on mass of a new sequential charged lepton L in a fourth family has been experimentally given as

$$m_L > 41 \text{ GeV}$$

obtained by UA1 from missing E_T sample ($W \rightarrow L\nu_L$, assuming ν_L is massless). This would provide a constraint on new sequential families; for example, *assuming*

$$m_s/m_\mu = m_b/m_\tau = m_{b'}/m_{\tau'}$$

we would obtain $m_{b'} > 120$ GeV. If we further assume that $m_{t'} \gg m_{b'}$ then such a further family would already be excluded by the agreement of $\rho_{\nu N}$ with present experimental data.

4. The Higgs Story.

So far as the Higgs particle is concerned, theory does not specify its mass. Defining with Kane, a *light Higgs* as an object with a mass $< 1/2\ M_Z$, an *intermediate* Higgs with a mass $< 2\ M_Z$, a *heavy* Higgs with mass up to 700 GeV and an *obese* Higgs with a mass beyond, one may remark that certainly for an *obese* Higgs, the concept of a particle would be lost since it would have a large width. (In this case, the W and Z would interact strongly. One would then expect a new spectroscopy of bound states and Regge trajectories, which may include spin 1 resonances. No one likes this possibility, but it could happen.)

In 1985, G. Kane showed the possible signals of the standard model Higgs. Beyond a mass of 60 GeV, one would need the LEP II accelerator to detect these and eventually the LHC and the SSC supercollider if the mass is higher still.

5. The Top Quark. The « discovery » of the top quark claimed during 1985 has been further questioned.

Lower Limits to the mass are provided by $m_t > 23\text{-}25$ GeV (Petra, Tristan) and by the « direct » (UA1) Experiment which suggests $m_t > 41$ GeV

(95 % confidence level). Assuming a Standard Model with three families, a number of analyses of the ARGUS experiments on $B\bar{B}$ mixing appear to indicate $m_t > 45\text{-}100$ GeV. Thus the top mass is being pushed up. Upper limits of course exist ($<$ 220 GeV from the smallness of radiative corrections of the ρ parameter of neutral currents).

6. Consolidation of the Standard Model.

In 1987 at the Uppsala Conference, there has been a further consolidation of the standard model (see Altarelli's report, Uppsala Conference, 1987).

The examples of relevant experiments reported are:

a) Second class currents in τ decay ferociously killed-Skwarmicki.

b) Equal sign dimuons in ν-N diseased-Sciulli.

c) 2σ anomaly in $e^+e^- \to \mu^+\mu^-$ asymmetry (if any) reduced with statistics-Grunshe.

7. Number of light neutrinos.

One of the measurements which was first reported during 1985, relevant to the number of families in the standard model, is the estimate of the number of *light* neutrinos which may couple to the Z^0 particle. This number was estimated from the collider measurements (on Z^0 width) to be $< 5.4 \pm 1$-consistent with the 3 or 4 which cosmological data would appear to favour. (See also data from SNa (1987) (see paragraph IX, E).) No longer can one say with Landau « Cosmologists are seldom right, but never in doubt ». They could be right this time!

8. Radiative Corrections.

A set of experiments which would be carried out at SLC and LEP concern the radiative corrections to the tree level predictions of the standard model in the electroweak sector have been emphasized by Lynn.

Assuming that Z^0 mass will be measured with extreme accuracy at SLC or LEP (up to 50 MeV or possibly better), one could then propose clean tests of the electroweak theory at the one loop level. These could consist of measurements of one loop level longitudinal polarization, measurement of W mass and measurement of neutrino $\sigma(\nu e)/\sigma(\nu e)$ ratio.

Consider the case of the longitudinal polarization in A_{LR}. On top of the Z^0 resonance, the one loop prediction is $\delta A_{LR}^{GSW} = -.03$ for $m_H = 100$ GeV, $m_t = 30$ GeV. A (new) heavy quark pair would contribute $+.02$, a heavy scalar lepton pair another $+.012$ and so on. *Thus one may hope to determine from the comparative measurements of* δA_{LR}, δM_W, *etc., the top quark* *mass or the Higgs mass or the existence of new heavy quark pairs, etc. in an indirect fashion.*

Recently, Blondel, Lynn, Renard and Verzegnassi (1987) have proposed to consider new kinds of asymmetries—for example, polarized forward-backward asymmetries $\mathrm{AF}_{\mathrm{FB}}^{\mathrm{pol}\,(f)}$ for the final (f) heavy quark $b\bar{b}$, $c\bar{c}$ state. The combined use of these, and of the longitudinal polarization asymmetry A_{LR}, would allow radiative corrections of different origin (heavy quarks, new neutral gauge bosons, etc.) to be separately identified and measured since these corrections are, in general, different for the different asymmetries. One could therefore, in principle, determine from these combined precision measurements whether, for example, new neutral gauge bosons exist or not.

V. IDEAS WHOSE TIME HAS NOT YET COME

A) The most important idea in this category is: N = 1 supersymmetry and N = 1 supergravity. N = 1 supersymmetry is the hypothetical symmetry (between fermions and bosons) which decrees that a spin 1/2 must be accompanied by a spin zero particle: a spin one gauge particle must be accompanied by a massless spin 1/2 particle (gaugino: a massless spin 2 graviton must be accompanied by one (N = 1) massless spin 3/2 gravitino, and so forth. (For N = 2 extended supersymmetry, one would group in one multiplet, two spin zeros, two spin 1/2's and one spin 1 object. Such a theory would contain two gravitinos. Thus, the nomenclature N = 2.) For the maximal N = 8 extended supersymmetry, there is just one supermultiplet containing one spin 2, accompanied by *eight* spin 3/2 gravitinos (N = 8), *28* spin 1 gauginos, *56* spin 1/2 and *70* spin 0 states.

Supersymmetry is an incredibly beautiful theory—a compelling theory if there is one, even though there is no physical evidence of the existence of any supersymmetry partners to the known particles.

One aspect of its compellingness lies in its superior renormalisability properties and the possibility which these open up of understanding why the hierarchical large numbers which occur in particle physics could arise « naturally ».

Consider as an example one of the « large number », $m_{\mathrm{P}}/m_{\mathrm{W}} = 10^{17}$ where m_{P} is Planck mass. ((Planck mass)$^{-2}$ is the measure of the Newtonian constant: Planck mass thus occurs naturally for gravity theories. Large numbers similar to $m_{\mathrm{P}}/m_{\mathrm{W}}$ can however occur in all grand unification theories which synthesis electroweak with strong forces.) Now in supersymmetric theories one can demonstrate that such a number, *once fixed at the tree level*, would be unaffected by radiative corrections. This is one of the virtues of supersymmetric theories.

But supersymmetry must be a highly broken symmetry. What is the supersymmetry breaking mass? Or more physically, where do the missing supersymmetry partners of quarks, leptons, photons, W^+ and Z^0 lie? The theoretical expectation seems to be: Below 1 TeV, *if supersymmetry is relevant to the electro-weak phenomena.*

If such particles lie beyond 100 GeV, it is expected that supersymmetry may make itself manifest with *highly luminous* accelerators (e. g. LHC, SSC or an e^+e^- linear collider of > 1 TeV).

B. Supersymmetry and N = 1 supergravity.

About supersymmetry, note the following points:

1) The N = 1 supersymmetrisation of the standard model will need two multiplets of Higgs particles, i. e. five physical Higgs, H_1, H_2, H_3, $H^\pm$ (of which H_1 is light scalar, H_2 is heavy scalar and H_3 is pseudo-scalar).

2) The Signature of supersymmetry is the R quantum number which is $+1$ for all known particles and -1 for their supersymmetric partners. Thus (with beams of « old » particles) the new particles must be produced in pairs. Among the expected supersymmetry partners therefore, there must be a lowest mass *stable* object which must be neutral in order to survive survive the Big Bang. Further, it must be weakly coupled otherwise it will be concentrated in condensed form in the galaxies. The favoured candidates for this object are scalar neutrinos ν, photinos γ, Higgsinos or gravitinos—the spin 3/2 partners of the gravitons.

3) If N = 1 supersymmetry comes, N = 1 supergravity cannot be far behind. The argument goes as follows: the major theoretical problem regarding supersymmetry is supersymmetry breaking. The one *decent* known way to break supersymmetry is to break it spontaneously. For this to work, one starts with a gauge theory of supersymmetry-i. e. a supergravity theory which (for the N = 1 case), would contain one spin 3/2 gravitino for every spin 2 graviton. One would then postulate a super-Higgs effect-i. e. a spin 1/2 and spin zero matter multiplet (of « shadow » matter which interacts with known particles only gravitationally). The spin 1/2 member of this multiplet would be swallowed by the spin 3/2 gravitino —the latter becoming massive in the classic Higgs fashion to break supersymmetry spontaneously. The (mass)^2 of the gravitino —in analogy with the standard Higgs effect—could then be of the order of the gravity coupling parameter $(1/m_p^2)$ times the expectation value of the supersymmetry breaking potential $(m_{3/2}^2 \simeq 1/m_p^2 \langle 0 | V | 0 \rangle)$.

One of the major unsolved problems of our subject is that of the cosmological constant and its value, which is empirically very near to zero $(\simeq 10^{-120} m_p^2)$. For N = 1 supersymmetry, this number is identically zero, but supersymmetry is manifestly broken. How can we understand the tiny value of this constant?

VI. UNIFICATION OF GRAVITY WITH OTHER FORCES

So far we have considered ($N = 1$) supergravity, as following on the heels of ($N = 1$) supersymmetry in order to provide for an orderly breaking of supersymmetry—there was no true unification of gravity with other forces. Let us now discuss a true unification of gravity with the rest of particle physics.

1. History of Unification of Gravity with Other Forces.

The first physicist to conceive of gravity unifying with electromagnetism and to try to look for experimental evidence for such a phenomenon was Michael Faraday. The failure of this attempt did not dismay Faraday. Fresh from his triumph with unifying electricity with magnetism, he wrote: « If the hope should prove well founded, how great and mighty and sublime in its hitherto unchangeable character is the force I am trying to deal with, and how large may be the new domain of knowledge that may be opened to the mind of man. »

2. Compactification from Higher Dimensions.

The first semi-successful theoretical attempt (in the 1920's) to unify gravity with electromagnetism was that of Kaluza (and following him that of Klein) who showed in a theory based on a *5 dimensional space-time*, that the appropriate curvature component in the fifth dimension, corresponds to electromagnetism. Further, if the fifth dimension happens (somehow) to be compactified to a scale R, and charged matter is introduced into the theory, one can show that the fine structure constant a and Newton's constant G must be related as $\alpha \simeq G/R^2$. Incredible audacity-first, to conceive of a fifth dimension, secondly to suggest that, unlike the other four dimensions, the fifth must be compactified to a scale of length R as small as $\simeq \sqrt{G/\alpha} \simeq 10^{-33}$ cms. These ideas were beautifully generalised in an extended supergravity context, when Cremmer and Julia discovered in 1979 that the extended $N = 8$ supergravity in 4 dimensions emerges as the zero mass limit of the compactified $N = 1$ supergravity in 11 dimensions. Technically, this was an astounding achievement. Since 1979, all supergravitators have lived in higher dimensions.

At that time, this theory was hailed as the first T. O. E. (Theory of Everything). If this could be physically motivated as a spontaneously-induced phase transition the compactification of eleven dimensional Kaluza-Klein supergravity down to four dimensions should give, in its zero mass sector, gravitons as well as gauge particles like spin—one photon γ, $W^{\pm}$ and Z, as well as the 56 fermions—all part of the unique multiplet of $N = 8$ supergravity. Unfortunately, the $N = 8$ theory and this particular multiplet suffered from two fatal defects: the fermions were not chiral and the theory did not have the content of the standard model so far as quarks, leptons or even the $W^{\pm}$ were concerned. And, in addition to the zero mass vector, there would, of course, be higher Planck mass particles ($(\text{mass})^2 \simeq$ multiples of $1/R^2$—the so-called pyrgons)—providing another embarrassment of riches.

Can one ever obtain direct evidence for the existence of higher dimensions? The answer is, possibly yes. If the extra dimensions happen to have been compactified through a spontaneous compactification mechanism (which, ideally, should be a part of this theory)—why should they remain compactified for ever? Why should these extra dimensions not share the Universal expansion? Could $\dot{R} \neq 0$? Since α, G and R are expected to be related to each other—if we are fortunate and if $\dot{\alpha}/\alpha$ and/or $\dot{G}/G$ should turn out to be non-zero at the present experimental level, such an effect might most simply be explained by postulating extra dimensions and their expansion at the present spoch. The experimental limits happen to be less than $1 \times (10^{17}\ \text{years})^{-1}$ for $\dot{\alpha}/\alpha$ while $\dot{G}/G$ is less than $1 \times (10^{11}\ \text{years})^{-1}$ at present. A definite non-zero answer would be most welcome.

3. **Anomaly-free Supergravities.**

Strictly for supergravity theories, where do we stand theoretically to-day so far as higher dimensions are concerned? It would appear that the only theories which may combine *chiral* fermions and gravity are the $N = 1$ in ten dimensions or $N = 2$ supergravity in six (or in ten dimensional) spacetimes. In order that such theories contain the known chiral quarks and leptons (as well as the W's and Z and photons and gluons) the most promising is the $N = 1$ supergravity in ten dimensions, *but it would have to be supplemented with a supersymmetric Yang-Mills multiplet of matter in addition to the supergravity multiplet.* Thus a pure Kaluza-Klein supergravity will never be sufficient. Higher dimensions, may be yes; but to generate the known gauge theories of electroweak and strong forces, we need in addition (higher dimensional) super-Yang Mills.

As if this was not trouble enough, both $d = 6$ or $d = 10$ theories were shown to be anomalous and also replete with gravitational infinities. This impasse was broken only in autumn 1984 by Green and Schwarz who showed that $N = 1$ supergravity in ten dimensions with an added Yang-Mills in SO(32) (or $E_8 \times E_8$) could be made anomaly-free by the addition of a certain number of new terms.

Green and Schwarz further showed that these additional terms were already present in the supersymmetric string theories (see Sec VII) in ten dimensions. An this brings us to the new world of superstrings and the new version of A Theory of Everything (T. O. E.).)

VII. SPINNING SUPERSYMMETRIC STRINGS

A) A closed string is a (one-dimensional) loop which may live in a d-dimensional space-time ($d = 4, \ldots$ or $10, \ldots$ or 26). The string replaces the *point particle* (in d-space-time, with which conventional field theory works). The quantum oscillations of the string correspond to particles of higher-spins and higher masses, which may be strung on a linear trajectory in a spin-versus-mass^2 (Regge) plot. If the slope parameter of this trajectory—the only parameter in the theory—is adjusted to equal Newtonian constant, one can show that there is contained in the spectrum of the *closed* string theory, the spin 2 graviton, with zero mass.

In its first modern version, the theory was $N = 1$ supersymmetric and was formulated in $d = 10$ dimensions. This supersymmetric version of string theory could exist in a « heterotic » form (descended from $d = 26$) and was invented by Gross and his collaborators. The theory has a built-in Yang-Mills gauge symmetry. The gauge group G must be of rank 16 which could *uniquely* be $G = SO(32)/Z_2$ or $E_8 \times E_8$. The theory is chiral and anomaly-free. The descent from 26 to 10 dimensions is accomplished by a compactification on a sixteen-torus ($26 - 10 = 16$) which—using the beautiful results of Frenkel and Kac—reproduces the full complement of 496 Yang-Mills massless gauge particles associated with $SO(32)/Z_2$ or $E_8 \times E_8$ even though we started with only 16 gauge particles corresponding to the 16-torus. The remaining 480 gauge particles are the solitons in the theory—a purely « stringy » effect. The hope is that such a theory may also be finite to all loop orders—the only finite theory of physics containing quantum gravity. It is these remarkable features of superstring theories which made the string-theorist « purr » with deserved pride.

Can we proceed from 10 down to 4 physical dimensions? Early in 1985, Witten and his collaborators showed that the 10 dimensional theory can indeed be compactified to 4 dimensional Minkowski spacetime × an internal six-dimensional manifold with SU(3) holonomy (a Calabi-Yau space) which preserves a chiral residual $N = 1$ supersymmetry in 4-dimensions. A number of families emerge; their count is equal to 1/2 of the Euler number of the compactified space. The Yukawa couplings allowed in the theory are expected to be topologically determined.

But could the heterotic string theory be formulated in four-dimensional space time in the first place. The answer is YES, as we shall see.

B. String Theory as the « Theory of Everything » (T. O. E.).

Could the heterotic theory be the long-awaited unified theory of all low energy phenomena in Nature? The amazing part of this story is that —on account of its conformal properties, the equivalence principle of Einstein emerges from the theory, and does not have to be built in.

Would such a theory be a T. O. E.-a Theory of Everything? The answer in my opinion is NO. As remarked before, all theories which descend from higher to lower dimensions must contain massive particles with masses in multiples of Planck mass $m_{\mathrm{P}} \simeq 1/\mathrm{R} \simeq /\alpha/\mathrm{G}$. Since no *direct* tests of existence or interactions of such objects can be fessible—(with accelerators of less than 10 light years in length)—there will always remain the experimentally unexplored area of these higher masses and energies. What we are saying is that before any theory can be called a T. O. E., one must prove, at the least, a *uniqueness* theorem—one which states that if a theory fits all known phenomena at low energies, it can have only *one* extrapolation to higher energies. From all past experience, this is unlikely—even as regards the framework. (Think of the framework of Newtonian gravity versus that of Einstein's gravity.)

But apart from these matters of interpretation, the one crucial question which our experimental colleagues are entitled to ask, is this, what are the compelling experimental consequences of string theories?

The emergence of (necessarily a supersymmetric) standard model with the right number of families may, of course, be a triumph (likewise of Einstein's gravity) but will it establish the superiority of the *string attitude*? Can one predict the Cabibbo-Kobayashi-Maskawa matrix and the Yukawa couplings? At present, there are few unambiguous *new* predictions. One of them concerns the existence of one or two new Z^0's.

Unfortunately, the masses of the new Z^0—even their existence—are not firmly predicted by the theory. A possibly firmer and more spectacular prediction (at least so far as Calabi-Yau compactification is concerned), is the possibility of the existence of fractionally charged non-confined dyons which would, of course carry the appropriate integral magnetic monopolarity in accordance with the Dirac formula.

C. Strings Formulated Directly in 4 dimensions (Schellekens).

« What is meant by a consistent (closed, fermionic) string theory in *d* dimensions, is a theory based on a two-dimensional field theory with the following properties:

i) reparametrization invariance,
ii) conformal invariance,
iii) modular invariance,

iv) world-sheet supersymmetry and superconformal invariance
v) the presence of d right- and left-moving scalars (X_R, X_L).

whose zero modes are the space-time coordinates ».

« The existing ways of satisfying condition *ii*) are most easily classified by the left- and right-moving ghost contribution $(c_L, c_R)_{ghost}$ to the central charge of the Virasoro algebra. The possibilities relevant for four dimensions are (– 26, – 26) (bosonic strings), (– 15, – 15) (type II strings) and (– 26, – 15) (heterotic strings). The « matter » fields cancelling these conformal anomalies were traditionally chosen to be 26 bosons ($c = 26$) or ten bosons and ten Majorana-Weyl fermions ($c = 15$) ».

Now the art of constructing consistent string theories for $d = 4$ is simply to find the solutions to the conditions listed above, particularly of item *v*). The case of $d = 26$ for Bose strings and $d = 10$ for the supersymmetric strings corresponds to the case where ALL the Bose fields in the 2-dimensional underlying theory possess zero modes. This is clearly not necessary and the modern art of constructing consistent theories for $d = 4$ is simply to postulate *only* four scalars (X'*s*) possessing zero modes to correspond to $d = 4$ space-time coordinates.

One of the promising lines of development is to consider internal *orbifolds* for the remaining 6 degrees of freedom in the case of the supersymmetric conformally invariant heterotic theory.

« Orbifolds were first discussed as singular limits of Calabi-Yau manifolds, and later started to lead a life of their own. Their construction has recently been generalized in several ways, by adding background fields (« Wilson lines ») or by allowing left- and right-movers to live on different orbifolds (« asymmetric orbifolds ») ».

« Modular invariant theories *iii*) are obtained by twisting boundary conditions of an already modular invariant theory, imposing (at least for Abelian orbifolds) a « level matching » condition to ensure that modular invariance is not destroyed ».

It appears that one can construct a number of theories with three families and which preserve the standard model symmetry group $SU_C(3) \times SU_L(2) \times U(1)^n$. The use of Wilson's lines is particularly important in this construction, especially in limiting the number of families.

But even so, there are hundreds of thousands, if not millions, of such theories claimed.

« If all these theories are in fact just different vacua of the same theory, we are still faced with a bewildering choice of vacua. Nevertheless, one should not lose sight of the superiority of string theory over field theory in this respect. In field theory, one can choose arbitrary gauge groups, arbitrary (anomaly-free) representations for all fields, and arbitrary coupling constants. In string theory, one can choose world-sheet boundary conditions. In the space of all possible field theories, the ones that can come from strings are a subset of measure zero. Most of the more exotic Grand Unified Theories that have been proposed in the past cannot come from string theory ».

Thus spake zarathustra.

VIII. PASSIVE AND NON-ACCELERATOR EXPERIMENTS: TESTS OF GRAND UNIFIED THEORY

Next we come to the passive non-accelerator experiments which mainly test electronuclear grand unification. From the asymmetry of matter versus antimatter in the Universe this unification is expected to take place at scales of the order of 10^{14}-10^{15} GeV, much below the gravitation scale of 10^{19} GeV. It is fully conceivable that this unification corresponds to a gauge group like $E_6 \rightarrow SO(10) \rightarrow SU_c(4) \times SU_L(2) \times SU_R(2) \rightarrow SU_c(3) \times U(1)_{B-L} \times SU_L(2) \times U(1) \rightarrow SU_c(3) \times SU_L(2) \times U(1) \rightarrow SU_c(3) \times U_{E.M.}(1)$. The magnitude of $\sin^2 \theta$ is predicted by the theory.

A. Grand Unified Theory Predictions.

One set of such experiments is concerned with testing *gauge* aspects of grand unification theories (unifying electroweak and strong nuclear interactions). These are the tests for *i*) *monopoles* (topological defects in a technical sense). Though, in the early universe, the monopole formation is predicted (by the gauge theories concerned) in the conditions prevailing, one would not like too many monopoles around now; otherwise there will be problems with the magnitudes of the cosmic magnetic fields. *ii*) *Cosmological strings* which are good for galaxy seeding and *iii*) *domain walls* which apparently would be a cosmological disaster. Surely, this set of predictions present a mixed bag of desirables and undesirables.

B. In addition there is the question mark on varieties of remnant hot (relativistic) and cold (non-relativistic) dark (weakly interacting) and shadow matter (which interacts only gravitationally), endemic to most of our theories. (I shall not dwell on the role of inflation in cosmology, which apparently resolves the problem of over-abundance of monopoles and may help in making these early remnants rather scarce.)

C. Among the most celebrated passive and non-accelerator experiments is proton decay. A limit on $P \rightarrow e^+ + \pi^0 > 2.5 \times 10^{32}$ years partial decay-time is suggested by the IMB collaboration. There are, however, claims for (seven) candidate-events for $P \rightarrow e^+ + K^0$ and $N \rightarrow \nu + n^0$ and $N \rightarrow \nu^0 + K^0$ modes, by the Kolar Gold Fields collaboration, Kamiokande and Nusex. (A firm detection of K's would signal supersymmetry and also explain the longer life-time.) A worrisome background is due to atmospheric neutrinos which would make it difficult, on earth, to be sure of a real signal for proton decay if its life much exceeds 10^{34} years. Pati, Sreekantan and Salam have suggested experiments on the moon where even though the primary flux of cosmic rays is unhindered by the existence of an atmosphere or magnetic fields, an experiment carried out in a tunnel or a cavern with 100 metres of moon-rock surrounding it on all sides, would cut down the backgrounds—in particular of ν_e neutrinos—to a figure less than 1/100 of the background on earth. If proton life-time lies within the range of 10^{34} and 10^{35} years, experiments on the moon may become necessary for its unambiguous detection.

D. There are the on-going experiments for solar neutrinos, reactor neutrino oscillations, and double β-decay. « The problem with solar neutrinos is that there seem to be too few of them, at least near the top end of the spectrum, since the ^{37}Cl detector finds only about 35 % of the standard predicted flux. Various kinds of explanation have been offered: *a*) the standard *solar model* is wrong. There are dark matter candidates—the cosmions—which accrete onto the sun and make its temperature lower; *b*) neutrinos decay (apparently ν_e does not decay, see E)below); *c*) neutrinos have magnetic moments; and *d*) neutrinos oscillate. Masses of the order of 10^{-6} eV would give oscillation lengths of the order of sun-searth distance ».

Oscillations in matter have recently (1986) been considered by Mikheyev and Smirnov, following on the earlier work of Wolfenstein—the MSW effect. Neutrino masses of the order of 10^{-2} eV allow for amplified resonances within the sun. Masses of the order of eV—models with Nambu-Goldstone bosons (Majorons)—allow for decays while neutrinos arrive at the earth. A number of techniques are being used to distinguish between these possibilities. These include: Water Cerenkov detectors, Gallium detectors, Indium detectors, Bromine detectors, Heavy Water detectors and Liquid Argon detectors.

E. *SN 1987 a.*

Finally, there is the 1987 most celebrated of all non-accelerator happenings which opens up the prospects of *Neutrino Astrophysics from Supernova.* « The observation, in large-volume underground detectors, of short burst of neutrinos several hours before the visual observation of the associated supernova explosion, has provided data of considerable significance to both astrophysicists and high energy particle theorists. Limits on the neutrino mass and lifetime have been calculated, from different points of view, by a number of authors ($m_{\nu e} < 20$ eV, comparable to the laboratory limit and typically $\gamma_{\tau\nu e} > 10^5 y$) while the limit on the number of neutrino species is given by these experiments as $6 < N(\nu) < 12$. (If « invisible axions », particles with ultraweak interactions, were emitted together with the neutrinos from the supernova core, one can also exclude the possibility of such light pseudoscalar bosons with coupling to the electron $< 1.1 \times 10^{-27}$ for an assumed supernova temperature $T \rightarrow 5.1$ MeV.)

This concludes our brief overview of today's particle physics.

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