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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

THE ELECTROWEAK FORCE, GRAND UNIFICATION AND SUPERUNIFICATION

Abdus Salam

INTERNATIONAL ATOMIC ENERGY AGENCY

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ERRATA

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E R R A T A

Page 2 - second last line - should read:

b) Provided a logical basis for charm through the GIM mechanism and triangular anomaly cancellation.

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International Atomic Energy Agency
and
United Nations Educational Scientific and Cultural Organization

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

THE ELECTROWEAK FORCE, GRAND UNIFICATION AND SUPERUNIFICATION *

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ABSTRACT

Unification of the electromagnetic force with the weak (within the context of the SU(2) × U(1) theory), unification of the strong force with the electroweak (within the context of Grand Unification schemes) and unification of gravitational quanta with leptons, quarks, Yang-Mills quanta and Higgs particles (within the context of supergravity theories) is reviewed.

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I. INTRODUCTION

Following on the High Energy Conference at Tokyo, I shall report briefly on recent progress in three topics relating to the theme of unification:

(A) The status of the electroweak unification and the $SU_L(2) \times U_{L+R}(1)$ gauge theory.

(B) Possible grand unification of the electroweak with the strong force. Is unification energy likely to be as low as 10^4-10^6 GeV or is it much higher $\geqslant 10^{15}$ GeV?

(C) Superunification of gravitational quanta with leptons, quarks and gauge quanta of the strong and the electroweak forces, within the context of supergravity theories.

II. THE ELECTROWEAK UNIFICATION AND THE $SU_L(2) \times U_{L+R}(1)$ THEORY

A. The $SU_L(2) \times U_{L+R}(1)$ theory of weak and electromagnetic phenomena

The characteristics of the "standard" renormalizable $SU_L(2) \times U_{L+R}(1)$ gauge theory are:

1. There are two charged left-handed $\left(J_L^{\pm} = \left(\frac{J_1 \mp iJ_2}{\sqrt{2}}\right)_L\right)$ and two neutral currents: the familiar electromagnetic J_{em}, and the weak neutral, $J_Z = J_{3L} - \sin^2\theta \, J_{em}$, coupling to gauge mesons $W^{\pm}$, γ and Z^0 respectively. Weak and electromagnetic unification implies that the respective coupling strengths are: $e/\sin\theta$, e and $e/\sin\theta\cos\theta$, while $m_W^2 = \frac{\sqrt{2}\, e^2}{8G_F \sin^2\theta}$ ($\sin^2\theta$ is the one universal parameter of the theory which was originally unknown).

2. The $W^{\pm}$, Z^0 and the fermion masses are generated through the same Higgs-Kibble spontaneous symmetry-breaking mechanism. As a consequence, $m_Z = m_W/\cos\theta$, or equivalently the parameter ρ defined as $m_W^2/m_Z^2 \cos^2\theta$ (and which determines the "effective" strength at low energies of the charged versus the neutral current effects) is predicted to equal unity.

3. Leptons and quarks are left-handed doublets and right-handed singlets.

For the neutral current sector, the theory:

a) Predicted the existence of neutral currents, motivating their discovery [Gargamelle CERN (1973), CIFT, HPWF].

b) Provided a logical basis for charm through the GIM mechanism (triangular anomaly cancellation).

c) Predicted a one-parameter fit (with a universal $\sin^2\theta$) for all neutral current data on νN and νe interactions [confirmation from model-independent analysis (1977-78), see later].

d) Predicted parity violation in e + deuteron $\to eX$ and e + proton $\to eX$ with correct magnitude and sign [SLAC-Yale-CERN-Aachen-Hamburg experiment (1978)].

For the charge current sector (assuming that strong interactions are described by QCD-type gauge theory) the theory:

e) Does not admit right-handed currents, nor the resulting high y-anomaly [absence of this anomaly confirmed, Hamburg Conference (September 1977)].

f) Does not admit second class currents [absence confirmed, Zurich and Tokyo Conferences (1977)]. Second class currents are analogous to Pauli moment terms in QED and are ruled out for a renormalizable gauge theory.

g) Makes it meaningful to speak of precise QED tests for $(g-2)_{e,\mu}$. This is because the renormalized weak contribution to $(g-2)_{e,\mu}$ is now precisely calculable, and not subject to ambiguities of an unknown cut-off.

h) Leads, in a basic manner, to fruitful theoretical constructs like universality, current algebra, CVC, PCAC. This is because the vector and axial currents possess simple forms like $\bar{u}\gamma_\mu d$, $\bar{u}\gamma_\mu\gamma_5 d$.

B. Tests of $SU_L(2) \times U_{L+R}(1)$ predictions

1. Model independent analysis [1] of $\nu N \to \nu X$

(Sehgal (1977), Hung and Sakurai (1977), Eckar (1977), Abbott and Barnett (1977, 1978), Sidhu and Langacker (1978), Monsay (1978), Claudson, Paschos and Sulak (1978).) Assuming V, A (for a discussion on experiments which show that empirically S, T, P may be excluded, see C. Baltay, report to the Tokyo Conference), the most general low-energy interaction involving neutrinos and u, d quarks has the form

$$\frac{G_F}{\sqrt{2}}\left[g_{uL}(\bar{u}_L\gamma u_L) + g_{uR}(\bar{u}_R\gamma u_R) + g_{dL}(\bar{d}_L\gamma d_L) + g_{dR}(\bar{d}_R\gamma d_R)\right](\bar{\nu}\gamma\nu) \quad .$$

Four types of data are available and have been analysed:

i) Inclusive NC/CC; NC: ν + nucleon $\to \nu + X$,
$\bar{\nu}$ + nucleon $\to \bar{\nu} + X$.

This data determines the combinations of parameters $g_{uL}^2 + g_{dL}^2$ and $g_{uR}^2 + g_{dR}^2$.

ii) Semi-inclusive $\dfrac{\nu + N \to \nu + \pi^+ + \ldots}{\nu + N \to \nu + \pi^- + \ldots}$

and $\dfrac{\bar{\nu} + N \to \bar{\nu} + \pi^+ + \ldots}{\bar{\nu} + N \to \bar{\nu} + \pi^- + \ldots}$

Data known from Gargamelle and Fermi-Lab determines the combinations of parameters:

$$\left(g_{uL}^2 + \tfrac{1}{3}g_{uR}^2\right)\Big/\left(g_{dL}^2 + \tfrac{1}{3}g_{dR}^2\right) \quad \text{and} \quad \left(g_{uR}^2 + \tfrac{1}{3}g_{uL}^2\right)\Big/\left(g_{dR}^2 + \tfrac{1}{3}g_{dL}^2\right) \quad .$$

A model-independent analysis of i) and ii) gives four solutions (with $V \leftrightarrow A$, $I = 0 \leftrightarrow I = 1$ ambiguity persisting at this stage), labelled in the literature as solutions Ⓐ, Ⓑ, Ⓒ, Ⓓ.

iii) Elastic data $\nu + p \to \nu + p$
$\bar{\nu} + p \to \bar{\nu} + p$

Harvard-Penn-BNL groups + observation of $I = 0$ non-dominance, now selects one (solution Ⓐ) from the four solutions (Claudson, Paschos and Sulak, Tokyo Conference, 1978).

iv) Exclusive pion production: This solution Ⓐ is confirmed (inverting history) by using results of Adler's analysis of π production for $(\nu,\bar{\nu}) + N \to (\nu,\bar{\nu}) + N + \pi$ (Abbott and Barnett [1], Purdue Conference, 1978).

v) It is also possible, by using new data for the ratio $\dfrac{\nu n \to \nu X}{\nu p \to \nu X}$, to do without the semi-inclusive data ii) altogether. This again yields solution Ⓐ (Abbott and Barnett, SLAC preprint, 1978).

Thus three independent types of data and their analyses independently support solution Ⓐ.

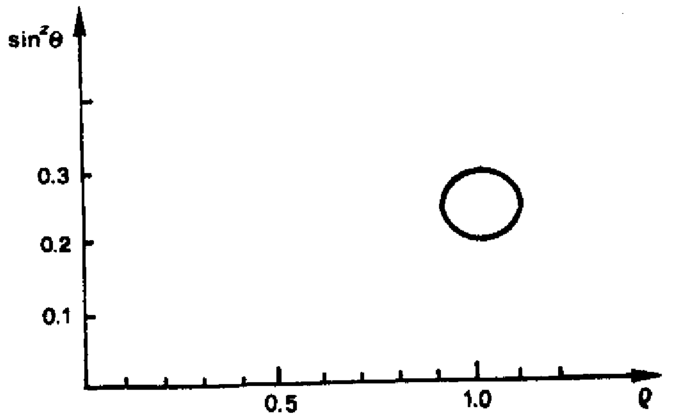
To conclude, the results of this model-independent analysis as compared with the predictions of the theory are:

		Theory	
	Experiment	$\sin^2\theta = \frac{1}{4}$	As functions of $\sin^2\theta$
g_{uL}	$+ 0.35 \pm 0.07$	0.33	$\frac{1}{2} - \frac{2}{3}\sin^2\theta$
g_{dL}	$- 0.40 \pm 0.07$	-0.42	$-\frac{1}{2} + \frac{1}{3}\sin^2\theta$
g_{uR}	-0.19 ± 0.06	-0.17	$-\frac{2}{3}\sin^2\theta$
g_{LR}	$0 \quad \pm 0.11$	0.08	$\frac{1}{3}\sin^2\theta$

Table I

C. Baltay, Tokyo Conference, 1978, using Abbott and Barnett's analysis.

Apart from the magnitudes, the agreement of relative signs for the g's between prediction and experiment is striking. (The overall sign is unobservable except for interference with gravity.) Since the analysis relies on fifteen different processes representing some thousands of neutrino events, each process from data of two or more independent experimental groups, the convergence of the experimental results is in itself truly remarkable and demonstrates the extraordinary stage of maturity reached by neutrino-hadron physics.



$\rho = 0.98 \pm 0.05$

90% c.ℓ.

Fig.1

Theoretical prediction $\rho = 1$.

Experimental results, presented at the Tokyo Conference (1978)

(Report by H. Fritzsch).

2. $\nu e \to \nu e$ and $\bar{\nu} e \to \bar{\nu} e$

Purely leptonic neutral current processes are easiest to interpret theoretically (no hadrons involved) and are potentially the best means of determining $\sin^2\theta$. However, the cross-sections are the smallest on record in physics: [$\approx 10^{-42}$ E_ν/GeV cm^2, with $\sigma(\nu e)$ typically 2000 times (m_e/m_N) smaller than $\sigma(\nu N)$]. Thus statistics still play a bigger role in $\sigma(\nu e)$ physics than in $\sigma(\nu N)$. Tables II and III reproduce C. Baltay's compilation of his own and other groups' data as compared with theory. Since earlier (February 1978) Gargamelle results showed a deviation from their own still earlier and Aachen-Padua results, their subsequent convergence with Baltay's more statistically significant experimental results, as well as with the theory (achieved when their data-sample was increased and a number of previously reported events discarded on subsequent analysis) is pleasing indeed. (The results of the Reines group on $\bar{\nu}_e + e \to \bar{\nu}_e + e$, also agree with the predictions of the theory.)

i) $\nu_\mu + e \to \nu_\mu + e$

	Total sample of $\nu + N \to \mu^- + \cdots$	Events observed	Cross-section
Gargamelle		≤ 1	≤ 3
Aachen-Padua		32	1.1 ± 0.6
Gargamelle	~~24 000~~	~~10~~	~~$7.3\,^{+3.3}_{-2.6}$~~
	41 000	9	$4.0\,^{+2.0}_{-1.5}$
Columbia + BNL	106 000	11	1.8 ± 0.8

$\sigma_{average}$ = $(1.7 \pm 0.5) \times 10^{-42}$ E_ν/GeV cm^2

February (1978)

Revised(average)August (1978)

$\sigma_{Th} = 1.5 \times 10^{-42}$ E_ν/GeV cm^2

ii) $\bar{\nu}_\mu + e \to \bar{\nu}_\mu + e$

Gargamelle		3	$1.0\,^{+2.1}_{-0.9}$
Aachen-Padua		17	2.2 ± 1.0
BEBC	7 500	≤ 1	≤ 3.5
Fermi-Mich-JETP-IHEP	6 300	0	≤ 2.9
Gargamelle	4 000	0	≤ 3.3

$\sigma_{average}$ = $(1.8 \pm 0.9) \times 10^{-42}$

$\sigma_{Th} = 1.3 \times 10^{-42}$

Table II

Presented by C. Baltay, Tokyo Conference, 1978, $\sin^2\theta = 0.23$.

3. eN neutral currents

There are two types of experiments reported, testing for evidence of parity violation, predicted by SU(2) × U(1).

a) SLAC-Yale-CERN-Aachen-Hamburg experiment on polarized electron scattering off deuterons and protons. (For theory, see Cahn and Gilman [2); Love, Ross and Nanopoulos; and Wolfenstein, who has shown that results of the theory depend little on the parton model assumptions.) The asymmetry expected in e + deuteron → e + X , when the electron polarization direction is reversed, is given by

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -\frac{9G_F q^2}{20\sqrt{2}\pi\alpha}\left[1 - \frac{20}{9}\sin^2\theta + (1 - 4\sin^2\theta)\left\{\frac{1-(1-y)^2}{1+(1-y)^2}\right\}\right] .$$

The experiment gives

$$A/q^2\Big|_{experiment} = (-9.5 \pm 1.6) \times 10^{-5}\ GeV^{-2} \quad , y = 0.21$$

(with 1.6×10^{-5} GeV^{-2} representing cumulative systematic and statistical errors), to compare with

$$A/q^2\Big|_{theory} = (-9.7 \leftrightarrow -7.2) \times 10^{-5}\ GeV^{-2}\ (\sin^2\theta = 0.20 \leftrightarrow 0.25) .$$

For hydrogen, experiment [$(-9.7 \pm 2.7) \times 10^{-5}$ GeV^2] again gives parity violation with a value which agrees with theory.

The νe and eN data can be put together with the results of the model-independent analysis of νN interactions to obtain model-independent results for the vector and axial-vector neutral current couplings of the electrons. The results as given in Baltay's Tokyo summary are shown below:

		Theory	
	Experiment	$\sin^2\theta = \frac{1}{4}$	As functions of $\sin^2\theta$
g_V	0.0 ± 0.1	0.0	$-\frac{1}{2} + 2\sin^2\theta$
g_A	−0.55± 0.1	−0.5	$-\frac{1}{2}$

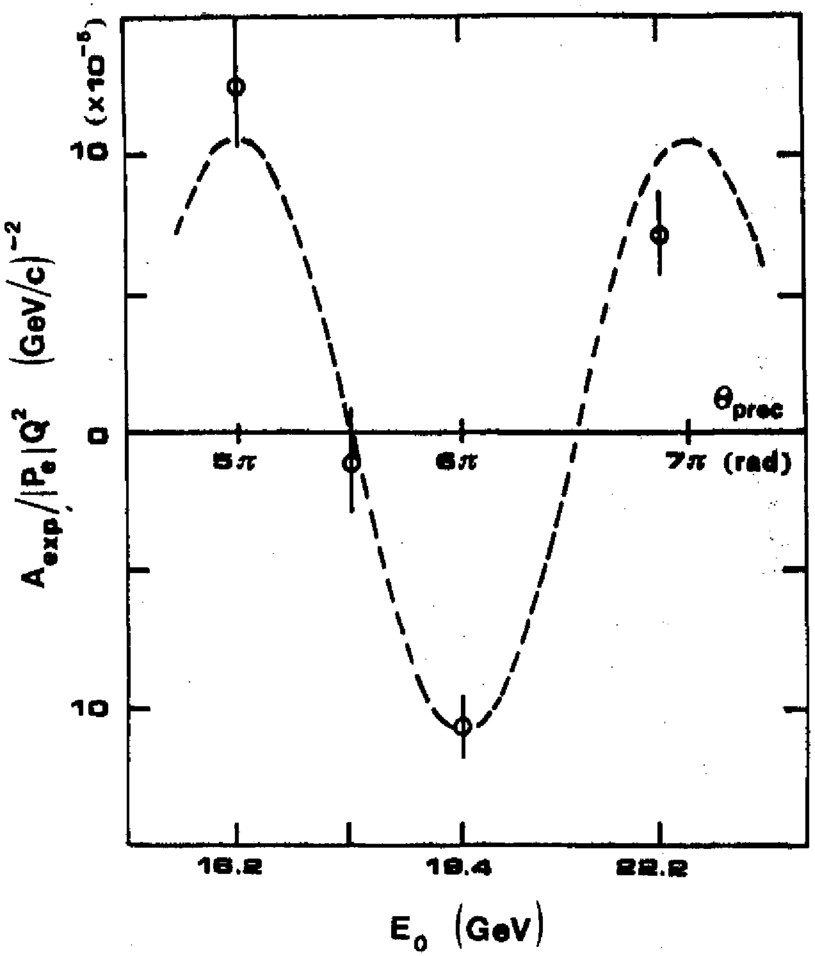


Fig.2

SLAC experiment; note the beautiful manner in which the asymmetry follows the direction of electron polarization, which depends on beam energy , owing to (g-2) precession of the spin.

b) Atomic parity violation experiments

Here the situation with regard to the very difficult experiments as well as the atomic physics part of the calculations is confused.

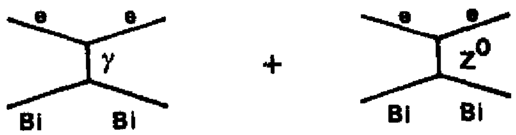


Fig.3

Theory (R)	64 76 A^0	87 57 A^0
Central field calculation	-23	-18
Calculation with shielding due to the core	≈ -11 The atomic physics part of this calculation is highly uncertain	≈ -9
Experiment	Oxford (1977) 2.4 ± 4.7 Novosibirsk (1978) -19 ± 5 Oxford (1978) (preliminary) -5 ± 1.6	Seattle (1977) 0.7 ± 3.2 Seattle (1978) -0.5 ± 1.7 Seattle (1978, preliminary) -2.4 ± 0.9

Table III

Bismuth (83 electrons, 80 in the core), $\sin^2\theta = 0.24$, $R = \mathrm{Im}\, E_1/M_1 \times 10^8$.

Preliminary results on thallium dichroism (one electron outside the core), from Berkeley, $(+ 5.2 \pm 2.4 \times 10^{-3})$ support the central field calculation $(+ 2.3 \pm 0.9 \times 10^{-3})$. To summarize, all experiments are now united in observing atomic-parity violation with the predicted sign. Some of these contradict others (and the uncertain atomic theory) in the magnitude of the effect observed. However, after the elegant and theoretically unambiguous SLAC experiment, the issue of atomic parity violation and its magnitude is now a problem for atomic physics rather than for particle physics.

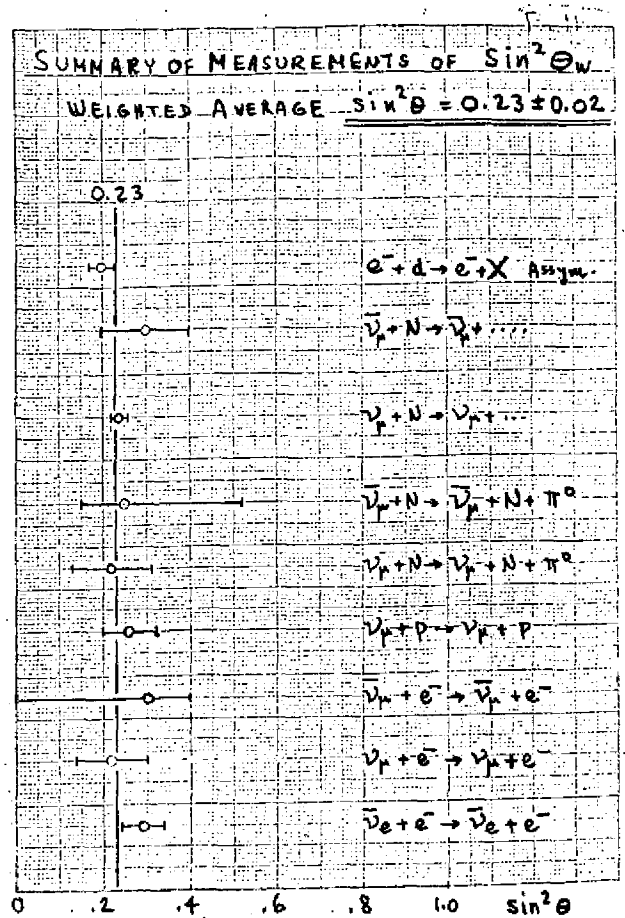


Fig.4

Presented by C. Baltay, Tokyo Conference, 1978.

Table IV

Summary of neutral currents.

Process	Experimental results	$\sin^2\theta$	Weinberg-Salam prediction with $\sin^2\theta = 0.23$
1. Purely leptonic			
$\bar{\nu}_e + e \to \bar{\nu}_e + e$	$(5.7 \pm 1.2) \times 10^{-42}\ E_V\ cm^2$	0.29 ± 0.05	5.0
$\nu_\mu + e \to \nu_\mu + e$	$(1.7 \pm 0.5) \times 10^{-42}\ E_V\ cm^2$	$0.21 {+0.09 \atop -0.06}$	1.5
$\bar{\nu}_\mu + e \to \bar{\nu}_\mu + e$	$(1.8 \pm 0.9) \times 10^{-42}\ E_V\ cm^2$	$0.30 {+0.10 \atop -0.30}$	1.3
2. Elastic scattering			
$\nu_\mu + p \to \nu_\mu + p$	$(0.11 \pm 0.02) \times \sigma(\nu_\mu + n \to \mu^- + p)$	0.26 ± 0.06	0.12
$\bar{\nu}_\mu + p \to \bar{\nu}_\mu + p$	$(0.19 \pm 0.08) \times \sigma(\bar{\nu}_\mu + p \to \mu^+ + n)$	≤ 0.5	0.11
3. Single pion production			
$\nu_\mu + N \to \nu_\mu + N + \pi^0$	$(0.45 \pm 0.08) \times \sigma(\nu_\mu + N \to \mu^- + N + \pi^0)$	0.22 ± 0.09	0.42
$\bar{\nu}_\mu + N \to \bar{\nu}_\mu + N + \pi^0$	$(0.57 \pm 0.11) \times \sigma(\bar{\nu}_\mu + N \to \mu^+ + N + \pi^0)$	$0.15 - 0.52$	0.60
4. Inclusive			
$\nu_\mu + N \to \nu_\mu + \ldots$	$(0.29 \pm 0.01) \times \sigma(\nu_\mu + N \to \mu^- + \ldots)$	0.24 ± 0.02	0.30
$\bar{\nu}_\mu + N \to \bar{\nu}_\mu +$	$(0.35 \pm 0.025) \times \sigma(\bar{\nu}_\mu + N \to \mu^+ + \ldots)$	0.3 ± 0.1	0.38

Table reproduced from the lecture of C. Baltay, Tokyo Conference, 1978.

4. Conclusion

From the preceding, one sees that the simple gauge theory $SU(2) \times U(1)$ correctly embraces and dynamically describes observed weak as well as electromagnetic phenomena. Wherever a conflict developed between preliminary experimental findings and the predictions of the simple theory (e.g. the existence of neutral currents, their magnitude in purely leptonic processes and their parity characteristics) the theory has been eventually confirmed. The gauge symmetry structure ($SU(2) \times U(1)$) will be a part of any future theory of particle physics.

5. The next developments: Embedding of $SU(2) \times U(1)$ into a larger symmetry structure

There are theoretical reasons to expect that $SU(2) \times U(1)$ may be part of a larger gauge structure. This larger structure is likely to be strongly broken, entailing new interactions much weaker than those so far observed. With $SU(2) \times U(1)$ embedded into such a larger structure, one may hope to explain the magnitudes of certain (phenomenological) parameters which enter into particle physics.

i) A group structure larger than $SU(2) \times U(1)$ may provide a "natural" explanation for the mass ratios:

$$\frac{m_e}{m_\mu} = 4.8 \times 10^{-3}, \quad \frac{m_u}{m_c} \approx 4 \times 10^{-3}, \quad \frac{m_d}{m_b} \approx 1.5 \times 10^{-3},$$

and for mixing angles like $\theta_{Cabibbo}$.

ii) Embedding the abelian $U(1)$ piece in a non-abelian gauge structure will give a raison for the quantization of the associated quantum numbers as well as for the asymptotic freedom of the theory.

iii) Embedding $SU(2) \times U(1)$ in a gauge group which is simple (or with suitable discrete symmetries, semi-simple) would dictate the ratio of the two basic gauge constants, or equivalently the universal parameter (Fig.4) $\sin^2\theta$.

iv) And finally, the fundamental unification hypothesis should also embrace strong interactions - for example the reasonably successful strong gauge theory, $SU_C(3)$ of colour.

All in all, then, one must look for a Grand Unification non-abelian symmetry G, which includes $SU(2)\times U(1)$ as well as $SU_C(3)$. So far as the energy scales are concerned, such a unification may go through a number of intermediate scales (e.g. the electroweak $SU_L(2) \times U_{L+R}(1)$ (with its unification scale of around 100 GeV) may become part of a bigger left-right symmetric structure [4] with a scale of a few hundred or a thousand GeV before the grand unification with the strong $SU_C(3)$ becomes manifest). Experiments relating to "forbidden" transitions like $K \to \mu e$, $\mu \to e + \gamma$, $\mu \to 3e$, $\mu N \to eN$, to motivate the existence of interactions weaker than those presently observed, as well as experiments at energies higher than the present are needed to find this out.

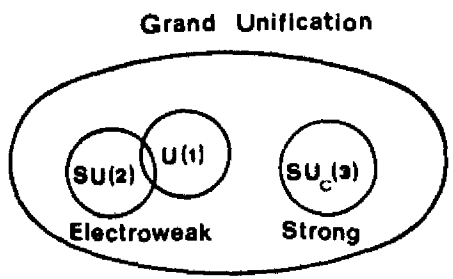


Fig.5

There may be intermediate unification steps in between.

In the next section we ignore these intermediate energy scales and the intermediate unification steps and concentrate on the main problem of the Grand Unification schemes of electroweak and strong unification: What is the probable Grand Unification mass, M , beyond which the three forces, electromagnetism, weak and strong, may manifest themselves with the same effective strength? This problem is important for the prospects of an eventual accelerator for the year 2000.

III. GRAND UNIFICATION OF THE ELECTROWEAK WITH THE STRONG FORCE: THE UNIFICATION MASS

On present form, the current choices for the Grand Unifying symmetry group G (which must include $G_{EW} = SU(2) \times U(1)$ and $G_{strong} = SU_C(3)$) are not extensive. The G's on offer fall into two broad categories:

1. The "simple" options

"Simple" groups, in the technical sense, with one basic gauge constant, which are currently being considered are $G = SU(5)$ or $SO(10)$ or E_6 . [SU(5) (Georgi and Glashow (1974), Buras, Ellis, Gaillard and Nanopoulos (1977))] or [its foster-brother SO(10) (Fritzsch and Minkowski (1975), Georgi (1975))] or [E_6 (Gürsey, Ramond and Sikivie (1976), Serdaroglu (1978), Achiman and Stech (1978), Shafi (1978)).] For all these groups $G_{strong} = SU_C(3)$, but G_{EW} could range over intermediate stages like $SU(2) \times SU(2) \times U(1)$ for SO(10) and $[SU(2) \times U(1)]^2$ for E_6 . (Note that E_7 , till recently a possible candidate, can now be discarded; since $\sin^2\theta$ predicted for it = 3/4.)

2. The semi-simple option

$$G = SU_L(4) \times SU_R(4)|_F \times SU_L(4) \times SU_R(4)|_C$$

of Pati et al. [4], with the discrete symmetry, flavour (F) $\to$ colour (C), left $\leftrightarrow$ right, which guarantees one bare coupling parameter. Here G_{EW} could be $[SU(2) \times U(1)]_L \times L \leftrightarrow R$ (or its subgroup $SU_L(2) \times U_{L+R}(1)$), but the real difference from the "simple option" is for G_S (the low-energy strong symmetry below 100 GeV contained inside $G = G_{EW} \otimes G_S$). G_S may be as large as $SU_L(3) \times SU_R(3)|_C$: i.e. colour may be chiral rather than vectorial.

To find the unifying mass M , use the renormalization group formalism of Georgi, Quinn and Weinberg [5]. If the one bare gauge constant associated with G manifests itself at low energy (μ) , as α for the electroweak and as α_s for the strong sectors, then

$$\alpha^{-1} - \alpha_s^{-1} \approx [C(S) - C(EW)] \frac{11}{6\pi} \ln\frac{M}{\mu} .$$

Here C(S) and C(EW) are the respective Casimir operators for the residual low-energy, strong and electroweak symmetries G_S and G_{EW} . (The exact formula is somewhat more complicated for the electroweak sector since the symmetry $SU(2) \times U(1)$ contains U(1). However, the orders of magnitude and the basic ideas are well represented by the above expression.)

Clearly, given α , given α_s , given C(EW), M would be small if the Casimir C(S) is large. Since for the "semi-simple option" $[SU(4)]^4$, G_S can be as large as $SU_L(3) \times SU_R(3)|_C$ (chiral colour), the relevant Casimir C(S) is twice its value for the "simple" options (SU(5), SO(10) and E_6) which contain only $SU(3)_C$. The formula above gives

$M \gtrsim 10^{15}$ GeV for SU(5), SO(10) or E_6 ,

$M \approx 10^4$-10^6 GeV for $[SU(4)]^4$ (assuming low-energy chiral colour).

What are the possible indirect signatures of the low-mass (10^4-10^6 GeV) Grand Unification? These are summarized in the table below.

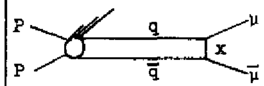
	Simple G SU(5) or SO(10) or E_6	Semi-simple G $[SU(4)]^4$ with chiral colour
Unifying mass M	$\gtrsim 10^{15}$ GeV A physics desert between (10^2-10^3) GeV and 10^{15} GeV, so far as unification ideas are concerned. (Lepto-quarks $X = \bar{q}\ell$ have masses in excess of 10^{15} GeV.)	10^4-10^6 GeV Lepto-quarks of mass 10^4 GeV ($X = \bar{q}\ell$) would make their existence felt already at Isabelle 
Quark charges	Necessarily $\frac{2}{3}$ and $-\frac{1}{3}$	Possibility of (integer-charge) liberated quarks: quarks and gluons exhibit the "Archimedes effect": light inside a hadronic bag, heavy outside. A bag model formula by de Rújula, Giles and Jaffe gives $m_{out} - m_{in} \approx C/2\pi\alpha'\mu$ α' = Regge slope parameter μ = gluon mass inside
Axial gluons	None	For integer-charge quarks, expect (integer-charge) axial colour gluons (masses $\lesssim$ 100 GeV). Their decay modes exhibit characteristic signatures, e.g. $1^+ \to \text{gluon } (1^-) + \phi$ $\to \mu^+ + \mu^- + K + \bar{K}$
Proton decay Experimental status Reines, $\tau_p \gtrsim 10^{30}$ years for essentially the mode: $P \to \mu^+ + \gamma$ (or $\mu^+ + \pi^0$) (determined from five suspected events).	$q + q \to X \to \bar{q} + \bar{\ell}$, i.e. $P_{proton} \to \mu^+$ + pions (second-order gauge process) with a mediation through heavy lepto-quarks ($M_X \gtrsim 10^{15}$ GeV). In general τ_p is long; $\tau_p \gtrsim 10^{37}$ years (though renormalization group corrections may reduce this estimate (Ross, CERN (1978)) to $\sim 10^{33}$ years.	Primary process: Integer-charge quarks decay into $q \to \nu + \pi$ (not $\bar{\nu} + \pi$); $\tau_q \lesssim 10^{-13}$ secs. Most probable decay mode for the proton is: proton $\to q + q + q \to 3\nu$ + one or more pions $\tau_p \sim 10^{29} - 10^{32}$ years (contrary to the case of "simple" G's, the basic remark here is that the proton's lifetime cannot be overly long).

Table V

Comparison of the "simple" and "semi-simple" options for the Grand Unification Symmetry.

To summarize

1) Grand Unification mass is low (10^4-10^6 GeV) if colour is chiral. A natural choice for the Grand Unification Group containing chiral colour is the semi-simple $[SU(4)]^4$.

2) If colour is liberated (with integer-charged quarks), the (integer-charge) axial gluons ($m_A \lesssim$ 100 GeV) would exhibit characteristic decays into axial gluons $\to$ gluons $+ \phi \to \mu^+ + \mu^- + K + \bar{K}$.

3) Proton decay life and decay modes ($P \to 3\nu$ + pions vs. $P \to \mu^+$ + pions) may provide important distinctions between the two alternatives of grand unification around 10^4-10^6 GeV vs. 10^{15} GeV.

If indirect evidence supports the semi-simple alternative, a 10-TeV accelerator (around the year 2000 AD) may hopefully provide direct evidence of strong unification with the electroweak.

IV. SUPERUNIFICATION OF GRAVITONS WITH MATTER

How may gravity theory be united with the electroweak and the strong. One suggestion is, by gauging extended supersymmetries.

A. Simple supersymmetry

Supersymmetry is Fermi-Bose symmetry, implemented by anticommuting spinor operators Q_α, which satisfy

$$\{Q_\alpha , Q_\beta\} = -P_\mu (\gamma^\mu C) ,$$

P_μ's are Poincaré translations: Thus supersymmetry is an extension of Poincaré spacetime symmetry. *)

"Simple" supersymmetry unites Fermi and Bose objects in one multiplet. Some multiplets of interest are:

a) Matter multiplet $\begin{pmatrix} 1/2 \\ 0 \end{pmatrix}$

This unites spin $\frac{1}{2}$ and spin zero (e.g. quarks (or leptons) with Higgs scalars). A supersymmetric Lagrangian (invariant under an internal symmetry G) would have the same Higgs as basic fermions. ("Simple" supersymmetry commutes with an internal symmetry G.)

b) The gauge multiplet $\begin{pmatrix} 1 \\ 1/2 \end{pmatrix}$

This unites spin-one gauge bosons with spin-$\frac{1}{2}$ "gauge" fermions. For supersymmetric SU(2) × U(1), one would predict the existence of gauge fermions with masses of $m_{W^\pm}$, m_{Z^0}, m_γ, if supersymmetry itself does not break (spontaneously or otherwise).

*) If the Poincaré group is considered as a contraction of the de Sitter O(3,2) ≈ Sp4, supersymmetry may, in its turn, be considered as contracted "graded" OSp(4,1) - ("graded" means containing anticommuting generators). The unitary transformation corresponding to an anticommuting generator Q_α, naturally needs an anticommuting c-number parameter θ^α ($U = \exp i\, Q_\alpha \theta^\alpha$). If the Poincaré group is embedded into a conformal structure, a different type of supergravity theory emerges (see later).

c) Supergravity multiplet $\begin{pmatrix} 2 \\ 3/2 \end{pmatrix}$

This unites a graviton (helicity 2) with a gravitino of helicity $\frac{3}{2}$.

B. Gauging simple supergravity

The supergravity supermultiplet $\begin{pmatrix} 2 \\ 3/2 \end{pmatrix}$ is the gauge supermultiplet of "simple" supersymmetry itself:

	$-P_\mu (\gamma^\mu C)_{\alpha\beta}$ =	$\{Q_\alpha , Q_\beta\}$
Gauge current	↓ $T_{\mu\nu}(x)$	↓ $\mathcal{J}_{\mu\alpha}(x)$
Couples to	graviton helicity 2	gravitino helicity $\frac{3}{2}$

As is well known, a consistent theory of the graviton must

i) be generally covariant;

ii) with Einstein, be capable of formulation in terms of the geometry of curved spacetime;

Likewise, supergravity theory must

i) be generally covariant, besides being supersymmetric,

ii) be capable of formulation in terms of the geometry of a curved superspace.

What is superspace? Superspace is the extension of spacetime (x^m), (m = 0,1,2,3) to include four new fermionic dimensions, with associated co-ordinates θ^α;

$$x^m x^n - x^n x^m = 0 ,$$

$$\theta^\alpha \theta^\beta + \theta^\beta \theta^\alpha = 0 ,$$

$$x^m \theta^\alpha - \theta^\alpha x^m = 0 .$$

The above two requirements i) and ii) on supergravity theory have occupied most theoretical attention in the last two years.

C. Extended supersymmetries: unification of gravitons with matter

1. So far, there is no real union between supersymmetric matter $\left[\begin{pmatrix}1/2\\0\end{pmatrix}, \begin{pmatrix}1\\1/2\end{pmatrix} \text{ supermultiplets}\right]$ and supergravity $\begin{pmatrix}2\\3/2\end{pmatrix}$. We solve this problem by extending supersymmetries through marrying intimately with them, SO(N) types of internal symmetries, i.e. generalize supersymmetric charges Q_α to Q_α^i, $i = 1,2,3,\ldots,N$ (and their algebra to a "contracted" graded OSp(4,N)). Apparently, for reasons ill understood at present, N must be ≤ 8 for consistency of the resulting equations of motion.

2. The maximal N = 8 extended supersymmetry: One single multiplet of this structure contains the following succession of antisymmetric representations of SO(8):

Helicity (±) =	2	3/2	1	1/2	0
Multiplicity =	$\underset{\sim}{1}$	$\underset{\sim}{8}$	$\underset{\sim}{28}$	$\underset{\sim}{56}$	$\underset{\sim}{70}$.

Remarkably, this multiplet is also the gauge multiplet of the extended N = 8 supersymmetry. Clearly helicity-2 gravitons are united with ($\underset{\sim}{8}$) helicity-3/2 gravitinos, ($\underset{\sim}{28}$) helicity-one (possibly) Yang-Mills particles, ($\underset{\sim}{56}$) helicity-one-half quarks and leptons and ($\underset{\sim}{70}$) spin-zero Higgs'. The gauge multiplet of an extended supersymmetry has thus united gravity with matter.

3. Regretfully, SO(8) - the maximal marriageable internal symmetry in an extended scheme - is still too small to contain $SU_C(3) \times SU(2) \times U(1)$. Thus, though we may identify the gluon octet + Z^0 + γ from among the spin-one objects, there are no $W^\pm$. We may identify (u,d,s,c) quarks + e^- + (ν,ν') + (a six-fold of b-quarks) from among the spin-$\frac{1}{2}$ objects, but there are no (μ,τ) leptons or t quarks.

4. To summarize, the uni-multiplet unification of gravitons with matter achieved through extended supersymmetries is an attractive idea, but regretfully not yet implementable in a physically satisfactory manner through Poincaré-based supersymmetries. This is because the maximal extended supersymmetry N = 8 cannot accommodate an internal symmetry larger than SO(8), which unfortunately appears to be too small to serve as a Grand Unification symmetry for matter ($SO(8) \not\supset SU_C(3) \times SU(2) \times U(1)$).

D. The two problems of formulating consistent supergravity theories

As stated before there are two problems of a theoretical nature with supergravity theories:

Problem I

Formulate supergravity theories (simple and extended), preserving their (A) gauge character, (B) supersymmetry as well as (C) general covariance.

Problem II

Formulate supergravities in terms of geometrical quantities in superspace.

Problem I was first solved

i) for simple supergravity at Stonybrook (Freedman, Ferrara, van Nieuwenhuizen) and at CERN (Deser and Zumino) in 1976 for on shell matrix elements [6].

ii) The same problem has been solved off-shell this year (1978) by three groups working independently: at Imperial College, London (Stelle and West), at CERN (Ferrara and van Nieuwenhuizen) and at Lebedev (Fradkin and Vasiliev) [7] for (simple N = 1) supergravity by itself and for N = 1 supergravity in interaction with supermatter. The secret of going off-shell apparently lies in the introduction of non-propagating auxiliary fields. This so-called "Component Approach" is indeed a memorable advance for the N = 1, supergravity theory.

iii) For extended supergravities, only the on-shell Stonybrook approach exists, developed by a number of authors for N = 2,3,4 and 8. The notable result of this work is that extended supergravity Lagrangians contain two basic parameters; the Newtonian constant plus a cosmological constant. In addition to the pure (extended) supergravity interaction, one may introduce Yang-Mills couplings which make the global SO(N) contained in the extended supersymmetry into a local SO(N). Remarkably, the coupling strength of this interaction is fixed; it equals (square root of the product of) the cosmological constant with the Newtonian constant. Alternatively stated, extended supergravities admit two types of interactions; the gravitational with a Newtonian coupling constant and the Yang-Mills of strength $\approx e$. The theory must then contain a cosmological term with a fantastically large constant $\approx e^2 G_N^{-1}$. (Whether such a large constant is a physical disaster is an unresolved problem.)

iv) A different approach to supergravity theories using covariantized contracted OSp(4,N) has been pursued by MacDowell and Mansouri, Chamseddine and West, and Neeman and Regge. Whether the Lagrangians obtained in this approach are identical to those in other approaches (except for simple supergravity itself) needs further study.

Problem II: Superspace formulations of supergravity theory

i) Superspace: Superspace is the first non-trivial extension of spacetime, with eight co-ordinates; four bosonic x^m and four fermionic θ^α. (Note that the anticommutativity of the four θ's implies

$$(\theta^\alpha)^5 = (\theta^\alpha)^6 = \theta^\alpha)^7 = \ldots = 0.)$$

ii) Superfields: One may define superfields $\Phi(x,\theta)$ in superspace (Strathdee et al.) 8). Remark that a scalar superfield $\Phi(x,\theta)$ contains sixteen ordinary local fields (eight Fermi and eight Bose) as "components". This may be seen by expanding $\Phi(x,\theta)$ in powers of θ. The number sixteen results when we remark that the expansion stops at θ^4.

iii) The Dubna minimal superfield for describing supergravity: It has been shown (1978) by Ogievetsky and Sokatchev 9) that the IC-CERN-Lebedev simple supergravity Lagrangian can be written in terms of a special superfield $V^\mu(x,\theta)$ built out of the IC/CERN/Lebedev component fields $V^\mu(x,\theta) = e^\mu_a\, \bar\theta\, \gamma_a \gamma_5\, \theta + (\bar\psi^\mu \theta)\,(\bar\theta\theta)$ + auxiliary IC/CERN/Lebedev fields occurring as coefficients of $\bar\theta\theta$ and $(\bar\theta\theta)^2$ terms. Does this solve the problem of the superspace formulation of supergravity? Unfortunately not. The Dubna superfield $V^\mu(x,\theta)$ has no geometrical status in a superspace context.

iv) Geometrical entities in superspace: The geometrical objects in superspace are either the supermetric $g_{MN}(x,\theta)$, introduced by the North-Eastern group of Arnowitt and Nath, or supervielbein $E^A_M(x,\theta)$ and superconnection $\Phi^A_{MB}(x,\theta)$ – or equivalently supercurvature R^B_A and supertorsion T^A (CERN, Wess and Zumino; CALTECH, Brink, Gell-Mann, Ramond, Schwarz (and Neeman and Breitenlohner), and recently Yale, MacDowell). (Presentations to the Tokyo Conference 1978.)

The problem of a superspace formulation of supergravity devolves into the problem of starting with a Lagrangian involving geometrical quantities, e.g. the supervielbein and superconnection, and expressing these in terms of the Dubna superfield. Table VI lists the approaches to this problem, discussed at the Tokyo Conference.

	CERN Wess, Zumino	CALTECH Brink, Gell-Mann, Ramond, Schwarz	NORTHEASTERN Arnowitt, Nath	YALE MacDowell
Primary objects for simple supergravity	$E(x,\theta)$ supervielbein (1024 components) $\Phi(x,\theta)$ superconnection (1792 components)	E Φ 112 independent fields	$g_{MN}(x,\theta)$ supermetric (1024 components) $g_{MN} = E^A_M E_{AN}$	E Φ
Constraints and equations of motion	Impose constraints on certain components of R (supercurvature) and T (supertorsion). Solve these to obtain (Grimm, Siegel) $E = \bar{\mathcal{D}}\mathcal{D}\, V$ ($V^\mu(x,\theta)$ = Dubna superfield with same components as IC/CERN/Lebedev)	Write a minimal set of 112 equations for 112 fields	Equations of motion $R_{MN} = \frac{8}{k^2}\, g_{MN}$ (k = 0, Stonybrook limiting supergravity)	Minimal set of equations like CALTECH
	$\int \det E\, d^4x\, d^4\theta = \int f(V)\, d^4x\, d^4\theta$ coincides with IC/CERN/Lebedev Lagrangian (2nd order formalism)	Equations of motion derivable from $\int \det E(\sigma.R - 3\gamma.T)\, d^4x\, d^4\theta$ (1st order formalism)	Establish equivalence to CALTECH approach on shell	
Matter couplings	Same as IC/CERN/Lebedev	Can couple $(1,\frac{1}{2})$ matter		
Extended supergravities	No superspace Lagrangian known for extended supergravities	Approach extends to N = 2,3	Equations extend for all N	Approach extends to N = 2,3

Table VI

Status of superspace formulations of supergravities as reported at the Tokyo Conference, 1978.

E. Summary

The simple supergravity ($N = 1$) has had two technical triumphs this year.

1) The so-called component approach, with auxiliary fields; IC/CERN/Lebedev (off-shell) formulation of the simple supergravity Lagrangian, for supergravity by itself and in interaction with matter.

2) Superspace formulations of simple supergravity. With these formulations becoming available, ideally one should now be able to write down superpropagators in superspace and investigate, for example, the off-shell infinity structure of the theory. One may even consider making a dent on the supertopology of the superspace.

All this is, unhappily, for simple $N = 1$ supergravity alone. Simple supergravity does not lead to a unification of gravitons with quarks, leptons or Yang-Mills particles. For this we need extended supergravities.

The maximal extended Poincaré-based supergravity ($N = 8$) has an inbuilt Grand Unification Group $G = SO(8)$. This unfortunately is too small to contain $SU_C(3) \times SU(2) \times U(1)$ and to describe known physics.

Perhaps we need altogether different types of supersymmetries, instead of the underlying Poincaré supersymmetry. For example, conformal (rather than Poincaré) supersymmetry can lead to an extended conformal supergravity which could admit of $SU(8)$ rather than $SO(8)$ internal Grand Unifying Group.

When spontaneously broken $\left(\langle R \rangle = \frac{1}{G_N}\right)$, such supergravities lead, in the spin-2 sector, to Lagrangians of the type $R^2 + R/G_N$. It is known[10] that such Lagrangians:

i) are renormalizable (Stelle),
ii) may contain no ghosts if certain criteria are satisfied (Strathdee et al., Julve and Tonin),
iii) are asymptotically free in the Newtonian coupling G_N (Fradkin and Vilkovisky),
iv) provide matrix elements which are Froissart bounded (Strathdee et al.).

V. ORIGIN OF INTERNAL SYMMETRIES

Finally I wish to mention some recent ideas in respect of a possible origin for internal symmetries. In view of the flavour explosion, there is no problem more urgent than that of understanding the deeper basis of the generalized charge concept (flavour or colour). When I say "deeper basis", I have in mind as an example the one charge - the gravitational (mass) - for which we believe we do have a deeper basis in terms of spacetime curvature. Some while back, Wheeler suggested that the electric charge - and presumably other "internal" charges like the isotopic, or the unitary charges - possess a basis similarly deep, in terms of spacetime topology.

Recently, Hawking and Pope[11] have made Wheeler's conjecture plausible by considering applications of the most famous theorem in algebraic topology (Atiyah-Singer theorem), which relates the difference ($n_R - n_L$) of numbers of zero mass right-handed and left-handed fermions to curvature.

Applying the theorem naively for spacetimes with no internal charges, one may be tempted to write

$$n_R - n_L = -\frac{1}{384\pi^2} \int R\, R^* \sqrt{g}\ d^4x \ .$$

Hawking and Pope evaluate the right-hand side for a special (compactified) spacetime CP^2. The computation gives for the right-hand side the number $-\frac{1}{8}$. The left-hand side, however, must be an integer - a contradiction!

Hawking and Pope resolve the contradiction by remarking that CP^2 is not a spin structure; one cannot define spinors on CP^2, unless one defines a generalized spin^C structure. For this, as apparently all algebraic topologists know, one needs a U(1) symmetry and a gauge field $F_{\mu\nu}$, such that the correct formulation (for the CP^2 case) of the Atiyah-Singer theorem reads:

$$n_R - n_L = \left\{-\frac{1}{384\pi^2} \int R\, R^* + \frac{e^2}{16\pi^2} \int F^*_{\mu\nu} F_{\mu\nu}\right\} \sqrt{g}\ d^4x$$

$$= -\frac{1}{8} + \left\{\frac{1}{2} m(m+1) + \frac{1}{8}\right\} = \frac{1}{2} m(m+1) \ \rightarrow \ \text{an integer.}$$

Thus the topology CP^2 of a possible spacetime dictates an "internal" U(1) symmetry plus a gauge field $F_{\mu\nu}$.

Back, Freund and Forger [11] (1978) have carried this analysis one step further. They ask the pertinent question: why CP^2? What is so special about CP^2 universes? They would rather start with the class of four-dimensional Reimannian or (pseudo-Riemannian) manifolds - at the least such manifolds are necessary for a path-integral quantization of gravity. An analysis like that of Hawking and Pope then leads them to conclude that for a $spin^C$ structure to be defined, one needs a universal gauge SU(2) or $SU_L(2) \times SU_R(2) \times G$ together with a definite spin-isotopic relation. (If k_L, k_R are quantum numbers labelling representations $SU_L(2)$ and $SU_R(2)$, then $k_L + k_R$ must be a $\frac{1}{2}$ odd integer for fermions and $k_L + k_R$ = integer for bosons.) **Could** it be that the electroweak group is indeed $SU_L(2) \times SU_R(2)$ and that its origin lies in spacetime topology?!

This is profound, but according to Freund, such an analysis will not extend over to all internal quantum numbers. It is conceivable that in addition to the ideas of four-dimensional spacetime topology giving a clue to some of the internal charges, we need also the brashest though at the same time (in Sakurai's phrase) perhaps the "least imaginative" approach to the origin of internal symmetries, pioneered by Kaluza and Klein in the Nineteen-Twenties. In this approach - developed further in the Fifties and the Sixties by Pais and Takabayashi and recently by Cremmer, Scherk and Schwarz and by Horvath and Palla (Tokyo Conference 1978) - one assumes that the internal symmetries are windows on the existence of extra (bosonic) spacetime dimensions of small size $\sim 10^{-33}$ cm (Planck length), curling up on themselves on account of the associated high curvature. With Cremmer, Scherk and Schwarz, the idea started with the ten dimensions (10 = 4 + 6) in which dual models thrive. These authors interpreted the extra six dimensions when compactified as representing an internal symmetry space carrying $O(6) \approx SU(4)$. The exciting development is that Cremmer and Scherk have recently shown compactification of this type emerging spontaneously, such that starting with 4 + N dimensions, one may spontaneously descend to $\rightarrow R^4 \times S^4 \rightarrow$ Poincaré $\times$ SO(N+1). Further, Horvath and Palla, using the Atiyah-Singer theorem, related the differences in numbers of observed right- and left-handed zero-mass fermions (neutrinos) - a number delimited by cosmological considerations of helium abundance - to the topological invariants referring to the compactified space.

I have spoken, in this lecture, of extra Bose dimensions - of related Noether charges - of related topological charges - and of extra fermionic dimensions. I shall conclude by describing in Table VII a model due to Olive and Witten [12] which can be described in three equivalent approaches, where the medley of these seemingly disparate ideas appears to converge in an exciting synthesis.

Table VII

The Olive and Witten [12] model looked at from three distinct points of view

	Approach I	Approach II	Approach III
Spacetime	four dimensions	four dimensions	six dimensions
Symmetry	Simple supersymmetry $\otimes$ local SU(2)	Extended (N = 2) supersymmetry $\otimes$ SU(2)	Simple supersymmetry in six dimensions. Extra two (bosonic) dimensions compactified
Basic particles introduced in the model	Yang-Mills SU(2) triplet $\begin{pmatrix}1\\1/2\end{pmatrix}$ plus matter triplet $\begin{pmatrix}1/2\\0\end{pmatrix}$	$\equiv$ (SU(2) triplet) representation of N = 2 extended supersymmetry helicity 1 1/2 0 multiplicity 1 2 1	$\equiv$ an SU(2) Y-M simple supersymmetry representation in six dimensions
In addition there exist classical solutions corresponding to 't Hooft-Polaykov monopoles + dyons			
Anti-commutation relations of charges		$N = 2,\quad Q^i_\alpha,\quad i = 1,2,$ $\{Q^i_\alpha, Q^j_\beta\} = -\not{p}\,\delta^{ij} + \epsilon^{ij}(U + \gamma_5 V)$ U,V are central charges in the definition of Haag, Lopuszanski and Sohnius.	
	Compute $\{Q_\alpha, Q_\beta\}$; confirm that the anticommutation relations do contain U,V. Find $U = \int_{surface}$ field strength $= aQ_{el}$ $V = \int_{surface}$ field strength $= aQ_{mag}$	$\Longrightarrow$ Compare approach I and II Infer central charges (U,V) are topological	
Mass relations	Find to all orders $M^2 = P^2_\mu = a^2(Q^2_{el}+Q^2_{mag})$ for all objects in the theory; e.g. monopoles, dyons, fermions, gauge bosons	$\Longrightarrow$	Confirmation of the six-dimensional approach; All particles are light-like in [6], with components of six momenta, given by P_μ, aQ_{el}, aQ_{mag}; $P^2_\mu - a^2(Q^2_{el}+Q^2_{mag}) = 0$. Note aQ_{el}, aQ_{mag} correspond to momenta along the compactified dimensions

The most interesting feature of the model is the last: in the six-dimensional approach, the electric and the magnetic charges are associated with momenta corresponding to the fifth and the sixth bosonic compactified dimensions.

To summarize, in the Olive-Witten model we have three equivalent formulations: we may pass from a simple supersymmetric Yang-Mills theory in SU(2), with a triplet of supermatter fields, to an extended N = 2 supersymmetry (with extra fermionic dimensions) and central charges. We find the supersymmetric central charges are topological and represent electric and magnetic charges of the particles in the theory. And finally, in an equivalent formulation of the theory in six dimensions, these rather familiar charges find meaning as momenta corresponding to the compactified dimensions! Crazy, but with Niels Bohr, one must ask, is this crazy enough?

I'd like to conclude with a quotation from J.R. Oppenheimer on the future of our subject: "Physics ..... will change even more ..... If it is radical and unfamiliar , and a lesson that we are not likely to forget, we think that the future will be only more radical and not less, only more strange and not more familiar, and that it will have its own new insights for the inquiring human spirit".

Reith Lectures BBC 1953

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