SPECULATIONS

One morning a woodcutter saw Hoja by the edge of a lake, throwing quantities of yeast into the water. "What the devil are you doing, Hoja?" he asked. Hoja looked up sheepishly and replied, "I am trying to make all the lake into yogurt." The wooducutter laughed and said, "Fool, such a plan will never succeed." Hoja remained silent for a while, and stroked his beard. Then he replied, "But just imagine if it should work!"

1. STRONG INTERACTIONS

SPECULATIONS ABOUT THE STRONG INTERACTION ARE MAINLY CONCERNED WITH THE NATURE OF QUARK CONFINEMENT. THERE ARE AT LEAST 2 SORTS OF QUESTIONS: WILL CONFINEMENT FAIL AT SOME SUITABLY HIGH ENERGY; AND WHAT CAN WE LEARN ABOUT CONFINEMENT AT PRESENT ENERGIES?

PERHAPS THE PATH TO ASYMPTOTIC FREEDOM IS NOT COMPLETELY SMOOTH. THERE MAY BE A SHARP THRESHOLD IN ENERGY ABOVE WHICH COLORED QUARKS AND GLUONS CAN EXIST SINGLY. THIS POSSIBILITY REITERATES THE THEME OF THIS COURSE: NEW PHENOMENA IN HIGH ENERGY PHYSICS ARE EXPECTED TO BE REVEALED AS THE ENERGY OF OUR PROBE INCREASES. THERE ARE HOWEVER NO DEFINITE EXPECTATIONS FOR A COLOR THRESHOLD.

SOME PEOPLE ADVOCATE THE USE OF URANIUM-URANIUM COLLISIONS AS A MEANS OF RAISING THE ENERGY WITH EXISTING TECHNOLOGY. THAT IS, WE MIGHT BE ABLE TO ACCELERATE URANIUM NUCLEI TO ENERGIES OF, SAY, 100 GeV/NUCLEON. THEN IN A U-U COLLISION, $E_{CM} \sim 50{,}000$ GeV ONE MIGHT HOPE FOR A 'PHASE TRANSITION' FROM NUCLEAR MATTER TO A 'QUARK-GLUON PLASMA' DURING SUCH A COLLISION. IN THIS PLASMA HEAVY QUARKS MIGHT BE AS COMMON AS LIGHT QUARKS, SO PERHAPS THE PLASMA WOULD DECAY TO MANY MORE PARTICLES WITH b, c & s QUARKS THAN IS TYPICAL AT PRESENT ENERGIES. IN COLLISIONS OF URANIUM HAVING 100 GeV/NUCLEON THE ENERGY DENSITY IS HOWEVER NOT MUCH GREATER THAN IN $p\bar{p}$ COLLISIONS — ONLY THE LONGITUDINAL DENSITY INCREASES, BY $\sim \sqrt[3]{238} = 6$ TIMES. SO UNLESS THE 'PHASE TRANSITION' IS ALMOST POSSIBLE IN PRESENT p-$\bar{p}$ COLLISIONS IT MAY NOT BE MUCH MORE FAVORABLE TO UTILIZE U-U COLLISIONS.

IN THINKING ABOUT CONFINEMENT AT PRESENT ENERGIES PEOPLE NOTE THAT THE FEYNMAN DIAGRAM APPROACH IS INSUFFICIENT. THE EXPANSION OF THE STRONG INTERACTION IN A SERIES OF TERMS OF SUPPOSEDLY HIGHER AND HIGHER ORDER IS A BAD APPROXIMATION AT ENERGIES $\lesssim \Lambda \sim 100$ MeV. ONE SPEAKS OF THE NEED FOR UNDERSTANDING OF 'NON-PERTURBATIVE' QCD. EFFORTS AT PRINCETON AND ELSEWHERE HAVE FOCUSSED ON THE HIGHLY INTRIGUING 'SOLITON' SOLUTIONS TO NON-LINEAR DIFFERENTIAL EQUATIONS. A RELATIVISTIC

variation of the soliton called the 'instanton' is supposed to play a role in confinement. But the experimentally verifiable content of these notions remains unclear at this time.

Does the existence of the nucleus imply that the color field is not absolutely confined inside the nucleons? Of course Yukawa's idea of the meson still has some validity. Perhaps all nuclear binding is just due to exchange of color singlet $q\bar{q}$ states. An intriguing possibility is that inside a nucleus there can be a component of the color field with range equal to the nuclear radius rather than 1 Fermi. This might allow the valence quarks to wander around inside the whole nucleus rather than be confined to a particular nucleon. Then the quark momentum distributions of a nucleus could be somewhat different from those of a free proton or neutron, contrary to the assumptions of Lectures 8 and 19. There is some evidence that this may be true in comparisons of μ-d and μ-iron inelastic scattering. This is the so-called 'EMC effect' reported in the last year by the European Muon Collaboration. See also Arnold et al, P.R.L. 52, 729 (1984). The full significance of the experimental result is not yet clear....

(glueballs ... top quark ....)

2. The Weak Interaction

Within the standard model of Glashow, Salam & Weinberg the speculations subject to verification in the next few years concern W and Z decays, discussed in Lecture 22. The most far reaching question which may be answered soon is the number of families of neutrinos, and by inference, of quarks as well. The other major speculation of the standard model concerns the nature of the Higgs field. People hope this question may be answered in the next decade by experiments with E_{cm} up to 2000 GeV.

There is no shortage of variations on the standard model. We mentioned one in Lecture 16, that there may be right-handed W bosons of mass somewhat higher than the recently discovered left handed W's. This would restore parity conservation at very high energies. In Lecture 19 we discussed the possibility that neutrinos might have mass, and the further possibility that different neutrinos 'mix' leading to 'neutrino oscillations'. Other variations consider the existence of very heavy neutral leptons, etc. Many of these options are reviewed by Strovink, in the 1982 SLAC Summer Study Proceedings (which is a good collection of speculative articles).

Another type of alternative to the standard model substitutes new phenomena for the Higgs field. We mention 2 of these in section 4.

3. GRAND UNIFICATION

PERHAPS THE MOST IMPRESSIVE OUTGROWTH OF THE STANDARD MODEL OF THE ELECTRO-WEAK INTERACTION IS GRAND UNIFICATION. IN THIS VIEW QUARKS AND LEPTONS BELONG TO SUPER FAMILIES CONVENIENTLY CHARACTERIZED BY MULITPLETS OF THE SU(5) GROUP (OR ALSO THE SO(10) GROUP). IN SU(5) THERE ARE $5^2-1=24$ 'GENERATORS' OR BASIC ROTATIONS, WHICH SUGGEST 24 POTENTIALS IN A GAUGE THEORY. OF THESE WE READILY IDENTIFY 12 AS THE 8 GLUONS, THE $W^\pm$, Z^0 AND γ. THE OTHER 12 POTENTIALS ARE PRESUMED TO HAVE EXTREMELY HEAVY QUANTA WHICH CAN INDUCE TRANSITIONS AMONG THE QUARKS AND LEPTONS. THIS LEADS TO THE FAMOUS PREDICTION OF PROTON DECAY.

WE ALREADY REMARKED IN LECTURE 3 HOW THE STRONG AND ELECTROMAGNETIC COUPLING CONSTANTS CONVERGE TO A VALUE $\alpha_U \sim 1/60$ AT $E \sim 10^{15}$ GeV. THIS ENERGY IS TAKEN AS CHARACTERISTIC OF THE MASS, M_X, OF THE HEAVY QUANTA OF THE GRAND UNIFIED THEORY. UNIFICATION IS POSSIBLE AT THIS ENERGY IN THAT ASYMPTOTIC FREEDOM OF THE COLOR FIELD LOWERS α_{STRONG} AS E INCREASES, CONTRASTING WITH THE RISE OF α WITH E. WE ESTIMATED IN LECTURE 3 THAT THE PROTON DECAY RATE IS

$$\tau_p^{-1} \sim \alpha_U^2 \frac{M_p^5}{M_X^4} \Rightarrow \tau_p \sim 10^{33} \text{ YEAR} \quad \text{WITH } M_X \sim 10^{15} \text{ GeV}.$$

A PARTICULAR VERSION OF GRAND UNIFICATION, THE SO-CALLED MINIMAL SU(5) THEORY PREDICTS $\tau_p \sim 10^{30}$ YEAR.

OTHER FEATURES OF GRAND UNIFICATION INCLUDE:

- EXPLANATION OF THE EQUALITY OF ELECTRON AND PROTON CHARGE.
- PREDICTION THAT $\sin^2\theta_W = 3/8$ AT $E \sim 10^{15}$ GeV, AND $\sin^2\theta_W = \frac{3}{8}\cdot\left(1 - \frac{N}{4\pi}\left(\frac{11}{3}\right)\ln\left(M_X^2/Q^2\right) + \cdots\right) \sim .21$ AT $Q \sim 10$ GeV
- SIMPLE ACCOMODATION OF MASSIVE NEUTRINOS INTO MULTIPLETS OF SO(10) RATHER THAN SU(5)
- $n \leftrightarrow \bar{n}$ TRANSITIONS, LEADING TO POSSIBLE 'NEUTRON OSCILLATIONS'

THERE IS ONE OTHER DRAMITIC PREDICTION (OR ASSUMPTION) WHICH IS ASSOCIATED WITH GRAND UNIFICATION: THAT BETWEEN ENERGIES OF $\sim 10^3$ GeV AND 10^{15} GeV THERE ARE NO FUNDAMENTALLY NEW PARTICLES OR INTERACTIONS. THAT IS, THE INCREDIBLE INTELLECTUAL LEAP ACROSS 12 ORDERS OF MAGNITUDE IN ENERGY IS ONLY POSSIBLE IF THERE IS NOTHING OF INTEREST IN THE GAP. GRAND UNIFICATION PRESUPPOSES A 'DESERT' IN PHYSICS WHICH SHOULD BEGIN SHORTLY BEYOND PRESENTLY ACCESSIBLE

ENERGIES. IT REMAINS FOR THE FUTURE TO DETERMINE HOW PLAUSIBLE THIS ASSUMPTION IS IN FACT. BUT THE ATTEMPTED SYNTHESIS OF GRAND UNIFICATION SURELY DOES HAVE A SENSE OF GRANDEUR ABOUT IT.

WE INCLUDE AS AN APPENDIX TO THIS LECTURE THE ORIGINAL PAPER BY GEORGI & GLASHOW, WHICH IS RATHER ACCESSIBLE. FOR FURTHER REMARKS OF AN INTRODUCTORY NATURE SEE THE BOOK OF PERKINS, OR THE LECTURE BY WILLIAMS IN THE 1982 SLAC SUMMER STUDY. THE BOOK 'UNITY OF FORCES IN NATURE' BY ZEE (WORLD SCIENTIFIC, 1982) INCLUDES AN EXTENSIVE COLLECTION OF REPRINTS ON GRAND UNIFICATION.

EXPERIMENTAL LIMITS ON THE PROTON LIFETIME SUMMARISED IN THE TABLE BELOW ARE TAKEN FROM A RECENT PAPER BY PERKINS (CERN/EP 84-7) WHICH WILL APPEAR IN THE 1984 EDITION OF ANNUAL REVIEWS OF PARTICLES AND FIELDS. THE LIMIT THAT

$$\tau_{p \to e^+ \pi^0} > 10^{32} \text{ YEARS}$$

ARGUES AGAINST THE 'MINIMAL SU(5)' THEORY.

ALL OF THE EXPERIMENTS HAVE A FEW LOW QUALITY PROTON DECAY CANDIDATES, BUT NO TRULY CONVINCING EVIDENCE IS AVAILABLE AT THIS TIME.

THE IMB EXPERIMENT ALSO GIVES A LIMIT ON NEUTRON DECAY

$$\tau_n > 2 \times 10^{31} \text{ YEAR}$$

[JONES ET AL P.R.L. 52, 720 (1984)
PARK ET AL P.R.L. 54, 22 (1985)]

FROM THIS THEY INFER THAT IF $n \leftrightarrow \bar{n}$ TRANSITIONS DO OCCUR, THE CHARACTERISTIC OSCILLATION TIME MUST BE GREATER THAN 10^8 SECONDS (3 YEARS).

Recent limits on proton lifetime

In units of 10^{31} yrs x branching ratio. 90% CL lower limits, unless ~ indicates signal claimed. Number of candidates, if any, given in brackets.

Experiment	KGF	NUSEX	KAMIOKA	IMB
Reference	[102]	[91]	[100]	[79]
$p \to e^+\pi^0$	~ 2 (1)	1.5	2.0	15
$\to \mu^+\pi^0$	~ 2 (1)	1.0	2.0	15
$\to e^+\rho^0$	-	-	2.5	-
$\to \mu^+K^0$	~ 2 (1)	0.6 (1)	0.8 (1)	2.6 (1)
$\to \mu^+\eta^0$	-	-	0.4 (1)	5.0
$\to e^+K^0$	-	-	0.9	3.1
$\to \nu K^+$	~ 2 (1)	0.2	0.5 (2)	-
$\to \nu\pi^+$		0.2 (≤ 3)	0.3 (2)	-
$n \to e^+\pi^-$	~ 2 (1)	1.5	1.2	-
$\to \nu\pi^0$	-	0.7	0.6	-
$\to \nu K^0$	-	0.5	0.3	0.8 (3)

ANOTHER AMUSING FEATURE OF GRAND UNIFICATION IS THAT MAGNETIC MONOPOLES ARE EXPECTED TO OCCUR AS STABLE BOUND STATES OF THE HIGGS PARTICLE AND THE HEAVY QUANTA X. HENCE MONOPOLE MASS $\sim M_X \sim 10^{15}$ GEV. SEE CHAPTER 10 OF THE BOOK BY MORIYASU, OR THE ARTICLE BY CABIBBO IN TECHNIQUES AND CONCEPTS IN HIGH ENERGY PHYSICS II, ED BY FERBEL PLENUM (1982).

The report in 1983 by Cabrera of evidence for a single monopole event has not been confirmed by him or others. (The implied event rate was alarming to cosmologists, if exciting to many others.)

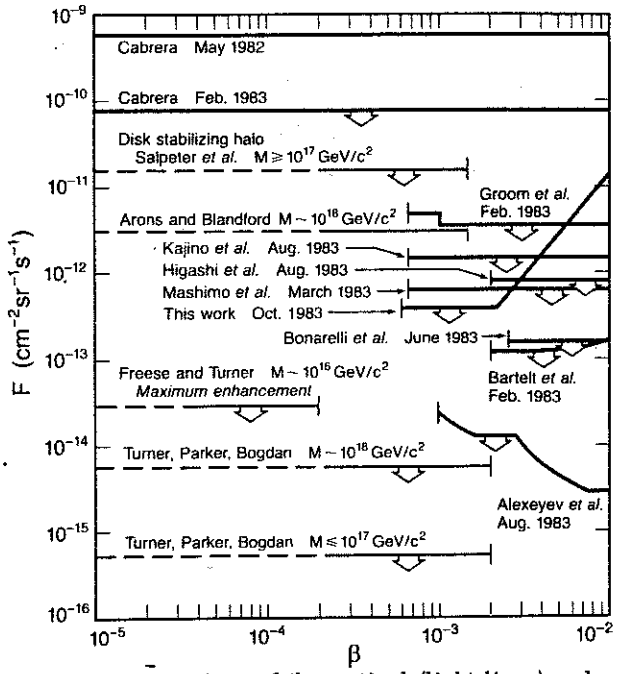


FIG. 2. Comparison of theoretical (light lines) and experimental (bold lines) limits for monopole flux. Solid lines for theoretical limits indicate the most probable velocity window.

Tarle et al P.R.L. 52, 90 (1984)

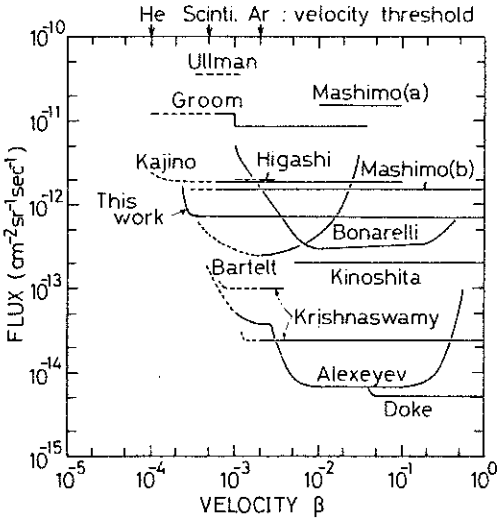
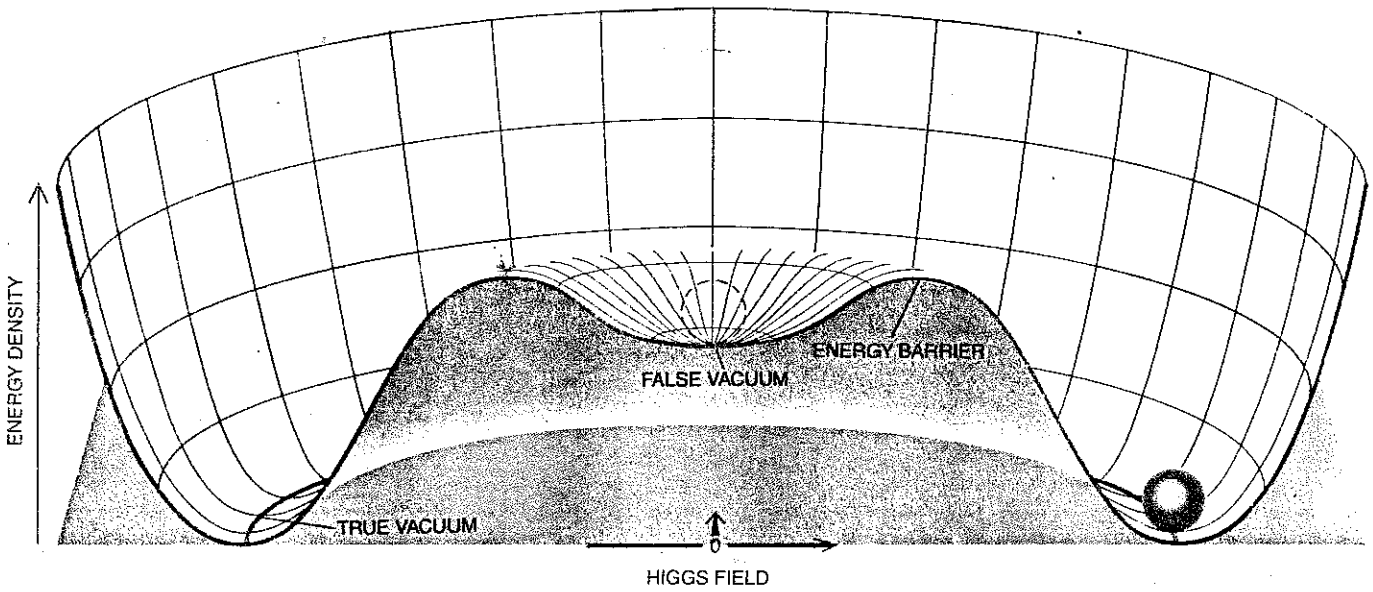


FIG. 3. Compilation of upper limits on the flux of magnetic monopoles as a function of velocity β at a 90% confidence level for ionization/excitation experiments. The broken lines mean that it is impossible to measure if calculations for the energy losses taking into account the binary encounter approximation for scintillators and argon gas are valid.

Kajino et al P.R.L. 52, 1373 (1984)

Rubakov, and Callan [Nuc. Phys. B212, 391 (1983)] have remarked that a monopole passing within 1 Fermi of a proton would 'catalyse' the decay of the latter. This is a surprisingly long range effect for the monopole which weighs 10^{15} GeV. The proton decay experiments have not yet seen any evidence for multiple proton decays along the path of a passing monopole. The resulting flux limits are about 10^{-19} cm^{-2} sr^{-1} s^{-1}, as on the plots above.

The theory of Grand Unification has had considerable application to cosmology of the very early universe. CP violation in proton decay is presumed to account for the observed preponderance of matter over antimatter. The Higgs view of the vacuum also plays an important role. It is supposed that the transition from Higgs field with $\phi = 0$ to $\phi = f/\sqrt{2}$ occurs spontaneously at about 10^{-30} sec., leading to a major rearrangement of the structure of the (tiny) universe at that time. The illustration of the universe on p. 427 as a bowl of Higgses is taken from the article 'The Inflationary Universe' by Guth & Steinhardt, in Scientific American, May 1984.



4. Oases on the Desert

The elegant sparseness of grand unification contrasts with the feeling of many people that nature has many levels of phenomena awaiting us as we probe to smaller distances with higher energy. Concerns about the details of the Higgs mechanism have led to at least 2 suggestions of quite new phenomena already at energies $\lesssim$ 1000 GeV.

An early version was the model of 'technicolor' in which a new clan of quarks is postulated with a new kind of strong interaction, due to the technicolor field. Interactions of the particles of the standard model with the technicolor particles mimic the effects of the Higgs field, eliminating the specific need for the latter. See the lecture by Susskind in the 1982 SLAC Summer Study.

A more popular model in recent times is 'supersymmetry'. This originated in attempts to quantize gravity, but has found a home in 'ordinary' particle physics as well. According to supersymmetry each ordinary fermion has a new boson partner, and each ordinary boson has a new fermion partner. The names assigned to the new supersymmetric particles are among the most unfortunate yet in high energy physics. See the table on p 428.

In principle the masses of the partners should be similar if not equal. So there is supposed to be an 'alternate universe' of particles lurking somewhere in presently accessible regimes. The new particles carry a conserved quantum number different from that carried by ordinary particles. Hence the lightest supersymmetric particle

MUST BE STABLE. IF IT IS NEUTRAL IT COULD BE VERY HARD TO DETECT (COMPARE THE DIFFICULTY OF FINDING THE NEUTRINO.) SEE THE REVIEW BY ELLIS IN THE 1983 SLAC SUMMER STUDY.

SEE ALSO HABER & KANE, PHYS. REPORTS 117 (1985)

Supersymmetric Sspectroscopy

Particle	Spin	Sparticle	Spin	Mass
quark q	½	squark $\tilde{q}$	0	≥ O(15) GeV
lepton ℓ	½	slepton $\tilde{\ell}$	0	≥ O(15) GeV
photon γ	1	photino $\tilde{\gamma}$	½	
gluon g	1	gluino $\tilde{g}$	½	≥ O(2) GeV
$W^{\pm}$	1	wino $\tilde{W}$	½	≥ O(15) GeV
Z^0	1	zino $\tilde{Z}$	½	
Higgs $H^{\pm}$	0	shiggs $\tilde{H}^{\pm}$	½	≥ O(15) GeV
H^0	0	$\tilde{H}^0$	½	

ANOTHER KIND OF NEW PHENOMENON MIGHT BE STRUCTURE OF THE QUARKS AND LEPTONS. ALREADY WE HAVE EVIDENCE THAT ANY SUCH STRUCTURE WILL REQUIRE $E > 500$ GeV TO BE DEMONSTRATED. BUT THERE IS STILL A LARGE ENERGY RANGE BEFORE 10^{15} GeV IS REACHED. AN INTERESTING SUGGESTION IS THE 'RISHON' MODEL OF HARARI (1982 SLAC SUMMER STUDY). HE SUPPOSES THAT THERE EXISTS 2 RISHONS:

T, WITH $e = 1/3$ V WITH $e = 0$

EACH RISHON COMES IN 3 COLORS, AND ALSO CARRIES A NEW QUANTUM NUMBER $H = B - L$ (HYPER COLOR = BARYON NUMBER − LEPTON NUMBER)

$H_T = 1/3$ $H_V = -1/3$

THE RESULTING TABLE OF STATES IS CERTAINLY CLEVER.

THUS FAR THE RISHON MODEL HAS NOT ADVANCED BEYOND BEING A CLASSIFICATION SCHEME, BUT IT REMINDS US THAT THERE IS NO FUNDAMENTAL REASON WHY THE LEPTONS AND QUARKS MUST BE REGARDED AS 'ELEMENTARY' PARTICLES.

(AXIONS .... FAMILONS ....)

	Color	Q	B-L	Rishon Combination
e^+	1	1	1	TTT
u	3	$\frac{2}{3}$	$\frac{1}{3}$	TTV
d	$\bar{3}$	$\frac{1}{3}$	$-\frac{1}{3}$	TVV
ν_e	1	0	-1	VVV
$\bar{\nu}_e$	1	0	1	$\bar{V}\bar{V}\bar{V}$
d	3	$-\frac{1}{3}$	$\frac{1}{3}$	$\bar{T}\bar{V}\bar{V}$
$\bar{u}$	$\bar{3}$	$-\frac{2}{3}$	$-\frac{1}{3}$	$\bar{T}\bar{T}\bar{V}$
e^-	1	-1	-1	$\bar{T}\bar{T}\bar{T}$

Table 2: Rishon model assignments of first generation fermions and antifermions.

5. AN EXPERIMENTAL COMMENT

THE SUCCESS OF THE GAUGE THEORIES NATURALLY LEADS TO MANY SPECULATIONS BASED ON THE BEAUTIFUL AND ELEGANT IDEAS THEREOF. BUT OTHER THAN SOME ASPECTS OF GRAND UNIFICATION THESE SPECULATIONS HAVE LED TO LITTLE CONFRONTATION WITH EXPERIMENT. IF THIS SITUATION REMAINS THE SPECULATIONS BECOME STERILE FROM THE POINT OF VIEW OF PHYSICS, NO MATTER HOW APPEALING THE MATHEMATICS MAY BE. (THIS POINT IS DEEPLY APPRECIATED BY MANY OF THE SPECULATORS.)

On the experimental side the quest for higher energies in elementary particle interactions has slowed somewhat due to the tremendous costs involved. By the year 2000 we may expect that the regime $E_{cm} \lesssim 5000$ GeV will be well explored using presently foreseen technology. It may be within the resources of this planet to push this technology to energies 1 order of magnitude greater. Of course, our technology is basically that of the cyclotron and Cockroft-Walton accelerator introduced in 1932. We have enjoyed 50 years of continued success in which the energies have risen 5 orders of magnitude from 1 MeV to 100 GeV in the c.m. frame. We have certainly extracted an incredible amount of information and insight into the nature of things from one basic approach. We may hope for a major technological advance which will bring unification energies of 10^{15} GeV within our grasp. But the method is by no means clear at this time.

We may also be able to pursue the hint that high energy physics indeed has something in common with solid state physics. Already in 1927 the physics of 2 particle interactions with $E \lesssim 10$ eV was well understood (the hydrogen atom). Further progress in understanding few body interactions required higher energies so that the strong and weak forces could be explored. On the other hand, the physics of low energy particle interactions with an extended medium (= solid) remains a vital field today. Correspondingly there may await discovery a rich realm of phenomena involving particle interactions with unusual, extended states of matter at high energies. A possible example, the quark-gluon plasma, was mentioned in section 1. Another case might be a 'photon solid' - a wave field so intense that the photons act collectively in a non-perturbative manner (i.e. expansions in $\alpha = 1/137$ become useless). The field strengths in certain fusion lasers may be within 2 orders of magnitude of that needed to create the 'photon solid'....

The challenge to explore the microworld remains before us. As always, progress will only follow felicitous combination of imagination and hard work.