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DEVELOPMENTS IN FUNDAMENTAL PHYSICS *

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

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I am concerned to-day with the developments in this century - and particularly during its third and fourth quarters - in respect of what we consider to be the elementary particles and the elementary forces between them. Table I summarises those developments which are relevant to my theme in the first three quarters* of this century. The major thrust of the discoveries upto 1950 was that there were four elementary particles; protons, neutrons, neutrinos and electrons with four elementary forces between them; gravitational, electromagnetic, weak nuclear and strong nuclear. After 1950, we came to believe that protons and neutrons were composite entities made up of quarks.

Comments on the Developments in the Third Quarter of this Century

If there is one concept which is the hall-mark of particle physics and which has emerged over the course of this century, it is the concept of charge - first gravitational charge (mass), second electric charge, third flavor charge (the doublet character of protons and neutrons and of neutrinos and electrons) and fourth, the color charge concept of quarks (objects of which protons and neutrons are made). The charge concept has three distinct aspects:

A. The Concept of Charge: Its three Aspects

1. Charge as a Label of Elementary Particles: Note from the table the emergence of conserved charges as labels of elementary particles. Such labelling charges are of two types: a) those connected with space-time: Examples are inertial mass and spin of an isolated particle. Conservation of inertial mass $\sqrt{P_0^2 - \underline{P}^2}$ is connected with invariance of the theory for space-time translations while spin conservation is connected with invariance under Lorentz rotations.

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1. These notes represent the source material from which the lecture was developed.

* Emergence of scientific ideas of course does not follow passage of time in a strict temporal sequence; thus this table is an approximation, so far as chronology is concerned.

b) The second type of conserved charges are the electric, the flavor and the color charges which are connected with symmetries of mysterious "internal" manifolds.

2. Charge as the Measure of Force: The second aspect of charge is as a measure of force. This aspect is particularly tied to the concept of a gauge force. The hall-mark of a gauge force is that (in the lowest order of approximation) a gauge force is proportional to the product of charges carried by the particles between which the force acts. Not all forces are gauge forces. Electromagnetism and gravity were known to be gauge forces from the outset. The great discovery of the third quarter of this century was that the weak nuclear, as well as the strong nuclear forces are basically also gauge forces: the weak force associated with flavor charges, the strong nuclear associated with color charges.

This second ("dynamical") aspect of the charge concept is to be contrasted with the first, which was kinematical. The kinematical aspects of charge (which included its conservation) were connected with the invariance of the theory under some symmetry operation. All our recent triumphs in particle physics are connected with the recognition of these dual aspects (kinematical and dynamical) of the charge concept, though Einstein had foreshadowed this. One may recall that the cornerstone of Einstein's theory of gravitation was the recognition (in his equivalence principle) which states the equality of the inertial (labelling) mass of a particle with its gravitational (dynamical) mass.

3. The third aspect of the charge concept is the unification of basic forces - assuming they are all gauge forces - through a postulated symmetry obtaining between these conserved charges. For example, a postulated symmetry of flavor with color charges would motivate the placing of quarks in the same multiplets as leptons (u, d, ν, e) on the one hand and the emergence of a unification between electromagnetism, the weak nuclear and the strong nuclear forces.

B. Unification of Forces, a Transition Phenomenon

4. This postulated symmetry, however, does not manifest itself for low energies experimentally. So we borrow an idea from condensed matter

TABLE I

	Conceptual Framework	Elementary Entities	Elementary Froces
1st Quarter	1) Sepcial Relativity 2) General Relativity (Theory of the Gravitational Force 3) Quantum Hypothesis and Bohr's Theory	1) Electron (e^-) 2) Proton ($\underline{P}^+$)	1) Maxwell's Electrodynamics Electric Force proportional to electrical charges (e) $F \propto e_1 e_2/r^2$ 2) Einstein's Gravity Gravitational Force proportional to Gravitational charges (m) $F \propto m_1 m_2/r^2$
2nd Quarter	4) Quantum Mechanics 5) Quantum Theory of Fields 6) Renormalization Theory of spin $\frac{1}{2}$ and spin zero particle interactions	3) Neutrino (ν_e) 4) Neutron (N) 5) Flavor doublets baryons $\begin{pmatrix} P \\ N \end{pmatrix}$ leptons $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$	3) Fermi's theory of the short range weak nuclear force $N \rightarrow P + e^- + \bar{\nu}$ Question: Is there a weak nuclear charge? 5) Strong Nuclear Force (short range) Is there a strong nuclear charge such that strong nuclear forces are portional to it?
	7) Spontaneous symmetry Breaking; the concepts of "order" for basic forces. 8) Energy dependence of gauge coupling constants (Renormalization Group)	6) Protons and neutrons are made up of three quarks each P = uud, N = udd 7) Quarks in three colors (R,Y,B) and two flavors (u,d) making up one family 8) 3 families $(\nu_e, e); (u,d)_{R,Y,B}$ $(\nu_\mu, \mu); (c,s)_{R,Y,B}$ $(\nu_\tau, \tau); (t?,b)_{R,Y,B}$ (R = Red, Y = Yellow, B = Blue)	6) Weak nuclear charge is the <u>Flavor charge</u> 7) Strong nuclear charge is the Color charge 8) Symmetry between charges (flavor and color) manifests itself as unification of forces: a) electric charge and flavor charge symmetry → unification of electromagnetism + weak forces (Electroweak Force) b) electric charge, flavor charge and color charge symmetry → unification of Electromagnetism + weak + strong nuclear forces (Electronuclear Force)

physics – the idea of symmetry restoration. At high energies – or in an environment of high temperature – such as that provided by the hot early Universe – there is a transition to a state of higher symmetry where the basic forces will appear perfectly symmetrical with each other; more precisely, these may be considered as components of a single unified fundamental force.

We believe that such a transition would take place at temperatures of the order of 1000 GeV ~ 10^{16} K^0 for electroweak unification of weak with electromagnetic forces and around 10^{14} GeV ~ 10^{27} K for electronuclear unifications of weak nuclear, strong nuclear and electromagnetic forces.

C The Emergence of the Electro-Weak Unification during 1957 – 1978

The gauge force of electromagnetism is mediated between electrically charged sourceparticles (electrons and protons) through the exchanges of the spin one (in units of h) particle – the photon. The question posed in 1957 was: Are there (a set of) particles ($W^\pm$) which may likewise mediate weak nuclear forces? Do they carry spin one?

The photon is electrically neutral. The $W^\pm$ would contrastingly have to be electrically charged in order to mediate neutron decay $N \rightarrow P + e^- + \bar{\nu}$ or $N + e^+ \rightarrow W^+ \rightarrow \underline{P} + \bar{\nu}$. They would carry weak gauge charges in addtion. Since (P, N) and (ν, e^-) are flavor doublets, the suspicion was that the weak charges must be flavor charges, corresponding to a rotation in the mysterious flavor space.

Now if this is so, one can easily show that there must be <u>three</u> W-particles (and not just <u>two</u> $W^\pm$), corresponding to three rotations in this space. These were christened, W^+, W^- and W^0, all of spin one. W^0 would have to mediate a new type of weak force hitherto unsuspected – between neutrinos and nucleons ($\nu + P \rightarrow \nu + P$, $\nu + N \rightarrow \nu + N$) or between neutrinos and electrons ($\nu + e \rightarrow \nu + e$), or even between electrons and protons, or electrons and neutrons. The rotation symmetry in the mysterious flavor space is represented by the group O(3) or SU(2).

A variant of this theory would treat these three weak charges symmetrically with the well known electro-magnetic charge (symmetry group SU(2) x U(1)) and mix the photon with W^0 with a mixing angle θ. Such a theory would have the merit of unification of weak and electromagnetic forces if experimentally $\sin^2 \theta \neq 0$.

The new type of weak interaction as postulated by the theory ($\bar{\nu} + N \longrightarrow \bar{\nu} + N$, $\bar{\nu} + P \longrightarrow \bar{\nu} + P$, $\bar{\nu} + e \longrightarrow \bar{\nu} + e$) were first discovered at CERN in 1973. These experiments indicate indirectly the existence of Z^0. (The two eigenstates of the mixture of W^0 with the mediator of electromagnetism are called Z^0 and the physical photon γ^0.)

Already these experiments showed that $\sin^2 \theta \neq 0$. In a famous experiment at SLAC, the mixing was further experimentally demonstrated in experiments with $e + P \to e + P$. The theory predicts $W^{\pm}$ and Z^0 masses as

$$M_W = \frac{38.66 \text{ GeV}}{\sin \theta} \approx 84.36 \text{ GeV}$$

$$M_Z = \frac{M_W}{\cos \theta} \approx 94.91 \text{ GeV}$$

(Present emperical value of $\sin^2 \theta = .224 \pm .012$.)

The question arises: Why are $W^{\pm}$, Z^0 heavy, if they are partners of the massless photon?

Here the concept of this being a transition situation comes in. For a Universe with a temperature environment in excess of 10^{16} K ($\sim$1000 GeV), $W^{\pm}$, and Z^0 would also make a transition to masslessness. Such conditions obtained till some 10^{-12} secs. after the big Bang. After this lapse of time $W^{\pm}$, Z^0 acquired masses.

The CERN $p\bar{p}$ collider just completed with centre of mass energy 270 + 270 GeV is expected to produce these particles in the laboratory and directly verify the unification of electromagnetism and weak nuclear forces.

D The Electronuclear Unification

Assuming that electrons and quarks are elementary[*] – i.e. there is no further level of elementarity to be discovered and assuming that all nuclear forces and the associated charges (flavor and color) are known – and one must stress that these are big assumptions which we question later – one may attempt to create a unified electronuclear theory which combines strong nuclear, weak nuclear as well as electromagnetic forces. This has been done, with a number of different versions. The most comprehensive attempt gauges a symmetry group SU(16) – the number sixteen corresponding to the sixteen quark and lepton (particles and antiparticles) constituting one family. The most economical attempt needs only a symmetry SU(5).

Such an electronuclear theory would place photons, $W^{\pm}$, Z^0 as well as gluons (gauge particles corresponding to the color charges of the strong nuclear force) into one multiplet. The most crucial prediction of the electronuclear theory and one which is receiving considerable experimental attention at present is the decay of the proton.

E Proton Decay

The economical SU(5) version of the electronuclear force (the so-called Grand Unified Theory – GUT) predicts proton decays of the type:

$$\begin{array}{l} P \to e^+ + \pi^0 \\ \qquad\quad\; \hookrightarrow \gamma + \gamma \end{array}$$

with $\tau_p \sim 10^{31 \pm 1.5}$ years.

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[*] Recall that there are three families, each a replica of the other – Table I a circumstance which some of us consider a strong argument in favour of new elementary entities – Preons – of which quark and leptons are composites.

The associated transition temperature above which there is expected to be a complete symmetry between weak, strong and electromagnetic forces is $\approx 10^{14}$ GeV in this model.

For the maximal SU(16) model, other modes are also predicted:

$P \rightarrow e^- + \pi^+ + \pi^+$ Transition temperature $\gtrsim 10^9$ GeV

$P \Rightarrow e^- + \nu + \nu + \pi^+ + \pi^-$
$\Rightarrow e^+ + \bar{\nu} + \bar{\nu} + \pi^0$ Transition temperature $\gtrsim 10^5$ GeV

$N \Rightarrow \bar{N}$ Transition temperature $\gtrsim 10^5$ GeV

(Note that this model predicts intermediate mass scales (10^5 GeV, 10^9 GeV) between present energies and high mass scale 10^{14} GeV of the SU(5) model.)

The Future

F Elementarity

We have spoken of the unification symmetry of fundamental forces as one which is temperature-(energy-)dependent. The full symmetry and the unification this implies manifests itself only for high temperatures (energies).

Is elementarity also an energy dependent concept; is there a succession, P, N, quarks, preons, prepreons, preprepreons ... each level of particles behaving as "elementary" point particles (with zero radius in a field theoretic sense) for successive energy ranges? Are the corresponding gauge particles ($W^{\pm}$, Z^0, gluons and the lepto-quarks which appear in the unified electronuclear theories and mediate proton decays) also composites?

Do the preons or prepreons ... carry completely unsuspected charges; for example, could they be Dirac monopoles — or dyons (carrying both electric and magnetic charges)? What are the transition energies associated with the elementarity of these successive stages? These are questions about which there is considerable speculation at present. However, without input from higher energy accelerators or other empirical sources (like cosmological observations relating to the early Universe) there is little hope of progress in developing from the stage of speculation to the stage of hard physics.

G Unification of Gravity with the Electronuclear Force

For this final step to be taken and Einstein's dream of an ultimate unification — with which he lived for 35 years — to be realized, we must deepen our understanding of the mysterious internal manifolds whose symmetries are associated with the electronuclear charges. We know (from Einstein) that the gravitational charge is associated with space-time curvature. The conservation of electronuclear charges shows that their existence implies symmetries of an internal space. What is the nature of this internal space? Are we possibly dealing with an extension of space-time where the extra dimensions have compactified to a very small size, invisible at ordinary energies, apprehended at present only through the indirect manifestation of electronuclear charges?

Just such a theory uniting gravity with electromagnetism — or gravitational charge with electric charge — was postulated by Kaluza and Klein in the 1920's. The size of the new fifth dimension — the fifth conjugate momentum being electric charge — would be of the order of Planck length ($G_N^{\frac{1}{2}} \sim 10^{-33}$ cms.) while the masses of all charged particles would be in Planck units of $G_N^{\frac{1}{2}} \sim 10^{19}$ GeV. What led to this compactification ? Was this also a transition phenomenon? This is a fascinating and of course an unanswered question.

One can ask how many dimensions would be needed if we wish to construct a Kaluza-type of unified theory for one electric, three flavor (weak-nuclear) and eight color (strong-nuclear) charges. The answer has recently been given; the minimum number of extra dimensions appears to be seven. In an eleven (rather than four) dimensional space-time, one would have the possibility of uniting gravity and electronuclear forces. Together they manifest curvature of this extended space.

But what about "elementary" matter — quarks, leptons, or preons of spin ½. Can we postulate a symmetry between spin ½ matter and spin-one gauge-force mediators? This final Fermi-Bose symmetry could also be understood as a manifestation of a space-time symmetry, provided there were (thirty-two) fermionic dimensions of space-time in addition to the (eleven) bosonic dimensions. This theory uniting gravity, electronuclear forces and fermionic matter (of spin 3/2 besides spin ½) is called extended supergravity of order eight.

This is the present level of speculation in our subject. The unification implied in the extended supergravity theory would clearly be relevant only at energies of the order of 10^{19} GeV. What are the possible indirect experimental tests of this at low energies? One such test* proposed in 1979 by the late French physicist, Joel Scherk - is the detection of anti-gravitational forces between objects separated from each other within distances of 100 metres to 1 Km.

Before I conclude, I shall summarise in somewhat greater detail the developments from 1950 of which I have spoken about (Table 2) dividing my story into decades. I shall then make some remarks about the experimental prospects of our subject, which are crucial for its continuation as an empirical science.

H Experimental Outlook for Particle Physics

The experimental outlook for testing the ideas we have been expressing, one must confess, is bleak.

There are four types of experiments which are presently yielding data on particle physics:

a) Accelerator Experiments; (b) Cosmic Ray Experiments; (c) Non-Accelerator Experiments and finally (d) Cosmological Data. Consider the prospects for each in turn.

a) Accelerators: Let us assume the $\bar{P}P$-collider, the Tevatron, Isabelle and Lep are available for experimentation during at least part of the decade. We shall then be well off in the TeV range of energies. In the decade after, between 1990-2005, one may envisage the possible installation of a $\bar{P}P$ collider in the Lep tunnel and the construction of the supertevatron. With superconducting technology these might optimistically reach 10 TeV, centre of mass. What happens to the subject twenty-five years from now, around 2005, when most of you in the audience would still be in your prime?

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* This test unfortunately is not a very conclusive one in the sense that if it is not fulfilled, supergravity would not be ruled out. This is because the test depends on a parameter, not yet computable from the theory as it has developed so far.

TABLE 2 - A HISTORY OF EMERGENCE OF CONCEPTS IN PARTICLE PHYSICS

EPOCH	ELEMENTARY ENTITIES	SYMMETRIES SPACE-TIME	SYMMETRIES INTERNAL	FIELD THEORY AND RELATIVISTIC QUANTUM MECHANICS		UNIFICATION	ACCELERATORS
Pre-1950 "Legacy"	$(PN),(e\ \nu)$ $(??),(?\ \mu)$	Poincaré conformal	charge U(1) flavor SU(2)	local U(1)-Weyl {local SO(1,3) + GR	{Dispersion Theory Renormalization of QED	Kaluza-Klein	
1950 - 1960	$(PN \wedge \Sigma^{\pm 0})$	{Parity (P) and charge conjugation (c) violated {Emergence of a broken chiral symmetry.	strangeness	{local SU(2) Yang-Mills Theory	Dispersion Theory Renormalization of Meson Theories Complex Angular Momenta		6 GeV (Lab.) (PP)
1960-1970	$(PN \wedge \Sigma^{\pm 0})$ ↓ QUARKS (ud) $(\nu_e e)$ (Os) $(\nu_\mu \mu)$ PARTON-MODEL	{Discovery of CP violation	{Global SU(3) Eight-fold way Global SU(4) {Non-linear realisations: of SU(2) x SU(2)	local $SU_L(2)xU(1)$ with spontaneous symmetry breaking {Fadeev-Popov Rules Anomalies	spontaneous symmetry breaking current algebra Regge Pole Theory	SU(2)xU(1) Electroweak	30 GeV (Lab.) PP
1970-1980	$(u\ d\ \nu_e e)$ {$(c\ s\ \nu_\mu \mu)$ $(0\ b\ \nu_\tau \tau)$ ↓ ? confinement?	super-symmetry	{$SU(3)_{color}$ SU(2)xU(1) {SU(5),SO(10),E_6, SU(16) ? violation of B,L Proton Decay?	local SU(3) of color Supergravity Confinement?	Renormalisation of Yang-Mills Renormalization Group; Asymptotic Freedom Marriage of particle physics and early cosmology Broken symmetry as a transition phenomenon Topological solutions solitons, monopoles, instantons; topological charge	Electronuclear (Grand) Proton decay as its test Extended super-gravities	30+30 (ISR)$_{c.o.m.}$ 400 GeV Lab. 40 GeV (e^+e^- c.o.m.
1980 -	PREONS? Prepreons?	Extended space-times in higher dimensions	Resolution of the mystery of charge	Finiteness of extended super-gravities	Topological structures and charges	Extended Kaluza-Klein Extended supergravities	270+270GeV (c.o.m.) LEP Isabelle (400+400) lab. Tevatron (1000+1000) lab. SuperLep+super-Tevatron 10 TeV Laser accelerators: 100 TeV

For definiteness, let us consider reaching 100 TeV – the presently accepted inverse radius of the muon, as revealed by limits on $\mu \rightarrow e + \gamma$. With present accelerator technology we shall have reached a saturation (1) in the CERN and Fermi-laboratory sites (2) in available funds and (3) most crucially in ideas for further machine design, which, let us gratefully recall were created for our generation by far-seeing men twentyfive years ago.

We desperately need, on a 25-year perspective, new ideas on accelerator design. To emphasise this point, let us remember that present designs are limited by the gradients of accelerating fields, E_{acc}. These presently attain values around $\sim$1.2 MV/metre and will improve to $\sim$5 MV/metre with superconducting magnets. If a credible design using lasers, for example, could be made available, $E_{acc.}$ could register values of the order of GV/metre. (Willis at CERN has considered collective ion effects, which promise field gradients of the order 3 GV/metre; Palmer estimates 2 GV/metre using surface effects of a grating; this figure rising to 20 GV/metre if gratings were permitted to be destroyed at each pulse).

If such designs could become reality – and one must not underestimate their difficulties – (laser wave-lengths are in the micron region)– a 100 TeV accelerator need be no longer than $\sim$30 KM; perhaps even as compact as 5 KM.

What I am trying to emphasise is that accelerators may become extinct as dinosaurs in twenty-five years, unless our community takes heed now and invests effort on new design.

b) Cosmis Ray Experiments: The highest possible cosmic-ray energies on earth unfortunately do not exceed 100 TeV (centre of mass). The global cosmic-ray detection effort produces no more than 300 events/year at this energy and no more than 2000 events/year at 10 TeV (centre of mass). These numbers would increase by a factor of 10 if there was a 100 KM^2 coverage with detection devices – certainly worthwhile until a 100 TeV accelerator becomes available, but no substitute for investment in new accelerators and their design.

c) Non-Accelerator Experiments which include (i) search for proton-decays (ii) search for N-$\bar{N}$ oscillations (iii) neutrino mass and oscillation experiments, involving reactors and (iv) search (also geochemical) for neutrino-less double β-decay are likely to provide some of the most eagerly awaited information on the distribution of intermediate mass scales. For example, each of the proton-decay modes ($P \rightarrow e^+ + \pi^0$, $P \rightarrow e^- + \pi^+ + \pi^+$, $P \rightarrow 3\nu + \pi^+$ and $P \rightarrow 3\bar{\nu} + K^+$) if seen, is associated with a different mass-scale (10^{14} GeV, 10^9–10^{10} GeV, 10^5 GeV). All these modes can co-exist though some of them may be rare. Thus proton decay experiments will have a long life-span, with the vast information that they and they alone can provide. There is a good case for buying real estate under the Mont Blanc for long occupancy.

d) Finally early Cosmology: Notwithstanding Landau's famous admonition: "Cosmologists are often wrong, but seldom in doubt" – Cosmology, while also exploring other intermediate mass scales, provides our only window on masses beyond 10^{14} GeV.

But, even after painting this bleak picture for the experimental prospects of our subject, I am continually and forever being amazed how relatively rapidly our experimental colleagues, succeed in demolishing (or sometimes demonstrating) the seemingly inaccessible and often outrageous of our theoretical speculations. This continual vigilance back and forth is the glory of all science, including our own.

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