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Is Simplicity — Many Particles BUT A Unique Gauge Principle ?

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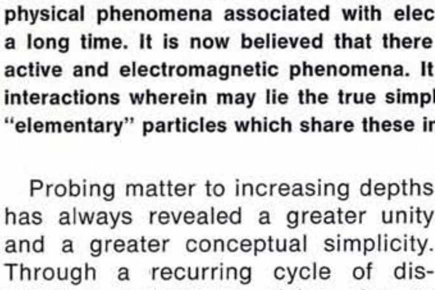
Above - Professor Abdus Salam of Imperial College, London and Director of the International Centre for Theoretical Physics in Trieste; below - Professor Sheldon L. Glashow of Harvard University.

100 years after Maxwell, the physics world is now confident that a major step forward has been taken in establishing a close relationship between the electromagnetic and weak forces. Recognition of this historic achievement is made in the award of the 1979 Nobel Prize for physics to Sheldon Glashow, Abdus Salam and Steven Weinberg who established the theoretical grounds for unification and stimulated the experimental work that has triumphantly confirmed many of their predictions. The interdependence of the physical phenomena associated with electricity and magnetism have been familiar for a long time. It is now believed that there is a similar interdependence between radioactive and electromagnetic phenomena. It opens the possibility of a great unity among interactions wherein may lie the true simplicity of the world rather than in the myriad of "elementary" particles which share these interactions.

Probing matter to increasing depths has always revealed a greater unity and a greater conceptual simplicity. Through a recurring cycle of discoveries, sometimes giving rise to increased confusion at first, then to the emergence of new structure and the opening of new and wider perspectives, the molecular, atomic and nuclear levels have been successively unravelled. Now, evidence is accumulating for a new structure at a deeper level. The quark and parton models of the past decade have merged into the presently understood quark structure of the hadrons. There remains no doubt that the hundreds of hadrons generated by high energy physics in its quest to find the structure of the proton are all composite systems, built out of a small number of more basic constituents. The theory which describes such structures, Quantum Chromodynamics, emerges as a promising approach to strong interactions analyzed at the quark level.



Professor Steven Weinberg of Harvard University. All photos taken recently at CERN following the Nobel Prize award.

While unity and simplicity are being restored in the hadronic world, the increasing complexity of which has been a great puzzle for many years, one may be surprised by the rather large variety of quarks whose existence is now accepted. Three types of quark were enough to reproduce all particles known up to five years ago. There is now evidence for five types and theorists are inclined to expect six quarks, arranged in three doublets :

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \quad (1)$$

Moreover each quark exists in three varieties referred to as colours.

At the same time the long standing puzzle raised by the existence of the muon has gained in complexity with the discovery of the τ lepton, twice as heavy as the proton. The leptons seem also to be organized in three doublets:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad (2)$$

Such a symmetry between quarks and leptons replaces at a deeper level the hadron-lepton symmetry of 40 years ago, namely :

$$\begin{pmatrix} p \\ n \end{pmatrix} \begin{pmatrix} \nu_e \\ e \end{pmatrix}$$

However the reason for which Nature appears to repeat the same

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pattern at least three times is a great mystery. The first doublets in (1) and (2) are in effect enough to reproduce or describe all structures and processes within the realm of atomic and nuclear physics.

One may even be tempted to think that high energy physics is now generating its own world, with new doublets which do not exist outside the ephemeral particles created with multi GeV accelerators. Nevertheless, high mass intermediate states do occur naturally through virtual transitions in the framework of quantum mechanics, even though the actual energies may not be enough to produce them as isolated real particles. Any detailed understanding of the mechanisms involved has to include them, and the present problems of high energy physics have thus a much broader scope than one might casually conclude. Furthermore, the experimental conditions typical of high energy physics bring us closer to those which are likely to have existed at the very beginning of the Universe. The precise nature of interactions as they are currently understood, must have been of great relevance as the world which we observe was just emerging from the "Big Bang". Any clue about such a mysterious and fundamental process should be of great intellectual value.

The Basic Interactions

While the large number of quarks and leptons may generate some passing disappointment in an atavistic quest for simplicity at the constituent level, their rather large number could emerge as a necessity in a new perspective where the different basic interactions, which may at present appear unrelated are seen as a different facet of a unique mode of interaction. Simplicity may not be in an economy of particles but in an economy of principles.

A unified theory of weak and electromagnetic interactions is the recent great step forward. The theoretical work of Glashow, Salam and Weinberg led to the discovery of weak interactions through neutral currents for which evidence was first obtained at CERN, in a 1973 experiment using the bubble chamber Gargamelle. The existence of such a new mode of weak interactions, where there is no transfer of electric charge in lepton-hadron and lepton-electron collisions, was a key prediction for a theory where weak and electromagnetic interactions are combined in the framework of a "unified" theory.

The discovery of weak interactions through neutral current was the first in a list of important discoveries which all appeared as verifications of the predictions stemming from a unified theory. In 1974 came the discovery of the new particles. Their unexpectedly narrow width is now understood as a consequence of their being built out of a new type of quark, the charmed quark and its antiquark. In 1976 we had the discovery of charmed particles proper followed in 1978, by the discovery of parity violation effects in electron scattering which demonstrated for neutral currents, the universal property expected for weak interactions.

The formulation of the theory in terms of the particularly simple Weinberg-Salam model has been extremely successful. A host of experimental results of *a priori* widely different character can be expressed in terms of one parameter, which relates the probability of a neutral current interaction to that of similar charged current interactions. Written as $\sin^2\Theta_w$, the value is known to be 0.23 ± 0.01.

Six years elapsed between the first formulation of the model and the discovery of the weak interactions by neutral currents. In the meantime, a very important theoretical advance had been made by G-t'Hooft who showed how the unified model could lead to an actual theory of weak processes, as all divergences known to occur beyond the lowest order calculations could be removed through renormalization.

Meanwhile, neutral current effects had already been thoroughly searched for in specific processes, such as K meson decay, but without success. It was shown by S. Glashow, I. Iliopoulos and L. Maiani that compensating effects due to a new type of quark could, however, provide a consistent picture with neutral current effects limited to certain processes such as neutrino inelastic scattering. This is where they were eventually discovered, with evidence for the charmed particles following within a few years. Weak and electromagnetic interactions can thus be combined within a unique theory. A great new synthesis is achieved but a new quark is necessary.

The obvious next step in testing the present electroweak interaction theory is finding the quanta of the weak forces, the $W^\pm$ and the Z° for which masses of about 80 and 90 GeV respectively can now be predicted from the known value of $\sin^2\Theta_w$. Producing them is the goal of major new experimental programmes, both in Europe and in the United States.

It may sound puzzling that a unique unified theory for weak and electromagnetic processes can accommodate field quanta as different as the massless photon and the very heavy W and Z bosons and hence interactions which are infinite in range and very short range, parity conserving and parity violating. This is achieved in the framework of a gauge theory.

The theory generalizes the gauge symmetry of electromagnetism to include weak processes. Gauge symmetry stems from the association between invariance properties and conserved quantities, e.g. rotational invariance and the correlated conservation of angular momentum. Charge conservation is thus related to the invariance of the theory under a group of phase transformations. Postulating invariance when the phase may depend on space time location (gauge invariance) implies the existence of a massless vector field (gauge field) which is identified with the photon field.

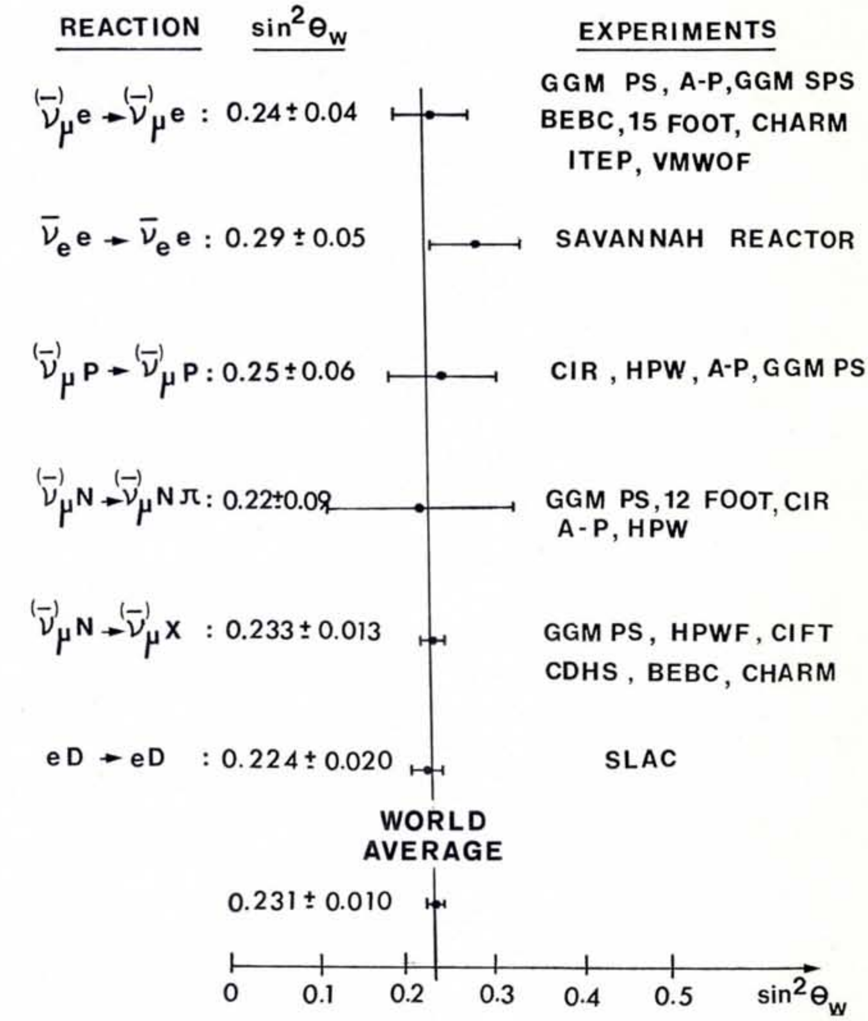
The local gauge symmetry which is assumed, no longer corresponds to phase transformations but to transformations under the group $SU(2) \times U(1)$. It is necessary for the renormalizability of the theory, and should normally lead to four massless gauge bosons. However, the theory is built in such a way that the symmetry is spontaneously broken. Many of its conseqences may thus be concealed from direct observation even though the symmetry remains at some basic level.

A Spontaneously Broken Gauge Symmetry

Spontaneously broken symmetries are known in everyday life. An example is offered by the bending of a metal rod subjected to an axial force. The set up and the applied force are both symmetric with respect to the axis of the rod, yet it is well known that, for a sufficiently intense force, the rod bends in a particular plane. The symmetry is broken before the rod. Of course the symmetry is nevertheless maintained in some sense by the fact that all bending planes are equally probable.

While the equations which describe the dynamics of the system are symmetric under rotation around the axis of the rod, the symmetry is apparently lost when one merely looks at the bent rod. One says then that the symmetry is *spontaneously* broken. In the classical case, as in the quantum case, it is associated with a degenerate ground state (all bending planes are equally favoured), a feature which, in the quantum case, corresponds to the presence of a massless scalar meson.

It turns out that when one combines a gauge theory of massless vector mesons (i.e. mesons with spin 1 associated with the gauge symmetry) with massless and spinless (scalar) mesons, generating a spontaneous break down of the symmetry (with a degenerate vacuum) a remarkable effect occurs. While the symmetry is apparently broken, as expected, the massless scalar mesons disappear as the massless vector mesons acquire a mass. This has been known for many years as the Higgs mechanism, named after one of its originators. While any symmetry may seem absent between the photon and the very massive weak quanta, it exists at a deeper level in much the same way as it was present in the equations for the bent rod. Even when broken in this way, the gauge properties are enough to guarantee a satisfactory theory. Particle fields which enter the theory without a mass, acquire a mass through the symmetry breaking mechanism. The existence of at least one heavy scalar particle called the Higgs boson, is expected. No prediction can however be made at present for its mass.
The presence of such a boson and its unique property of coupling the more strongly, the heavier the particle is to which it couples, is a very specific feature of the theory. It may take time before this can be proved or disproved experimentally, but one should not under-rate the present great phenomenological success of the theory. It is displayed in the Table which shows how a wide variety of processes are all described in terms of the unique parameter of the theory: $\sin^2\Theta_w$. These processes involve neutrino scattering off leptons, and off hadrons including both eleastic and inelastic reactions in the latter case, and electron scattering.



Measurements of $\sin^2\Theta_w$ derived from the observation of weak neutral current effects in a variety of expriments, with acknowledgements to P. Musset.

A Gauge Theory of Strong Interactions

In parallel with the development of a unified theory of weak and electromagnetic interactions, great progress has been made in the understanding of the quark structure of hadrons, and Quantum Chromodynamics has emerged as a very serious contender for a theory of strong interactions. Quantum Chromodynamics is also a gauge theory with quarks interacting through the exchange of gluons coupled to colour. The gauge group is SU(3), with accordingly three colour states for the quarks and eight colour states for the gluons and a non-Abelian nature which results in "asymptotic freedom", i.e. the effective coupling constant decreases as one probes at larger transfers or at shorter distance.

When formulated at the quark level, strong interactions thus show some formal similarity with weak and electromagnetic interactions. We have in all cases, gauge theories based on different gauge groups associated with the different properties of quarks and leptons. Such a similarity may have a deep meaning and it is tempting to consider a unique grand unified theory, which, when spontaneously broken, would result in the apparent variety of interactions: strong, electromagnetic and weak, which we actually observe.

Towards a Grand Unified Theory

Having thus gained confidence in a unified approach to weak and electromagnetic processes, one may still be somewhat unsatisfied that the theory has still two coupling constants — or one adjustable parameter: $\sin^2\Theta_w$, when a real unified theory should have only one coupling. At present, trying to solve this riddle one is led to consider some grand unified theory, and this leads us from what has recently become fact to what still remains speculation. Nevertheless the interest which this now raises justifies some discussion.

The value of a coupling constant depends upon the momentum transfer at which it is measured, or upon the distance at which the interaction is being probed. The nature of the gauge group, SU(2) × U(1) is such that the two couplings have a tendency to converge towards each other, albeit logarithmically as the probing distance decreases. This opens the way to full unification but the easiest route to a unified theory may be far more ambitious, as it could be that the gauge symmetry is only part of a much larger, spontaneously broken symmetry, which would include strong interactions as well. We should now see at low energy just the remains of a very large symmetry which assumes all its grandeur only at very very high energy, as *all* couplings converge.

Such a theory may at present be based tentatively on the group SU(5) (the Georgi-Glashow model) or on some other group embodying the different subgroups associated with the SU(3) colour symmetry of strong interactions and the SU(2) $\times$ U(1) symmetry of the electroweak interaction. In such a framework, three interactions are unified in one stroke, and one can then calculate $\sin^2\Theta_w$.

A key point of such a unified approach is that quarks and leptons appear as members of the same multiplet, and the postulated symmetry thus implies transitions transforming quarks and leptons into one another.

The decay of the proton is then an inescapable consequence. The energy at which the symmetry would become manifestly realized is however so high ($\sim 10^{15}$ GeV) that its manifestation through virtual quantum effects are extremely improbable. The expected mean life of the proton is of the order of 10^{30} years while the age of our expanding Universe is only about 2×10^{10} years. While the decay probability is extremely small, it appears nevertheless to be within experimental possibilities, provided adequate detectors are built. The stability of the proton, long considered dogma, has now become a subject for debate.

Summary

While basic constituents are numerous and nothing yet even limits quarks and leptons to three doublets, a great unity appears to emerge among basic interactions. A unified theory of weak and electromagnetic processes has already scored many impressive successes and there is little doubt that the two hitherto different basic interactions share many common features and are but two facets of a unique mode of interaction. While still speculative, the understanding of strong interactions at the quark level raises the possibility of a grand unified theory of all three interactions with a prominent consequence : proton decay.

While we do not meet simplicity in the sense of an economy of particles, the new unified approach to basic interactions opens great perspectives through an economy of principle.

Further Reading

"Gauge Theory and Neutrino Physics", Phys. Reprint Book Series 2, 78.

Copies of the Plenary Lecture given at the closing session of the 4th EPS General Conference in York, by A. Zichichi entitled "New Developments in Elementary Particle Physics" are available at the EPS Secretariat on request.

Alchemy in 20th Century Atomic Physics

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The study of heavy ion-atom collisions has grown out of the field of plasma physics and gas discharges, where ionisation processes in electronic and atomic collisions were found to obey the so-called adiabatic criterion (Massey and Burhop, 1952). The impact of electrons or protons on atoms will be adiabatic (projectile velocity small compared with orbiting velocity of the electron concerned in the ionisation) and ionisation will be absent, if $\Delta E.b/h.v > 1$ where ΔE is the electron binding energy, b the impact parameter and v the collision velocity. However, in the early 1960's, in pioneering work with heavy ion beams, the groups of Fedorenko and of Everhart showed that the ionisation processes occurring in heavy ion-atom collisions did not obey the above criterion. Then Fano and Lichten in 1965 suggested that inner shell ionisation could be understood assuming that under adiabatic conditions the colliding atom and ion form a quasi-molecule.

In slow collisions, the atomic electrons can adjust adiabatically to the changing Coulomb field of projectile and target. As the two nuclei approach each other, the atomic states merge into molecular states and in the limit of zero internuclear distance, even into the united atom state. This is the well-known Born-Oppenheimer approximation, according to which the electronic states only depend on the internuclear distance, not on the nuclear motion. At some internuclear distances, however, quasi-molecular levels may come so close, that this approximation is no longer valid and coupling of electronic levels may result from nuclear motion. In terms of the Massey criterion one might say that for some inner electrons in a quasi-molecular state, the energy gap ΔE to a vacant state is reduced so much that excitation is possible. This occurs for impact parameters for which the inner shells start to overlap. Cross-sections for inner shell ionisation in heavy ion-atom collisions are in consequence, large.

This interpretation in terms of a molecular model became very popular among theorists and experimentalists immediately upon its formulation. Large cross sections for inner shell ionisation could be easily verified experimentally by measuring X-ray emission cross-sections in a variety of collision systems and energy regions. At the same time, developments in computer technology made possible the evolution of a better theoretical description of the transiently formed quasi-molecular states. Especially appealing was the predicted formation of united atom states in these ion-atom collisions, which in principle opened the possibility of studying super-heavy quasi-atoms long before the nuclear physicists had reached the islands of stability expected in the region of atomic numbers larger than 100.

Inner Shell Ionisation

Figure 1 shows the calculated molecular orbitals (MO) of two nitrogen atoms as a function of internuclear distance. The MOs correlate the levels of the separated atoms to those of the united atom. At large internuclear distance there are four nitrogen K-shell electrons, so that only two can correlate to the silicon K-shell via 1sσ. The other two have to correlate to the silicon L-shell via 2pσ. This effect is called electron promotion and was recognized by Fano and Lichten as the prime mechanism for K-shell ionisation in heavy ion-atom collisions. As

Fig. 1 — Calculated molecular orbits of two nitrogen atoms as a function of nuclear distance.