Piecing together a theory

In 1968, Abdus Salam spoke of the 'dream' of unifying weak and electromagnetic interactions in a single theory. Fifteen years later, his dream was found to be a reality.

A new physical theory needs many ingredients. In addition to the basic physics insights, it requires new techniques and formalism. The development of these ingredients cannot be guaranteed to happen in the optimal order, and experts working in one field may not even know that useful progress is being made somewhere else. Fettered by preconceptions and blinded by ignorance, even the most gifted scientists sometimes have to blunder their way through the unknown.

The development of what is now called the 'electroweak' picture illustrates how a complex theory, elegant and supremely logical when viewed with hindsight, is pieced together with almost exasperating slowness.

Gauge theories

The formulation of the laws of physics in terms of 'gauge' theories must be one of the major intellectual achievements of this century.

The oldest gauge theory is that of electromagnetism. Every physics student is familiar with the potentials from which electric and magnetic fields can be calculated. But potentials are not directly observable. Maxwell's equations fix only potential differences, and potentials can be suitably modified without upsetting the physics. These modifications are called 'gauge transformations', and Maxwell's equations are said to be 'gauge invariant'.

As sometimes happens in physics, the word 'gauge' stems from a misconception. Hermann Weyl once suggested the changes in electromagnetic potentials should correspond to some change in a basic length parameter, or gauge. This was soon recognized to be incorrect, but the name stuck.

Gauge transformations are characterized by arbitrary functions, as opposed to transformations which depend on a finite number of parameters. Thus ordinary rotations, which are completely described by three angles, do not permit gauge transformations.

The method for handling gauge theories was developed in the mid 50s by C.N. Yang and R. Mills, and independently by R. Shaw. But application of these techniques required first the injection of imaginative new physics ideas.

The dream of unification

Addressing a Nobel Symposium at Lerum in Sweden in 1968, Abdus Salam spoke of the 'dream' of unifying weak and electromagnetic interactions in a single theory. Apart from the aesthetic appeal of having one picture instead of two, there were clues which pointed towards such a unification.

But Salam was not the first to have this dream. Enrico Fermi had toyed with the idea back in 1934. By 1961, bold theoreticians, notably Sheldon Glashow, were putting forward detailed models. While these ideas contained more than a germ of truth, they were premature. The vital mechanism of spontaneous symmetry breaking was not yet understood.

As Glashow said in his 1979 Nobel lecture — 'the intermediate boson of neutral currents had to be made very much heavier than its charged current counterparts. This was an arbitrary but permissible act in those days: the symmetry breaking mechanism was unknown. I had "solved" the problem of strangeness-changing neutral currents by suppressing all neutral currents: the baby was lost with the bath water.'

In the 1960s, Sheldon Glashow's bold ideas were vital to the development of the final form of the electroweak theory, applying to all particles.

At about this time, attention in particle theory was turning to the idea of 'spontaneous' symmetry breaking, already known in solid-state physics. A theory could possess an exact symmetry, but the physical states, particularly the vacuum, would not.

(An example of spontaneous symmetry breaking is a round dining table set for a meal. When the guests sit down, there is total symmetry, with a serviette between each person. In principle, each guest could take a serviette from his left or his right. However this symmetry is broken when the first guest picks up his serviette, conventionally from the left, and all the others have to follow suit.)

Initially, these ideas were unfruitful, as they produced an embarrassing proliferation of unwanted massless 'Goldstone bosons'. Describing his initial encounters with these theories, Steven Weinberg said, 'I remember being so discouraged by these zero masses that I wrote a note to underscore the futility of supposing that anything could be explained in terms of a noninvariant vacuum'.

For the weak interactions, the field particles had to be heavy, and at first these masses could not be obtained without destroying the symmetry. The problem was only solved with the development of the so-called 'Higgs mechanism', which showed that the carriers of the weak force could be heavy, as long as they were accompanied by other ('Higgs') particles.

Once freed of unwanted massless particles, the next step was for Weinberg and Salam, working independently, to show how these new symmetry breaking ideas could be exploited in an elegant model which linked the carriers of the weak force with the photon, thus unifying electromagnetic and weak interactions.

But even this took time. In the mid 60s, particle theory was dominated by the 'eightfold way' — the approximate SU(3) symmetry incorporating isospin and strangeness.

Later, Weinberg described how he stumbled on the right idea. 'At some point in the fall of 1967, it occurred to me that I had been applying the right ideas to the wrong problem. It is not the rho meson that is massless: it is the photon. And its partner is not the A1, but the massive intermediate bosons, which since the time of Yukawa had been suspected to be the mediators of the weak interactions. The weak and electromagnetic interactions could then be described in a unified way in terms of an exact but spontaneously broken gauge symmetry.'

'Initially we were confused,' Salam admits. 'We were trying to gauge the wrong symmetry.'

Elegant and appealing though it was, the Weinberg-Salam model fell on unfertile ground. It described only leptons (electrons, muons and neutrinos) and said nothing about the weak and electromagnetic behaviour of the strongly interacting particles, hadrons.

The model predicted that there would be neutral currents, but none had ever been seen. If neutral currents existed, they should show up in particle decays. For instance the neutral kaon (carrying strangeness) should decay into two muons. Why were such strangeness-changing neutral currents suppressed?

Charmed

In 1964, Glashow (with Bjorken) tested the idea of extending the usual trio of quarks (up, down, strange) to four, with the introduction of the charmed quark. Part of the motivation came from 'mistaken notions of hadron spectroscopy', but they were also eager to find a parallel between lepton and hadron behaviour under the weak interaction.

Says Glashow: 'Had we inserted these currents into the earlier theory (1961), we would have solved the problem of strangeness-changing neutral currents. We did not. I had apparently quite forgotten my earlier ideas of electroweak synthesis. The problem which was explicitly posed in 1961 was solved, in principle, in 1964. No one, least of all me, knew it. Perhaps we were all befuddled by the chimera of relativistic SU(6), which arose at about this time to cloud the minds of theorists.'

In 1969, Glashow, now working with John Iliopoulos and Luciano Maiani (the 'GIM' model) returned to the implications of the charmed quark and found that strangeness-changing neutral currents were naturally suppressed. 'It seems incredible that the problem was totally ignored for so long,' says Glashow.

Most of the physics ideas were now in place. The Weinberg-Salam model had unified weak interactions and electromagnetism. The GIM four-quark model showed how to construct the weak and electromagnetic currents of hadrons. But there was still a potential spanner in the works. The formalism was not 'renormalizable' — there was no set of well-defined rules (as in quantum electrodynamics) which naturally avoided calculations encountering infinities.

The renormalizability of gauge theories had been examined for some time, but it was Gerard 't Hooft in 1971 who proved that in this case it

Steven Weinberg — 'in 1967 it occurred to me that I had been applying the right ideas to the wrong problem'. This was quickly rectified, and physics made one great stride forward.

In 1976 Burt Richter (left) and Sam Ting received the Novel Prize for Physics in recognition of their discovery of new particles carrying 'charm'. The existence of this new type of matter was another important confirmation of the new theory.

From AA to Z

was possible. In theorist Sidney Coleman's words,' 't Hooft's work turned the Weinberg-Salam frog into an enchanted prince.'

In 1979, Sheldon Glashow, Abdus Salam and Steven Weinberg shared the Nobel Prize for Physics, a courageous move by Stockholm in view of the fact that the W and Z particles predicted by the electroweak theory had not yet been discovered. As one notable experimenter was heard to remark on learning the news, 'does this mean they'll have to give the prize back if we don't find the Z?' The question was to remain a hypothetical one.

(Most of the quotes used in this article come from the Nobel laureates' lectures. Extracts were published in the CERN Courier, November 1980, pages 350-7, and the full versions are to be found in Reviews of Modern Physics, July 1980 issue, vol. 52 No. 3).

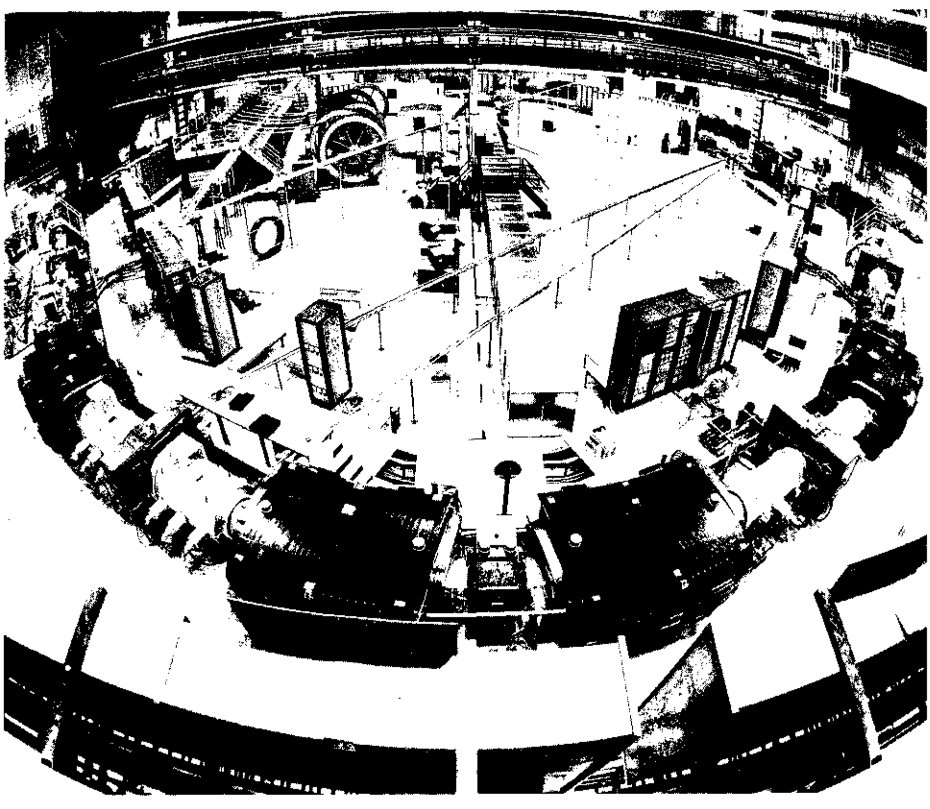
The conditions for proton-antiproton physics were attained thanks to a remarkable sequence of developments in accelerator physics.

The first ideas about beam cooling (though not, in the end, the ideas used in the CERN project) came in 1966 from the imaginative Gersh Budker and his colleagues at Novosibirsk. They were then launching a 25 GeV proton-antiproton storage ring named VAPP-NAP and obviously needed some scheme to produce intense antiproton beams.

They termed their technique 'electron cooling'. The idea was to run an electron beam along with the antiproton beam at the same velocity and to continually refresh the electron beam. The electrons have precisely the desired momentum and, in their collisions with the antiprotons, energy is transferred in such a way that the continually refreshed electron beam conditions gradually predominate. The antiproton beam settles around the desired momentum.

In 1974, tests led by A. N. Skrinsky in a small storage ring, NAP-M, at Novosibirsk demonstrated that cooling was being achieved. These results were confirmed later at CERN and at Fermilab. However the alternative idea of stochastic cooling (described in our opening article) from Simon van der Meer proved so successful that in the final schemes for proton-antiproton colliding beams at both CERN and Fermilab, electron cooling was dropped.

The first successful tests on stochastic cooling took place on 21 October 1974 on proton beams in the Intersecting Storage Rings. This followed the development of electronics sufficiently fast (GHz range) to allow the beam to be monitored in an intersection region on the machine (using two directional loop pick-ups connected to a differ-



The Antiproton Accumulator, the heart of the CERN antiproton project.

(Photo 582.10.80)