

Physics monitor

Jet set

Proton-proton scattering experiments at the CERN ISR and at Fermilab now show all the signs of highly inelastic collisions between small, hard objects hidden deep inside the protons. This is analogous to the classic experiment of Rutherford which showed for the first time that the nucleus is a small object hidden deep inside the atom.

If a target appears uniform to a beam of particles being thrown at it, the resulting scattering will look very much like a diffraction pattern with a central maximum and with an intensity dropping off sharply at wider and wider scattering angles. However if the target has some small impenetrable points buried in it, occasionally one of the particles from the beam will hit one of these points head-on and will bounce off at a very wide angle, possibly even backwards. Such wide angle scatterings are not to be expected from a 'grey' target of even density and are immediately indicative of some deep inner structure.

In the same way, if a proton presents a uniform target to an incoming beam, it should show a diffraction-like pattern of elastic scattering which would be a measure of the overall extent of the proton. This is indeed the dominant phenomenon at the ISR and in 1972 a diffractive minimum was observed for the first time in proton-proton scattering.

The existence of a substructure within the proton was first noticed on the electron linear accelerator at Stanford in high energy electron-proton experiments and was confirmed later at CERN in neutrino experiments using Gargamelle. These investigations gave the first information on the structure inside the proton, proposed by Feynman and others as being due to pointlike constituents called 'partons'.

The idea of parton constituents has more than a passing resemblance to

the quark model and the neutrino measurements made using Gargamelle enabled these two pictures of proton structure to be reconciled. While the quark model gives the intrinsic properties of the proton constituents (spin, charge, etc.), the study of deep inelastic scattering gives the momentum distribution of the constituents — something which the quark model is unable to predict.

So, when probed in deep inelastic electron as at Stanford or in neutrino scattering experiments at proton Laboratories, the proton no longer behaves (under the influence of the electromagnetic force or of the weak force) as a solid particle with dimensions of the order of 1 fermi but as a collection of small, solid, quark-like objects.

But what happens in strong interactions? In 1972, experiments at the ISR showed that they too can produce energetic particles at wide angles to the original beam, showing that the proton has a grainy inner structure for strong as well as electromagnetic and weak interactions. When these grains hit each other and interact as in the ISR, then the sparks really fly! Actually the grains must sometimes hit each other at lower energies, but it is only at higher energies that the interaction really becomes noticeable.

The big question is whether these strong interaction effects are produced by the same quark / parton constituents as are responsible for the high momentum transfer phenomena seen in lepton-proton scattering? This is proving difficult to answer, partly because of the difficulty of sorting the grain interactions from the rest of the hadronic debris.

If nothing else were happening, the results of a deep scattering between two inner proton constituents should result in two coplanar 'jets' of secondary particles shot out at large angles to the incident beam direction and fairly well collimated along their directions of motion. These 'jets' need not neces-

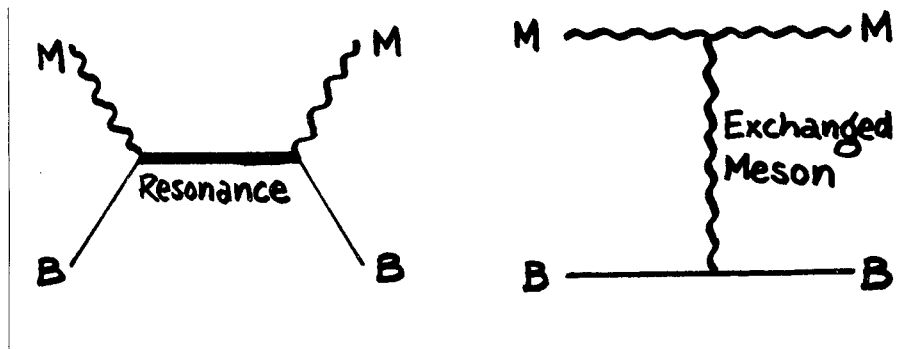
sarily be opposite each other. If they are the result of incoherent scattering of proton constituents, they will be opposite only in the centre-of-mass frame of the constituents, which is not necessarily the same as the proton-proton centre-of-mass system.

In practice the situation is blurred by the more usual types of strong interactions and early experiments at the ISR such as those of the Pisa / Stony Brook and Aachen / CERN / Heidelberg / Munich collaborations found it difficult to distinguish between wide angle scattering and everything else which was going on. Then experiments using double arm spectrometers, such as those of the CERN / Columbia / Rockefeller / Saclay collaboration, discovered that the observation of one secondary particle with large transverse angular momentum made it much more likely that other large transverse angular momentum particles would be picked up, both in the direction of the trigger particle and in the opposite direction.

Pioneer work by these collaborations together with observations by the CERN / Columbia / Rockefeller / Saclay / Strasbourg and British / Scandinavian groups paved the way for the first reports of evidence for definite jet structure by a CERN group using the Split Field Magnet at the ISR. Supporting evidence is now coming from the CERN / Collège de France / Heidelberg / Karlsruhe and British / French / Scandinavian collaborations.

The components of the jets are confined not so much in angle but more in momentum. The observed particle momenta perpendicular to the jet axis is limited but is fairly independent of the jet momenta. This means that particles with only a small component of momentum along the jet axis can still move off at a large angle to the axis. To take this into account, and to get over the difficulty of the jets not necessarily being back-to-back, experiments have to try to measure momenta over as

1. The theoretical picture of meson-baryon scattering as it was seen in the mid '60s. Both diagrams had to be included in any calculation, although the resonance was supposed to be a good low energy approximation and the exchange was good for high energy reactions.



wide a solid angle as possible. This has only lately been achievable at the ISR with the help of special instrumentation like the Split Field Magnet.

This technique together with the use of high momentum triggers has now enabled ISR teams to isolate the wide angle scattering products. Further progress will be made by using higher momentum particles as triggers, eliminating as much as possible of the unwanted hadronic background, and by determining as much as possible about as many secondary particles as possible.

It is too early to say whether these constituents which cause the jets are definitely the same quark / partons seen in lepton-nucleon scattering and which also characterise hadron formation in high energy electron-positron collisions. The form of the interaction between the constituents is also not known, although theorists make sure that there is no shortage of candidate mechanisms, many of which account for different aspects of the observed behaviour. The rich structure seen in ISR experiments has still to be fully explored.

Complementary experiments at Fermilab capitalise on the different experimental techniques available there and shed additional light on the problem. In particular, the intense incident beams enable higher momentum transfers to be monitored. The results show a strong excess of positively-charged secondary particles, which is just what would be expected from the quark constituents of the proton (two positively charged quarks and only one negatively charged).

Fermilab experiments also use pion beams to study large momentum transfers, and it is found that pions are more adept than protons at producing wide angle scattering. This could be because the pions, with only two quark components instead of three, are able to produce constituent-constituent interactions where a larger fraction of

the momentum is available.

A particle with high transverse momentum can be produced in a number of ways. Either it is one of several coming from a jet with very high transverse momentum indeed, or it can be the lead particle in a jet where most of the transverse momentum has been given to one particle.

If, as at the ISR, the wide angle scatterings are monitored by looking for outgoing single particle triggers with large transverse momentum, then the second mechanism is detected in preference to the first. This means that much valuable information is being lost and is known in the trade as 'trigger bias'. To overcome this problem, experiments at Fermilab have collected all the energy coming off in a definite solid angle and have been able to trigger on a whole jet, as opposed to a single particle. This has boosted the observed transverse momentum yield by a factor of about 100.

Rutherford's epic experiments with alpha particles which gave us the first indication of the nuclear atom marked only the beginning of a long road of investigation into nuclear structure. If the inner structure of the proton proves as difficult to unravel, many models will come and go and many more experiments will have to be done before we begin to understand what is going on.

Just a few years ago, physicists thought that very high energies could bring simplicity to strong interactions. This could still be possible, but it looks as though it is the logarithm of the energy, and not the energy itself, which needs to be large! However, if the detection techniques can be made sophisticated enough, then looking at large momentum transfers might be the place where hadron physics starts to become simple, with the exchange of gluons between quarks providing the basic interaction. We have travelled very deep into the proton since Rutherford showed us the way.

Baryonium explained?

The appearance at CERN of two narrow proton-antiproton resonances is giving additional inspiration to theoreticians who have long been worrying about their picture of baryon-antibaryon interactions.

Ten years ago, people used to think of meson-nucleon interactions as either the result of an intermediate nucleon resonance decaying back into a nucleon and a meson, or as the result of the exchange of some meson between the two particles.

Then D. Horn, C. Schmid, G. Veneziano and others showed that these two mechanisms are really different disguises of the same basic interaction. This 'dual' picture of the meson-nucleon interaction can be represented by 'duality diagrams' where some of the participating quarks go straight through while others are exchanged. This way baryon resonances and exchanged mesons occur simultaneously.

Although fine for the meson-meson and meson-nucleon interactions, this attractive picture breaks down for the baryon-antibaryon case. Duality diagrams here have to include intermediate states or exchanged mesons containing two quarks and two antiquarks. Until recently, these 'exotic' quark configurations did not correspond to anything that had been discovered. Application of duality ideas to baryon-antibaryon interactions was, therefore, frequently referred to by ominous names like the 'Rosner Paradox' or the 'Duality Catastrophe'.

Since then, theoreticians have been hoping that the experiments would come up with something, and have in the meantime been polishing up their models of baryon-antibaryon interactions.

When the duality model was first proposed, people were not too concerned about quark 'colours' (of which