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Recent Advances in Particle Physics*

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The results obtained in high energy physics in the last three to four years have profoundly affected our conception of even such basic notions as the internal structure of the proton and neutron, two of the three particles out of which ordinary matter is composed. Our knowledge of the electron, the third of these particles, is much more advanced and has changed little in recent years.

Our main purpose will be to sketch what we have learned about the nucleon structure from recent experiments carried out on proton-proton collisions (at the Intersecting Storage Rings of CERN and at the American 400 GeV synchrotron of the Fermi National Accelerator Laboratory), on neutrino-proton and neutron collisions (mainly Gargamelle heavy liquid bubble chamber experiments at CERN) and on electron-proton and electron-neutron collisions (mainly at the 20 GeV electron accelerator of the Stanford Linear Accelerator Center). It is remarkable that a rather unified picture of proton and neutron structure begins to emerge from all these experiments and, although many aspects are still beyond our understanding, this picture reveals some form of basic simplicity.

We shall also mention the discovery of neutral-current reactions of neutrinos on nuclei, first made in 1973 at CERN, and the discovery of new, very heavy and surprisingly narrow mesons, first found at the Brookhaven National Laboratory and at SLAC in the fall of 1974.

Classes of proton-proton collisions at high energies

In a proton-proton collision, two protons fly towards each other and interact by the strong interaction, after which one of various things can happen. In the simplest case of elastic scattering, just two protons fly out after the collision and they have the same energy, E, as the incident protons. In all other cases (inelastic collisions) new particles are created.

At the very high energies available at the ISR and the FermiLab (center-of-mass energies in the range 20 to 60 GeV), these inelastic collisions reveal striking properties which were not clearly recognizable at lower energies and which lend themselves to simple phenomenological interpretation. The inelastic collisions neatly separate into two main classes. In the first class, called diffractive dissociation, either of the two incident protons gets excited into an object composed of a few particles ; this group or cluster of particles is usually composed of a nucleon (proton or neutron) and of a few mesons all flying roughly in the same general direction and carrying in total about the energy E. The other proton flies out alone in the opposite direction also carrying about the energy E.

In the second and main class of inelastic collisions, called non-diffractive, the protons come out in opposite directions, excited or not, and with strongly reduced amounts of energy, E' and E'' which are on average equal to about half of the energy E of the incident protons. In addition, a considerable number of other particles, mostly mesons of lower energy, come out. They show quite remarkable correlations which suggest that they somehow come out in clusters of three to four mesons each and there is evidence that the clusters are frequently neutral (the total electric charge of a cluster is frequently zero). These clusters, the average number of which may be itself around three or four per collision, are called central clusters to distinguish them from the protonic clusters occurring when an incident proton gets excited in the collision.

Electron-nucleon and neutrino-nucleon collisions

By studying collisions of high energy electrons on nucleons we can obtain information on the distribution of electric charge inside the nucleon. Similarly, collisions of high energy neutrinos on nucleons give information on the distribution inside the nucleon of what can be called the weak charge (a quantity controlling how the weak interaction acts on the nucleon, just as the electric charge controls how the electromagnetic interaction, i.e. the electric and magnetic forces, act on the nucleon).

Recent electron experiments at SLAC and neutrino experiments with the Gargamelle bubble chamber at CERN have concentrated on deep inelastic collisions, meaning collisions where the nucleon gets very heavily excited. In such collisions, we can measure the texture of the distribution of charges inside the nucleon at very short distances (in space-time).

The results of the experiments are quite remarkable. In a first approximation, it appears that the electric and weak charges of the nucleon are concentrated on three small grains. These grains have a radius which is at

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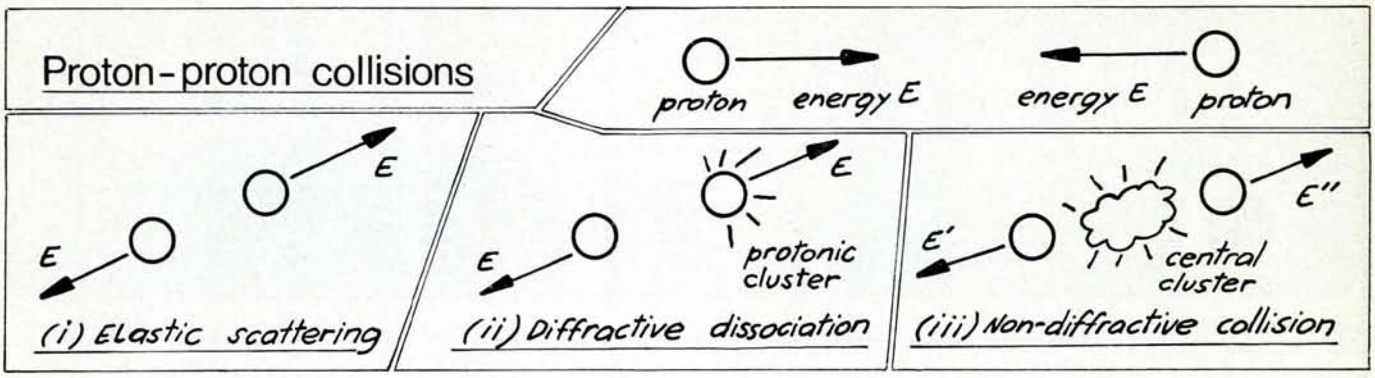
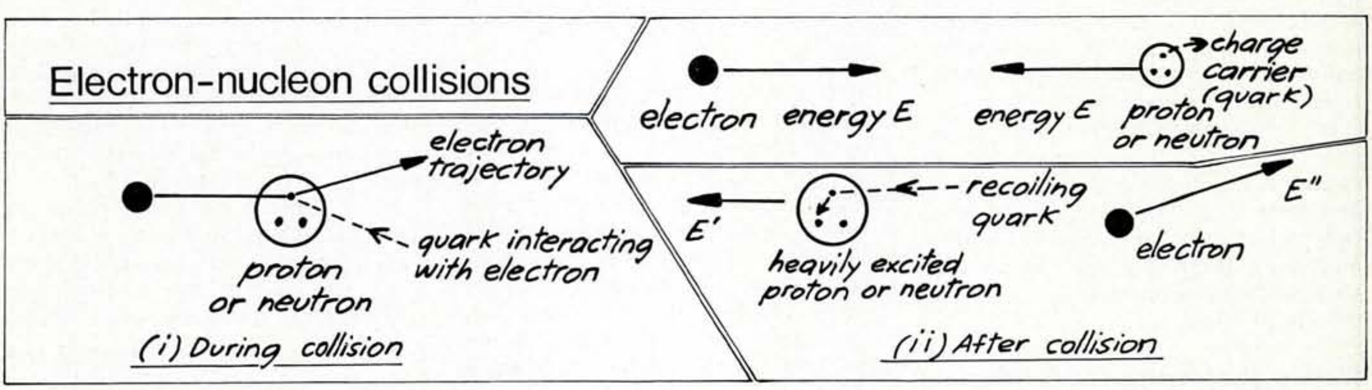


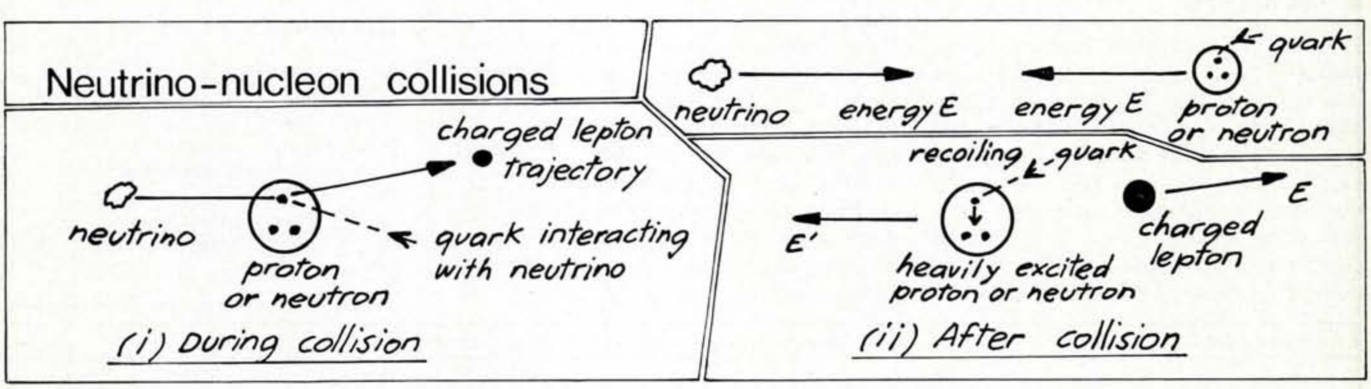
most about one-tenth of the nucleon radius. Their charges and spin appear to have the same values as those of the celebrated quarks. These are the conceptual building blocks of nucleons, mesons, etc., which were postulated in 1964 as a very simple but amazingly successful model for the classification of all hadrons (of all particles which partake in the strong interaction).

The resulting picture of deep inelastic electron and neutrino collisions on nucleons is sketched above. In both cases, one and only one quark is hit in the collision and by its recoil it heavily excites the nucleon. It does not escape however, (this is the big mystery about quarks) and the excited nucleon separates into many particles. We believe these to be in general a nucleon and many mesons but the very important experimental question of what they are and how they share the recoil energy has hardly been investigated up to now.

In the neutrino case, the collision converts the neutrino into another particle, which is an electrically charged lepton — electron, positron, negative or positive muon — depending on the nature of the incident neutrino. This is the normal case. As is by now well known, good evidence for an abnormal type of neutrino collision has been discovered in 1973 at CERN in the Gargamelle experiment and found again, more recently, at the FermiLab and Argonne (see also *Europhysics News, Vol. 5, No. 4, p. 1,* April 1974). In these abnormal collisions, the neutrino does not convert into a charged lepton. It is believed (although not checked experimentally) that it remains a neutrino. In the physicist's terminology, normal neutrino collisions are said to be of charged current type and the abnormal ones of neutral current type. Electron collisions are also of neutral current type. The experimental findings about the neutrino collisions of neutral current type, coupled with important developments in quantum field theory, have raised lively hopes for a possible theoretical unification of electromagnetic and weak interactions. It should be stressed, however, that the discovery of the new type of neutrino interaction is of great scientific importance in itself, quite irrespective of what its final theoretical interpretation turns out to be.

To return to the consequences of the SLAC and CERN experiments for the internal structure of the proton and neutron — not only did they show that the charges are mainly concentrated on three small grains, which can be identified with quarks, but their detailed interpretation leads to a determination of the fraction, x, of the nucleon energy, E, which is carried by a single quark. This quantity is found to have an interesting distribution with mean value of about 1/6, so that the energy fraction carried by the three quarks is about a half (three





times 1/6). This result, which came as a surprise, means that the nucleon contains more than the three quarks and that the additional stuff which carries the remaining half of the energy must be essentially neutral (without electric or weak charges). The name of 'glue' is often used for this additional stuff because it is believed to be associated with a very strong field which would be responsible for binding or 'gluing' the quarks together inside the nucleon.

More about proton-proton collisions

It is natural to ask whether the recently discovered internal structure properties of protons and neutrons have anything to do with the processes taking place when high energy nucleons collide with each other. The answer seems to be positive in the sense that interesting, though still speculative, connections can be established for the main non-diffractive class of inelastic proton-proton collisions. The other classes are then automatically linked also to structure properties since they can be regarded as shadow effects.

In its simplest form, the picture is the following. In a non-diffractive proton-proton collision, the quarks of each incident proton fly through with their own fraction of incident energy, and they give rise to the outgoing protons (excited or not). The glue contained in the incident protons converts into the central clusters where it then decays into the particles finally observed (mostly mesons). There are two attractive features of this picture. Firstly, the property of the glue being mostly neutral is reflected in the fact that the total charge of the central clusters seems to be dominantly zero. Secondly, the property that the quarks inside a proton of high energy, E, carry on average about half of its energy is reflected in the fact, that the protonic energies E', E" are on average one half of E.

Another phenomenon discovered at ISR is that, as we go to higher energies, proton-proton collisions produce a small but rapidly increasing number of high energy particles flying off sideways. (Sideways means that these particles fly off in directions very different from the direction of flight of the incident protons). This so-called large transverse momentum phenomenon is one of the most interesting under study.

Two types of explanation have been proposed. The phenomenon could result from occasional processes where quarks of the two incident protons collide with each other, or perhaps are interchanged with each other, producing a strong sideways deflection (the latter property could naturally result from the small size of the quarks). Alternatively the phenomenon could result from occasional production of an exceptionally massive cluster, the decay of which would naturally give rise to energetic particles flying off sideways. The careful study of the large transverse momentum phenomenon may well become an important source of progress for a better understanding of internal proton structure.

As a final point in this section, we mention the finding that total cross-sections of protons and mesons on protons show an increase as the incident energy becomes sufficiently high (this was first found at Serpukhov for positive kaon-proton, then at the ISR for proton-proton and at the FermiLab for other cases as well). Many possible causes can be invoked for explaining this phenomenon. The most likely one seems to be the increasing cross section observed for diffraction dissociation, but other types of inelastic processes may also contribute to the effect.

Surprising new particles

The new picture described above for the internal structure of protons and neutrons has emerged gradually over a period of about four years, from a variety of experiments and theoretical considerations. In 1973, the discovery of neutrino collisions of neutral current type in the Gargamelle experiment at CERN created quite a surge of enthusiasm among particle physicists. A further, even more sudden stir came in November 1974 when the Brookhaven National Laboratory and SLAC reported the simultaneous but independent discovery of a neutral meson of very high mass, 3.1 GeV, and amazingly narrow width, of order 100 keV. This particle, called J at BNL and ψ at SLAC, is quite hard to detect and study with proton machines, its discovery at the BNL proton synchrotron being a great feat of experimentation. In contrast, it is copiously produced above the background continuum in electron-positron annihilation, and electron-positron storage rings are ideal machines for its study. It is in the SPEAR ring that the SLAC discovery was made.

A few days later the 3.1 GeV meson was also found at Frascati with the electron-positron ring ADONE, and somewhat later again at Hamburg with the DORIS rings. Still in the same month of November 1974, the SPEAR ring of SLAC discovered another particle of the same type at mass 3.7 GeV, again with very small width.

Although little can yet be said at the time of writing (January 1975) on the nature of these amazing new particles, the realm of possibilities is singularly rich and absolutely fascinating. We shall just mention a few.

The coupling of the new mesons with electrons is compatible in size with the weak interaction. If they have a similar coupling to neutrinos, their exchange in neutrino-nucleon and neutrino-electron collisions should contribute to neutral current type collisions. This is one way in which the new particles found in 1974 may be related to the new neutrino collisions found a year earlier.

Can one assume all couplings of the new mesons to be of weak interaction size ? The answer appears to be *no,* because the heavy meson decays with considerable probability into the light one and two pions, and this decay process appears to have a strength characteristic of strong interactions.

It is now generally believed that the new particles have also strong interactions, their narrow widths resulting from a highly effective selection rule, as would be provided by a new quantum number conserved by the strong interactions. For this quantum number, theorists have at least two candidates in store, called « charm » and « colour ». These play an important role in the renormalizable field-theoretical models recently developed in order to unify the weak and electromagnetic interactions while incorporating the quark-glue structure of hadrons. Most such schemes predict neutrino collisions of neutral current type, another possible relation of the new particles with the new neutrino collisions.

There is little doubt that the new mesons belong to a novel family of particles, and it would be surprising if this family would not contain more members, mostly resonances but may be also some metastable particles. The first place to look is again electron-positron annihilation, and indeed news from SPEAR reports a pronounced maximum in the annihilation cross section around 4 GeV. But in the big search now launched in all high energy physics laboratories, all machines and in particular proton machines have their chance, and the challenge to experimentalists has rarely been so great. In the mean time, the data from electron-positron rings on the mesons already discovered should help theorists to narrow down the wide spectrum of possible interpretations. Whatever the outcome, everything suggests that a new chapter of particle physics is being written.