Physics at FermiLab

Some theorists may think they know the plot, but the drama is likely to surprise them as it unfolds

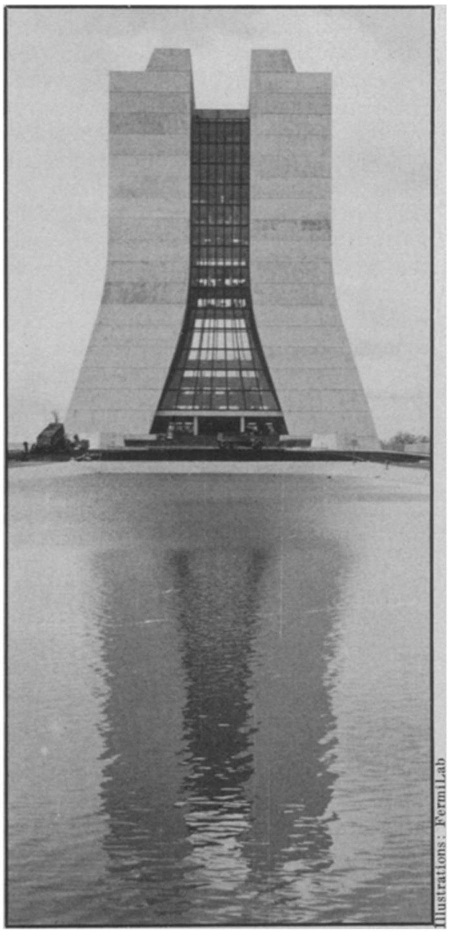
by Dietrick E. Thomsen

The basic question in high-energy physics is the structure of the ultimate constituents of matter. That statement could have been made at any time in the last 80 years. It is a kind of Zeno's paradox of high-energy physics that although every leap that particle physicists make (and before them atomic physicists and chemists) carries them ostensibly nearer their goal, it leaves them with still another jump to go.

Hence the grand progression to ever bigger laboratories, ever more energetic accelerators, and the examination of ever finer bits and pieces of matter. Yet each new level reveals new complexities. At the Fermi National Accelerator Laboratory the physicists soon will be banging protons with 500 billion electron-volts (500 GeV) energy against targets to see what they can find out. They are already working on a project to double that energy and they hope that they won't have to stop even there. Meanwhile the laboratory has already contributed to the present state of simmering confusion in particle theory.

Physicists divide the elementary particles (let us use the adjective with the understanding that it is probably a false attribution) into two general classes, the hadrons and the leptons. The hadrons are the particles that respond to the strong interaction, the force that binds atomic nuclei together. They include the two nuclear particles, the neutron and the proton, and the many others that make up with them the class called baryons and the class of mesons. The leptons are the particles that do not respond to the strong interaction. There are only four of them (and four corresponding antileptons): the electron, the muon and two kinds of neutrino.

Questions of internal structure center mainly on the hadrons these days. Internal structure of leptons (if they have any) is a complex and subtle problem that awaits lepton experiments at ultrahigh energies. The theory of hadron structure today is rather in the state of the famous croquet game in "Alice in Wonderland," where the wickets, instead of staying put in their proper pattern, got up and walked around.



Illustrations: FermiLab

FNAL's *high rise reflects the latest physics.*

For some time physicists have had a theory, the quark theory, that tells how all the hadrons can be built of either two or three out of six fundamental entities, three quarks and three antiquarks. The various possible permutations group the hadrons in what are called multiplets, thus bringing some order out of their chaos. The theory was successful in explaining why the different hadrons have some of the properties they do and in predicting the properties of missing members of the multiplets. At the end of the sixties came what seemed to be evidence for quarks inside protons.

Within the last year experiments have been reported dealing mainly with the electromagnetic interactions of hadrons that do not show such evidence, though they were expected to. The new results, if upheld, threaten major modifications in the theory if they do not blow it away entirely. Thus the curtain rises at FermiLab at a time when a certain theoretical confidence is being replaced by uncertainty and concern. The quark theory is too neat for theorists to give it up without a struggle. The very-high-energy experiments that FermiLab can do will be crucial in determining whether that effort succeeds.

The immediate question, according to Martin B. Einhorn, a FermiLab theorist, is how good is scaling (the technical evidence for quark structure) in electromagnetic interactions? One tends to assume that questions about the breakdown of scaling relate to the theory of the strong interaction, but it might equally well have to do with quantum electrodynamics, the theory of electromagnetism. It might indicate important differences in the behavior of the two classes of virtual photons (timelike and spacelike) that mediate electromagnetic forces. We know that the photon does interact with hadrons. It gets more and more confusing. "Everything gets tangled up at some level of accuracy," says Einhorn.

The picture of how particles are built up out of quarks contains paradoxes that need to be elucidated, removed or argued around. Free quarks are not seen; therefore they ought to be heavier than the particles current experiments can produce. They ought also to be tightly bound and difficult to knock out of the structure of a hadron. But it looks as if they don't interact with each other at all and are very light. "They act like light, weakly interacting particles but can't be," Einhorn says. Physicists have to "try to understand the paradoxes" and find some way "to have our quarks and eat them too."

There are also problems with what happens to the quarks when two hadrons collide. Do the quarks of one interact with those of the other? A collision of this kind is a heavy jolt, in which a lot of momentum is transferred, and it should affect the internal structure of the particles. But it turns out that one can simply neglect the direct interaction of quarks and suppose that they simply rearrange themselves.

Important questions regarding the

Crossed arrays of hodoscopes are the most conspicuous elements in this experimental setup on the floor of FermiLab's meson building.

nature of the strong interaction, the force involved in this kind of collision, arise. Such a force is understood as an exchange of particles, and the nature of the particles and the conditions of the exchange are intimately related to questions of structure. The strong interaction was easier to contemplate when the intermediaries were pi mesons or certain resonances. Now there is an intermediary, the f^0, which carries two units of spin. Exchanging that much spin tends to violate cherished rules. It raises serious questions about the relationships among spin, mass, force and structure.

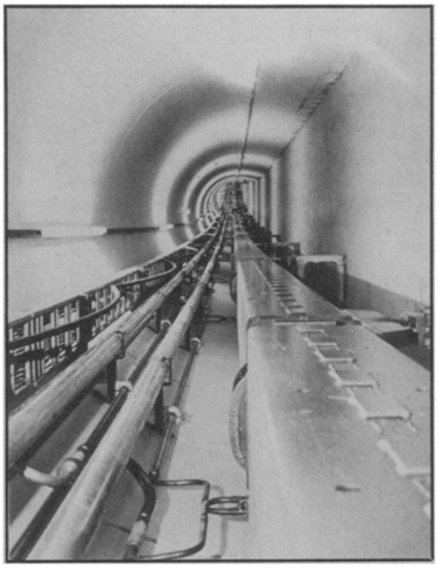
What seems to be needed overall is a new way of looking at how a particle can be made of subparticles. Instead of looking at a hadron as an entity in which quarks are tightly bound and intimately involved with each other, theorists are tending to see it as simply a region of space, a bag or a well, in which the quarks are confined, but in which they exist without having much to do with each other. Experiments will attempt to see whether this picture corresponds to reality.

In the world of the weak interaction, the domain of the leptons par excellence, theorists are going great guns with a formulation that seeks to unite the weak interaction and the electromagnetic in a single description. FermiLab has already made a large contribution to this effort by confirming that what are called neutral weak currents exist. In other words, certain interactions under the governance of the weak force can take place without necessarily exchanging a unit of electric charge between the participating particles. The existence of neutral weak currents is a crucial requirement of the new theories.

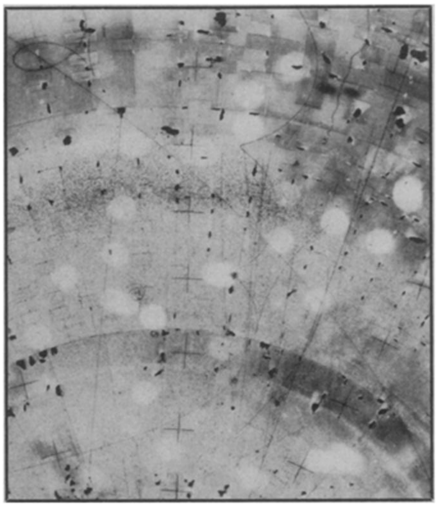
But the confirmation raises new questions. Are the neutral weak currents exactly what theory envisions, or will reality require modifications to the theory? Do the heavy leptons that the theory predicts really exist? Particle physics seems to be proceeding dialectically: Each new synthesis carries the momentum over balance to a new antithesis.

The sort of question experimenters ask is exemplified by John Peoples's description of experiment 87: "What happens when a high-energy photon hits matter?" He is talking about photons with energies of 100 or 200 GeV. "Why photons?" he asks. Photons are the particles that embody electromagnetic forces. Using them as probes in a way to study electromagnetism. Physicists had thought they understood electromagnetism well. Then came the experiments in which quarks failed to manifest themselves in electromagnetic interactions. Now there is a great deal of interest in electromagnetic effects at the highest energies available.

The experiment will study relations between electromagnetism and the weak interaction, specifically the possibility of producing new, heavy leptons, but the main thrust seems to be toward the relations between electromagnetism, the strong interaction and quark structure. There is a curious phenomenon there.



The main ring is four miles of this.



The bubble chamber shows every track.

When a photon approaches a hadron it tends to turn itself into, or act as if it has become, a kind of particle called a vector meson. Vector mesons are particles with the same spin as a photon, but they are hadrons. Thus it seems that the mediation of electromagnetic effects to hadrons involves the photon changing itself to a hadron, which then delivers the effect.

One of the simplest questions is whether this kind of behavior continues at high energies. It is generally assumed that it does, but that has to be tested. Are there more vector mesons than the few now known? The known ones can't explain everything that happens, so the suspicion is that there are more and that they may be more massive than lower-energy experiments could produce. There is the phi meson, a combination of a strange quark and a strange antiquark, which does not couple to neutrons or protons at all. The experimenters want to check its production rate and its transmission through atomic nuclei.

The experiment will send the photon beam against chunks of metal—beryllium, aluminum, copper, eventually lead and uranium. Uranium will introduce another interesting possibility. The uranium nucleus is surrounded by virtual photons. Sending a photon beam in there could do photon-photon scattering. This would be one of the neatest experimental achievements of recent time, and it could give very fundamental information about the electromagnetic interaction.

The big 15-foot bubble chamber is the place to study neutrino interactions especially. As Russell Huson puts it: "In the bubble chamber you can see every track and know the particles." Much work is concentrated on the neutral weak current, trying to

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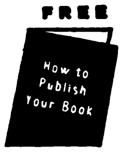

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understand it better and get better numbers. In the future two other crucial weak-interaction points will be taken up. One is whether K mesons decay into muon pairs. Whether they do or not could lead either to a violation of the law of conservation of matter or some changes in weak interaction theory. Another thing to look for is a "four-fermion" interaction, a relationship among four weakly interacting particles that would test the theory of the weak interaction in a very basic way.

Quarks get into the neutrino business too. To solve some of the problems with the quark theory, a fourth quark is sometimes introduced endowed with a special new quality called "charm." If the charmed quark does exist, says Huson, it is probably heavy and decays by the weak interaction to a strange quark. Neutrino interactions might produce the charmed quark. Recent experiments at the Stanford Linear Accelerator Center and Brookhaven National Laboratory (SN: 11/23/74, p. 324; 11/30/74, p. 340) have turned up two odd new particles that some theorists think may be charmed quarks. More experiments and theoretical cogitation are needed before the situation is clear.

Finally FermiLab is a proton laboratory. They do hit 300-GeV protons against proton targets. Jeffrey A. Appel describes one experiment that is mainly interested in studying what comes off at large angles transverse to the direction of the impinging beam of probe particles. The reason for looking at the transverse products is that they give a clue to what is happening in the heart of the nucleon. Here too the accent is on the unified field theories, the relations among the strong, electromagnetic and weak interactions. The experiment is a good probe of the electromagnetic structure of nucleons and will help to tell whether this jibes with the strong-interaction structure. As we have seen there is serious question about that since the quark structure does not seem to be manifesting itself in electromagnetic interactions. Another motivation of this experiment was to look for the intermediate vector bosons or heavy photons, particles required by the unified theory of weak and electromagnetic interactions, but so far it hasn't found any, although that, in the mass range the experiment can reach, is consistent with the latest theories.

There are dozens of experiments at FermiLab, motivated by these and other theoretical considerations. The data are coming in large doses. What they will do to particle physics is not clear, but it will be fundamental. It's an exciting time to be watching. ☐