cotics as causes of childhood hyperactivity, Hutchings says.

Synthetic sex hormones also seem to be human behavioral teratogens, but in this case, the behavioral effects that have been detected are not necessarily detrimental. Until recently, obstetricians often prescribed synthetic estrogens (such as diethylstilbestrol), progestins, or a combination of the two for women whose pregnancies were at risk. Two years ago, the Federal Drug Administration tried to put a stop to this practice since the hormones were found not only to be ineffective in maintaining pregnancies but to cause increased incidences of congenital heart defects as well (*Science*, 26 November 1976, p. 926).

June Machover Reinisch of Rutgers University finds that prenatal exposure to sex hormones affects children's personalities but not their intelligence quotients (IQ's). Children exposed prenatally to progestins, which act like male sex hormones, were significantly more independent, individualistic, self-assured, and self-sufficient than their siblings who were not so exposed. Children exposed prenatally to estrogens were significantly less individualistic and less self-sufficient than their unexposed siblings.

Reinisch reached her conclusions by studying personality and IQ test results of 75 children whose mothers had taken synthetic estrogens and progestins during pregnancy. She and others suspected that the hormones might affect the children's behavior because prenatal exposure of laboratory animals to the hormones affects a wide range of behaviors, including activity level, social interactions, curiosity, emotionality, dominance, and aggression. Moreover, it was known that central nervous system tissue in human and animal fetuses is permanently altered by the presence or absence of sex hormones during critical periods of development.

During the course of her research on the sex hormones, Reinisch came across a curious phenomenon that illustrates a difficulty in conducting retrospective studies. She found that women often did not remember, or did not admit to remembering, taking sex hormones during their pregnancies, even though, according to their medical records, many had received as many as two intramuscular injections each week. Yet these women insisted they had taken no medication during their pregnancies except vitamins.

Although researchers are, of course, interested in detecting more human behavioral teratogens among commonly used drugs, they would ultimately like to use animal studies to assess the risk that new drugs are behavioral teratogens. Japan and the United Kingdom already require that new drugs be tested for behavioral teratogenicity in animals, but neither country specifies what tests should be used or what animal species should be tested. Rodier comments "The danger is that anyone who knows what he's doing can choose a series of 20 behavioral tests that would show no effect, even in animals with severe brain damage."

The appropriate choice of behavioral tests is crucial because animals with severe central nervous system defects may perform normally on certain behavioral tests. For example, Raef Haddad of the New York State Institute for Basic Research in Mental Retardation finds that ferrets missing half of their cerebral cortexes still performed normally on operant conditioning tests, which are popular tests of learning. These ferrets did poorly on certain maze learning tests, however.

Despite the difficulties in establishing tests for behavioral teratogenicity, researchers believe that eventually animal behavioral tests will be an accepted aspect of drug screening in this country. They admit that studies of behavioral teratology are only now gaining momentum, but they point out that there are at least a few general principles that apply to this new discipline. As Richard Butcher of the Children's Hospital Research Foundation in Cincinnati explains, it is now clear that behavioral defects can occur in the absence of physical malformations. Moreover, the fetus is vulnerable to brain damage throughout gestation—there is no safe period. Finally, drugs that in high doses produce physical malformations often produce behavioral defects in lower doses.

The ramifications of behavioral teratology have only begun to be sensed. Drugs that seemed safe because they were given late in gestation or because they seemed to cause no physical malformations may have to be reevaluated. It may well be that, as Hutchings speculates, possibly women have already been exposed to a behavioral teratogen comparable to thalidomide in its potency. But, unlike thalidomide, the effects of such a behavioral teratogen would have gone unnoticed in the general population.—GINA BARI KOLATA

The New Physics: Quarks, Leptons, and Quantum Field Theories

Two electron-positron colliding beam storage rings, one recently completed at the Deutsches Elektronen-Synchrotron (DESY) laboratory in Hamburg, West Germany, and the other a year away from being turned on at the Stanford Linear Accelerator Center (SLAC), are the first of a new generation of accelerators that physicists expect to answer some of the basic questions about what makes elementary particles tick (*Science*, 10 November, p. 608). In short, the experimental agenda for the new storage rings includes searches for new particles and information that can show whether the current theoretical notions as to how particles interact are correct (or, if not, where they have gone wrong).

This is the second of two Research News articles on electron-positron storage rings and elementary particle physics.

Elementary particles fall into one of three general categories. The first of these, the leptons, are by many criteria the most "elementary" of the elementary particles. They behave as pointlike entities with no spatial extent and there are only six of them (so far)—the electron, the muon, the recently found tau particle, and their respective neutrinos.

The second class of elementary particles comprises the hadrons, including the proton, neutron, and pi meson. But there are well over a hundred species of hadrons known, giving rise to the term elementary particle "zoo," as well as to considerable doubt as to whether there is anything elementary about them at all. Order was restored to the particle zoo 15 years ago when Murray Gell-Mann and George Zweig of the California Institute of Technology showed, independently, that the pattern of hadron masses, electric charges, spin angular momenta, and other characteristics made sense if the hadrons were composed of still more elementary entities that came to be called quarks. Quarks are distinguished by a new property with the whimsical name flavor. Gell-Mann and Zweig postulated three flavors.

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In the early 1970's, experiments at SLAC by Jerome Friedman and Henry Kendall of the Massachusetts Institute of Technology and Richard Taylor of Stanford, and by physicists at the European Organization for Nuclear Research (CERN) and other laboratories showed that the proton and neutron have a definite size and evidence of an internal structure—they are lumpy. Although physicists have associated quarks with this lumpiness, there is no direct evidence of their existence. When protons and neutrons are bombarded, what comes out are leptons and hadrons, never quarks. Nonetheless, in late 1974, the discovery at the Brookhaven National Laboratory and at SLAC of the J/psi particle began the process of building a much more persuasive but still circumstantial case for these fabled entities. The J/psi is a meson that is simultaneously very massive and long-lived, and is now believed to contain quarks with a fourth flavor. Thus began the era of quark and lepton (or new) physics.

As things stand now, evidence for a fifth quark flavor was unearthed by Leon Lederman of Columbia University and his co-workers at the Fermi National Accelerator Laboratory (Fermilab) last year and confirmed by three German collaborations at DESY this year. There is a strong predisposition among physicists to believe that quark flavors come in pairs, hence a sixth is in the offing. Finally, elaborations of the quark theory by O. Wallace Greenberg of the University of Maryland and by Moo-Young Han of Duke University and Yoichiro Nambu of the University of Chicago require each flavor to come in three varieties with a property called color. All told, then, there could be 18 types of quarks, hardly, as SLAC theorist Sidney Drell puts it, "a very exclusive social register."

Accelerators that are so expensive ($50 million or more plus an additional $30 million for a complement of particle detectors), so huge (2.2 kilometers in circumference), and so hungry for electrical power (up to 20 megawatts when operating at full capacity) as the new storage rings at SLAC and at DESY are needed to study the interactions between elementary particles, which take place over extremely short distances (10^{-13} centimeter or less). At such distances, particles are anything but simple entities. An electron, for example, is surrounded by a cloud of continuously appearing and disappearing electrons, positrons, and photons, all suggesting the frenetic activity at a disco club. A similar condition holds for other elementary particles, and the calculation of their mutual interaction is bound to be complex.

Most theories devised by physicists to describe this behavior fall into the class called quantum field theories.* Discounting gravitational interactions, which are much too weak (by about 34 orders of magnitude) to have any influence, theorists recognize three types of forces: the familiar electromagnetic effects between electrically charged particles, the strong nuclear force, which holds the protons and neutrons together in the nucleus of an atom, and the weak force, which is responsible for radioactive decay by the emission of beta particles.

One basic feature of the field theories is that a third class of elementary particles, identified as the quanta of the fields, comprises the entities that transmit the forces. Thus, the photon is the carrier of the electromagnetic force. A second feature is that the ranges of the forces are determined by the masses of the quanta. The electromagnetic force has an infinite range because the photon has no mass, whereas the weak force operates over only very short distances (10^{-15} centimeter) because the corresponding quanta of its fields are quite

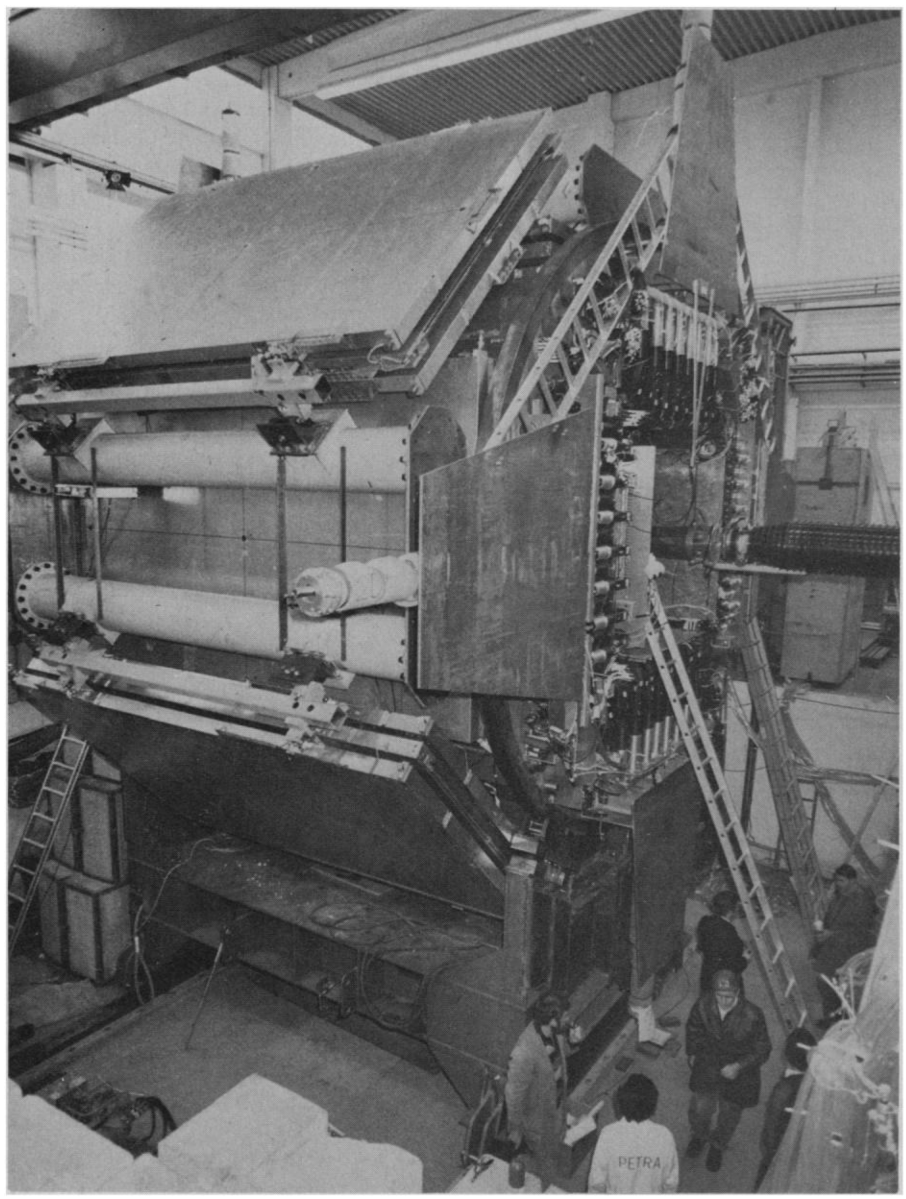

Fig. 1. MARK J, one of the five particle detectors slated for use at the PETRA storage ring, in position in one of the four experimental halls. Built and operated by a German-American-Chinese collaboration under the direction of Samuel Ting of MIT, the 400-ton detector is unique in that it rotates about two axes in order to measure very accurately asymmetries in the angular distributions of particles produced in electron-positron collisions. The pipe running along the axis of the detector is one of eight sections of the storage ring where electrons and positrons collide. [Source: DESY]

*An unusually lucid account of quantum field theories of the type called gauge theories can be found in the article by Daniel Freedman and Peter van Nieuwenhuizen in *Scientific American* (February 1978, p. 127).

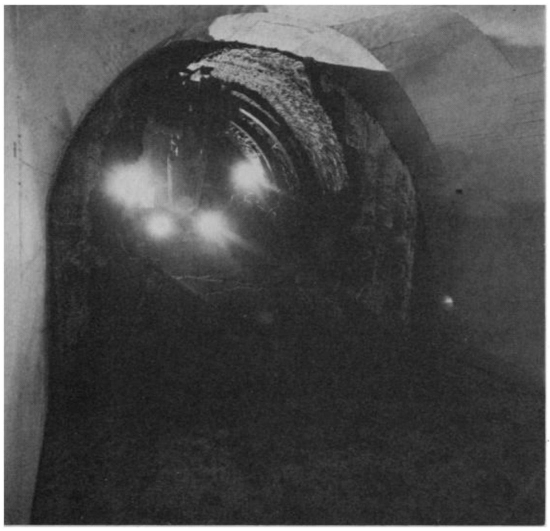

Fig. 2. Digging the tunnel for the PEP storage ring. For protection from radiation, the ring must be covered by concrete and dirt. Because of the hilly terrain at Stanford, construction is part cut and cover and part tunneling. Here an "Alpine Miner" emerges after finishing the last tunnel. [Source: SLAC]

massive, perhaps as large as 80 GeV. (Because of Einstein's $E = mc^2$, physicists frequently cite particle masses in terms of the equivalent energy.)

Quantum electrodynamics, the modern theory of electromagnetism and the first of the quantum field theories, got its start with the work of Paul Dirac, now at Florida State University, shortly after the advent of quantum mechanics in the 1920's. Since then this theory has proved to be quantitatively in agreement with experiment at distances ranging from thousands of kilometers to about 10^{-15} centimeter. One thing physicists will surely try at the German machine PETRA and the Stanford storage ring PEP (a joint project of SLAC and the Lawrence Berkeley Laboratory) is to continue verification to 10^{-16} centimeter. There is much more involved in extending the range of validity of the theory than simply adding a decimal point. For one thing, quantum electrodynamics, as the one quantitatively successful field theory, is the prototype on which other field theories are modeled; any sign that it has a problem would carry over to these as well, a kind of domino effect.

More important, however, at increasingly shorter distances, the electromagnetic and weak forces become comparable in strength, whereas the electromagnetic is normally a thousand times stronger. The collision energy in storage rings needed to reach the distance of equal strengths is about equal to that of the quanta of the weak force fields (there are three). PETRA's maximum collision energy of 38 GeV (PEP's is 36 GeV) is not high enough to reach this point, but it is getting close enough for observable effects to begin showing up. Of particular interest to particle physicists is seeing whether the effects match those predicted by the first of the so-called unified field theories, constructed a decade ago by Steven Weinberg of Harvard University and by Abdus Salam of the International Center for Theoretical Physics in Trieste, with important contributions made more recently by Gerard 't Hooft of the University of Utrecht and the late Benjamin Lee of Fermilab.

Among the cherished goals of theorists is the construction of a framework that explains all four of the basic physical forces as manifestations of a single underlying mechanism, a dream that dates back to early 20th-century attempts to tie together gravity and electromagnetism. The Weinberg-Salam model is a first step in this direction in that it unites the electromagnetic and weak forces. In the process, the theory makes a number of specific predictions, some of them spectacularly backed up by later experiments at CERN, Fermilab, and SLAC. Among the predictions still not directly verified are the masses of the weak field quanta: There are three such beasts corresponding to the three fields, two electrically charged and one neutral.

The angular distribution of muons and antimuons produced when electrons and positrons collide in a storage ring is one of several properties sensitive to the mass of the neutral particle. The distribution becomes more asymmetrical as the collision energy nears the mass of the particle. PETRA or PEP will have sufficient energy to indicate whether some of these predictions of the Weinberg-Salam model are correct but probably will not be able to nail down the mass precisely (Fig. 1). Other accelerators yet to be built will be needed for this.

By analogy with quantum electrodynamics, the unified field theory is beginning to be called quantum flavor dynamics. Both quarks (and the hadrons constructed from them) and leptons are subject to the weak force, and it is the flavor property of quarks that is involved—hence the name. In the simplest version of the unified theory, quark flavors come in pairs. Since five flavors are known experimentally, it is important that a particle containing a sixth quark flavor also be found. Most theorists expect that the mass of such a particle will lie within reach of PETRA and PEP. In fact, a successful search may be the first of the major qualitative discoveries (some like this one expected and some not yet even imagined) that physicists hope will emerge from the two storage rings. Because their machine will come on line a year later, SLAC experimenters virtually concede that the most obvious of these kinds of findings will likely come from groups working at DESY (Fig. 2).

Leptons, as well as quarks, come in pairs, says the unified theory, although the number of pairs of either is not specified. Experimentally, the situation is also similar to that of quark flavors. Using SLAC's current, smaller storage ring called SPEAR, Martin Perl's group there had accumulated by last year convincing experimental evidence for the existence of a so-called heavy lepton, the tau particle, which is almost twice as heavy as the proton, and more recently for the tau neutrino. Work by a second SLAC group and by two teams using DESY's analog of SPEAR, a storage ring named DORIS, confirmed the discovery. Searches for additional heavy leptons are thus on the agenda of experimentalists at the new storage rings.

A third feature of quantum field theories is that the quanta of the fields are initially massless. But an effect called spontaneous symmetry breaking provides a mechanism by which some quanta, such as the weak field quanta, can acquire masses. One way the unification of weak and electromagnetic forces can be viewed is that at short distances (high energies), the masses of the weak field quanta become unimportant and the original symmetry is restored. (Here symmetry refers to the properties of the equations of motion of particles in the field theories. Spontaneous symmetry breaking occurs when solutions of the equations do not exhibit the full symmetry. Physicists sometimes point out the example of a ball moving on a roulette wheel, whose equations of motion are symmetrical about the axis of rotation even though it always stops in an asymmetric position.)

A consequence of theories of spontaneous symmetry breaking is that new particles called Higgs bosons, after Peter Higgs of the University of Edinburgh, are required to exist. The mass of the Higgs boson responsible for symmetry breaking in the unified theory depends on a number of factors, such as the masses of the quarks, and cannot be specified with the present knowledge. But, physicists consider it possible, if not likely, that this particle may be seen among the debris of electron-positron collisions at PETRA or PEP.

Quantum chromodynamics is the name theorists have come up with for the quantum field theory of the strong nuclear force that was proposed originally by Harold Fritzsch of CERN, Gell-Mann, and Hans Leutwyler of the University of

Bern, by David Gross and Frank Wilczek of Princeton University, and by Weinberg. Quarks (and hadrons) but not leptons feel the strong force, and the name of the theory derives from the color property of quarks, which is the characteristic involved in the strong interaction.

The theory is the most complicated of the field theories, in one sense, because there are eight fields and corresponding force-carrying quanta. The quanta are massless; hence the force between quarks is of infinite range. For complex reasons, however, the force between hadrons is of short range—10^{-13} centimeter.

But the most difficult feature of quantum chromodynamics is the strength of the strong force. Because it is "so strong," theorists cannot calculate its properties in the way successfully used in quantum electrodynamics and in the unified theory. For example, in order to explain why quarks do not seem to exist as free particles, physicists have postulated that the strong force is too strong to permit quarks to pull free from one another. But theorists have as yet been unable to show that quantum chromodynamics has this property.

Paradoxically, a success of quantum chromodynamics is related to the experiments that showed the lumpiness of the proton and neutron. The same experiments also suggested that the quarks in these particles behave as if they are only weakly bound together. Gross and Wilczek of Princeton and David Politzer, now at the California Institute of Technology, have shown that quantum chromodynamics is the only realistic field theory with this behavior—namely, that the force between quarks becomes weaker as they are squeezed together.

Because high-energy experiments will probe the short distance behavior of the strong force, they will contribute little to the resolution of what some theorists consider the major challenge of particle theory, namely, the problem of quark confinement (that is, why free quarks do not exist). The short-range behavior of the strong nuclear force is not without interest, however, and the higher energies available at PETRA and PEP will be important to the quantitative verification of two aspects of quantum chromodynamics. The first phenomenon is given the term jets. In the electron-positron collision, two quarks may be created and they will proceed to speed away from the collision region in opposite directions. The hadrons created as these quarks transform (as they must because there "are" no free quarks) will, then, tend to be in two groups that assume the quark trajectories. The effect, already convincingly demonstrated at lower collision energies, is much more prominent at high collision energies. In addition, jets due to the appearance of additional particles such as the quanta of the strong nuclear force may be observable. Quantum chromodynamics makes quantitative predictions concerning the details of jet behavior that will be testable at PETRA and PEP.

A second important feature is the detailed form of the force between quarks at short distances—that is, the force law that is analogous to the inverse square of the separation that enters into the coulomb force between electrically charged particles. One of the exciting aspects of the J/psi particle is that physicists have been able to deduce possible forms of the quark-quark force from the masses of the J/psi and the many other particles in its immediate family. A particle such as the J/psi, which is also called a resonance, occurs when the two quarks created in the electron-positron collision do not fly apart, but remain bound by the strong nuclear force. The energy (mass) of the resulting particle depends on the separation between the quarks when they become bound, much as the energy of a hydrogen atom depends on the orbital radius of the electron around the proton. The members of the J/psi family correspond to different separation distances.

The upsilon particle is also a resonance but contains heavier quarks with the fifth flavor. The still undiscovered particle containing even more massive quarks with the sixth flavor will also be a resonance. By finding the masses of the other particles in their respective families, physicists will have a more complete and quantitative picture of the quark-quark interaction. Study of these heavier particles, accessible at PETRA and PEP, will be even more useful than the J/psi because relativistic effects are less important when the quarks become heavier, thus simplifying extraction of the form of the strong interaction. [An intermediate energy storage ring to be in operation at Cornell University by the spring of 1979 (*Science*, 4 November 1977, p. 480) may be the best machine to study the upsilon family.]

These and numerous other possible experiments constitute a busy schedule for the two new electron-positron storage rings, PETRA and PEP. By getting on line first, the German machine will have first crack at skimming the cream from an unexplored region of high energy physics. But precisely because it is unexplored, physicists may find surprises that could thoroughly upset the well thought out program of experiments described above. This would not be an unhappy outcome. The J/psi discovery launched the intensely exciting age of the new physics. If a comparable impact were to result from an unexpected finding at PETRA or PEP, physicists would be overjoyed.—ARTHUR L. ROBINSON

Fields Medals (IV): An Instinct for the Key Idea

Pierre Deligne was born in Brussels, Belgium, in 1944. When he was 14 an enthusiastic high school teacher, M. J. Nijs, lent him several volumes of the *Elements of Mathematics* by N. Bourbaki. This work develops a solid foundation for all of modern mathematics, in a most logically efficient manner, proceeding from the general to the particular; for example, the real number system is discussed only in the fourth chapter of the third long book, after general topology and abstract algebra have been extensively treated. In the whole treatment there is (except perhaps for the excellent historical notes) no motivation given at all, other than the internal logic of the development itself. That Deligne not only survived but even thrived on his exposure to such a work at such a tender age was perhaps already an indication of his genius, as well as of Nijs' good judgment.

Thus when Deligne went to the University of Brussels he already knew the fundamentals of most of modern mathematics. There he learned much from group theorist Jaques Tits now at the College de France, and Tits gave him excellent advice on his general mathematical development. In 1965, at Tits' suggestion, Deligne went to Paris to pursue further his interests in algebraic geometry and number theory. It would be hard to imagine a better place for this at the time. Among other activities there were

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