

ciently high energies, just using simple Feynman diagrams that are valid despite the existence of strong interactions.

As Gross told us, "all the fog of the strong interactions suddenly goes away and you suddenly see the underlying dynamics. You can hope from there to extrapolate backwards from the region in which the interaction is weak, and therefore discernible, to the region where the really tough dynamical problems remain." We have not yet been able to explain the spectrum of hadrons with a dynamical theory, he said but "at least we have a starting point." Eventually, Weinberg feels, there is hope of unifying the strong, weak and electromagnetic interactions and testing this theory experimentally.

The method used by Gross and Wilczek and by Politzer to analyze the small-distance behavior of field theory is the renormalization group, an approach developed in the 1950's by Murray Gell-Mann and Francis Low and by E. C. G. Stueckelberg and André Peterman. Subsequently the importance of the renormalization group in strong interactions was emphasized by Kenneth Wilson (Cornell), who also applied this technique to critical phenomena (PHYSICS TODAY, March 1972, page 17) and by Kurt Symanzik (DESY) and Curtis Callan (Princeton). Gross, Wilczek and Politzer have actually evaluated the renormalization group parameters for a gauge field theory.

The renormalization group approach says that at high energies field theories behave as if there were an effective coupling that depends on energy. Using perturbation theory one finds that for any kind of scattering in second order the amplitude at high energies is proportional to the square of the charge but it has powers of $\log E$, where E is energy. In fourth order one might get the fourth power of charge and powers of $\log E^2$ and $\log E$ and so on. Summing all the logarithms one finds that effectively the whole series behaves as if it involved a single expansion parameter, which is the charge times some function of E , which one can call the effective charge. In quantum electrodynamics the effective charge increases with energy, at least for small energy and small charge, so that the electromagnetic interactions would get stronger for higher energies. But theorists have always thought there might be a field theory in which the effective charge decreased at higher energies. In addition, there had been the experimental observation at SLAC of the scaling predicted by J. D. Bjorken (SLAC); these experiments suggested that somehow strong interactions were becoming weak at very high energy.

As Gross explained to us, in an

asymptotically free theory one can think of the coupling constant as going to zero as the momentum becomes larger; that is the theory is free—it has no interactions. In the free theory the behavior is pointlike, which gives one a way of understanding scaling, he said. Gross and Callan have shown⁴ that for most field theories the only way one could explain the pointlike behavior seen at SLAC is if the theory is asymptotically free and the interaction turns off at large momentum. In this case one does not get scaling exactly; rather one obtains logarithmic deviations from scaling. Other theories, Gross told us, would yield a decrease with powers of momentum transfer.

Asymptotic freedom allows theorists to compute the actual behavior of the electroproduction structure function, $f(q^2, x)$ where q^2 is the four-momentum transfer squared and x is $q^2/2\nu$ and ν is the energy transferred to the hadrons in the lab system. This has been done by Gross and Wilczek⁵ and by Howard Georgi (Harvard) and Politzer,⁶ whose numerical results agree. They computed the moments of the structure functions, where the n th moment is

$$\int_0^1 x^n f(q^2, x) dx$$

Although they could not calculate the magnitude of the moments, they were able to find the q^2 dependence. Bjorken scaling would require the moments to be constant because the structure functions themselves are constant. Instead the two groups find the moments go as powers of $1/\log q^2$. In a typical theory the power is about $1/6$ for low moments and very slowly grows, becoming quite large for large moments.

Coleman points out that it is an open question whether SLAC is in the limiting region, asymptopia. "Some people say we are really seeing the Bjorken limit and the scaling that's observed is a reflection of things that are going on in that limit. And other people say what we're seeing at SLAC is some sort of low-energy epiphenomenon, and when we go to higher energy it will have absolutely nothing to do with an asymptotic limit." The approach to the asymptotic limit behaves as $1/\log q^2$, not as $1/q^2$.

Another calculation involving asymptotic freedom has been done by Zee⁷ and by Thomas Appelquist (Harvard) and Georgi,⁸ who calculated the total rate for electron-positron annihilation into hadrons at high energy. They showed that in an asymptotically free theory the rate is the same as the rate one would calculate if one ignored the strong interactions altogether. In addition they calculated the $1/\log q^2$ correction.

Gross and Weinberg have speculated that perhaps asymptotically free

theories are singular enough at low momenta to explain why quarks are never observed. Gross explained to us that the charges might be totally shielded. The infrared singularities that make it difficult to discuss the low-energy behavior of an asymptotically free theory might also explain why quarks cannot be pulled out of hadrons.

—GBL

References

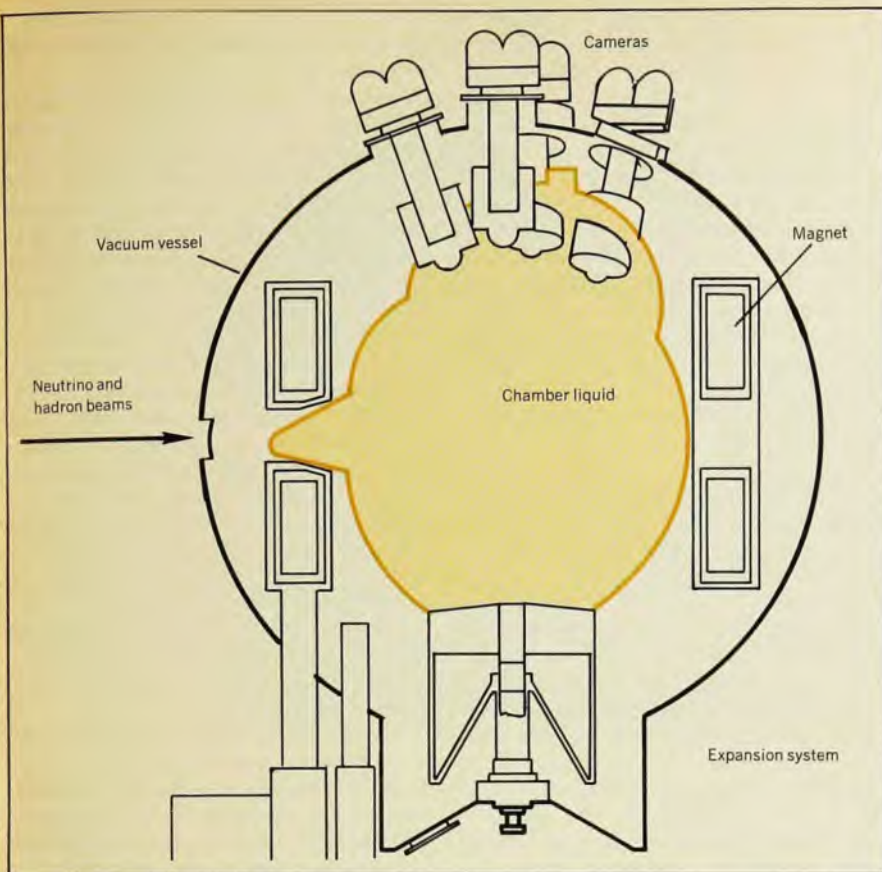
1. D. J. Gross, F. Wilczek, Phys. Rev. Lett. **30**, 1343 (1973).
2. H. D. Politzer, Phys. Rev. Lett. **30**, 1346 (1973).
3. S. Coleman, D. J. Gross, Phys. Rev. Lett. **31**, 851 (1973).
4. C. G. Callan, D. J. Gross, Phys. Rev. D **8**, 3871 (1973).
5. D. J. Gross, F. Wilczek, Phys. Rev. D, **15** Jan. 1974.
6. H. Georgi, H. D. Politzer, Phys. Rev. D, **15** Jan. 1974.
7. A. Zee, Phys. Rev., to be published.
8. T. Appelquist, H. Georgi, Phys. Rev., to be published.

Two new bubble chambers may be last big ones

The world's largest bubble chamber, the 15-foot device at the National Accelerator Laboratory, was operated successfully at the end of September and in October it ran with its 30-kG magnet at 86% of full field, using the 300-GeV repetition rate. Earlier this year the Big European Bubble Chamber (BEBC) began operating at CERN and is now being used for physics runs; it is a 3.70-meter device. These machines, together with the Argonne 12-foot chamber and the Brookhaven 7-foot chamber, may be the last generation of big bubble chambers to be built, according to Charles Peyrou, who heads the track-chambers division at CERN and Nicholas P. Samios of Brookhaven, who has many years of bubble-chamber experience.

The NAL chamber contains contributions from Argonne (superconducting magnet), SLAC (expansion system actuator), Brookhaven (vacuum vessel design) and CERN (optics, piston and seal). The 15-foot device is essentially a sphere with a nose, the sphere with a 12.5-foot diameter and the nose with a protrusion of 2.5 feet, which sticks out between the magnet coils; overall track length for charged particles is 15 feet. The volume of the liquid, which can be hydrogen, neon-hydrogen mixtures or deuterium, is 32 000 liters. Provision has been made for the installation of track-sensitive targets and for internal metal plates to help make gamma rays visible.

For photography the chamber has six 26-inch-diameter ports, each of which



Fifteen-foot bubble chamber at the National Accelerator Laboratory is the world's largest. The sphere has a 12.5-foot diameter, and the nose protrudes 2.5 feet more.

contains three hemispherical windows and a lens and film transport system. There is a 108-deg wide-angle lens that produces a demagnification of 65. The chamber is lined with 3M Scotch-lite consisting of small glass beads applied to the wall.

The superconducting magnet is designed to have a central magnetic field of 30 kG, created by a 5000-A operating current with a stored energy of almost 400 MJ. Its inner diameter is 14 feet and outer diameter almost 17 feet. Made of twisted filaments of niobium-titanium embedded in copper, the magnet has about 3000 turns. The bubble-chamber group is led by William Fowler.

NAL first tried using a piston made of Fibreglas reinforced with wood. During tests in August 1972 the piston failed, was repaired and then failed catastrophically on the second test. Meanwhile NAL obtained information on CERN's backup design for the BEBC piston. Fowler told us that although there had been a great deal of experience with Fibreglas-reinforced plastic in cryogenic tankage, no one had employed the bulk volumes NAL did. He attributes the failure to internal defects caused by heat cycling, environmental changes and the huge bulk volume involved, all leading to an internal stress concentration that causes cracking when the piston is pressure-loaded.

When it became clear that the plastic piston could not be repaired, NAL turned to a stainless-steel one based on the CERN design. It is basically an umbrella with 36 stainless-steel ribs covered by a skin. The steel piston will not work for multiple pulsing at NAL's fastest repetition rate, Fowler explained, because of eddy current heating. Although NAL has abandoned wood-reinforced Fibreglas, they plan eventually to run with a modified plastic piston. Meanwhile they expect to be able to run at a 300-GeV repetition rate at full field, using a single pulse each accelerator cycle. In its initial operation on 15 October, NAL used 300-GeV protons and obtained 500 events with two cameras operating.

The NAL chamber will first be used for six neutrino experiments: an NAL-Michigan one with neutrinos in hydrogen; an Argonne one for antineutrinos in hydrogen; a Columbia-Brookhaven one for neutrinos in a neon-hydrogen mixture and a similar one for the University of Wisconsin with a lower concentration of neon; a USSR-NAL-Michigan one and a University of Washington-Berkeley one for antineutrinos in neon.

BEBC. We visited the Big European Bubble Chamber during a recent visit to CERN, where we chatted with Peyrou. Unlike the NAL machine, BEBC is a cylinder with a dome; the cylinder has a diameter of 3.70 meters.

Scotch-lite is used for illumination. BEBC uses a superconducting magnet, but because its construction was started a year earlier than the NAL chamber, it employs a copper-stabilized niobium-titanium wire, rather than the twisted conductor used by NAL. Because BEBC does not have twisted conductor, there are some remanent fields and over a period of time the field will vary. So, Peyrou told us, they have a permanent system of monitoring the field continuously, using a large number of Hall probes. The system works well, he said, and at most, at the top field, the frozen currents produce 500 gauss.

BEBC started operating at the beginning of last year and by the beginning of March, the experimenters had their first tracks. When we visited, they were in the midst of their first physics run. The CERN team, too, had trouble with its plastic piston, and is currently using a metallic piston, which they are able to operate with at 20 kG, but not 25 kG. So eventually they will have to turn to a plastic piston. Meanwhile, the high-field operation is not urgent, Peyrou explained, since the device is being used with the 30-GeV Proton Synchrotron. Eventually, however, when the Super Proton Synchrotron (SPS) starts operating, it will run at 300 GeV, (scheduled to take place in 1976 or 1977), and the higher field will be needed.

The magnet has been operated at 30 kG; at this field the eddy currents are noticeable but not catastrophic.

In the new plastic piston design, CERN will use more metal but will not have any closed loops to avoid eddy currents. It will be shaped like an umbrella with metallic ribs, and the cloth will be of plastic.

No more chambers? Peyrou told us that he believes no new large chambers will be built and that in 15-20 years the new ones will close down. In fact, he notes, some people feel that bubble chambers are dead already. He disagrees, noting that for BEBC they are receiving proposals from several groups for 3 million pictures each. When BEBC operates with the SPS, it will only take one or two pictures every nine seconds so that over the year it will only take 1.0-1.5 million pictures, which might be divided 50-50 into neutrino experiments and hadronic physics. Thus the groups asking for 3 million pictures would have to wait six years to get them; so it would appear there will be a demand for such chambers for quite a few years to come.

Bigger chambers will not be built, however, because we are at the limit of construction, both technically and financially, Peyrou told us. Although big bubble chambers will die, Peyrou says, their spirit will continue. Electronic experiments don't have enough

redundancy, frequently, whereas usually the bubble chamber has too much (one doesn't need ten bubbles per centimeter, he notes), although not always. People criticize bubble chambers because they cannot be triggered. "The beauty of the bubble chamber is that it is stupid; it takes everything." Peyrou is in favor of electronic techniques using non-destructive triggering. Some experimenters are using the bubble chamber as a target instrument; the energy is measured downstream by a spectrometer. "That slows down the data taking," Peyrou notes, "but maybe that's not unfortunate because the analysis takes too long anyhow." Such a technique is being considered for CERN.

Samios, too, feels that the present generation of bubble chambers is probably the last one. Small chambers will continue to be used as track-sensitive targets, he feels. They will be used in hybrid form, as is presently being done at NAL and SLAC. One first has a bubble chamber and then follows it with electronic equipment such as wire or drift chambers. This allows very accurate track measurements, and one can make decisions on whether or not to take a picture, depending on some electronic signal. Such hybrid devices do not require big chambers. —GBL

Meteorites

continued from page 17

chemical and nuclear processes: A reaction that produces a two-percent change in the O^{18}/O^{16} ratio should produce a one-percent change in the same direction in the O^{17}/O^{16} ratio.

When Clayton and his colleagues looked at O^{17} abundances and plotted a certain function of the O^{17}/O^{16} ratio versus the same function of the O^{18}/O^{16} ratio, they found their data fell on a straight line with a slope of one, in sharp contrast with the slope of one-half for the line linking data points from all other samples so far analyzed. The result, they conclude, indicates that different nuclear processes occurred here from those in the other samples. (Urey himself, Clayton told us, had earlier suggested that some meteorites might contain material from outside the solar system. His idea had been to search for meteorites that had had hyperbolic orbits.)

Before they speculated on a separate nucleosynthetic origin for the chondritic inclusions they considered what other nuclear processes might have led to the observed ratios. Irradiation by protons, neutrons or alpha particles, for example, could remove larger amounts of the relatively unstable O^{17} and O^{18} than of the O^{16} . But, the experimenters point out, any such reaction must have equal cross sections for

the two heavy isotopes to cause the observed equal fractional depletions of both. And no peculiarities in the abundances of other elements or their isotopes have been observed, as might be expected from radiation strong enough to deplete O^{18} and O^{17} by the observed three percent.

Alternatively the samples could be a mixture of a component with the ordinary composition and varying amounts of some other component, highly depleted in O^{17} and O^{18} . This O^{16} -rich component might be the result of helium burning or of carbon burning, in our Sun or other stars. If it were derived from the Sun, the amounts of O^{17} and O^{18} in the solar wind should be relatively low. There is as yet no evidence on the abundances of these isotopes in the solar wind.

Suppose that the O^{16} -rich component in the meteoritic inclusions did come from outside the solar system. Previous evidence from isotopic abundance studies, Clayton explained to us, indicated that all matter in the solar system had passed through a stage of complete homogenization, implying that it had all been in the gaseous state. Most classic theories of solar-system evolution, therefore, have included a vaporization stage. But, Clayton points out, there is no apparent astronomical evidence that requires such a stage: "If you look at regions where stars are being formed now, you see clouds of opaque material," he told us.

The next work to be done is to analyze the meteoritic inclusions for isotopic anomalies in the other elements present, in order to determine the composition of the substance that apparently survived the high-temperature stage. The Chicago group expects to have ready a microprobe that will allow them to do elemental and isotopic analyses on a microscopic scale. They expect that magnesium and silicon will be among the elements found, both of which—fortunately—have three stable isotopes. Then, from the known condensation temperatures of these minerals, the temperature through which the solar system passed can be estimated.

Even if the isotopic composition shows that the meteoritic inclusions were solid grains before the formation of the solar system, there may be no answer to the question "How long before?" As Clayton explained to us: "If the material we're looking at had the kind of nucleosynthetic history that could give us enriched O^{16} without the other elements, it's very likely that this event just wasn't the one that made heavy elements, and it's the heavy elements that are used for age determinations." A. G. W. Cameron (Harvard-Smithsonian Astrophysical Observatory) is somewhat less pessimistic

and expects that uranium could be present.

Cameron has invoked² initial variations in isotopic abundance at different parts of the primitive solar nebula as a way of explaining apparent large time differences in meteorite formation. The standard methods of dating with strontium and lead sometimes lead to differences of the order of 10^7 years in the ages of meteorites that should be about the same age. Questioning whether these age differences are real, Cameron shows how parent and daughter isotopes could have been created by separate events and undergone incomplete mixing. His estimates, however, are of a 0.1% isotopic depletion for the heavy elements he discusses, whereas the observed change for the oxygen is three percent. He also explained to us that any predictions about the O^{16} -rich component would depend on whether or not the O^{17} and O^{18} resulted from a common (nuclear) production process.

Urey has recently reconsidered the fractionation question and come up with a possible non-nuclear explanation for fractionation of O^{16} relative to O^{17} and O^{18} together, although he does not consider the process very probable. Fractionation could be photochemically induced if a narrow wavelength radiation band that happened to coincide with an absorption band for a molecule containing O^{16} (but not O^{17} or O^{18}) were to hit a gas that was in incomplete local thermodynamic equilibrium. This laser-like radiation could change the relative abundance of the O^{16} quite differently from the change caused by mass-related chemical fractionation.

Relating this process to conditions in the primitive solar nebula, Cameron explained to us that the nebula could have had regions where the mean free path for photons was comparable to the dimensions of a region with changing temperature and pressure. Accidental coincidences could occur between, say, emission bands from silicates and absorption bands of a molecule containing O^{16} . "How would you differentiate between nuclear and non-nuclear processes?" we asked. For the nuclear processes you would expect high relative C^{12} to accompany the high O^{16} because all of these would result from explosive nucleosynthesis. For the photochemical case, no such consistent relation would be expected. "Whatever the explanation, it's obviously going to tell us some very important things about nature."

—Marian S. Rothenberg □

References

1. R. N. Clayton, L. Grossman, T. K. Mayeda, *Science* **182**, 485 (1973).
2. A. G. W. Cameron, *Nature* **246**, 30 (1973).