search & discovery

Dimuons at Fermilab suggest new form of hadronic matter

Neutrino experiments at Fermilab conducted over the past two years, in which pairs of muons are produced, appear to show the existence of a new form of hadronic matter. The discovery suggests that matter carrying a new quantum number has been observed. This quantum number is often generically referred to as "charm."

The experiments have been done by a collaboration between Harvard University, University of Pennsylvania, University of Wisconsin and Fermi National Accelerator Laboratory, consisting of Alberto Benvenuti, David Cline, William T. Ford, Richard Imlay, Ta-Yung Ling, Alfred K. Mann, Robert Orr, Donald Reeder, Carlo Rubbia, Ray Stefanski, Larry Sulak and Peter Wanderer. Their first results were reported in the summer of 1974 at the London Conference on High-Energy Physics.[1] Since then about 80 more events have been found so that the situation has become clearer.

Over the past couple of months the group has published three new papers[2,3,4] reporting their results for neutrinos and antineutrinos and stating the case for their belief that they have found a new form of hadronic matter. The belief rests strongly on an analysis by Abraham Pais (Rockefeller University) and Sam Treiman (Princeton University), which puts stringent bounds on the properties of a heavy lepton; the experimental results lie outside these Pais–Treiman bounds.

Meanwhile a different neutrino experiment at Fermilab, done by Barry Barish, Frank Sciulli (Cal Tech) and their collaborators has also found two muons in the final state. The group reported their preliminary results at the Paris Conference held last March. In Paris Soviet experimenters from Serpukhov also reported two muons in the final state.

Recently at the Conference on Quarks and the New Particles held at the University of California, Irvine on 5 December, Juergen von Krogh (University of Wisconsin, Madison) reported that he and his collaborators, using the 15-foot bubble chamber at Fermilab, had observed four dilepton events, in which one of the leptons was a negative muon and the other a positron. (In all four events a K^0 was also seen.) Also at the Irvine conference, Charles Peyrou reported that experiments from Gargamelle at CERN had recently seen a second neutrino-induced event in which a negative muon and positron were produced.

The Fermilab experiment employs a beam of neutrinos striking a target. In most events a single muon is produced (although 30% of the events involve neutral currents; in this case no muon exists), but about 1% of the time a pair of muons comes off, usually one of each sign; such a pair is called a "dimuon." Over the past twenty years it has been

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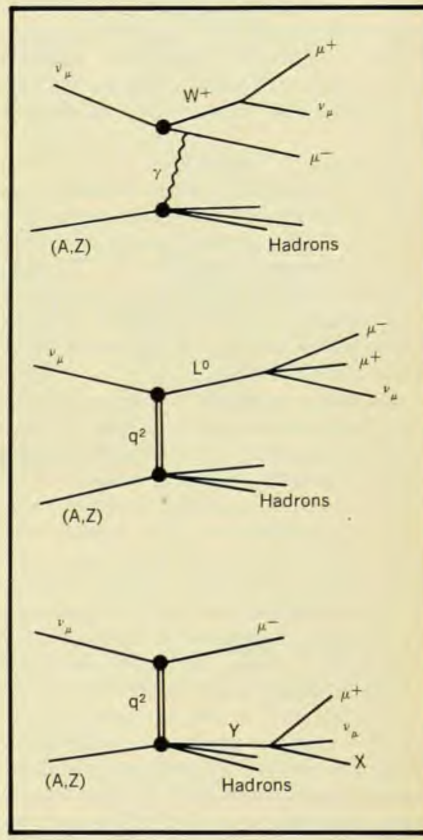


Feynman diagrams for neutrino-induced production and subsequent decay of (top) charged intermediate vector boson, W^+, (middle) neutral heavy lepton, L^0, and (bottom) the proposed new type of hadron, Y.

Argonne and others propose intense pulsed neutron source

Development of an intense pulsed neutron source for solid-state physics research has been proposed by Argonne National Laboratory to the Energy Research and Development Administration. Meanwhile, scientists at Oak Ridge National Laboratory and Los Alamos Scientific Laboratory continue to examine their own facilities' advantages as source sites for neutron scattering studies.

The view from Argonne. The Argonne laboratory's proposed facility would be a much more ambitious version of the earlier projected ZGS Intense Neutron Generator, a $16 million effort, which was to have employed the lab's new injector for the Zero Gradient Synchrotron. The present $58 million proposal specifies construction of the intense pulsed source in two stages: The first stage would be based upon the 500-MeV ZGS Booster II synchrotron, which will be capable of generating 5×10^{12} protons/pulse at 30 Hz and which is expected to operate in the autumn of 1976. In the second phase, an 800-MeV dedicated high-intensity synchrotron system would produce 5×10^{13} protons/pulse at 60 Hz. Two neutron-producing targets would be employed in separate facilities for slow-neutron scattering and for radiation-effects research.

Researchers chose the synchrotron as their proton accelerator because it can provide the very short pulses needed for high-resolution slow-neutron spectroscopy. In the neutron scattering source, a hydrogenous moderator would serve to produce short pulses for scattering research. In the radiation damage source, a tungsten moderator surrounding the target would enhance the fast-neutron flux for radiation-effects experiments.

In the first state, the 4π-equivalent thermal neutron flux at the neutron-scattering facility would be 1.5×10^{15} neutrons/cm^2-sec; in the second, the peak flux would reach 10^{16} neutrons/cm^2-sec. In addition, the neutron specbut they are considering several possibilities. All other tokamaks seem to observe that τ is proportional to N, but the range over which N can be varied is generally only factors of five.

Because Alcator can be operated over such a large range of densities, Coppi told us, one can explore both the collisional (low ratio of mean free path to the device length) and collisionless (high ratio) regimes. Until now, tokamak experiments have all operated in the collisional regime (or between the two regimes), where trapped particles modes (driven by particles that are trapped in mirror-like regions and causing plasma to leak out of the machine) are not important. The Princeton Large Torus, about to go into operation, is also designed to reach the collisionless regime, to explore what happens when phenomena associated with trapped particles take over. The record parameters achieved in Alcator were all in the intermediate region between collisional and collisionless. When the plasma was studied in the collisionless regime, the confinement time deteriorated to the extent that the density was decreased; Coppi says that among the various possible explanations of this phenomenon it is not yet known what the correct one is.

Another cause of enthusiasm is the exceptionally clean plasma obtained for peak particle densities larger than 10^{14} particles/cm^3. Its effective ion charge is about one. Some other tokamaks have had effective ion charge of one, but typically have had about four. In addition, the lack of impurities, Coppi feels, may prevent the onset of disruptive instabilities.

The ability to raise plasma densities in tokamaks is limited by the maximum plasma pressure (product of density and temperature) that can be supported by the poloidal magnetic field pressure, and depends also on the density of the available heating power and the size of the toroidal field. There is a strong incentive to raise the poloidal field so as to maintain the plasma density as the temperature is raised, but it is technically difficult to do so.

Alcator has achieved about an order of magnitude stronger ohmic heating than any previous tokamak because of its high magnetic field and small size. To reach temperatures of reactor interest, however, some form of non-ohmic heating will be needed, for example neutral-beam heating or microwaves.

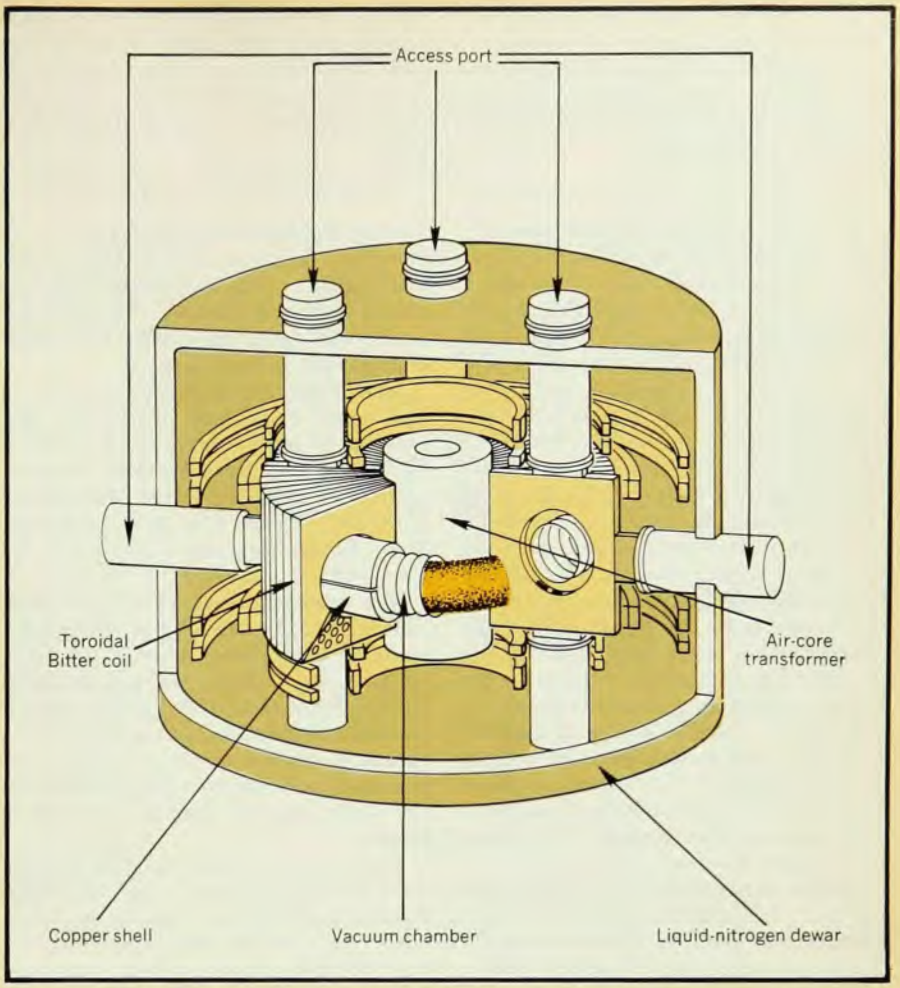
One possible application of the Alcator concept is to use it as a compact materials-testing reactor, in which one burns deuterium and tritium in the device to study the behavior of materials being bombarded by 14-MeV neutrons, alpha particles and thermonuclear plasma in general.

Reactor possibilities. However, the Alcator concept conceivably could also be used for a power-producing reactor. At present, ERDA's emphasis is on the Tokamak Fusion Test Reactor (PHYSICS TODAY, October 1974, page 77), a $215-million facility to be completed at Princeton by 1981. This is a device with a major plasma radius of 250 cm and a minor radius of 85 cm. The present Alcator has a major radius of 54 cm and minor radius of 9.5 cm—considerably smaller.

We asked Robert Hirsch, head of ERDA's controlled thermonuclear research program, how the Alcator results are going to affect the tokamak program. The results are too new to be sure, he says, but they are definitely causing ERDA to look more intensely at this regime of tokamak operation. Before following this approach, we must improve our understanding of scaling and whether or not the economics of a very high-field reactor are favorable, he says. ERDA's technology studies have concentrated on systems that use lower magnetic fields. Alcator, on the other hand, uses higher magnetic fields in a smaller system. Whether or not this will be more economical is not yet known.

Right now ERDA is continuing to go ahead with the Princeton Large Torus approach, which is incorporated in the TFTR design—larger size and lower magnetic fields—because that approach appears to be reasonable for reactors. Hirsch cites a statement made by S. J. Buchsbaum (Bell Labs) and others, "If Nature is going to let one approach work, she will let all of them work."

—GBL



MIT tokamak device, Alcator, has reached an $N\tau$ value greater than 10^{13} sec/cm^3, a record.

Dimuons

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thought that a search for such dimuons might yield a charged intermediate vector boson (W particle). In the early 1960's such a search was made at Brookhaven, for example, but the W was not found. With the higher energies available at Fermilab, it was of course natural to conduct the search again. And this time the experiment yielded dimuons—but apparently not a charged intermediate vector boson.

Although the Harvard–Penn–Wisconsin–Fermilab group only see two muons in the final state, they believe that a third lepton is produced because of the universally held belief in conservation of lepton number. They do not see a third muon (trimuons); so they believe that the third lepton in the final state is a neutrino. Thus they observe the following reaction:

$$\nu_\mu + (A,Z) \rightarrow \nu_\mu + \mu^- + \mu^+ + \text{hadrons}$$

In a process initiated by a muon neutrino, one automatically expects a negative muon in the final state. But where do the positive muon and the second muon neutrino come from? They could be coming from the decay in flight of a pion or kaon. To check for this possibility the group used targets with two different hadron absorption lengths—solid iron and a liquid scintillator. The probability of a pion or kaon decaying in flight is roughly four times less in the iron than in the liquid scintillator. So you would expect, if pions or kaons are being produced, that the number of dimuon events in the liquid scintillator would be four times larger than in the iron for equal masses of target. Instead, the number of events is equal.

A second possible source of the second muon and second neutrino is from a direct process. The calculated cross section for this four-fermion process is 1000 times smaller than the rate the experimenters observe.

All other possibilities are of considerable interest. It could be a charged intermediate vector boson, W; it could be a neutral heavy lepton, L^0; it could be a new type of hadronic matter, which the experimenters call a Y particle.

Mann told us there are several reasons for ruling out the charged W and the L^0. From their data on single-muon production, the experimenters find that the mass of the charged W would probably be greater than 25 GeV—a value too high to account for the dimuon events. If a low-mass charged W were being formed in the single-muon events, the mean four-momentum transfer would severely depart from linear dependence. Instead it is linear with energy up to 200 GeV.

Pais and Treiman, in their analysis,[5] assume that a heavy lepton is formed and then show that the data do not agree with this assumption. To describe in dynamic detail the process of a heavy lepton producing muon pairs is extremely complicated because one must assume details of the production mechanism (or mechanisms), the decay mechanism, the polarization and the mass. Instead, Pais and Treiman found an argument that depends on practically no theoretical assumptions.

They assume that the heavy lepton or leptons have spin ½ and that the decay coupling of the heavy lepton to the positive muon, negative muon and neutrino is local; that is, the coupling is vector, axial vector, scalar, pseudoscalar or tensor.

Pais and Treiman were able to find a simple upper and lower bound on the size of the ratio R of the average energy of the negative muon to the average energy of the positive muon. They found that

$$[9 - 4(2)^{1/2}]/7 \leq R \leq [9 + 4(2)^{1/2}]/7$$

That is, the ratio has to lie between 0.48 and 2.1. To their delight this bound was useful. The experimentally observed value is 3.7 ± 0.65. Thus the experimental value lies outside the region allowable for a heavy lepton.

(A less general argument concerning the same ratio was made for the charged W several years ago by Robert Brown, now at Case Western Reserve University, and John Smith of the State University of New York at Stony Brook. They found that the ratio would be about 0.4.)

New hadronic matter. With all other possibilities eliminated, the group concludes that they have found a new form of hadronic matter. Indeed in 1973 George Snow (University of Maryland) pointed out[6] that one of the most characteristic signals for the existence of charmed particles would be the discovery of neutrino-induced dilepton events.

Mann explains that the new matter must necessarily carry a new quantum number because the Y particles decay weakly to a second muon and a neutrino. If there were no new quantum number, the massive Y particles would decay strongly or electromagnetically. Because the new quantum number must be conserved, the decay of the Y particle by strong or electromagnetic processes is forbidden.

The experimenters do not know how many of the new particles exist, but at least some of them have masses in the range 2–4 GeV. Their lifetimes are less than 10^{-10} sec. At least some of them are charged.

In addition Mann expects Y particles to exhibit a weak decay into hadrons exclusively, as well as the observed semileptonic or leptonic decay modes. (Such a hadronic decay was reported last March in Paris by Robert Palmer and his collaborators at Brookhaven.) Furthermore, in neutrino and antineutrino inelastic reactions, single Y particles seem to be produced about as abundantly as single strange particles.

The Harvard-Penn-Wisconsin-Fermilab group has also found seven dimuon events produced[4] in antineutrino-induced interactions. Further analysis shows that the rate for dimuon events produced by neutrinos and by antineutrinos could be roughly comparable. If this is indeed the case, then, Pais and Treiman[7] note, important new constraints arise on the question, much discussed recently, how many kinds of generic charm exist. The simplest possibility, according to them, is that there is only one kind of charm—the type introduced by J. D. Bjorken (SLAC) and Sheldon Glashow (Harvard) in 1964. That is, instead of three quarks, one would need one more, the charmed quark. If there is only one kind of charm and if the new experiments are correct, then it follows that the charm-producing antineutrino reaction is associated with the so-called "sea" of quark–antiquark pairs in the nucleon. That result would put very severe constraints, they say, on attempts to build a model that involves right-handed doublets of quarks. —GBL

References

1. D. B. Cline, A. K. Mann, C. Rubbia, PHYSICS TODAY, March 1975, page 23.
2. A. Benvenuti, D. Cline, W. T. Ford, R. Imlay, T. Y. Ling, A. K. Mann, R. Orr, D. D. Reeder, C. Rubbia, R. Stefanski, L. Sulak, P. Wanderer, Phys. Rev. Lett. **35**, 1199 (1975).
3. A. Benvenuti, D. Cline, W. T. Ford, R. Imlay, T. Y. Ling, A. K. Mann, R. Orr, D. D. Reeder, C. Rubbia, R. Stefanski, L. Sulak, P. Wanderer, Phys. Rev. Lett. **35**, 1203 (1975).
4. A. Benvenuti, D. Cline, W. T. Ford, R. Imlay, T. Y. Ling, A. K. Mann, R. Orr, D. D. Reeder, C. Rubbia, R. Stefanski, L. Sulak, P. Wanderer, Phys. Rev. Lett. **35**, 1249 (1975).
5. A. Pais, S. Treiman, Phys. Rev. Lett. **35**, 1206 (1975).
6. G. Snow, Nucl. Phys. **B55**, 191 (1973).
7. A. Pais, S. Treiman, Phys. Rev. Lett. **35**, 1556 (1975).

Indiana cyclotron begins scattering experiments

Scientists at the Indiana University Cyclotron Facility have extracted a proton beam from the cyclotron and are beginning high-resolution scattering experiments. The $11-million variable-energy device represents a joint effort on the part of the university and the National Science Foundation.

Protons were first accelerated to an energy of 130 MeV at the laboratory in August, with energies of up to 200 MeV anticipated. The beam was subsequently delivered to a target at the spectrograph station, and early inelastic scattering spectra were obtained with 0.07% overall energy resolution. Thus the device, the largest isochronous cyclotron in the US, is nearly ready for full operation.

About 60% of the initial capital funds for the regional facility were provided by NSF and the rest by Indiana University. The design of the cyclotron was conceived and directed by Martin Rickey, and it has been brought into operation under the direction of Robert Pollock; both are members of the university's physics department. □