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## Puzzle of two-pion production: Is the pion a point charge?

The pion is acting more like a point charge than most particle physicists had expected. The behavior shows up in electron-positron collision experiments performed during the first six or seven months of operation of the Adone storage ring in Frascati, Italy.

It appears that the pion is acting like the atom that bounced too many alpha particles back at Ernest Rutherford to be explained by the Thomson model, thus indicating that the atom had a hard core, the nucleus. Rutherford's cross sections were far too big for a diffuse structure, and so are those found at Frascati. The cross section for multihadron (more than two) production is surprisingly high, suggesting that the instantaneous charge distribution of the pion corresponds to pointlike constituents, giving strong support for a parton picture of the pion structure.

The cross section for producing a  $\pi^+\pi^-$  pair is very high, too, high enough to indicate that the pion may be behaving as a pointlike structureless particle like the electron or muon, but the data are still being interpreted.

Preliminary results were reported in September at the "Rochester" high-energy conference in Kiev and then at an informal conference in Frascati by four groups, designated by Frascati as the " $\mu\pi$  group" (whose spokesmen were Marcello Conversi and Mario Grilli), " $\gamma\gamma$  group" (G. Salvini), "boson group" (V. Silvestrini), and the "Bologna-CERN-Frascati group" (Antonino Zichichi). The energy of each beam ranged from 0.75 to 1.1 GeV, or 1.5 to 2.2 GeV in the center-of-mass system.

Despite the surprises for some cross sections, quantum-electrodynamics predictions for cross sections were borne out in preliminary results from electron-positron elastic scattering and muon pair production.

**Two-pion production.** Both the  $\mu\pi$  and Bologna-CERN-Frascati groups reported on production of collinear pion pairs. Because the experimenters only use those events in which the pions come off 180 deg apart, they exclude events in which additional particles are produced. Zichichi told *PHYSICS TODAY* that accurate calibrations must be made

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In Adone storage ring at Frascati electrons and positrons collide, each with 1.1 GeV.

## Low-temperature physics runs both hot and cold

The domain of the low-temperature physicist now extends down as low as microdegrees Kelvin and, on the high side, up to the rather startling temperature of  $10^8$  K. Valid claims to these two extreme regions of temperature were staked out by two papers presented at the recent 12th International Conference on Low Temperature Physics at Kyoto. In the first, P. M. Berglund, G. J. Ehnholm, R. G. Gylling, O. V. Lounasmaa and R. P. Søvik (Helsinki University of Technology) reported the successful operation of a large cryostat that has reached temperatures as low as 500 microdeg K. The system, which combines dilution refrigeration with the relatively new technique of nuclear adiabatic demagnetization, promises to open the way for physicists to study the properties of matter at temperatures an order of magnitude lower than has previously been possible.

A report on low-temperature phenomena at  $10^8$  K was made by David Pines (University of Illinois) who gave a general survey of the states of matter within neutron stars. Although the ambient temperature in such stars is believed to be around  $10^8$  K, because of the tremendously high pressure within these superdense stars the relative temperature is such that matter exists in states that would correspond on earth to temperatures in the milli-

degree region. Thus the free neutrons that make up most of the core of a neutron star are believed to be in a superfluid state.

**Nuclear cooling.** Although the potential of nuclear demagnetization for reaching temperatures much lower than is possible with electronic cooling has been recognized since the 1930's, the technique has become practical only with the advent recently of dilution refrigeration and high-field superconducting magnets. Representing the farthest advance in nuclear cooling to date, the cryostat built and operated by Berglund's group features an enormous dilution refrigerator that serves as the pre-cooling stage for the nuclear stage. This refrigerator, considerably larger than those now operating in the US, is capable of absorbing the heat of magnetization from the nuclear stage at the rate of 10 erg/sec at 15 millideg K. The rate of  $\text{He}^3$  circulation in the refrigerator is 200 micromole/sec.

In the nuclear stage the latest word in superconducting magnets produces an average field of 45 kG over the 12-mole copper specimen. The magnet is 20 cm long with 7-cm inner diameter and is wound with filamentary Nb-Ti wire, which is guaranteed to operate free of flux jumps. The copper specimen is in the form of 0.05-mm wire, which makes thermal contact with a precooling stage through eight sintered

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before firm conclusions can be reached about the hadronic nature of the pion events. So far he was able to show that the observed pion events can not be background tails coming from the following four sources: full-energy muon pairs, full-energy electron-positron pairs, beam-gas interactions and cosmic rays; so the only possible source of simulation is the low-energy electron and muon pairs. At present a special calibration run is being made to clarify this point. Assuming this background source is not causing the observed events, Zichichi says his data give a cross section that is about half of the pointlike cross section for pions.

The vector-dominance model, popularized by J. J. Sakurai (UCLA), predicts a  $1/E^6$  energy dependence and a cross section that is a factor of about ten less than Zichichi and his collaborators observe. In the vector-dominance picture, one thinks of the electron and positron annihilating to give one photon, which changes into a rho (or omega) meson and then produces two or more hadrons.

Even if the vector-dominance considerations are wrong, how can we explain the apparent contradiction with CERN and Brookhaven experiments on proton and antiproton going to electron and positron? Considering the time-reversed situation, these experiments set an upper limit on proton-antiproton pairs being produced at 2.2 GeV in the center of mass that was 1/100th of the pointlike yield. Form-factor measurements have shown that the mean-square radius of the pion is not very different from that of the proton, yet the Frascati data show about half of the pointlike cross section. It will be interesting to hear the results of the Frascati experiment to measure proton-antiproton production whose results are now being analyzed by a group from the University of Naples.

**Multiparticle production.** The various Frascati experimenters find that the cross section for multiparticle production has either a  $1/E^2$  dependence or is a constant. From vector-dominance considerations the cross section was expected to decrease by  $1/E^4$  or even faster. The multiparticle cross section is found to be from  $1/4$  to two times as much as the cross section for muon pair production, Zichichi said. Here again Zichichi emphasized to us that the low-energy calibration must be completed before definite conclusions can be reached. Because the pion has a spin of 0 and the muon a spin of  $1/2$ , the point cross section for pion pairs is predicted to be  $1/4$  of the muon-pair cross section.

One way to explain at least part of the large number of multibody events has been suggested by Stanley Brodsky (SLAC), Toichiro Kinoshita and Hidezumi Terazawa (Cornell),<sup>1</sup> by V. M. Budnev and I. F. Ginzburg (Novosibirsk), and by Paul Kessler and his associates at Collège de France in Paris. They argue that for beam energies higher than 1 GeV the cross section for producing two photons in the intermediate state in processes of the type  $e^+ + e^- \rightarrow e^+ + e^- + 2\gamma \rightarrow e^+ + e^- +$  hadrons becomes increasingly more important than for one photon, varying as a power of  $\log E$  near the beam direction. If these "two-photon collisions" are a strong contributor, it would be useful to know how many multibody events contained a lower-energy electron-positron pair emitted in the beam direction.

When the present Frascati experiments were designed, the strong-interaction cross sections were expected to be small except for peaks at resonances. (In fact, no resonances have shown up as yet.) The apparatus was generally designed to study elastic scattering, muon pair production, pion pair production, two-photon annihilation and for resonance hunting. None of the equipment approaches complete solid-angle coverage or is sensitive to low-energy secondaries. So the existing equipment must be modified to tell what the energy and types of particles are. One possibility is to make a true  $4\pi$  magnetic detector. Another is to put an analyzing system on the beam itself, bending out of the pipe those particles whose energy is significantly lower than the beam energy. Another possibility is to use electron-electron collisions where annihilation is not possible.

If one integrates the two-photon collision cross section over the acceptance angle of the Frascati apparatus, it is unlikely that one can account for more than 20 or 25% of the multibody events, according to Brodsky and Burton Richter (SLAC).

## Three-level oscillator in indium phosphide

A microwave oscillator with three electronic levels instead of two has been built by Cyril Hilsum and his collaborators at the Royal Radar Establishment in Malvern, UK. At the International Conference on the Physics of Semiconductors (at MIT in August) Hilsum said he had made a three-level microwave oscillator that oscillated sinusoidally at frequencies higher than the Gunn effect would produce. He made the oscillator out of indium phosphide after predicting theoretically that the device should work. One solid stater

Some theorists are not at all surprised by the Frascati results, saying they can be understood in the framework of scale invariance. Deep inelastic electron-proton scattering results at SLAC had indicated that protons might not have a diffuse structure, that in the scaling limit (when energies are very large compared to the masses in the problem) pointlike "partons" are observed inside the proton.

A number of theorists had suggested that the electron-positron cross section might have a  $1/E^2$  energy dependence. (A cross section has dimensions of area, and in the scale-invariant limit, the only quantity that can be formed, in suitable units, with this dimension is  $1/E^2$ .)

M. A. Baqi Beg (Rockefeller University), Jeremy Bernstein (Stevens Institute of Technology), David J. Gross (Princeton), Roman Jackiw (MIT) and Alberto Sirlin (New York University)<sup>2</sup> have noted that the  $1/E^2$  dependence, if it is not to conflict with relativistic invariance, rules out certain models of the electromagnetic current. In particular the well known field-algebra model (of T. D. Lee, Steven Weinberg and Bruno Zumino) would appear to be inconsistent with scale invariance and relativity.

**Future storage rings.** The excitement coming from Frascati has raised additional enthusiasm for other electron-positron colliding-beam experiments soon to get under way: the Cambridge Electron Accelerator bypass project (3.5 GeV and 30 times the Frascati luminosity) to operate in 1971, the Stanford SPEAR (2.5 GeV and 300 times the Frascati luminosity) to operate in 1972, the German DESY ring (3.5 GeV and 3000 times the Frascati luminosity) to operate in 1971. —GBL

## References

1. S. J. Brodsky, T. Kinoshita, H. Terazawa, Phys. Rev. Lett. **25**, 972 (1970).
2. M. A. B. Beg, J. Bernstein, D. J. Gross, R. Jackiw, A. Sirlin, Phys. Rev. Lett. **25**, 1231 (1970).

remarking on the work said, "It shows we really understand the solid state well enough that we can almost design materials."

In the ordinary Gunn effect in gallium arsenide a high electric field is applied to a sample of gallium arsenide, causing a domain to travel from one end to the other and then start again. The oscillation frequency is the ratio of the distance between the two contacts and the drift velocity of the domain (constant for a particular material). Typically in a long sample this gives