

Puzzle of two-pion production

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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),¹ 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 4π 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)² 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

you current oscillations that are non-sinusoidal. In gallium arsenide, electrons are transferred within the conduction band from a low valley to an upper valley; the transfer is responsible for the negative differential conductivity.

Two-level oscillators have some inherent problems, Hilsum told us: the effect is not very pronounced because the peak-to-valley ratio is not very high; because the material automatically breaks into domains you can't use all of the negative resistance available.

Hilsum had observed that certain semiconductors would permit electron transfer from a low-energy valley to an intermediate-energy and also a high-energy valley. If the energy differences are suitable the peak-to-valley ratio may

be much higher than in a two-level system; so the oscillation may be more pronounced. Domain formation is also suppressed; so the frequency can be controlled by the circuit itself. Although LSA-(limited space-charge accumulation) mode devices also suppress domains and thereby give you a higher frequency in the same sample, Hilsum remarked that the devices tend to oscillate at the Gunn frequency as soon as anything goes wrong in the circuit. The Malvern group has made an indium phosphide oscillator with 7% efficiency and a wide tuning range.

In the discussion following Hilsum's talk, Esther Conwell (General Telephone and Electronics) commented that the three-level structure itself was not sufficient to suppress domain forma-

tions, that low-field contacts such as Hilsum presumably used were also required.

Hilsum thinks indium arsenide phosphide and some alloys of indium gallium antimonide should also work as three-level devices. Indium phosphide, however, is easier to make, and because it's a good thermal conductor, you can put a lot of power in. Hilsum foresees extensive applications in radar and general microwave instrumentation.

In J. B. Gunn's original paper in 1963, he reported sinusoidal oscillations in indium phosphide but attributed them to another mechanism. The effects were much less pronounced than in gallium arsenide, probably because of the poor quality crystals available at the time.

—GBL

A Mott transition? It all depends on what you mean . . .

One of the most talked-about talks at the International Conference on the Physics of Semiconductors (held in Boston in August) was that given by Maurice Rice of Bell Labs. The discussion period lasted longer than the talk itself. It was part of a year-long controversy over whether or not the metal-insulator transition in V_2O_3 should be regarded as a Mott transition.

Part of the problem is in defining the transition that was first discussed twenty years ago by Sir Nevill Mott (Cavendish Laboratory). The Bell group defines the Mott transition roughly as the path a system of electrons and ions will take as a function of interatomic distance in going from the metallic state for small distances to a highly correlated insulating state for large separations. This path of transition is determined by electron-electron interactions and was originally suggested by Mott to be discontinuous—that is, a first-order transition. Some people now believe, based on experience with doped semiconductors, that the transitions should occur in a continuous fashion, as has been proposed by Walter Kohn (University of California, La Jolla).

The Bell workers say that to observe such a transition one must be able to vary the lattice parameters continuously. This is experimentally impossible, as there will usually be an excluded volume region. However, the Bell Labs experimenters choose to call experimental transitions in which the system transforms from localized to non-localized states "Mott transitions."

Last December Dennis McWhan, Rice and J. P. Remeika reported that they had found a sharp first-order transition in chromium-doped V_2O_3 at room temperature with no apparent change in symmetry from a metal to an insulator.

The transition occurs either as a function of pressure or chromium doping. McWhan explains that by observing this transition they deduce a phase diagram that includes the well known metal - to - antiferromagnetic - insulator transition at lower temperatures in pure V_2O_3 . This phase diagram led the Bell workers to claim that the metal-insulator transition is a Mott transition.

Because there is no change in symmetry across the high-temperature metal-to-insulator transition it can and in fact experimentally does terminate at a solid-solid critical point. At certain pressures and compositions the material goes from antiferromagnetic insulator to paramagnetic metal and then back to paramagnetic insulator as the temperature is raised, Rice says.

In the early work only electrical resistivity and x-ray measurements were reported. Since then Bell workers and others have done optical, nuclear magnetic resonance, susceptibility and Mossbauer measurements on V_2O_3 , which, according to McWhan, support their original findings.

One major objection to the work, raised by John Goodenough (Lincoln Lab), William Paul (Harvard), David Adler (MIT) and others, is that electron-lattice interactions have been largely ignored in the interpretation of the transitions by the Bell workers. There are several oxides of vanadium that have first-order semiconductor-to-metal transitions associated with lattice changes, and none of these represent a Mott transition.

Goodenough, who spoke next at the meeting, pointed out that a significant band crossing is associated with the crystallographic changes across the high-temperature transition; band splittings are associated with the symmetry changes across the low-temperature transition. Although he agrees that

electron-electron Coulomb forces play an important role in these two transitions, he felt that the Bell workers had not adequately defined what they meant by electron localization in the so-called "insulator phases."

Paul emphasizes the need to consider dynamical motion of the lattice, the actual vibrations of the lattice in the transition. Furthermore he argues that the d electrons may produce a large effect by modifying the vibration spectra; so the frequency of the vibrations would be different in the two phases. He feels that the effect should be examined experimentally before final conclusions are drawn.

Adler points out that amorphous films of V_2O_3 fail to exhibit the conductivity jump, which indicates that inhibiting the change in short-range order that is represented by the lattice change suppresses the transition. He feels that this is strong evidence that the transition is driven by the electron-lattice interaction rather than electronic correlations and thus is not a Mott transition. Another objection raised by him is that in the Bell data the "metallic" phase has lower conductivity than the "insulating" phase near the supercritical transition, an unusual result. McWhan feels that such behavior is not unreasonable near the critical region and at the same time points out that at low temperatures the two phases are in fact well characterized.

What does Mott himself say? He thinks that there are many kinds of metal-nonmetal transition, some due to electron-electron interaction and some not. He thinks that V_2O_3 is probably in the former class and is therefore a kind of Mott transition, but that the crystal structure and electron-lattice interaction both play an essential part in making possible the observed behavior.

—GBL □