

tivity problems resulting from neutron activation of the reactor materials. But Fowler cautions that D-D reactors would require much better plasma confinement than would machines employing the D-T cycle.

—BMS

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CESR shows bare-bottomed mesons

In its first year of operation, the Cornell electron-positron storage ring, CESR, has provided strong evidence for the existence of a fifth quark flavor. The three narrow upsilons mesonic states near 10 GeV, first seen at Fermilab in 1977 and 1978, had offered the initial experimental evidence for a hadronic building block heavier than the charmed quark (see *PHYSICS TODAY*, October 1977, page 17 and January 1979, page 17). The Υ , Υ' and Υ'' were generally believed to be bound states of a massive new "bottom" quark, b , and its antiparticle.

But being $b\bar{b}$ bound states, these upsilons mesons would exhibit no *net* bottom flavor—just as positronium, the bound state of e^+e^- , has no net charge. It was felt that the case for the new flavor would not be made until one had actually seen "bare bottom" states—particles containing an unpaired b or $\bar{b}$ quark. (The reader who

objects to this vivid nomenclature may consider the only alternative usage in general circulation—"naked beauty.")

It seems that the production of bottom-flavored (B) mesons has now been observed. In April, two groups at CESR reported^{1,2} the observation of a fourth upsilons state (Υ'''), which appeared to be above the threshold for decaying into B and $\bar{B}$ mesons. In July, at the International High-Energy Physics Conference in Madison, both groups presented the first direct evidence for the production of these bottom-flavored mesons. The properties of the Υ''' and B thus far measured appear to be in good agreement with the expectations of the "standard model," which anticipates that a still heavier "top" quark will eventually make itself known.

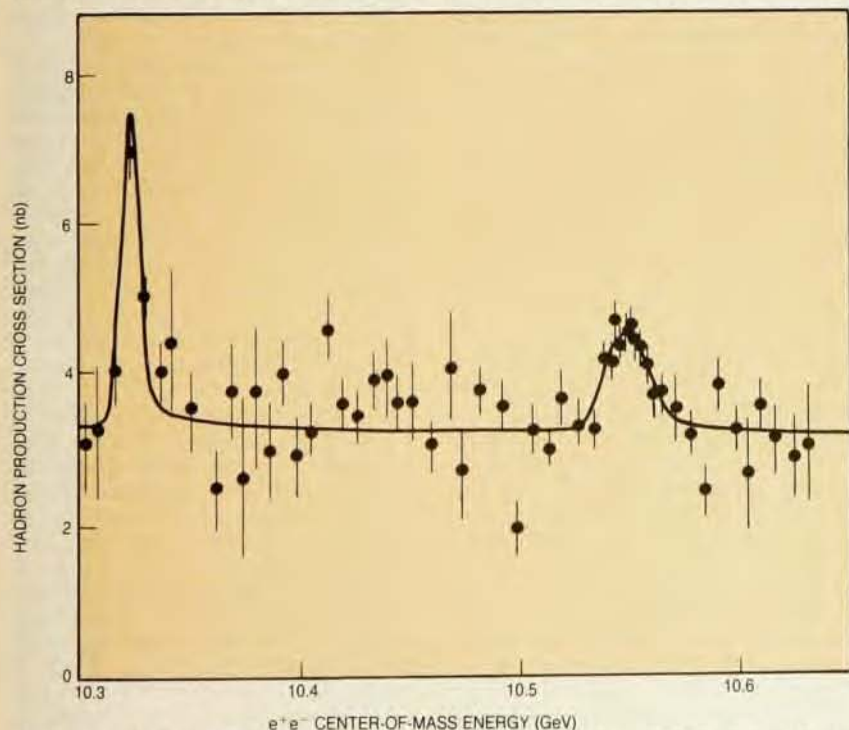
Resonant widths. The three lower-lying upsilons states, with masses near 9.4, 10.0 and 10.3 GeV, had been seen

first as resonant enhancements in the mass spectrum of $\mu^+\mu^-$ pairs produced in hadronic collisions at Fermilab. But these states are more easily studied in e^+e^- colliding-beam storage rings. The Υ'' was not well established until its existence was confirmed at CESR last fall. Experiments at CESR and the lower-energy storage ring, DORIS, at DESY in Hamburg, have found no detectable resonant widths for these three upsilons states, beyond the irreducible energy spread of the colliding beams. This puts an upper limit of about 1 MeV on the intrinsic widths of these resonances, making them at least two orders of magnitude narrower than what one would expect for conventional hadronic states. In fact, a study of the $\mu^+\mu^-$ decay mode of the Υ at DORIS puts its full width at only 60 keV.

The Heisenberg uncertainty principle tells us that the resonant width is inversely proportional to the lifetime of a state. When a state is unusually narrow, something is inhibiting its decay. For the three narrow upsilons states, just as in the case of the narrow J/ψ "charmonium" states (see *PHYSICS TODAY*, January 1975, page 17), that inhibiting mechanism is believed to be the absence of any energetically available decay channels that can be reached without quarks having to change flavor. If these upsilons were heavier than twice the mass of the lightest bottom-flavored meson in Nature, they could decay strongly into $B\bar{B}$ pairs. Flavor-changing processes can occur only in the weak interactions. Therefore, if the lightest B meson is too heavy, the only hadronic mechanism by which any of these upsilons can decay is the mutual annihilation of its b and $\bar{b}$ quarks. But this sort of self-annihilation is empirically known to be strongly suppressed.

Hence the excitement when the fourth upsilons state was found last spring, with an intrinsic width of about 20 MeV. This Υ''' , very broad by the standards of its three predecessors, was discovered at about 10.55 GeV in both of the major detector systems at CESR—the large magnetic detector, CLEO, of the Cornell, Harvard, Rochester, Rutgers, Syracuse, Vanderbilt collaboration and the nonmagnetic, sodium iodide CUSB detector of the Columbia, Stony Brook, Louisiana State, Munich collaboration. The sudden increase in width from one excited $b\bar{b}$ state to the next strongly suggested that the threshold for decay to $B\bar{B}$ lay somewhere between the Υ'' and Υ''' masses—implying a mass between 5.18 and 5.28 GeV for the lightest bottom-flavored meson.

A lowest B mass in this region agrees well with what one deduces from phenomenological models of quark-quark



Upsilon states Υ'' and Υ''' are seen as resonant bumps near 10.3 and 10.55 in the total cross section for hadron production in e^+e^- collisions. Data are from CLEO detector at Cornell CESR storage ring. Similar results were obtained by CUSB detector group, also at CESR. The fact that the Υ''' resonance is significantly wider than the three lighter upsilons states suggests that it lies above threshold for decay into bottom-flavored mesons.

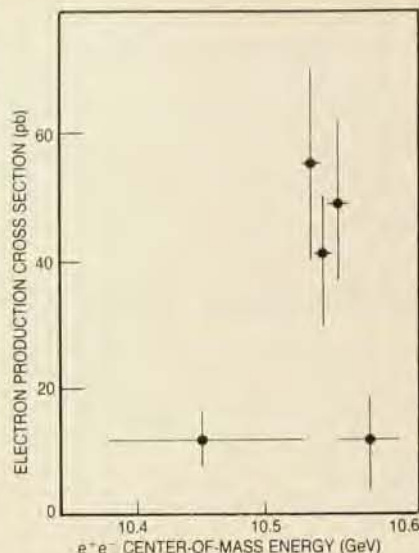
interactions using simple nonrelativistic potentials. Employing a variety of simple potentials that account for the permanent "confinement" of the quarks by growing linearly with separation at large distances, a number of theorists have predicted³ that there would be precisely three triplet S-wave $\bar{b}b$ states below threshold for the production of B mesons. The next radial $\bar{b}b$ excitation (4^3S_1 , presumably the Υ'' just observed), they calculated, would lie just above threshold for decaying into a $\bar{B}B$ pair. The spin and parity of these states is known because their formation in e^+e^- collisions proceeds via a virtual-photon intermediate state.

The reason why nonrelativistic potential models appear to do so well in describing the spectroscopy of $\bar{c}c$ (charmonium) and $\bar{b}b$ ("bottomonium") states, while no such simple phenomenology works for ordinary mesons involving the old-fashioned up, down and strange quarks, is that the new quarks are enormously massive compared to their binding energies. While the up and down quarks that constitute protons and pions are thought to have masses of less than 10 MeV, the charmed and bottom quarks presumably have masses near 1.5 and 5 GeV, respectively.

Direct evidence. The width of the Υ'' resonant peak was still only indirect evidence for its decay into bottom-flavored mesons. After its discovery, both groups at CESR began at once to look for more direct traces of the presence of B and $\bar{B}$ mesons in e^+e^- collisions at center-of-mass energies near the resonant peak (10.55 GeV). For the moment, CESR has something of a monopoly in this energy range. DORIS can't get above the Υ' energy, and the higher-energy e^+e^- colliders, PETRA (at DESY) and PEP (at Stanford), have reduced luminosities at so low an energy.

The high mass of the B meson (more than five times the proton mass) makes it difficult to detect in conventional ways. The high mass speeds up the decay by increasing the available phase space, preventing the B from travelling a macroscopic distance intact, and hence being seen as a track. Once it does decay, its high mass raises the multiplicity of decay products to a level (typically about ten) where one cannot in practice deduce the mass of the decaying object by measuring all its fragments. The best handle one has, Karl Berkelman (Cornell) of the CLEO group told us, is the presence of high-energy leptons (electrons and muons).

Leptons are found among the direct decay products of a hadron only when it is forced to decay by weak interactions—when faster decay mechanisms are forbidden. That an object as heavy



Yield of electrons with greater than 1 GeV energy rises dramatically at Υ'' resonance. High-energy electrons are presumed to come from decay of bottom-flavored mesons. Data are from the CLEO detector.

as a B meson should have to resort to weak decay would clearly herald the advent of a new flavor, Berkelman pointed out. Being the lightest object to bear that flavor, it could only decay by a flavor-changing (weak) mechanism.

Both groups therefore set out to look for electrons with more than 1 GeV of energy in e^+e^- collision events near 10.55 GeV producing at least three charged hadrons. Such energetic electrons are expected to be common in the decay of the heavy B. The electrons (and muons) coming from the decay of the lighter hadrons (for example charmed mesons) produced in profusion in the e^+e^- collisions are predominantly less energetic than 1 GeV.

Detectors. The heart of the CLEO detector is a large magnetic solenoid of 2-meter diameter, containing a drift chamber and proportional wire chambers for the measurement of charged tracks. The momentum of electrons and other charged particles is measured by their curvature in the magnetic field. Outside the solenoid are Cerenkov and shower counters that permit one to distinguish K mesons from π mesons and protons. A two-foot-thick steel absorber surrounding the system passes energetic muons while absorbing hadrons. The μ 's are then identified by detectors outside the absorber.

The nonmagnetic CUSB detector, on the other side of CESR, had been built by the Columbia and Stony Brook groups primarily for the accurate detection of monochromatic photons from the decay of Υ states to $\bar{b}b$ bound states not directly produced in e^+e^-

collisions. It relies therefore on an extensive array of sodium-iodide crystals, which have extremely good energy resolution for photons and electrons. Good spatial resolution is provided by a central drift chamber and wire chambers interspersed between layers of sodium iodide. Hadrons are efficiently detected in this system, but in the absence of a magnetic field their momenta are not well known.

Looking for electrons with energy above 1 GeV, both groups found a sudden and dramatic increase in the yield of high-energy electrons as the e^+e^- beam energies were tuned through the Υ'' resonant region. The roughly fourfold increase in the electron signal as one passes from the continuum into the resonant region is more striking than the 50% increase in the hadronic cross section that uncovered the Υ'' in the first place. The observed electron rates translate into a semileptonic branching ratio for the B meson in good agreement with the 34% expected by the theorists.

One expects the number of high-energy muons produced in B decays to equal the number of electrons. Looking at particles that passed through its hadron absorber, the CLEO group found a similar striking increase in its muon signal as the beam energy was swept through the Υ'' region. The μ rate thus far observed is only half the electron rate, but within errors the rates are compatible. The CUSB group plans to install a muon detector in the near future.

In 1973, even before the discovery of charm, M. Kobayashi and T. Maskawa in Japan had pointed out that a world with precisely six quark flavors offers a natural explanation for the puzzling CP-violating behavior of the neutral K mesons. They generalized to the six-quark case the "Cabibbo angle" that describes the preference of charmed mesons for decay to strange mesons. Applying the charm data to their formalism leads one to expect that the B meson will decay predominantly to charmed mesons.

The CLEO group therefore used its time-of-flight counters to look for an enhanced K-meson signal in the Υ'' region. If the prediction from the Kobayashi-Maskawa formalism was correct, the B mesons would decay predominantly to charmed D mesons, whose subsequent decays would produce the enhanced kaon signal. They found that the charged kaon signal did in fact rise to about three times its background level at the Υ'' peak. This observed rate suggests that the B decays almost invariably to charmed mesons, as expected.

The width of the Υ'' grows rapidly with distance above the $\bar{B}B$ threshold in all the theoretical models in circulation,

but calculations differ substantially on the precise threshold mass implied by the 20-MeV Υ^* width. Paolo Franzini (Columbia) believes his group has good evidence that the Υ^* is less than 100 MeV above threshold. One knows from the spectrum of the charmed mesons that the first excited bottom mesonic state (B^*) should be about 50 MeV heavier than the B . If the Υ^* were more than 100 MeV above $\bar{B}B$ threshold, it could decay into $B^*\bar{B}^*$. Franzini is confident that if this were the case, the CUSB detector would be seeing at least one of the two 50-MeV photons from the subsequent decay of the two excited B^* mesons to the ground-state B 's.

Because the semileptonic decays, which provide the best B signature, always involve an undetectable neutrino, there is little hope, Berkelman told us, of seeing the B meson in the near future as a classic bump on an invariant-mass plot of its decay products. But the signals found in the electron, muon and kaon rates all rise strikingly above the nonresonant background, and all agree well with the standard theory that sees the b quark as the lighter member of a top-bottom pair. No trace of the top quark has yet been seen.

—BMS

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of these beams make it possible to focus them down to submicron spots at the semiconductor or insulating surface to be processed. The longer infrared CO_2 -laser wavelengths (9 to 11 microns), though particularly efficient for heating such substrates, are limited by diffraction to focused spots no smaller than about 20 microns.

The Lincoln Lab group focused the frequency-doubled output (257.2 nm) of a 514.5-nm argon-ion laser at semiconducting and insulating surfaces in contact with a few torr of a metal-alkyl gas such as $\text{Cd}(\text{CH}_3)_2$ or $\text{Al}(\text{CH}_3)_3$ in a buffering atmosphere of helium. When the laser was operated in a continuous mode at modest power levels, photodissociation and deposition of metal films took place essentially at room temperature. The group found that they could localize these metal deposits down to about a micron—the limit imposed by the optics in their experiment.¹ By moving the substrate across the laser focus they were able to "write" metal lines one micrometer in width, with deposition rates as fast as 1000 Å (thickness) per second. With better optics, they expect ultimately to be able to do submicron deposition.

It was not initially clear why the resolution of the deposits laid down by this gas-phase photolysis should be so good. It turns out that not all the metal comes from the photolysis of molecules in the gas phase. Some organometallic molecules are initially adsorbed on the substrate surface. The group concludes that the photolytic breakup of these adsorbed molecules at the laser beam focus provide a nucleation or seeding site for the further deposition of metal atoms freed in the surrounding gas. The metal atoms have much higher "sticking coefficients" on this initial metal deposition than on the surrounding substrate material. Thus the deposition pattern appears to be sharpened by this "prenucleation" effect.

Doping and etching on a micron scale have also been demonstrated with the Lincoln Lab laser photochemical technique. Microelectronic etching ordinarily involves the exposure of photoresist films through a lithographic mask. To achieve their "maskless" etching,² the group used methyl-halide gases in place of the metal alkyls. When exposed to a frequency-doubled argon-laser beam focused at various semiconducting surfaces, the gas molecules break up, providing the free halogen atoms that etch the surface. With GaAs and InP substrates, the group has achieved laser-induced etching with a spatial resolution of about a micron.

Laser-induced doping as done by the Lincoln Lab group is a hybrid technique, involving laser heating as well as pure photolysis. The group doped

Laser chemistry for microstructures

The rapidly increasing complexity of microelectronic circuits is confronting the designers and manufacturers of integrated circuitry with new technological difficulties. By the end of the decade it may well be possible to pack a million logic gates onto a single chip. But the yield of defect-free chips falls rapidly with increasing number of components. With current lithographic techniques, the production of custom circuits in small numbers is often uneconomical, and it is widely felt that the semiconductor industry is not meeting the need for such circuits. Furthermore, these lithographic procedures cannot produce large-area integrated circuits bigger than a few square inches, and their slow turnaround time hinders the design testing necessitated by increasing miniaturization.

But laser-induced microchemistry may be coming to the rescue. A group at the MIT Lincoln Laboratory has recently demonstrated the ability of ultraviolet lasers to deposit metallic films and introduce dopants into semiconductor substrates with a spatial resolution of about a micron. At the same time, a Xerox-USC collaboration is using infrared CO_2 lasers to deposit metal structures about 50 microns wide by laser-induced chemical vapor deposition. Both groups believe that these "direct-writing" techniques, by circum-

venting the usual arduous photolithographic procedures, hold great promise for dealing with the present difficulties and future needs of microelectronic design and fabrication.

The work at Lincoln Lab being done by Daniel Ehrlich, Thomas Deutsch, and Richard Osgood differs from other laser-induced materials-processing techniques, Deutsch told us, which depend essentially on thermal effects. Conventional laser annealing and laser-assisted chemical vapor deposition induce solid-state and chemical processes by heating substrates or by thermal (multiphoton) excitation of vibrational modes in gas molecules. In the Lincoln Lab technique, by contrast, the valence bonds of organometallic gas molecules are photochemically broken by single ultraviolet photons. This direct "photolytic" action of the uv laser beam dissociates the molecules into their metallic and organic constituents.

Ultraviolet beams at wavelengths below about 250 nm have two attributes that suit them particularly well for high-resolution photolytic deposition of metals. First of all, photons in that part of the spectrum have just the right energy to break up organometallic molecules such as metal alkyls, providing free metal atoms for deposition of metallic films or doping of substrates. Secondly, the coherence and short wavelength