

search Laboratories (Redhill).⁵

In the Max Planck-Chernogolovka-CNRS experiment the new luminescence line occurs at ν values smaller than $1/5$ as well as at ν values a little larger than $1/5$. The intensity of the new peak is presumed to be zero at $\nu = 1/5$, but it grows, and that of the peak due to the incompressible state at $\nu = 1/5$ diminishes, as ν changes away from $1/5$. For a given ν value at which the new peak occurs at some low temperature, the peak's intensity decreases to zero at a critical temperature when the sample is warmed. Finally, the wavelength at the peak intensity of this line is longer than that of the line due to the incompressible liquid state at $\nu = 1/5$, which implies that the new peak arises from electrons whose energies are lower than those in the incompressible quantum liquid state. These features of the new luminescence line suggest that electrons in magnetic fields close but not equal to the value for $\nu = 1/5$ form a new ground state that is different both from the incompressible state at $\nu = 1/5$ and from the conventional electron gas in a magnetic field, and that this state has a lower energy than either of those states. The experimenters identify the new state with the Wigner crystal.

The second, Oxford-Philips group finds that the appearance of a new feature in their luminescence studies correlates with the onset of out-of-phase conduction—that is, it first occurs at the same temperature and ν values as that onset. Current in a normal electron system is in phase with the applied voltage, and out-of-phase conduction has not been reported in the quantum Hall effect. The group therefore regards the data as indicative of a new phase of the electron system. Once again, by elimination, the new phase is identified with the Wigner crystal.

Why now?

If the Wigner crystal has at last been observed, one might ask, why did it

take so long? After all, the incompressible quantum liquid state at $\nu = 1/3$ was reported in 1983. An important factor in the success of the recent experiments, Stormer told us, is the sample quality. One measure of the "goodness" of a sample is the electron mobility. For example, the 1983 samples in which the fractional quantum Hall effect was discovered had electron mobilities of $80\text{--}100 \times 10^3 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$. Electron mobilities in samples used in the recent experiments were 50–100 times higher. Since inhomogeneities and imperfections in the samples scatter electrons and increase the resistivity, the higher the electron mobility is, the easier it is to unravel new features—in, for example, the resistivity data—that arise from electron-electron interactions.

Hints of an insulating phase around $\nu = 1/5$ began to appear in measurements of the temperature dependence of the resistivity about two years ago.⁶ According to Tsui, "In spite of the evidence for thermally activated conduction indicative of an insulating phase, it has been extremely difficult to tell if the insulating state is indeed due to the pinning of a solid." A group of experimenters claim, however, that their 1988 experiment gave indirect evidence for the Wigner crystal. Eva Andre (Rutgers University), Gérard Deville, Christian Glatthli, Francis (Tito) Williams (all at Saclay), Etienne Paris and Bernard Etienne (CNRS, Bagneux) measured rf absorption by a two-dimensional electron gas in a strong magnetic field.⁷ They observed strong resonance absorption at some frequencies which they identified with those of the normal modes of the electron solid.

Most experimenters challenge that interpretation even today. However, Robert Clark (now at the University of New South Wales, Sydney) told us that recent experiments show a strong correlation between the onset of threshold behavior in the current-voltage characteristics and the onset

of resonance absorption.⁸ He thinks that both effects can be understood if one assumes that the electron solid is not perfect but is broken into domains by the disorder in the substrate. As true long-range translational order cannot exist at nonzero temperatures in two dimensions, experimenters and theorists are busy trying to understand the new phase—already sometimes referred to as the Wigner glass, in analogy with other phases whose solid-like properties arise from imperfections and disorder. Hopefully any new understanding of the phase will also resolve the two-year-old controversy regarding the significance of the resonance absorption experiment.

—ANIL KHURANA

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CONSTRUCTION PROPOSALS TAKE AIM AT TOP AND BOTTOM QUARKS

Cornell and Stanford are competing to build a B-meson "factory," and Fermilab wants to build a new injector ring for its Tevatron Collider. These are the two principal new construction initiatives proposed by the US high-energy-physics community for completion by the middle of this decade. They are intended to address the two

remaining "dangling particples" of the spectacularly successful standard model of the elementary particles: Understanding the violation of *CP* symmetry would seem to require a new source of B mesons much more profuse than the existing electron-positron rings; and determining the properties of the (still missing) top

quark in adequate detail appears to necessitate an order of magnitude increase in the luminosity of the Tevatron proton-antiproton collider.

The assault on the unfinished business of the standard model has been enlivened in recent months by new experimental results. High-statistics studies of the intermediate vector

bosons at CERN^{1,2} and Fermilab³ have narrowed the mass range in which one expects to find the top quark; and a K-decay experiment⁴ at Fermilab has revived the possibility that *CP* violation might be a phenomenon outside the standard model's purview.

The Sciulli report

The price tags of the three new proposals range from about \$100 million to \$180 million, very small potatoes when compared with the Superconducting Super Collider, but formidable nonetheless at a time of falling budgets. A year ago DOE asked its High Energy Physics Advisory Panel to convene a subpanel to consider how best to maintain the soundness and continuity of the nation's particle-physics research program during the decade before the SSC produces its first results, some time around the turn of the millenium. The recommendations of the HEPAP subpanel, headed by Frank Sciulli (Columbia), were published by DOE in April.

The Sciulli subpanel's report "strongly endorse[d] the physics aims of a B factory," but it gave its highest priority to "the immediate commencement and speedy completion of construction of the [new] Tevatron Main Injector." The subpanel considered several budget scenarios for DOE funding of high-energy physics (other than the SSC) during the 1990s. Assuming a "constant [inflation adjusted] budget scenario" over the decade, with some year-to-year flexibility, "the subpanel will recommend only one major construction project, the Fermilab [Tevatron] Main Injector. . . . It is impossible to reconcile a constant budget scenario with two large construction projects." The B-factory scheme, the subpanel noted, was the more daring extrapolation from proven accelerator technology. But if the high-energy-physics budget were to rise throughout the decade by even 1% per year, the subpanel concluded that "the B factory should [also] be built, assuming [the existence of] a successful accelerator design."

Next month, both Cornell and the Stanford Linear Accelerator Center will be submitting B-factory proposals. Does that mean there's now good reason to believe in the Sciulli subpanel's "rising budget scenario"? Quite the contrary. The recently enacted FY1991 federal budget gives DOE \$33 million less for high-energy physics (other than the SSC) than the President's \$621 million request, on which the Sciulli subpanel had based its deliberations. (See the budget story on page 22.) "So all bets are off," says

SLAC director Burton Richter, citing a sentence at the end of the Sciulli subpanel's recommendations: "If significant budget reductions occur, then we urge that another subpanel be convened to advise the DOE on specific actions to be taken."

Karl Berkelman, director of Cornell's Newman Laboratory, is side-stepping the subpanel's assignment of priorities with a different rationale. "We're submitting our B-factory proposal to NSF, our traditional funding agency," he told us. "The Sciulli recommendations concern themselves primarily with DOE funding."

CP violation

Why all this fuss about making B mesons in profusion? The B^+ , B^0 and their antiparticles, with masses around 5.28 GeV, are the lightest mesons containing the bottom-flavored b quark. The b quark, with electric charge $-\frac{1}{3}e$, is the fifth of the six quarks confidently presumed by the standard model. (We will come to the search for the sixth quark, "the top," when we discuss the new Tevatron injector). The B mesons are the bottom-flavored analogs of the strangeness-flavored K mesons, although they are more than 10 times heavier than the latter. The B^+ , for example, is a bound state of the antiquark $\bar{b}$ and the much lighter up quark (charge $+\frac{2}{3}e$).

We have known since 1964 that K-meson decay is not quite invariant under the symmetry transformation *CP*, the combined operations of parity inversion and charge conjugation. But to this day, *CP* violation has been seen in no other physical system, and it is still unclear whether this profound asymmetry fits into the standard model. Two years ago a very delicate experiment at the CERN Super Proton Synchrotron appeared to clinch the argument that *CP* violation in K decay is a subtle effect of the weak interactions within the standard model, rather than a manifestation of some new "superweak" force. (See *PHYSICS TODAY*, October 1988, page 17). But recently the issue has been reopened by preliminary results from a similar experiment at Fermilab, led by Bruce Winstein (University of Chicago), which seems to contradict the CERN finding.⁴

In any case, K-decay experiments offer only a very limited window on *CP* violation. To test the predictions of the standard model in satisfactory detail, it is essential to see *CP* violation in some system other than K decay. The B mesons promise the first such opportunity. In fact, the theory predicts that *CP* violation

should manifest itself more strongly among the B's than among the kaons.

The *sine qua non* of *CP* violation in K decay is the exotic quantum-mechanical mixing between K^0 and its antiparticle $\bar{K}^0$, two states that differ only in strangeness, a hadronic quantum number not respected by the weak interactions. The particle-antiparticle system B^0 , $\bar{B}^0$ presents an analogous opportunity. B mesons were first seen at CESR, the Cornell electron-positron collider, in 1983. Four years later an experiment at the DORIS e^-e^+ collider in Hamburg demonstrated dramatically that the magnitude of B^0 - $\bar{B}^0$ mixing exceeded the fondest hopes of the theorists. (See the illustration on page 22 and *PHYSICS TODAY*, August 1987, page 17). The standard model relates the magnitude of B mixing to the mass of the top quark. The surprising DORIS result (and a similar finding at the CERN SPS) was an early indication that the top quark would turn out to be much heavier than most people thought.

Ever since then it has been clear that one could study *CP* violation in B-meson decay, if one could build an e^-e^+ collider with the same center-of-mass energy as CESR (roughly 11 GeV), but with two orders of magnitude greater luminosity. The call for B factories had begun.

The violation of *CP* invariance in elementary-particle processes is more than just an untidy corner of the standard model. For some theorists it has an almost metaphysical significance. "It's why we're here," says Rockefeller University theorist Anthony Sanda, alluding to the role *CP* violation presumably played in producing the cosmic preponderance of matter over antimatter, a role first pointed out by Andrei Sakharov in the 1960s. Sanda is one of the leading advocates of B factories.

B factories

Making B mesons in an environment uncluttered by hadronic debris is quite straightforward. One simply collides electrons against positrons with a center-of-mass energy of 10.58 GeV, the mass of the Υ''' meson. All the Υ mesons are $b\bar{b}$ bound states, but the Υ''' is the first excited state heavy enough to decay into a $B\bar{B}$ meson pair. When the e^- and e^+ beam energies in the collider are tuned precisely to the Υ''' resonance, fully $\frac{1}{4}$ of all collisions results in $B\bar{B}$ pairs. But the existing e^-e^+ colliders in this energy range—CESR, DORIS and PEP at SLAC—simply can't produce B mesons at rates adequate for the study of the elusive *CP*-violating decays.

One might, for example, look for *CP*

violation in the particularly interesting decay mode B^0 or $B^0 \rightarrow J/\psi + K_s$, where K_s is the short-lived version of the neutral kaon and J/ψ is the celebrated (but still not properly christened) bound state of the charmed quark and its antiquark that started the whole heavy-quark business in 1974. The standard model predicts a CP -violating difference of at least 10% between the decay rates of the B^0 and the $\bar{B}^0$ into this final state. But only a few B^0 's in ten thousand decay by this much-desired mode. The existing e^-e^+ storage rings could not produce adequate statistical samples.

The appropriate figure of merit for the performance of a collider is its luminosity, the collision rate per unit scattering cross section. Elaborate studies of what is required to test the standard-model predictions of CP -violation in B decays conclude that one needs a collider with 100 times the luminosity of CESR, the most suitable of the existing machines, if one sticks to the conventional, symmetrical design of countercirculating beams of equal energy (5.29 GeV).

But there is an alternative, *asymmetrical* scheme that could make do with only a thirtyfold increase in luminosity over present machines. Both Cornell and SLAC are proposing to build such machines, with a 9-GeV (approximately) electron beam countercirculating against a 3-GeV positron beam. (The center-of-mass energy is given, to good approximation, by twice the geometric mean of the two beam energies.) The experimental advantage of such an asymmetrical arrangement is that the B meson decays would be spatially separated from their point of origin, making them easier to identify. The mass difference between the Υ''' and the pair of B mesons into which it decays is so small that the B s are produced almost at rest in the laboratory, if the beam momenta are equal and opposite. With the proposed asymmetrical arrangement, the motion of the center of mass in the laboratory gives the two B mesons about 10^{-12} seconds (their lifetime) to get away from the collision point before they decay.

The problem is that no one has ever built such a high-luminosity, asymmetrical e^+e^- collider. The Sciulli report pointed out that there were accelerator problems still to be resolved, and that a detailed design did not yet exist. The Cornell proposal incorporates higher-luminosity symmetrical operation as a fallback if it should prove impossible to achieve adequate colliding-beam density in asymmetrical running. Both Cornell

and SLAC propose to build the B factory in the pre-existing collider tunnel, and to reuse much of the old magnet and vacuum hardware.

Electron-positron colliders produce $B\bar{B}$ pairs in relatively clean, uncomplicated states that make detection and analysis comparatively easy. Their principal problem is achieving adequate luminosity. For high-energy proton-antiproton colliders the situation is just the reverse. The Tevatron can produce far more $B\bar{B}$ pairs, especially with the proposed new injector, than any B factory. Its main problem is the intense shower of pions and other hadronic debris produced in every collision. The challenge here is to the detectors. Nonetheless, both detector groups at the Tevatron collider express confidence that they will be able to do good $B\bar{B}$ physics. The CDF group (Collider Detector at Fermilab) has already harvested several dozen fully reconstructed $B \rightarrow J/\psi + K$ events—a world record.

The top quark

The standard model having been so successful over the whole range of particle physics thus far explored, it seems inconceivable that there should be no top quark. And yet it has still not been found. The six quarks of the standard model come in three pairs. The top quark, t , is the charge $+\frac{2}{3}e$ partner of the b . It was expected to be considerably heavier than the 5-GeV bottom quark. But we now know that its mass cannot be less than 89 GeV, the lower limit established by top searches with the CDF. That's much heavier than most people were guessing when the search began.

There has however been a heartening convergence in recent months of various indirect determinations of the top mass from other data related to the top quark by the standard model. At the XXVth International Conference on High Energy Physics in Singapore last summer, two groups from the high-energy LEP e^+e^- collider at CERN reported their detailed analyses^{2,3} of the shape of the 91-GeV Z^0 resonance, based on the decay of more than a hundred thousand Z^0 s. The width of the resonant peak depends on radiative corrections that involve the exchange of virtual top quarks.

The Z^0 is the neutral member of the triplet of heavy vector bosons that mediate the weak interaction. LEP, which has harvested almost a million Z^0 s since it began operating in the summer of 1989, is aptly called a Z^0 factory. Its American rival, the Stanford Linear Collider, is still two orders of magnitude short of its design luminosity.

Combining the results of the OPAL and ALEPH detector groups at CERN, one gets a top-quark mass of $137 \pm 35 \pm 20$ GeV, where the second quoted error is a theoretical uncertainty due largely to our ignorance of the mass of the Higgs boson, another ingredient of the standard model that still awaits discovery.

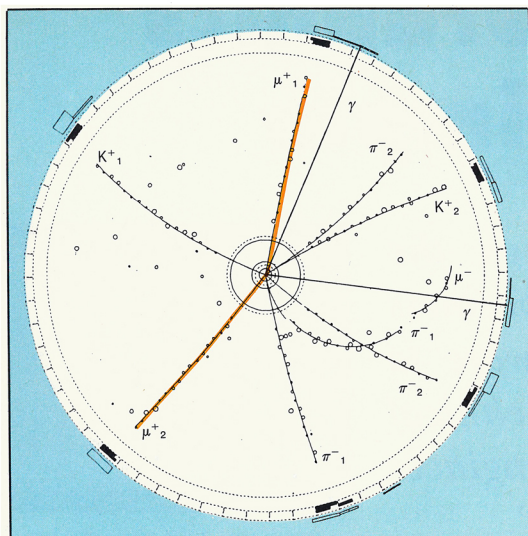
The W^+ and W^- vector bosons are the charged siblings of the Z^0 . A new measurement of the W mass (79.9 ± 0.4 GeV), reported in October by the CDF group,³ yields a one-standard-deviation upper limit of 175 GeV for the top quark mass, M_t . The 95% confidence-level upper limit is 220 GeV. The best estimate of M_t from measurements of the W mass is about 130 GeV. This estimate is somewhat less dependent on the unknown Higgs mass than are the deductions from the Z^0 data.

The oldest of the indirect measurements of M_t come from deep inelastic neutrino scattering data. These data yield an M_t estimate in the neighborhood of 120 GeV. At Singapore, rapporteur Friedrich Dyak (CERN) put all the indirect data together to arrive at a joint estimate of 130 ± 40 GeV for the mass of the top quark. All of this, of course, assumes the validity of the standard model.

Until we have the SSC, or something like it, the Fermilab Tevatron Collider, with its countercirculating beams of 900-GeV protons and antiprotons, is the world's only machine still able to search for the top quark. If it were just a question of energy, the Tevatron could find a top quark as heavy as 900 GeV. (Remember that top quarks must be made in $t\bar{t}$ pairs.) But in fact the Tevatron, with its present injector system, could not find a top quark heavier than about 150 GeV by the end of 1992, even with the advent of its new D0 detector facility. (Pronounced "d zero." See the cover of this issue.) Projecting to the end of the decade on the assumption that the minor upgrade program now under way is completed, it appears that 175 GeV is just about the upper mass limit for a top quark that could be found by the year 2000, *unless* one builds the new Main Injector called for by the Sciulli subpanel.

The new Tevatron injector

The essential problem is that the cross section for the production of $t\bar{t}$ pairs in $p\bar{p}$ collisions, as predicted by the standard model, falls like M_t^{-4} . For a 90-GeV top quark, the production cross section would be about 100 picobarns. But that already tiny cross section falls to 10 pb if M_t is 150 GeV. The smaller the cross section,



B meson mixing is illustrated by this Υ''' decay into two neutral B's at the DORIS collider's ARGUS detector. The Υ''' , produced at rest in the center, must decay into a $B^0\bar{B}^0$ pair. When a subsequent B decay yields a μ lepton, the charge of the μ tells whether the decaying B was a B^0 or a $\bar{B}^0$. But this event has two μ^+ tracks (red), indicating that neither B decayed as a $\bar{B}^0$. The $\bar{B}^0$ must have changed into a B^0 .

the greater is the collider luminosity required to find a convincing signal.

The chief bottleneck constricting the luminosity of the Tevatron Collider in its present configuration is the old Main Ring, which now serves as the final injector of 150-GeV protons and antiprotons into the 900-GeV collider ring. The Main Ring is the original 500-GeV proton synchrotron, 6 kilometers in circumference, that did all the work at Fermilab before the superconducting Tevatron ring and eventually the full-blown collider were built underneath it. Though it has done honorable service in its old age as an injector, the Main Ring was not designed to do that job particularly well. Nowadays it must execute awkward excursions over the collider's two detector areas. And besides, the state of the art has advanced considerably since the Main Ring took on its new role in 1983. Without a new injector, the present upgrade program cannot raise the collider's luminosity above $1 \text{ or } 2 \times 10^{31} \text{ sec}^{-1} \text{ cm}^{-2}$, which translates to only 100 or 200 events per picobarn in each detector before the end of the decade.

The plan at Fermilab, if the requisite \$160 million are made available, is to replace the Main Ring by an entirely new "Main Injector," only half the circumference of its predecessor. Unlike the old Main Ring, which lies directly on top of the Tevatron, the new injector would sit outside the collider, touching it only at the injection point. The new injector would raise the collider's luminosity by an additional factor of 5 or 6 beyond what the other upgrades can do.

This higher luminosity should be enough to see a top quark as heavy as

250 GeV by the year 2000. That's just about the extreme upper limit of M_t compatible with the vector-boson and neutrino-scattering data in the context of the standard model. Thus, if the new Main Injector is built, the Tevatron collider will have produced an extremely interesting result by the end of the decade, whether or not the top quark is found: Finding it would, of course, be a great triumph for the standard model. But *not* finding a top quark lighter than 250 GeV would point to a serious pathology in the theory. The latter is perhaps the more interesting alternative.

But what if M_t turns out to be only 150 GeV? Would not the expense of the new Main Injector then have been wasted? Not at all, its proponents argue. Without the Main Injector, the detectors would only find about 100 of such top quark pairs before the end of the decade, enough to establish their existence but not much else. One couldn't even make a direct mass measurement. One would have to infer M_t from the production rate, using the relation between mass and cross section provided by the very theory one is trying to test.

The top-quark mass is an important parameter of the standard model. A good direct measurement of M_t would provide a crucial test of the theory's consistency. Without the Main Injector, the Tevatron collider probably would not provide enough top decays of the right sort to yield a mass measurement of adequate precision.

How will they look?

The traditional wisdom is that quarks never show themselves naked. Thus far we have only seen them bound

inside mesons and baryons. But a quark as heavy as the top appears to be would have no time to dress itself in hadronic garb before it decays. Its lifetime, which falls quickly with increasing M_t , would be less than 10^{-22} seconds, not enough time for a quark to "hadronize." Therefore the experimenter can speak of the decay of the top quark without reference to any top-flavored mesons.

Now that the vain searches have shown that M_t must be greater than the sum of the W and b masses, it is assumed that a $t\bar{t}$ pair will decay only by

$$t \rightarrow b + W^+ \quad \text{and} \quad \bar{t} \rightarrow \bar{b} + W^-$$

One could say that, as M_t has grown, the expected production cross section has unhappily shrunk but the expected signal has happily become much simpler. Each W subsequently decays into a charged lepton of the same sign plus a neutrino or into a quark-antiquark pair. The former decay mode is particularly well suited for signaling the production of top quarks. The cleanest signature of a $t\bar{t}$ pair, freest from background mimicry, would be the observation of an $e^-\mu^+$ or $e^+\mu^-$ pair of sufficiently high energy. But such events are useless for reconstructing the mass of the decaying top quarks because they involve two invisible neutrinos. To that end one wants one of the two W's to decay into a quark-antiquark pair, which then evolves into measurable jets of hadrons. The new \$60-million D0 detector, which will join the veteran CDF in time for next fall's Tevatron collider run, is explicitly designed to optimize the identification and measurement of charged leptons and hadron jets.

If the top quark turns out to be much heavier than the vector bosons, an intriguing possibility arises. It might then be that the mass-generating and electroweak-symmetry-breaking role assigned by the standard model to the elusive Higgs boson is actually played by some very tightly bound $t\bar{t}$ state. This would require some binding force stronger than the conventional hadronic force. But if such a state existed, it would obviate the need for a fundamental Higgs particle in the standard model.

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