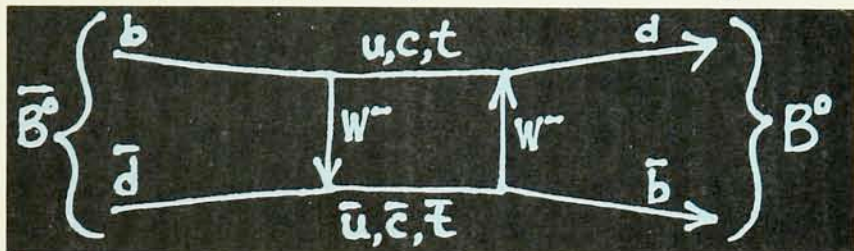


Neutral B mesons show surprisingly large flavor mixing

In its heyday in the 1950s and 60s, the K meson was a spectacular source of profound surprises. Its "strange" longevity gave us the first hint of flavor conservation in the strong interactions, and eventually the concept of quarks as the carriers of these hadronic flavors. Its decay into states of opposite parity freed us from rigid adherence to mirror symmetry. Then the neutral kaon was seen to oscillate wondrously between states of opposite strangeness, and finally, in 1964, one of its decay modes yielded up the last great surprise. It provided us the only example we have to this day of *CP* violation. We had known since 1957 that *P* (parity inversion) was not an inviolate symmetry of nature. Now the last hope for mirror symmetry—invariance under the combined operation of *P* and *C* (charge conjugation)—was also dashed.

The neutral kaon could show us things to be seen nowhere else—flavor mixing and *CP* violation—because it was, in its day, unique among the known elementary particles. The K^0 differs from the $\bar{K}^0$, its antiparticle, only by virtue of its hadronic flavor, a quantum number not respected by the weak interactions; they are states of opposite strangeness. Thus the two neutral kaons are coupled by their ability to decay weakly to the same states, for example $\pi^+\pi^-$. Such couplings give rise to "flavor mixing." The two neutral-kaon states of definite mass are superpositions of the two states of opposite strangeness, with slightly different masses and very different lifetimes. This flavor mixing was the *sine qua non* for the observation of *CP* violation in the decay of the longer-lived neutral kaon.

The neutral kaon is no longer unique. In 1977 Leon Lederman and coworkers at Fermilab found the first indication of the bottom-flavored quark, the "third-generation" analog of the strange quark, and in 1983 the Cleo collaboration at CESR, the Cornell



Second-order weak process couples B^0 to its antiparticle, thus permitting a mixing metamorphosis. A $\bar{B}^0$, consisting of a bottom quark (charge $-\frac{1}{3}$) and an antidown quark, becomes a B^0 by the exchange of two charged weak vector bosons W^- . In the intermediate state, all 3 generations of charge $+\frac{2}{3}$ quarks (up, charmed, top) can contribute, together with their antiquarks. The top quark, being the heaviest, dominates the amplitude.

electron-positron storage ring, announced the first direct observation of the B^0 meson, the bottom-flavored analog of the K^0 , with a mass of about 5 GeV—more than ten times that of the K (PHYSICS TODAY, April 1983, page 20.)

Now we have the first clear evidence of flavor mixing between the B^0 and its antiparticle, the $\bar{B}^0$. In February, the ARGUS collaboration reported¹ that their data from the DORIS electron-positron storage ring at DESY in Hamburg indicate a mixing parameter of about 20%, much bigger than the fondest hopes of the theorists.

Briefly stated, if the B^0 meson did not engage in flavor mixing with the $\bar{B}^0$ during its brief picosecond lifetime, its semileptonic decay modes (those that yield leptons and hadrons) would always produce a characteristic *positive* lepton—a positron or a positive muon, never an electron or a μ^- . Correspondingly the $\bar{B}^0$ would signal its semileptonic decay with an e^- or a μ^- , never a positive lepton. What the ARGUS group found, in essence, was that roughly one semileptonic neutral B decay in six produced the wrong lepton charge, thus signaling that the B meson's bottom flavor had changed sign between its birth and death. By convention, in keeping with the analogy to K mesons, the bottom quark b , with bottom flavor (or "bottomness") -1 and electric

charge $-\frac{1}{3}$, resides in the $\bar{B}^0$ meson, while its antiquark $\bar{b}$, with positive flavor and charge, inhabits the B^0 .

Theorists had jumped on the first hint of B mesons in 1977 with great enthusiasm, pointing out that nature might well be offering here a second chance to see flavor mixing and *CP* violation. So long as *CP* violation data were limited to the decay of the neutral kaon, one couldn't really be sure what physics underlay this striking phenomenon. The data were consistent with the "standard model" of elementary particle interactions, with its 3 generations of quarks and leptons, but the data were painfully limited. Theorists longed for a new vantage point from which to observe *CP* violation. Even if the new observations remained consistent with the standard model, they might shed light on the observed value of the *CP*-violating phase angle in the three-generation formalism, which remains an unexplained free parameter in the model. The abundance of such arbitrary parameters in the standard model impels the search for a deeper theory. Furthermore, as Andrei Sakharov pointed out 20 years ago, by seeking to understand *CP* violation we come to grips with the matter-antimatter asymmetry of the cosmos.

But the surprising and welcome ARGUS result comes at a time when the

early expectations of the theorists had in fact dwindled severely. As experimental and theoretical work in the last few years provided new estimates of many of the parameters of the standard model, the theoreticians calculated that the flavor mixing parameter of the B^0 would only be about 1%, making mixing very difficult to observe and leaving little prospect of seeing the even more elusive CP violation, whose observation depends on mixing. The most sanguine of the theoretical estimates on the eve of the ARGUS result had an uncertainty that reached as high 8% mixing. The $(21 \pm 8)\%$ reported by the ARGUS group in February was a sensation. As we shall see, a significant contributor to the presumption of very little mixing had been the belief that the mass of the still unseen "top" quark would not turn out to be extravagantly large.

Doubly flavored mesons. Although the B^0 , its antiparticle and their charged siblings are the only bottom-flavored mesons clearly identified to date, they are confidently assumed to be merely the lightest of a large family. That family has two principal branches. The B^0 belongs to the more prosaic branch, in which the second quark inhabiting the meson is simply an old-fashioned "up" or "down" quark—the light first-generation quarks that make up protons, neutrons and pions. There is presumed, however, to be a second, somewhat heavier branch, the B_s mesons, in which the bottom-flavored quark is cohabiting with a strange quark, the kind one finds in kaons. Not put off by the fact that no member of this strange-bottomed branch has as yet been isolated, the theorists have been saying for years that neutral B_s mesons, unlike the non-strange B^0 , should exhibit generous mixing.

Therefore it came as no great surprise when the CERN UA1 collaboration reported² last summer at Berkeley that they had seen indications of considerable B flavor mixing at their proton-antiproton collider. The CERN experiment differs in an important respect from those at the low-energy e^+e^- colliders DORIS and CESR. Precisely because the B mesons at the CERN $\bar{p}p$ collider are produced in much higher energy collisions, one doesn't know what fraction of these B mesons are B_s , that is, carriers of bottom and strange quarks. At DORIS and CESR, by contrast, the B -mixing searches are carried out at collision energies low enough to exclude all but pairs of nonstrange B mesons.

In keeping with the theoretical expectations of the day, the CERN UA1 group attributed the bulk of the like-sign lepton pairs they saw to B_s

mixing. Given the nature of their experiment, it was impossible to distinguish strange from nonstrange B mesons. One could only say, very roughly, that something like 15% of this undifferentiated mix decayed with the wrong bottom flavor. This was quite consistent with standard-model predictions based on the best guesses of the empirical model parameters available last summer. At the same Berkeley conference, the UA1 supposition that almost all the mixing was due to strange B mesons received support from the fact that both the ARGUS and Cleo groups reported that they had as yet seen no evidence of B mixing at their low-energy e^+e^- colliders.

As this situation stood at year's end, the good news was that the standard model, with its best-guess parameters, appeared to be in excellent shape. The bad news was that, if the nonstrange B mesons one can make and study easily at DORIS and CESR were to show no mixing, the prospects for seeing exotic new CP violation would recede into the dim future.

The new ARGUS results reported in February turned all this on its head. The initial reaction of the theorists was that we were seeing an assault on the standard model; that the new data could not be made to fit without invoking some "new physics." But then two groups of theorists took a closer look. John Ellis and John Hagelin at CERN, working with Serge Rudaz (University of Minnesota) came essentially to the same conclusion³ as Ikaros Bigi (SLAC) and Anthony Sanda⁴ (Rockefeller University). The new ARGUS result with its 20% B^0 flavor mixing, these theorists conclude, is indeed consistent with what we know of the standard model parameters, if the top quark is heavier than about 50 GeV. Their best guess is in fact closer to 100 GeV.

The three-generation standard-model assumes the existence of three pairs of progressively heavier quarks, each pair associated with a charged lepton: The electron goes with the down and up quarks, the muon with the strange and charmed quarks, and the heavy tau lepton, discovered at SLAC in 1975, belongs to the third-generation bottom and top quarks. Only the top quark is still missing from this pretty picture. No one seriously doubts its existence, but we have had no reliable prediction of its mass. When the UA1 group, led by Carlo Rubbia, discovered the $W^\pm$ and Z^0 vector bosons that mediate the weak interaction four years ago, they had the great advantage of knowing the presumed mass of their quarry—roughly 90 GeV. Looking for the top quark without a serious mass prediction is much harder. After years of rumors,

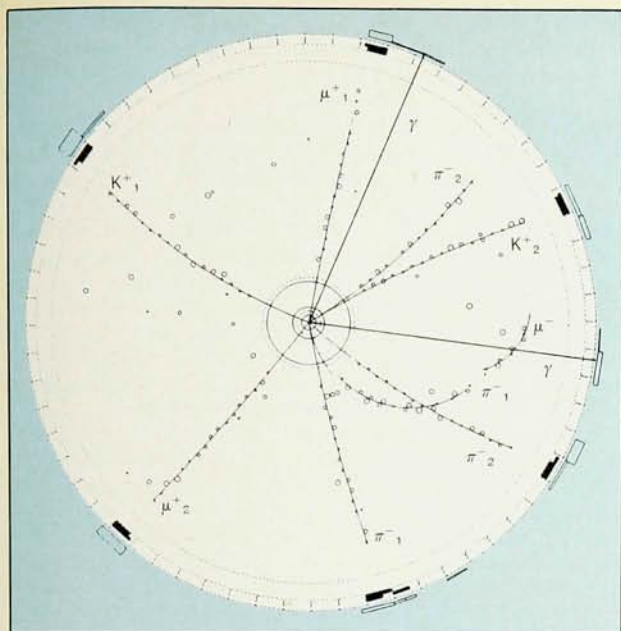
the UA1 group reported at the Uppsala meeting of the European Physical Society in June a new experimental lower limit on the top quark mass. Their search having thus far turned up no durable signal, the group asserts that the lightest meson bearing a single top quark must be heavier than 44 GeV. With slightly stronger assumptions this limit goes up to 51 GeV.

Thus the negative result of the UA1 top-quark search agrees with the theorists' deduction from the unexpectedly large B^0 mixing: The top-flavored mesons will very likely all be heavier than half the 93 GeV mass of the Z^0 . This is a matter of considerable practical import. The new generation of e^+e^- colliders soon to be doing physics—the Stanford Linear Collider in a few months and the gargantuan LEP ring at CERN in 1989—will have their maximum collision energies not far above the Z^0 mass. It was hoped that these colliders, operating right at the Z^0 mass, would be a abundant sources of top-flavored mesons. That is to say the Z^0 would decay into $T + \bar{T}$. But if the lightest of the T mesons is heavier than half a Z^0 , that can't happen. SLC and LEP, at least in its initial phase, will, in all likelihood, do no top-quark physics.

Of course the proton-antiproton colliders already in operation at CERN and Fermilab have more than enough energy to produce top mesons. But, especially when one doesn't know the mass beforehand, a top meson is not easily found in the copious shower of particles produced in a high-energy hadron collision. If, however, the top-flavored mesons are really as heavy as the best theoretical guess in light of the ARGUS result, there may be a saving grace. If the T is a bit heavier than 82 GeV, the mass of the charged W boson, it would decay into a W plus a bottom-flavored meson, a relatively easy configuration to find.

Box diagrams. What has B^0 flavor mixing to do with predicting the top-quark mass? Like K^0 mixing, B^0 mixing, in the standard model, is presumed to result primarily from the second-order weak interaction illustrated in the Feynman diagram on page 17, a so-called box diagram. The $\bar{B}^0$ begins life as a bound state of b and $\bar{d}$, a bottom quark and an anti-down quark. By the consecutive exchange of two charged W bosons, the b is transformed into a d , while the $\bar{d}$ becomes a $\bar{b}$. The $\bar{B}^0$ has become a B^0 , changing its bottom flavor from $+1$ to -1 . In the intermediate state one can have any one of the three positively charged quarks top, charmed and up, and their antiquarks, $\bar{t}$, $\bar{c}$ and $\bar{u}$.

Calculating this Feynman amplitude gives the mass splitting between the



Fully reconstructed B^0 - $\bar{B}^0$ mixing event. Looking along the colliding beams, we see the end products of the decay cascade (see text) beginning with an $\Upsilon(10.6)$ produced at rest. It must have decayed to $B^0\bar{B}^0$, but the two μ^+ tell us that the $\bar{B}^0$ had become a second B^0 . The subscripts 1,2 refer to the end products from the two B^0 mesons. Small circles indicate the passage of charged tracks, recorded by the drift-chamber wires. Rectangles at periphery indicate hits at time-of-flight and shower counters. The two straight photon tracks, from a π^0 decay, show up only in the shower counters.

two B^0 mass eigenstates, a measure of the coupling that does the mixing, analogous to the tiny mass difference between the long- and short-lived neutral kaons. In diagrams of this sort, the relative contributions of the different intermediate quarks is proportional to the square of their masses. The t quark, being by far the heaviest, wins hands down, and the coupling strength increases almost as M_t^2 . Thus the degree of observed mixing tells us about the t mass.

One also learns about other important parameters of the standard model. At each vertex one pays a price for generation jumping. The transformation $t \rightarrow d$, being a two-generation jump, is suppressed by roughly two orders of magnitude relative to a same-generation metamorphosis like $b \rightarrow t$. B_s mixing is in fact favored precisely because it involves no two-generation jump. In the 1950s the suppression of the one-generation jumps necessary for K decay relative to ordinary beta decay, which involves only transformations within the first generation, was parametrized by the Cabbibo angle, whose sine is roughly 0.2. With the discovery of charmed and bottom quarks, Nicola Cabbibo's angle has been generalized to the 3×3 Kobayashi-Maskawa mixing matrix of intergenerational mixing angles. (This mixing between generations should not be confused with the particle-antiparticle mixing we've been talking about.) The Cabbibo angle is essentially the off-diagonal matrix element U_{us} , describing the metamorphosis of a strange quark into an up quark by the emission of a W^- . Comparing the ARGUS mea-

surement of B^0 flavor mixing with the box diagram thus gives us a strong handle on the off-off-diagonal matrix element U_{td} , which one expects to be on the order of the cube of the Cabbibo angle.

Makoto Kobayashi and T. Maskawa, at the University of Nagoya in 1973, were in fact the first to point out that such a generalization of the standard model to at least three generations introduces a phase angle between matrix elements that provides a natural explanation for CP violation. Their work is all the more remarkable when one realizes that it was done a year before the discovery of charm in 1974 completed the second generation. Of the third generation there was as yet no inkling.

"The ARGUS result, if it is confirmed, is very exciting," says theorist Rudaz. "It points to an almost complete specification of the mixing matrix, just about nailing down the standard model." Thus the standard model now gives us several important new predictions, Rudaz stresses, by which it must stand or fall. If, for example, the new Tristram e^+e^- collider in Japan (PHYSICS TODAY, January, page 21), with its 25 GeV beams, were to find the top quark tomorrow, the three-generation standard model would be mortally wounded. Similarly, Rudaz and his colleagues have exploited the ARGUS result to calculate a stringent prediction of the branching fraction for the extremely rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. If the experimental effort now being mounted by Thaddeus Kycia and his coworkers at Brookhaven finds something significantly different from the predicted

10^{-10} branching fraction, the standard model is once again in great trouble, pointing to some kind of new physics we don't yet know of.

The relatively straightforward box diagram describing the weak coupling of B to $\bar{B}$ is unfortunately not the whole story. In the real world one must take account of the wave functions of the quarks in the hadrons they inhabit, and of the presence of a "sea" of quark-antiquark pairs that share the stage with the "valence" quarks that characterize the hadron. These and other hadronic complications add considerable uncertainty to the assertion that the ARGUS result is consistent with the standard model, and to the predictions flowing therefrom.

The ARGUS collaboration that started all this excitement, is primarily a German (DESY, Dortmund, Heidelberg) and Canadian (Carleton, McGill, Toronto, York) undertaking, with participants from the universities of Kansas, Ljubljana, Lund, South Carolina, Stockholm and ITEP, Moscow. Their spokesman is Walter Schmidt-Parzefall of DESY. The ARGUS detector is a large magnetic spectrometer installed at the DORIS e^+e^- ring in 1982, with a design specifically optimized for doing B -meson physics.

At both DORIS and the similar Cornell CESR ring one does B -meson physics by tuning the machine energy so that the electron-positron collision energy sits precisely atop the $\Upsilon(10.6)$ resonance at 10.6 GeV. This is the fourth of the upilon mesons, all of them bound states of the bottom quark and its antiquark. Thus they have zero net bottom flavor, but if they are heavy enough they decay readily to pairs of bottom-flavored mesons. The $\Upsilon(10.6)$, being the first and foremost of those that are indeed massive enough to decay into $\bar{B}B$ pairs, has been exploited since its discovery in 1980 as a milch cow for B mesons.

The ARGUS detector surrounds the intersection point of the electron and positron beams countercirculating in the DORIS storage ring with a cylindrical solenoid about 3 meters long and 3 meters across. Its axial 0.8-tesla magnetic field produces the track curvatures that let one measure the momentum and sign of charged particles emanating from an e^+e^- collision. A drift chamber with thousands of sense wires filling the solenoid cavity records the charged-particle trajectories and their energy loss as they ionize the propane filling the chamber.

The drift chamber is surrounded by electromagnetic shower counters that stop, identify and measure the energy of photons and electrons. For the heavier particles they do not stop, the

shower counters help distinguish hadrons from muons. Because the observation of B^0 mixing depends crucially on the efficient detection of muons as well as electrons, great care must be taken to distinguish muons from the more abundant pions, which weigh almost the same. To this end the thick steel of the magnet yoke beyond the solenoid coils is covered with muon detection chambers. Pions, being hadrons, are most unlikely to get through the steel.

A gold-plated event. The most spectacular and clear manifestation of B^0 mixing in the ARGUS experiment was the complete reconstruction of a single "gold plated event," illustrated in the figure on page 19. A $\Upsilon(10.6)$ created at rest by e^+e^- collision decays into two neutral B mesons. One doesn't know which one is the $\bar{B}^0$, but flavor conservation in hadronic decays requires that the two must begin life with opposite bottom flavor.

The subsequent sequence of decays involves B mesons and charmed D and D^* mesons whose lifetimes are far too short to show any finite travel distance in the ARGUS detector. Everything appears to emanate directly from the e^+e^- production vertex, but one determines the cascade of decays from the invariant masses of pairs and triplets of decay products. Only the neutrinos escape detection entirely.

► The "first" neutral B, which we label B_1^0 , initiates the following decay sequence:

$$\begin{aligned} B_1^0 &\rightarrow D^{*-} \mu^+ \nu \\ D^{*-} &\rightarrow \bar{D}^0 \pi^- \\ \bar{D}^0 &\rightarrow K^+ \pi^- \end{aligned}$$

The positive muon tells us that B_1^0 decayed as a B^0 , with bottom flavor +1, not a $\bar{B}^0$.

► The other B meson created in the same collision decayed as follows:

$$\begin{aligned} B_2^0 &\rightarrow D^{*-} \mu^+ \nu \\ D^{*-} &\rightarrow D^- \pi^0 \\ D^- &\rightarrow K^+ \pi^+ \pi^- \end{aligned}$$

The μ^+ once again tells us that this neutral B also decayed as a B^0 . But they could not both have been born with positive bottom flavor. Flavor conservation permits only the initial state $B^0\bar{B}^0$. Thus one of them must have undergone a flavor metamorphosis, and we have our one unambiguous B^0 mixing event.

Of course accidental mimicry often produces spurious events in particle detectors. To evaluate the possibility that the gold-plated event might be such a fake, the group performed a Monte Carlo computer simulation of some twenty thousand $B^0\bar{B}^0$ decays, and found not a single configuration that would have been mistaken for a mixing event.

To obtain a more quantitative measure of flavor mixing, the ARGUS group employed two different methods of counting mixing events. The higher-statistics method involves no attempt to reconstruct B decays. One "simply" looks for events with a pair of charged leptons of like sign. From among 88 000 $\Upsilon(10.6)$ decays, the group was able to attribute 25 such like-sign lepton pairs to $B^0\bar{B}^0$ flavor mixing, as compared with 270 unlike-sign events. A second method identifies fewer mixing events, but it is less sensitive to lepton misidentification. Here the group sought events in which one of the neutral B decays (whether semileptonic or hadronic) could be fully reconstructed, and then looked for a wrong-sign lepton from the other B decay in the event. After background subtraction, 4 such events were attributed to mixing, against 23 proper-sign events. One gets so few events because most B decays involve too many particles to permit full reconstruction. About one B decay in five is semileptonic.

Combining these two results, the ARGUS group reports a value of 0.21 ± 0.08 for the mixing parameter R , an order of magnitude larger than what the theorists were expecting. This mixing parameter is defined by

$$R = \frac{N(B^0B^0) + N(\bar{B}^0\bar{B}^0)}{N(B^0\bar{B}^0)}$$

The numerator tallies the number of decays in which one of the neutral B mesons has changed its flavor.

Any significant discrepancy between $N(B^0B^0)$ and $N(\bar{B}^0\bar{B}^0)$ would be a manifestation of something even more exotic— CP violation. But that will have to wait for experiments with much higher statistics, perhaps at one of the high-luminosity "B factory" colliders now under active consideration.

The Cleo group at Cornell has not yet found evidence of B^0 mixing. Their detector, being of an earlier vintage, was not as efficient as ARGUS at turning up like-sign lepton pairs. The Cleo group has however published an upper limit for the B^0 mixing parameter that is not in conflict with ARGUS. Their detector having recently been upgraded, the Cleo group has begun taking more data. In this time of relative quiet on the experimental particle-physics front, most everyone is eager to see the ARGUS finding confirmed.

'For the last few years the theorists have been running wild in an experimental desert,' Rudaz contends, "devising all sorts of unification schemes in the absence of substantiating data. Results of direct relevance to particle theorists have been meager since the discovery of the W and Z. Finally we

have here an experimental input relevant to the ultimate unification. Experimenters now have a clear but difficult task—to look for the rare processes predicted by the standard model with the parameters pinned down by the B^0 mixing. It's a possible door to new physics beyond the standard model—perhaps a fourth generation, perhaps new gauge interactions that violate CP on their own."

Sanda has long advocated exploiting the B^0 for the investigation of CP violation. The fact that it is a part-in-a-thousand effect in K^0 decay, he argues, is not a good indicator of its intrinsic strength, as measured by the CP -violating phase of the Kobayashi-Maskawa generation mixing matrix. In K^0 decay, CP violation is heavily suppressed by the generation-mixing angles. The phase angle itself, on the other hand, may be close to maximal. Thus, Sanda points out,⁵ one might see as much as 20% CP asymmetry in the flavor mixing of B^0 decay cascades. CP violation, in the standard model, requires that the decaying particle communicate with all 3 quark generations. The K^0 and its light quark can do this only virtually (the box diagram), but the B^0 and its b quark are heavy enough to decay physically to both other generations. In this latter case, Kobayashi-Maskawa suppression expresses itself principally by reducing decay rates; one can trade off small branching ratios for large CP asymmetry.

"Now that ARGUS has shown us there's twenty times more B^0 mixing than we expected," Sandra told us, "seeing these new CP violations should be twenty times easier than I imagined only a few months ago." But it will still require at least 10^6 neutral B decays. To this end SIN (Zurich) is considering a proposal to build a B factory collider ring with five or six times the luminosity of CESR, and groups at UCLA and Frascati are considering linear collider designs. Such proposals have been in the works since last year, but the ARGUS result now makes them all the more attractive.

—BERTRAM SCHWARZSCHILD

References

1. The ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. B **192**, 245 (1987).
2. N. Ellis, in *Proc. XXIII Int. Conf. High Energy Physics*, S. C. Loken, ed., World Scientific, Singapore (1987), Vol. 1, p. 801.
3. J. Ellis, J. S. Hagelin, S. Rudaz, CERN preprint TH.4679 (1987).
4. I. I. Bigi, A. I. Sanda, SLAC preprint 4299 (1987).
5. A. I. Sanda, in *Proc. Linear Collider BB Factory Design Workshop (UCLA, January 1987)*, D. Stork ed., World Scientific, Singapore (1987). □