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WITH THE BABAR DETECTOR
USING THE PEP-II MACHINE AT SLAC**

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*Invited talk to the 2nd International Workshop on B-Physics at Hadron Machines
Le Mont-Saint-Michel, 25-29 April 1994*

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**Measuring CP violating asymmetries
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using the PEP-II machine at SLAC**

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Abstract

The potential for the precise understanding of the CP violation phenomenon in the $B\bar{B}$ system produced in the decay of the $\Upsilon(4S)$ resonance is presented. The construction of the asymmetric B-factory machine PEP-II has recently started at SLAC. An international collaboration, BABAR is now formed to perform this exciting program from 1999 onwards. The key items of this detector and its physics capabilities are reviewed. A precision per 30 fb^{-1} , i.e one year of data taking, of 0.09 and 0.11 on $\sin 2\beta$ and $\sin 2\alpha$ respectively, is expected, providing severe constraints on the Standard Model predictions in the CP violation sector.

1 Introduction

The concept of a perfect symmetry between matter and antimatter is so deeply anchored in our minds that we barely realize that the fact that our Universe is only made up of matter does imply in fact the breaking of such a symmetry. Furthermore, even though a CP violation mechanism is indeed present in the Electroweak Standard Model, it does not seem to be able to generate the desired asymmetry between matter and antimatter to explain the baryon number of the Universe [1]. The deep understanding of the CP violation phenomenon is therefore not only mandatory to understand the formation of our Universe but also appears to be a good way to learn about what lies beyond the Standard Model.

This is precisely the goal of the BABAR experiment: explore in detail all the Standard Model predictions concerning the CP violation in the B sector and look up for definitive disagreements. The success of this ambitious program is based on the wide variety of the

predictions that can be checked with good precision. With the very clean environment of the $\Upsilon(4S)$ resonance, CP violating asymmetries will not only be measured in the modes where large effects are expected such as $B_d^0 \rightarrow J/\psi K_S^0$ or $B_d^0 \rightarrow \pi^+\pi^-$ but also in modes where asymmetries are expected to be small only in the Standard Model such as $B_d^0 \rightarrow \phi\pi^0$.

This experimental program is therefore complementary with the one that will be pursued by the LHC experiments where the statistical power is large but on a limited range of final states. In that respect, it will probably turn out that many systematic checks needed to exploit the high statistical precision in the interpretation of their results in terms of fundamental parameters can only be done at a B factory such as PEP-II/BABAR. For instance, to keep the few % precision when going from an asymmetry measurement in the mode $\pi^+\pi^-$ to $\sin 2\alpha$, the relative strength of the penguin diagrams has to be measured. This can be done by measuring the $B_d^0 \rightarrow \pi^0\pi^0$ branching ratio, a very difficult task only doable in a B-factory experiment.

In complement to this primordial goal, the BABAR physics program will be extremely rich in other sector of B physics, the main point being probably a precision measurement of V_{bu} , but also in charm physics where interesting limits on the CP violation in the D sector can be reached and in tau physics where the τ neutrino mass limit could be brought down to a few MeV.

2 The PEP-II machine

The PEP-II complex [2], a joint realization of SLAC, LBL and LLNL, consists of a two-ring electron-positron collider, schematically drawn in Fig. 1. The SLAC Linear Collider (SLC) is reused with its two damping rings. The high energy (HER) and the low energy ring (LER) are both housed in the old PEP tunnel, thus avoiding the need for any civil construction. The HER will also reuse most of the old PEP magnets after refurbishing. The philosophy for getting an high luminosity is to keep the bunch-bunch interaction parameters to the present standard in existing e^+e^- machines but increase significantly the bunch number to around a thousand. The main problems are then expected more on the engineering side more than from a physics limitation. Intensive R&D is presently going on several key points such High Order Mode (HOM) damping in the RF cavities or longitudinal feedback systems. Very encouraging results have already been obtained on beam tests at SPEAR and at the ALS in Berkeley.

The schedule foresees the completion of the High Energy Ring in mid 1997. At that time, many detailed tests can already be done : injection studies, multibunch system tuning, background understanding and optimization. The first collisions should take place in October 1998. A six month commissioning period is then foreseen so that the machine luminosity is

close to the design of $3 \cdot 10^{33} \text{ cm}^{-2}/\text{s}$ when the BABAR detector is rolled in March 1999.

The project has approved by the US Government in October 1993 and will receive 50% of its financial needs (around 160 M\$) in 1994 and 1995. The project is therefore proceeding well and should not be delayed by financial problems.

3 The BABAR detector

3.1 Detector overview

To be sensitive to CP violating asymmetries in an experiment running at the $\Upsilon(4S)$ resonance, three different tasks have to be performed on the same event :

- (i) reconstruct a CP eigenstate such as $J/\psi K_S^0$ or $\pi^+\pi^-$ or these channels with an additional π^0
- (ii) tag the flavour of the other B particle
- (iii) measure the z distance between the decay points of the two B mesons in order to reconstruct their proper time difference.

These three requirements define the key points of the detector. The largest acceptance and best energy resolution are needed for both charged and neutral particles. This implies a low-mass drift chamber and a high magnetic field (1.5 T) on one side, a CsI crystal calorimeter on the other. Because of the large price of this type of device, it is not easy to get the best tracking which would require a large chamber and the best calorimeter at the same time and some working compromise has to be found.

To enhance the tagging efficiency, it is mandatory in such an experiment to use, in addition with the well known lepton tagging, a kaon tagging. This implies a Particle Identification Device (PID) capable to separating pions, kaons and protons from 300 MeV to 1.5 GeV with good efficiency (since events containing two kaons have to be rejected to reduce the wrong tag rate) and quite small misidentification probability. The ionisation measurement in the central drift chamber, even made with high precision, can't fulfill this task alone because the pion and kaon dE/dx are the same around 700 MeV. A specific PID system is therefore needed with a range of possible options from a simple TOF counter to a sophisticated Cerenkov ring imaging device. The PID specifications are in fact not only driven by point (ii) but also by the vital need to be able to fully separate some B decay modes which differ only by a K/π exchange such as $B_d^0 \rightarrow \pi^+\pi^-$ vs $B_d^0 \rightarrow K\pi$. In these few prong modes, the π/K separation capability has to be extended up to 4 GeV, providing a strong incentive in favour of the more powerful PID devices. However it has to be stated that in this high energy domain, the dE/dx measurements and the use of kinematic fitting already provide some separation power. The PID requirements can then be summarized as

follows : it has to provide extremely robust performances in the K-tagging region while its high-energy performances have to be compromised with associated cost, technical risks and impact on other subsystems.

A precise vertex detector is of course required to measure the average 250 μm distance between the two B meson with reasonable (25% to 40%) relative accuracy. Because of the modest momenta of B decay products, the Δz resolution is always dominated by multiple scattering rather than intrinsic precision. Special care is therefore needed in the thickness of the beampipe and of the first measuring layer that has also to be located at the smallest possible radius. A Silicon double-sided strips system fulfills these requirements. In the forward region, in order to enhance acceptance and resolution, a gaseous device could be used as well (see below).

Another peculiarity of the detector is imposed by the machine. Beam separation dipoles and focusing quadrupoles have to be placed in the detector volume, starting only 20 cm away from the interaction point. This has two important consequences. Firstly, a thin 20 cm radius 0.5% X° support tube runs through the detector to provide support and precise alignment to these magnetic elements. The drift chamber inner radius can not therefore be smaller than 22 cm, resulting in poorer momentum resolution and worse pattern recognition for low momentum tracks. These nuisances have to be accepted since the machine luminosity would be endangered in the absence of such a support tube. Secondly, the forward acceptance limit in the drift chamber and the calorimeter is set at 300 milliradians by the magnets' shadow.

A much more detailed description of the BABAR detector can be found in the Letter of Intent (LOI) [3] of the BABAR collaboration. The figure 2 shows the design of the BABAR detector.

3.2 Schedule and Cost

After the review of the Letter of Intent by the SLAC Experimental Program Advisory Committee (EPAC), the BABAR collaboration, made of 300 physicists (50% being non US) will write a Conceptual Design Report for the end of 1994. This will therefore leave 4 years to build the detector in order to be ready in time with the machine, a challenging schedule. The CDR will contain the final technological choices for all subsystems as well as the construction responsibilities for the collaboration institutes. Many decisions have already been taken at the LOI stage such as the detector geometry, the calorimeter technology and the magnet parameters. The open alternatives are discussed in the next section. The estimated cost of the detector is approximately 70 M\$. The single most expensive item will be the CsI electromagnetic calorimeter, tagged at 23 M\$.

3.3 Open questions

3.3.1 The Particle Identification Device

The most outstanding remaining open issue for the BABAR detector is the choice of the PID system. Besides a Time-Of-Flight system that can be viewed as a backup solution, three Cerenkov-based technologies are still competing.

The aerogel solution consists in two sets of aerogel blocks of two different indices ($n=1.008$ and 1.06) to cover the full momentum range working in a threshold mode. Recent progress in aerogel block fabrication has been made by various companies. The predicted performances are adequate for the physics program although no kaon/proton identification would be provided in some momentum range. Its main advantages are simplicity and cost. Its main drawback is the possible lack of robustness if faced to severe experimental conditions: a large background would generate a drop of K tagging efficiency in this yes/no detector. Other worries are possible ageing, behaviour of the photon detection device in a 1.5 T field, influence of delta-rays that could produce some light for particles below threshold and of backscattering from the calorimeter.

The Fast-RICH solution, based on the pioneering work of J. Seguinot and T. Ypsilantis, consists in a radiator filled with liquid freon (as those being currently used in DELPHI and SLD) and photodetector devices using CsI photocathodes disposed as pads on the cathode plane of a MWPC. This setup suppresses long drift times and also many problems introduced by the TMAE and more generally the complex fluid systems developed for DELPHI and SLD. The predicted values based on a 18% quantum efficiency at 190 nm for the CsI photocathodes are quite adequate for the tagging region but at large incident angle, when the incoming track is still in the barrel but close to the endcap, the K/π separation drops around 3 GeV. Its main advantages are the large world-wide experience now gained on this type of devices, the robustness with respect to the background conditions because of the very fine segmentation. Its main drawback is the worry concerning the quantum efficiency that can be reached and preserved over large periods of time on a large scale system.

The DIRC solution consists of a long quartz bar radiator in which the Cerenkov light trapped by internal reflection is read out at the end of the bar in a large photomultiplier array to reconstruct the emission angle. The main advantage of this technique is that its performances increases with the track incident angle since a larger fraction of the Cerenkov light is captured in the bar. It therefore provides quite good π/K separation in the whole barrel. However, because these long quartz bars have to go outside of the return yoke of the detector, it seems impossible to use the DIRC in the endcap region. The preferred DIRC solution would be to suppress the endcaps altogether and replace them by an extended barrel. This solution has not been retained in the LOI because of its severe implications on the rest

of the detector. The main advantage of the DIRC is that the PID material inside the detector is totally inert, compact (5 cm of radial space) and homogenous. It allows either a larger drift chamber or a smaller calorimeter. Its main drawback is the technical difficulties that have to be overcome to let these quartz bars go out of the detector, cutting the calorimeter and the return yoke and reducing the access to inner parts of the detector.

The BABAR collaboration is expected to choose in fall 1994 the preferred PID system, balancing the arguments given above and using the results of the latest prototype beam tests.

3.3.2 The μ TPC option

Another open question in the LOI, with less far-reaching consequences than the PID choice for the rest of the experiment, is the technology to be used for the forward vertex detector. In that region, the very good intrinsic resolution of Silicon strips is useless because of the very large multiple scattering contribution. A small Time Projection Chamber (TPC), a down-sized version of the TPC equipping for instance the ALEPH and DELPHI detectors, would actually provide a Δz resolution 30% better than a Silicon system because of the thinness of its entrance windows. Another important advantage would be to enhance the charged particle acceptance down to 200 mrad, in a region where no drift chamber information is present, using its very good pattern recognition capabilities. (In the proposed setup which uses MicroStrip Gas Chambers for the TPC endplates, 100 points would be recorded along a track at 300 mrad and 22 at 200 mrad). This extra acceptance provides an higher efficiency reconstruction for the multiprong B final states that have to be reconstructed for measuring the CP violating asymmetries : 20% for the $J/\psi K_S^0$ decay mode and 25% for $D^* D^*$. The disadvantage of such a scheme resides in the novelty of the proposed technique and on the background sensitivity, presently under study. In this case also, a decision should be reached in the fall 1994 after the summer beam test campaign.

4 The CP reach

The CP reach of the BABAR experiment has been quantified using a simulation of the detector being described in the LOI. The results are still preliminary because the various pieces of the detector have not yet been simulated in the same level of details. They are also pessimistic in some sense because they do not take into account the recent development on tagging techniques that ought to bring an important efficiency gain nor do they consider all possible decay channels (the mode $J/\psi K_L^0$ for instance is not included yet). The background contribution from $B\bar{B}$ events as well as the continuum contribution has been

taken into account. It has been found negligible except for the mode $\rho\pi$. The table 1 summarizes the number of reconstructed events in the channels of interest whereas the table 2 gives the estimated tagging efficiency using the lepton and kaon tags. The proper dilution factors have been applied for wrong tags and finite vertex resolution. The final results are

Mode	Events Reconstructed	Background	$\delta[\sin 2\phi]$
ψK_S^0	367	0	0.13
ψK^{*0}	150	0	0.20
$D^+ D^-$	158	0	0.20
$D^{*+} D^{*-}$	272	30	0.16
$\pi^+ \pi^-$	106	9	0.24
$\rho^\pm \pi^\mp$	567	126	0.12

Table 1: CP reach of the BABAR detector for some major decay modes in a data sample of 30 fb^{-1} (one "Snowmass year") accumulated on the $\Upsilon(4S)$ resonance.

Tag Type	Branching Fraction (b)	Efficiency ($b\epsilon$)	Wrong-sign Fraction (w)	$\epsilon(1 - 2w)^2$
kaons	37	30	10.0	19
muons	11	8.8	11.7	5.2
electrons	11	8.5	9.9	5.5

Table 2: Summary of tagging efficiencies (%).

then given below where the precision reached for each mode in one year of running at the nominal luminosity - corresponding to an yearly integrated luminosity of 30 fb^{-1} is given. For $\sin 2\beta$, the precision combining the different modes is 0.09, with the $J/\psi K_S^0$ mode giving the best sensitivity, while for $\sin 2\alpha$, the precision of 0.11 is mainly given by the $\pi^+ \pi^- \pi^0$ mode, illustrating once more the need for an excellent calorimeter.

Conclusions

After the fast start off of the construction of the PEP-II machine, the BABAR collaboration is now finalizing the design of a top class detector which will be able to begin in 1999

the measurements of the CP violating asymmetries in B decays. The clean environment provided by the $\Upsilon(4S)$ decays will provide to that experiment the opportunity to study these asymmetries in many different modes. Important systematic cross checks such as the role of the penguin decays in the $\pi\pi$ channels will be made possible. A yearly precision of 0.09 and 0.11 for $\sin 2\beta$ and $\sin 2\alpha$ respectively will allow in a reasonable running time to severely constrain the Standard Model predictions in the CP violation sector and hopefully to get the first hint of what lies beyond it.

References

- [1] A. D. Sakharov, Sov. Phys. Usp. 34 (1991) 417.
- [2] The PEP-II machine Conceptual Design Report, SLAC 418, June 1993.
- [3] A Letter of Intent for the study of CP violation and heavy flavour physics, the BABAR collaboration, SLAC 443, June 1994.

SLAC/LBL/LLNL B FACTORY

Fig. 1 : Schematic view of the PEP-II complex

Fig. 2 : Design of the BABAR detector. One can see going from the beam pipe outwards: the vertex detector, the support tube, the conical shape drift chamber, the space reserved for the PID system, the CsI calorimeter, the supraconducting coil and the instrumented flux return.