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Prospects for High-Luminosity Rare-B-Decay Experiments*

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PROSPECTS FOR HIGH-LUMINOSITY RARE-B-DECAY EXPERIMENTS

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Abstract

An approach to the study of rare B decays, exemplified by Fermilab E789, is described. It is characterized by a restricted acceptance specialized for low-multiplicity decay modes, allowing extremely high luminosity to be achieved. Some problems associated with increasing the luminosity still further are discussed, and solutions are outlined.

1 Introduction

Rare charmless decays of neutral B mesons, such as $B \to$ dihadrons, hold out the promise of large CP asymmetries, making them attractive (though extremely challenging) targets for experiment. Since the expected branching ratios for such decays are small ($\sim 10^{-5}$), a specialized experiment of extremely high luminosity is required if they are to be studied at fixed-target energies. The only extant example of such an experiment is E789[1], which will begin data-taking in the 1990 fixed-target run and will have sensitivity at the level of 10^9 produced $b\bar{b}$ pairs per run. With acceptance times efficiency at the percent level, this yields of order 10^2 reconstructed events for a 10^{-5} branching mode. Useful levels of sensitivity will also be obtained for other low-multiplicity B decays, such as $B^\pm \to D\pi \to K\pi\pi$ and $B^\pm \to J/\psi K^\pm$, permitting lifetime and mixing measurements as well as the possible discovery of strange and charmed B mesons and b baryons.

This note is motivated by the possibility of obtaining a large enough sample of dihadronic B decays to begin setting useful limits on CP violation. Given the more than order-of-magnitude uncertainty in the cross-section times branching ratio, it is remotely possible that E789 will approach this level, but the lack of efficient tagging of the other B in the event is at present a serious handicap. One must therefore consider ways of increasing the sensitivity and the tagging efficiency each by an order of magnitude.

The most straightforward way to increase sensitivity is to increase the luminosity. I discuss below some of the problems in doing so and propose approaches for their solution. Tagging efficiency is most straightforwardly improved by increasing muon coverage. In principle there is no serious obstacle to doing this, and I do not discuss it further here. I assume that an upgrade could be put into place by the latter half of the 1990's, thus new techniques which might take some years to develop could be employed.

2 Brief Description of E789

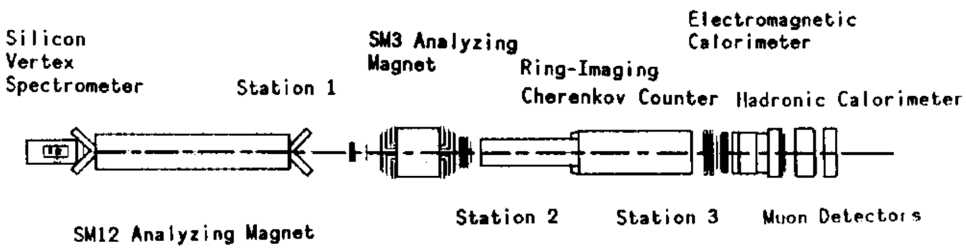

Figure 1.
E789 Apparatus

Figure 1 shows the E789 apparatus. Proceeding more or less from left to right, its main features are:

1. a small, dense, platinum target, localizing the primary interaction vertex within ± 1 mm longitudinally to facilitate recognition of decay vertices, and improving the signal-to-background via the $A^{0.29}$ nuclear enhancement;
2. a vertex spectrometer located in a fringe magnetic field, consisting of 13k channels of silicon microstrip detectors, organized as two arms of 8 planes each, with a horizontal gap allowing the uninteracted beam and small-angle secondaries to pass through;
3. a water-cooled copper beam dump, located within a large magnet, to absorb the uninteracted beam as well as secondaries having low-p_t (< 1 GeV) or small production angle (< 20 mrad);
4. scintillation hodoscopes and high-rate small-cell drift chambers for triggering and track reconstruction;

5. a second large magnet for momentum analysis and partial focusing of secondaries;
6. a ring-imaging Cherenkov counter for hadron identification;
7. scintillation-sandwich electron and hadron calorimeters for triggering;
8. scintillation and proportional-tube muon detectors.

The combination of large magnets and drift chambers with long lever arms provides excellent mass resolution (~0.1%), important in rejecting non-beauty background. The apparatus is expected to perform at interaction rates up to 10 interactions/rf-bucket, making very rare decay modes accessible. Triggering at such high rates will be accomplished via hodoscope-matrix roads implemented in fast lookup logic, coupled with calorimeter and muon-detector requirements, and feeding a sophisticated data-driven trackfinding trigger processor[2] looking at information from the bend-view drift chambers and silicon-strip detectors. The trigger will require two high-p_t tracks in the main spectrometer having large impact parameter at the target, but there will also be acceptance for three-body modes in which the third particle is measured in the vertex spectrometer (or, if it is a muon, passes through the beam dump).

3 Increasing Luminosity

3.1 Silicon Microstrip Detectors

The most obvious luminosity limitation of E789 is the rate in its silicon vertex spectrometer. At 10 interactions per RF bucket, we expect some 15 hits per bucket per silicon plane, or 1.2 hits per cm^2 on the most upstream planes. A typical fixed-target run of 3×10^{15} buckets (10^5 30s spills) would thus expose the upstream planes to an average of 4×10^{14} particles/cm^2, and their innermost strips to twice this value. Silicon-strip detectors are generally considered to suffer significant degradation in signal-to-noise ratio after 4 MRad, or 10^{14} particles/cm^2, which flux E789 will exceed by an order of magnitude. We expect that the detectors will nevertheless survive this irradiation due to possible annealing and to operation at low temperature (say 0°C) to suppress leakage current. Failing this, we will replace detectors as they become unuseable. (We have already exposed a silicon plane to 4×10^{14} particles/cm^2 in a test beam at Los Alamos, and it appears to be still operational and performing acceptably when cooled to 0°C.)

Could this approach be extended to operation at an order-of-magnitude higher rate (100 interactions/bucket)? The preamps to be used[3] are of bipolar type and radiation-hard to several MRad. Since they are located about 30 cm off beam axis, they will encounter only about 10^{-3} of the flux seen by the detector planes, so they should survive. To withstand the damage-induced leakage current in the detectors, it may be sufficient to operate the detectors at still lower temperature (say $-20°$C).

Taking spill fluctuations into account, each detector plane will record an average of 300 charged particles per event: what configuration of planes, and of what pitch, are required to reconstruct tracks reliably in this enormous flux? A plausible guess is ten times the number of strips and twice as many planes as in E789, e.g. 32 planes of 20μm pitch, with each plane divided into two halves read out to the right and to the left. Since each strip would then have five times smaller area than the E789 strips, leakage current per strip would be reduced by the same factor, implying five times the radiation hardness of the E789 detectors even without additional cooling.

3.2 Pixel Planes

Could silicon pixel detectors withstand this rate? Various groups are now considering fabrication of planes with pixels of about $900\mu m^2$ area, with each pixel bump-bonded to its own signal processing circuitry in a custom VLSI chip. The radiation hardness of these pixel planes should be orders of magnitude better than that of the E789 microstrip detectors, due to the reduction in element size by a factor of 3×10^3. However, the readout electronics sits in the same radiation bath as does the detector and so sees a flux of 400 MRad per fixed-target run. While the pixel plane may survive, the readout chips are to be fabricated using a process which is hard to 10 MRad, not nearly good enough.

We have thus ruled out known VLSI solutions due to radiation damage, but it is instructive to consider another challenge which such an application presents: extreme requirements on the speed and architecture of the readout chip. Limits on rate capability can arise from pile-up at the pixel level and at the row-and-column level, and also from requirements for readout speed. The readout chip needs to store hits from many successive buckets while the first-level trigger decision is being made. This decision typically takes about 0.5μs, or 25 buckets. The probability of multiple hits per pixel must be small during this interval. For definiteness I assume a square plane of 4×10^6 pixels organized as 2000 rows by 2000 columns. Since 300 pixels are hit per bucket, only 10^{-3} of pixels are hit in the trigger interval, which is acceptably small.

In addition, the row-and-column logic needs to record the time of each hit occurring in a given row or column, so that when the trigger is satisfied the in-time hits can be identified and encoded. On average a row or column will record 2 hits during the trigger interval, but rate variations over the face of the detector will give 4 hits in the highest rate regions, and fluctuations in instantaneous rate then imply a need for 16- to 32-hit buffering. Finally, the pixel information needs to be made available at high speed to the trigger processor whenever the low-level trigger is satisfied. This means that the scanning of rows, columns, and pixels needs to be completed within 10 μs or so.

These requirements are perhaps an order-of-magnitude more severe than those proposed for SSC detectors, but (radiation hardness aside) they do not seem prohibitive in principle. However, no presently-contemplated device has such performance[4]. To assess the feasibility of achieving it will require some detailed engineering work.

3.3 Rates in the Main Spectrometer

The main E789 spectrometer is composed largely of drift chambers, of cell sizes 0.5, 1, and 2 cm, increasing downstream as the rates fall off. Their rate capability will need to be increased by an order of magnitude. Rate capability of wire chambers increases quadratically as cell size decreases, since both the particle rate per wire and the integrating time decrease linearly. The cell sizes would thus need to decrease by a factor of 3. This is within the range of cell sizes which have been successfully used by many groups. In addition, the number of planes may need to be increased by a factor of 2 to 3 to handle the more complicated pattern recognition problem.

A key element in E789 is the ring-imaging Cherenkov counter. Designed almost a decade ago, its electronics limit it to about 1 MHz of $\beta = 1$ particles. Newer electronics should permit operation at 10 MHz.

3.4 Trigger Rates and Data Acquisition

The E789 trigger processor is expected to take 10 to 100μs per low-level trigger, limiting the low-level trigger rate to 1 to 10 kHz if 10% deadtime is to be maintained. However, the E690 group is building a processor of greater complexity which operates at 100 kHz. A currently planned upgrade to the E789 data acquisition system is limited to about 2 Mbytes/s to tape, but the E791 group is building a system with $>$ 4 times this bandwidth. Thus there is no obstacle in principle to upgrading trigger and data-recording rates by an order of magnitude each.

4 Conclusion

As E789 has not yet taken any data, it is premature for detailed conclusions. Despite much Monte Carlo work, we surely do not yet know what the real problems will turn out to be at 10 interactions/bucket, let alone 100. However, the considerations presented here suggest that with some work, an order of magnitude or more increase in sensitivity may be possible in future runs.

References

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