Towards a Hyperon "Super-*CP*" Experiment: Report of the Hyperon-*CP*-Violation Working Group

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Abstract

The Hyperon-*CP*-Violation working group at the $\overline{p}$2000 Workshop met together with the Beta-Decay working group. After briefly introducing the physics, I summarize the working-group discussions relevent to *CP* violation. The working group sketched issues that need to be explored in designing a hyperon *CP*-violation experiment that might achieve 10^{-5} sensitivity for the *CP* asymmetry A_Λ, one order of magnitude beyond that of the current HyperCP experiment and in the range at which an effect is predicted by the Standard model.

1 Hyperon *CP* Violation

In addition to *CP* violation in kaon decays [1], the Standard Model predicts a slight *CP* asymmetry in decays of hyperons [2, 3, 4]. The most accessible signals involve comparison of the (nonuniform) angular distributions of the decay products of polarized hyperons with those of the corresponding antihyperons [3]. For a precision measurement, it is necessary to know the polarizations of the initial hyperons and antihyperons to high accuracy.

By angular-momentum conservation, in the decay of a spin-1/2 hyperon to a spin-1/2 baryon plus a pion, the final state must be either S-wave or P-wave. As is well known, the interference term between the S- and P-wave decay amplitudes gives rise to parity violation, parametrized by Lee and Yang [5] in terms of two independent parameters α and β: α is proportional to the real and β to the imaginary part of this interference term. *CP* violation can be sought as a difference in $|\alpha|$ or $|\beta|$ for a hyperon decay and its *CP*-conjugate antihyperon decay or as a particle-antiparticle difference in the partial widths for such decays [3, 6].

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Table 1: Summary of experimental limits on *CP* violation in hyperon decay.

Experiment	Facility	Mode	A_Λ or $A_{\Xi\Lambda}$
R608	ISR	$pp \to \Lambda X, pp \to \overline{\Lambda} X$	$-0.02 \pm 0.14^*$
DM2	Orsay	$e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$	$0.01 \pm 0.10^*$
PS185	LEAR	$\overline{p}p \to \overline{\Lambda}\Lambda$	$0.006 \pm 0.015^*$
E756	Fermilab	$pN \to \Xi^- X, \Xi^- \to \Lambda\pi^-$, $pN \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$	$0.012 \pm 0.014^\dagger$
CLEO	CESR	$e^+e^- \to \Xi^- X, \Xi^- \to \Lambda\pi^-$, $e^+e^- \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$	$-0.057 \pm 0.064 \pm 0.039^\dagger$

$^*A_\Lambda$ $\quad$ $^\dagger A_{\Xi\Lambda}$

Table 1 summarizes the experimental situation. The first three experiments cited studied Λ decay only [7, 8, 9], setting limits on the *CP*-asymmetry parameter [3, 6]

$$A_\Lambda \equiv \frac{\alpha_\Lambda + \alpha_{\overline{\Lambda}}}{\alpha_\Lambda - \alpha_{\overline{\Lambda}}}\,, \tag{1}$$

where α_Λ ($\alpha_{\overline{\Lambda}}$) characterizes the Λ ($\overline{\Lambda}$) decay to (anti)proton plus charged pion and, if *CP* is a good symmetry in hyperon decay, $\alpha_\Lambda = -\alpha_{\overline{\Lambda}}$.

Fermilab E756 [10] and CLEO [11] employed a new technique in which the cascade decay of charged Ξ hyperons is used to produce polarized Λs, in whose subsequent decay the slope of the (anti)proton angular distribution in the "helicity" frame measures the product of α_Ξ and α_Λ. If *CP* is a good symmetry in hyperon decay this product should be identical for Ξ and $\overline{\Xi}$ events. The *CP*-asymmetry parameter measured is thus

$$A_{\Xi\Lambda} \equiv \frac{\alpha_\Xi\alpha_\Lambda - \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}}{\alpha_\Xi\alpha_\Lambda + \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}} \approx A_\Xi + A_\Lambda\,. \tag{2}$$

The power of this technique derives from the large α value for the $\Xi \to \Lambda\pi$ decay ($\alpha = 0.64$). A further advantage in the fixed-target case is that within a given $\overset{(-)}{\Xi}$ momentum bin the acceptances and efficiencies for Ξ and $\overline{\Xi}$ decays are very similar, since the switch from detecting Ξ to detecting $\overline{\Xi}$ is made by reversing the polarities of the magnets, making the spatial distributions of decay products across the detector apertures almost identical for Ξ and for $\overline{\Xi}$. (There are still residual systematic uncertainties arising from the differing cross sections for p and $\overline{p}$ and for π^+ and π^- to interact in the material of the spectrometer.)

Subsequent to E756, this technique has been used in the "HyperCP" experiment [12] (Fermilab E871), depicted schematically in Fig. 1, which ran during 1996–99. Like E756, HyperCP used a secondary charged beam produced by primary protons interacting in a metal target. The secondary beam was momentum- and sign-selected by means of a curved collimator located within a 6-m-long dipole magnet. No measurements were made until after the 13-m-long (evacuated) decay region. HyperCP recorded the world's largest samples of decays of the Ξ^- and $\overline{\Xi}^+$, amounting to 2×10^9 and 0.5×10^9 events, respectively. When the

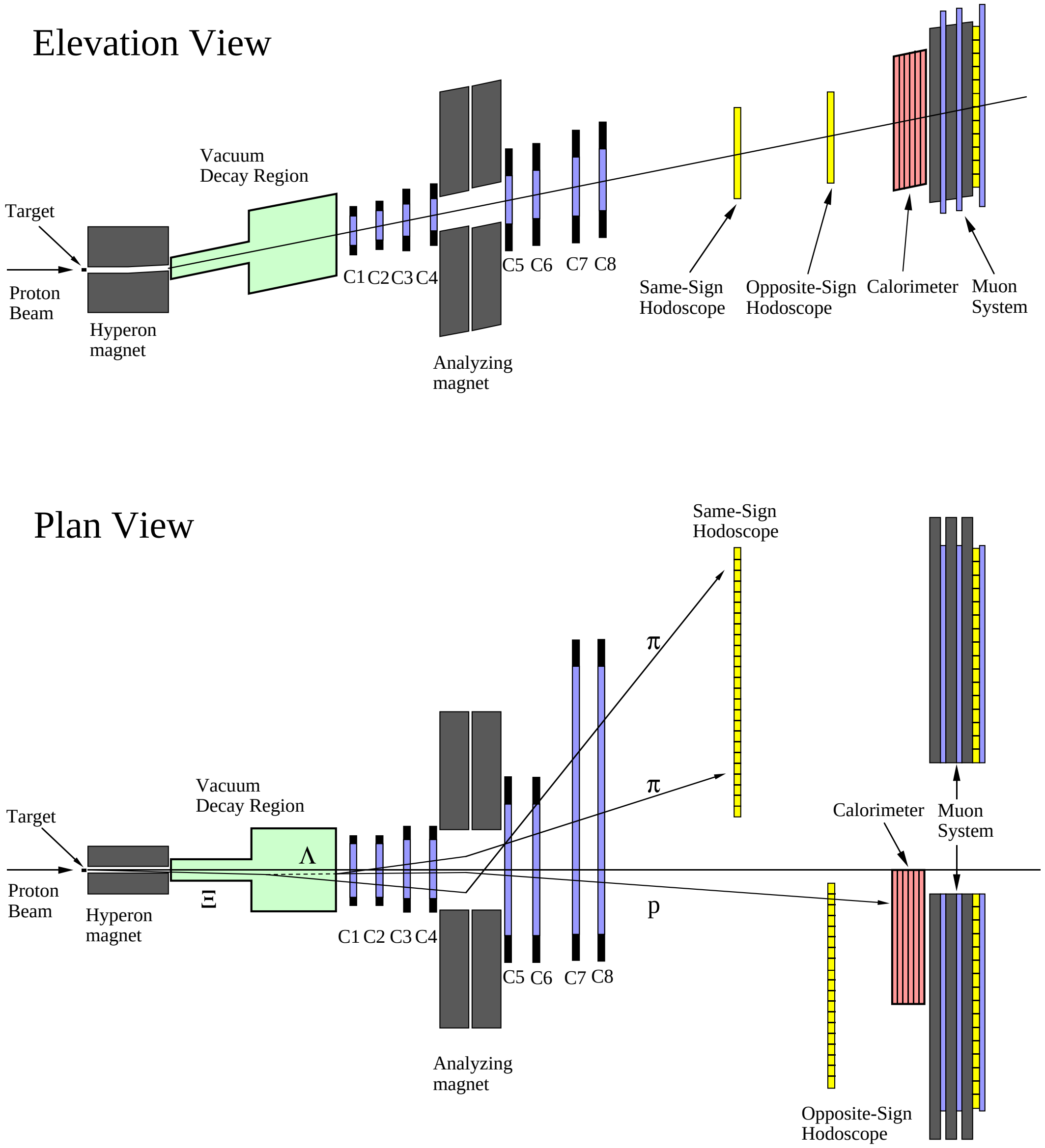

Figure 1: Elevation and plan views of the HyperCP spectrometer, consisting of eight (or in the 1999 run, nine) four-plane MWPC stations (C1–C8) located downstream of the hyperon channel and decay pipe and surrounding a pair of momentum-analysis magnets. The trigger calorimeter and hodoscopes are located far downstream of the analyzing magnets, where the positive and negative hyperon decay products have separated from each other and from the beam, allowing the trigger elements to be kept outside the ≈20 MHz charged secondary beam. The muon detectors located beyond the calorimeter give sensitivity to rare decays.

analysis is complete, these should determine $A_{\Xi\Lambda}$ with a statistical uncertainty

$$\delta A = \frac{1}{2\alpha_\Xi\alpha_\Lambda}\sqrt{\frac{3}{N_{\Xi^-}} + \frac{3}{N_{\overline{\Xi}^+}}} = 1.4 \times 10^{-4}\,. \tag{3}$$

The Standard Model predicts this asymmetry to be of order 10^{-5} [3]. Thus if HyperCP sees a significant effect, it will be evidence for *CP* violation in the baryon sector substantially larger than predicted by the Standard Model.

2 A Future Experiment

Whether or not HyperCP observes a statistically-significant effect, it is of interest to ask whether an experiment with substantially larger event samples is feasible [13]. Since HyperCP sensitivity is an order of magnitude short of the Standard Model prediction, a desirable goal would be two orders of magnitude in sample size.

We have begun to explore this question. While we believe that the approach taken in HyperCP is near the limit of what is possible with present-day particle-detection technology,[1] an alternative approach pioneered by the PS185 Collaboration at CERN may have the requisite "head room." The PS185 experiment [14] operated at the Low-Energy Antiproton Ring (LEAR) at CERN between 1984 and 1996 and utilized $\overline{p}p$ annihilation slightly above the threshold for production of a $\overline{\Lambda}\Lambda$ pair. (In this case, the requirement that the hyperon and antihyperon polarizations be precisely known is modified, since by *C*-parity conservation in the strong interaction the polarizations of the hyperons and antihyperons are equal.)

Limited by the available antiproton intensity at LEAR, PS185 has achieved a sensitivity of only 1.5% [9]. However, in the early 1990s the CERN "CP-Hyperon Study Group" designed a hyperon *CP*-violation experiment for SuperLEAR aimed at 10^{-4} sensitivity [15] (see Fig. 2). While SuperLEAR was never built, the antiproton production rate at the Antiproton Source at Fermilab is already at least four orders of magnitude beyond that achieved at LEAR, and substantial improvements to its capabilities are planned. A new antiproton storage ring at Fermilab capable of producing $\overline{\Lambda}\Lambda$ events at a 60 kHz rate may be feasible at relatively modest cost [16]. This would allow the accumulation of a sample of order 10^{11} good events within a few years' running time [13]. Challenges that will need to be met include the design of beam optics and a gas-jet target that permit $\approx 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ luminosity, detecting the Λ decay products and reconstructing their tracks with good efficiency at ≈200 MHz charged-particle rate, triggering with good efficiency and adequate background rejection at ≈100 MHz interaction rate, and acquiring data at the resulting high trigger rate. (Additional uses for such a facility include experiments designed to study quark confinement and soft QCD effects, rare hyperon decays, and hyperon beta decays, many of which are discussed elsewhere in these Proceedings.)

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[1] The high rate of secondary beam in HyperCP — about 20 MHz spread over an area of several cm^2 — caused detector inefficiencies in the beam region at the percent level (in the most upstream MWPCs) due to MWPC deadtime.

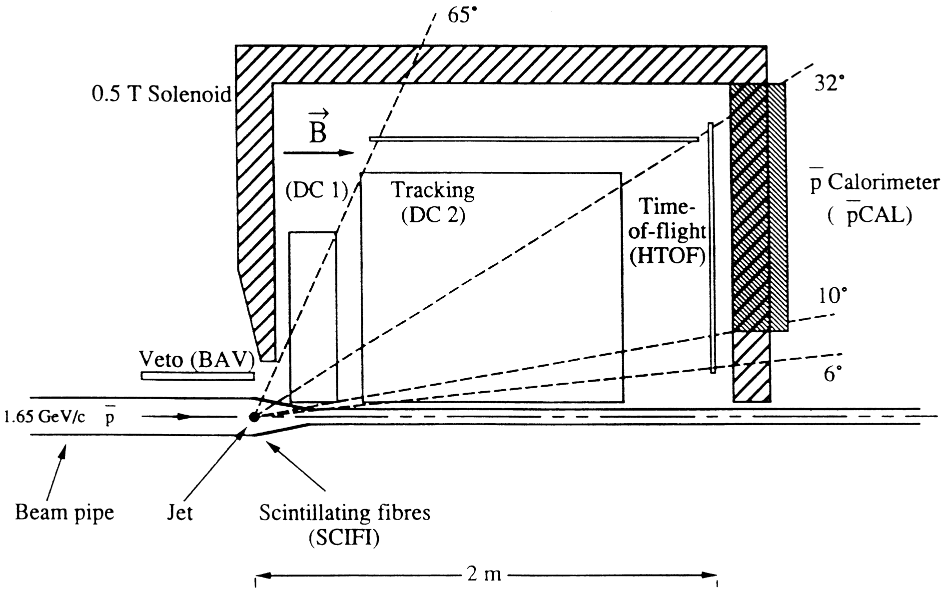

Figure 2: Schematic of $\overline{\Lambda}\Lambda$ spectrometer designed for SuperLEAR (from Ref. [15]).

3 Working Group Discussions and Conclusions

Various ideas on the design of a hyperon "Super-*CP*" experiment were discussed in the working group:

1. The experiment could be designed to operate in either colliding-beam or fixed-target mode. However, the Lorentz boost of hyperons produced in fixed-target mode is likely to play an important role in permitting a trigger to distinguish the relatively rare $\overline{\Lambda}\Lambda$ events from background interactions.

2. In the Standard Model there is a hierarchy of *CP*-violating effects in hyperon decay [4]: The asymmetry $B \equiv (\beta+\overline{\beta})/(\beta-\overline{\beta})$ (measuring the difference of hyperon and antihyperon β parameters, where $\beta = -\overline{\beta}$ if *CP* is a good symmetry) is expected to be largest, followed by A, followed by $\Delta \equiv (\Gamma-\overline{\Gamma})/(\Gamma+\overline{\Gamma})$ (measuring differences of partial decay widths between hyperon and antihyperon). Some corresponding experimental options are summarized in Table 2. Of these measurements, A_Λ is the least speculative (having been studied before in PS185) and also requires the lowest storage-ring energy.

   Measuring B requires knowing the polarizations of both the parent and daughter hyperons, thus it could not practically be measured in Λ decay, but could be in Ξ decay, using the self-analyzing decay of the Λ to $p\pi$. While B_Ξ is likely to be an order of magnitude larger than A_Λ, this is likely to be outweighed by the lower $\overline{\Xi}\Xi$ production cross section, thus it appears to have little (if any) statistical advantage over A_Λ. Moreover, the greater complexity of reconstructing the cascade decay near threshold may

Table 2: Comparison of various possible hyperon *CP* measurements.

Signal	Process	p_{beam} [GeV/c]	σ [μb]
A_Λ	$\overline{p}p \to \overline{\Lambda}\Lambda$	1.642	≈ 65
B_Ξ	$\overline{p}p \to \overline{\Xi}\Xi$	> 2.62	$\approx 2^*$
Δ_Ω	$\overline{p}p \to \overline{\Omega}\Omega$	> 4.93	0.06?

* While the cross section just above the $\overline{p}$ 2.62 GeV/c beam-momentum threshold has not been measured, the cross section at 3.5 GeV/c has been [15] and is shown in Table 2.

make the measurement of B_Ξ impractical. However, if feasible, it would be a desirable complementary measurement to that of A_Λ.

For the Λ and Ξ, Δ is expected to be the smallest asymmetry, however for the Ω it could be as large as 10^{-4} [4]. But since the cross section for $\overline{p}p \to \overline{\Omega}\Omega$ has not been measured and the reconstruction of events containing six decay vertices will be challenging, the feasibility of measuring Δ_Ω is difficult to assess.

3. While much of the PS185 data on A_Λ were obtained at 1.642 GeV/c beam momentum, there could be systematic advantages to operating at slightly higher momentum, $\approx$1.7 GeV/c. The idea here would be to symmetrize the Λ and $\overline{\Lambda}$ momentum and angle distributions, which at 1.642 GeV/c differ somewhat from each other, contributing a small systematic uncertainty on A_Λ. While the CERN study group concluded that this uncertainty would be small enough for a measurement at 10^{-4} sensitivity [15], at 10^{-5} sensitivity it may matter. The trade-off is background from $\overline{p}p \to \overline{\Lambda}\Sigma$ (threshold $\overline{p}$ momentum $= 1.65$ GeV/c) followed by $\Sigma \to \Lambda\gamma$ (and charge conjugate), which might in some cases be confused with $\overline{p}p \to \overline{\Lambda}\Lambda$. The possible dilution of the observed A_Λ due to these processes needs to be assessed.

4. Two beam-pipe options need to be considered: If the Λs are required to decay inside the beam pipe a large pipe (radius $r \approx 10$ cm) is necessary, while if they are required to decay outside the pipe as small a pipe as possible ($r \approx 1$ cm) would be desired. One issue bearing on this question is possible *CP* bias due to interactions of Λs or their decay products in the beam-pipe wall.

5. The large interaction rate raises various issues:
   (a) What sort of tracking detectors will have the necessary rate capability while not introducing excessive amounts of material? Possibilities to be considered include MicroMegas [17, 18] and multi-GEM [19, 18] chambers, scintillating fibers [20], and silicon pixels [21].
   (b) What crossing rate is required: Can events with multiple interactions be tolerated, or would they bias the *CP* measurement? Should the beam be bunched at a high frequency or unbunched?

Table 3: Antiproton Accumulator stacking-rate projections.

When	What	How
Aug. 2000	10 mA/hr	
March 2001 goal	20 mA/hr	
Run IIB goal	100 mA/hr	using e^- cooling in Recycler, possibly also slip-stacking etc.

6. How to trigger? To reject background interactions it would appear desirable to veto events containing charged particles within a few mm of the beam. To avoid excessive event loss due to accidental vetoes, this veto detector would need to be quite fast, for example a Cherenkov detector. One could follow the lead of BTeV [22] by digitizing all interactions and triggering using a pipelined vertex-finding track processor. An optical impact-parameter pretrigger might be helpful in reducing the rate into the processor [23].

7. Would a detector optimized for the measurement of A_Λ also be capable of doing other physics well, for example precision studies of hyperon beta decay?

We also met jointly with the accelerator working group for one session and raised the following points:

1. At the interaction point, both beam size and beam divergence matter: both need to be small.

2. Especially if a small beam pipe is used, this suggests that the beam should be cooled and decelerated to the desired collision energy before injection into the storage ring. Another advantage of "on-energy" injection is the possibility of "topping up" the beam to maintain approximately constant luminosity.

3. 10^{33} luminosity consumes $\overline{p}$s at a rate corresponding to 30 mA/hr stacking rate in the Accumulator. As shown in Table 3, this is beyond what has been achieved so far but is only a fraction of the Run IIB goal of 100 mA/hr. Thus the stacking-rate luminosity limitation on a 10^{-5}-sensitivity hyperon *CP* experiment is likely to have been overcome by $\approx$ 2006. Another issue of course is what demands for $\overline{p}$s the Tevatron Collider experiments will be making in the LHC era. An additional factor ≈ 4 in $\overline{p}$ production rate can be expected if the proposed Proton Driver upgrade is built [24].

4. How might it make sense for construction of the facility to be staged? The best scenario for the *CP*-violation experiment is a $\approx$2 GeV/c ring dedicated to that experiment that can run constantly. It should use electron cooling (similar to LEAR and IUCF). For other experiments, which do not require such high integrated luminosity as the *CP* experiment, a larger, time-shared storage ring with momentum variable over $\approx$

$1-10\,\mathrm{GeV}/c$ would be suitable. While the GSI upgrade proposal [25] considers a 15 GeV $\overline{p}$ storage ring, it is not clear that the physics case for going beyond 10 GeV is strong enough to justify the extra expense and difficulty of electron cooling at 15 GeV. The 2 GeV ring may well be built in the next few years to provide $\overline{p}$s for NASA space-propulsion studies and other purposes [26].

References

[1] See for example J. L. Rosner, in *Proc. 8th Jorge Andre Swieca Summer School: Particles and Fields*, Rio de Janeiro, Brazil, 5–18 Feb. 1995, J. Barcelos-Neto, S. F. Novaes, V. O. Rivelles, eds., World Scientific (1996), p. 116.

[2] A. Pais, Phys. Rev. Lett. **3**, 242 (1959); O. E. Overseth and S. Pakvasa, Phys. Rev. **184**, 1663 (1969); J. F. Donoghue and S. Pakvasa, Phys. Rev. Lett. **55**, 162 (1985).

[3] J. F. Donoghue, X.-G. He, S. Pakvasa, Phys. Rev. D 34, 833 (1986); X.-G. He, H. Steger, G. Valencia, Phys. Lett. B 272 (1991) 411.

[4] G. Valencia, this Workshop.

[5] T. D. Lee and C. N. Yang, Phys. Rev. **108**, 1645 (1957).

[6] J. F. Donoghue, B. R. Holstein, and G. Valencia, Phys. Lett. **178B**, 319 (1986) and Int. J. Mod. Phys. A **2**, 319 (1987).

[7] P. Chauvat *et al.*, Phys. Lett. **163B** (1985) 273.

[8] M. H. Tixier*et al.*, Phys. Lett. **B212** (1988) 523.

[9] P. D. Barnes *et al.*, Nucl. Phys. B (Proc. Suppl.) **56A** (1997) 46.

[10] K. B. Luk *et al.*, "Search for Direct CP Violation in Nonleptonic Decays of Charged Xi and Lambda Hyperons," hep-ex/0007030 (2000).

[11] D. E. Jaffe *et al.*, "Search for Direct CP Violation in Ξ Hyperon Decay," CLNS 98/1587, CLEO 98-16 (2000).

[12] J. Antos *et al.*, Fermilab Proposal 871 (revised), Mar. 26, 1994; see also http://ppd.fnal.gov/experiments/e871/welcome.html.

[13] D. M. Kaplan, in *Proc. Hyperon 99: Hyperon Physics Symposium*, Batavia, Illinois, 27–29 Sept. 1999, D. A. Jensen, E. Monnier, eds., Fermilab-Conf-00/059, p. 165.

[14] P. Barnes *et al.*, Nucl. Phys. **A526**, 575 (1991).

[15] N. Hamann *et al.*, CERN/SPSLC 92019, SPSLC/M491, 30 March 1992.

[16] G. Jackson, this Workshop.

[17] Y. Giomataris *et al.*, Nucl. Instr. Meth. **A376**, 29 (1996); Y. Giomataris, Nucl. Instr. Meth. **A419**, 239 (1998); P. Cussonneau *et al.*, Nucl. Instr. Meth. **A419**, 452 (1998).

[18] J. P. Perroud *et al.*, Nucl. Instr. Meth. **A453**, 159 (2000).

[19] S. Bachmann *et al.*, CERN-OPEN-2000-299 (2000).

[20] A. Bross *et al.*, in *Proc. SCIFI 97*, AIP Conference Proceedings **450**, A. Bross *et al.*, eds., American Inst. Phys. (1998), p. 221.

[21] A. Mekkaoui *et al.*, in Proc. 5th Workshop on Electronics for the LHC Experiments (LEB 99), CERN 99-09, CERN-LHCC-99-33, p. 98.

[22] D. M. Kaplan, Nucl. Instr. Meth. **A446**, 282 (2000); E. Gottschalk, to appear in *Proc. APS Meeting of the Division of Particles and Fields (DPF 99)*, Los Angeles, CA, 5–9 Jan. 1999; see also the BTeV proposal, http://www-btev.fnal.gov/public_documents/btev_proposal/index.html.

[23] G. Charpak, L. M. Lederman, and Y. Giomataris, Nucl. Instr. Meth. **A306**, 439 (1991); D. M. Kaplan *et al.*, *ibid.* **A330**, 33 (1993); G. Charpak *et al.*, *ibid.* **A332**, 91 (1993), M. Atac *et al.*, *ibid.* **A367**, 372, 1995; G. Charpak *et al.*, "The Optical Trigger for the E871 Experiment," RD30 Note, March 16, 1995.

[24] W. Chou, this Workshop.

[25] See the GSI upgrade Letter of Intent at http://tau.ep1.ruhr-uni-bochum.de/gsi/.

[26] G. Jackson, private communication.