HyperCP: Search for *CP* Violation in Charged-Hyperon Decays

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Discovered forty years ago by Cronin and Fitch, who were awarded the Nobel Prize for their work, *CP* violation has remained a mysterious and puzzling aspect of particle physics. Its origin is unknown, and although it is a tiny effect in the laboratory, its implications are profound: *CP* violation is thought to be responsible for the nearly absolute asymmetry between matter and antimatter in the universe, indeed why there is any matter at all in the universe. But it is widely believed that the *CP* violation observed thus far (in only the decays of the K_L and B_d mesons) is too feeble to produce the asymmetry between matter and antimatter in the universe. Other sources are needed, perhaps from physics beyond that in the standard model. To quote Bigi and Sanda from their recent book, *CP Violation*:

> *"We are willing to stake our reputation on the prediction that dedicated and comprehensive studies of CP violation will reveal the presence of New Physics."*

The goal of HyperCP is to search for new sources of *CP* violation in the decays of charged-Ξ and Λ hyperons. These are sensitive to sources of *CP* violation that kaon decays, for example, are not. The signature for the *CP* asymmetry is a difference between the angular distributions of the Λ and $\overline{\Lambda}$ decay products, where the Λ and $\overline{\Lambda}$ have been produced from Ξ^- and $\overline{\Xi}^+$ decays. The HyperCP spectrometer was designed to have a sensitivity in the *CP* asymmetry of about 2×10^{-4}, three orders of magnitude better than the experimental limit at the time. Current theoretical predictions range from a high of several times 10^{-3} in some supersymmetric models of *CP* violation, to a low about 10^{-5} in standard model calculations.

The HyperCP sensitivity goals demand a large number of events, and hence an extremely high-rate spectrometer was built in the short space of two years, one capable of recording up to 100,000 events per second. The spectrometer accumulated the largest dataset ever taken — 231 *billion* events — in two running periods: 1997 and 1999. The primary event reconstruction (of almost 30,000 tapes) was done on the Fermilab computer farms and completed in the summer of 2001. This work involved reconstructing a dataset twenty-five times larger than the total amount of data on all of the Web sites in the world at the time. It resulted in by far the largest sample of hyperon decays ever taken as well as the largest sample of charged-kaon decays.

The scope of the physics topics that HyperCP addresses goes beyond *CP* violation in hyperon decays. The complete HyperCP physics menu includes: (1) a high-precision search for *CP* violation in charged-Ξ and Λ decays; (2) the measurement of the branching ratios in the flavor-changing neutral-current (FCNC) decays: $K^+ \to \pi^+\mu^+\mu^-$ and $K^- \to \pi^-\mu^+\mu^-$; (3) the search for the $\theta^+(1.54)$ pentaquark; (4) the search for the decay $\Sigma^+ \to p\mu^+\mu^-$; (5) the search for the lepton-number-violating decay $\Xi^- \to p\mu^-\mu^-$; (6) the search for the $|\Delta S| = 2$ decays $\Omega^- \to \Lambda\pi^-$ and $\Xi^0 \to p\pi^-$; (7) the precise measurement of the Ω^- and $\overline{\Omega}^+$ α decay parameters and the corresponding *CP* asymmetry; (8) the precise measurement of the α, β, and γ parameters in $\Xi^- \to \Lambda\pi^-$ decays; (9) the measurement of the Λ-π^- strong phase shift; (10) the measurement of the branching ratio $\Omega^- \to \Xi^-\pi^+\pi^-$; and (11) the search for the FCNC decays $\Omega^- \to \Xi^-\mu^+\mu^-$ and $\Omega^- \to \Xi^-e^+e^-$.

The analysis of the data has produced eight refereed publications; six more are in progress. A few highlights follow. Results from the main goal of the experiment, the search for *CP* violation in charged-Ξ and Λ hyperon decays, has recently been published. No *CP* violation was found in an analysis of about 17% of the dataset, a factor of twenty improvement over the best previous result. This new measurement is beginning to constrain some supersymmetric predictions of the asymmetry. HyperCP has reported the first unambiguous evidence of parity violation in the decays of the Ω^- and the $\overline{\Omega}^+$ from an analysis of about five million Ω^- and two million $\overline{\Omega}^+$ events. Of the various searches for rare and forbidden hyperon decays HyperCP has made, perhaps the most interesting is the evidence for the decay $\Sigma^+ \to p\mu^+\mu^-$. The three found events constitute the smallest branching ratio ever observed in a baryon decay. These events have a narrow dimuon mass, suggesting that perhaps the decay proceeds by a hitherto unknown neutral intermediate state of mass $214.3\pm0.5\,\mathrm{MeV}/c^2$. Other searches for rare and forbidden hyperon decays, such as the search for $\Delta S = 2$ decays and lepton-number violation, are many orders of magnitude more sensitive than previous results.

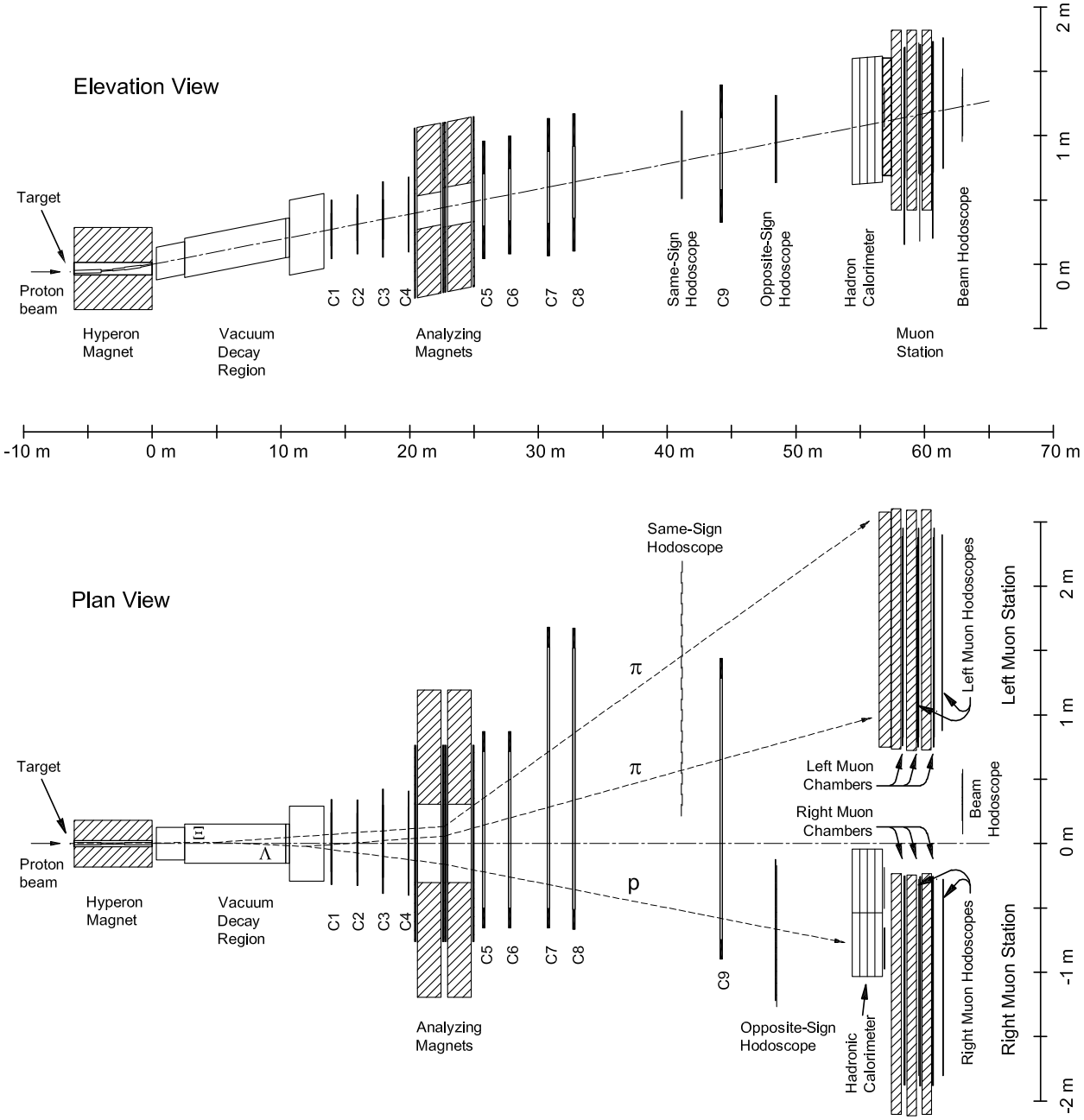
Although the HyperCP spectrometer was designed to detect hyperons, it accumulated an enormous sample of charged-kaon decays. The collaboration's first publication, a new measurement of the branching ratio of the FCNC decay $K^+ \to \pi^+\mu^+\mu^-$, as well as the first observation of the conjugate decay, $K^- \to \pi^-\mu^+\mu^-$, resolved an outstanding disagreement between two BNL experiments for this important test of chiral perturbation theory. HyperCP has also searched for pentaquarks, which were very much in the news in 2004, many sightings having been reported. A high-statistics search for the θ^+ pentaquark was made, none were found. This was one of the first in a now growing list of null searches.

Refereed Publications

1. *Evidence for the Decay* $\Sigma^+ \to p\mu^+\mu^-$ H.K. Park *et al.*, Phys. Rev. Lett. **94**, 021801 (2005).
2. *Search for CP Violation in Charged-*Ξ *and* Λ *Hyperon Decays*, T. Holmstrom *et al.*, Phys. Rev. Lett. **93**, 262001 (2004).
3. *High statistics search for the* $\theta^+(1.54)$ *pentaquark state*, M.J. Longo *et al.*, Phys. Rev. D **70**, 111101(R) (2004).
4. *New Measurement of* $\Xi^- \to \Lambda\pi^-$ *Decay Parameters*, M. Huang *et al.*, Phys. Rev. Lett. **93**, 011802 (2004).
5. *Tripling the Data Set for the HyperCP Experiment*, C. White *et al.*, IEEE Trans. on Nucl. Sci. 49:568–576 (2002).
6. *Observation of the Decay* $K^- \to \pi^-\mu^+\mu^-$ *and Measurements of the Branching Ratios for* $K^\pm \to \pi^\pm\mu^+\mu^-$, H.K. Park *et al.*, Phys. Rev. Lett. **88** (2002) 111801.
7. *Upgraded DAQ system for the HyperCP experiment*, C. White *et al.*, Nucl. Instrum. and Methods, **A474**, 67 (2001).
8. *A high-throughput data acquisition system for the HyperCP experiment*, Y.-C. Chen *et al.*, Nucl. Instrum. and Methods, **A455**, 424 (2000).

Theses

1. T. Holmstrom, University of Virginia (2003).
2. M. Huang, University of Virginia (2003).
3. D. Rajaram, Illinois Institute of Technology (2002).
4. N. Leros, Université de Lausanne (2001).
5. W.-S. Choong, University of California/Berkeley (2000).
6. M. Morales, Universidad de Guanajuato (2000).
7. Z. del Cid, Universidad de Guanajuato (2000).
8. D. Rajaram, University of Virginia (1996).



Elevation and plan views of the HyperCP spectrometer. The 1999 configuration is shown. Superimposed on the plan view are the charged tracks of a $\Xi \to \Lambda\pi \to p\pi\pi$ decay. For clarity, enclosures, support structures, and helium bags are not shown. Transverse dimensions have been exaggerated by a factor of ten.