Perspectives for Direct CP Violation Tests in Hyperon Decays

M. Conte¹, E. Di Salvo¹, A. Penzo² and M. Pusterla³.

(1) Dipartimento di Fisica dell’Università di Genova, INFN Sezione di Genova, Via Dodecaneso 33, 16146 Genova, Italy.
(2) INFN Sezione di Trieste, Via Valerio 2, 34127 Trieste, Italy.
(3) Dipartimento di Fisica dell’Università di Padova, INFN Sezione di Padova, Via Marzolo 8, 35131 Padova, Italy.

ABSTRACT

We discuss the perspectives of measuring direct CP violation parameters in hyperon decays by measurements with proton and/or antiproton beams, to be carried out at various facilities, and in particular we propose new experiments at the Tevatron and at the LHC.

1 Introduction

Violation of CP symmetry is a crucial problem in particle physics, and has attracted much theoretical and experimental interest, as witnessed by numerous review papers on the subject (see, for example, [1, 2, 3, 4]). Up to now only one process has exhibited such a violation: $K_L^0$ decay into two pions. Various experimental tests have been proposed in order to find further confirmations of such violations [3] and, possibly, signatures of new physics [5, 6, 7, 8].

Some of these experiments, based on comparison between hyperon and antihyperon decays [3, 6, 7], were proposed more than ten years ago, but their practical realization appeared to be hard, mainly due to the difficulty in creating a sufficiently intense antihyperon factory [7]. Results from few pioneering experiments [8, 9, 10] have a statistical precision too poor to be compared in a significant way with theoretical predictions. More recently, [11] a viable scheme for a high precision experiment was proposed at FNAL, where the approved experiment was performed during the last fixed-target run, and represents a first serious step in the field of CP violation in the hyperon sector.

Meanwhile strong efforts are being engaged in a new generation of precision measurements, deeply exploring CP violation in the neutral kaon sector. These will be followed by experiments in the beauty sector, both at hadron machines [12] and at $e^+ - e^-$ beauty factories [13], that appear best suited for establishing indirect CP effects, similar to neutral kaons. We consider here the perspectives for a full programme
on direct CP violation tests in the hyperon sector, that could be performed by using \( p\bar{p}, \) \( pp \) and \( \bar{p}\bar{p} \) collisions at various facilities, including the Tevatron \[14\] and the Large Hadron Collider (LHC) \[15\]. These seem to be particularly favourable for testing charge conjugation and CP invariance. Our main purpose consists of illustrating the practical conditions required in this sense. Moreover we shortly review the problem of CP violation, especially in connection with (anti-)hyperon decays.

## 2 Physics Outline

CP symmetry has attracted the interest of particle physicists since the discovery of parity violation. In particular Landau \[16\] pointed out that parity violation should be compensated by a charge conjugation asymmetry, in such a way that CP is conserved. should leave the Lagrangian invariant. On the other hand a CP violation (or T violation, if CPT theorem is true, as we shall assume from now on) is a much more serious and puzzling problem. Now we know that the Landau hypothesis is likely to be true with a good approximation. Indeed, in the very few cases when it has been measured, CP violation appears very small; furthermore all existing models predict, in various systems, even smaller effects.

We expect CP to be violated by weak interactions. However, recently people have focused their interests also on strong interactions \[17\], where CP could be violated by nontrivial configurations of QCD theory \[18\]. These violations have not been observed; consequently the theoretical question is still open \[19\].

As regards CP violations in weak interactions, the most popular model is Kobayashi-Maskawa’s \[20\] (KM). They show that the weak Hamiltonian matrix of quarks with three different quark families can carry a phase which is not invariant by time reversal. To be more specific, let us consider the contribution of CP violations in Feynman diagrams. They are

i) “penguin” diagrams, exhibiting the “direct” CP violations due to the decay process;

ii) “box” diagrams, corresponding to “indirect” CP violations; indeed in some neutral mesons carrying strangeness, charm or beauty (such as \( K^0, B^0, D^0 \)), a CP violating mass matrix can occur; these diagrams produce typical particle-antiparticle mixings with oscillations of quantum numbers.

In both cases one has interference among virtual exchanges of \((u,c,t)\)-quarks or \((d,s,b)\)-quarks, so that the amplitude may be sensitive to the CP-noninvariant phase of the weak Hamiltonian. For the \( K^0_L \) decay into two pions the main source of CP violation is the indirect one, characterized by the well-known parameter \( \epsilon \), whereas the direct CP violation parameter \( \epsilon' \) is affected by a large uncertainty and consistent with zero \[21\].

Both effects can be looked for in different decay processes. Beauty factories \[13\] appear to be the most promising for establishing indirect effects, similar to neutral kaons. However also direct effects are important, not only for further confirmations
of CP violations, but also for a possible discrimination among various models, which predict quite different values of violation parameters. Indeed, they vanish according to the “superweak” Hamiltonian by Wolfenstein [22], but not in the KM model, because of “penguin” diagrams. To this end hyperon decays are very suitable, since they cannot exhibit indirect CP violations.

A necessary condition for observing direct CP violations is that the process should consist of two interfering amplitudes at least, which differ in (strongly) conserved quantum numbers, e.g., isospin. In this connection Brown et al. [6] point out that similar violations may be observed in processes of the type

$$\Lambda \rightarrow p\pi^-(n\pi^0), \quad \Sigma^+ \rightarrow n\pi^+(p\pi^0),$$

(1)

but not in decays like [7]

$$\Sigma^- \rightarrow n\pi^-, \quad \Xi^0(-) \rightarrow \Lambda\pi^0(-),$$

(2)

where the final state is a pure isospin state. This argument might be not completely correct, since in the KM model penguin diagrams are also involved in the decays (2), which therefore would proceed through intermediate states of different isospin.

The CP violation effects, which are expected to be very small (although one predicts them to be quite different, according to the model and to the asymmetry parameter considered [3, 7]), would produce slight differences in hyperon - antihyperon decay width ($\Gamma$) and in the parameters $\alpha, \beta$ and $\gamma$, defined below. These tiny differences look very hard to be detected from separate measurements of the parameters. Only direct comparison between the hyperon and the corresponding antihyperon decays, measured simultaneously in the same apparatus, can hopefully show evidence of such effects. The decays we consider are of the type $Y \rightarrow B\pi$, where $B$ is the final baryon. To this end some asymmetry parameters have been defined [3, 7]:

$$A_1 = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}, \quad A_2 = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}, \quad A_3 = \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}},$$

(3)

where bars refer to antiparticles. In particular $\Gamma$ is the partial decay width (e.g., $\Lambda \rightarrow p\pi^-$), while

$$\alpha(\beta) = \frac{2Re(Im)[S^*P]}{|S^2| + |P^2|}$$

(4)

and $S \ (P)$ is the s(p)-wave amplitude in the hyperon decay. It is worth noticing that, while the CPT theorem implies equal total decay widths for particle and antiparticle, CP violation allows differences between partial decay widths.

The decay distribution of the daughter spin $\frac{1}{2}$ baryon in the rest frame of the parent hyperon is given by

$$\frac{dP}{d\Omega} = \frac{1}{4\pi}(1 + \alpha \vec{P}_p \cdot \vec{P}_d),$$

(5)
where $\vec{P}_p$ is the parent hyperon polarization and $\hat{p}_d$ is the daughter baryon momentum direction in the rest frame of the parent. The daughter itself is polarized with a polarization given by

$$\vec{P}_d = \frac{\left(\alpha + \vec{P}_p \cdot \hat{p}_d\right)\hat{p}_d + \beta(\vec{P}_p \times \hat{p}_d) + \gamma(\hat{p}_d \times (\vec{P}_p \times \hat{p}_d))}{1 + \alpha \vec{P}_p \cdot \hat{p}_d},$$

(6)

where $\alpha^2 + \beta^2 + \gamma^2 = 1$. We note that in the case of unpolarized parent the daughter is in a helicity state with a polarization $\alpha$. Hence $\alpha$ and $\beta$ can be extracted from polarization measurements of the hyperon and of the final baryon [23]. In this connection we point out that, while $\alpha$ can be measured from the decay angular distribution of an unpolarized hyperon, $\beta$ cannot be determined if the hyperon is unpolarized. However it is well known (see [24] and references quoted therein) that most of the hyperons (and some antihyperons) are produced polarized transverse to their production plane.

3 Preliminary Experimental Results

The existing experimental results on CP violation in hyperon decays are scarce and have a limited statistical precision; at the moment only three experiments give limits on $A_2$ for $\Lambda^0(\Xi^0)$.

Experiment R608 at the ISR [8] studied the production and decay of $\Lambda(\Xi)$ from the $pp \to \Lambda X$ ($\bar{p}p \to \Xi X$) reaction; the measured decay asymmetries of the $\Lambda(\Xi)$ give a ratio $\left(\alpha_{P_{\Lambda}}\right) / \left(\alpha_{P_{\Xi}}\right) = -1.04 \pm 0.29$; assuming the polarizations $P_\Lambda = P_\Xi$, one obtains $A_2 = -0.02 \pm 0.14$.

Experiment PS185 at LEAR [9] studied the exclusive reaction $\bar{p}p \to \Lambda \Xi$ at 1.5 GeV/c $\bar{p}$ incident momentum; in this case $P_\Lambda = P_\Xi$ by C-parity conservation in strong interactions; it results an average value $< A_2 > = -0.07 \pm 0.09$.

The third result comes from $e^+e^- \to J/\Psi \to \Lambda \bar{\Lambda}$, measured by DM2 at DCI-Orsay [10], and provides $A_2 = 0.01 \pm 0.10$.

These experimental results are limited by statistical errors that should be significantly improved in order to be compared in a useful way with theoretical predictions.

More recently, a proposal (P871) [11] for a search of CP violation in the decay of $\Xi(\Xi)$ and $\Lambda(\Lambda)$ hyperons was approved at FNAL; the experiment E871 has been taking data during the last fixed-target Tevatron run. The measurement consists of producing (unpolarized) beams of $\Xi(\Xi)$ and detecting their decays into $\Lambda(\Xi)$, the latter exhibiting a helicity polarization $\alpha_\Xi$ ($\alpha_\Xi$). The $p(\bar{p})$ distributions from the (polarized) $\Lambda(\Xi)$ from $\Xi(\Xi)$ decays are determined by the products $\alpha_\Xi \alpha_\Lambda$ ($\alpha_\Xi \alpha_\Xi$); the differences of these distributions will measure the sum $A_2^\Xi + A_2^\Lambda$ to a good accuracy. A statistically significant nonvanishing result would represent a first serious signal of CP-violation in the hyperon sector.
4 Hyperon Processes for CP-Violation Studies

The study of CP-violation in the hyperon sector has so far been considered for exclusive (2-body) reactions at low or intermediate energy, for instance, hyperon-antihyperon production in $\bar{p} - p$ interactions, and inclusive processes at very high energy, where intense hyperon (antihyperon) beams can be produced. Now we propose new experiments where direct CP violations in hyperon decays could be observed, considering inclusive and exclusive reactions feasible at various facilities.

4.1 Inclusive processes at high energy

The inclusive reactions we refer to are

i) $p\bar{p} \rightarrow YYX$ (feasible at Tevatron),

ii) $pp \rightarrow Y(Y)X$ (feasible at LHC).

iii) $\bar{p}\bar{p} \rightarrow \bar{Y}(Y)X$ (feasible at LHC).

In cases i) and ii) one assumes the hyperons and antihyperons to be polarized (away from the forward direction), however in reaction ii) we expect a much lower antihyperon production cross section to test CP violation [24].

To this end $\bar{p}\bar{p}$ collisions have definite advantages. More precisely, the production of hyperons in $pp$ and of antihyperon in $\bar{p}\bar{p}$ collisions, should be equal, assuming CP symmetry in strong interactions, and therefore the comparison of decay distributions in these two cases becomes a direct test for CP violation. This makes it possible to reformulate the tests proposed by Donoghue and Pakvasa [7]: in particular, according to their evaluations, the largest signal could be found in $A_3$ ($10^{-3}$ to $10^{-2}$ in $\Xi^0 \rightarrow \Lambda\pi^0$, according to different models).

Finally the suggested strategy of employing $\bar{p}$ beams could avoid the drawbacks connected with particular features of the detector, clearly illustrated in ref. [25].

As far as the study of the inclusive reaction i) is concerned, we obviously suppose to use the upgraded Tevatron at FNAL, where presumably the luminosity reaches the value

$$L_{p\bar{p}} = 1.61 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}. \quad (7)$$

4.2 A possible $\bar{p}\bar{p}$ option for LHC

In order to have $\bar{p}\bar{p}$ collisions, the planned Large Hadron Collider (LHC) appears to be the most suitable machine since consisting of a double ring with an antiproton source nearby. Bearing in mind that the luminosity $L$ fulfils the relation

$$L \propto \frac{N^2}{b}, \quad (8)$$

where $N$ is the total number of particles per beam and $b$ is the number of interacting bunches, the design parameters of LHC in its normal $pp$ mode, i.e.,

$$n_p = 1.05 \times 10^{11} \text{ protons per bunch}, \quad (9)$$

5
\[ b_p = 2835 \text{ proton bunches}, \quad (10) \]

\[ N_p = b_p n_p = 2.98 \times 10^{14} \approx 3 \times 10^{14} \text{ protons per beam}, \quad (11) \]

yield a luminosity

\[ L_{pp} \approx 10^{34} \text{ cm}^{-2} \text{s}^{-1}. \quad (12) \]

If we assume the \( \bar{p} \) production rate to be the same as the ACOL \[ \text{yield of} \]
\[ N_{\bar{p}} = 1.8 \times 10^{12} \bar{p} \text{ 's per day, we plan to achieve} \]
\[ \bar{N}_{\bar{p}} \approx 10^{12} \bar{p} / \text{beam}. \quad (13) \]

Then if the number of antiprotons per bunch equals the number of protons per bunch
(see formula (11)), we find
\[ b_{\bar{p}} = 10 \text{ antiproton bunches}. \quad (14) \]

Therefore, combining eqs. (10), (11), (12), (14), and (13), we obtain
\[ L_{\bar{p}p} = \frac{b_p}{b_{\bar{p}} \left( \frac{N_{\bar{p}}}{N_p} \right)^2} L_{pp} \approx 3.15 \times 10^{31} \text{ cm}^{-2} \text{s}^{-1}, \quad (15) \]

which would allow us to obtain quite a good rate of events.

### 4.3 Exclusive processes with \( \bar{p} \) beams

The process \( \bar{p}p \to Y \bar{Y} \), feasible at FNAL \( \bar{p} \) accumulator, has the following advantages:

- high luminosity;
- clear kinematical configuration;
- polarizations of \( Y \) and \( \bar{Y} \) identical in binary reactions;
- cascade decays of polarized hyperons providing access to \( \beta \) parameters.

The most promising scenario in this case is the reaction \( \bar{p}p \to \Xi \bar{\Xi} \), followed by
the decays \( \Xi \to \Lambda \pi, (\bar{\Xi} \to \bar{\Lambda} \pi) \). This reaction can be produced in interactions of
the accumulated \( \bar{p} \) beam with a jet target. The produced \( \Xi(\bar{\Xi}) \) hyperons will have a
polarization \( P_Y(\theta^*) \) as a function of the production angle (vanishing at zero degrees)
and therefore the polarization of the decay \( \Lambda(\bar{\Lambda}) \) will depend only on \( \alpha_\Xi \) for forward
production and on both \( \alpha_\Xi \) and \( \beta_\Xi \) for production at an angle \( \theta^* \). We notice that it
is not necessary to measure the \( \Xi(\bar{\Xi}) \) polarization, because, being the same for both,
it cancels out in the ratios measuring CP-violation effects. In this way the final \( p(\bar{p}) \)
distributions for fully reconstructed events \( \bar{p}p \to \Xi(\to \Lambda \pi) \bar{\Xi}(\to \bar{\Lambda} \pi) \) will determine a
set of combinations \( \alpha_\Xi \alpha_\Lambda \) and \( \beta_\Xi \alpha_\Lambda \) for hyperons and antihyperons, in exactly
the same conditions, with minimal systematic biases.
5 Conclusions

Since the discovery of CP violation several generations of experiments have been performed in the neutral kaon sector and others are planned in the beauty sector. In both cases the accessible CP effects are essentially "indirect".

On the other hand, concerning "direct" CP violations, a full experimental program is still missing, although few exploratory measurements have been attempted.

We have outlined suggestions for such a program in the hyperon sector, on the basis of present and future facilities, among which the Tevatron and the LHC, using $p\bar{p}$, $pp$ and $\bar{p}p$ collisions.

References

[1] I. Bigi: Preprint UND-HEP-97-BIG 09.
[2] B. Kayser: Preprint NSF-PT-97-4.
[3] Xiao-Gang He: Lecture given at the CCAST workshop on "CP violation and Various Frontiers in Tau and Other Systems", Beijing, China, 11-14 August, 1997.
[4] A.J.Buras: Preprint MPI-PhT/94-30, TUM-T31-64/94.
[5] Dan-Di Wu: Preprint hep-ph/9710845.
[6] T.Brown, S.F.Tuan and S.Pakvasa: Phys. Rev. Lett. 51 (1983) 1823.
[7] J.F. Donogue and S.Pakvasa: Phys Rev. Lett. 55 (1985) 162.
[8] P.Chauvat et al. (R608): Phys. Lett. B163 (1985) 273.
[9] P.D.Barnes et al. (PS168): Phys. Lett. B199 (1987) 147.
[10] M.H.Tixier et al. (DM2): Phys. Lett. B212 (1988) 523.
[11] Fermilab Proposal P-871, March 26, 1994.
[12] H. Albrecht et al. (HERA-B): DESY-PRC 92/4 (1992).
[13] BaBar Collaboration, Status report, SLAC-419 (1993); BELLE Collaboration (KEKB), KEK-94-2 (1994).
[14] Fermilab Luminosity Upgrade Group, Run II Handbook, Updated on February 4 1998 (site: http://adwww.fnal.gov/lug/).
[15] The Large Hadron Collider, *The LHC Study Group*, CERN/AC/95-05(LHC).

[16] L. Landau: Nucl. Phys. 3 (1957) 254.

[17] Z. Huang: Phys. Rev. D48 (1993) 270.

[18] R. Peccei: “CP violations”, C. Jarlskog (ed.), World Sci. Singapore, 1989, p. 503.

[19] R. Peccei and H. Quinn: Phys. Rev. Lett. 38 (1977) 1440; Phys. Rev. D 16 (1977) 1791.

[20] M. Kobayashi and T. Maskawa: Prog. theor. Phys. 49 (1973) 652.

[21] Particle Data Group (R. Barnett et al.): Phys. Rev. D54, (1996) 1.

[22] L. Wolfenstein: Phys. Rev. Lett. 13 (1964) 562.

[23] R.E. Marshak, Riazuddin and C.P. Ryan: "Theory of Weak Interactions in Particle Physics", Wiley, New York, 1969

[24] K. Heller: Proceedings "Polarization Dynamics in Particle and Nuclear Physics", Y. Onel, N. Paver and A. Penzo (ed.), World Sci., Singapore, 1995, p. 231. (to be corrected)

[25] C.J.-C.In, G.L. Kane and P.J. Molde: Phys. Lett. B317 (1993) 454.

[26] M. Sands: The Physics of Electron Storage Rings, SLAC Report 121 (1970).

[27] Design Study of an Antiproton Collector for the Antiproton Accumulator (ACOL), *Design Study Team*, CERN Yellow Report 83-10.