

TEST OF CP AND C INVARIANCES IN  $\bar{p}p$  ANNIHILATIONS AT  
1.2 GeV/c INVOLVING STRANGE PARTICLES

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Abstract : We have found no indication of violation of either CP or C invariances. Using a simple model, one can make an estimate of  $(0.4 \pm 1.0) \times 10^{-2}$  for the relative amplitude of CP violation and of  $(0.4 \pm 1.0) \times 10^{-2}$  for C violation. Our data is also consistent with a relative amplitude of P violation of  $(0.1 \pm 1.0) \times 10^{-2}$ .

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The possible violation of CP invariance observed by CHRISTENSON et al. (Ref.1) in  $K_2^0$  decay opens the way to the suggestion that C invariance could be violated in strong interactions (Ref.2).

In this paper, we would like to present the results of a search for a possible violation of C and/or of CP invariance in strong interactions, using  $\bar{p}p$  annihilations at 1.2 GeV/c.

Similar tests have been carried out previously with more limited statistics (Ref.3). A search for a possible violation of C invariance has also been made, using  $\bar{p}p$  annihilations at rest (Ref.4); however, in this case, no attempt was made to distinguish between C and CP invariance (Ref.5).

Let us consider the 2 reactions :

$$\bar{p}p \quad 1 + 2 + X \quad (1)$$

$$\bar{p}p \quad \bar{1} + \bar{2} + \bar{X} \quad (2)$$

where X may be any assembly of particles.

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In these reactions, one can define the operations CP and CR, where C is charge conjugation, P is parity inversion and R is a rotation of 180 deg. around any axis perpendicular to the direction of motion of both the p and  $\bar{p}$ . We assume conservation under R to be true and treat a test of CR to be a test of C alone.

Let  $W(p_1, \theta_1, p_2, \theta_2, \varphi_{12})$  denote the probability of finding particle 1 (2) with a momentum  $p_1$  ( $p_2$ ) at an angle  $\theta_1$  ( $\theta_2$ ) relative to the direction of  $\bar{p}$ , where  $\varphi_{12}$  is the azimuth of 2 relative to the ( $\bar{p}$  1) plane.

Pais (Ref.6) has shown that CP conservation predicts :

$$W(p_1, \theta_1, p_2, \theta_2, \varphi_{12}) = W(p_{\bar{1}}, \pi - \theta_{\bar{1}}, p_{\bar{2}}, \pi - \theta_{\bar{2}}, \varphi_{\bar{1}\bar{2}})$$

and that CR conservation predicts :

$$W(p_1, \theta_1, p_2, \theta_2, \varphi_{12}) = W(p_{\bar{1}}, \pi - \theta_{\bar{1}}, p_{\bar{2}}, \pi - \theta_{\bar{2}}, -\varphi_{\bar{1}\bar{2}})$$

By integrating over some of the variables we get the relations:

$$\begin{aligned} W(p_1) &= W(p_{\bar{1}}) & W(p_2) &= W(p_{\bar{2}}) \\ W(\theta_1) &= W(\pi - \theta_{\bar{1}}) & W(\theta_2) &= W(\pi - \theta_{\bar{2}}) \end{aligned}$$

as predictions of either C or CP.

Moreover, if CP is conserved we have  $W(\varphi_{12}) = W(\varphi_{\bar{1}\bar{2}})$  whereas if C is conserved we have  $W(\varphi_{12}) = W(-\varphi_{\bar{1}\bar{2}})$ .

These predictions are valid for all similar pairs of particles of the reactions (1) and (2), (Ref.7).

The events used for this study were obtained in a study of 300,000 pictures of the Saclay 81 cm H.B.C. exposed to a beam of 1.2 GeV/c of anti-protons at the CERN proton synchrotron.

After analysing all events with at least a  $V^0$ , we have found:

$$344 \text{ events of the reaction } \bar{p}p \rightarrow \bar{K}_1^0 K^+ \pi^- \quad (3)$$

$$343 \text{ " " " } K_1^0 K^- \pi^+ \quad (4)$$

$$744 \text{ " " } \bar{p}p \rightarrow \bar{K}_1^0 K^+ \pi^- \pi^0 \quad (5)$$

$$791 \text{ " " } \bar{p}p \rightarrow K_1^0 K^- \pi^+ \pi^0 \quad (6)$$

$$783 \text{ " " " } K_1^0(K^0) \pi^+ \pi^- \quad (7)$$

$$352 \text{ " " " } K_1^0 K^0 \pi^+ \pi^- \quad (8)$$

$$165 \text{ " " } \bar{p}p \rightarrow \bar{K}_1^0 K^+ \pi^- \pi^+ \pi^- \quad (9)$$

$$135 \text{ " " " } K_1^0 K^- \pi^+ \pi^+ \pi^- \quad (10)$$

The application of the tests mentioned above (excluding reactions (7) and (8) for which we cannot distinguish between the two charge conjugate states) gives  $(0.4 \pm 1.0) \times 10^{-2}$  for the relative amplitude of CP violation and  $(0.4 \pm 1.0) \times 10^{-2}$  for C violation, using a simple model to be explained below.

From these results, one could conclude that we do not observe any definite violation; however, one could expect a possible enhancement of the violating amplitude for reactions dominated by a strong final state interaction.

Since our experimental data shows a large production of  $K^{\pm}$  (890), we have then applied the tests to the following charge conjugate states :

$$\bar{p}p \rightarrow K^{\pm} + \bar{K} + n\pi \quad (11)$$

$$\bar{p}p \rightarrow \bar{K}^{\pm} + K + n\pi \quad (12)$$

$$(n = 0, 1, 2)$$

Another reason to prefer this type of classification is that reactions which at first view look like charge conjugates of each other, for example  $\bar{p}p \rightarrow K^+ K^0 \pi^-$  and  $\bar{p}p \rightarrow K^- K^0 \pi^+$ , can come from the same reaction, either reaction (11) (for example  $\bar{p}p \rightarrow K^{\pm 0} \bar{K}^0 \rightarrow (K^+ \pi^-) \bar{K}^0$  and  $\bar{p}p \rightarrow K^{\pm+} K^- \rightarrow (K^0 \pi^+) K^-$ ) or reaction (12). Also the reactions (7) and (8), which look self conjugate, can be separated in reaction (11) and (12). One drawback of this type of classification is the difficulty to choose the  $K^{\pm}$ .

In the reactions (3) and (4) only 50% of the events give  $K^{\pm}$  (Ref.8), and we choose for  $K^{\pm}$  the  $K\pi$  combination with  $0.7 < M_{K\pi}^2 < 0.9 \text{ GeV}^2/c^4$ . In the other reactions we have more than 70% of  $K^{\pm}$  production; therefore we take as  $K^{\pm}$  the  $(K\pi)$  combination whose effective mass is the nearest of the  $K^{\pm}$  mass (891 MeV), (Ref.9). In this way we do take some events with wrong  $K^{\pm}$ , but the predictions of CP and C are still good for these events.

To test the invariance, we first weight each event with the inverse of the probability to find the  $K_1^0$  decaying in  $\pi^+ \pi^-$  (Ref.10), and make distributions of the momentum and angles of the particles in reactions (11) and (12). Most of the angular distributions are very anisotropic which make the tests more meaningful. Any prediction of CP and of C invariances means the similarity of 2 histograms (Ref.11). We examine

the  $\chi^2$  of the difference in the two distributions i.e.:

$$\chi^2 = \frac{1}{W_a} \sum_{i=1}^{NB} (N_i - \bar{N}_i)^2 / (N_i + \bar{N}_i)$$

where  $W_a$  is the average weight of each event,  $N_i$  and  $\bar{N}_i$  are the number of events of the distribution in the  $i^{\text{th}}$  bin of reactions (11) and (12), and NB the number of bins of the distribution. In the case of non violation the  $\chi^2$  value is expected to be equal to the number of  $N_B$ . It should be mentioned that a particular reaction gives more than one distribution. We believe that these distributions are essentially independent for the purpose of this test.

In table I we list the tests which were performed for CP invariance. In table II we give the test which was performed for C invariance alone, and in table III, the test related to P invariance (Ref.12).

We do not see any statistically significant deviation from the expected  $\chi^2$ .

The preceding tests show only that our data are in good agreement with the predictions of CP and C invariances. We need to make a model in order to estimate the relative amplitude of a possible non conserving part of the annihilation interaction.

Rigorously, we should introduce a C non conserving amplitude  $\alpha_{\ell S}$  and a C conserving amplitude  $\beta_{\ell S}$  for each possible quantum state (defined for  $\bar{p}p$  by the orbital angular momentum  $\ell$  and the spin  $S$ ).

In first approximation, we neglect this dependance and assume moreover that the relative contribution of C non-conserving amplitude  $\alpha$  to the conserving amplitude  $\beta$ , and their relative phase  $\phi$ , are the same in all bins of all distributions. Then the ratio  $\frac{N - \bar{N}}{N + \bar{N}}$  is related to the amplitudes  $\alpha$  and  $\beta$  :

$$\frac{N - \bar{N}}{N + \bar{N}} = \frac{2 \operatorname{Re} \alpha \beta^*}{|\alpha|^2 + |\beta|^2} = 2V$$

This ratio gives then a lower limit of the violation.

We find :

$$V_{CP} = (0.4 \pm 1.0) \times 10^{-2}$$

$$V_C = (0.4 \pm 1.0) \times 10^{-2}$$

$$V_P = (0.1 \pm 1.0) \times 10^{-2}$$

To test the model, we have computed for each distribution the  $\chi^2$  (presented as  $\chi^2$  minimum in the tables) corresponding to the admixture of  $\alpha$  and  $\beta$  amplitudes found above. The examination of these  $\chi^2$  minimum gives some confidence in our model.

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because the  $\theta$  and  $\phi$  angles can not be defined.
- 8) Experimental results on the annihilations of 1.2 GeV/c antiprotons  
into two and three body final state : CERN, College de France,  
Institut du Radium, Liverpool Collaboration. To be published.
- 9) In each of these events there are  $4(K\pi)$  combinations with  $I_z = \pm 1/2$ .
- 10) This weight varies from 1.0 to 1.3 with an average of 1.15.
- 11) When a prediction can be made by both CP invariance and C invariance,  
we consider it as a test of CP invariance.
- 12) P invariance could be deduced from the study of C and CP invariances.  
In a more direct way, Pais (Ref.6) has shown that for any  $\bar{p}p$  reaction,  
P invariance would predict :

$$W(\phi_{12}) = W(-\phi_{12})$$

TABLE 1

SUMMARY OF CP INVARIANCE TEST

Reactions studied	Number of counts $N_c$	DISTRIBUTIONS WHICH ARE COMPARED		$\chi^2 = \frac{1}{W} \sum_{i=1}^{N_B} \frac{(N_i - \bar{N}_i)^2}{(N_i + \bar{N}_i)}$	$\chi^2$ minimum	Number of intervals $N_B$
$K^* \bar{K}$ (171.1 evts) $\downarrow$ $K \pi$ $\bar{K}^* K$ (184.2 evts) $\downarrow$ $\bar{K} \pi$	355.3	PK in $K^*$	P $\bar{K}$ in $\bar{K}^*$	13.9	13.3	11
	"	$\cos \theta K^*$	$\cos \theta \bar{K}^*$	6.9	6.2	5
	"	$\cos \theta \pi$ in $K^*$	$-\cos \theta \pi$ in $\bar{K}^*$	8.5	8.0	5
	"	$\Delta \phi K^* K$	$\Delta \phi \bar{K}^* \bar{K}$	5.6	3.1	6
$K^* \bar{K} \pi$ (1565.4 evts) $\downarrow$ $K \pi$  $\bar{K}^* K \pi$ (1537.5 evts) $\downarrow$ $\bar{K} \pi$	3102.9	PK*	P $\bar{K}^*$	8.5	18.0	9
	"	PK in $K^*$	P $\bar{K}$ in $\bar{K}^*$	10.6	9.0	10
	"	P $\bar{K}$ out $K^*$	P K out $\bar{K}^*$	5.7	4.7	10
	"	P $\pi$ out $K^*$	P $\pi$ out $\bar{K}^*$	7.7	6.3	9
	"	$\cos \theta K^*$	$-\cos \theta \bar{K}^*$	5.4	4.4	5
	"	$\cos \theta K$ in $K^*$	$-\cos \theta \bar{K}$ in $\bar{K}^*$	10.0	8.3	5
	"	$\cos \theta \bar{K}$ out $K^*$	$-\cos \theta K$ out $\bar{K}^*$	14.0	11.7	5
	"	$\cos \theta \pi$ out $K^*$	$-\cos \theta \pi$ out $\bar{K}^*$	2.9	2.3	5
	"	$\Delta \phi K^* K$ in $K^*$	$\Delta \phi \bar{K}^* \bar{K}$ in $\bar{K}^*$	6.7	5.5	6
	"	$\Delta \phi K^* \bar{K}$ out $K^*$	$\Delta \phi \bar{K}^* K$ out $\bar{K}^*$	1.5	1.1	6
"	$\Delta \phi K^* \pi$ out $K^*$	$\Delta \phi \bar{K}^* \pi$ out $\bar{K}^*$	6.0	4.9	6	
$K^* \bar{K} \pi \pi_S$ (172.5 evts) $\downarrow$ $K \pi$  $\bar{K}^* K \pi \pi_S$ (166.8 evts) $\downarrow$ $\bar{K} \pi$	339.3	PK*	P $\bar{K}^*$	8.7	2.5	8
	"	PK in $K^*$	P $\bar{K}$ in $\bar{K}^*$	7.7	5.9	9
	"	P $\bar{K}$ out $K^*$	P K out $\bar{K}^*$	5.1	5.8	8
	"	P $\pi$ out $K^*$	P $\pi$ out $\bar{K}^*$	5.5	2.3	8
	"	P $\pi_S$ out $K^*$	P $\pi_S$ out $\bar{K}^*$	5.5	5.1	7
	"	$\cos \theta K^*$	$-\cos \theta \bar{K}^*$	7.9	8.7	5
	"	$\cos \theta K$ in $K^*$	$-\cos \theta \bar{K}$ in $\bar{K}^*$	4.0	6.8	5
	"	$\cos \theta \bar{K}$ out $K^*$	$-\cos \theta K$ out $\bar{K}^*$	9.4	7.6	5
	"	$\cos \theta \pi$ out $K^*$	$-\cos \theta \pi$ out $\bar{K}^*$	3.3	6.6	5
	"	$\cos \theta \pi_S$ out $K^*$	$-\cos \theta \pi_S$ out $\bar{K}^*$	4.6	3.8	5
"	$\Delta \phi K^* K$ in $K^*$	$\Delta \phi \bar{K}^* \bar{K}$ in $\bar{K}^*$	3.3	2.8	6	
"	$\Delta \phi K^* \bar{K}$ out $K^*$	$\Delta \phi \bar{K}^* K$ out $\bar{K}^*$	5.9	5.0	6	
"	$\Delta \phi K^* \pi$ out $K^*$	$\Delta \phi \bar{K}^* \pi$ out $\bar{K}^*$	5.0	4.2	6	
"	$\Delta \phi K^* \pi_S$ out $K^*$	$\Delta \phi \bar{K}^* \pi_S$ out $\bar{K}^*$	5.0	4.2	6	
Total	$N_c = 47\ 502$			$\chi^2_t = 194.8$	1791	$\chi^2_m = 192$





**TABLE 2**

**SUMMARY OF C INVARIANCE TEST**

Reactions studied	Number of counts	DISTRIBUTIONS WHICH ARE COMPARED		$\chi^2 = \frac{1}{W} \sum_{i=1}^{N_B} \frac{(N_i - \bar{N}_i)^2}{(N_i + \bar{N}_i)}$	$\chi^2$ minimum	Number of intervals $N_B$
$K^* \bar{K}$ (171.1 evts) $\bar{K}^* K$ (184.2 evts)	355.3	$\Delta \phi K^* K$ in $K^*$	$-\Delta \phi \bar{K}^* \bar{K}$ in $\bar{K}^*$	2.9	2.0	6
$K^* \bar{K} \pi$ (1565.4 evts)	3102.9	$\Delta \phi K^* K$ in $K^*$	$-\Delta \phi \bar{K}^* \bar{K}$ in $\bar{K}^*$	5.4	4.4	6
	..	$\Delta \phi K^* \bar{K}$ out $K^*$	$-\Delta \phi \bar{K}^* K$ out $\bar{K}^*$	5.4	4.0	6
	..	$\Delta \phi K^* \pi$ out $K^*$	$-\Delta \phi \bar{K}^* \pi$ out $\bar{K}^*$	4.3	3.2	6
$\bar{K}^* K \pi$ (1537.5 evts)	339.3	$\Delta \phi K^* K$ in $K^*$	$-\Delta \phi \bar{K}^* \bar{K}$ in $\bar{K}^*$	7.5	5.1	6
	..	$\Delta \phi K^* \bar{K}$ out $K^*$	$-\Delta \phi \bar{K}^* K$ out $\bar{K}^*$	5.7	6.5	6
	..	$\Delta \phi K^* \pi$ out $K^*$	$-\Delta \phi \bar{K}^* \pi$ out $\bar{K}^*$	8.9	8.0	6
$\bar{K}^* K \pi \pi_s$ (172.5 evts)	..	$\Delta \phi K^* \pi_s$ out $K^*$	$-\Delta \phi \bar{K}^* \pi_s$ out $\bar{K}^*$	3.5	3.0	6
$\bar{K}^* K \pi \pi_s$ (166.8 evts)	..	$\Delta \phi K^* \pi_s$ out $K^*$	$-\Delta \phi \bar{K}^* \pi_s$ out $\bar{K}^*$	3.5	3.0	6
<b>Total</b>	<b>N = 11021.2</b>			<b>43.6</b>	<b>36.2</b>	<b>48</b>

**TABLE 3**

**SUMMARY OF P INVARIANCE TEST**

Reactions studied	Number of counts	DISTRIBUTIONS WHICH ARE COMPARED		$\chi^2 = \frac{1}{W} \sum_{i=1}^{N_B} \frac{(N_i - \bar{N}_i)^2}{(N_i + \bar{N}_i)}$	$\chi^2$ minimum	Number of intervals $N_B$
$K^* K$ (171.2 evts)	171.2	$\Delta \phi K^* K$ in $K^*$	$-\Delta \phi K^* K$ in $K^*$	4.5	4.0	3
$\bar{K}^* K$ (184.2 evts)	184.2	$\Delta \phi \bar{K}^* \bar{K}$ in $\bar{K}^*$	$-\Delta \phi \bar{K}^* \bar{K}$ in $\bar{K}^*$	1.2	0.2	3
$K^* \bar{K} \pi$ (1565.4 evts)	1565.4	$\Delta \phi K^* K$ in $K^*$	$-\Delta \phi K^* K$ in $K^*$	0.9	0.7	3
	1537.5	$\Delta \phi \bar{K}^* \bar{K}$ in $\bar{K}^*$	$-\Delta \phi \bar{K}^* \bar{K}$ in $\bar{K}^*$	1.2	1.1	3
	1565.4	$\Delta \phi K^* \bar{K}$ out $K^*$	$-\Delta \phi K^* \bar{K}$ out $K^*$	2.8	2.5	3
	1537.5	$\Delta \phi \bar{K}^* K$ out $\bar{K}^*$	$-\Delta \phi \bar{K}^* K$ out $\bar{K}^*$	1.3	1.0	3
$\bar{K}^* K \pi$ (1537.5 evts)	1565.4	$\Delta \phi K^* \pi$ out $K^*$	$-\Delta \phi K^* \pi$ out $K^*$	0.4	0.4	3
	1537.5	$\Delta \phi \bar{K}^* \pi$ out $\bar{K}^*$	$-\Delta \phi \bar{K}^* \pi$ out $\bar{K}^*$	1.4	1.0	3
	1537.5	$\Delta \phi \bar{K}^* \pi$ out $\bar{K}^*$	$-\Delta \phi \bar{K}^* \pi$ out $\bar{K}^*$	1.4	1.0	3
$K^* \bar{K} \pi \pi_s$ (172.5 evts)	172.5	$\Delta \phi K^* K$ in $K^*$	$-\Delta \phi K^* K$ in $K^*$	4.4	3.0	3
	166.8	$\Delta \phi \bar{K}^* \bar{K}$ in $\bar{K}^*$	$-\Delta \phi \bar{K}^* \bar{K}$ in $\bar{K}^*$	1.4	1.1	3
	172.5	$\Delta \phi K^* \bar{K}$ out $K^*$	$-\Delta \phi K^* \bar{K}$ out $K^*$	0.9	0.8	3
	166.8	$\Delta \phi \bar{K}^* K$ out $\bar{K}^*$	$-\Delta \phi \bar{K}^* K$ out $\bar{K}^*$	1.8	1.6	3
$\bar{K}^* K \pi \pi_s$ (166.8 evts)	172.5	$\Delta \phi K^* \pi$ out $K^*$	$-\Delta \phi K^* \pi$ out $K^*$	8.6	8.0	3
	166.8	$\Delta \phi \bar{K}^* \pi$ out $\bar{K}^*$	$-\Delta \phi \bar{K}^* \pi$ out $\bar{K}^*$	1.5	1.3	3
	172.5	$\Delta \phi K^* \pi_s$ out $K^*$	$-\Delta \phi K^* \pi_s$ out $K^*$	3.5	3.0	3
	166.8	$\Delta \phi \bar{K}^* \pi_s$ out $\bar{K}^*$	$-\Delta \phi \bar{K}^* \pi_s$ out $\bar{K}^*$	3.5	3.2	3
<b>Total</b>	<b>11021.2</b>			<b>39.3</b>	<b>32.7</b>	<b>48</b>

