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

L. DOBRZYNSKI, NGUYEN-HUU XUONG *,
College de France, Paris

L. MONTANET, M. TOMAS,
CERN, Geneva

J. DUBOC,
Institut du Radium, Paris

R. A. DONALD,
University of Liverpool, Liverpool

Received 23 May 1966

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 are also consistent with a relative amplitude of *P* violation of $(0.1 \pm 1.0) \times 10^{-2}$.

The possible violation of *CP* invariance observed by Christenson et al. [1] in K_2^0 decay opens the way to the suggestion that C invariance could be violated in strong interactions [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 [3]. A search for a possible violation of *C* invariance has also been made, using $\bar{p}p$ annihilations at rest [4]; however, in this case, no attempt was made to distinguish between *C* and *CP* invariance **.

Let us consider the 2 reactions:

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

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

where X may be any assembly of particles.

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 θ_1 (θ_2) relative to the direction of $\bar{p}$, where φ_{12} is the azimuth of 2 relative to the ($\bar{p}$ 1) plane.

Pais [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:

$$W(p_1) = W(p_{\bar{1}}) \qquad W(p_2) = W(p_{\bar{2}})$$

$$W(\theta_1) = W(\pi - \theta_1) \qquad W(\theta_2) = W(\pi - \theta_2)$$

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)***.

The events used for this study were obtained in a study of 300 000 pictures of the Saclay 81 cm

* John Simon-Guggenheim fellow, on leave of absence from the Physics Department, University of California at San Diego.

** In nuclear reactions an upper limit of P non-conserving amplitude of 10^{-5} has been established [e.g. 5].

*** In $\bar{p}p$ annihilation at rest, some of these predictions do not exist because the θ and φ angles cannot be defined.

Table 1
Summary of *CP* Invariance test

Reactions studied	Number of counts N_c	Distributions which are compared		$\chi^2 = \frac{1}{W}\sum_{i=1}^{N_B}\frac{(N_i-\overline{N}_i)^2}{(N_i+\overline{N}_i)}$	χ^2 minimum	Number of intervals N_B
$K^*\overline{K}$ (171.1 events)	355.3	PK in K*	P$\overline{K}$ in $\overline{K}$*	13.9	13.3	11
↳ $K\pi$	355.3	cos θK*	cos $\theta\overline{K}$*	6.9	6.2	5
$\overline{K}^*$ K(184.2 events)	355.3	cos $\theta\pi$ in K*	-cos $\theta\,\pi$ in $\overline{K}$*	8.5	8.0	5
↳ $\overline{K}\pi$	355.3	$\Delta\varphi$K*K	$\Delta\varphi\overline{K}^*\overline{K}$	5.6	3.1	6
	3102.9	PK*	P$\overline{K}$*	8.5	18.0	9
	3102.9	PK in K*	P$\overline{K}$ in $\overline{K}$*	10.6	9.0	10
	3102.9	P$\overline{K}$ out K*	PK out $\overline{K}$*	5.7	4.7	10
$K^*\,\overline{K}\pi$ (1565.4 events) ↳ $K\pi$	3102.9	Pπ out K*	Pπ out $\overline{K}$*	7.7	6.3	9
	3102.9	cos θ K*	-cos $\theta\,\overline{K}$*	5.4	4.4	5
	3102.9	cos θ K in K*	-cos $\theta\,\overline{K}$ in $\overline{K}$*	10.0	8.3	5
$\overline{K}^*\,K\pi$ (1537.5 events)	3102.9	cos $\theta\,\overline{K}$ out K*	-cos θ K out $\overline{K}$*	14.0	11.7	5
↳ $\overline{K}\pi$	3102.9	cos $\theta\,\pi$ out K*	-cos $\theta\,\pi$ out $\overline{K}$*	2.9	2.3	5
	3102.9	$\Delta\varphi$K*K in K*	$\Delta\varphi\overline{K}^*\overline{K}$ in $\overline{K}$*	6.7	5.5	6
	3102.9	$\Delta\varphi$K*$\overline{K}$ out K*	$\Delta\varphi\overline{K}$*K out $\overline{K}$*	1.5	1.1	6
	3102.9	$\Delta\varphi$K*π out K*	$\Delta\varphi\overline{K}^*\pi$ out $\overline{K}$*	6.0	4.9	6
	339.3	PK*	P$\overline{K}$*	8.7	2.5	8
	339.3	PK in K*	P$\overline{K}$ in $\overline{K}$*	7.7	5.9	9
	339.3	P$\overline{K}$ out K*	PK out $\overline{K}$*	5.1	5.8	8
	339.3	Pπ out K*	Pπ out $\overline{K}$*	5.5	2.3	8
$K^*\,\overline{K}\pi\,\pi_s$ (172.5 events) ↳ $K\pi$	339.3	Pπ_s out K*	Pπ_s out $\overline{K}$*	5.5	5.1	7
	339.3	cos θ K*	-cos $\theta\,\overline{K}$*	7.9	8.7	5
	339.3	cos θ K in K*	-cos $\theta\,\overline{K}$ in $\overline{K}$*	4.0	6.8	5
$\overline{K}^*\,K\pi\,\pi_s$ (166.8 events)	339.3	cos $\theta\,\overline{K}$ out K*	-cos θ K out $\overline{K}$*	9.4	7.6	5
↳ $\overline{K}\pi$	339.3	cos $\theta\,\pi$ out K*	-cos $\theta\,\pi$ out $\overline{K}$*	3.3	6.6	5
	339.3	cos $\theta\,\pi_s$ out K*	-cos $\theta\pi_s$ out $\overline{K}$*	4.6	3.8	5
	339.3	$\Delta\varphi$K*K in K*	$\Delta\varphi\overline{K}^*\overline{K}$ in $\overline{K}$*	3.3	2.8	6
	339.3	$\Delta\varphi$K*$\overline{K}$ out K*	$\Delta\varphi\overline{K}$*K out $\overline{K}$*	5.9	5.0	6
	339.3	$\Delta\varphi$K*π out K*	$\Delta\varphi\overline{K}^*\pi$ out $\overline{K}$*	5.0	4.2	6
	339.3	$\Delta\varphi$K*π_s out K*	$\Delta\varphi\overline{K}^*\pi_s$ out $\overline{K}$*	5.0	4.2	6
Total	$N_c = 47\,502$			$\chi^2_t = 194.8$	179.1	$\chi^2_m = 192$

H.B.C. exposed to a beam of 1.2 GeV/c of antiprotons at the CERN proton synchroton.

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

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

343 events of the reaction $K^0_1\, K^-\pi^+$ (4)

744 events of the reaction $\bar{p}p \rightarrow \overline{K}^0_1\, K^+\pi^-\pi^0$ (5)

791 events of the reaction $\bar{p}p \rightarrow K^0_1\, K^-\pi^+\pi^0$ (6)

783 events of the reaction $K^0_1(K^0)\,\pi^+\pi^-$ (7)

352 events of the reaction $K^0_1\, K^0_1\,\pi^+\pi^-$ (8)

165 events of the reaction $\bar{p}p \rightarrow \overline{K}^0_1\, K^+\,\pi^-\pi^+\pi^-$ (9)

135 events of the reaction $K^0_1\, K^-\,\pi^+\pi^+\pi^-$ (10)

The application of the tests mentioned above (excluding reaction (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 show a large production of K*(890), we have then applied the tests to the following conjugate states:

$$\bar{p}p \rightarrow K^* + \overline{K} + n\pi \qquad (n=0,1,2) \qquad (11)$$

$$\bar{p}p \rightarrow \overline{K}^* + K + n\pi \qquad (12)$$

Table 2
Summary of C invariance test

Reactions studied	Number of counts	Distributions which are compared		$\chi^2 = \frac{1}{W}\sum_{i=1}^{N_B} \frac{(N_i - \bar{N}_i)^2}{(N_i + \bar{N}_i)}$	χ^2 minimum	Number of intervals N_B
$K^*\bar{K}$ (171.1 events) $\bar{K}^*K$ (184.2 events)	355.3	$\Delta\varphi K^*K$ in K^*	$-\Delta\varphi\bar{K}^*\bar{K}$ in $\bar{K}^*$	2.9	2.0	6
	3102.9	$\Delta\varphi K^*K$ in K^*	$-\Delta\varphi\bar{K}^*\bar{K}$ in $\bar{K}^*$	5.4	4.4	6
$K^*\bar{K}\pi$ (1565.4 events)	3102.9	$\Delta\varphi K^*\bar{K}$ out K^*	$-\Delta\varphi\bar{K}^*K$ out $\bar{K}^*$	5.4	4.0	6
	3102.9	$\Delta\varphi K^*\pi$ out K^*	$-\Delta\varphi\bar{K}^*\pi$ out $\bar{K}^*$	4.3	3.2	6
$\bar{K}^*K\pi$ (1537.5 events)						
	339.3	$\Delta\varphi K^*K$ in K^*	$-\Delta\varphi\bar{K}^*\bar{K}$ in $\bar{K}^*$	7.5	5.1	6
$K^*\bar{K}\pi\pi_s$ (172.5 events)	339.3	$\Delta\varphi K^*\bar{K}$ out K^*	$-\Delta\varphi\bar{K}^*K$ out $\bar{K}^*$	5.7	6.5	6
	339.3	$\Delta\varphi K^*\pi$ out K^*	$-\Delta\varphi\bar{K}^*\pi$ out $\bar{K}^*$	8.9	8.0	6
$\bar{K}^*K\pi\pi_s$ (166.8 events)	339.3	$\Delta\varphi K^*\pi_s$ out K^*	$-\Delta\varphi\bar{K}^*\pi_s$ out $\bar{K}^*$	3.5	3.0	6
Total	N = 11 021.2			43.6	36.2	48

Table 3
Summary of P invariance test

Reactions studied	Number of counts	Distributions which are compared		$\chi^2 = \frac{1}{W}\sum_{i=1}^{N_B} \frac{(N_i - \bar{N}_i)^2}{(N_i + \bar{N}_i)}$	χ^2 minimum	Number of intervals N_B
K^*K (171.2 events)	171.2	$\Delta\varphi K^*K$ in K^*	$-\Delta\varphi K^*K$ in K^*	4.5	4.0	3
$\bar{K}^*K$ (184.2 events)	184.2	$\Delta\varphi\bar{K}^*\bar{K}$ in $\bar{K}^*$	$-\Delta\varphi\bar{K}^*\bar{K}$ in $\bar{K}^*$	1.2	0.2	3
	1565.4	$\Delta\varphi K^*K$ in K^*	$-\Delta\varphi K^*K$ in K^*	0.9	0.7	3
$K^*\bar{K}\pi$ (1565.4 events)	1537.5	$\Delta\varphi\bar{K}^*\bar{K}$ in $\bar{K}^*$	$-\Delta\varphi\bar{K}^*\bar{K}$ in $\bar{K}^*$	1.2	1.1	3
	1565.4	$\Delta\varphi K^*\bar{K}$ out K^*	$-\Delta\varphi K^*\bar{K}$ out K^*	2.8	2.5	3
	1537.5	$\Delta\varphi\bar{K}^*K$ out $\bar{K}^*$	$-\Delta\varphi\bar{K}^*K$ out $\bar{K}^*$	1.3	1.0	3
$\bar{K}^*K\pi$ (1537.5 events)	1565.4	$\Delta\varphi K^*\pi$ out K^*	$-\Delta\varphi K^*\pi$ out K^*	0.4	0.4	3
	1537.5	$\Delta\varphi\bar{K}^*\pi$ out $\bar{K}^*$	$-\Delta\varphi\bar{K}^*\pi$ out $\bar{K}^*$	1.4	1.0	3
	172.5	$\Delta\varphi K^*K$ in K^*	$-\Delta\varphi K^*K$ in K^*	4.4	3.0	3
	166.8	$\Delta\varphi\bar{K}^*\bar{K}$ in $\bar{K}^*$	$-\Delta\varphi\bar{K}^*\bar{K}$ in $\bar{K}^*$	1.4	1.1	3
$K^*\bar{K}\pi\pi_s$ (172. 5 events)	172.5	$\Delta\varphi K^*\bar{K}$ out K^*	$-\Delta\varphi K^*\bar{K}$ out K^*	0.9	0.8	3
	166.8	$\Delta\varphi\bar{K}^*K$ out $\bar{K}^*$	$-\Delta\varphi\bar{K}^*K$ out $\bar{K}^*$	1.8	1.6	3
	172.5	$\Delta\varphi K^*\pi$ out K^*	$-\Delta\varphi K^*\pi$ out K^*	8.6	8.0	3
$\bar{K}^*K\pi\pi_s$ (166.8 events)	166.8	$\Delta\varphi\bar{K}^*\pi$ out $\bar{K}^*$	$-\Delta\varphi\bar{K}^*\pi$ out $\bar{K}^*$	1.5	1.3	3
	172.5	$\Delta\varphi K^*\pi_s$ out K^*	$-\Delta\varphi K^*\pi_s$ out K^*	3.5	3.0	3
	166.8	$\Delta\varphi\bar{K}^*\pi_s$ out $\bar{K}^*$	$-\Delta\varphi\bar{K}^*\pi_s$ out $\bar{K}^*$	3.5	3.2	3
Total	11 021.2			39.3	32.7	48

Another reason to prefer this type of classification is that reactions which at first view look like charge conjugates of each other, for example $\bar{p}p \to K^+K^0\pi^-$ and $\bar{p}p \to K^-K^0\pi^+$, can come from the same reaction, either reaction (11) (for example $\bar{p}p \to K^{*0}\bar{K}^0 \to (K^+\pi^-)\,\bar{K}^0$ and $\bar{p}p \to K^{*+}K^- \to (K^0\pi^+)K^-$) 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 of choosing the K*.

In the reactions (3) and (4) only 50% of the events give K* [7] and we choose for K* the Kπ combination with $0.7 < M^2_{K\pi} < 0.9$ GeV$^2/c^4$. In the other reactions we have more than 70% of K* production; therefore we take as K* the (Kπ) combination whose effective mass is nearest to the K* mass (891 MeV) †. In this way we do take some events with wrong K*, but the predictions of CP and C are still good for these events.

To test the invariance, we first weight each

† In each of these events there are 4(Kπ) combinations with $I_z = \pm\frac{1}{2}$.

AM+O 77

event with the inverse of the probability of finding the K_1^0 decaying in $\pi^+\pi^-$ † 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 ††. We examine the χ^2 of the difference in the two distributions i.e.:

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

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 ith bin of reactions (11) and (12) and N_B the number of bins of the distribution. In the case of non violation the χ^2 value is expected to be equal to the number 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 1 we list the tests which were performed for CP invariance. In table 2 we give the test which was performed for C invariance alone and in table 3, the test relating to P invariance ‡.

We do not see any statistically significant deviation from the expected χ^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 α_{lS} and a C conserving amplitude β_{lS} for each possible quantum state (defined for $\bar{p}p$ by the orbital angular momentum l and the spin S).

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

$$\frac{N-\bar{N}}{N+\bar{N}} = \frac{2\,\mathrm{Re}(\alpha\beta^*)}{|\alpha|^2 + |\beta|^2} = 2V\ .$$

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 χ^2 (presented as χ^2 minimum in the tables) corresponding to the admixture of α and β amplitudes found above. The examination of these χ^2 minimum gives some confidence in our model.

We would like to thank Prof. J. Prentki and Dr. Equer for many helpful discussions.

1. J.H. Christenson, J.W. Cronin, V.L. Fitch and R. Turlay, Phys. Rev. Letters 13 (1964) 138.
2. J. Prentki and M. Veltman, Physics Letters 15 (1965) 88;
T.D. Lee and L. Wolfenstein, Phys. Rev. 138 (1965) B1490.
3. Ng.H. Xuong, G.R. Lynch and C.K. Hinrichs, Phys. Rev. 124 (1961) 575;
B.C. Maglić, G.R. Kalbfleisch and H.L. Stevenson, Phys. Rev. Letters 7 (1961) 137.
4. C. Baltay, N. Barash, P. Franzini, N. Gelfand, L. Kirsch, J. Lützens, J.C. Severiens, J. Steinberger, D. Tycho and D. Zanello, Phys. Rev. Letters 15 (1965) 951:
Study of the charged $K\bar{K}$ system in $\bar{p}p \rightarrow K\bar{K}$ annihilation at rest and a test of C conservation in strong interactions; CERN, College de France, Institut du Radium, Liverpool Collaboration; presented by A. Astier at the 1965 Oxford Conference.
5. L. Grodzins and F. Genovese, Phys. Rev. 121 (1961) 228.
6. A. Pais, Phys. Rev. Letters 3 (1959) 242.
7. Experimental results on the annihilations of 1.2 GeV/c antiprotons into two and three body final states: CERN, College de France, Institut du Radium, Liverpool Collaboration. To be published.

† This weight varies from 1.0 to 1.3 with an average of 1.15.

†† When a prediction can be made by both CP invariance and C invariance, we consider it as a test of CP invariance.

‡ P invariance could be deduced from the study of C and CP invariances. In a more direct way, Pais [6] has shown that for any $\bar{p}p$ reaction, P invariance would predict:

$$W(\varphi_{12}) = W(-\varphi_{12})\ .$$

* * * * *