DETERMINATION OF THE RELATIVE BRANCHING RATIOS
FOR $p\bar{p} \rightarrow \pi^+\pi^-$ AND $p\bar{p} \rightarrow K^+K^-$

CPLEAR Collaboration

R. Adler², A. Angelopoulos¹, A. Apostolakis¹, E. Aslanides^{4,12}, G. Backenstoss²,
C.P. Bee¹⁰, J. Bennet¹⁰, P. Bloch⁴, Ch. Bula¹⁴, G. Burgun¹⁵, P. Carlson¹⁶, J. Carvalho⁵,
M. Chardalas¹⁷, S. Charalambous¹⁷, H. Cobbaert⁵, S. Dedoussis¹⁷, M. Dejardin¹⁵,
J. Derre¹⁵, M. Dodgson¹⁰, J.C. Dousse⁸, J. Duclos¹⁵, A. Ealet¹², B. Eckart², L. Faravel⁸,
P. Fassnacht¹², J.L. Faure^{15, a}, C. Felder², R. Ferreira-Marques⁵, W. Fetscher¹⁸,
M. Fidecaro⁴, A. Filipčič¹¹, D. Francis⁴, J.R. Fry¹⁰, C. Fuglesang¹⁶, E. Gabathuler¹⁰,
R. Gamet^{4,10}, D. Garreta¹⁵, T. Geralis¹², H.-J. Gerber¹⁸, A. Go³, P. Gumplinger^{18, b},
C. Guyot¹⁵, P.F. Harrison^{10, c}, P.J. Hayman¹⁰, W.G. Heyes⁴, R.W. Hollander⁶,
H.U. Johner⁸, K. Jon-And¹⁶, K. Jansson¹⁶, A. Kerek¹⁶, J. Kern⁸, P.-R. Kettle¹⁴,
C. Kochowski¹⁵, P. Kokkas^{7,9}, E. Kossionides⁷, R. Kreuger⁶, T. Lawry³, R. Le Gac¹³,
E. Machado⁴, P. Maley¹⁰, N. Manthos⁹, G. Marel^{4,15}, P. Marotte¹³, M. Mikuž¹¹,
J. Miller³, F. Montanet¹², T. Nakada¹⁴, A. Onofre⁵, B. Pagels², T. Paradelis⁷,
P. Pavlopoulos⁴, F. Pelucchi¹², J. Pinto da Cunha⁵, A. Policarpo⁵, H. Postma⁶,
R. Rickenbach², B.L. Roberts³, E. Rozaki¹, T. Ruf¹⁸, L. Sacks¹⁰, L. Sakeliou¹,
P. Sanders¹⁰, C. Santoni², K. Sarigiannis^{1,7}, L.A. Schaller⁸, A. Schopper⁴, P. Schune¹⁵,
U. Seljak¹¹, S. Szilagyi¹⁶, L. Tauscher², C. Thibault¹³, F. Touchard¹³, C. Touramanis^{7,17},
F. Triantis⁹, D.A. Troester^{2, d}, E. Van Beveren⁵, M. Van den Putte⁶, C.W.E. Van Eijk⁶,
G. Varner³, S. Vlachos¹⁰, D. Warner³, P. Weber¹⁸, C. Witzig^{18, e}, C. Yeche¹⁵,
D. Zavrtanik¹¹ and D. Zimmerman³

Abstract

The ratio of the branching fractions for $p\bar{p} \rightarrow K^+K^-$ and $p\bar{p} \rightarrow \pi^+\pi^-$ was determined with the CPLEAR detector, by stopping antiprotons in a gaseous hydrogen target at 15 bar pressure. It was found to be $BR(K^+K^-)/BR(\pi^+\pi^-) = 0.205 \pm 0.016$. The fraction of P-wave annihilation at rest at this target density was deduced to be $(38 \pm 9)\%$.

(Submitted to Physics Letters B)

¹ University of Athens, Greece.

² University of Basle, Switzerland.

³ Boston University, USA.

⁴ CERN, Geneva, Switzerland.

⁵ LIP and University of Coimbra, Portugal.

⁶ Technical University of Delft, Netherlands.

⁷ Demokritos INP, Athens, Greece.

⁸ University of Fribourg, Switzerland.

⁹ University of Ioannina, Greece.

¹⁰ University of Liverpool, England.

¹¹ J. Stefan Institute and Department of Physics,

University of Ljubljana, Yugoslavia.

¹² CPPM, CNRS/IN2P3, Marseille, France.

¹³ CSNSM, CNRS/IN2P3, Orsay, France.

¹⁴ Paul-Scherrer-Institut (PSI), Villigen, Switzerland.

¹⁵ DPhPE, CEN Saclay, France.

¹⁶ MSI, Stockholm, Sweden.

¹⁷ University of Thessaloniki, Greece.

¹⁸ ETH-IMP Zurich, Switzerland.

^a Now at DPhN/STEN, Saclay, France.

^b Now at TRIUMF, Vancouver, Canada.

^c Now at Queen Mary and Westfield College,
University of London, England.

^d Now at SBS, Basle, Switzerland.

^e Now at Brookhaven National Laboratory,
Upton, NY, USA.

The ratio of the branching fractions for the reactions $p\bar{p} \rightarrow \pi^+\pi^-$ and $p\bar{p} \rightarrow K^+K^-$, $BR(K^+K^-)/BR(\pi^+\pi^-)$, was determined at the Low-Energy Antiproton Ring (LEAR) at CERN in the framework of the experiment PS195 (CPLEAR) [1]. This experiment is designed to study CP violation in the decay of the neutral K meson, whose strangeness at the time of production is measured by selecting, among the many other channels, the annihilations of antiprotons with protons at rest into $K^+\pi^-\bar{K}^0$ and $K^-\pi^+K^0$. By making use of some of the features of the CPLEAR detector during the running-in phase, the final states $\pi^+\pi^-$ and K^+K^- could be identified exclusively. The branching ratios for these channels provide information on annihilation dynamics in general and, more specifically, can be used to extract the fraction of P-wave annihilation at rest at the target density used in the experiment, thus allowing a check of models for the de-excitation of protonium.

The detector is shown in Fig. 1. It has cylindrical geometry, with the $\bar{p}$ beam defining the z -axis, and is built inside a solenoid of 1 m radius, 3.6 m length, with a field of 0.44 T. The 200 MeV/c $\bar{p}$'s are stopped in the target, which is at the centre of the detector and consists of a laminated Kevlar sphere (7 cm radius, 800 μ m wall thickness) filled with gaseous hydrogen at 15 bar pressure. The beam enters the target through a window of 11 mm diameter and 120 μ m thickness. The stopping depth of the $\bar{p}$'s extends over 25 mm (FWHM) in the hydrogen gas. Tracking is done by means of two multiwire proportional chambers, followed by six drift chambers (DC1–DC6) and two layers of streamer tubes. The z -coordinates are determined using cathode-strip readout from the proportional and drift chambers, and the time difference obtained from the upstream and downstream signals of the streamer tubes. Particle identification (PID) is provided by a Cherenkov counter, sandwiched between two plastic scintillators, S1 and S2 (PID). A more complete description of the detector can be found in Ref. [2].

The present analysis uses data taken in December 1989 with a minimum-bias trigger, requiring at least one hit in the scintillator S1. In this run only the cathode strips of the drift chambers DC1, DC2, and DC6 were read out, with reduced efficiency, and only digitally. Further details can be found in Ref. [3].

The particular type of events under investigation are expected to exhibit back-to-back features, if the $\bar{p}$'s had really come to rest. Therefore, in a first step, the following obvious and rather loose requirements were imposed:

- i) the event should have two tracks only, from oppositely charged particles;
- ii) the z -coordinates of the two tracks ($z = 0$ corresponds to the centre of the detector), as provided by the DC6 cathode strips or streamer tubes, sum up to $|z_1 + z_2| < 20$ cm;
- iii) the angle Φ_{12} between the two tracks in the transverse plane, evaluated at the point of closest approach of each track to the z -axis, is $|\Phi_{12}| \geq 170^\circ$.

This selection reduced the original data sample of 1.7×10^6 events to one of 19,577 back-to-back events. This sample contains only geometrically defined back-to-back events, where the curvature of the two tracks may, however, not be the same. For true two-body annihilations, the two tracks correspond to the same momentum and are contiguous parts of the same circle in the transverse plane. A further selection of two-body final states was therefore done by fitting the two tracks by only one circle in the transverse plane and removing events with large χ^2 in the track fit. This leads to a reduction of background and to a substantial improvement of the momentum resolution by more than a factor of 4 with respect to the single-track resolution. Figure 2 shows the momentum distribution obtained by this 'merged' fit. The peaks for K^+K^- and $\pi^+\pi^-$ are clearly visible.

In a final step the remaining background was further reduced by the following sharp ‘back-to-back’ requirements:

- i) the angle between the two tracks in the transverse plane satisfies $|\Phi_{12}| \geq 178^\circ$, corresponding to a cut at about 3σ , hence accepting more than 99% of the candidate events,
- ii) at least three z -values per track are available,
- iii) the angle between the two tracks in the z -direction is close to 180° through the condition $|p_z(1)/p_T(1) + p_z(2)/p_T(2)| < 0.20$, where p_T and p_z are the transverse and longitudinal components of the momentum.

Figure 3 shows the momentum distribution of the events fulfilling these requirements. The peaks for K^+K^- and $\pi^+\pi^-$ are well separated, and only a small background remains.

This momentum distribution was fitted by a function

$$P(p) = P_{BG}(p) + P_K(p) + P_\pi(p) ,$$

where $P_{BG}(p)$, $P_K(p)$, and $P_\pi(p)$ describe the background, the K^+K^- , and the $\pi^+\pi^-$ peaks, respectively. The best parametrization was found to be a linear function for the background (which was justified by a Monte Carlo simulation of different background channels, such as $\pi^\pm\pi^\mp\pi^0$ or $\pi^\pm\pi^\mp\pi^0\pi^0$, whose distributions extend up to the momenta under investigation) and Gaussians for the K^+K^- and $\pi^+\pi^-$ peaks. The number of K^+K^- and $\pi^+\pi^-$ events are then given by the area under the Gaussian peaks, whose positions coincided with the expected momenta within the errors, and whose widths $\sigma(p)/p$ were about 3%, in agreement with Monte Carlo simulations. A total of $N_{K^+K^-} = 417 \pm 25$ and $N_{\pi^+\pi^-} = 2377 \pm 51$ events were found, which result in a relative yield of

$$R_{\text{raw}} = \frac{N_{K^+K^-}}{N_{\pi^+\pi^-}} = 0.175 \pm 0.011_{\text{stat}} \pm 0.007_{\text{syst}} .$$

The systematic error arises from the influence of the limits of the fit interval and from possible deviations of the background from the linear parametrization, especially under the K^+K^- peak.

The ratio R_{raw} must be corrected for the different acceptances for K^+K^- and $\pi^+\pi^-$ events, arising mainly from the different lifetimes of charged kaons and pions. The ratio of the acceptances was obtained from a simulation using GEANT3 [4] as

$$\kappa = \frac{\text{acc}(K^+K^-)}{\text{acc}(\pi^+\pi^-)} = 0.856 \pm 0.015_{\text{stat}} \pm 0.011_{\text{syst}} .$$

The systematic error has two contributions. The first one, estimated to be 0.005, arises from the choice of the cut parameters for the back-to-back selection, and from the non-Gaussian tails of the K^+K^- and $\pi^+\pi^-$ momentum distributions. The second one stems from uncertainties in the simulation, which were estimated to amount to 1%.

Thus the final result is

$$R = \frac{\text{BR}(K^+K^-)}{\text{BR}(\pi^+\pi^-)} = \frac{R_{\text{raw}}}{\kappa} = 0.205 \pm 0.016 ,$$

where the statistical and systematic errors have been added quadratically.

Previous experiments measured R to be 0.161 ± 0.009 in gaseous hydrogen at NTP [5] and 0.327 ± 0.008 [6] in liquid hydrogen. The target densities in these two

experiments differ by a factor of almost 1000. The present measurement provides a value at an intermediate density and confirms the rise of R with increasing target density. This is because, at high target density, annihilation from atomic P-states becomes less probable than annihilation from atomic S-states due to Stark-effect induced mixing.

The ASTERIX Collaboration at LEAR has obtained the partial widths $\gamma_l = \Gamma_l/\Gamma$ for $p\bar{p}$ annihilation into K^+K^- and $\pi^+\pi^-$ for initial S and P states separately [5]: $\gamma_S(K^+K^-) = (1.08 \pm 0.05) \times 10^{-3}$, $\gamma_P(K^+K^-) = (0.287 \pm 0.051) \times 10^{-3}$, and $\gamma_S(\pi^+\pi^-) = (3.19 \pm 0.20) \times 10^{-3}$, $\gamma_P(\pi^+\pi^-) = (4.81 \pm 0.49) \times 10^{-3}$. Our result for R may be used to determine, with the help of these partial widths, the fraction of P-wave annihilation f_P in gaseous hydrogen at a pressure of 15 bar through

$$f_P = \frac{\gamma_S(K^+K^-) - R\gamma_S(\pi^+\pi^-)}{R[\gamma_P(\pi^+\pi^-) - \gamma_S(\pi^+\pi^-)] - [\gamma_P(K^+K^-) - \gamma_S(K^+K^-)]} .$$

We derive

$$f_P = 0.379 \pm 0.039_{\text{stat}} \pm 0.025_{\text{syst}} \pm 0.072_{\text{ext}} .$$

The statistical and systematic errors are due to the errors of our measurement. The dominant error (ext) is due to the errors of the above absolute branching ratios [5]. Our value $f_P = 0.379 \pm 0.086$ is consistent with cascade calculations of Reifenroether and Klempt [7].

This work was supported by the following funding institutions: the Swiss National Science Foundation, the Swedish Natural Science Research Council, the French CNRS/Institut National de Physique Nucléaire et de Physique des Particules, the French Commissariat à l'Energie Atomique, the Science and Engineering Research Council of the UK (SERC), the Greek General Secretariat of Research and Technology, and NSRC (Nuclear Physics Institute) 'Demokritos', the Laboratorio de Instrumentacao e Fisica Experimental de Particulas (LIP) and the University of Coimbra (Portugal), the Netherlands Foundation for Fundamental Research on Matter (FOM), the US National Science Foundation, and the Slovene Secretariat for Research and Technology. We also wish to thank the CERN LEAR staff for their support and co-operation. Furthermore, we are indebted to the technical staff of the collaborating institutes. We also acknowledge the useful discussions we had with C. Amsler and E. Klempt.

REFERENCES

- [1] CPLEAR Proposal, CERN/PSCC/85-6 (1985).
- [2] R. Adler et al., LEAP 90, Proc. First Biennial Conference on Low Energy Antiproton Physics, Stockholm, 1990, eds. P. Carlson, A. Kerek and S. Szilagyi (World Scientific, Singapore, 1991), p. 414.
- [3] Ch. Witzig, Thesis, ETH Zurich, 1990.
- [4] GEANT3, DD/EE 84-1, Data Handling Division, CERN, Geneva, 1987.
- [5] M. Doser et al., Nucl. Phys. **A486** (1988) 493.
- [6] A. Angelopoulos et al., Antiproton 86, Proc. 8th European Symposium on Nucleon-Antinucleon Interactions, eds. S. Charalambous, C. Papastefanou and P. Pavlopoulos (World Scientific, Singapore, 1987), p. 79.
See also: R. Armenteros and B. French, in 'High Energy Physics', ed. E.H.S. Burhop (Academic Press, New York, 1969), and
C. Baltay et al., Phys. Rev. Lett. **15** (1965) 532.
- [7] G. Reifenroether and E. Klempt, Nucl. Phys. **A503** (1989) 885 and Phys. Lett. **B245** (1990) 129.

Figure captions

Figure 1: Transverse view of the CPLEAR detector. For details see text. A typical signature for a $\pi^+\pi^-$ event is shown. A hit on the wire chambers is marked by an X, in the streamer tubes by a hatched circle. The hit PID scintillators are marked by their hatched areas, the hit and fired Cherenkov detectors by their black areas.

Figure 2: Momentum distribution when the two tracks are fitted as one track ('merged fit'). The K^+K^- and $\pi^+\pi^-$ peaks appear at the expected momenta of 797 MeV/c and 927 MeV/c, respectively. The broad enhancement at low momenta is due to background events.

Figure 3: Momentum distribution obtained with the final cuts.

Fig. 1

Fig. 2

Fig. 3