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Experimental measurement of the $K_S K_S / K_S K_L$ ratio in antiproton annihilations at rest in gaseous hydrogen at 15 and 27 bar

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Abstract

The ratio R between the branching fractions of $\bar{p}p \to K_SK_S$ and $\bar{p}p \to K_SK_L$ for antiprotons annihilating at rest in gaseous hydrogen at 27 bar pressure was measured with the CPLEAR detector to be $R(27\ \text{bar}) = 0.037 \pm 0.002$. The fraction of P-wave annihilation at rest at this target density was deduced to be 0.45 ± 0.06. A value of R was also measured at 15 bar, with less statistics, yielding $R(15\ \text{bar}) = 0.041 \pm 0.009$.

1. Introduction

The branching fractions for two-body channels in $\bar{p}p$ annihilation at rest provide information on the annihilation dynamics and can be used to extract the fraction of P-wave annihilation [1]. It is known that this fraction depends on the target density, due to the Stark effect which favours atomic S-states at higher densities. The reaction $\bar{p}p \to K_SK_S$ at rest occurs through the $^3P_0(J^{PC} = 0^{++})$ and $^3P_2(J^{PC} = 2^{++})$ initial states while the reaction $\bar{p}p \to K_SK_L$ at rest occurs only through the $^3S_1(J^{PC} = 1^{--})$ state. The ratio R = BR ($\bar{p}p \to K_SK_S$) / BR ($\bar{p}p \to K_SK_L$) therefore provides a measurement of the P- to S-wave relative abundance. We report here on two measurements of R with gaseous hydrogen targets at 27 and 15 bar.

2. Experimental apparatus

The measurements were performed with the CPLEAR detector at the Low-Energy Antiproton Ring (LEAR) at CERN. The CPLEAR experiment was designed to study the discrete symmetries CP, T and CPT in the neutral kaon system.

We recall briefly the main components of the detector; a more detailed description of the apparatus can be found elsewhere [2]. Antiprotons of 200 MeV/c momentum are extracted from LEAR with an intensity of 10^6 particles per second and stopped inside a gaseous hydrogen target. A cylindrical tracking detector is located inside a solenoid (radius 1 m, length 3.6 m) providing a 0.44 T magnetic field parallel to the beam, and consists of two layers of MWPCs (PC1, PC2), six layers of drift chambers and two layers of streamer tubes (Fig. 1a). A hodoscope of 32 threshold Cherenkov counters sandwiched between two scintillator hodoscopes provides fast trigger signals.

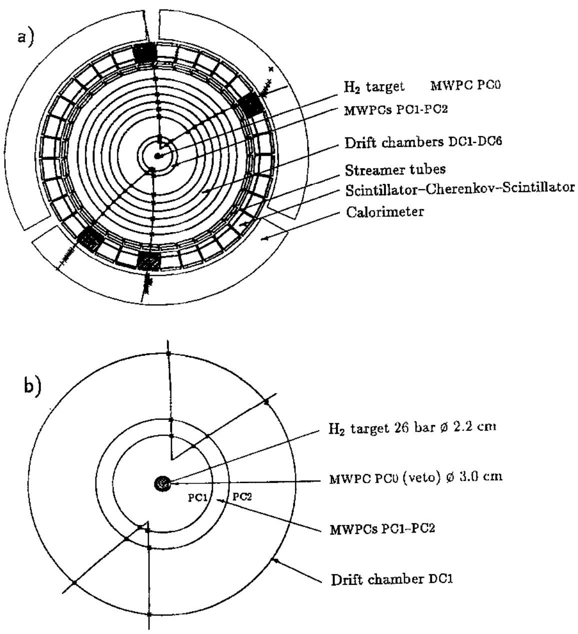

Fig. 1. (a) Transverse view of the CPLEAR detector with a typical $\bar{p}p \to K_SK_S$ event. The solenoid coils are not shown. (b) Expanded view of the detector's central region.

In the following we will concentrate on the 27 bar measurement with a dedicated trigger. We used a cylindrical target (radius 11 mm) surrounded by a cylindrical proportional chamber PC0 (radius 15 mm, pitch 1 mm) with more than 99.5% efficiency for tracking charged particles (see Fig. 1b). The trigger required that no charged particle came out of the target (PC0 in veto), and at least two charged tracks were detected by the tracking device.

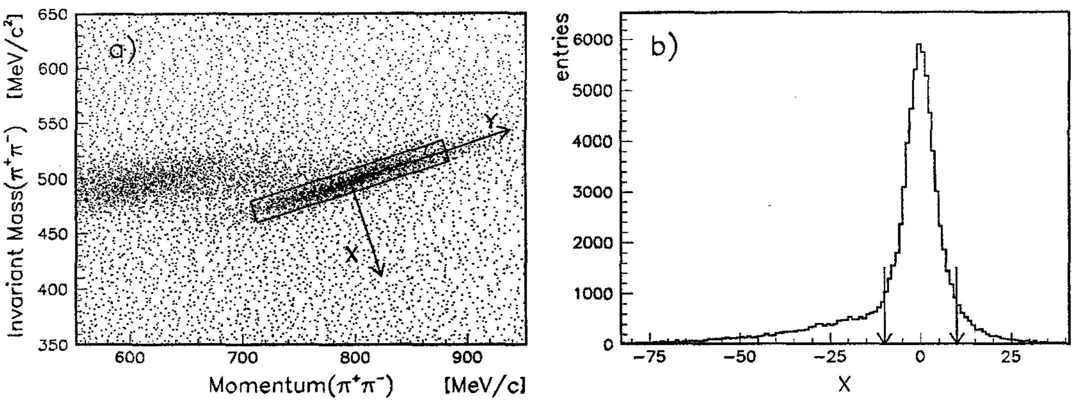

Fig. 2. 1-V sample: (a) Invariant mass M vs. momentum P for the $\pi^+\pi^-$ pair. X and Y are the coordinates of the auxiliary frame and the rectangle indicates the final cuts; (b) X distribution after cutting on Y. The arrows indicate the final cuts.

3. Event selection

The data were taken during a short run in 1995. A total of 4.3×10^6 events were recorded. Two- and four-track events were selected. The topologies searched for were one or two pairs of opposite charge tracks with vertices at a radial distance from the central axis larger than 1.5 cm (PC0) and smaller than 12 cm (PC2) – a cut on the vertex projection along the beam axis was not necessary. These topologies, called Vs below, are candidates for K_S decays. We selected 308 690 two-track (1-V topology) events and 51 340 four-track (2-V topology) events. They correspond to candidates for annihilation final states with production of either one or two K_S followed by a $K_S \to \pi^+\pi^-$ decay. There is only a few per mil probability that K_L decays inside the accepted volume; therefore, most of the K_SK_L events give 1-V topologies or no V at all when K_S decay products are not detected.

The kinematic characteristics of the two-body reactions

$$\bar{p}+p \to K_S + K_S \qquad (1)$$

and

$$\bar{p}+p \to K_S + K_L \qquad (2)$$

are simple. For a V, the measured invariant mass M of the two tracks, assumed to be pions, should correspond to the K^0 mass, $M_0 = 497$ MeV/c^2, and the V momentum P to the K^0 momentum, $P_0 = 795$ MeV/c.

The scatter plot of the invariant mass M versus the momentum P is shown in Fig. 2a for all the 1-V events. A strong accumulation can be seen near P_0 and M_0. A second accumulation around $P = 620$ MeV/c is due to the two-body $K_SK^*(892)$ production. Note that a strong correlation exists between the measured values of M and P. In order to optimize the cuts, a new auxiliary coordinate system is introduced, with the origin fixed at the nominal values M_0 and P_0 and with the axes rotated with respect to the M and P axes by an angle defined by the correlation coefficient. The new coordinates are

$$X = 0.310(P-P_0) - 0.951(M-M_0)$$

and

$$Y = 0.951(P-P_0) + 0.310(M-M_0),$$

where P is measured in MeV/c and M in MeV/c^2.

After cutting in Y ($|Y| < 90$), we obtain the X distribution shown in Fig. 2b. The final cut on X is chosen to be $|X| < 10$. There are 61 188 events which survive the above selection and constitute the sample of $\bar{p}p \to K_S(K)$ events where K indicates an undetected K^0, either an escaping K_L or a K_S decaying into neutrals.

Fig. 3a shows the invariant mass M versus the momentum P for all Vs of the four-track sample. Once again an enhancement is observed in the signal region around M_0, P_0. In order to separate better the signal from the background, we use the same coordinate system (X, Y) as defined above and we plot the value of

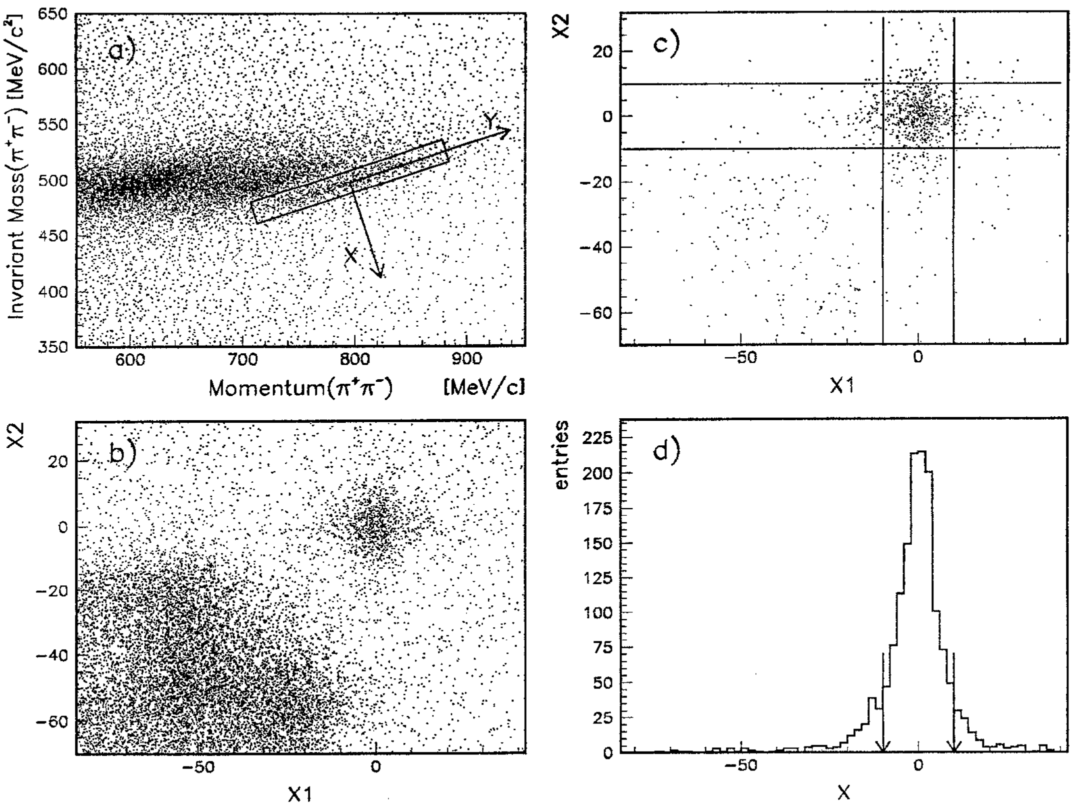

Fig. 3. 2-V sample: (a) Invariant mass M vs. momentum P for the $\pi^+\pi^-$ pair. X and Y are the coordinates of the auxiliary frame (the rectangle indicates the final cuts; one entry per V); (b) $X1$ vs. $X2$ plot; (c) $X1$ vs. $X2$ with cuts on $Y1$ and $Y2$ (the lines indicate the final cuts); (d) X distribution after cutting on its Y and on the X and Y of the other V (the arrows indicate the final cuts; one entry per V).

X for one V ($X1$) against the value of X for the other V ($X2$) (see Fig. 3b).

The K_SK_S events are clearly isolated. By applying the Y cut to both Vs, we reduce the background significantly (Fig. 3c). Fig. 3d shows the X distribution for one V when both Vs satisfy the cuts on Y and the other V satisfies the cut on X defined above. 617 events survive the cuts $|X| < 10$ and $|Y| < 90$ for both Vs and constitute the sample of $\bar{p}p \to K_SK_S$ events.

In order to obtain the ratio of the two branching fractions for reactions (1) and (2), we have determined their detection efficiencies from a Monte Carlo simulation using the GEANT code [3]. The channels simulated were

$$\bar{p} + p \to K_S + K_L\,(K_S \to \pi^+\pi^-;\ K_L \to \pi\ell\nu, \pi^+\pi^-\pi^0),$$

$$\bar{p} + p \to K_S + K_S\,(K_S \to \pi^+\pi^-;\ K_S \to \pi^0\pi^0),$$

$$\bar{p} + p \to K_S + K_S\,(K_S \to \pi^+\pi^-;\ K_S \to \pi^+\pi^-).$$

The overall efficiency for detecting a 1-V topology in K_SK_L events and K_SK_S events with one of the K_S decaying to 2 π^0 is $e_1 = 0.1395 \pm 0.0005$ within the above defined cut intervals. The efficiency to observe a 2-V topology within the same cut intervals in the K_SK_S reaction is $e_2 = 0.0561 \pm 0.0003$. For the relative efficiency, $\rho = e_1/e_2$, where most of the systematic errors cancel, one obtains: $\rho = 2.487 \pm 0.017_{\text{stat}}$.

3.1. Background

Some genuine K_SK_L events may fall in the 2-V category and vice-versa. The K_SK_L events can give a 2-V topology if the K_L decays within the accepted

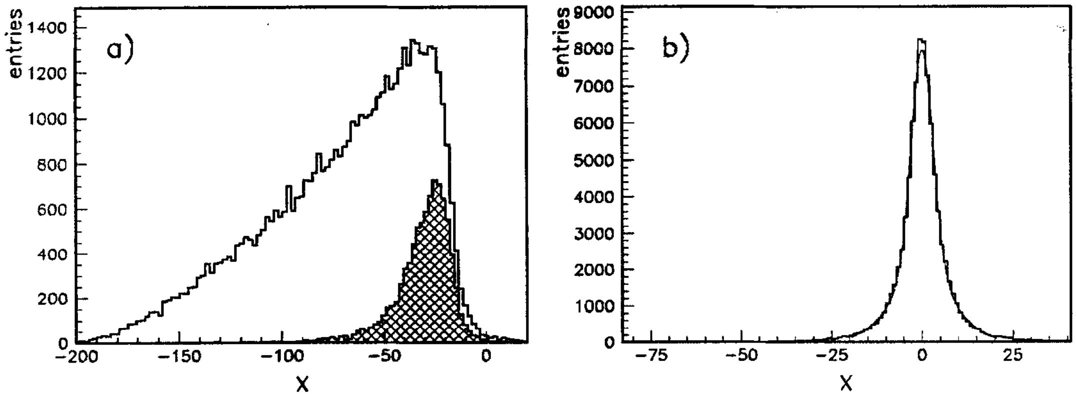

Fig. 4. (a) X distribution for the simulated $\bar{p}p \to K_S K_L \pi^0$ background without Y cut (solid line) and with Y cut (shaded area). (b) X distribution of the simulated $\bar{p}p \to K_S K_L$ signal. Superimposed is the double-Gaussian fit.

fiducial volume. It has been calculated from Monte Carlo simulation that 3.4 ± 1.7 decays of this kind contribute to the 2-V events, and therefore they were subtracted from the 2-V sample. On the other hand a $K_S K_S$ event with both kaons decaying into $\pi^+\pi^-$ may simulate a 1-V topology if both tracks for one of the Vs are not reconstructed. The corresponding correction was calculated to be 1.3 ± 0.2 events. The $\pi^+\pi^-$ decay of the K_L and the three-body decay of K_S were not simulated since they are negligible at the present level.

The main background is given by the annihilation channels

$$\bar{p} + p \to K + K + (\text{neutrals})$$

where (neutrals) could be one or several π^0s or neutral decay products of other particles such as the η; the maximum K- momentum for this type of background is 714 MeV/c with one π^0 which corresponds to $X = -23.5$. This background was studied by simulating the $K_S K_L \pi^0$ channel. Fig. 4a shows the X distribution simulated for this particular channel with and without the Y cut. Only a small amount of events falls within the accepted interval $|X| < 10$. In Fig. 4b one can see however that for signal $K_S K_L$ events, the X distribution is symmetric and can be fitted by a double-Gaussian distribution.

Since there are too many annihilation channels with poorly known branching fractions contributing to the background, we chose to evaluate the background from the data themselves. The X distribution of real $K_S K_L$ events was fitted as the sum of the signal (using a symmetric double-Gaussian distribution) and of a background (with a second-order polynomial in the negative X region).

For the 1-V events, a fitted background of $307 \pm 19_{\text{stat}}$ events in the accepted X interval was obtained. The same result within the errors was obtained by symmetrizing the $X < 0$ region to the $X > 0$ region. The corrected number of events is therefore $N_{1-\text{V}} = 60\,879 \pm 248_{\text{stat}}$.

From Fig. 3c it can be seen that the 2-V sample is free of this type of contamination: a $K_S K_S$ + (neutrals) event faking a $K_S K_S$ event would require that both measured K_S fall within the X interval. The very few events in the tail of the X distribution observed on Figs. 3c and 3d are essentially due to the resolution in X (included in the efficiency calculation) and, to some extent, to the three-body decays of the K_L already corrected for. The corrected number of 2-V events in the accepted X range is $N_{2-\text{V}} = 613 \pm 27_{\text{stat}}$.

3.2. Results

The number of 1-V and 2-V events is related to the number of produced $K_S K_L$ (N_{SL}) and $K_S K_S$ (N_{SS}) events through:

$$N_{1-\text{V}} = N_{\text{SL}} \times e_1 \times r_c + 2 \times N_{\text{SS}} \times e_1 \times r_c r_0 ,$$

$$N_{2-\text{V}} = N_{\text{SS}} \times e_2 \times r_c^2 ,$$

where r_c is the $K_S \to \pi^+\pi^-$ branching ratio (= 0.6861 [4]), r_0 the $K_S \to \pi^0\pi^0$ branching ratio (= 0.3139 [4]), and e_1 and e_2 are the detection efficiencies mentioned above ($\rho = e_1/e_2$). The branching fraction ratio of the two classes of events is

$$\begin{aligned} R &= BR(\bar{p}p \to K_S K_S)/BR(\bar{p}p \to K_S K_L) \\ &= N_{SS}/N_{SL}, \end{aligned}$$

with

$$\begin{aligned} N_{SS}/N_{SL} &= (N_{2-V}/N_{1-V}) \\ &\times \frac{\rho}{r_c - 2 \times r_0 \times \rho \times (N_{2-V}/N_{1-V})}. \end{aligned}$$

We obtain:

$$R(27\,\text{bar}) = 0.0374 \pm 0.0015_{\text{stat}}.$$

We recall that the result depends only weakly on the Monte Carlo simulation, since only the ratio ρ of the efficiencies comes into play. The stability of the result against the simulation and the cuts was checked by varying the accepted X and Y intervals. For example, varying the Y cut by 20% (from ± 90 to ± 70) changes R by -0.0010, i.e. 0.7 standard deviations. Similarly, changing the X cut interval from ± 10 to ± 8 changes R by -0.0016. On this basis, we give a systematic error on R of 0.0016. The final measured value for R is $R(27\,\text{bar}) = 0.0374 \pm 0.0015_{\text{stat}} \pm 0.0016_{\text{syst}}$ at 27 bar hydrogen pressure.

4. Measurement of R at 15 bar

We repeated the analysis described above using data previously recorded by CPLEAR at a hydrogen pressure of 15 bar. These data were taken without PC0 and with a spherical target (radius 7 cm) [2]. The trigger conditions (minimum-bias) were not as selective as in the dedicated measurement at 27 bar, resulting therefore in lower statistics.

We obtain a value of $R(15\,\text{bar}) = 0.041 \pm 0.009$, where the error is mainly statistical [5].

5. Discussion

Until recently, the $\bar{p}p \to K_S K_S$ and $\bar{p}p \to K_S K_L$ branching fractions at rest were measured mainly with liquid hydrogen or with gaseous hydrogen at normal temperature and pressure. A compilation of the existing data can be found for example in Ref. [1]. Since then, a new measurement at 5 mbar pressure was published by the OBELIX Collaboration [6]. The CPLEAR measurements are the only ones for pressurized gaseous hydrogen.

The fraction of P-wave annihilation, f_P, is deduced from the measured values of R using the model developed in [1]. From the conservation of P- and C-symmetry in the annihilation process it is known, that $\pi\pi$ and KK final states (charged and neutral) can be produced at rest from $^3P_0$, $^3P_2$ and $^3S_1$ atomic states. The contribution from a given J-state $^{2S+1}L_J$ can be related to the value of f_P (dependent on the target density) and to the statistical weight of the state (dependent on J) corrected by an enhancement factor to account for the presence of the Stark mixing. These enhancement factors, which depend in turn on the density, were obtained from an atomic cascade calculation performed for different optical potentials. A global fit to the branching fractions of $\bar{p}p \to \pi\pi$, KK measured at different target densities gives the values of f_P (one value per density) and the branching fractions $BR(^{2S+1}L_J \to \pi\pi, KK)$. After including the CPLEAR result, $R(27\,\text{bar}) = 0.037 \pm 0.002$, a value of $f_P(27\,\text{bar}) = 0.45 \pm 0.06$ is obtained in good agreement with the expectation [1]. The same fit was constrained at 15 bar by a previous precise CPLEAR measurement of the ratio $BR(\bar{p}p \to K^+K^-)/BR(\bar{p}p \to \pi^+\pi^-)$ [7], and gave a value of $f_P(15\,\text{bar}) = 0.43 \pm 0.06$. This translates into an expected value of $R(15\,\text{bar}) = 0.031 \pm 0.010$, in agreement with the measurement reported in Section 4.

Finally it can be concluded that, for the cases of pressurized gaseous hydrogen considered here, the $\bar{p}p$ annihilation at rest in two neutral kaons proceeds mostly from an initial antisymmetric $^3S_1$ ($J^{PC} = 1^{--}$) state to a final $K_S K_L$ state.

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