PROTON-ANTIPROTON ANNIHILATIONS AT REST INTO $\pi^0\omega$, $\pi^0\eta$, $\pi^0\gamma$, $\pi^0\pi^0$, AND $\pi^0\eta'$

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** Abstract **

Proton-antiproton annihilations at rest in liquid hydrogen were investigated through the inclusive $\gamma$ spectrum, related to the annihilation. The high-energy part of the spectrum was used to deduce branching ratios for the so far unobserved annihilation channels: $R(\bar{p}p \rightarrow \pi^0\omega) = (2.38 \pm 0.65)\%$, $R(\bar{p}p \rightarrow \pi^0\eta) = (0.82 \pm 0.10)\%$, $R(\bar{p}p \rightarrow \pi^0\gamma) = (0.015 \pm 0.007)\%$, and $R(\bar{p}p \rightarrow \pi^0\pi^0) = (0.06 \pm 0.04)\%$. An upper limit for the $\pi^0\eta'$ channel was deduced to be $R(\bar{p}p \rightarrow \pi^0\eta') < 1.1\%$.

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1. INTRODUCTION

Investigations of $p\bar{p}$ annihilations at rest have so far been done mostly using bubble-chamber techniques, and the most comprehensive review of these works is still the one by Armenteros and French [1]. Updates may be found elsewhere [2].

From these earlier works it appears that multipionic final states in $p\bar{p}$ annihilation are frequently reached via intermediate resonance production, e.g.

$$p\bar{p} \rightarrow \rho^0\pi^0 = \pi^+\pi^-\pi^0.$$ 

Only those intermediate states could have been identified there for which the final states contain at most one $\pi^0$. Final states with more than one $\pi^0$ or purely neutral channels are very difficult to determine in bubble-chamber experiments owing to their poor sensitivity to $\gamma$ radiation.

New information on annihilation channels involving more than one $\pi^0$ in the final state -- or simple, purely neutral channels -- can be expected from experiments using $\gamma$ spectrometers of sufficient resolution.

In an experiment on the inclusive $\gamma$ spectrum after $p\bar{p}$ annihilation at rest, we were able to measure branching ratios for the so far unobserved multi-$\pi^0$ channels $\pi^0\omega$, $\pi^0\eta$, and the channel $\pi^0\gamma$. A new value for the $\pi^0\pi^0$ and an upper limit for the $\pi^0\eta'$ channel were deduced as well.

2. THE EXPERIMENT

2.1 Experimental set-up

The experiment was set up at the low-energy electrostatically separated $k_{23}$ beam at the CERN Proton Synchrotron (PS). A detailed description of the layout is given elsewhere [3] and only the essentials will be described here.

A low-energy $\bar{p}$ beam (600 MeV/c) of $\Delta p/p = \pm 2\%$ was slowed down in a graphite moderator and then stopped in a 25 cm long liquid-hydrogen ($\text{LH}_2$) target. The moderation was adjusted such that the maximum of the range distribution was in the centre of the target; the longitudinal width of this distribution (FWHM) was equivalent to about 14 cm of $\text{LH}_2$. 
The target was viewed by a large modular NaI $\gamma$ spectrometer placed perpendicularly to the beam. The properties of this spectrometer have been described elsewhere [4]. Events where charged particles entered the $\gamma$ spectrometer were rejected, using plastic scintillators in front and at the sides of the NaI spectrometer. Double $\gamma$ events were recognized by topology cuts and were rejected as well.

2.2 Data-taking and results

The $\gamma$ radiation emerging after $p\bar{p}$ annihilation was measured for $33 \times 10^6 \bar{p}$'s entering the target. The effective running time was about two weeks in total. During this time, the system could be stabilized off line to better than 1%. The resulting spectrum is shown in fig. 1 in logarithmic scale. It exhibits a smooth behaviour and ends sharply, as it should, at $\sim 950$ MeV.

3. ANALYSIS

3.1 Method

Proton-antiproton annihilation at rest leading to two-body final states, where one particle decays into two $\gamma$'s, such as

\[ p\bar{p} \rightarrow \pi^0X \rightarrow \gamma\gamma \]

may be studied via the $\gamma$ spectrum of the decaying particle. Owing to the fact that the particles are monoenergetic, the $\gamma$ spectrum exhibits a uniform shape between the limits

\[ \frac{E_\gamma^{\text{max/min}}}{E} = \frac{1}{2} (1 \pm \beta), \]

where $E$ is the total energy of the decaying particle and $\beta$ is its velocity. The edges of these distributions are sharp if the particles involved have narrow widths, and thus may show up in the inclusive $\gamma$ spectrum from $p\bar{p}$ annihilation at rest. The lower the background and the better the resolution, the higher are the chances of observing these edges. Thus at the high-energy end of the spectrum (fig. 1) such edges are most likely to be observed.

Table 1 shows the limits of the uniform $\gamma$ distribution for some relevant annihilation channels. From the table one may conclude that the lower edges are of
no use, as they are either below the experimental energy threshold (~ 20 MeV) or just fall into regions where the background is highest.

3.2 Monte Carlo simulation

3.2.1 Construction of the $\gamma$ spectrum

The crucial point in extracting the uniform distributions from the experimental $\gamma$ spectrum is the proper subtraction of the continuous background which comes from annihilations into more than two particles. To this end, the $\gamma$ spectrum was simulated by Monte Carlo calculations, using the annihilation channels of table 2. This spectrum is shown in fig. 2. It was used to extract the shape of the continuous background. The assumption has to be made that the purely neutral channels, which are not contained in the simulated spectrum, produce the same spectral shape.

The simulated spectrum was then approximated by an analytical function. This shape function has the form

$$F(E_\gamma) = N \left[ (E_0 - E_\gamma) ^{\alpha_1} e^{\beta_1} + (E_0 - E_\gamma) ^{\alpha_2} e^{\beta_2} + \alpha_3 e^{-\beta_3 E_\gamma} \right],$$

with

$$E_0 = 938.28 \text{ [MeV]}$$
$$\alpha_1 = 4.155$$
$$\beta_1 = -33.494$$
$$\alpha_2 = 1.673$$
$$\beta_2 = -19.982$$
$$\alpha_3 = -0.03273 \text{ [MeV}^{-1}]$$
$$\beta_3 = -0.006921 .$$

With these constants, which (except $E_0$ and $N$) were fit parameters, the expression in the brackets of eq. (2) is normalized to one. The constant $N$ being the average number of $\gamma$'s per annihilation, the shape function $F(E_\gamma)$ represents the average number of $\gamma$'s per MeV and per annihilation. The constant $N$ has to be determined appropriately, as will be described in the next section. Inspection of $F(E_\gamma)$ shows that at high energies the term $(E_0 - E_\gamma) ^{\alpha_2} e^{\beta_2}$ is dominant.
Figure 2 demonstrates the quality of the fit. The spectrum can be reproduced from 20 MeV to 1000 MeV with only six free parameters and a $\chi^2$/DF of only 1.33.

It is assumed that the spectral shape given by eq. (2) represents well the continuous part of the real spectrum. This might not fully correspond to reality since the intermediate resonances in the channels with more than one $\pi^0$ are not known.

3.2.2 Normalization of the simulated spectrum

In order to relate the shape function (1) to the number of annihilations, the number of $\gamma$'s per annihilation has to be evaluated. This number is defined by

$$N_\gamma = \frac{\sum_{\nu} R_{\nu} \nu N_{\gamma}^{\nu}}{\sum_{\nu} R_{\nu}},$$

where $R_{\nu}$ is the branching ratio of the channel $\nu$, and $N_{\gamma}^{\nu}$ is the average number of $\gamma$'s for this channel, as indicated in table 2. The number of $\gamma$'s from the decay of $\omega$'s and $\eta$'s was taken to be 2.06 and 3.20, respectively.

From table 2 the average number of $\gamma$'s per annihilation is derived to be

$$N_\gamma = 3.93 \pm 0.24.$$  \hspace{1cm} (3)

The error stems mostly from the uncertainties of the branching ratios, i.e. $N_\gamma$ may be wrong by $\pm 6\%$. A further source of error might be found in the average multiplicity of $\pi^0$'s in the purely neutral channels, leading to an estimated error of $\pm 0.06$ $\gamma$'s per annihilation.

Since the Monte Carlo simulated spectrum does not account for the uniform distributions of two-body annihilations, their contributions have to be subtracted from the above number. Anticipating the final results for these uniform distributions (see section 4), 0.11 $\gamma$'s per annihilation have to be deducted. Thus the average number of $\gamma$'s for the continuous part of the spectrum is 3.82 per annihilation, and the factor $N$ in eq. (2) is

$$N = 3.82.$$  \hspace{1cm} (4)
3.3 Normalization and background subtraction for the experimental spectrum

The total γ-spectrum emerging from pp annihilation at rest is assumed to be composed of the continuous part discussed in the previous subsections 3.2.1 and 3.2.2 and a superposition of distributions from two-body annihilation channels of table 1. The measured spectrum may therefore be approximated by a function of the form

$$S(E_\gamma) = S_0 \left[ F(E_\gamma) + \sum \nu R_\nu B_\nu(E_\gamma) \right] ,$$

(5)

where $F(E_\gamma)$ is defined by eqs. (2) and (4), $R_\nu$ is the branching ratio of the annihilation channel $\nu$, and $S_0$ is a scaling factor.

The $B_\nu(E_\gamma)$ in eq. (5) is the function describing the γ-energy distribution for the channel $\nu$,

$$B_{pp\rightarrow ab} = \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{tot}} B_a^{a}(E_\gamma) + \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{tot}} B_b^{b}(E_\gamma) ,$$

with $\Gamma_{\gamma\gamma}^{a,b}$ being the partial widths of the particle $a$ or $b$ decaying into γ's (e.g. $\Gamma_{\gamma\gamma}^{a,b}/\Gamma_{\gamma\gamma}^{tot} = 0.3$). The $B_a^{a,b}(E_\gamma)$ are the uniform distributions defined by

$$B_a^{a,b}(E_\gamma) = \frac{N_a^{a,b}}{E_a^{b} - E_a^{a}} \text{ for } E_a^{a} < E_\gamma < E_a^{b}$$

$$= 0 \text{ otherwise} .$$

$E_a^{\text{max}}$ and $E_a^{\text{min}}$ are defined by eq. (1) and table 1; $N_a^{a,b}$ is the number of mono-energetic γ's into which particle $a$ or $b$ decay at rest.

With these definitions the integral of the expression in brackets of eq. (5), i.e. $\int_0^{\infty} S(E_\gamma) / S_0 dE_\gamma$ equals the average number of γ's per annihilation. Hence $S_0$ represents the number of pp annihilations which contributed to the measured spectrum.

The scaling factor $S_0$ is determined by a fit of eq. (5) to the measured spectrum. In order to reduce the number of parameters to a minimum, a fit region has
to be selected where none of the boxes starts or ends. Then eq. (5) has only two
free parameters, namely $S_0$ and a constant $C = \sum_V R_V B_V$, i.e.
\begin{equation}
S(E_\gamma) = S_0 F(E_\gamma) + C. \tag{6}
\end{equation}
After folding this function with the experimental energy-resolution, it was fitted
to the measured spectrum in the energy range from 400 to 600 MeV. The accuracy
of this determination of $S_0$ is ±5%.

The advantage of such a normalization procedure is obviously its independence
of errors in solid angle, stop-rates, dead-time of the electronics, etc. Figure 3
shows the measured spectrum after subtraction of the continuous background $S_0 F(E_\gamma)$
and the distributions of the known $\pi^0 p^0$ and $\eta p^0$ contributions as specified in
table 2. This reduced spectrum is then approximated by the function
\begin{equation}
S_{\text{red}}(E_\gamma) = S_0 \sum_V R_V B_V(E_\gamma),
\end{equation}
folded with the detector resolution. The branching ratios $R_V$ are the fitting
parameters.

3.4 Fitting procedures

3.4.1 Energy calibration, resolution, and continuous background

The parameters to be verified before entering into the detailed analysis of
the spectrum are the energy calibration and the resolution of the $\gamma$ spectrometer.

The energy calibration was obtained from the reactions $\pi^- p + n\gamma$ and $n\pi^0$ at
rest, as described in ref. 4. A final adjustment was done using the end point of
the spectrum $E_0$ [eq. (2)] and the edge of the $\pi^0\omega$ distribution at $E = 774.15$ MeV.

The resolution, as determined in ref. 4 from the reaction $\pi^- p + n\gamma$ at rest,
does not have to be the same as in the $\bar{p}$ experiment since the detector load is
different. In fact there is no way of checking the energy resolution on-line. It
is therefore a parameter to be determined. The resolution turned out to be not
entirely independent of the composition of channels contributing to the spectrum,
particularly the $\pi^0 p^0$ channel (see next section) and hence was not treated inde-
pendently.
The analysis is based on the assumption that the continuous background is properly described in eq. (2). Variation of the parameter $\alpha_2$ in eq. (2) when fitting the spectrum showed correlations between $\alpha_2$ and $\pi^0/\omega$ and $\pi^0/\eta$ and less or no correlation for the other channels. In the further analysis, $\alpha_2$ is, however, kept fixed.

3.4.2 Procedures for the different annihilation channels

From the channels listed in table 1, those whose uniform distributions ("boxes") end at different energies are quite independent of each other. However, the channels where the box-edges are not resolved are correlated to a great extent. The latter case holds particularly for the channels $\pi^0/\omega$, $\eta/\omega$ and $\pi^0/\eta$, $\eta/\eta$. It was thus impossible to disentangle their individual contributions. Instead, an over-all $\eta/\pi^0$ ratio of 0.16 was adopted when fitting the spectrum. This value is suggested by the ratio of the measured branching ratios (see table 2) of $\eta^0/\pi^0 = 0.16 \pm 0.10$. The $\eta/\pi^0$ ratio was also varied stepwise within the limits $0 \leq \eta/\pi^0 \leq 0.33$ in order to estimate systematic errors.

The $\pi^0/\omega$ and $\pi^0/\rho^0$ channels obviously interfere, as the masses of $\rho$ and $\omega$ are almost identical. The $\pi^0/\rho^0$ channel leads, however, to a smeared-out edge owing to the width of the $\rho$. This in consequence leads also to some correlation with the detector resolution. The fits were therefore done for different $\pi^0/\rho^0$ contributions, varying between 1.4 and 1.8%, and for different values for the detector resolution, varying between $3.5\%/\sqrt{E}$ and $5.5\%/\sqrt{E}$. The data favour a $\pi^0/\rho^0$ contribution of 1.6%, which is somewhat higher than that listed in table 2, but still compatible with it. This value was adopted for the final fits. The resolution was found to be with large errors around $5\%/\sqrt{E}$, and was fixed at this value for the further fits.

The $\pi^0/\eta$ channel has a box-edge energy which renders its contribution extremely uncorrelated and thus obtainable with the least amount of ambiguities.
Both channels, $\pi^0\eta'$ and $\eta\eta'$, have their box-edges at energies below the $\pi^0\omega$ edge. They are thus showing up in regions of the spectrum where the background is already high. The determination of their branching ratios is correspondingly difficult, and values between 0 and 0.5% for $\pi^0\eta'$ were obtained under the different fit conditions.

The edges of both the $\pi^0\pi^0$ and the $\gamma\pi^0$ channel and the $\gamma$ peak of the $\pi^0\gamma$ channel fall within 5 MeV (see table 1) and are thus not resolved. The correlation between the two channels is, however, not very high. A simultaneous fit of both parameters resulted in a branching ratio of $(0.06 \pm 0.04)\%$ for $\pi^0\pi^0$. Since the $\pi^0\pi^0$ channel had been measured before [5,6], it was kept fixed at values between $0.01 \leq \pi^0\pi^0 \leq 0.08\%$ when fitting, thus allowing for estimates of systematic errors. In the final fits a value of 0.04% was adopted for $\pi^0\pi^0$, a value which is close to that of ref. [5] and which is slightly favoured by our data with respect to the lower value of 0.014% quoted in ref. [6].

The edges of the distributions from $\pi^0\omega$, $\pi^0\eta$, and $\pi^0\pi^0$ show up at energy intervals of $\sim 80$ MeV, and thus are well resolved. The data require an additional distribution ending at 811 MeV, coming from a hypothetical process $p\overline{p} \rightarrow \pi^0X$. This assumption is arbitrary, and a process $p\overline{p} \rightarrow \gamma X$ would, from the fitting point of view, work equivalently. Without any additional contribution in this energy region the $\chi^2$ would be worse by almost a factor of 2.

3.4.3 Parameter variations, errors, and results

When fitting the spectrum, the branching ratios $R$ [see eq. (5)] of the channels $\pi^0\eta'$, $\pi^0\omega$, $\pi^0\pi$, $\pi^0\eta$, and $\pi^0\gamma$ were always varied simultaneously, but under different conditions for $\pi^0\pi$, $\pi^0\rho^0$, $\eta/\pi^0$, resolution, and $\alpha_2$, as described in subsections 3.4.1 and 3.4.2. The results are listed in table 3. The branching ratios $R$ have statistical errors as obtained from a MINOS error analysis [7]. In addition, systematic errors are quoted which reflect the maximum and minimum values obtained for $R$ under the different fit conditions.
Furthermore, all branching ratios have an uncertainty of ±6% of their value originating from the error of $N_\gamma$ [eq. (3)] and of ±5% from the scaling factor $S_0$ of the function [eq. (6)].

The fit quality is demonstrated by the solid line in fig. 3. The single distributions as used for the final fit are displayed in fig. 4.

It should be noted that the $\pi^\circ$ annihilation channels of table 3 together with the corresponding $\pi$-channels yield 0.11 $\gamma$'s per annihilation which contribute to uniform distributions. This result was used already in subsection 3.2.2.

4. DISCUSSION OF RESULTS

4.1 $\bar{p}p + \pi^\circ\omega$

The branching ratio of this state is found to be 2.38%. This value is surprisingly high if we compare it with the result for the equivalent reaction in $\bar{p}n$ annihilation at rest, whose branching ratio is $R(\bar{p}n \rightarrow \omega\pi^{-}) = (0.41 \pm 0.08)%$ [8].

The initial state for both reactions, $\bar{p}p + \pi^\circ\omega$ and $\bar{p}n + \pi^{-}\omega$, could be an $\epsilon = 1$ state but in liquid hydrogen most likely is a $^2S_1$ state. Assuming only atomic S-states, the $^3S_1$ state population in the $\bar{p}p$ atom is 75%, but in the $\bar{p}n$ case, which is formed from a $\bar{p}d$ atom, it is only 66%. Moreover, the $\bar{p}n$ is a pure $I = 1$ state, but the $\bar{p}p$ state is an isospin mixture, whereas the final $\pi^\circ\omega$ state is in both cases pure $I = 1$. We therefore expect

$$\frac{\Gamma(\bar{p}p \rightarrow \pi^\circ\omega)}{\Gamma(\bar{p}n \rightarrow \pi^{-}\omega)} = \frac{1}{2} \times \frac{0.75}{0.66} = 0.52,$$

and thus $\pi^\circ\omega = 0.2\%$, assuming pure S-wave absorption. The latter condition seems to be controlled by the observation of the recoil proton in the deuterium bubble chamber, when the $\bar{p}$ is absorbed on the neutron of the deuterium. A momentum cut at 250 MeV/c should largely eliminate P-wave annihilation [8]. In our experiment a similar control was not possible, and P-wave annihilation from interactions in flight may occur in a few per cent of all $p\bar{p}$ annihilations, as discussed in the next subsection, but by no means could it account for 2% of extra $\pi^\circ\omega$ final states.
On the other hand, the inclusive $\omega$ production in $p\bar{p}$ annihilation at rest was found in a bubble-chamber experiment to be comparable with inclusive $\rho^0$ production [9].

4.2 The channel $p\bar{p} \rightarrow \pi^0\eta$

The $\pi^0\eta$ channel is found to be 0.82%. This is unexpectedly high in view of the fact that this annihilation channel has to come from an initial $\varphi$-state. The generally believed S-wave dominance in annihilations of $\bar{p}$'s in liquid targets, caused by Stark mixing in the initial atomic states, seems to be at variance with this finding. P-wave annihilation could, however, occur in reactions in flight. Our experiment has no control over whether or not a $\bar{p}$, entering the 25 cm long H$_2$ target, really stops before annihilating. In fact the momentum spectrum of $\bar{p}$'s when entering the target extends up to 360 MeV/c. Since the beam keeps its direction when slowing down in the target, and since our detector sees only $\gamma$ radiation perpendicular to the beam axis, the $\gamma$-energy distortions are of the order of $8^2 \approx 17$. Thus in this experiment interactions in flight are indistinguishable from interactions at rest. On the other hand, of all $\bar{p}$'s entering the target, at most $\sim 4\%$ would annihilate in flight, and thus cannot alone lead to the above branching ratio for $\pi^0\eta$.

A sizeable P-wave annihilation has already been seen in the channel $p\bar{p} \rightarrow \pi^0\eta^0$. There it was concluded that it amounts to as much as 38% of the annihilations going to $\pi\pi$ [5].

4.3 $p\bar{p} \rightarrow \pi^0\pi^0$

The $2\pi^0$ final state can only be reached from initial $^3P_0$ and $^3P_2$ states. Its branching ratio had been determined by two experiments to be $(0.048 \pm 0.010)\%$ [5] and $(0.014 \pm 0.003)\%$ [6], respectively. Our result of $(0.06 \pm 0.04)\%$ favours the higher value.
4.4 $p\bar{p} \rightarrow \pi^0\gamma$

This channel is formed from initial $^3S_1$ and $^1P_1$ states and was never observed before. The branching ratio was determined to be 0.015%. In the frame of vector dominance the $\pi^0\gamma$ channel is linked to the channels involving vector mesons such as $\pi^0\rho$, $\pi^0\omega$, etc. Assuming pure $s$-wave annihilation (hence $p$-wave in the final state) we obtain in a straightforward calculation

$$R_{\pi^0\gamma} = \frac{4\pi}{f_{\gamma}} \alpha \left[ R_{\pi^0\rho} + 2 \frac{f_{\gamma}}{f_{\omega}} \sqrt{R_{\pi^0\rho} R_{\pi^0\omega}} \cos (\phi_{\pi^0\rho} - \phi_{\pi^0\omega}) + \frac{f_{\gamma}^2}{f_{\omega}} R_{\pi^0\omega} \right] \left( \frac{P_{\gamma}}{P_{\rho}} \right)^3.$$

Here $\alpha$ is the fine structure constant, $f$ is the vector meson-photon coupling constant, $\phi$ is the strong phase and $(P_{\gamma}/P_{\rho})^3$ is the $p$-wave phase space factor, the $P$'s being the momenta and $P_{\rho} = P_{\omega}$. Using the measured value of table 3 for $R_{\pi^0\omega}$, the value of table 2 for $R_{\pi^0\rho}$, $f_{\gamma}^2/4\pi = 2.26$ and $f_{\omega}^2/4\pi = 18.4$, and assuming $\cos (\phi_{\pi^0\rho} - \phi_{\pi^0\omega}) = 1$ we obtain

$$R_{\pi^0\gamma} = 0.017\%,$$

in agreement with our measurement.

4.5 $p\bar{p} \rightarrow \pi^0X$

The fact that reproducing the spectrum properly requires a reaction involving a particle $X$ is puzzling. Although the spectrum could be fitted by using a reaction of the type $p\bar{p} \rightarrow \gamma X'$, the reaction $\pi^0X$ was considered to be the more likely one in $p\bar{p}$ annihilation, if the process is considered as a physical process at all rather than as a particular way of correcting the background. The particles mass would be $m_X = 680$ MeV and its width narrow, thus falling into a domain which is reserved for the ground states of the light quark $q\bar{q}$ -- or more exotic configurations. The nature of the phenomenon has to await a final clarification in forthcoming experiments on dedicated $\pi^0$ spectroscopy.
4.6 $p\bar{p} \rightarrow \pi^0\eta'$

Owing to reasons already discussed in subsection 3.4.2, this channel was not seen clearly. The upper limit for it with 1σ confidence is

$$\pi^0\eta' < 1.1\% .$$

4.7 The channels $p\bar{p} \rightarrow \eta\omega$, $\eta\eta$, etc.

These channels were not determined separately since they interfere too much with the corresponding channels $\pi^0\omega$, $\pi^0\eta$, etc. Instead, an over-all ratio

$$\tau_{\omega}/\pi^0 = \eta\eta/\pi^0 = \eta\rho/\pi^0 = \eta\eta'/\pi^0$$

was assumed. This ratio could still not be determined uniquely, and fits usually converged to values between 0 and 0.28 with a statistical uncertainty of ±0.22. We conclude from our data that with 1σ confidence

$$\eta/\pi^0 < 0.50 .$$

In inclusive $\eta$ production in low-energy $p\bar{p}$ annihilation the $\eta/\pi^0$ ratio was found [9] to be $\eta/\pi^0 < 0.11$ with 90% confidence.

5. SUMMARY AND CONCLUSIONS

By analysing the high-energy portion of the inclusive $\gamma$ spectrum after $p\bar{p}$ annihilation at rest, it was possible to obtain branching ratios for the so far unobserved annihilation channels $p\bar{p} \rightarrow \pi^0\omega$, $\pi^0\eta$, and $\pi^0\gamma$. Whereas the $\pi^0\gamma$ branching ratio is in accordance with vector dominance, the large $\pi^0\omega$ contribution to annihilation cannot be explained easily. The $S$-wave dominance in $p\bar{p}$ annihilation at rest seems not to hold generally, as is indicated by the large $\pi^0\eta$ branching ratio. Upper limits could be obtained for the channel $\pi^0\eta'$ and for the $\eta/\pi^0$ ratio in the reactions $p\bar{p} \rightarrow \pi^0\omega/\eta\omega$, $\pi^0\eta/\eta\eta$.

Pure single $\gamma$ spectroscopy, provided the spectrometer resolution is sufficiently good, has thus proved to be a useful method of investigating annihilation channels involving more than one $\pi^0$ in the final state or purely two-body neutral channels. Direct $\pi^0$ spectroscopy by $\gamma\gamma$ coincidence measurements seems therefore to be the next step in further studies of $p\bar{p}$ annihilations at rest.
Acknowledgements

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REFERENCES


Table 1
Limits of the uniform distributions of the $\gamma$ spectra for some two-body channels in $p\bar{p}$ annihilation at rest

<table>
<thead>
<tr>
<th>Channel</th>
<th>Decaying particle</th>
<th>$E_\gamma^{\text{min}}$ (MeV)</th>
<th>$E_\gamma^{\text{max}}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p\bar{p} \rightarrow \eta^0\omega$</td>
<td>$\pi^0 \rightarrow \gamma\gamma$ $\omega \rightarrow \pi^0\gamma$</td>
<td>5.88</td>
<td>774.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>159.25</td>
<td>904.65</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \eta^0\eta$</td>
<td>$\eta \rightarrow \gamma\gamma$ $\eta \rightarrow \gamma\gamma$</td>
<td>5.31</td>
<td>857.57</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80.71</td>
<td>932.97</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \eta\omega$</td>
<td>$\eta \rightarrow \gamma\gamma$ $\omega \rightarrow \pi^0\gamma$</td>
<td>99.62</td>
<td>755.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>177.05</td>
<td>813.70</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \eta\eta$</td>
<td>$\eta \rightarrow \gamma\gamma$</td>
<td>88.62</td>
<td>849.66</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \pi^0\pi^0$</td>
<td>$\pi^0 \rightarrow \gamma\gamma$</td>
<td>4.88</td>
<td>933.40</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \pi^0\gamma$</td>
<td>$\pi^0 \rightarrow \gamma\gamma$</td>
<td>4.85</td>
<td>938.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(E$_\gamma$ = 933.43)</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \pi^0\eta'$</td>
<td>$\pi^0 \rightarrow \gamma\gamma$</td>
<td>6.58</td>
<td>692.24</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \eta\eta'$</td>
<td>$\eta \rightarrow \gamma\gamma$</td>
<td>114.05</td>
<td>660.16</td>
</tr>
</tbody>
</table>
Table 2

Branching ratios and relative number of $\gamma$'s from $p\bar{p}$ annihilation at rest. Channels used for Monte Carlo simulation are marked MC. Branching ratios are taken from Refs. 1 and 2.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Branching ratio $R$ (%)</th>
<th>Number of $\gamma$'s $= R \times N_\gamma$</th>
<th>Comment</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$</td>
<td>3.7</td>
<td>7.4</td>
<td>MC</td>
<td>1</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^0$ ($\rho^0 \pi^0 \pi^0$)</td>
<td>2.7</td>
<td>5.4</td>
<td>MC</td>
<td>1</td>
</tr>
<tr>
<td>$\pi^+ \pi^- 2\pi^0$</td>
<td>9.3</td>
<td>37.2</td>
<td>MC</td>
<td>2b</td>
</tr>
<tr>
<td>$\pi^+ \pi^- 3\pi^0$</td>
<td>23.3</td>
<td>139.8</td>
<td>MC</td>
<td>2b</td>
</tr>
<tr>
<td>$\pi^+ \pi^- 4\pi^0$</td>
<td>2.8</td>
<td>22.4</td>
<td>MC</td>
<td>1</td>
</tr>
<tr>
<td>$2\pi^+ 2\pi^- \pi^0$ ($\omega \pi^+ \pi^-$)</td>
<td>3.8</td>
<td>7.83</td>
<td>MC</td>
<td>1</td>
</tr>
<tr>
<td>$2\pi^+ 2\pi^- \pi^0$ ($\rho^0 \pi^0 \pi^+ \pi^-$)</td>
<td>7.3</td>
<td>14.60</td>
<td>MC</td>
<td>1</td>
</tr>
<tr>
<td>$2\pi^+ 2\pi^- 2\pi^0$ ($\rho^0 \pi^0 \pi^+ \pi^0$)</td>
<td>6.4</td>
<td>12.80</td>
<td>MC</td>
<td>1</td>
</tr>
<tr>
<td>$2\pi^+ 2\pi^- 2\pi^0$</td>
<td>16.6</td>
<td>66.40</td>
<td>MC</td>
<td>2b</td>
</tr>
<tr>
<td>$3\pi^+ 3\pi^- \pi^0$</td>
<td>4.2</td>
<td>25.20</td>
<td>MC</td>
<td>2b</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \eta$</td>
<td>1.3</td>
<td>2.60</td>
<td>MC</td>
<td>1</td>
</tr>
<tr>
<td>$\pi^0 \eta$</td>
<td>1.2</td>
<td>3.84</td>
<td>MC</td>
<td>1</td>
</tr>
<tr>
<td>$2\pi^+ 2\pi^- \eta$</td>
<td>0.6</td>
<td>1.92</td>
<td>MC</td>
<td>1</td>
</tr>
<tr>
<td>$\eta\eta$</td>
<td>1.4</td>
<td>2.80</td>
<td>MC</td>
<td>1</td>
</tr>
<tr>
<td>$\eta\eta$</td>
<td>0.22</td>
<td>0.64</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$n\pi^0$</td>
<td>3.2</td>
<td>31.94*</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>0.4</td>
<td>0</td>
<td>2a</td>
<td></td>
</tr>
<tr>
<td>$2\pi^+ 2\pi^-$</td>
<td>6.9</td>
<td>0</td>
<td>2b</td>
<td></td>
</tr>
<tr>
<td>$3\pi^+ 3\pi^-$</td>
<td>2.1</td>
<td>0</td>
<td>2b</td>
<td></td>
</tr>
<tr>
<td>$K\Lambda\pi$ ($n \geq 0$)</td>
<td>2.4</td>
<td>9.02</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Total 99.8 391.79

*) Obtained with an average number of $\pi^0$'s of 4.99.
Table 3

Results for branching ratios of different channels in p\(\overline{p}\) annihilation at rest. Yields are given in per cent of all annihilations. The \(\pi^0\rho^0\) yield was assumed to be 1.6\%, and an \(\eta/\pi^0\) ratio of 0.16 was used.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Yield</th>
<th>Error (stat.)</th>
<th>Error (syst.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi^0\eta^f)</td>
<td>0.30</td>
<td>±0.53</td>
<td>+0.58</td>
</tr>
<tr>
<td>(\pi^0\omega)</td>
<td>2.38</td>
<td>±0.27</td>
<td>+0.32</td>
</tr>
<tr>
<td>(\pi^0\eta)</td>
<td>0.82</td>
<td>±0.07</td>
<td>±0.06</td>
</tr>
<tr>
<td>(\pi^0\chi)</td>
<td>1.19</td>
<td>±0.25</td>
<td>±0.44</td>
</tr>
<tr>
<td>(\pi^0\gamma)</td>
<td>0.015</td>
<td>±0.004</td>
<td>±0.003</td>
</tr>
<tr>
<td>(\pi^0\eta^0)</td>
<td>0.06</td>
<td>±0.03</td>
<td>±0.01</td>
</tr>
</tbody>
</table>
Figure captions

Fig. 1 : Inclusive $\gamma$ spectrum as obtained from $33 \times 10^6$ $\bar{P}$'s.

Fig. 2 : $\gamma$ spectrum from a Monte Carlo simulation using the annihilation channels from Table 2. The solid line represents the fit to it.

Fig. 3 : Experimental spectrum after subtraction of the continuous background and the $\pi^0\rho^0$ and $\eta\rho^0$ contributions. The solid line shows the fit.

Fig. 4 : Uniform distributions, folded with the resolution as used in the fit of fig. 3.
Fig. 1