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# Observation of $\bar{p}p \to 2\pi^0$ at Rest: Evidence Concerning s-State Annihilation*

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We have identified the annihilation mode $\bar{p}p \to 2\pi^0$ for antiprotons stopping in liquid hydrogen at a rate which is 0.15 (±20%) times that reported for $\bar{p}p \to \pi^+\pi^-$. This indicates that about 40% of all annihilations into $2\pi$ take place from odd-orbital atomic $\bar{p}p$ states, in contrast to the usual assumption that annihilation from the $s$ state predominates.

Since the original study of Day, Snow, and Sucher[1] of the Stark mixing of $K^-$-$p$ atomic states, it has generally been assumed that the nucleonic capture of strongly interacting particles—$\pi^-$, $K^-$, $\Sigma^-$, $\bar{p}$—stopping in liquid hydrogen proceeds mainly via $s$ atomic states. For stopping $\pi^-$, $K^-$, and $\Sigma^-$ this assumption is in accord with observed capture rates, as deduced from capture-to-decay ratios.[2] For $\bar{p}$, no such test is possible; and, until recently, the main evidence for the assumption of $s$-state capture has come from the very small rate observed for the particular mode $\bar{p}p \to K_S K_S$ as compared with that for $K_L K_S$.[3]

This question can also be illuminated by comparing the rate for $\bar{p}p \to 2\pi^0$ (which by parity conservation and Bose statistics cannot result from $\bar{p}p$ atomic $s$, or generally even, states) to the rate for $\bar{p}p \to \pi^+\pi^-$ [which can result from *both* $s$ (even) states, and $p$ (odd) states]. If the mode $2\pi^0$ is observed, it would follow from charge independence that some of the $\bar{p}p \to \pi^+\pi^-$ must also proceed from the odd-$L$ states; explicitly: $[(\bar{p}p)_{L\text{ odd}} \to \pi^+\pi^-] = 2[(\bar{p}p)_{L\text{ odd}} \to 2\pi^0]$, so that from observed $\pi^+\pi^-$ and $\pi^0\pi^0$ rates, one can deduce the ratio $p$ (odd) to $s$ (even) from atomic states to the $2\pi$ annihilation mode. We have previously reported[4] evidence for an unexpectedly large rate for $\bar{p}p \to 2\pi^0$; here we present results of further analysis of this experiment, which confirms our previous estimate and the conclusion that in the process $\bar{p}p \to 2\pi$ there are comparable contributions from even and odd $\bar{p}p$ atomic orbital states.

The measurements were part of a study made at the Brookhaven alternating-gradient synchrotron of the neutral annihilation modes of $\bar{p}$'s stopping in hydrogen. The experimental arrangement and techniques, which have been described in detail elsewhere,[5] were briefly as follows: A partially separated beam (~ 700 MeV/$c$ and ~800 $\bar{p}$'s per pulse) was suitably degraded, so that the remaining $\bar{p}$'s (~100 per pulse) stopped in a liquid-hydrogen target (15.5 in. long, 5.5 in. diam) with the stopping distribution 10 in. in width (full width at half-maximum). This hydrogen target was completely surrounded by scintillation counters and by four large optical $\gamma$-detecting spark chambers, each comprised of seventy stainless-steel plates $\frac{1}{16}$ in. thick (6 radiation lengths). As much as possible of the solid angle not covered by these spark chambers (~15%) was occupied by two lead-glass counters of high $\gamma$-detection efficiency. The spark chambers were triggered by the signal that a $\bar{p}$ entered, no charged particles left the hydrogen target, and no $\gamma$ entered the lead-glass counters. We obtained 250 000 photographs part of which ($\sim\frac{1}{2}$) was scanned once and classified as follows: blank, 26%; 1$\gamma$, 3%; 2$\gamma$, 4%; 3$\gamma$, 6%; 4$\gamma$, 10%; 5$\gamma$, 11%; 6$\gamma$, 10%; 7$\gamma$, 5%; 8$\gamma$, 4%; 9$\gamma$, 1%; $\geq 10\gamma$, 1%; $\bar{n}$-stars, 15%. Here "$\gamma$" signifies a spark shower pointing towards the target; and "$\bar{n}$-stars" are annihilations of an $\bar{n}$ in the spark chambers, attributed to $\bar{p}p \to \bar{n}n$. The triggering rate was consistent with a branching ratio for $\bar{p}p \to$ neutrals of about 3%, as determined in bubble chambers.[6,7] The $\gamma$ directions were obtained by fitting straight lines to the initial straight section of each shower and finding the most probable common vertex. The estimated resulting accuracy in these directions is $\pm 2°$. $\gamma$ energies were estimated, to an accuracy of about a factor 2, from the number of sparks in each shower.

*(1) Identification of the $2\pi^0$ mode.*—$2\pi^0$ annihilation can result in pictures with four or fewer $\gamma$'s. The primary evidence for this process comes from a study of the 4$\gamma$ pictures. However, in order to assess the actual rate for this process without undue reliance on *a priori* estimates of the detection and scanning efficiencies, we have measured and analyzed pictures with four, three, and two $\gamma$'s for their contribution to the $2\pi^0$ process. In each case, the contribution has to be separated from a "background" (due to events of higher $\gamma$ multiplicity in which only four or fewer $\gamma$'s are detected). The form of this background was simulated by a sample of measured 5$\gamma$ pictures, with one, two, or three $\gamma$'s randomly rejected, and analyzed as if they were "real" events. The analysis and contribution of events of each multiplicity is as follows:

(i) 4$\gamma$: Using only measured $\gamma$ angles and assuming zero momentum for the whole system, the $\gamma$ energies are deduced by solving the four energy-momentum equations. Only events with all $\gamma$ energies positive are accepted. The invariant mass of all six $\gamma$-$\gamma$ pairs is then calculated; and for each event three possible pairs of masses —$M_1(\gamma,\gamma)$, $M_2(\gamma,\gamma)$—are obtained. All these

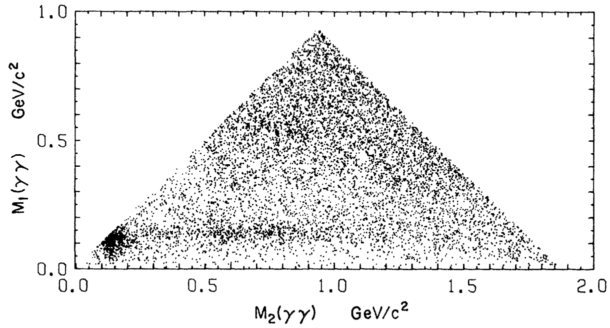


FIG. 1. 4$\gamma$ events. $M_1 < M_2$.

combinations are displayed in the in the scattergram Fig. 1. A striking enhancement is apparent in the region where both $M_1$ and $M_2$ equal the $\pi^0$ mass. Figure 2(c) is a histogram of the projection of part of Fig. 1. The peak in Fig. 2(c) is centered on the $\pi^0$ mass to within 1 MeV. That most of the events in this peak cannot be attributed to "background" is demonstrated by comparison with Figs. 2(d), 2(b) which display the corresponding distributions for a sample of "background" events. Moreover explicit checks by Monte Carlo methods have shown that some specific annihilation modes, $\bar{p}p \to \pi^0\omega^0$, $3\pi^0$, etc., could not simulate the observed peaked distribution. We fitted the distribution in Fig. 2(a) using the amounts of $2\pi^0$ (shape from Monte Carlo) and of background, and also the uncertainty in $\gamma$ angle measurement, as variable parameters. The fit ($\chi^2 = 126$ over a 55-element grid) gives 530 $2\pi^0$ events and an angular uncertainty of $\pm 2°$. With this angular resolution, only 73% of the true $2\pi^0$ events satisfy the criterion that all $\gamma$ energies are positive. Thus $720 \pm 93$ is the estimated number of $2\pi^0$ events here.

(ii) 3$\gamma$: True $2\pi^0$ events with one $\gamma$ undetected will normally result in three nearly coplanar $\gamma$'s with the opening angle of one pair near 16.5° (the minimum opening angle for a $\pi^0$ with momentum 940 MeV/$c$). Figure 2(e) is a portion of the scattergram of $\theta_c$, the angle between the plane of these $\gamma$'s and the third, versus $\theta_{\gamma\gamma}$, the opening angle of two of the $\gamma$'s. All three combinations for each event are plotted. As before, the distribution has been fitted with adjustable amounts of a Monte Carlo $2\pi^0$ signal and of "background" whose form is obtained from 5$\gamma$ pictures. We obtain $660 \pm 100$ $2\pi^0$ events ($\chi^2 = 55$, 30-element grid).

(iii) 2$\gamma$, 1$\gamma$, 0$\gamma$: $2\pi^0$ events with two $\gamma$'s undetected typically exhibit two roughly opposite $\gamma$'s. The observed distribution of the angle between

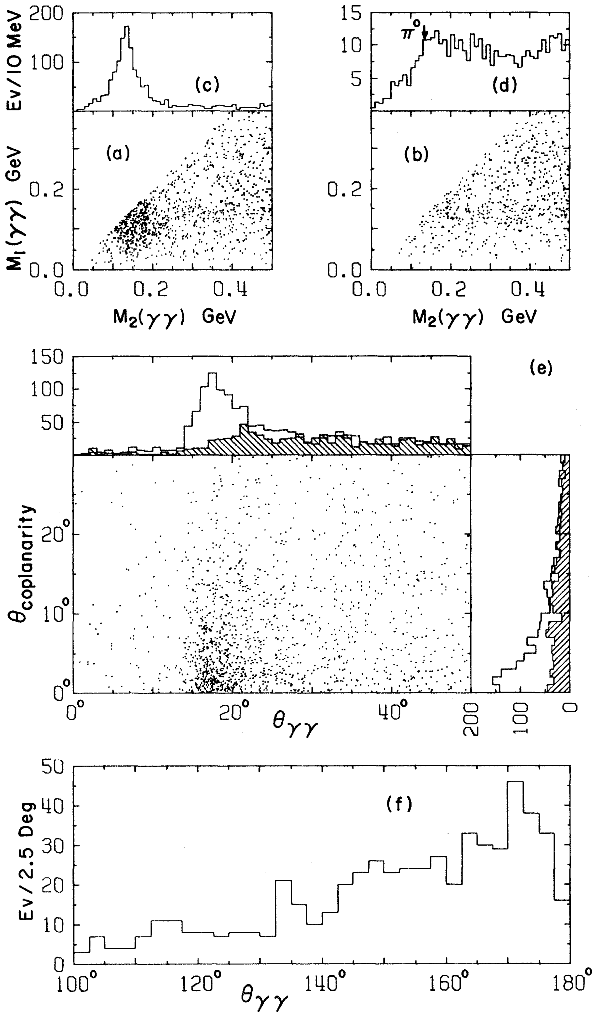


FIG. 2. (a) The real $4\gamma$, (b) the $4\gamma$ background (see text) normalized by the fit (see text). (c), (d) $M_1$ ($M_2$) histograms of (a), (b) if $M_2$ ($M_1$) = 135 ± 60 MeV. (e) $3\gamma$ events. In the projections of the scattergram the background normalized by fit is shown shaded. (f) $2\gamma$ pictures.

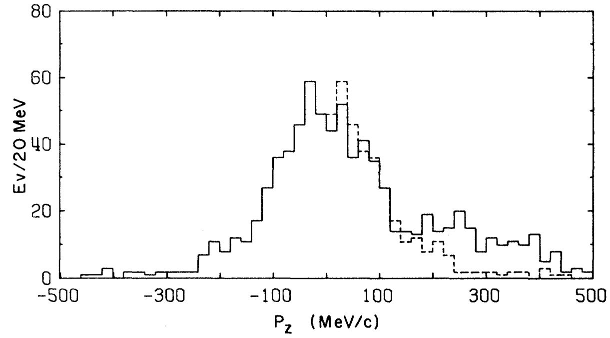


FIG. 3. $4\gamma$ events. Beam momentum as determined by kinematics. Dashed histogram is the reflected $p_z < 0$ part of the spectrum.

the two $\gamma$'s in $2\gamma$ pictures is shown in Fig. 2(f). The broad peak in the region 140°–180° is attributed to the $2\pi^0$ mode, and we estimate 230 ± 100 for this small contribution to the overall number of $2\pi^0$ events. The ratio of the number of $2\pi^0$ events observed in the $4\gamma$ and $3\gamma$ pictures implies an overall $\gamma$ detection efficiency of 0.82 ± 0.02 (consistent with an upper limit of 0.91 estimated from a Monte Carlo calculation). Using this value (0.82) for the efficiency we would expect 214 $2\pi^0$ events in the $2\gamma$ pictures and 32 and 2 events in the $1\gamma$ and $0\gamma$ pictures, respectively.

*(2) Evidence for annihilation at rest.*—A preliminary indication that the observed $2\pi^0$ events are mostly from anninilations at rest is provided by their vertex distribution along the beam direction, which is similar to that for all other events. A more sensitive test comes from a kinematic fit of the $4\gamma$ events, using the program SQUAW. The fit is made with the hypothesis $\bar{p}p \rightarrow 2\pi^0$, using the measured angles *and* energies (from spark count), but now allowing $p_z$ (the $\bar{p}$ momentum along the beam direction) to vary from a starting value of +200 MeV/$c$. Figure 3 shows the distribution of the fitted values of $p_z$ for all events consistent with the $2\pi^0$ mode. It is peaked at $p_z = 0$, but shows an excess for $p_z > 0$, indicating that (18 ± 4)% of the events are annihilations in flight (~200–400 MeV/$c$).

*(3) Branching ratio.*—The total number of $\bar{p}p \rightarrow 2\pi^0$ events in the analyzed film [Sect. (1)] is 1664 ± 170. This number must be corrected for the following loss factors: 1.20 ± 0.06 for $\gamma$'s entering lead glass counters, 1.28 ± 0.06 for $\gamma$'s converting in the target or surrounding scintillators, 1.3 ± 0.1 for scanning and measuring losses, and 1.32 for the reconstruction program. The corrected number of $\bar{p}p \rightarrow 2\pi^0$ events is then 4350 ± 700, of which 3550 ± 600 are estimated to be at rest [Sect. (2)]. The number of $\bar{p}$'s which annihilate in the target to produce these events is (7.4 ± 0.8) × $10^6$. In arriving at this number, we have corrected the $\bar{p}$ flux given by the beam-monitoring system for spurious $\bar{p}$ signatures (0.9 ± 0.1), annihilations unrecorded because of annihilation products triggering the beam-defining veto counter (1.39 ± 0.05), and stability of the electronics (1.0 ± 0.06); but no correction has been included for annihilations in flight. For the purpose of establishing the rates of $p$-(odd) state and $s$-(even) state anninilations, it is a comparison with the reported $\bar{p}p \rightarrow \pi^+\pi^-$ rate[7] that is significant, and there the correction for in-flight annihila-

tions was likewise omitted. For the actual $2\pi$ branching ratios, the correction, which depends on knowledge of the rapidly varying annihilation cross section at low energy, may not be insignificant. Excluding this factor, then, we find the ratio

$$(\bar{p}p \to 2\pi^0)_{\text{at rest}}/(\bar{p}p \to \text{all annihilations}) = 4.8\times 10^{-4}\ (\pm 20\%).$$

The quoted uncertainty is mainly due to our estimates of the systematic errors.

*Conclusions.*—(a) This $\bar{p}p \to 2\pi^0$ rate implies a contribution to $\bar{p}p \to \pi^+\pi^-$ from odd-$L$ states of twice this: $9.6\times 10^{-4}$ ($\pm 20\%$). Combining this with the value $(32\pm 3)\times 10^{-4}$ for the branching fraction for $\bar{p}p \to \pi^+\pi^-$ gives

$$[(\bar{p}p)_{L\ \text{odd},\ I=0} \to 2\pi]/(\bar{p}p \to 2\pi) = 0.39\ (\pm 20\%).$$

This surprisingly large value is at variance with the supposition that annihilations from atomic $s$ states predominate in all annihilation processes. (b) Comparison of the above ratio with the analogous ratio for $K^0\bar{K}^0$,[3]

$$[(\bar{p}p)_{L\ \text{odd},\ I=0,1} \to K_0\bar{K}_0]/(\bar{p}p \to K_0\bar{K}_0) = 0.018\pm 0.009,$$

establishes that important dynamical effects are present in these two channels and underlines the danger of making inferences about the overall annihilation process from the study of individual rare modes. (c) Benvenuti *et al.*[8] have recently reported that the small ratio in the kaon case persists even for annihilations in flight where it is known that many angular momenta other than $L=0$ are involved. Moreover, using the observed $2\pi^0$ events in flight (~200–400 MeV/$c$) and $\bar{p}p$ annihilation cross sections we find that the ratio $(\bar{p}p \to 2\pi^0)/(\bar{p}p \to \text{all})$ is the same, to within a factor of about 2, as that at rest. This, as well as the $K_1K_1/K_1K_2$ independence of energy, indicates that no order-of-magnitude changes occur in the odd/even ratio at rest and in flight for these processes.

In view of the above results we conclude that there is no clear experimental support for $s$-state dominance in $\bar{p}p$ annihilations at rest and our results provide some direct evidence to the contrary.

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## $\gamma+\gamma\to 3\pi^0$ and $\pi^+ + \pi^- + \pi^0$ in a Linear $\sigma$ Model*

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We present the low-energy limit of the one-loop contribution to $\gamma+\gamma\to 3\pi^0$ and $\pi^+ + \pi^- + \pi^0$ in a linear $\sigma$ model. In this model calculation we have the Adler-Schwinger anomaly and we do not have to set all pion momenta equal to zero. Our result maintains gauge invariance and both amplitudes vanish in contradiction to the previous result of Aviv, Hari Dass, and Sawyer.

Since Brodsky, Kinoshita, and Terazawa[1] pointed out recently the possibility of measuring cross sections such as $\gamma+\gamma\to 3\pi$ in electron colliding beam experiments, there have been many theoretical calculations of $\gamma+\gamma\to$($n$ pions). Aviv, Hari Dass, and Sawyer[2] construct a nonlinear phenomenological Lagrangian which gives an amplitude for $\gamma+\gamma\to$ (odd number of pions) analogous to the Adler-Schwinger[3]