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Evidence for a Second Neutral Pion

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Abstract

Evidence suggests the existence of a second neutral pion based on: (1) the anomalous branching ratios in the reactions $\bar{p}p \to \pi\pi$ and $\bar{p}d \to \pi\pi N$, and (2) the 1960s findings of Tsai-Chü *et al.* regarding antinucleon annihilation stars in emulsions. The anomaly in (1) disappears if the two neutral pions in the reactions $\bar{p}p \to \pi^0\pi^0$ and $\bar{p}d \to \pi^0\pi^0 n$ are not identical. Tsai-Chü *et al.* observed a second neutral pion that "decays more rapidly into electron pairs with larger opening angles and more frequently into double pairs." One antineutron annihilation event produced three neutral particles, each with a mass of 135 ± 14 MeV, decaying into four electrons with significantly wider opening angles than those of the internal conversion electrons observed in π^0 decays. The larger opening angles and higher frequency of double pair production could be caused by neutral pions with such a short lifetime that they decay into photon pairs before they can leave the annihilation nucleus (e.g., Ag) of the emulsion. We discuss several methods for searching for a second neutral pion.

Keywords

Second Neutral Pion, Antiproton-Proton Annihilation

1. Introduction

Significant experimental evidence indicates that capture and annihilation reactions occur predominately from the atomic S states in liquid hydrogen. The anomalously large fraction of antiproton annihilations proceeding from the P states in two sets of reactions ($\bar{p}p \to \pi\pi$ and $\bar{p}d \to \pi\pi N$) was not measured directly, but was inferred using the theoretical argument that $\bar{p}p \to \pi^0\pi^0$ cannot occur from a $\bar{p}p$ atomic S state. However, if the two π^0's are not identical, $\bar{p}p \to \pi_L^0\pi_S^0$ and $\bar{p}d \to \pi_L^0\pi_S^0 n$ can occur from an atomic S states, and there is no anomaly. Here, we denote the usual π^0 that decays in ~10^{-16} s as π_L^0 and a second neutral pion that decays with a much shorter lifetime as π_S^0.

The rules governing the $\bar{p}p \to \pi\pi$ reactions are discussed in Section 2, and the experimental evidence of the anomaly is presented in Section 3. In Section 4, we present a slightly different interpretation of the results of Tsai-Chü *et al.* Their main point is that a second neutral pion with a very short lifetime exists is unchanged. Although they assumed that the observed electrons came directly from the decay of this second neutral pion, π_S^0, we suggest that the observed electrons came from pair production inside the annihilation nucleus. Our interpretation has the advantage of explaining why such electron pairs and double pairs are not observed in $\bar{p}$ annihilation in hydrogen and deuterium. (These electron pairs are not Dalitz pairs as discussed in Section 4).

Experimental tests that could demonstrate the existence of two distinct π^0 are discussed in Section 5, along with another test (based on the results of Tsai-Chü *et al.*) that can prove the existence and determine the lifetime of this second neutral pion.

2. Allowed Antiproton-Proton Reactions

The conservation of angular momentum, parity, and charge parity dictates the allowed reactions in which protonium is annihilated into two pions. The eigenvalues of parity and charge parity of a fermion-antifermion pair are given by [1],

$$\begin{aligned} \omega_{\text{Parity}} &= (-1)^{X+1}, \\ \omega_{\text{Charge parity}} &= (-1)^{X+s}, \end{aligned} \tag{1}$$

where X is the relative orbital angular momentum of the two particles and s is the spin of the fermion-antifermion system. The eigenvalues of parity and charge parity of a two-pion system are given by [1],

$$\begin{aligned} \omega_{\text{Parity}} &= (-1)^{Y}, \\ \omega_{\text{Charge parity}} &= (-1)^{Y}, \end{aligned} \tag{2}$$

where Y denotes the relative orbital angular momentum of the two pions.

Further contraints exist for the $\pi^0\pi^0$ system. Because of Bose statistics, the states of two identical pions must be symmetric under interchange. Thus Y must be even and both parity and charge parity must be +1 for the $\pi^0\pi^0$ system. From these considerations, we obtain **Tables 1-3** for the initial and final states, respectively.

Using the conservation of parity, charge parity, and total angular momentum to match the initial and final states, we determine the allowed reactions:

$$\begin{aligned} &\bar{p}p\left({}^3S_1\right) \to \pi^+\pi^-\left(P_1\right), \\ &\bar{p}p\left({}^3P_0\right) \to \pi^0\pi^0\left(S_0\right),\ \bar{p}p\left({}^3P_0\right) \to \pi^+\pi^-\left(S_0\right), \\ &\bar{p}p\left({}^3P_2\right) \to \pi^0\pi^0\left(D_2\right),\ \bar{p}p\left({}^3P_2\right) \to \pi^+\pi^-\left(D_2\right). \end{aligned} \tag{3}$$

Thus, we see that the $\bar{p}p \to \pi^0\pi^0$ reaction cannot occur from an atomic S

Table 1. Initial state of $\overline{p}p$ Atom.

State	J	Parity	Charge parity
$^1S_0$	0	−1	+1
$^3S_1$	1	−1	−1
$^3P_0$	0	+1	+1
$^1P_1$	1	+1	−1
$^3P_1$	1	+1	+1
$^3P_2$	2	+1	+1

Table 2. Final state of $\pi^0\pi^0$ system.

State	J	Parity	Charge parity	Comment
S_0	0	+1	+1	$Y = 0$
D_2	2	+1	+1	$Y = 2$

Table 3. Final state of $\pi^+\pi^-$ system.

State	J	Parity	Charge parity	Comment
S_0	0	+1	+1	$Y = 0$
P_1	1	−1	−1	$Y = 1$
D_2	2	+1	+1	$Y = 2$

state of the $\overline{p}p$ system if the two π^0's are identical. To match the initial $^3S_1$ state of $\overline{p}p$, the $\pi^0\pi^0$ system requires a P_1 state with parity = −1 and charge parity = −1 as shown in the second line of Table 3 for the $\pi^+\pi^-$ system. The significant difference in eigenvalues between the $\pi^+\pi^-$ system and the $\pi^0\pi^0$ system arises because the two π^0's are identical whereas the π^+ and π^- are not.

If the π^0's are different, there is no requirement that the state of the two π^0's must be symmetric under interchange. Therefore, Y can be odd for some $\pi_L^0\pi_S^0$ states similar to the $\pi^+\pi^-$ system, leading to a P_1 state with parity of −1. Charge parity also depends upon the relative angular momentum of the two particles. Thus, the charge parity becomes the same as in the $\pi^+\pi^-$ case, as given by Equation (2), and the reaction,

$$\overline{p}p\left(^3S_1\right) \to \pi_L^0\pi_S^0\left(P_1\right) \tag{4}$$

is allowed.

3. Need for Two Neutral Pions to Explain Anomalous Branching Ratios

When an antiproton or some other negatively charged particle slows down in liquid H_2 it is typically captured into a Bohr orbit by a proton at a principle quantum number $n \approx 30$ and with high orbital angular momentum, X. The process is depicted in **Figure 1**. Collisional deexcitations and radiative transitions transform the atom to lower n and lower X values, allowing the electrically neutral atom to penetrate neighboring atoms and experience the electric field of the protons. This causes Stark effect transitions between the degenerate orbital angular momentum states. The rates for radiative transition and nuclear absorption (or annihilation) from P states are small in comparison with the rate at which the Stark effect populates the S state. Because S-state absorption (or annihilation) can occur from high n values, the atom is unlikely to deexcite to low n values for which P state nuclear absorption (or annihilation) is more important.

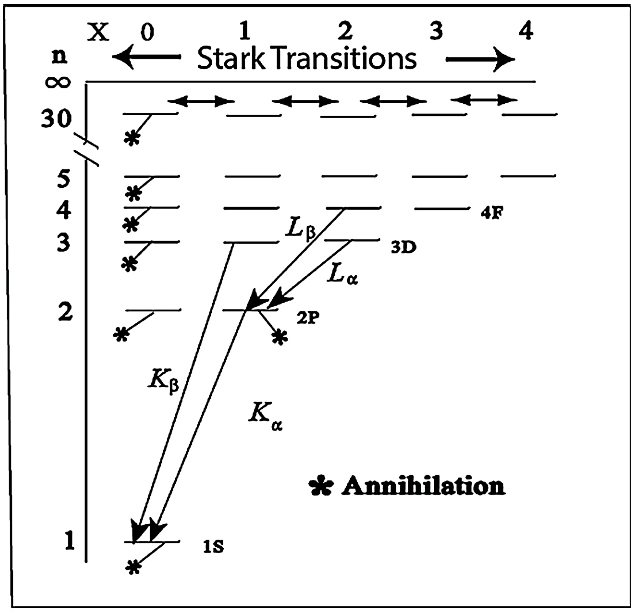

Figure 1. Levels of atomic orbital states for a negatively charged particle and a proton with principle quantum number n and orbital angular momentum X. It shows the effect of Stark transitions on different X states, radiative deexcitations, and levels from which nuclear absorption or annihilation are likely.

Thus, according to theory [2] [3] absorption occurs predominantly from S states for π^- and K^-. In 1960, Desai [4] concluded, "Rough calculations indicate that for protonium also the capture will take place predominantly from S states."

There is also strong experimental evidence that S-state capture dominates in liquid H_2. The $\pi^- p$ [5] [6], $K^- p$ [7] [8], and $\Sigma^- p$ [9] reactions have been studied. Since these negatively-charged particles decay, the nuclear absorption time can be determined by observing the fraction that decay. The cascade times are approximately two orders of magnitude shorter than those required for radiative deexcitation. Because the antiproton does not decay, such a measurement is not possible. Since the short cascade times for π^-, K^-, and Σ^- cannot be explained without recourse to the Stark effect, the Stark effect must also play a role in the $\bar{p}p$ case.

There is some direct evidence of S-state dominance in $\bar{p}p$ reactions. It has been determined [10] that $\bar{p}p \to KK < 6\%$ from P states with a 95% confidence level. From the ρ decay angular distribution, it has been determined [11] [12] that $\bar{p}p \to \pi^+\pi^-\pi^0 < 5\%$ from P states. Thus, the experimental evidence strongly supports S-state domination for $\bar{p}p$ reactions.

We first examined the experimental results for $\bar{p}p \to \pi\pi$. In liquid hydrogen the branching ratio for $\bar{p}p \to \pi^+\pi^-$ is (32 ± 1) × 10^{-4} [13] [14], and measurements of the branching ratio for $\bar{p}p \to \pi^0\pi^0$ are given in **Table 4**.

The experimental results obtained using the Crystal Barrel detector are likely to be the most accurate. As they noted in their paper [20], "Owning to our large detection efficiency and small background our result is least likely influenced by undetected systematic errors. The reliability of the result is strengthened by the internal consistency of a large set of two-body branching ratios measured with the Crystal Barrel detector and their agreement with previous determinations, especially with bubble chamber data."

Assuming that the two π^0's in the reaction $\bar{p}p \to \pi^0\pi^0$ are identical, one can calculate the fraction of annihilations proceeding from P states, $P_{LH}(\pi\pi)$, for $\bar{p}p \to \pi\pi$ as follows,

$$P_{LH}(\pi\pi) = \frac{BR(\bar{p}p \to \pi^+\pi^-)_P + BR(\bar{p}p \to \pi^0\pi^0)_P}{BR(\bar{p}p \to \pi^+\pi^-)_{S\&P} + BR(\bar{p}p \to \pi^0\pi^0)_P}. \tag{5}$$

Assuming charge independence,

$$BR(\bar{p}p \to \pi^+\pi^-)_P = 2 \times BR(\bar{p}p \to \pi^0\pi^0)_P, \tag{6}$$

We obtain the % proceeding from P states which is given in Column 2 of **Table 4**. The result of 48% proceeding from P states, shown in **Table 4** (Crystal Barrel collaboration), is anomalously high.

Table 4. Branching ratio for $\bar{p}p \to \pi^0\pi^0$.

Measured value	% from P states	Year	Reference
(4.8 ± 1.0) × 10^{-4}	39%	1971	Devons *et al.* [15]
(1.4 ± 0.3) × 10^{-4}	13%	1979	Bassompierre *et al.* [16]
(6 ± 4) × 10^{-4}	47%	1983	Backenstoss *et al.* [17]
(2.06 ± 0.14) × 10^{-4}	18%	1987	Adiels *et al.* [18]
(2.5 ± 0.3) × 10^{-4}	22%	1988	Chiba *et al.* [19]
(6.93 ± 0.43) × 10^{-4}	53%	1992	Crystal Barrel [20]
(2.8 ± 0.4) × 10^{-4}	24%	1998	Obelix [21]
(6.14 ± 0.40) × 10^{-4}	48%	2001	Crystal Barrel [14]

We now consider antiproton annihilation in deuterium. By studying the reactions $\bar{p}d \to \pi^-\pi^+n$ and $\bar{p}d \to \pi^-\pi^0 p$ in a liquid deuterium bubble chamber, Gray *et al.* [22] reported that (75 ± 8)% of the annihilations originate from P states. The quantity measured is,

$$r = \frac{BR\left(\bar{p}d \to \pi^- \pi^0 p\right)}{BR\left(\bar{p}d \to \pi^+ \pi^- n\right)}. \tag{7}$$

The percentage proceeding from P states was then calculated using charge independence,

$$BR\left(\bar{p}d \to \pi^+ \pi^- n\right) = \frac{1}{2} BR\left(\bar{p}d \to \pi^- \pi^0 p\right) + 2 \times BR\left(\bar{p}d \to \pi^0 \pi^0 n\right), \tag{8}$$

and

$$P_{LD}\left(\pi\pi\right) = \frac{3BR\left(\bar{p}d \to \pi^0 \pi^0 n\right)}{BR\left(\bar{p}d \to \pi^+ \pi^- n\right) + BR\left(\bar{p}d \to \pi^0 \pi^0 n\right)}, \tag{9}$$

resulting in,

$$P_{LD}\left(\pi\pi\right) = \frac{3\left(2 - r\right)}{6 - r}. \tag{10}$$

Equation (9) is based on the theoretical argument that $\bar{p}d \to \pi^0 \pi^0 n$ cannot occur from an atomic S state. This argument is identical to that presented in Sec. 2 for the reaction $\bar{p}p \to \pi^0 \pi^0$.

The results of Gray *et al.* [22] and two other groups are listed in **Table 5**. The experimental results of Bridges *et al.* [23] using a magnetic spectrometer are in close agreement with those of Gray *et al.* [22]; however, the high statistics experiment of Angelopoulos *et al.* [24] using a magnetic spectrometer is consistent with a P-state fraction of 0%. Reifenröther and Klempt [25] noted that this low value [24] could have been caused by the tight cut on the colinearity of the $\pi^+\pi^-$ pair used. A cut that is too tight can result in $\pi^+\pi^-$ pairs being lost. Gray *et al.* [22] used a cut angle of 16 degrees, Bridges *et al.* [23] used 10 degrees, and Angelopoulos *et al.* [24] used 5 degrees.

We performed a Monte Carlo calculation of the expected deviation from the colinearity of the $\pi^+\pi^-$ pairs for the reaction $\bar{p}d \to \pi^+ \pi^- n$. We used the

Table 5. Ratio $BR\left(\bar{p}d \to \pi^- \pi^0 p\right) / BR\left(\bar{p}d \to \pi^+ \pi^- n\right)$.

Measured value	Method	% from P states	Year	Reference
(0.68 ± 0.07)	deuterium bubble chamber	75%	1973	Gray *et al.* [22]
(0.70 ± 0.05)	magnetic spectrometer	74%	1986	Bridges *et al.* [23]
(0.55 ± 0.05)		80%	1986	Bridges *et al.* [23]
(2.07 ± 0.05)	magnetic spectrometer	0%	1988	Angelopoulos *et al.* [24]

neutron momentum distribution shown in **Figure 2(a)**, which was derived from the results obtained by Gray *et al.* [22]. (See Fig. 1c of Ref. [22] and Fig. 5 of Ref. [23].) The calculated angular deviation from colinearity, plotted in **Figure 2(b)**, shows that a significant fraction of the pairs extending beyond 5 degrees. Our correction factor for pairs beyond 5 degrees is 1.58, whereas that used in Ref. [24] was 1.13. Using this new correction factor results in $r = 1.48$ and $P_{LD}(\pi\pi) = 34\%$, which is in good agreement with the first two experiments.

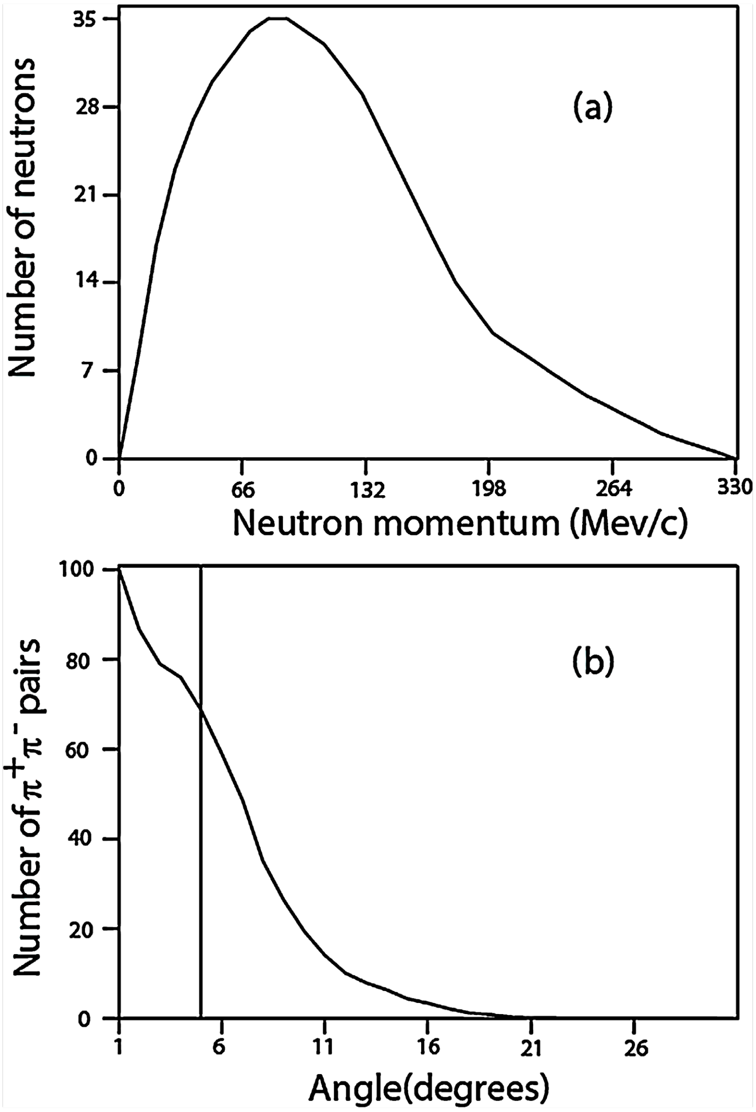

Figure 2. (a) Neutron momentum distribution in reaction $\bar{p}d \to \pi^+\pi^- n$ at rest, derived from result of Gray *et al.* [22]. (b) Monte Carlo calculation of number of $\pi^+\pi^-$ pairs versus their angular deviation from colinearity in reaction $\bar{p}d \to \pi^+\pi^- n$. Vertical line is at 5 degree cutoff.

Reifenröther and Klempt [25] have suggested a modification which includes the measured ratio (1.33) of $\bar{p}p$ to $\bar{p}n$ in D_2. This reduces the 75% from P states to 55%. With considerations similar to those of Equations (11)-(13) shown below, they obtain an f_P of 45%.

Efforts were made to resolve the discrepancies in $\bar{p}p \to \pi\pi$ by lowering the P-state fraction inferred from the measured branching ratios. Doser *et al.* [26] suggested that the total P-state fraction might be lower than that given by Equation (5), and it was just that the branching ratio into two pions (rather than into other particles) was greater from P states than that from S states. In support of this idea, Doser *et al.* [26] measured the branching ratio for $\bar{p}p \to \pi^+\pi^-$ from a pure P state (by detection of the reaction in coincidence with transition X-rays) to be $(4.81 \pm 0.49) \times 10^{-3}$.

The P-state annihilation fraction, f_P, can be calculated as follows [25] [27],

$$BR\left(\bar{p}p \to \pi^+\pi^-\right) = \left(1 - f_P\right)B_0 + f_P B_1, \tag{11}$$

$$BR\left(\bar{p}p \to \pi^0\pi^0\right) = \frac{1}{2} f_P B_1, \tag{12}$$

$$BR\left(\bar{p}p \to \pi^+\pi^-\right)_X = B_1. \tag{13}$$

where B_0 and B_1 are the branching-ratio coefficients (independent of density) from S and P states, respectively.

Using the Crystal Barrel collaboration result [14] and Doser *et al.* [26] for $BR\left(\bar{p}p \to \pi^+\pi^-\right)_X$, one obtains $B_1 = 4.81 \times 10^{-3}$ from Equation (13) and $f_P = 26\%$ from Equation (12).

Batty [27] discovered an interesting mechanism for further reducing this percentage. He introduced the enhancement of annihilations from fine-structure states over that expected from a statistical population. He modified the earlier calculations of Reifenröther and Klempt [25] using the Borie and Leon model [28] to incorporate enhancement factors. With these enhancement factors, Equations (11)-(13) become,

$$\begin{aligned} BR\left(\bar{p}p \to \pi^+\pi^-\right) = {} & \left(1 - f_P\right)\frac{3}{4}E\left({}^3S_1\right)B\left({}^3S_1\right) \\ & + f_P\left[\frac{1}{12}E\left({}^3P_0\right)B\left({}^3P_0\right) + \frac{5}{12}E\left({}^3P_2\right)B\left({}^3P_2\right)\right], \end{aligned} \tag{14}$$

$$BR\left(\bar{p}p \to \pi^0\pi^0\right) = \frac{1}{2} f_P\left[\frac{1}{12}E\left({}^3P_0\right)B\left({}^3P_0\right) + \frac{5}{12}E\left({}^3P_2\right)B\left({}^3P_2\right)\right], \tag{15}$$

$$BR\left(\bar{p}p \to \pi^+\pi^-\right)_X = \frac{1}{12}B\left({}^3P_0\right) + \frac{5}{12}B\left({}^3P_2\right). \tag{16}$$

The enhancement factors $E\left({}^3S_1\right)$ and $E\left({}^3P_2\right) \approx 1.0$ for all densities while the enhancement factor for the ${}^3P_0$ state, $E\left({}^3P_0\right) \approx 1.0$ at low density and increases to 2.076 to 2.556 (depending upon the model used in the calculation) at liquid H_2 density. To reduce f_P, Batty assumed $B\left({}^3P_0\right) \gg B\left({}^3P_2\right)$, but his result, $f_P = 10$ to 12%, is still at least a factor of two too high. This reduction depends strongly on the choice of parameters. For example, if we take $B\left({}^3P_0\right) = B\left({}^3P_2\right)$, f_p would only be reduced to 20%. Thus, Batty's mechanism is not sufficiently large to remove the discrepancy in the $\bar{p}p \to \pi\pi$ case. In addition, the enhancement factors are not effective in reducing the discrepancy in the $\overline{p}d \to \pi\pi N$ case [29] as the predicted enhancement factors are approximately 1.

In summary, if we assume that the two π^0's are identical, the branching ratios for the reactions $\overline{p}p \to \pi\pi$ and $\overline{p}d \to \pi\pi N$ indicate a fraction proceeding from P states that is 4 to 8 greater than that occurring in other reactions. However, if the two π^0's are not identical, reactions can occur from S states and the anomaly is eliminated.

4. New Interpretation of Tsai-Chü *et al.* Results

In the 1960s Tsai-Chü *et al.* [30] [31] found evidence of a second neutral pion with some surprising properties. They placed stacks of K-5 emulsions in the antiproton beam of the Berkeley Bevatron and looked for multi-prong stars. They were surprised to see many electrons coming from some of the annihilation vertices.

Through charge exchange some of the antiprotons were converted to antineutrons. Notably, one star caused by antineutron annihilation produced 12 electrons [30]. The analysis showed that electrons (four each) came from three neutral particles, with masses of 136 ± 14, 135 ± 14, and 136 ± 13 MeV. The likelihood of three ordinary neutral pions decaying with double Dalitz pairs is exceedingly rare, at less than 10^{-13}.

From an analysis of 15 antinucleon annihilation stars, Tsai-Chü *et al.* [31] reported the following properties for this second neutral pion: 1) It has a mass of the same order as the usual π^0, 2) it is emitted with the same energy as that of a charged pion, 3) it decays more frequently into electron pairs and into double pairs, 4) the electron pairs from this second π^0 have larger opening angles than those of Dalitz pairs, and 5) it has a very short lifetime (much shorter than the usual π^0) because the electrons are emitted directly from the origin of the stars.

More recent experiments using improved low-energy antiproton beams annihilating in liquid hydrogen and deuterium have not shown the emission of electron pairs with these characteristics. This raises the question: What was happening in those experiments of Tsai-Chü *et al.*? A plausible explanation is that this second neutral pion has a lifetime that is so short that it occasionally decays before it can leave the annihilation nucleus of the emulsion, for example, Ag nucleus. This is illustrated in **Figure 3**.

The primary decay mode of this second neutral pion must be $\pi_S^0 \to 2\gamma$ because this is the detection method for π^0 [14] in $\overline{p}p \to \pi_L^0 \pi_S^0$ experiments. The probability of creation of electron pairs by π^0 photons is very high inside the nucleus. This explains the appearance of electrons in heavy-nuclei annihilations but not in hydrogen and deuterium annihilations. The opening angles for pairs produced by high-energy photons on nuclei [32] are wider than those from Dalitz pairs and the distribution of angles is in reasonable agreement with the result given in Table III of Tsai-Chü *et al.* [31].

Analysis of Tsai-Chü *et al.*'s results suggests that the annihilations that produce these electrons occur in 1% to 10% of annihilation stars. Assuming one π_S^0 per

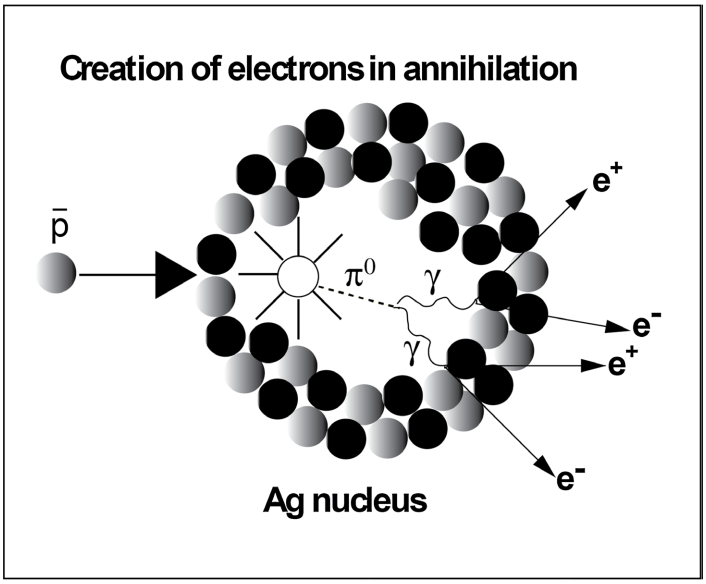

Figure 3. Illustration of proposed method by which second neutral pion appears to decay into four electrons. The π_S^0 decays inside the annihilation nucleus and its photons produce the observed electrons by pair production. Since π_S^0 must decay inside the nucleus, this process requires a lifetime ~10^{-21} s or less.

star, the estimated lifetime ranges from 10^{-21} s to 10^{-22} s. According to the uncertainty principle, this corresponds to a width is between 0.7 MeV and 7 MeV. The lifetime of π_S^0 cannot be significantly shorter than 10^{-22} s, as it would have been evident in the missing mass spectra for reactions such as $\bar{p}p \to \pi^+\pi^-\pi_S^0$. A broad resonance at m_{π^0} would appear significantly different from the detected, narrow π^0 peak.

5. Experimental Tests

Although seven different groups measured the branching ratio for $\bar{p}p \to \pi^0\pi^0$, showing the importance of this unexpectedly large branching ratio, no direct test has been performed to determine whether the reaction could be occurring from an atomic S state. Such a test could be conducted by establishing an initial $\bar{p}p$ atomic S state and observing the $\pi^0\pi^0$ final state. The method is illustrated in Figure 4. As discussed earlier, in liquid H_2 the Stark effect causes transitions to S states at high n-values, where annihilation occurs more readily than deexcitation. One can decrease the effect of Stark transitions by using H_2 gas at STP, and thereby observe the deexcitation radiation.

The coincidence of the L and K X-rays from protonium shows that the atom is in the 1S state. The energy of the K X-rays is between 9.4 KeV (K_α) and 12.5 KeV (K_∞), while energy of the L X-rays is between 1.7 KeV and 3.1 KeV. The energy of M X-rays is between 0.5 KeV and 1.3 KeV. Thus, X-rays from different transitions tend to be distinguishable.

The Asterix Collaboration detected K_α X-rays coinciding with L X-rays [33]. Our proposed experiment mirrors their setup but adds the complexity of requiring

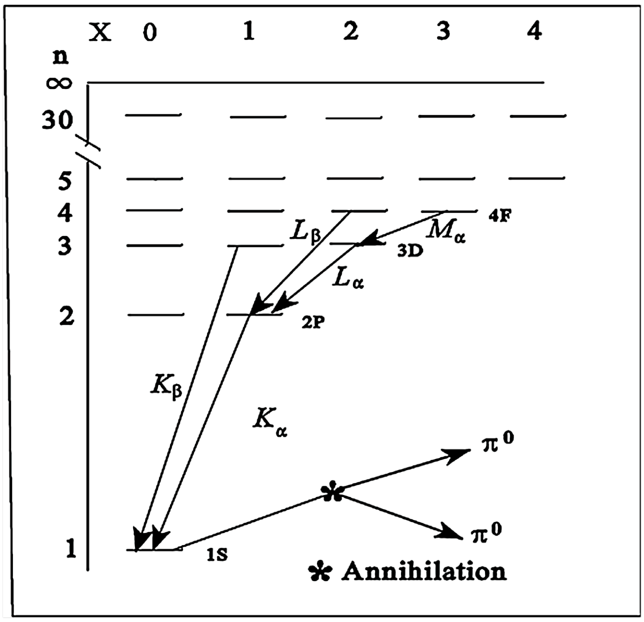

Figure 4. Test for $\bar{p}p \to \pi_L^0 \pi_S^0$ from S state. It shows radiative cascades to the 1S state which involve L and K X-rays followed by annihilation.

the triple coincidence of L and K X-rays from protonium and the $\pi^0\pi^0$ annihilation mode. The detection of such events proves that the annihilation reaction occurs from an atomic S state.

It should be noted that some vector mesons can decay into $\pi_L^0 \pi_S^0$ if the ${}^3S_1$ state of protonium can, because certain vector mesons also have $J = 1$, parity = −1, and charge parity = −1. We considered the $\pi_L^0 \pi_S^0$ decay mode of the $\rho(770)^0$, $\omega(782)$, $\phi(1020)$, and $J/\psi(1S)$. This decay mode of the $\omega(782)$, $\phi(1020)$, and $J/\psi(1S)$ is forbidden by G-parity conservation, but it can proceed electromagnetically. In estimating the branching ratios, we assumed that the $\pi_L^0 \pi_S^0$ mode would occur at approximately the same rate as the $\pi^+\pi^-$ mode, but reduced by a factor of two.

The $\rho(770)^0$ has $I = 1$, so the reaction $\rho(770)^0 \to \pi^+\pi^-$ is allowed by isospin conservation because the $\pi^+\pi^-$ system can have $I = 0,1$ or 2. The reaction $\rho(770)^0 \to \pi^0\pi^0$ is forbidden for the usual π^0 because the $\pi^0\pi^0$ system can only have $I = 0$ or 2. Occurring electromagnetically, the branching ratio is reduced by a factor α^2. Assuming that π_S^0 has isospin 1, reaction $\rho(770)^0 \to \pi_L^0 \pi_S^0$ is similarly suppressed. This assumption is crucial for otherwise the reaction would have occurred readily.

Our estimated branching ratios are,

$$\begin{aligned}
&BR\left(\rho(770)^0 \to \pi_L^0 \pi_S^0\right) = 5\times10^{-5}, \\
&BR\left(\omega(782) \to \pi_L^0 \pi_S^0\right) = 1\times10^{-2}, \\
&BR\left(\phi(1020) \to \pi_L^0 \pi_S^0\right) = 4\times10^{-5}, \\
&BR\left(J/\psi(1S) \to \pi_L^0 \pi_S^0\right) = 7\times10^{-5}.
\end{aligned} \tag{17}$$

The only measured upper limit [34], $BR\left(\phi(1020)\to\pi^0\pi^0\right)<4\times10^{-5}$, was in the expected range. The search for the decay mode, $\omega(782)\to\pi_L^0\pi_S^0$ with an expected branching ratio of 1×10^{-2} is particularly compelling. It is already known that $\omega(782)$ decays into undetermined neutrals with branching ratio between 1.8×10^{-3} and 1.4×10^{-2}.

The results of Tsai-Chü *et al.* [30] [31] suggest another test that could allow a determination of the lifetime of this second π^0. By varying the mass number, A, of the target material in low-energy antiproton annihilation, one should be able to observe the increase in electron-positron pairs (as A increases) from the decay of π_S^0's inside the annihilation nucleus.

6. Conclusions

This has been a phenomenon driver investigation. The anomalous results for the reactions $\bar{p}p\to\pi\pi$ and $\bar{p}d\to\pi\pi N$ strongly indicate the existence of two distinct π^0's. The results of Tsai-Chü *et al.* provide direct evidence of a different kind of π^0. With our reinterpretation of their results, it is not surprising that this second π^0 has not been noticed in other reactions, because the major difference between it and the other π^0 is its much shorter lifetime.

The quark structure of the two neutral pions, π_L^0 and π_S^0, should be related to each other as that of the K_L^0 and K_S^0 which is,

$$\begin{aligned} K_S^0 &= \frac{\left(d\bar{s}-s\bar{d}\right)}{\sqrt{2}}, \\ K_L^0 &= \frac{\left(d\bar{s}+s\bar{d}\right)}{\sqrt{2}}. \end{aligned} \tag{18}$$

Thus, we have,

$$\begin{aligned} \pi_S^0 &= \frac{\left(u\bar{u}-d\bar{d}\right)}{\sqrt{2}}, \\ \pi_L^0 &= \frac{\left(u\bar{u}+d\bar{d}\right)}{\sqrt{2}}. \end{aligned} \tag{19}$$

In addition, antinucleon-annihilation reactions suggest the concurrent production of π_L^0 and π_S^0, mirroring the production patterns observed for K_L^0 and K_S^0.

Because the main difference between the two neutral pions is that one has a lifetime ~10^{-16} s while the other has a lifetime from 10^{-21} s to 10^{-22} s, one might think that this short-lived π^0 would have been detected in the π^0 lifetime measurements [35]. However, because the usual π^0 has such a short lifetime, it is difficult to separate it from one with a shorter lifetime. In addition, because the experimenters were not looking for a prompt decaying π_S^0, they often eliminated prompt signals as unwanted background.

For example, the experiment of Atherton *et al.* [36] was designed such that the measurement of the mean decay length would not be affected by prompt decays such as $\eta \to \gamma\gamma$. In their ratio R = [Y(250) − Y(45)]/[Y(250) − Y(0)] the positrons from prompt decays, which are not dependent on foil separation, are cancelled. Shwe *et al.* [37] ignored prompt decays to eliminate confusing backgrounds. As they noted, "Among the events missed or unmeasured were… Events with very small gaps which lie within the 'circle of confusion' around the star center." Stamer *et al.* [38] worked with the $K^+ \to \pi^+\pi^0$ decay at rest, and their histogram of number of decays versus the gap shows a very large peak in the 0 to 0.5 micron bin that could contain half prompt decays by a short-lived π_S^0.

One of the most accurate methods of measuring the π^0 lifetime is based on the Primakoff effect, which involves coherent photoproduction of π^0's in the Coulomb field of nuclei. Unlike other techniques, this method is heavy on theory. Although the results do not indicate a short-lived π^0, this method may not be appropriate for a second π^0 that decays by a mechanism in the 10^{-21} s to 10^{-22} s range.

Finding this elusive, short-lived second neutral pion is paramount. We have suggested some tests in Sec. 5 which can prove the existence of two distinct π^0's and some tests to confirm the existence of a π_S^0 with a very short lifetime.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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