Difference Spectra: Dominance of Two-Body Cascades in Antiproton-Neutron Annihilations at Rest

D. Bridges,[a] I. Daftari, and T. E. Kalogeropoulos
Physics Department, Syracuse University, Syracuse, New York 13210

and

R. Debbe, W. Fickinger, and D. K. Robinson
Physics Department, Case Western Reserve University, Cleveland, Ohio 44106
(Received 8 May 1985)

A novel method of analysis which eliminates the combinatorial background in searches for states produced in $\bar{p}n$ annihilations and in association with a recoil π^- is presented. The difference between π^- and π^+ spectra in $\bar{p}n$ annihilations is the spectrum of the recoiling π^- or difference spectrum. We applied this analysis to the exclusive channels $\bar{p}n \to 2\pi^-\pi^+$, $2\pi^-\pi^+\pi^0$, $3\pi^-2\pi^+$. A new prominent state of mass and width $\simeq 1480$ and 100 MeV/c^2 is present in the first and dominates the third channel. These three channels are interpreted in terms of two-body intermediate states only. The suppression or absence of "direct" annihilation is consistent with theoretical models which view the annihilation as a short-range (0.1 fm) phenomenon.

PACS numbers: 13.75.Cs, 14.40.Cs, 13.25.+m

The study of the antiproton annihilation process has been a topic of continuous interest since its discovery. The first observations showed an average pion multiplicity of 5 while the Fermi statistical model predicted less than 3. The discovery of ρ, ω, and η in the 1960's and their abundance in annihilations reduced the number of produced mesons to about three. Naive quark-model considerations suggest dominance of three-body intermediate states. In recent years the emphasis has been on the search for bound $\bar{N}N$ states, four-quark states, etc. The study of pion spectra produced in annihilations at rest is a favored way to look for them. If these states are produced they will be revealed as peaks in such spectra. However, because of the large combinatorial background and the limited phase space available, these searches have been unfruitful and limited to narrow states.[1]

In the preceding Letter, evidence was presented for a broad (200 MeV/c^2) state with mass 1485 MeV/c^2 found by study of inclusive π^+ and π^- spectra from $\bar{p}d$ annihilations at rest. These studies led to the discovery of the difference spectrum (described herein) in $\bar{p}n$ annihilations at rest in which the combinatorial background is reduced or, for certain channels, eliminated, and searches for broad states become possible.

Difference spectrum.—Assume that the $\bar{p}n$ annihilation proceeds through intermediate states of isospin 0 or 1 (no exotics):

$$\bar{p}n \to \pi_1^- + X_0^0, \tag{1}$$

$$\bar{p}n \to \tfrac{1}{2}(\pi_1^- + X_1^0) + \tfrac{1}{2}(\pi_1^0 + X_1^-), \tag{2}$$

where X_I^q represents a hadronic "blob" of definite charge and isospin, and π_1^- and π_1^0 are the recoiling pions. In general, the X_I^q decays into $\pi^+\pi^-$ pairs plus neutrals. *Charge-conjugation invariance applied to $X^0 \to (\pi^+\pi^-)$ pairs plus neutrals implies identical π^+ and π^- spectra.* Consequently in the difference spectrum (subtracting the π^+ from the π^- spectrum) the π^+ and π^- produced from X^0 decays statistically cancel out. Thus the difference spectrum is the recoil-pion (π_1^-) spectrum. The $\pi_1^0 X_1^-$ contributes to channels involving at least one π^0. Thus if the $\bar{p}n$ annihilation proceeds through intermediate states of $I = 0, 1$ the inclusive difference spectrum contains the π_1^- spectrum and "background" from $\pi_1^0 X_1^-$. However, *final states with only charged pions have no such background if the annihilation proceeds entirely according to (1) and/or (2).*

C invariance is exact in the absence of interference effects between π_1^- and the other charged pions. This interference is expected to decrease with (a) decreasing X^0 width, (b) increasing X^0 mass [because it depends, for example, on terms of the form $\mathbf{p}(\pi_1^-)\cdot\mathbf{p}(\pi^-)$], and (c) increasing pion multiplicity. Therefore, channels with all or many charged pions are best suited for this analysis.

Rittenberg and Rubenstein[2] made some time ago an interesting observation on inclusive $\bar{p}n \to \pi^-$, $\to \pi^+$ spectra. They assumed a cascade fireball model for the annihilation and constrained intermediate states to total charge 0 and ± 1 which is analogous to (1),(2). They assumed masses for intermediate states lying on the Pomeron and normal (ρ) trajectories and obtained the inclusive spectra

$$\frac{1}{p_{\pi^+}}\frac{dN}{dM_X^2} = AM_X^2, \tag{3}$$

$$\frac{1}{p_{\pi^-}}\frac{dN}{dM_X^2} = AM_X^2 + BM_X. \tag{4}$$

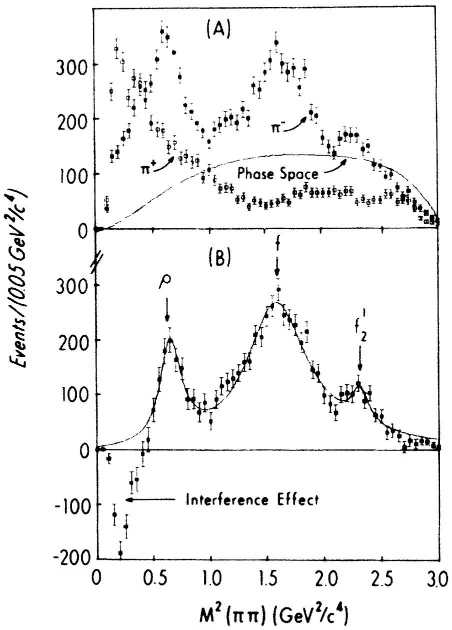

FIG. 1. (a) The $\pi^+\pi^-$ mass distributions recoiling against the π^+ and π^- in $2\pi^-\pi^+$ and phase space normalized to the π^+ spectrum. (b) The difference spectrum. The fit is made above 0.5 GeV$^2/c^4$ with $\pi^-\rho^0$, π^-f^0, π^-f_2' intermediate states.

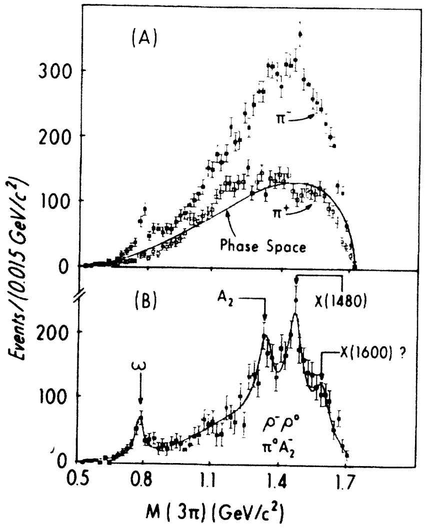

FIG. 2. (a) The mass of the three pions recoiling against the π^+ and π^- in $2\pi^-\pi^+\pi^0$ and phase space normalized to the π^+ spectrum. (b) Their difference spectrum. The fit is made with the $\pi^-\omega^0$, $\pi^-A_2^0(\rightarrow\rho\pi)$, $\pi^-X^0(1480)$, $\pi^-X(1600)$ and "background" from $\rho^-\rho^0$, $\pi^0A_2^-$.

Although these expressions did not turn out to describe the spectra accurately,[3] the same assumptions have been used by Orfanidis and Rittenberg[4] and resulted in the best description so far of observed channel frequencies. Notice that the difference spectrum from (3) and (4) does not contain the term AM_X^2. The cancellation of the AM_X^2 terms underlies C invariance and perhaps shows more explicitly how background gets reduced in the difference spectrum.

Applications.—We have found bubble-chamber data[5-7] on the reactions

$$\bar{p}d \rightarrow 2\pi^-\pi^+ + (p_s), \quad (5)$$

$$\rightarrow 2\pi^-\pi^+\pi^0 + (p_s), \quad (6)$$

$$\rightarrow 3\pi^-2\pi^+ + (p_s), \quad (7)$$

which are shown in Figs. 1(a), 2(a), and 3(a), respectively. These events are associated with invisible (<100 MeV/c) spectator protons. The π^+ spectra were fitted smoothly with polynomials and the fit was subtracted from the corresponding π^- spectrum yielding the difference spectra presented in Figs. 1(b), 2(b), and 3(b).

The $2\pi^-\pi^+$ [Fig. 1(b)] is dominated by f, ρ, and f_2'.[8] [The f_2' has the same mass and width as the $f'(1525)$ but does not decay into $\bar{K}K$.] This channel exhibits large interference effects, most notably a π^+ enhancement at high energies. The negative values in the difference spectrum at low mass reflect this interference. Apart from this interference, the difference spectrum fits reasonably well to a simple superposition of $\pi^-\rho$, π^-f^0, π^-f_2'. Addition of a phase-space distribution does not improve the χ^2 of the fit. Table I shows the results of the fits. The masses and

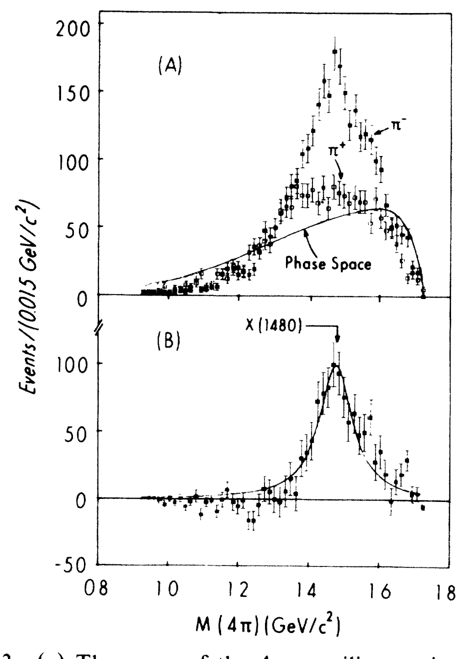

FIG. 3. (a) The mass of the 4π recoiling against the π^+ and π^- in $3\pi^-2\pi^+$ and (b) their difference spectrum. The fit is made with the $\pi^-X^0(1480)$.

TABLE I. Results of fits made to difference spectra for exclusive channels.

Final state	$\pi^- X^0$	M_X (MeV/c^2)	Γ_X (MeV/c^2)	Channel B (%)
$2\pi^-\pi^+$	$\pi^-\rho^0(\to\pi^+\pi^-)$	806 ± 6	140 ± 12	20 ± 1
	$\pi^- f^0(\to\pi^+\pi^-)$	1258 ± 3	262 ± 8	75 ± 2
	$\pi^- f_2'(\to\pi^+\pi^-)$	1522 ± 7	59 ± 12	5 ± 1
				100 ± 3
$2\pi^-\pi^+\pi^0$	$\pi^-\omega(\to\pi^+\pi^-\pi^0)$	784 ± 3	43 ± 9	5 ± 0.3
	$\pi^- A_2^0(\to\pi^{\pm}\rho^{\mp})$	1342 ± 4	81 ± 10	18 ± 1
	$\pi^- X^0(\to\pi^+\pi^-\pi^0)$	1468 ± 6	88 ± 18	25 ± 2
	$\pi^- X^{0\prime}(\to\pi^+\pi^-\pi^0)$	1594 ± 9	81 ± 12	9 ± 1
	$\pi^0 A_2^-(\to\rho^0\pi^-)$			9 ± 1
	$\rho^-\rho^0$			34 ± 3
				100 ± 4
$3\pi^-2\pi^+$	$\pi^- X^0(\to 2\pi^-2\pi^+)$	1477 ± 5	116 ± 9	82 ± 5

widths of ρ and f are in reasonable agreement with accepted values in spite of the simplicity of the fit and the large interference effects present in this channel.[9]

The $2\pi^-\pi^+\pi^0$ [Fig. 2(b)] difference spectrum has been fitted with $\pi^-\omega$, $\pi_1^- A_2^0(\to\rho\pi)$, $\pi_1^- X^0(1480)$, $\pi_1^- X^0(\sim1600)$, and the $\pi_1^0 A_2^-(\to\pi^-\rho^0)$, $\rho^-\rho^0$ "backgrounds." Phase space and $\pi^0 X^-(\to\rho^0\pi^-)$ backgrounds were introduced but do not improve the fit. The results of the fits are presented in Table I. Again, this channel is consistent with dominance of two-body intermediate states.

The most striking result of the difference technique is the $3\pi^-2\pi^+$ final state, a channel difficult to interpret by standard analysis because of the combinatorial problem and the limited phase space. As discussed above, the $\pi_1^0 X_1^-$ states do not contribute and interference effects are expected to be smaller than those with smaller numbers of pions as, for example, $2\pi^-\pi^+$. This difference spectrum can almost entirely be accounted for by the $X^0(1480)$ with possible contributions from higher-mass states. The impressive complete cancellation of the π^-, π^+ spectra up to ~1400 MeV/c^2 is the result of (a) dominance of $\pi_1^- X^0$ state(s), (b) absence of $\pi_1^0 X^-$ contributions, (c) absence of interference effects, and (d) small decay branching ratios of low-mass mesons (e.g., the f) to $2\pi^-2\pi^+$.

Kinematical reflections.—It is appropriate at this point to raise the question whether the copious production of ρ and other known mesons can account for the 1480-MeV peak in the difference spectra. First, kinematical effects are channel dependent and it will therefore be difficult to produce identical peaks in the inclusive difference spectrum of the previous paper and the exclusive channels discussed here. Second, we tried as part of a global analysis[10] and spin and parity determination of the $X(1480)\to2\pi^-2\pi^+$ to get fits assuming the following intermediate states: phase space (5π), $3\pi\rho$, $2\pi A_2(\to\rho\pi)$, $\pi\rho\rho$, and $\pi X(\to\rho\rho)$. Distributions based on these intermediate states were calculated by a Monte Carlo program and are presented in Fig. 4 together with the data. Smooth Monte Carlo distributions were generated. (Measurement error and Doppler smearing are not included in the Monte Carlo program because they are on the average comparable to the binning of the data.)

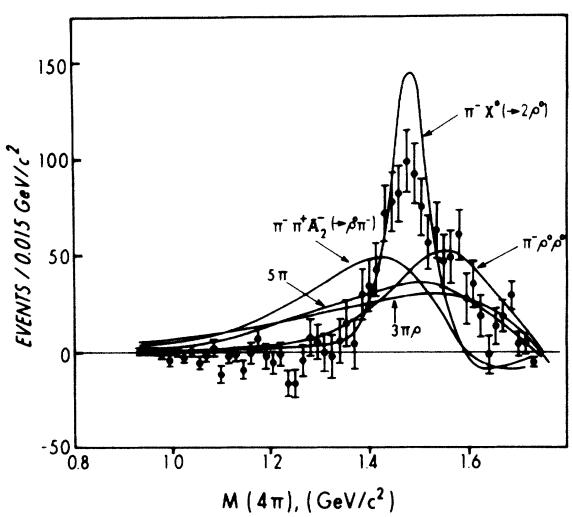

FIG. 4. The $\bar{p}n\to3\pi^-2\pi^+$ difference spectrum in comparison to distributions based on possible intermediate states. Distributions are normalized to the data.

Clearly, the $X(1480)$ effect is not a kinematical reflection of ρ and/or A_2 production. It fits best if we assume a new resonance of mass 1480 and width ~ 110 MeV decaying into $2\rho^0$.

The $2\pi^-\pi^+$ is the only other final state besides the $3\pi^-2\pi^+$ with a difference spectrum expected to be free of background if the annihilation proceeds entirely via two-body intermediate states. The f_2' is the new resonance, besides the ρ and f, enhanced by the reduction of background. In Ref. 6 possible kinematic reflections due to the complex 3π dynamics have been discussed. The latest and most extensive analysis of Kasper *et al.* (see Ref. 8) and earlier ones (see Ref. 5 for references) do not reproduce the f_2' peak. This is additional evidence that peaks in difference spectra are probably due to states and not to kinematical reflections. Mass and width of the f_2' suggest that it is the 2π decay of the $X(1480)\rightarrow 4\pi$.

Two-body dominance.—We estimate the total branching ratio for $\bar{p}n$ annihilations mediated by two-body intermediate states using the channel branching ratios given in Table I and the $2\pi^-\pi^+$, $2\pi^-\pi^+\pi^0$, $3\pi^-2\pi^+$ branching ratios of $(3.4\pm0.2)\%$,[5] $(17\pm2)\%$,[6] $(4.2\pm0.2)\%$,[11] respectively, and the $\pi^-\pi^0$ (0.8%), $\pi^-\rho^0$ (1.4%), $\pi^0\rho^-$ (1.4%), $\pi^-\omega$ (0.8%), $\pi^-\phi$ (0.1%) branching ratios. These observed channels amount to 32%. With the reasonable assumptions (a) $I=1$ for $X^0(\rightarrow\pi^+\pi^-\pi^0)$, (b) $X^0(\rightarrow\rho^0\rho^0)$,[10] and (c) $B(\bar{p}n\rightarrow\rho^-\omega^0)=B(\bar{p}n\rightarrow\rho^-\rho^0)$, a total two-body branching ratio of more than 50% is thus obtained. The copious $\pi X(1480)$ channels must have other (e.g., 2ω, 2η, $\eta\omega$, and $\rho\eta$) decay modes besides those that have been observed which will further increase it. This result and the absence of evidence for other than two-body contributions to the exclusive channels studied here imply dominance ($\gg 50\%$) of two-body cascading processes as the main mechanism of the $\bar{p}n$ annihilation in liquid deuterium.

Shapiro[12] has argued that direct $\bar{N}N$ annihilation into multiple pions is a short-range ($\sim 1/2m_N = 0.1$ fm) phenomenon. Because the predicted mesonic and quasinuclear states extend to ~ 1 fm, the probability of direct annihilation is expected to be suppressed by the ratio $(0.1\text{ fm})^3/(1.0\text{ fm})^3 = 10^{-3}$. Our observations support this view.

Conclusions.—The difference spectra in $\bar{p}n$ annihilations form a powerful tool to look for $\bar{p}n\rightarrow\pi^-X^0$ states. By use of bubble-chamber data the copious production of $X(1480)$ presented in the previous paper is confirmed. The $X(1480)$ decaying into $\pi^+\pi^-\pi^0$ badly needs more data and confirmation from other channels. On the basis of mass and width the f_2' can be the 2π decay of the $X(1480)\rightarrow 4\pi$. Additional states of higher mass (~ 1600 MeV/c^2) are suggested by the difference spectra. Finally, it is observed that most ($\gg 50\%$) of the $\bar{p}n$ annihilations proceed through two-body intermediate states, an unexpected result and in agreement with theories that view the annihilation as a short-range phenomenon. This picture supports the existence of quasinuclear $\bar{N}N$ states.

This work was supported by the National Science Foundation. One of us (D.B.) acknowledges the support of the Le Moyne College Committee on Faculty Development and Research.

[(a)]On sabbatical leave of absence from Le Moyne College, Syracuse, N.Y. 13214.

[1]See, e.g., G. S. Smith, in *Experimental Meson Spectroscopy—1983,* edited by S. J. Lindenbaum, AIP Conference Proceedings No. 113 (American Institute of Physics, New York, 1984); R. Klapisch, in *Proceedings of the Tenth International Conference on Particles and Nuclei, Heidelberg, Germany, 1984,* edited by B. Povh and G. zu Putlitz (North-Holland, Amsterdam, 1985), p. 207.

[2]V. Rittenberg and H. R. Rubinstein, Phys. Lett. **40B**, 257 (1972).

[3]Th. Papadopoulou *et al.*, Phys. Lett. **43B**, 401 (1973).

[4]S. J. Orfanidis and V. Rittenberg, Nucl. Phys. **B59**, 570 (1973).

[5]T. E. Kalogeropoulos, L. Gray, A. Nandy, and J. Roy, Phys. Rev. D **24**, 1759 (1981).

[6]L. Gray, Ph.D. dissertation, Syracuse University, 1969 (unpublished).

[7]T. E. Kalogeropoulos, Argonne National Laboratory Report No. HEP 6812, 1968 (unpublished).

[8]L. Gray, T. Kalogeropoulos, A. Nandy, J. Roy, and S. Zenone, Phys. Rev. D **27**, 307 (1983).

[9]P. Anninos *et al.*, Phys. Rev. Lett. **20**, 402 (1968).

[10]This analysis is similar to the one made in Ref. 8 and by A. Bettini *et al.*, Nuovo Cimento **42**, 695 (1966). It will be the subject of another paper in which the quantum numbers of this resonance will be determined.

[11]P. Hagerty, Ph.D. dissertation, Syracuse University, 1969 (unpublished).

[12]I. S. Shapiro, in *Proceedings of the Fifth European Symposium on Nucleon-Antinucleon Interactions, Bressanone, Italy, 1980,* edited by M. Cresti (Istituto Nazionale di Fisica Nucleare, Padua, Italy, 1980), p. 589 and in *Antiproton Physics—1984,* edited by M. R. Pennington, IOP Conference Series No. 73 (Hilger, Bristol, London, 1985).