Study of prompt e^+e^-, η^0, and ω^0 production in low-energy $\bar{p}p$ annihilations

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A study of prompt e^+e^- production has been made using the Argonne 12-foot bubble chamber exposed to a low-energy $\bar{p}$ beam. We found eleven annihilation events with e^+e^- pairs of invariant mass greater than the π^0 mass. The background to direct e^+e^- pair production comes mainly from $\eta^0 \to \gamma e^+e^-$ and $\omega^0 \to \pi^0 e^+e^-$ Dalitz pairs. To determine these backgrounds, we have measured the inclusive η^0 and ω^0 production rates using externally converted γ rays. We find $\omega^0/\pi^0 = 0.20 \pm 0.07$ and $\eta^0/\pi^0 < 0.11$ at the 90% confidence level. The $(\eta^0 + \omega^0)$ Dalitz background plus other small backgrounds yield $7.0^{+4.4}_{-3.0}$ events. The remaining events yield a 90%-confidence-level upper limit for the ratio of prompt e^+e^- pairs to π^0 production of 4×10^{-5}.

INTRODUCTION

In recent years, considerable effort has gone into the study of prompt charged-lepton production in hadronic interactions.[1] The quantity normally used to express the production rate of prompt leptons is R, the ratio of the number of leptons to the number of pions produced in a certain region of phase space. In order that R be interpreted as a measure of "new" processes, the expected contributions to electron production from π^0, η^0, ω^0, ρ^0, and ϕ^0 prompt decays are normally subtracted from the observed electron production rate before calculating R. Furthermore, R is normally defined as excluding electrons which belong to e^+e^- pairs of mass less than m_{π^0}, in order to exclude π^0 Dalitz decays. Thus R will exclude contributions from any "anomalous" prompt source of very-low-mass e^+e^- pairs. Important experimental questions concerning the production of prompt leptons are the energy and beam-particle dependence and whether the leptons are produced unpaired or in pairs.[2]

The first experiments at Fermilab[3-5] and at the CERN Intersecting Storage Rings (ISR),[6] which measured the production of prompt (single) leptons, found a value of $R \sim 10^{-4}$, with one experiment[7] finding a strong increase in R as the lepton's transverse momentum p_T decreased from 1.5 to 0.2 GeV/c. A later experiment at Brookhaven National Laboratory,[8] using both pion and proton beams with energies of 10, 15, and 24 GeV, also found $R \sim 10^{-4}$ for unpaired e^+ independent of energy and increasing as the p_T of the e^+ decreased from 1.5 to 0.5 GeV/c. A more recent counter experiment at Argonne National Laboratory[9] found no evidence for prompt unpaired $e^\pm$ production $[\langle R\rangle = (0.07 \pm 0.08) \times 10^{-4}]$ in 12-GeV/c pp collisions over the range $0.2 < p_T^{e^\pm} < 1.0$ GeV/c. An ISR experiment[10] has also found that for $p_T \sim 2$ GeV/c, the ratio of direct photon to π^0 production is $\gamma/\pi^0 = (0.55 \pm 0.92)\%$.

Most of the low-energy bubble-chamber experiments[11-14] do not see any excess e^+e^- pair production, although one experiment[14] does see an excess for π^-p collisions (though only for $p_T^{e^\pm} < 0.2$ GeV/c), but not for the π^+p case. None of the low-energy experiments has found evidence for an unpaired e^+ signal.[15] Experiments at low energies which detected prompt $\mu^+\mu^-$ pair production,[16,17] however, do find evidence for an excess of low-mass pairs. Thus the overall experimental situation concerning direct lepton production is still not clear.

EXPERIMENTAL PROCEDURES

In order to obtain new data on prompt e^+e^- pair production, we have performed an experiment using low-energy $\bar{p}p$ annihilations in the Argonne National Laboratory 12-foot hydrogen bubble chamber.[18] The 12-foot chamber is well-suited for such an experiment since its large visible volume (~16 m^3) and relatively high magnetic field (15 kG) result in a reasonable efficiency for identifying $e^\pm$ by spiralization. In addition, the bubble chamber affords a 4π geometry, allowing one to clearly see the event's vertex and all charged particles emerging from the vertex. Other bubble-chamber experiments which have studied prompt $e^\pm$ production have used a heavy-liquid filling, a track-sensitive target plus heavy-liquid filling, or have added plates inside the chamber.

The $\bar{p}$'s were produced by extracting the 12-GeV/c proton beam from the Zero Gradient Synchrotron and having the protons strike a 7-cm copper target. A conventional beam line with electrostatic separators delivered antiprotons which entered the visible chamber volume at 730 MeV/c (with a width of ±15 MeV/c), and then

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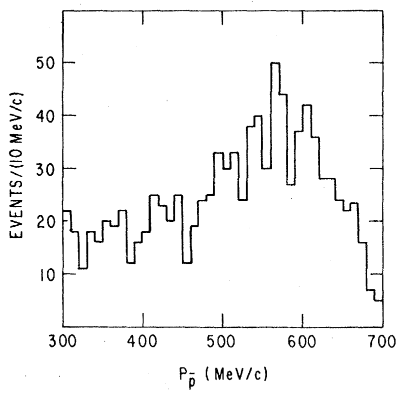

FIG. 1. The momentum distribution for those antiprotons that annihilate above 300 MeV/c.

came to rest within the visible chamber volume. The momentum distribution of the $\bar{p}$ annihilations within our fiducial volume is shown in Fig. 1 for those annihilations with $\bar{p}$ momentum greater than 300 MeV/c. For momenta less than 300 MeV/c, almost all of the $\bar{p}$'s annihilate at rest. We found that $(50\pm4)\%$ of the annihilations occurred at rest (E = 1877 MeV), and the remainder at an average $\bar{p}$ momentum of about 520 MeV/c (E = 1938 MeV). We found no evidence that any of the quantities we measured depended on whether the annihilation was in flight or at rest. The only sizable contamination in the beam was muons ($\mu^-/\bar{p} = 5\%$), which were easily identifiable by their lower ionization and lack of interactions. A total of 278 000 pictures were taken, of which we have analyzed 131 000 for prompt $e^{\pm}$ production.

In this experiment, the $e^{\pm}$ candidate tracks were identified on the scan table by their spiralization. Events were scanned for with a track(s) which turned through at least 360°. This candidate $e^{\pm}$ track had to be compatible with being an $e^{\pm}$ in that it did not scatter, had constant minimum ionization, and for an e^-, did not end in the liquid except as a very tight spiral. The candidate $e^{\pm}$ tracks were labeled according to their degree of spiralization. Class 1 (2, 3) tracks turned through at least 1 (2, 3) 360° turns, but less than 2 (3, 4) 360° turns. (Class 1, 2, or 3 tracks will be collectively called class B tracks.) A class 4 track turned through 360° at least four times. Tracks which turned through less than 360°, but which were otherwise compatible with being an $e^{\pm}$, were classed class 0.

Most of the recorded events result from π^0 Dalitz decays, and therefore have $m_{e^+e^-} < m_{\pi^0}$. Thus the main interest in this experiment centers on those e^+e^- pairs which have $m_{e^+e^-} > m_{\pi^0}$. However, these high-mass pairs can also arise from the Dalitz decays $\eta^0 \to \gamma e^+e^-$ and $\omega^0 \to \pi^0 e^+e^-$, so that it is important to know the inclusive η^0 and ω^0 production rates. To measure these rates, we carried out an independent analysis of multi-γ events on a sample of 93 000 frames. The multi-γ event sample consisted of those annihilations for which more than one externally converted γ pointed back to the annihilation vertex.

DATA ANALYSIS FOR e^+e^- EVENTS

A candidate event must have the annihilation vertex occur within a specified fiducial volume. The $\bar{p}$ may elastically scatter any number of times before annihilating. An average of 1.6 $\bar{p}$'s per frame annihilated within the fiducial volume, giving a total data sample of 206 250 annihilations.

Approximately 13% of the film was double-scanned for the topologies of interest. For events with a class 4 track(s), the single pass-scan efficiency was $82\pm2\%$, while for events that had only a class B track(s), the efficiency was $75\pm5\%$. The larger error for the latter sample results mainly from ambiguities concerning a possible change in the track's ionization. The scanning efficiency appeared to be independent of e^+e^- mass. For the analysis of low-mass pairs ($m_{e^+e^-} < m_{\pi^0}$), only events with a class 4 track(s) were used, as the possible systematic errors associated with class B tracks did not warrant their inclusion. For the high-mass sample, all classes were included.

For the sample of events with only class B tracks, a preliminary measurement pass was performed by measuring only the candidate $e^{\pm}$ track. Using the measured momentum at the annihilation vertex, the reconstruction program (TVGP) was modified to extend ("swim") the track until it left the chamber. If for the π or μ mass hypothesis the track was thus found to have a momentum less than 120 MeV/c at the chamber boundary, then the track was considered to be an $e^{\pm}$ candidate and the whole event was measured.

Two measurement passes were performed for the prompt $e^{\pm}$ sample. An acceptable measurement had to satisfy the following criteria: if an event contained both a positive and negative candidate electron of class 1 or greater (72% of the events were of this type, denoted Type I), then both tracks had to be well measured. (The number of events with 3 $e^{\pm}$ candidates was small.) For events with only one class 1 or greater candidate $e^{\pm}$ track (type II events), this track had to be well measured. Then the effective mass of this track with all other possible class 0 $e^{\pm}$ candidates of opposite sign was computed. The pairing which gave the lowest value for $m_{e^+e^-}$ was the one used.

This pairing procedure results in the possibility, that for events with more than one class 0 candidate $e^\pm$, an incorrect pairing gives the lowest value for $m_{e^+e^-}$. To determine the size of this effect for the low-mass sample, we examined type II events which had only one class 0 candidate $e^\pm$, but in addition had a track which scattered (both the class 0 and scattered track had to be of opposite charge to the class 1 or greater $e^\pm$ candidate). In less than 5% of these events was the effective mass of the class 1 or greater tracks with the scattered track less than its effective mass with the class 0 track. Thus, the overall background from this mispairing is negligible. The loss of real high-mass pairs resulting from the pairing procedure will be discussed below.

When the lowest effective-mass combination of the class 1 or greater and a class 0 $e^\pm$ candidate track was less than 60 MeV, the event was considered to be well measured. If the lowest value for $m_{e^+e^-}$ was greater than 60 MeV and a possible class 0 $e^\pm$ candidate failed the measurement, then the event was remeasured. Events which had the lowest value for $m_{e^+e^-}$ greater than m_{π^0} were remeasured until they passed.

A mispairing due to this measurement procedure could occur if the type II event had two class 0 $e^\pm$ candidates of opposite sign to the class 1 or greater $e^\pm$ candidate. If the incorrect pairing gave $m_{e^+e^-} < 60$ MeV while the correct class 0 $e^\pm$ candidate track failed, then the event would be considered well measured and an incorrect value for $m_{e^+e^-}$ would result. The magnitude of this effect was determined by seeing how often a type II event had two class 0 tracks of proper sign, both giving an effective mass of less than 60 MeV. This occurred about 7% of the time and, together with the probability that the correct track failed while the incorrect one passed, gives less than 1% wrong pairing background in the total data sample. Thus we believe that no high-mass event has been lost from our data sample by incorrect pairing.

This conclusion was checked by examining our sample of 11 events with $m_{e^+e^-} > m_{\pi^0}$. For these events, we calculated invariant masses by pairing identified $e^\pm$ tracks with the known non-$e^\mp$ tracks, and again found that the loss of high-mass events from incorrect pairing should be negligible. This loss is small because the opening angle and invariant mass are generally large for pairs of secondary tracks.

MASS SPECTRUM FOR e^+e^- EVENTS

Figure 2 shows the e^+e^- mass distribution. The calculated mass resolution is ± 2 MeV and is essentially independent of $m_{e^+e^-}$. The data are uncorrected for detection efficiency since the efficiency depends on the process that produces the e^+e^- pair. However, for e^+e^- pairs from π^0 Dalitz decay, the detection efficiency varies by only $\pm 10\%$ over the range $0 < m_{e^+e^-} < m_{\pi^0}$. The theoretical prediction (the curve in Fig. 2 which will be discussed later) with which we compare the data does have the detection efficiencies folded in. The data point from 0–5 MeV is corrected for the 30 ± 15 γ rays that externally convert within 1.5 mm of the vertex and so are mistaken for internal pairs (the spatial resolution was 1 mm).

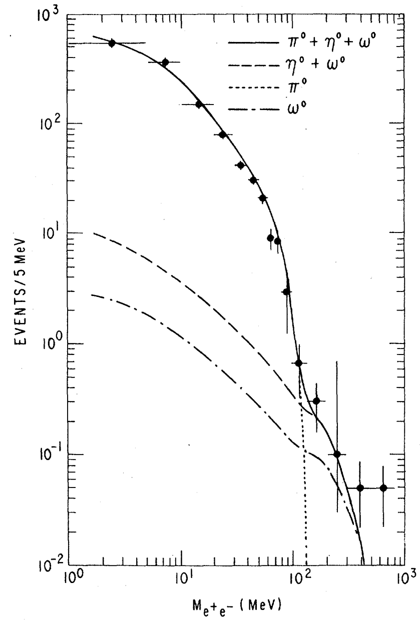

FIG. 2. The data points are the uncorrected results for the prompt e^+e^- mass spectrum. The errors are statistical only. The solid curve represents our prediction (discussed in the text) for the data from π^0, η^0 and ω^0 Dalitz decays. The dotted, dot-dashed, and dashed curves give the π^0, ω^0, and $\eta^0 + \omega^0$ predictions separately. The reason for the inflection point in the curves for $m_{e^+e^-} = m_{\pi^0}$ is because class 1, 2, 3, and 4 $e^\pm$ candidates are used for $m_{e^+e^-} > m_{\pi^0}$.

As will be discussed later, the 1635 events with $m_{e^+e^-} < 135$ MeV are well represented by π^0 Dalitz decays with η^0 and ω^0 decays (and perhaps direct e^+e^- pair production) contributing at the few percent level. For $m_{e^+e^-} > m_{\pi^0}$, a total of 11 events was found. Each of these 11 events was carefully studied by physicists. Measurement tables were used that gave a magnification which results in life-size images.

The characteristics of the 11 events with $m_{e^+e^-} > m_{\pi^0}$ are listed in Table I. Only the minimum-ionizing tracks were accepted as $e^\pm$ candidates. The relative ionization was determined by counting gap lengths between consecutive bubbles, and comparing the result to tracks which were known

TABLE I. Characteristics of events with $m_{e^+e^-} > m_{\pi^0}$.

Event	$m_{e^+e^-}$ (MeV) [a]	Number of prongs [b]	Class and identification of e^+ [c]	Class and identification of e^- [c]	P_{e^+} (MeV/c)	P_{e^-} (MeV/c)	$P_{\bar{p}}$ (MeV/c) [d]
1	160	4	C1, δ_μ, δ_π	C4	231	457	522
2	148	4	C2, ion, δ_μ, δ_π	C1, rms, range, ion	179	111	598
3	542	4	C1, ion	C0	360	243	621
4	413	4	C0	C4	332	138	0
5	370	4	C1, ion, δ_π	C1, ion	405	233	620
6	737	4	C4	C0	426	390	654
7	242	4	C4	C0	47	349	447
8	180	2	C4	C0, δ_π	61	475	0
9a	725	6	C0	C1, ion	227	584	633
9b	545	6	C0	C1, ion	227	554	633
10	148	4	C4	C0	27	308	0
11	292	4	C4	C0	150	249	0

[a] The typical error on the mass for $m_{e^+e^-} \sim 150$ MeV is ±2 MeV.

[b] The prong count includes the e^+e^- pair.

[c] CN stands for the class number, rms means that the root-mean-squared deviation in the geometric track fit favored the $e^\pm$ hypothesis over the $\pi^\pm$ or $\mu^\pm$ hypothesis by a factor of at least 2, range means that the track should have stopped (by at least 5σ) if it were a π or μ, δ_π (δ_μ) means that a δ ray ruled out the π (μ) hypothesis, and ion means the track was called an $e^\pm$ because it was minimum-ionizing, while if it were a $\mu(\pi)$, it should have been at least 1.8 (2.4) times minimum.

[d] If the measured $\bar{p}$ momentum was less than 300 MeV/c, the $\bar{p}$ was considered to have stopped and is assigned a momentum of zero in the table.

to be minimum-ionizing. Event 9 has two class 0 e^+ candidates, each given a weight of 0.5 in the mass plot. Seven of the events have a class 4 $e^\pm$, while only three of the 11 events have both an e^+ and e^- definitely identified. For event 2, the track-fitting program TVGP gave a root-mean-squared deviation which ruled out the π and μ hypothesis. In events 1 and 2, there were non-class-4 tracks which produced δ rays which ruled out the π and μ hypotheses. Events 5 and 8 had non-class-4 tracks with δ rays which rule out the π hypothesis. As can be seen in Fig. 2, the observed mass distribution falls off by a factor of about 5 from 140 to 500 MeV. Over this range, the average detection efficiency falls off by only a factor of 2.

Since all charged secondary tracks from the annihilation have been measured, it is possible to perform kinematic fits to various hypotheses. None of the 11 events fit the hypothesis that only charged particles were produced at the annihilation. Two of the events have a visible associated γ (external pair) which, when combined with the e^+e^- pair at the annihilation vertex, gives $m_{\gamma e^+e^-} = 570 \pm 7$ MeV and 494 ± 9 MeV (the absolute mass scale is known to within ~2 MeV). The η^0 hypothesis is ruled out for the second of these events, and is ruled out at the 99% confidence level for the first event. For our entire data sample, no events were found which definitely have an unpaired $e^\pm$.

BACKGROUNDS FOR e^+e^- EVENTS

In order to determine the source of these 11 events, the possible types of background must be studied. First, there are sources which produce nonprompt unpaired $e^\pm$ tracks through the weak decays of directly produced hadrons. These backgrounds are small and include (1) charged-kaon decays (either at rest or in flight), $K^\pm \to \pi^0 e^\pm \nu$, where the $K^\pm$ is not identified nor is the kink observed; (2) $K^0 \to \pi^\pm e^\mp \nu$, where the decay occurs within 2 mm of the annihilation vertex; (3) $\pi^\pm \to e^\pm \nu$, where the $\pi^\pm$ is not identified nor is the kink seen; and (4) $\pi-\mu$ decays in flight or at rest followed by $\mu-e$ decays, where neither the $\pi^\pm$ or $\mu^\pm$ is identified nor are either of the kinks observed. Backgrounds from close-in Compton electrons, δ rays, and asymmetric Dalitz decays are negligible since the event was required to have an even number of charged secondaries.

To determine the magnitude of backgrounds (1)-(4), a special scan was performed to search for (1) $e^\pm$ candidates which have kinks, (2) π-μ-e decays, (3) $K^\pm \to \pi^\pm\pi^\pm\pi^\mp$ decays, and (4) $K_L^0 \to \pi^\pm e^\mp \nu$, each occurring within a certain distance of the annihilation vertex. In addition, we have used published data[19] on the momentum distribution of charged kaons to estimate some of the backgrounds. Table II summarizes the results, which

TABLE II. Pion and kaon decay backgrounds to events with $m_{e^+e^-} > m_{\pi^0}$.

Background	Number of events
$K^{\pm} \to \pi^0 e^{\pm}\nu$	0.2 ± 0.1
$K_L^0 \to \pi^{\pm} e^{\mp}\nu$	0.1 ± 0.1
$\pi^{\pm} \to e^{\pm}\nu$	negligible
$\pi^{\pm} \to \mu^{\pm}\nu \to e^{\pm}\nu\nu\nu$	negligible

give an overall background of 0.3 ± 0.2 events.

A second kind of background is due to real e^+e^- pairs which come mostly from the Dalitz decays $\eta^0 \to \gamma e^+e^-$ and $\omega^0 \to \pi^0 e^+e^-$. Since the η^0 and ω^0 inclusive production rates have not been previously measured in either $\bar{p}p$ annihilations or in many other hadronic reactions, we decided to determine these production rates from our data by measuring events with multiple γ rays (external pairs) pointing back to the annihilation vertex.

DATA ANALYSIS FOR $\gamma\gamma$ EVENTS

The scan efficiency for the multi-γ events was 70%, but this is not important in our analysis as the main results we quote are in terms of ratios. It is important, however, to know the scan efficiency as a function of $\gamma\gamma$ mass since our sample consists only of events found on the first scan. On a sample of film, measurements were made of events found in scan 2 but missed in scan 1. The results showed that the scan efficiency was independent of $\gamma\gamma$ mass.

For the multi-γ sample, events which failed geometrical reconstruction after a first measurement pass were remeasured. If the event still failed, the results of the two passes were combined to give a good measurement whenever this was possible. With this procedure, the overall single- (two-) γ pass rate was 83% (62%), and was found to depend little on the $\gamma\gamma$ mass. In addition, to study ω^0 production, tracks at the primary annihilation vertex were also measured for those events for which the $\gamma\gamma$ mass was between 128.5 and 141.5 MeV/c. This mass interval was chosen to maximize the probability of accepting π^0's, while minimizing the probability of accepting background combinations. Essentially, all the $\gamma\gamma$ pairs with mass in this interval gave fits to the decay hypothesis $\pi^0 \to \gamma\gamma$ using the kinematics fitting program SQUAW. Again, two measurement passes were made of the tracks at the annihilation vertex with an overall measuring efficiency of 73% per track.

MEASUREMENT OF INCLUSIVE η^0 AND ω^0 PRODUCTION

Figure 3 shows the $m_{\gamma\gamma}$ distribution over the whole mass range and in fine bins around m_{π^0}. In Fig. 3, weights have not been assigned to the γ pairs, so the histogram is not corrected for conversion efficiency and other losses. The calculated efficiency varies with mass, increasing from 0.4% at m_{π^0} to 0.6% at m_{η^0}. The η^0 efficiency is larger because γ's from η^0 decay have higher momentum than those from π^0 decay. A fiducial volume selection has been made so that the γ's do not convert too close or too far away from the annihilation vertex. Various checks (e.g., conversion distance, production angle) were made of the properties of the converted γ's, and no evidence for systematic bias was seen. The mass resolution near m_{π^0} was calculated to be $\sigma = 5$ MeV. The observed width of the π^0 peak in Fig. 3 is $\sigma = 4$ MeV. To determine the number of π^0's in our sample, we have fitted the $\gamma\gamma$ mass distribution over the range 100–170 MeV to a Gaussian (with fixed central value but variable width) plus combinatorial background. The background shape

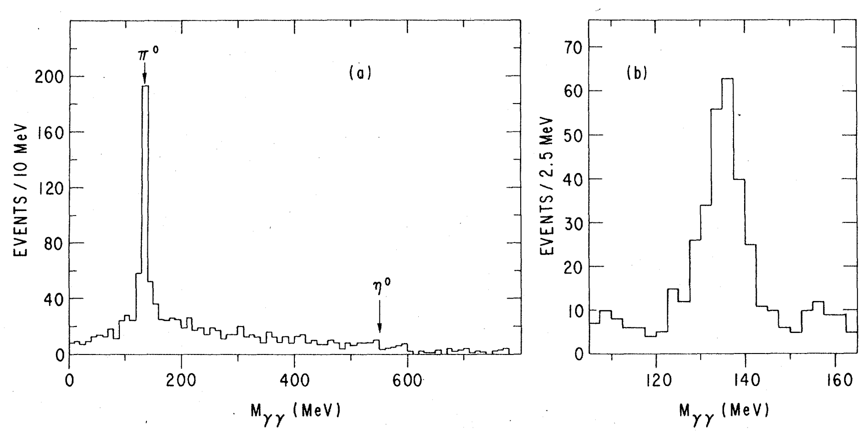

FIG. 3. The unweighted $\gamma\gamma$ mass spectrum in (a) 10 MeV and (b) 2.5 MeV bins.

was determined by taking γ's from different real events of the same charged topology, and agrees well with a Monte Carlo simulation. Allowing the amount of π^0 and background to vary, we find (225 ± 17) π^0's with a χ^2 per degree of freedom of 1.0. After correcting for scanning, measuring, and conversion efficiency and other losses, we find $\langle \pi^0 \rangle_{\rm annih} = 1.4 \pm 0.3$.

In Fig. 3, no clear η^0 signal can be seen. The expected mass resolution is $\sigma = 15$ MeV in the η^0 region. We have used several alternative techniques to estimate the background in the η^0 region: (1) use the side bands around the η^0, (2) use the combinatorial background (from different events) to fit the mass spectrum, and (3) use a polynomial form to fit the background. Using different mass regions around the η^0, averaging over the above methods, and taking all events above our expected background as η^0's, we find 7^{+9}_{-6} $\eta^0 \to 2\gamma$ events. Putting in branching ratios and the mass-dependent conversion efficiency, we find $\eta^0/\pi^0 = 0.05^{+0.06}_{-0.04}$ corresponding to $\eta^0/\pi^0 < 0.11$ at the 90% confidence level.

For all events for which $128.5 \leq m_{\gamma\gamma} < 141.5$ MeV, the charged tracks from the annihilation vertex were measured. Figure 4 shows the $\pi^+\pi^-\pi^0$ mass distribution for these events. In this plot, the π^0 momentum resulting from a kinematic fit to $\pi^0 \to \gamma\gamma$ is used, giving a calculated mass resolution of $\sigma = 15$ MeV in the ω^0 region. An ω^0 signal is present in the mass plot shown in Fig. 4 and occurs predominantly in the four-prong sample. To determine the amount of ω^0 production, the shape of the background spectrum must be known. We have tried several alternative methods to estimate the background shape: (1) take $\pi^\pm\pi^\pm\pi^0$ and $\pi^\pm\pi^\pm\pi^\mp$ mass combinations from the same event, (2) take $\pi^\pm\pi^\mp\pi^0$ mass combinations from different events (with charged pions from the same event),

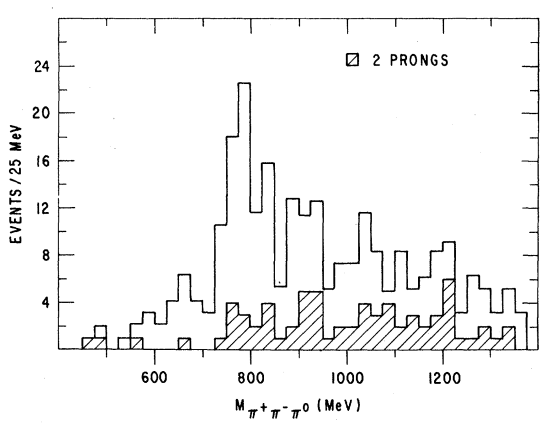

FIG. 4. The $\pi^+\pi^-\pi^0$ mass distribution. The shaded region shows the two-prong contribution.

(3) use a combination of method (2) and five-body phase space, and (4) use a quadratic function over a limited range around the ω^0. For all methods, the ω^0 mass and width ($\sigma = 15$ MeV) were fixed and a least-squares fit performed to determine the amount of ω^0 and background. All methods give consistent results, and we find after correcting for branching ratio and measuring efficiency that $\omega^0/\pi^0 = (20 \pm 7)\%$.

ANALYSIS OF THE e^+e^- MASS SPECTRUM

Knowing the rates of inclusive η^0 and ω^0 production, one can determine the amount of high-mass signal due to the decay of these two resonances. To accomplish this, one must calculate the detection efficiency for observing the $e^\pm$ from the η^0 and ω^0 Dalitz decays. A Monte Carlo program was written to simulate these decays. The theoretical decay matrix elements[20,21] were used, while the η^0 and ω^0 momentum distributions were estimated using experimental data. Once an $e^\pm$ was generated, its trajectory was followed until it hit a chamber boundary, and the track's class was determined. The $e^\pm$ was allowed to lose energy through ionization and bremsstrahlung (in hydrogen, bremsstrahlung is the larger of the two for electron energies above 250 MeV). For the π^0, η^0, and ω^0 Dalitz decays, the overall detection efficiencies for having at least one class 4 $e^\pm$ are 74%, 54%, and 45%, respectively. The uncertainty in these numbers is $\pm 2\%$ and was obtained by allowing the parameters of the Monte Carlo calculation to vary. Figure 5 shows how the detection efficiency varies as a function of $m_{e^+e^-}$. For $m_{e^+e^-} > m_{\pi^0}$, the detection efficiency for having at least one class 1, 2, 3, or 4 $e^\pm$ (for those tracks that left the chamber before going through four 360° turns, the $e^\pm$ also had to have a momentum of less than 120 MeV/c when it left) is also plotted. For completeness, the detection efficiency for the direct decay $M \to e^+e^-$ is also plotted.

The total number of π^0's (and consequently the number of η^0's and ω^0's) in our complete data sample can now be calculated using the formula:

$$\sum_{i=1}^{n} [(N_{\pi^0})(F^i_{\pi^0})(D^i_{\pi^0})(B_{\pi^0}) + (N_{\pi^0})(R_{\eta^0})(F^i_{\eta^0})(D^i_{\eta^0})(B_{\eta^0}) + (N_{\pi^0})(R_{\omega^0})(F^i_{\omega^0})(D^i_{\omega^0})(B_{\omega^0})] = N_D \ , \quad (1)$$

where i runs over the mass bins from $m_{e^+e^-} = 2m_e$ to m_{π^0}, N_{π^0} is the number of π^0's in our sample, R_{η^0} and R_{ω^0} are the ratios of inclusive η^0 and ω^0 production to π^0 production, $F^i_{\pi^0}$, $F^i_{\eta^0}$, and $F^i_{\omega^0}$ are the fraction of the Dalitz decays found in a given $m_{e^+e^-}$ interval as determined from theory,[20,21] $D^i_{\pi^0}$, $D^i_{\eta^0}$, and $D^i_{\omega^0}$ are the detection efficiencies for each mass interval, B_{π^0}, B_{η^0}, and B_{ω^0} are the

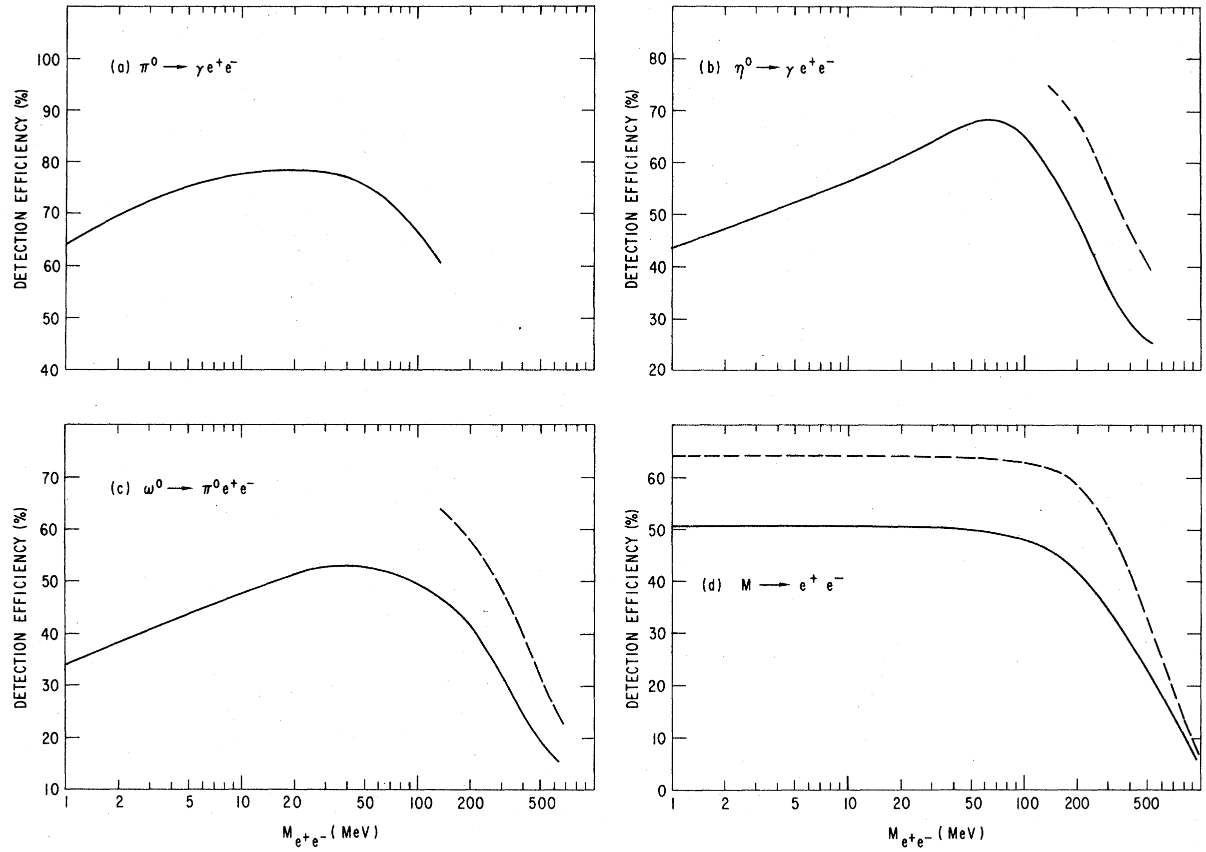

FIG. 5. The detection efficiencies for seeing at least one $e^{\pm}$ from the decays (a) $\pi^0 \rightarrow \gamma e^+e^-$, (b) $\eta^0 \rightarrow \gamma e^+e^-$, (c) $\omega^0 \rightarrow \pi^0 e^+e^-$, and (d) $M \rightarrow e^+e^-$. The solid curve is for the case when the identified $e^{\pm}$ must be in class 4. The dashed curve is for the case when the identified $e^{\pm}$ is of class 1, 2, 3, or 4. For the latter case, the $e^{\pm}$ must also have a momentum of less than 120 MeV/c when it hits the chamber boundary.

branching ratios for the Dalitz decays, and N_D is the total number of Dalitz decays with $m_{e^+e^-} < m_{\pi^0}$ observed in our data sample (corrected for scanning and measuring efficiency).

The above formula assumes that π^0, η^0, and ω^0 decays account for all the low-mass pairs. If there were any significant amount of direct photon production, then the above formula would overestimate the number of π^0's. Based on arguments given below, we estimate that 28^{+16}_{-28} of the e^+e^- pairs below m_{π^0} represent internal conversion of direct photons. With this correction, we find from Eq. (1) that $\langle \pi^0 \rangle_{\text{annih}} = 1.53 \pm 0.11$. This is consistent with the result $\langle \pi^0 \rangle_{\text{annih}} = 1.4 \pm 0.3$ obtained above using the multi-γ sample. The mean π^0 multiplicity is given as a function of prong number in Table III. Based on a prong count in our experiment, and correcting for K^- production,[22] we find $\langle \pi^- \rangle_{\text{annih}} = 1.45 \pm 0.07$.

The solid curve in Fig. 2 is a prediction for the $m_{e^+e^-}$ distribution based on Eq. (1). For low masses where π^0 Dalitz decays dominate, the curve represents the data quite well. For high masses, the data is within a standard deviation of the predicted curve, except for the last point. In the highest-mass interval where there are three events, the ω^0 Dalitz-decay contribution is small (0.1 event), and we estimate that the direct decays $\rho^0 \rightarrow e^+e^-$ and $\omega^0 \rightarrow e^+e^-$ incoherently contribute 0.40 ± 0.10 events.[23]

For all $m_{e^+e^-} > m_{\pi^0}$, we then have a total background of $7.0^{+4.4}_{-2.0}$ events with η^0 and ω^0 Dalitz de-

TABLE III. $\langle \pi^0 \rangle$ versus charged-particle multiplicity for annihilation events.

Number of prongs [a]	$\langle \pi^0 \rangle_{\text{annih}}$
0	2.98 ± 0.50
2	2.00 ± 0.12
4	1.15 ± 0.08
6	0.40 ± 0.13

[a] Does not include the e^+e^- pair.

cays contributing 6.3 events. Most of the error is due to the uncertainty in η^0 production. Our 11-event sample is thus 1σ above the background. The 90%-confidence-level upper limit for the number of anomalous high pairs is 8. Assuming that this anomalous signal results from the process $\gamma^* \to e^+e^-$, we can correct for detection efficiency using the results shown in Fig. 5(d). After correcting for scan efficiency, we find the 90%-confidence-level upper limit for the ratio of anomalous prompt $e^\pm$ production (resulting from high-mass e^+e^- pairs) to π^0 production of $R = 4 \times 10^{-5}$. This value is consistent with the result given in Ref. 13 that $R < 5.9 \times 10^{-5}$ at the 95% confidence level for $\bar{p}p$ annihilation at 2.0 GeV/c. We can use our estimated anomalous signal of (4^{+2}_{-4}) high-mass events from $\gamma^* \to e^+e^-$ to estimate[10] that there are also 28^{+16}_{-28} γ^* events with $m(e^+e^-) < m_{\pi^0}$. This rate of internal pair production would correspond to direct photon production at the rate of $\gamma/\pi^0 = (4^{+2}_{-4})\%$. This can be compared with an ISR result[10] determined from internal e^+e^- pairs that $\gamma/\pi^0 \approx (0.5 \pm 1)\%$ for $p_T \sim 2$ GeV/c, $\sqrt{s} = 55$ GeV.

Because of the excellent mass resolution in this experiment, it is also possible to search for narrow mass peaks in the data. We plotted the $\pi^\pm e^+e^-$ and $\pi^\pm\pi^\mp e^+e^-$ mass distributions but did not find evidence for any narrow enhancement. Baryonium states can be searched for in the reactions (1) $\bar{p}p \to \gamma + B$ and (2) $\bar{p}p \to B \to \gamma + B'$, with the γ converting to an external e^+e^- pair in each case. We plotted the missing mass recoiling from the γ, but saw no evidence for a peak. For reaction (2), when the annihilation occurs at rest, we should observe monoenergetic γ's. No peaking was observed in the γ energy distribution. Finally, when reaction (2) occurs in flight, we have plotted the center-of-mass γ energy versus $\sqrt{s}$. Again, no enhancement was seen.

SUMMARY AND REMARKS

We have searched for prompt e^+e^- pair production in low-energy $\bar{p}p$ annihilations, and have found 11 events which have e^+e^- pairs of mass greater than the π^0 mass. The major sources of background in this signal are η^0 and ω^0 Dalitz decays. To determine these backgrounds, we have measured the inclusive production rates of these resonances and find $\omega^0/\pi^0 = 0.20 \pm 0.07$ and $\eta^0/\pi^0 < 0.11$ at the 90% confidence level. The η^0 and ω^0 then contribute a background of $6.3^{+4.4}_{-3.0}$ events to our 11-event data sample. The anomalous e^+e^- pair signal is only a 1σ effect, and we thus quote a 90%-confidence-level upper limit of $R = e^-/\pi^0 \cong 4 \times 10^{-5}$ for e^+e^- pairs of mass above m_{π^0}.

Several remarks can be made about the interpretation of our results on inclusive ω^0 and η^0 production. First, we note that the measured ratio of $\omega^0/\pi^- = 0.20 \pm 0.07$ is equal within error to ρ^0/π^- which has been measured inclusively in $\bar{p}p$ annihilations[23] to be 0.16 ± 0.03 at 2.3 GeV/c and 0.15 ± 0.01 at 0.7 GeV/c. Thus, it appears that the near equality of exclusive ρ^0 and ω^0 production also holds for inclusive production. The near equality of ρ^0 and ω^0 production is not surprising in terms of quark-model ideas and the fact that $m_\omega \cong m_\rho$.

A different situation holds for the inclusive η^0/π^0 ratio. Here we obtain an inclusive result of $0.05^{+0.06}_{-0.04}$, whereas in exclusive reactions or at large p_T, a typical value is $\eta^0/\pi^0 = 0.5$. Presumably, the η^0/π^0 case differs from that of ρ/ω because of SU_3-breaking effects, particularly the large $\eta^0 - \pi^0$ mass difference. These effects strongly favor the decay of heavier mesons into π rather than η, so that most of the π^0 in the denominator of the inclusive η^0/π^0 ratio originate in fact from decays of heavier mesons (including ρ and ω^0).

To give a very simple numerical example: If direct production ratios for $\rho : \omega : \eta : \pi$ were $2 : 2 : 0.5 : 1$, and no other mesons were produced, then the inclusive ratios would be $\rho^0/\pi^0 = 0.27$, $\omega^0/\pi^0 = 0.27$, and $\eta^0/\pi^0 = 0.07$.

A final point regarding inclusive production rates: From results given above, one has $\langle\pi^0\rangle_{\text{annih}}/\langle\pi^-\rangle_{\text{annih}} = 1.07 \pm 0.09$. This agrees within error with the result 1.16 ± 0.05 obtained at 1.6 GeV/c by Fett *et al.*[24]

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