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Study of the η' Produced in K^-p Interactions at 2.885 GeV/c *

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We have accumulated a sample of ~ 400 $\eta'(958)$ decays in the modes (1) $\eta' \to \pi^+\pi^-\gamma$ and (2) $\eta' \to \pi^+\pi^-\eta_N^0$ (N = neutral decay) from a 15.4-eV/μb study of K^-p interactions at 2.89 GeV/c. We find a branching ratio $R = (1)/(2) = 1.11 \pm 0.18$, where (1) is entirely $\eta' \to \rho^0\gamma$. A matrix-element analysis yields $J^P(\eta') = 0^-, 2^-$ as acceptable values for both samples. Production-decay angular correlations suggest that a $J^P = 2^-$ assignment is unlikely.

Although the η' was discovered in 1964,[1] its spin-parity and branching ratios remain uncertain. While it has been shown that the only acceptable G parity and isospin assignments are $I^G = 0^+$, previous spin and parity determinations have led to an ambiguity of $J^P = 0^-$ and 2^-. The branching ratio of $\eta' \to \pi^+\pi^-\gamma/\pi^+\pi^-\eta$ is not well established, with results varying by a factor of two.[2,3,4]

The results presented below are derived from a one million picture exposure of the BNL 31-in. hydrogen bubble chamber to a K^- beam of momentum 2.885 GeV/c. We have scanned and measured events with topology two prongs plus a V^0 in a fraction of film corresponding to 15.4 eV/μb. The channels of interest for this study are

$$K^-p \to \Lambda\pi^+\pi^-\eta_N \text{ (neutral decay)} \quad (1)$$
$$\to \Lambda\pi^+\pi^-\gamma \quad (2)$$
$$\to \Lambda\pi^+\pi^-\pi^0 \quad (3)$$
$$\to \Sigma^0\pi^+\pi^- \quad (4)$$
$$\to \Lambda\pi^+\pi^- . \quad (5)$$

Branching ratios. The relevant channels for our η' branching ratio determination are (1) and (2) where we study the decays $\eta' \to \pi^+\pi^-\eta_N$ and $\eta' \to \pi^+\pi^-\gamma$. The major difficulty in determining the η' branching ratio is the unbiased selection of η' events in reaction (2). These events are highly ambiguous with channels (3) and (4), so that attempts to separate these channels by kinematic fitting can lead to biases. For selection purposes, we have therefore chosen to treat the events of channels (1) to (4) as "unfitted events" at production, viz.,

$$K^-p \to \Lambda\pi^+\pi^- \text{MM}$$

where MM is the "missing mass."[5] While the highly constrained reaction (5) is also ambiguous with reaction (2), our Monte Carlo analyses indicate that a negligible amount of η' events could achieve a fit to (5), so these events have been removed from our sample.[6,7]

Our selection of events of reaction (1) is based on Figs. 1(a) and 1(b). Figure 1(a) shows the production angular distribution for the $\pi^+\pi^-$MM system, with MM in the η region; the expected peripherality of η' production is apparent. Restricting $\cos\theta \geq 0.8$ (θ is the production angle between the proton and the Λ), we see in Fig. 1(b) an obvious enhancement where the $M^2(\pi^+\pi^-\text{MM})$ is in the η' region and the MM^2 is in the η region. The outlined selection region includes 215 events with an estimated 22 background events resulting in 193 ± 14 reaction (1) events.

As with reaction (1), we have selected reaction (2) events by restricting $\cos\theta \geq 0.8$. Resolution

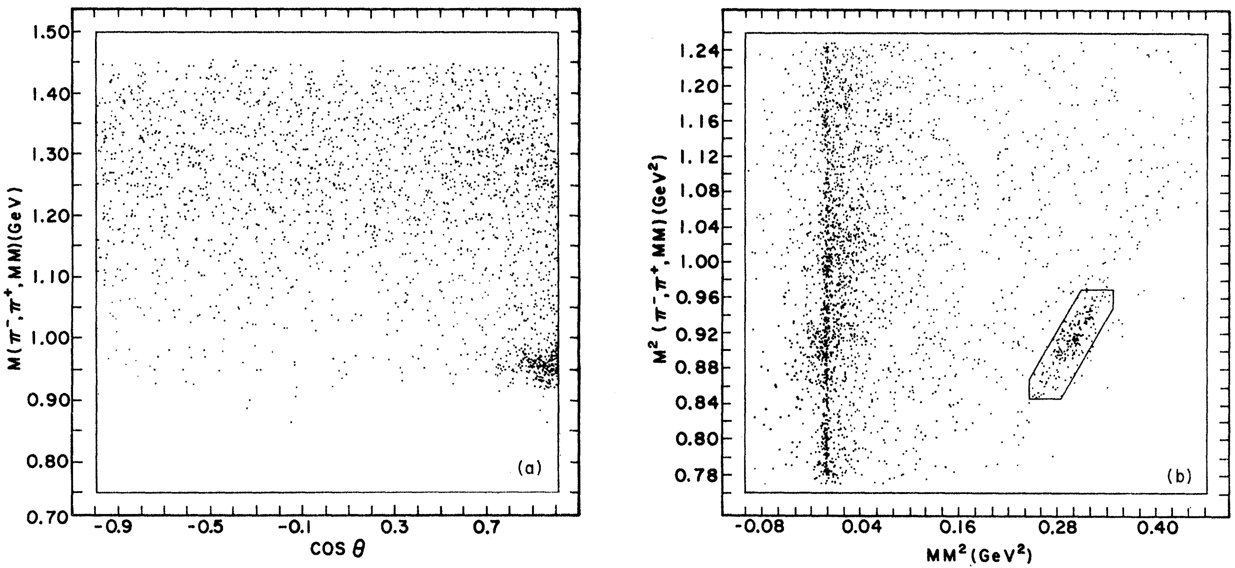

FIG. 1. (a) Angular distribution of the production angle between the Λ and the proton versus the $M(\pi^+\pi^-\,\mathrm{MM})$ for $0.245 \leq \mathrm{MM}^2 \leq 0.345\ \mathrm{GeV}^2$ (η region). (b) Scatter plot of MM^2 versus $M^2(\pi^-\pi^+\,\mathrm{MM})$ for events with $\cos\theta \geq 0.8$.

studies indicate that restricting MM^2 between -0.04 and $0.03\ \mathrm{GeV}^2$ includes 94.5% of all reaction (2) events.[7,8] To improve resolution, after our sample selection, the selected events have been fitted to hypotheses (1) and (2). Owing to inefficiencies in the fitting programs, 5% of the events, however, failed to produce the desired fit.

Figure 2, curve A, shows a typical maximum-

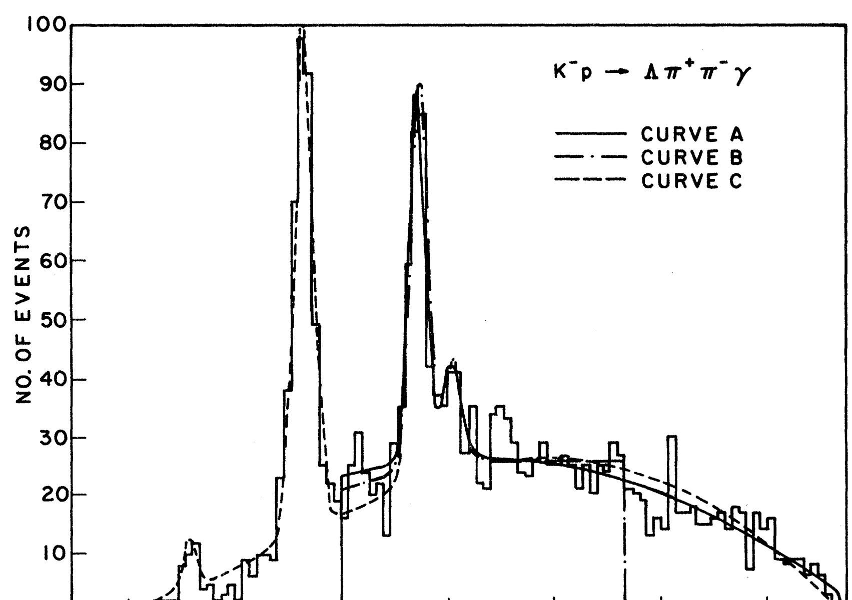

FIG. 2. Selection of events are $\cos\theta \geq 0.8$, $-0.04 \leq \mathrm{MM}^2 \leq 0.03\ \mathrm{GeV}^2$, and events ambiguous with 4-constraint fits removed. Curve A: Fitted curve of a quadratic with two Gaussians for the η' and ϕ resonances fit over the range $M^2(\pi^+\pi^-\gamma) \geq 0.7\ \mathrm{GeV}^2$ resulting in 186 η' events. Curve B: Fitted curve of a quadratic with two Gaussians for the η' and ϕ resonances fitted over the range $0.7 \leq M^2(\pi^+\pi^-\gamma) \leq 1.5\ \mathrm{GeV}^2$ resulting in 194 η' events. Curve C: Fitted curve of a cubic, with end points fixed at 0 and 2.1 GeV^2 with 4 Gaussians for the η, ω, η', and ϕ resonances fitted over the entire range resulting in 202 η' events. The cubic was weighted with a factor $(1-e^{-aM^2})$ in order to satisfactorily reproduce the low-M^2 region.

TABLE I. Matrix-element fits to decay distribution of $\eta' \to \pi^+\pi^-\eta$ for $J^P = 0^-, 2^-$ assignments. $l_{\eta^0}, l_{\pi\pi}$ are the angular momenta of the η^0 in the η' c.m. and the π in the dipion rest frame, a is a parameter to be fitted, $y = [(M_\eta + 2M_\pi)/M_\pi](T_\eta/Q) - 1$, q = momentum of π in dipion rest frame, k = momentum of η in η' rest frame, and θ = angle between π^- and η in dipion rest frame.

J^P	$l_{\eta^0}, l_{\pi\pi}$	Matrix element squared	No. of degrees of freedom	χ^2	Prob.	Fitted parameter(s)
0^-	0, 0	$(1+ay)^2$	33	34.1	0.35	$a = -0.19 \pm 0.07$
0^-	0, 0	1	34	40.3	0.14	...
2^-	Mix	$q^4 + \mathrm{Re}(a) q^2 k^2 (3\cos^2\theta - 1) + \lvert a \rvert^2 k^4$	32	39.2	0.18	$\mathrm{Re}(a) = -0.09 \pm 0.06$
	0, 2					
	2, 0					$\lvert a \rvert = 0.30 \pm 0.04$

likelihood fit of two Gaussians and a quadratic background over the effective mass range $0.7 \leq M^2(\pi^+\pi^-\gamma) \leq 2.1$ GeV^2 to events which fit $\Lambda\pi^+\pi^-\gamma$ and satisfied the above selections. We have also fitted the distribution by varying the size of the region surrounding the η' as well as the parametrization for the background. In Fig. 2, curves B and C represent the range in this systematic error. The results yield 192 ± 20 $\eta' \to \pi^+\pi^-\gamma$ decays. This result combines the systematic error in choosing an appropriate background with the statistical error in each fit.

There are two causes for loss of reaction (2) events. First, the selection on the MM^2 introduces a 5.5% loss. Second, there is the previously mentioned 5% loss of selected channel (2) events, which appear to be reaction (2) candidates from the $\Lambda\pi^+\pi^-$MM fit, due to the inefficiency of the fitting program.[9] Correcting for these losses gives a branching ratio of

$$\frac{\eta' \to \pi^+\pi^-\gamma}{\eta' \to \pi^+\pi^-\eta_N} = \frac{214 \pm 30}{193 \pm 14} = 1.11 \pm 0.18 .$$

We turn now to a determination of the amount of $\eta' \to \pi^+\pi^-\gamma$ with an intermediate ρ^0: $\eta' \to \rho^0\gamma$. In order to determine this, we have fitted two Gaussians with a quadratic background to the $M^2(\pi^+\pi^-\gamma)$ where $M(\pi^+\pi^-) \geq 0.66$ GeV. The selection on the $M(\pi^+\pi^-)$ defines the ρ region which is limited on the high-mass side by phase space. This fit yields 137 $\eta' \to \rho\gamma$, which when corrected for the low-mass tail of the ρ becomes 193 ± 20 η' events. This results in a ratio of

$$\frac{\eta' \to \rho^0\gamma}{\eta' \to \pi^+\pi^-\gamma} = \frac{193 \pm 20}{192 \pm 20} = 1.01 \pm 0.15 .$$

Thus the $\pi^+\pi^-\gamma$ decay of the η' is consistent with being entirely $\rho^0\gamma$.[10]

While previous experiments all agree with the $\rho^0\gamma/\pi\pi\gamma$ ratio, a previous experiment by a Brookhaven group,[4] based on a smaller sample, differs significantly in its value for the $\pi^+\pi^-\gamma/\pi^+\pi^-\eta_N$ branching fraction (0.54 ± 0.10) when compared with Ref. 2 (1.05 ± 0.14) and Ref. 3 (0.89 ± 0.09). These differences may be attributed to the different separation procedures employed by each experimenter. For this reason we emphasized a method which was not dependent on selecting $\Lambda\pi^+\pi^-\gamma$ events from the over-all ambiguity but rather coped with the background problem. The value of the branching ratio as reported above for this experiment was 1.11 ± 0.18. The world average, excluding the Brookhaven experiment, is 0.91 ± 0.07.

Mass and width. Using the mass calibrations for this experiment reported elsewhere,[11] we find the mass value for the η' from both decay modes to be consistent. Their average is $M = 958 \pm 1$ MeV. Based on average resolution of 23 MeV (full width at half maximum) in the $\eta' \to \pi^+\pi^-\eta_N$ mode, we determine the η' width $\Gamma < 5$ MeV at the 90% confidence level. Both of these results include systematic uncertainties and are consistent with previous experiments.

Spin and parity. We will now discuss the spin-parity determination for the η'. Since previous experiments have eliminated all but $J^P = 0^-$ or 2^- we will confine ourselves to these hypotheses. The sample of type 1 events is almost background-free, making a direct maximum-likelihood fit of the appropriate matrix elements possible. The results are given in Table I. Figure 3(a) shows the Dalitz-plot projections and their superimposed theoretical curves. The acceptable solutions are the $J^P = 0^-$ hypotheses, with and without a linear matrix element, and the "mixed" (l_η, $l_{\pi\pi} = 0, 2$ and $2, 0$) $J^P = 2^-$ solution.

A spin-parity analysis on the sample of $\eta' \to \pi^+\pi^-\gamma$ presents a more difficult problem. The amount of background, as we have previously shown, is itself a parameter with a large sys-

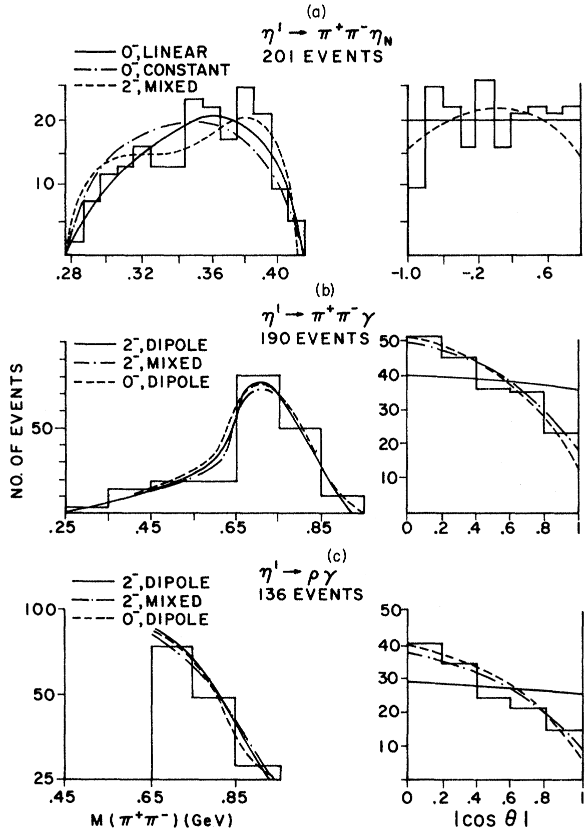

FIG. 3. Fits of indicated matrix elements to Dalitz-plot projection of (a) $\eta' \to \pi^+\pi^-\eta_N$, (b) $\eta' \to \pi^+\pi^-\gamma$, (c) $\eta' \to \pi^+\pi^-\gamma$ with effective mass $M(\pi^+\pi^-) > 0.66$ GeV (ρ region).

tematic error. A simple background subtraction would fix the amount of background and introduce large errors in the Dalitz-plot projections. In addition, a maximum-likelihood function would be poorly represented by the use of only the matrix elements. Instead we have chosen to parametrize the background as the phase space of three pions fitted as $\pi^+\pi^-\gamma$. This parametrization agrees with the background as ascertained by choosing adjacent bands to the η' region. It has the advantage that the amount of background can now vary and its value, as determined when it is combined with the different matrix elements in a maximum-likelihood fit, can be compared with results obtained above.

For spin-parity analysis a purer sample of $\eta' \to \pi^+\pi^-\gamma$ events was used by restricting

$$-0.03 \leq \mathrm{MM}^2 \leq 0.02 \ \mathrm{GeV}^2$$

and

$$0.89 \leq M^2(\pi^+\pi^-\gamma) \leq 0.95 \ \mathrm{GeV}^2 .$$

With the previous methods we estimate that there

TABLE II. Matrix-element fits to the decay distribution of $\eta' \to \pi^+\pi^-\gamma$ for $J^P = 0^-, 2^-$ assignments. a, b are parameters to be fitted, q = momentum of π in the dipion rest frame, k = momentum of the γ in the η' rest frame, m = invariant π^+, π^- mass, θ = angle between π^-, γ in the dipion rest frame, $f_{BW} = M_\rho \Gamma_0 / [(m^2 - M_\rho^2)^2 + (M_\rho \Gamma)^2]$, where $\Gamma = \Gamma_0 (q/q_0)^3$, Γ_0 = width of the ρ, and $q_0 = \pi^-$ momentum when $m = M_\rho$.

J^P	Multipole	Matrix element squared	Degrees of freedom	χ^2	Prob.	Fitted parameter(s)	No. of background events
0^-	Dipole	$q^2k^2m^2 \sin^2\theta f_{BW} + b$	11	12.4	0.33	$b = 0.05 \pm 0.01$	67
2^-	Dipole	$q^2k^2m^2 \left[6 + \sin^2\theta + 6\left(\frac{k}{M_{\eta'}}\right)^2 \cos^2\theta\right] f_{BW} + b$	11	23.4	0.02	$b = 0.48 \pm 0.09$	62
2^-	Mixed dipole and quadrupole	$q^2k^2m^2 \left\{ \left[6 + \sin^2\theta + 6\left(\frac{k}{M_{\eta'}}\right)^2 \cos^2\theta\right] - 4\frac{ak}{m}\left[1 + 2\cos^2\theta - \left(\frac{km}{M_{\eta'}^2}\right)(2 + \cos^2\theta)\right] + \frac{2a^2k^2}{M_{\eta'}^2}\left[2 + \cos^2\theta - 4\left(\frac{km}{M_{\eta'}^2}\right)\sin^2\theta\right] \right\} f_{BW} + b$	10	8.9	0.55	$a = 2.65 \pm 0.54$, $b = 0.38 \pm 0.07$	75

TABLE III. Matrix-element fits to the decay distribution of $\eta' \to \pi^+\pi^-\gamma$, where $M(\pi^+\pi^-) > 0.66$ GeV (ρ region).

J^P	Multipole	χ^2	No. of degrees of freedom	Prob.
0^-	Dipole	2.6	7	0.99
2^-	Dipole	16.0	7	0.03
2^-	Mixed dipole and quadrupole	3.0	6	0.80

are 130 ± 24 η' events in this sample with 60 ± 24 events in the background. The results of the maximum-likelihood fit can be seen in Table II and Fig. 3(b).[12] In addition, since this decay mode is mediated by $\rho\gamma$, we have restricted $M(\pi^+, \pi^-) \geq 0.66$ GeV. The results of the maximum-likelihood fit in this case are given in Table III, with the Dalitz-plot projections shown in Fig. 3(c).

The above Dalitz-plot analyses, the results of which agree with previous experiments,[2,3,4,13] demonstrate the indistinguishability of $J^P = 0^-$ and 2^- by this technique. We have also investigated production-decay correlations of the η' decays in various reference frames such as that shown in Fig. 4.[14] For nonzero-spin mesons, such distributions generally are anisotropic. As in previous experiments[2,3,4] a moments analysis yields no evidence of anisotropy.[15] Since experiments have now been carried out over a 2–5 GeV/c incident momentum range, a $J^P = 2^-$ assignment for the η' seems unlikely.

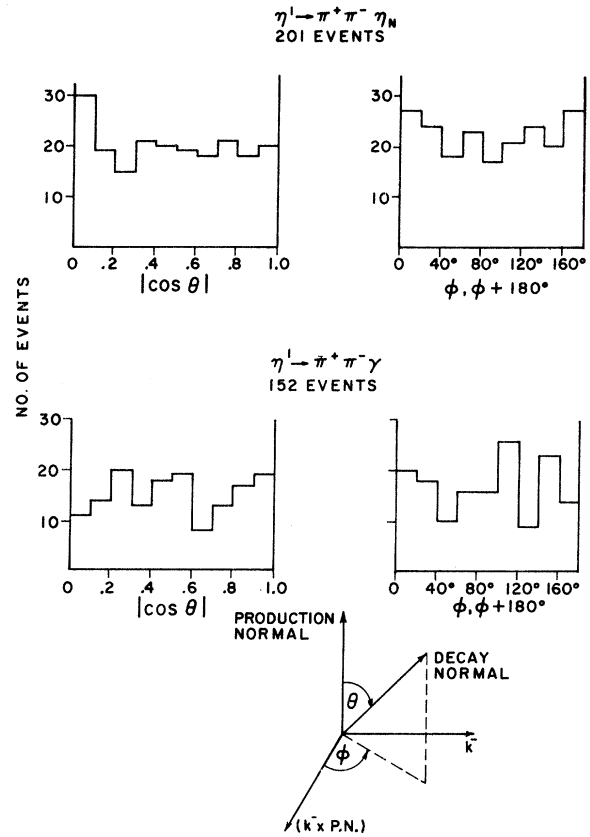

FIG. 4. Production-decay angular distributions in the reference frame shown for the decays $\eta' \to \pi^+\pi^-\eta_N$ and $\eta' \to \pi^+\pi^-\gamma$.

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[5]All events where the vee can be fitted as a Λ to production with a probability greater than 0.001 and where the missing 4-momentum, as calculated from the measured tracks and the fitted Λ to production, is within two standard deviations of possible values for a missing physical particle are included in the $\Lambda\pi^+\pi^-$ MM sample. In addition, any event which makes a production fit where the vee is a Λ also has its $\Lambda\pi^+\pi^-$ MM fit calculated.

[6]We have studied the missing momentum in the laboratory for the reaction (2) events with events ambiguous with 4-constraint fits removed. Instead of a depletion of events in the ambiguous region we found an excess of events which could not be reconciled with an appropriate Monte Carlo distribution of reaction (2) events. We concluded that instead of a loss of reaction (2) events we had a contamination from 4-constraint events which did not fit the 4-constraint hypothesis.

[7]For a more detailed discussion see S. Jacobs, Syracuse University, Ph. D. thesis, 1972 (unpublished).

[8]By observing the MM^2 distribution from $\Lambda\pi^+\pi^-$MM for events in the ω region, a Gaussian distribution with standard deviation $\sigma = \pm 0.018$ and centered at $[M^2(\pi^0) - 0.005]$ GeV^2 was obtained. As a further check we assumed $\eta' \to \rho\gamma$ and looked at the MM^2 distribution from $\Lambda\rho$MM where the $M(\rho$MM) was restricted to the η' region. This distribution was centered at -0.005 GeV^2 with a $\sigma = \pm 0.02$.

[9]A similar loss is observed for MM events in the η region.

[10]Independent of the η' spin-parity, approximately 50% of the $\pi^+\pi^-\gamma$ events would have $M(\pi^+\pi^-) < 0.66$ GeV if an

intermediate ρ was not produced.

[11]B. T. Meadows, Syracuse University High Energy Physics Memo No. 12-71, 1971 (unpublished).

[12]Besides the matrix elements included in Table II we have tried the matrix element suggested by V. Oglievetsky [see V. Oglievetsky, W. Taylor, and A. Zaslavasky, Phys. Lett. 35B, 69 (1971)], which appears to be almost identical with the 2^- dipole matrix elements and achieved the same fit probability.

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[14]We have not subtracted any background from the decay distributions of $\eta' \to \pi^+\pi^-\gamma$ since from the side bands we determined that their contribution is isotropic.

[15]The χ^2 probability that the significant moments up to $l, m=5$ are all zero is >80% in all reference frames.

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B-Meson Production in $\pi^- d$ Interactions at 7 GeV/*c* *

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We observe substantial *B*-meson production in $\pi^- d$ interactions at 7 GeV/*c*. The observed mass and width of the *B* are 1217 ± 12 MeV and 115 ± 40 MeV, respectively. We find that the *B* is produced largely in quasi-two-body final states, and, on the basis of the observed $\Delta^0 B$ production cross section, we expect a large $\pi A_2 B$ coupling which should be observable in other reactions.

Although the *B* meson was discovered about 10 years ago,[1] many of its properties are still relatively poorly known. Most of our knowledge concerning the *B* comes from the reactions $\pi^\pm p \to \omega\pi^\pm p$ (Ref. 2) and $\bar{p}p \to \omega\pi^+\pi^-$ at rest.[3] There has also been some evidence for *B* production in the reaction $K^-d \to p\Lambda\omega\pi^-$.[4] The data indicate that the spin-parity of the *B* is likely to be $J^P = 1^+$; however, assignments of 2^+, 3^-, 4^+, and higher cannot be excluded. The Particle Data Group[5] lists values of 1233 ± 10 MeV and 100 ± 20 MeV for the mass and width of the *B*, respectively. The available data, however, are not entirely consistent, with mass values ranging from 1200 MeV to 1260 MeV, and widths ranging from about 80 MeV to about 200 MeV. It appears that the total cross section for *B* production is falling rather slowly as a function of beam momentum ($\sim 1/p_{\text{beam}}$).[6]

We present here a study of *B* production in the reaction

$$\pi^- d \to pp\pi^+\pi^-\pi^-\pi^-\pi^0. \qquad (1)$$

The data are derived from exposures of the SLAC and BNL[7] deuterium-filled bubble chambers to beams of ~7-GeV/*c* π^- mesons. These exposures yielded ~20 ev/μb of cross section. The film was scanned for five-pronged events which had one track that could be identified by ionization as a proton candidate, and for six-pronged events which had two proton candidates. Owing to these scanning rules, our data are unbiased only for values of the square of the momentum transfer from the deuteron to the two outgoing protons of less than 0.7 GeV^2. These events were subsequently measured and processed through the TVGP-SQUAW programs yielding a total of 1616 events belonging to reaction (1).

Figures 1(a) and 1(b) show the $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\pi^-\pi^0$ mass spectra for these events, respectively. The shaded region of Fig. 1(b) corresponds to those $\pi^+\pi^-\pi^-\pi^0$ mass combinations whose $\pi^+\pi^-\pi^0$ mass lies within 65 MeV of the ω peak. An enhancement is visible in this mass spectrum in the *B* region.

Our measuring resolution (σ) in the $\pi^+\pi^-\pi^0$ mass spectrum at the mass of the ω is ~20 MeV. In order to both improve our mass resolution and to provide a means of ω selection, we further fitted all events that had made acceptable fits to the one-constraint hypothesis of reaction (1) and which had at least one $\pi^+\pi^-\pi^0$ mass combination less than 1000 MeV to the two-constraint reaction

$$\pi^- d \to pp\omega\pi^-\pi^-, \quad \omega \to \pi^+\pi^-\pi^0. \qquad (2)$$

A total of 605 events made acceptable fits to this hypothesis.[8] The shaded area of Fig. 1(a) shows the $\pi^+\pi^-\pi^0$ mass combinations identified as ω's by this two-constraint fit. Figure 1(c) shows the $\omega\pi^-$ mass spectrum for the events identified as belonging to reaction (2). The *B* meson is clearly visible at ~1220 MeV. The dashed curve is the result of a low-order polynomial fit to the histogram assuming no resonant peak. If the observed enhancement were a statistical fluctuation, it