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ANALYSIS OF THE B ENHANCEMENT*

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The reactions $\pi^\pm + p \rightarrow \pi^\pm + \omega + p$ in the region 3 to 4 GeV/ c have been studied by several groups. In each case the effective-mass distribution for the $\pi^\pm\omega$ system showed a strong enhancement (referred to as the B meson) centered at $M_{\pi^\pm\omega} \approx 1220$ MeV; estimates for the full width, Γ , vary between 80 and 160 MeV.^{1,2} The origin of the enhancement has remained obscure since (a) it has not been possible to determine whether the B represents a state of definite spin and parity, (b) no corresponding peak has been observed in any other final state, (c) evidence for a possible anomaly in ω 's associated with the B has been reported by Goldhaber *et al.*,² and (d) the enhancement has been observed only in $\pi^\pm p$ interactions. Recently, in extending a suggestion due to Deck,³ Maor and O'Halloran⁴ have pointed out that virtual dissociation of the incident pion, $\pi \rightarrow \omega + \rho$, followed by the strongly asymmetric inelastic process, $\rho + p \rightarrow \pi + p$, should result in a broad enhancement in the region $M_{\pi^\pm\omega} \approx 1200$ MeV. In the present Letter it is shown that such a model accounts naturally for the essential features of the B enhancement as observed in our data. Difficulties associated with interpretation of the B as a resonant state are also discussed.

In a continuing study of $\pi^- p$ interactions in the Lawrence Radiation Laboratory 72-inch hydrogen bubble chamber, 5112 events⁵ representing the final state $p\pi^+\pi^0\pi^-\pi^-$ have been measured at 3.2 GeV/ c and 3792 events at 4.2 GeV/ c . The Chew-Low plot for single- ω events (either neutral pion triplet, but not both,⁶ lies

in the ω interval, 760 to 800 MeV) is shown in Fig. 1(a); a strong concentration in the B region occurs only for events with low Δp^2 (squared four-momentum transfer to the proton). This feature is emphasized further in Fig. 1(b). The $M_{\pi^\pm\omega}$ distribution for single- ω events shows the characteristic B enhancement in the region near 1220 MeV; a negligible reduction in the peak occurs when events with $\Delta p^2 < 0.35$ (GeV/ c)² are plotted separately. We conclude that if the B represents a resonant state, production occurs in highly peripheral collisions.

It is widely recognized that Δ^2 distribution observed in peripheral interactions cannot be interpreted by using unmodified exchange models.⁷ Nevertheless, in most experiments involving resonance production, Δ^2 distributions for reactions mediated by π exchange are concentrated at significantly lower values than those proceeding through ρ or ω exchange.⁸ The observed Δ^2 distribution in the B region suggests resonance production through π exchange [inset in Fig. 1(a)]. If this were the case, possible spin-parity assignments would be $J^P = 1^-, 3^-, \text{etc.}$,⁹ and decay into $\pi + \pi$ and $K + \bar{K}$ should occur.¹⁰ If the absence of these decays is due to the sequence $J^P = 0^-, 1^+, 2^\pm, 3^+, \text{etc.}$, the B can be produced only through ω exchange; in this case a broader Δp^2 distribution would be expected.

A further difficulty arises in attempting to analyze the B as a resonant state. The Dalitz plot for the $\pi^-\omega p$ final state is shown in Fig. 1(c) for events with $\Delta p^2 < 0.35$ (GeV/ c)². It is ap-

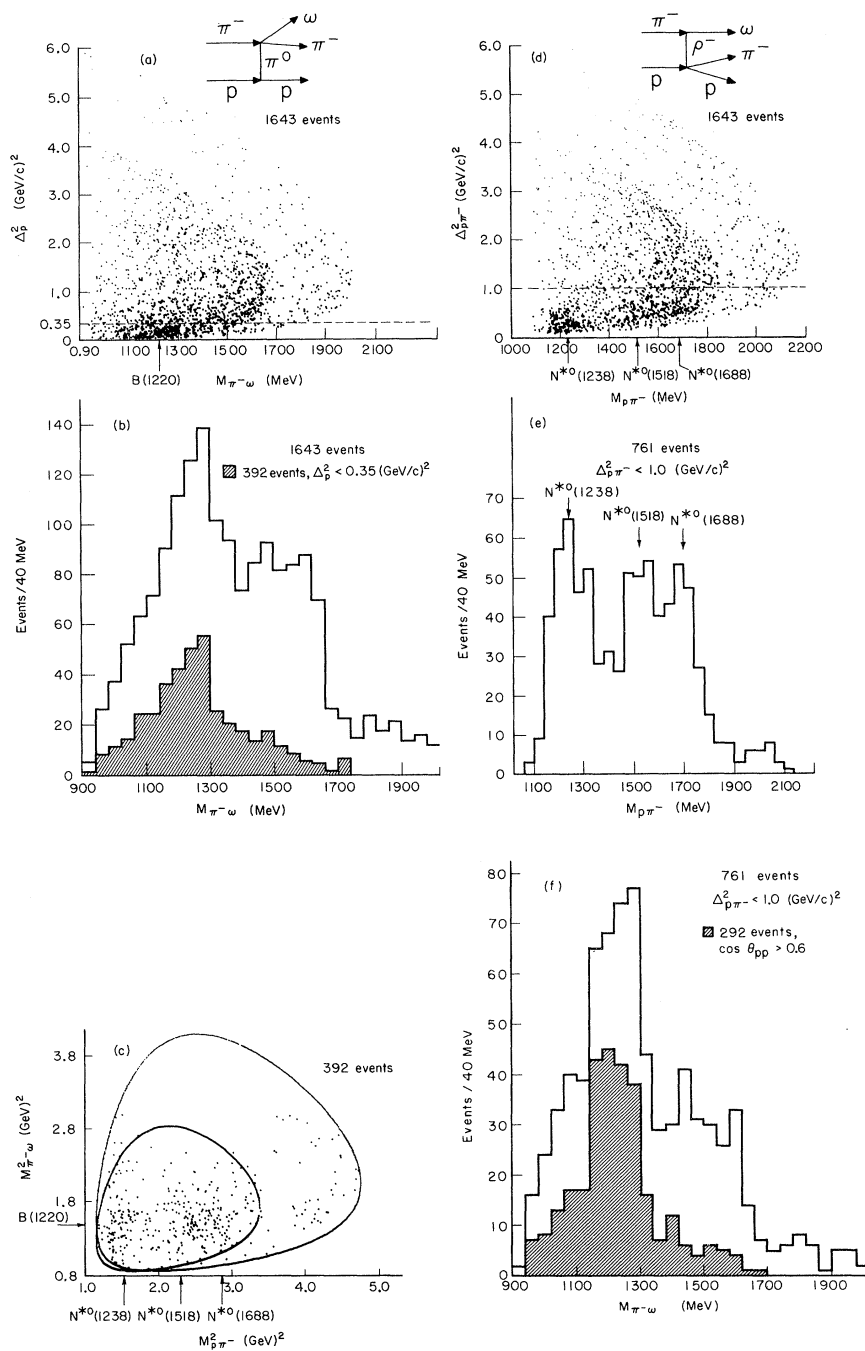


FIG. 1. (a) The Chew-Low plot of Δp^2 vs $M_{\pi^- \omega}$ for single- ω events and (b) the projection onto the $M_{\pi^- \omega}$ axis. (c) The Dalitz plot of $M_{\pi^- \omega}^2$ vs $M_{\rho \pi^-}^2$ for single- ω events with $\Delta p^2 < 0.35$ (GeV/c)². (d) The Chew-Low plot of $\Delta p_{\pi^-}^2$ vs $M_{\rho \pi^-}$ for single- ω events, and (e) the projection onto the $M_{\rho \pi^-}$ axis for events with $\Delta p_{\pi^-}^2 < 1.0$ (GeV/c)². (f) The $M_{\pi^- \omega}$ distribution for events with $\Delta p_{\pi^-}^2 < 1.0$ (GeV/c)²; the shaded region indicates events with $\cos \theta_{pp} > 0.6$.

parent that the B occurs most strongly in the $M_{\rho \pi^-}$ regions associated with isobars, i.e., $N^*(1238)$, $N^*(1518)$, and $N^*(1688)$. Consequent-

ly, should the B represent a valid resonance, $\pi^- p$ interactions at 3 to 4 GeV/c do not provide a suitable final state in which to determine

its quantum numbers.

To investigate the possibility that the B enhancement is a kinematic effect associated with ρ exchange [insert in Fig. 1(d)] we consider first the Chew-Low plot for single- ω events given in Fig. 1(d). Although partially obscured by background at higher mass values, it is apparent that isobar production is concentrated in the region¹¹ $\Delta p\pi^{-2} < 1.0$ (GeV/c)²; the $M_{p\pi^-}$ distribution for these events is given in Fig. 1(e). The $\Delta p\pi^{-2}$ distributions are in qualitative agreement with those observed in most other reactions involving exchange of vector mesons.⁸ For subsequent analysis of the $\pi^-\omega p$ final state, only events with $\Delta p\pi^{-2} < 1.0$ (GeV/c)² are used; as may be seen from Fig. 1(f), essentially all B events are retained with this selection.

A quantitative comparison with the ρ -exchange model is possible only in the $N^*(1238)$ region. The distributions of $\cos\theta_{\pi n}$, Treiman-Yang angle $\phi_{\text{T\Y}}$, and $\cos\theta_{pp}$ are given in Figs. 2(a), 2(b), and 2(c). [In the ω rest frame, $\theta_{\pi n}$ is the angle between the incoming pion and the normal to the ω decay plane; in the N^* rest frame, θ_{pp} is the angle between the incoming and outgoing protons, and $\phi_{\text{T\Y}}$ is the associated azimuthal angle ($\phi_{\text{T\Y}} = 0$ in the production plane)]. The solid curves, which provide a reasonable fit to the present data, were obtained by Aderholz *et al.*¹² in their analysis of the reaction $\pi^+ + p \rightarrow \pi^+ + \omega + p$ at 4.0 BeV/c; the curves are also in good agreement with calculations by Svensson based on the ρ -exchange

model with absorptive corrections.¹³

Theoretical calculations are not available for comparison in the higher isobar regions; however, it seems reasonable that given enough energy, the ρ -exchange process leading to $N^*(1238)$ will also produce $N^*(1512)$ and $N^*(1688)$. For the $M_{\pi-p}$ region accessible in the present experiment, strong contributions to the virtual process $\rho + p \rightarrow \pi + p$ should result from pion exchange in the t channel and isobar production in the s channel. The distributions in $\cos\theta_{pp}$ for several $M_{p\pi^-}$ intervals above $N^*(1238)$ are shown in Figs. 2(d) through 2(g). The striking feature is the strong peaking near $\cos\theta_{pp} \simeq +1$ for all $M_{p\pi^-} > 1420$ MeV. Pion exchange in the t channel for the process $\rho + p \rightarrow \pi + p$ should lead to a peak at¹⁴ $\cos\theta_{pp} \simeq +1$; the asymmetry in $\cos\theta_{pp}$ for isobar regions may be enhanced by interference between closely lying resonant states with opposite parity.¹⁵ Although it appears likely that these processes could account for the peaking observed at $\cos\theta_{pp} \simeq +1$, we know of no way to establish this point rigorously.

If the forward peak in $\cos\theta_{pp}$ is intrinsic to the virtual process $\rho + p \rightarrow \pi + p$ at the energies relevant in the present experiment, the B enhancement occurs as a necessary kinematic consequence. To demonstrate this, the $M_{\pi-\omega}$ distribution for events with $\cos\theta_{pp} > 0.6$ is shown separately in Fig. 1(f); it contains essentially the entire B enhancement. For more detailed analysis the $M_{\pi-\omega}$ distributions for events in each $M_{p\pi^-}$ mass interval were plotted separately for $\cos\theta_{pp} = 0.6$ to 0.8 and 0.8 to 1.0 , and the number of B events estimated; these events are indicated by the shaded areas in Fig. 2. It is apparent that the B enhancement and the strong asymmetry in $\cos\theta_{pp}$ result from the same events.¹⁶

We conclude that the observed correlations are consistent with the model for the B enhancement suggested by Maor and O'Halloran.¹⁷ The low Δp^2 distribution in the B region is accounted for by the strongly peaked $\cos\theta_{pp}$ distribution resulting from the process $\rho + p \rightarrow \pi + p$. In particular, the model provides a natural explanation for the strong tendency of the B enhancement in our data to be associated with isobar production. We emphasize that existence of a genuine background cannot be ruled out; however, we are unable to find any aspect of the present data which requires this fortuitous circumstance.

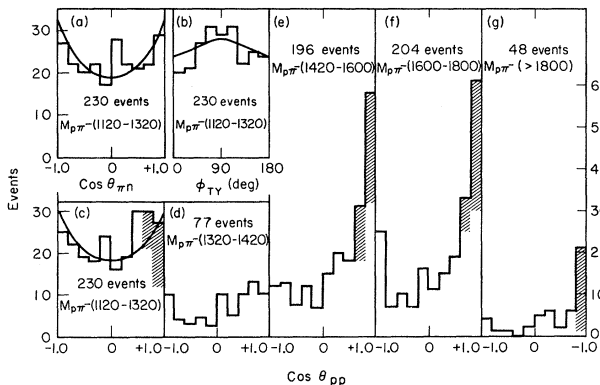


FIG. 2. Distributions in (a) $\cos\theta_{\pi n}$ and (b) $\phi_{\text{T\Y}}$ (see text) for $M_{p\pi^-}$ in the region of $N^*(1238)$. (c-g) Distributions in $\cos\theta_{pp}$ for various $M_{p\pi^-}$ intervals (in MeV). See the text for explanations of solid curves in (a), (b), and (c), and of the shaded areas in (c) through (g). Only single- ω events with $\Delta p\pi^{-2} < 1.0$ (GeV/c)² are plotted in these figures.

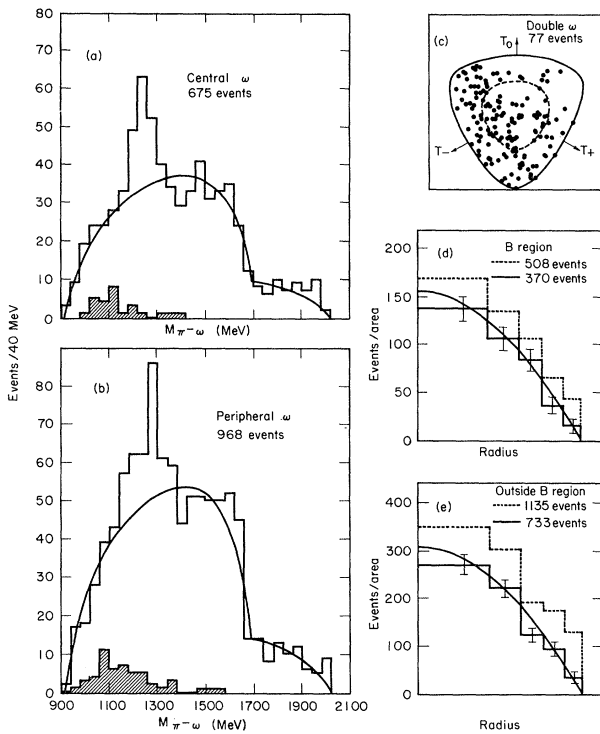


FIG. 3. The $M_{\pi^- \omega}$ spectra for the (a) central and (b) peripheral regions of the single- ω Dalitz plot. The shaded areas are for double- ω events. (c) Dalitz plot for double- ω events. For each event, two points are plotted for both combinations of neutral pion triplets. (d) Radial-density distributions of ω decay for the B region (1120 to 1300 MeV), and (e) outside the B region (no double- ω events). The dotted histograms represent the total number of ω events in each category; the solid histograms correspond to events with background subtracted (see text). Curves fitted to the solid histograms are those expected for the decay of a $J^P = 1^-$ resonance.

In the presence of background, the central region of the ω Dalitz plot should be richer in true ω events than the peripheral region.¹⁸ Goldhaber *et al.* observed a clear B enhancement for peripheral ω 's; within statistics, no enhancement was apparent for central ω 's.² In addition, the Dalitz plot density for ω 's associated with the B enhancement differed significantly from the theoretical prediction for a meson with $J^P = 1^-$.

The $M_{\pi^- \omega}$ distributions for the central and peripheral regions of the ω Dalitz plot are shown in Figs. 3(a) and 3(b). Within statistics, the number of B events above background for the central region (74 ± 15) and peripheral region (93 ± 20) are equal. When double- ω events

are included, the trend in the direction observed by Goldhaber *et al.* is enhanced; in this case the central ω region contains 81 ± 15 events and the peripheral region 116 ± 21 events.¹⁹ This is in part because double- ω events are kinematically constrained to lie in the lower left-hand part of the Dalitz plot as shown in Fig. 3(c). The detailed distribution within this region is presumably the result of Bose symmetrization.

The radial density distributions are given in Figs. 3(d) and 3(e) for single- ω events inside and outside the B enhancement. The background has been estimated from the $M_{\pi^+ \pi^0 \pi^-}$ spectrum plotted separately for each interval of r .¹⁸ Agreement with the theoretical curve is good in both cases.

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⁵This number includes 2498 measurements from a selected sample in which an outgoing proton could be identified on the scanning table. No significant differences were apparent in plots for the biased and unbiased samples in the region of interest, $\Delta p_{\pi^-} < 1.0$ (GeV/c)² (see text).

⁶In 77 events of our data both neutral pion triplets fall within the ω region (double- ω events). Since the

pion triplet corresponding to the ω cannot be identified, these events are not used in the present analysis; their distribution on the ω Dalitz plot is discussed later.

⁷J. D. Jackson, J. T. Donohue, K. Gottfried, R. Keyser, and B. E. Y. Svensson, Phys. Rev. **134**, B428 (1965).

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⁹An attempt to determine spin and parity has been described by D. D. Carmony, R. L. Lander, C. Rindfleisch, N. Xuong, and P. Yager, Phys. Rev. Letters **12**, 254 (1964).

¹⁰If B has $J^P = 1^-$, one obtains a branching ratio $\Gamma(B^\pm \rightarrow \pi^\pm + \pi^0)/\Gamma(B^\pm \rightarrow \pi^\pm + \omega) \approx 5$, assuming equal coupling constants for these two decay modes. The cross section for $\pi^- + p \rightarrow B^- + p$ with $B^- \rightarrow \pi^- + \pi^0$ is estimated to be $(0 \pm 20) \mu\text{b}$ based on 1940 events for the reaction $\pi^- + p \rightarrow \pi^0 + \pi^- + p$ at 3.2 GeV/c (L. D. Jacobs, Lawrence Radiation Laboratory, private communication). At the same energy, the cross section for $\pi^- + p \rightarrow B^- + p$ with $B^- \rightarrow \pi^- + \omega$ based on our data is approximately $(68 \pm 12) \mu\text{b}$ after correction for neutral decay of ω .

¹¹This feature can be seen more clearly with the 4.2-GeV/c data alone, where more phase space is available than at 3.2 GeV/c.

¹²M. Aderholz et al., Aachen-Berlin-Birmingham-Bonn-Hamburg-London (I. C.)-München Collaboration, Nuovo Cimento **35**, 659 (1965).

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¹⁴For the inverse reaction $\pi^- + p \rightarrow \rho^- + p$ at 1.25 GeV, E. Pickup, D. K. Robinson, and E. O. Salant, Phys. Rev. Letters **7**, 192 (1962), observed a strong peak at $\cos\theta_{pp} = +1$. The $\pi^- p$ c.m. energy, 1.8 GeV, corresponds to the highest mass interval observed in the present experiment.

¹⁵Recent analyses have indicated that both the $N^*(1518)$ and $N^*(1688)$ are probably superpositions of several closely spaced resonances [P. Bareyre, C. Bricman, A. Stirling, and G. Villet, Phys. Letters **18**, 342 (1965)]. For additional evidence regarding isobar excitation by ρ exchange, we have investigated the reaction $\pi^- + n \rightarrow p + \pi^- + \pi^-$ in deuterium at 3.2 GeV/c (to be published). Isobars (1238, 1518, 1688) are copiously produced at low $\Delta p \pi^{-2}$, suggesting ρ exchange. The distributions in $\cos\theta_{pp}$ for $N^{*0}(1518)$ and $N^{*0}(1688)$ showed strong peaks near $\cos\theta_{pp} = +1$.

¹⁶The forward peak in $\cos\theta_{pp}$ is associated with the B enhancement; consequently the nearly flat distribution of $\cos\theta_{pp}$ in the region of $N^*(1238)$ does not give rise to a strong B enhancement. The cluster of B events in $N^*(1238)$ region in Fig. 1(c) results from the selection $\Delta p^2 < 0.35 (\text{GeV}/c)^2$; this favors events in the region $\cos\theta_{pp} = +1$, which leads to an "exaggerated" B enhancement.

¹⁷M. A. Abolins, D. D. Carmony, R. L. Lander, N. Xuong, and P. M. Yager, in Proceedings of the Topical Conference on Resonant Particles, Ohio University, Athens, Ohio, 10-12 June 1965 (unpublished), p. 198, demonstrated that events in the final state $\omega + N^{*++}(1238)$ made no substantial contribution to the B enhancement. The origin of the enhancement was not investigated for higher mass $\pi^+ p$ systems.

¹⁸The central region of the Dalitz plot is defined by the condition $r = |M|^2/|M_{\text{max}}|^2 > 0.72$, and the peripheral region by $r < 0.72$, where M is the matrix element for ω decay, and M_{max} is its maximum value. With $J^P = 1^-$, equal numbers of ω events are expected in the two regions ($r = 0.72$ corresponds approximately to $\lambda = 0.07$ defined in Ref. 2).

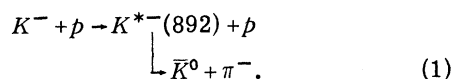
¹⁹In a recent compilation of $\pi^\pm \omega$ data, not including the present data, the anomaly discussed in Ref. 2 is less pronounced (G. Goldhaber, private communication). Although double- ω events were included, the number of B events in the central and peripheral regions were compatible within two standard deviations.

PRODUCTION AND DECAY PROPERTIES OF THE $K_0^*(892)$ PRODUCED IN THE REACTION $K^- + p \rightarrow \rho + \bar{K} + \pi^-$ AT 2.1, 2.45, AND 2.64 BeV/c*

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We have measured the total cross section, differential cross section, and $K^*(892)$ decay correlations for the reaction



Experimental decay distributions are consistent with the production and decay of a K^* relative-

ly free from interference with other processes. The 4300 K^* events in the sample allowed us to determine the decay correlations as a function of production angle. Comparison of these correlations with simple meson-exchange models imply that pseudoscalar-meson exchange dominates the extreme forward direction, while vector-meson exchange seems to be responsible for the decay correlations at larger angles.