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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] Moar and O'Halloran[4] 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 $M_{\pi^{\pm}\omega} \simeq 1200$ 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-in. hydrogen bubble chamber, 5112 events[5] 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. 1a; a strong concentration in the B region occurs only for events with low Δ^2 (four-momentum transfer squared) to the proton. This feature is emphasized further in Fig. 1b. The $M_{\pi^-\omega}$ distribution for all events shows the characteristic B enhancement in the region near 1220 MeV; a negligible reduction in the peak occurs when events with $\Delta_p^2 < 0.35\ (\mathrm{GeV/c})^2$ 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 distributions observed in peripheral interactions cannot be interpreted by using unmodified exchange models.[7] Nevertheless, in most experiments involving resonance production, interactions mediated by π exchange are concentrated at significantly lower Δ^2 values than those proceeding through ρ or ω exchange.[8] The observed Δ^2 distribution in the B region is characteristic of resonance production through π exchange (inset in Fig. 1a). In this case, possible spin-parity assignments would be $J^P = 1^-, 3^-$, 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 $J^P = 0^-, 1^+, 2^\pm, 3^+$, etc., the B can be produced only through ω exchange; in this case a broader Δ^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. 1c for events with $\Delta_p^2 < 0.35\ (\mathrm{GeV}/c)^2$. It is apparent that the B occurs most strongly in the $M_{p\pi^-}^2$ regions associated with isobars, i.e. $N^*(1238)$, $N^*(1518)$, and $N^*(1688)$. Consequently, should the B represent a valid resonance, π^-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 (inset in Fig. 1d) we consider first the Chew-Low plot for single-ω events given in Fig. 1d. Although partially obscured at higher mass values, it is apparent that isobar production is concentrated in the region[11] $\Delta_{p\pi^-}^2 < 1.0\ (\mathrm{GeV}/c)^2$; the $M_{p\pi^-}$ distribution for these events is given in Fig. 1e. The $\Delta_{p\pi^-}^2$ distributions are in qualitative agreement with those observed in other reactions involving exchange of vector mesons.[8] For subsequent analysis of the $\pi^-\omega p$ final state, only events with $\Delta_{p\pi^-}^2 < 1.0\ (\mathrm{GeV}/c)^2$ are used; 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 in $\cos\theta_{\pi n}$, Treiman-Yang angle ϕ_{TY}, and $\cos\theta_{pp}$ are given in Fig. 2 a, b, and 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 ϕ_{TY} is the associated azimuthal angle ($\phi_{TY} = 0$ in the production plane)]. The solid curves, which provide a reasonable fit to the present data, were obtained by Aderholz et al. in their analysis of the reaction $\pi^+p \rightarrow \pi^+\omega p$ at 4.0 BeV/c;[12] 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 $M_{p\pi^-}$ region accessible in the present experiment, strong contributions to the virtual process $\rho p \to \pi p$ 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. 2d through 2g. 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 $\rho p \to \pi p$ should lead to a peak at $\cos\theta_{pp} \simeq +1$;[14] 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.

With the reasonable assumption that the forward peak in $\cos\theta_{pp}$ is intrinsic to the virtual process $\rho p \to \pi p$ at the energies relevant in the present experiment, the B enhancement can be explained as a necessary kinematic consequence. To demonstrate this, the $M_{\pi^-\omega}$ distribution was plotted separately for events with $\cos\theta_{pp} < 0.6$; a negligible B enhancement was observed. The $M_{\pi^-\omega}$ distributions for events remaining 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 <u>same</u> events.[16]

We conclude that the observed correlations are consistent with the model for the B enhancement suggested by Moar and O'Halloran. The low Δ_p^2 distribution in the B region is accounted for by the strongly peaked $\cos\theta_{pp^-}$ distribution resulting from the process $\rho p \to \pi p$. 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.

In the presence of background, the central region of the ω Dalitz plot should be richer in true ω events than the peripheral region.[17] 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. 3a and 3b. 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.[18] This is in part because double-ω events are kinematically constrained to lie in the lower left part of the Dalitz plot as shown in Fig. 3c. The detailed distribution within this region is presumably the result of Bose symmetrization.

The radial density distributions are given in Figs. 3d and 3e 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.[17] Agreement with the theoretical curve is good in both cases.

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FOOTNOTES AND REFERENCES

*Work done under the auspices of the U. S. Atomic Energy Commission.

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2. G. Goldhaber, S. Goldhaber, J. A. Kadyk, and B. C. Shen, Phys. Rev. Letters 15, 118 (1965).
3. R. T. Deck, Phys. Rev. Letters 13, 169 (1964). Recent analyses of the A_1 tending to confirm the mechanism described in this paper have been reported by the Aachen-Berlin-Birmingham-Bonn-Hamburg-London (I. C.)-München collaboration, Phys. Rev. 138, B897 (1965); L. Seidlitz, O. I. Dahl, and D. H. Miller, Phys. Rev. Letters 15, 217 (1965); B. C. Shen, G. Goldhaber, S. Goldhaber, Phys. Rev. Letters 15, 731 (1965); V. E. Barnes, W. B. Fowler, K. W. Lai, S. Orenstein, D. Radajicic, M. S. Webster, A. H. Bachman, P. Baumel, and R. M. Lea, Phys. Rev. Letters 16, 41 (1966).
4. U. Maor and T. A. O'Halloran, Jr., Phys. Letters 15, 281 (1965).
5. This 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, $\Delta^2_{p\pi^-} < 1.0\ (\text{GeV}/c)^2$ (see text).

6. In 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.

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

8. See, for instance, the Aachen-Berlin-Birmingham-Bonn-Hamburg-London (I. C.)-München collaboration, Phys. Rev. 138, B897 (1965); H. O. Cohn, W. M. Bugg, and G. T. Condo, Phys. Letters 15, 344 (1965); S. Goldhaber, J. L. Brown, I. Butterworth, G. Goldhaber, A. A. Hirata, J. A. Kadyk, and G. H. Trilling, Phys. Rev. Letters 15, 737 (1965). See also reference 7.

9. An 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).

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

11. This 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.

12. Aachen-Berlin-Birmingham-Bonn-Hamburg-London (I. C.)-München collaboration, Nuovo Cimento 35, 659 (1965).

13. B. E. Y. Svensson, Nuovo Cimento 37, 714 (1965).

14. For the inverse reaction $\pi^- p \to \rho^- p$ at 1.25 GeV, E. Pickup, D. K. Robinson, and E. O. Salant, Phys. Rev. Letters 7, 192 (1962), observe 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.

15. Recent 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 $\pi^- n \to p\pi^-\pi^-$ in deuterium at 3.2 GeV/c (to be published). Isobars (1238, 1518, 1688) are copiously produced at low $\Delta^2_{p\pi^-}$, suggesting ρ exchange. The distributions in $\cos\theta_{pp}$ for $N^{*0}(1518)$ and $N^{*0}(1688)$ showed strong peaks near $\cos\theta_{pp} = +1$.

16. The 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 $\Delta^2_p < 0.35\ (\text{GeV}/c)^2$; this favors events in the region $\cos\theta_{pp}$ which leads to an "exaggerated" B enhancement.

17. The central region of the Dalitz plot is defined by the condition $r = |M|^2/|M_{max}|^2 > 0.72$, 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 reference 2).

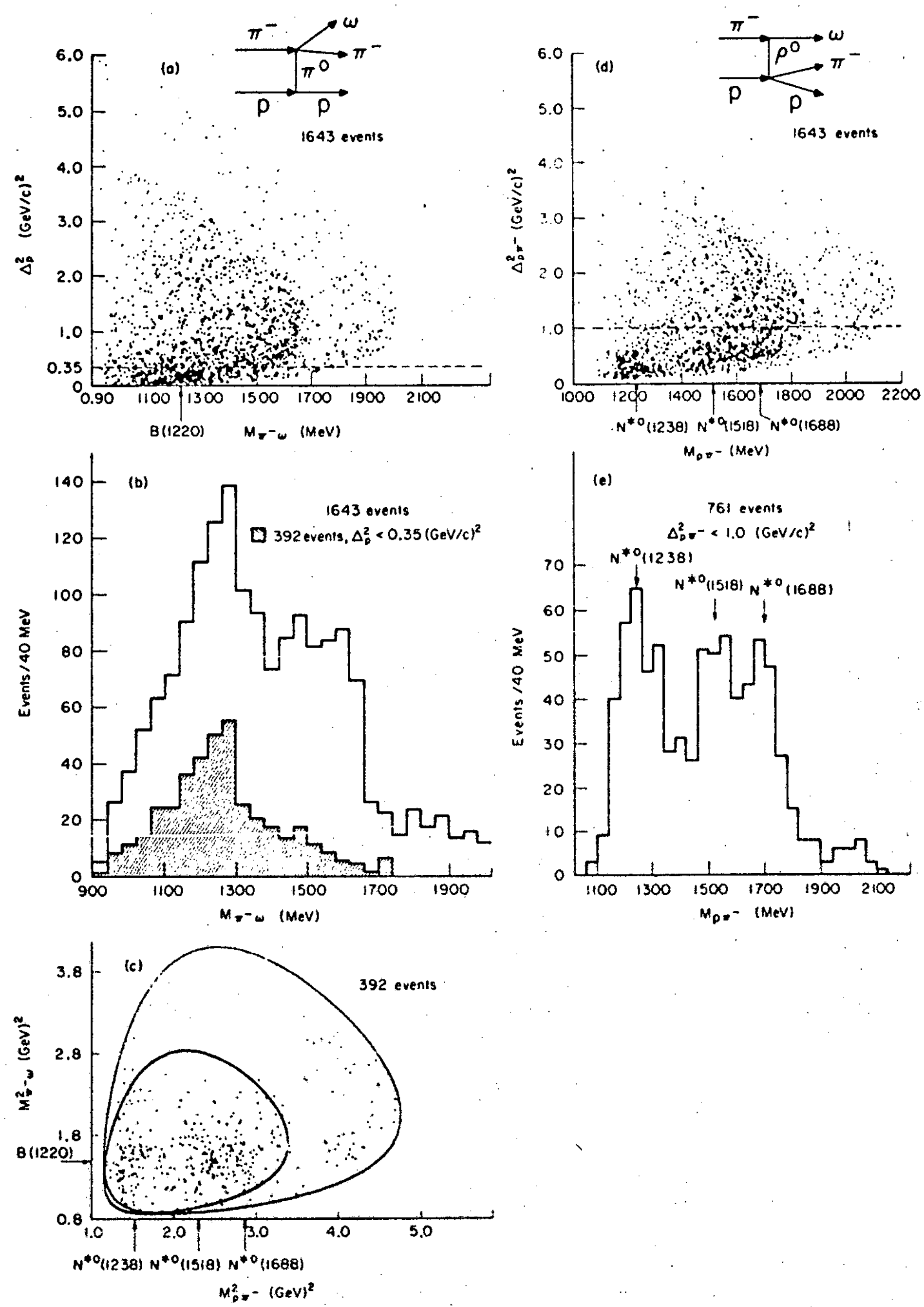
18. In a recent compilation of $\pi^{\pm}\omega$ data, not including the present data, the anomaly discussed in reference 2 is less pronounced (G. Goldhaber, private communication). Although double-ω events were included, the number of B events in the central and peripheral regions were compatible within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

FIGURE LEGENDS

Fig. 1. (a) The Chew-Low plot of Δ_p^2 vs $M_{\pi^-\omega}$ for single-ω events and (b) the projection onto the $M_{\pi^-\omega}$ axis. (c) The Dalitz plot of $M^2_{\pi^-\omega}$ vs $M^2_{p\pi^-}$ for single-ω events with $\Delta_p^2 < 0.35\ (\mathrm{GeV}/c)^2$. (d) The Chew-Low plot of $\Delta^2_{p\pi^-}$ vs $M_{p\pi^-}$ for single-ω events and (e) the projection onto the $M_{p\pi^-}$ axis for events with $\Delta^2_{p\pi^-} < 1.0$ $(\mathrm{GeV}/c)^2$.

Fig. 2. Distributions in (a) $\cos\theta_{\pi n}$ and (b) ϕ_{TY} (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), (c) and of the shaded areas in (c) through (g). Only single-ω events with $\Delta^2_{p\pi^-} < 1.0\ (\mathrm{GeV}/c)^2$ 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.



(a)
1643 events
Δ_p^2 (GeV/c)^2
B(1220)
$M_{\pi^-\omega}$ (MeV)
(b)
1643 events
392 events, Δ_p^2 < 0.35 (GeV/c)^2
Events/40 MeV
$M_{\pi^-\omega}$ (MeV)
(c)
392 events
$M^2_{\pi^-\omega}$ (GeV)^2
B(1220)
N*0(1238) N*0(1518) N*0(1688)
$M^2_{p\pi^-}$ (GeV)^2
(d)
1643 events
$\Delta^2_{p\pi^-}$ (GeV/c)^2
N*0(1238) N*0(1518) N*0(1688)
$M_{p\pi^-}$ (MeV)
(e)
761 events
$\Delta^2_{p\pi^-}$ < 1.0 (GeV/c)^2
N*0(1238)
N*0(1518) N*0(1688)
Events /40 MeV
$M_{p\pi^-}$ (MeV)

Fig. 1

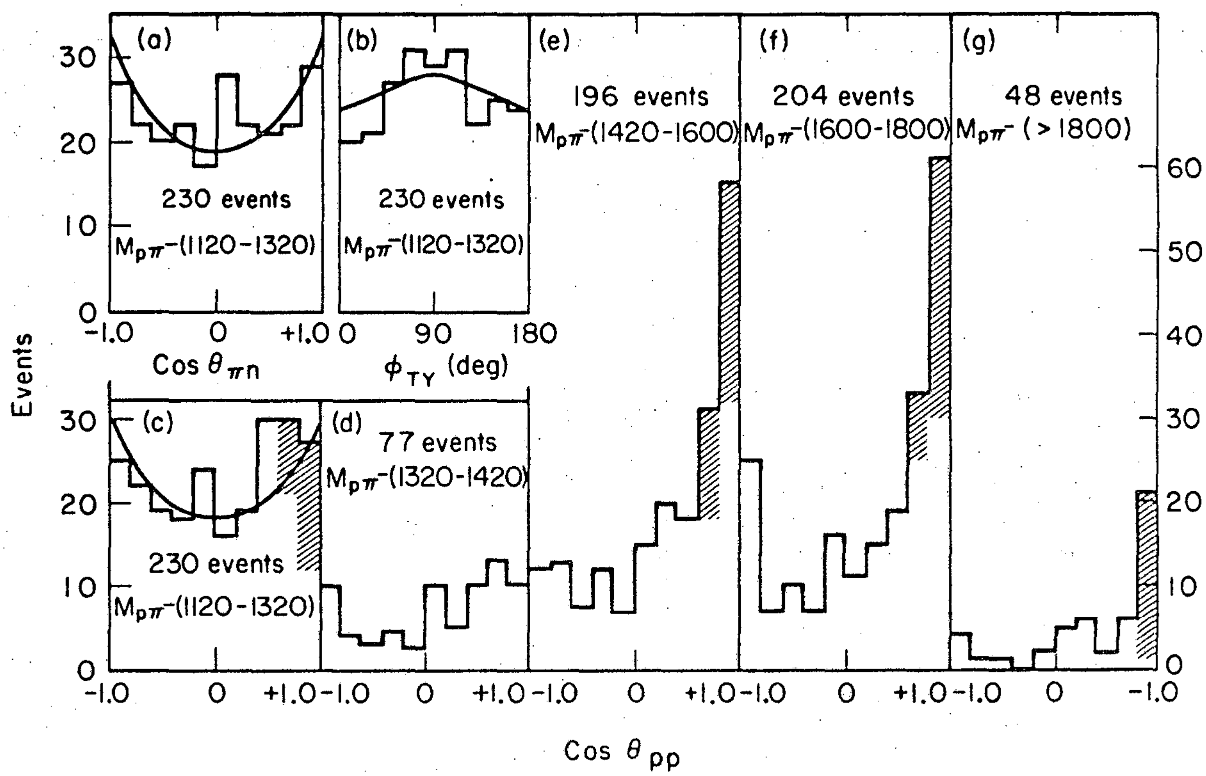


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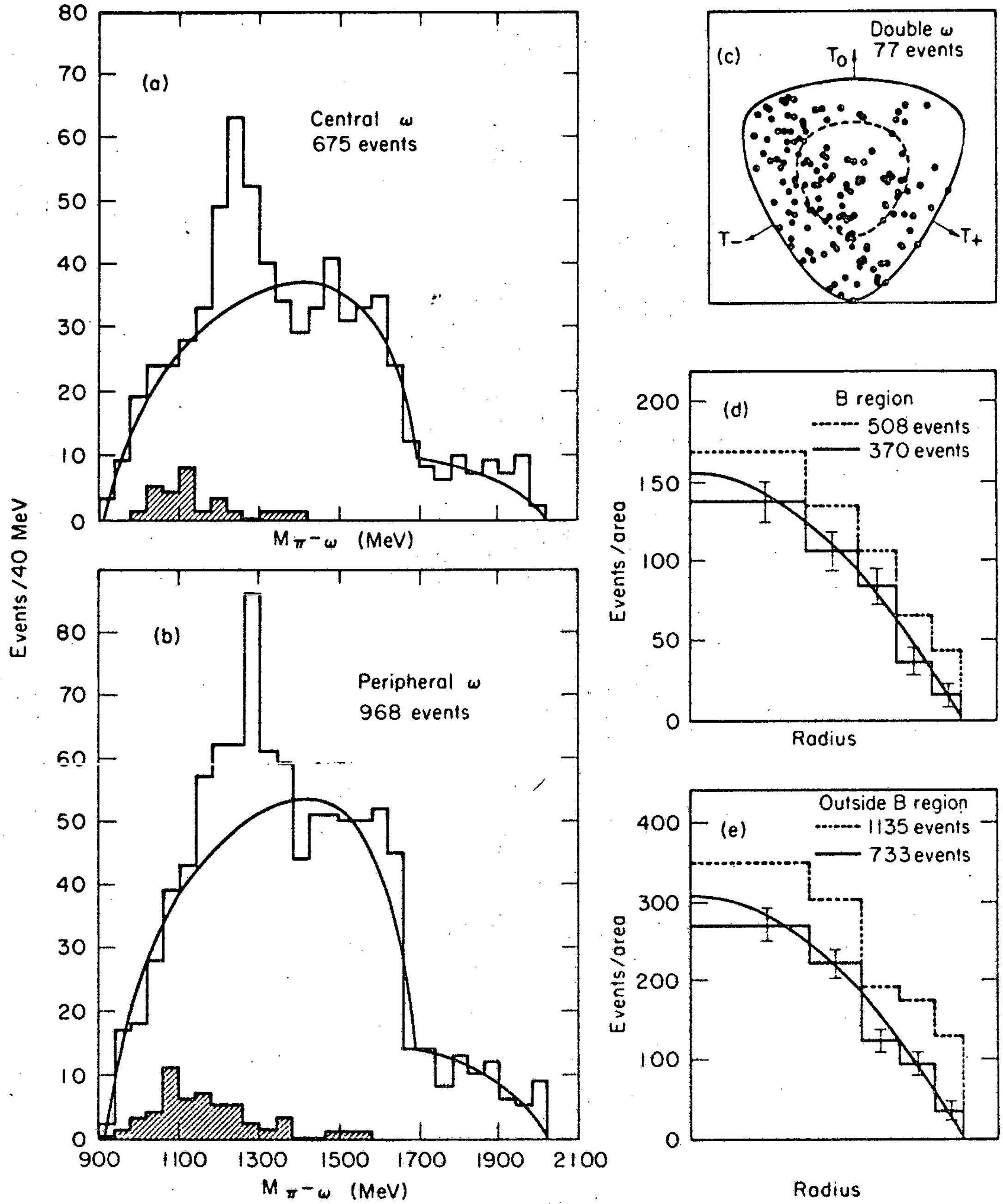
Fig. 2



Events/40 MeV
(a)
Central ω
675 events
$M_{\pi-\omega}$ (MeV)
(b)
Peripheral ω
968 events
900
1100
1300
1500
1700
1900
2100
$M_{\pi-\omega}$ (MeV)
(c)
Double ω
77 events
T_0
T_-
T_+
(d)
B region
508 events
370 events
Events/area
Radius
(e)
Outside B region
1135 events
733 events
Events/area
Radius
MUB-8938

Fig. 3