PHYSICAL REVIEW D VOLUME 10, NUMBER 11 1 DECEMBER 1974

Production and decay mechanism of the B meson and the $\omega\pi$ system in π^+p interactions at 5 GeV/c

U. Karshon, G. Mikenberg, Y. Eisenberg, S. Pitluck, E. E. Ronat, A. Shapira, and G. Yekutieli
Department of Nuclear Physics, Weizmann Institute of Science, Rehovot, Israel
(Received 19 February 1974)

The production and decay properties of the B meson are studied in the reaction $\pi^+p \to \omega\pi^+p$ at 5 GeV/c, where a cross section of 98 ± 16 μb is found for the final state pB^+. The production angular distribution of the B^+ shows a forward peak, a possible shoulder at $t' \sim 0.25$ GeV^2, and a small backward peak. The most likely spin-parity assignment for the B is found to be 1^+, and the D-wave fraction in the B decay is $\sim 11\%$. The differential cross section and density matrix elements of the B^+ suggest a dominant ω-exchange contribution. The suppression of A_2 exchange is also apparent in a study of the reaction $\pi^+p \to B^0\Delta^{++}$. We obtain for $t'_{p\Delta} < 1$ GeV^2 an estimated cross section of 15 ± 12 μb for $B^0\Delta^{++}$ production, which is about 5 times smaller than that of pB^+ at the same t' region. The reaction $\pi\pi \to \pi\omega$, extrapolated to the pion pole, is found to yield near the $\pi\omega$ threshold cross sections smaller than previously expected.

I. INTRODUCTION

Detailed results have recently been presented on the properties of the B meson from several $\pi^\pm N$ experiments.[1-7] Unlike some older results,[8] where the resonance interpretation of the B was dubious due to an anomaly in the ω Dalitz plot, or due to a "Deck"-type $\omega\pi$ kinematic enhancement, the recent experiments find that the B is a well-defined resonance with quantum numbers $I^{GC}=1^{+-}$ and $J^P=1^+$ or $2^+, 3^-, \ldots$ where 1^+ is favored. However, there are no reported results on the mechanism of the reaction $\pi^\pm p \to B^\pm p$ or on the final state $B^0\Delta^{++}$ from the "missing mass" $\Delta^{++}\pi^+\pi^-$MM events.

In this paper we present results on a study of the reactions

$$\pi^+p \to B^+p,\ B^+ \to \omega\pi^+,\ \omega \to \pi^+\pi^-\pi^0, \tag{1}$$

$$\pi^+p \to B^0\Delta^{++},\ B^0 \to \omega\pi^0,\ \omega \to \pi^+\pi^-\pi^0,\ \Delta^{++} \to p\pi^+, \tag{2}$$

at 4.93 GeV/c. Experimental details are given in Sec. II. Effective mass distributions and the values of the mass, width, and cross section for the B^+ are shown in Sec. III. In Secs. IV and V we describe the production and decay distributions of the B meson, respectively. The spin-parity of the B is discussed in Sec. VI. A detailed study of the production mechanism in reaction (1) is given in Sec. VII and the D-wave fraction of the B decay is calculated in Sec. VIII. Reaction (2) is described and discussed in Sec. IX and some implications concerning the reaction $\pi\pi \to \pi\omega$ are given in Sec. X. The conclusions are summarized in Sec. XI.

II. EXPERIMENT

The data for this study come from a complete subsample of ~320 000 pictures, which is ~40% of the final sample of a high-statistics experiment taken at the SLAC 82-in. hydrogen bubble-chamber exposed to a separated beam of π^+ mesons. The events were measured on the Weizmann Institute-Technion Spiral Reader and processed by the programs POOH-TVGP-SQUAW. After two measurements we obtained 8.36 ± 0.38 events/μb for the sample of successful 4-prong events. Applying appropriate cuts to clean the final sample,[9] we got 24094 events for the final state $\pi^+p\pi^+\pi^-\pi^0$ and 15765 unique events[10] for $\pi^+p\pi^+\pi^-$MM. The cross sections for these final states were found to be 2.93 ± 0.29 and 2.20 ± 0.30 mb, respectively, where the errors include systematic uncertainties.

III. EFFECTIVE MASS DISTRIBUTIONS

The effective mass distribution of $M(\pi^+\pi^-\pi^0)$ in the final state $\pi^+p\pi^+\pi^-\pi^0$ is plotted in Fig. 1. A very strong $\omega(784)$ signal is seen on top of a small background. [The background is only ~16% in the narrow ω band defined as $M(\pi^+\pi^-\pi^0)=0.76$–0.81 GeV.]

In Fig. 2(a) the mass distribution $M(\omega\pi^+)$ is given for the 5031 events with $M(\pi^+\pi^-\pi^0)$ in the ω region defined above. A strong B signal is clearly seen, and the background under it is significantly reduced by removing $\omega \to \pi_1^+\pi^-\pi^0$ events with $M(p\pi_2^+)$ in the Δ^{++} region [$M(p\pi_2^+)<1.4$ GeV] produced peripherally with $t'_{p\Delta}(=|t|-|t|_{\min})<1.0$ GeV^2 (shaded histogram). A good fit is obtained (full curve) by assuming a linear combination of an S-wave Jackson-type resonance shape for the B meson, reflection from the final state $\Delta^{++}\omega$, and

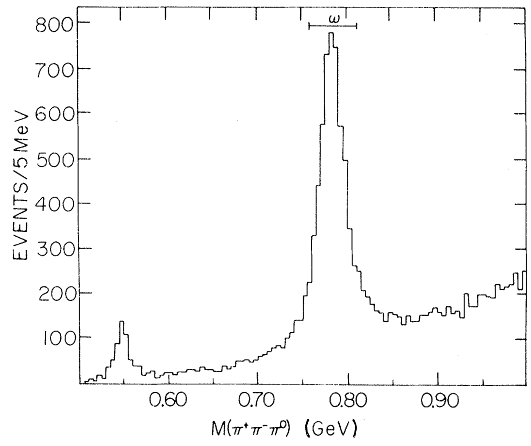

FIG. 1. The effective mass distribution $M(\pi^+\pi^-\pi^0)$ in the reaction $\pi^+p \to \pi^+p\,\pi^+\pi^-\pi^0$ (2 combinations per event).

an invariant phase space for $p\pi^+\omega$. The mass, width, and cross section[11] extracted from this fit are $M = 1220 \pm 7$ MeV, $\Gamma = 156 \pm 22$ MeV, and $\sigma(B^+) = 98 \pm 16$ μb, in good agreement with other recent results.[3-5] No anomaly in the ω Dalitz plot is found,[8] and the B signal appears strongly with ω's located at the center as well as at the periphery of the Dalitz plot. In cases where two $(\pi^+\pi^-\pi^0)$ combinations fall into the ω region (226 out of the 5031 ω events), we took for the forthcoming angular analysis the combination closer to the center of the ω Dalitz plot.

IV. PRODUCTION DISTRIBUTION

The differential cross section for reaction (1) is presented in Fig. 3(a) as function of t'_{pp} $(= |t| - |t|_{\min}$, where the average $|t|_{\min}$ at our energy is ~ 0.02 GeV^2). This distribution was obtained by fitting the $\omega\pi^+$ mass plot as above at various t' slices, but with fixed mass and width values for the B as obtained from the total fit. A B signal is seen

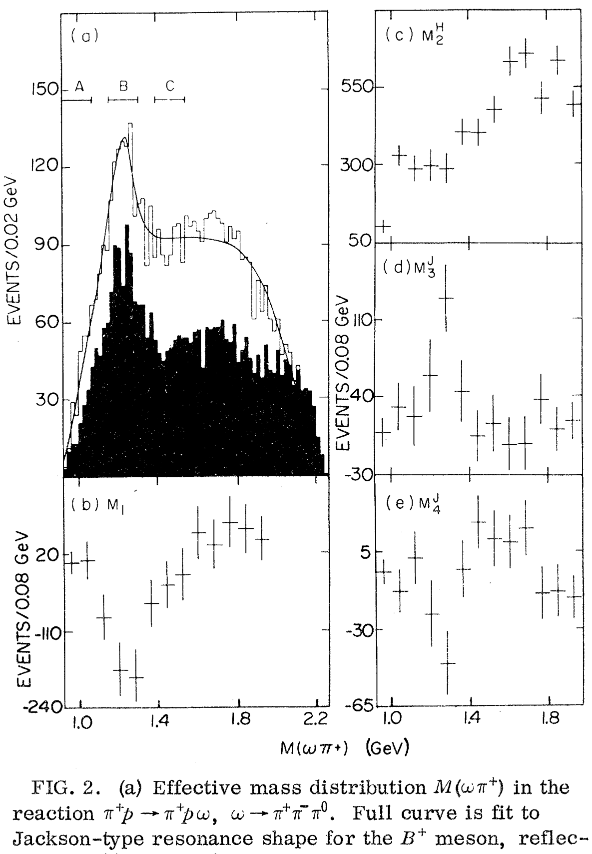

FIG. 2. (a) Effective mass distribution $M(\omega\pi^+)$ in the reaction $\pi^+p \to \pi^+p\omega$, $\omega \to \pi^+\pi^-\pi^0$. Full curve is fit to Jackson-type resonance shape for the B^+ meson, reflection of $\Delta^{++}\omega$ and $p\pi^+\omega$ phase-space. In the shaded plot the $\Delta^{++}\omega$ peripheral ($t'_{p\Delta} < 1$ GeV^2) events are removed. (b)–(e) Unnormalized moments $M_1 - M_4$, defined in text, as a function of $\omega\pi^+$ effective mass.

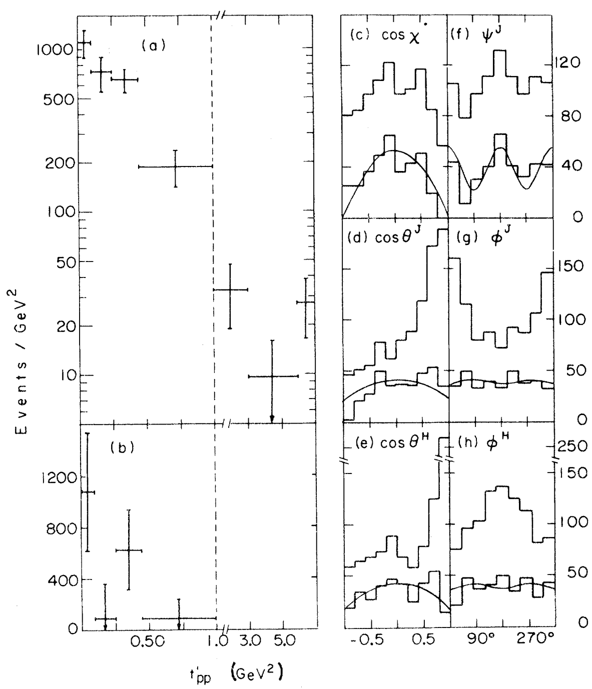

FIG. 3. (a) Differential cross section dN/dt' for the reaction $\pi^+p \to B^+p$ obtained by a background subtraction method described in text. Note the break in scale at $t' = 1$ GeV^2 (1 μb/GeV^2 = 6.0 events/GeV^2). (b) Helicity-nonflip contribution at the meson vertex of the differential cross section $\rho_{00}^H\, dN/dt'$ for the B meson, where ρ_{00}^H is calculated from the NSM M_2^H for all events [Table I(a)]. (c)–(h) Decay angular distributions cosχ, ψ, cosθ, ϕ in Jackson (J) and helicity (H) frames. Upper histograms include all events in the B region [$M(\omega\pi^+) = 1.16$–1.32 GeV]. Lower histograms are plotted after subtracting background distribution from control regions A and C of Fig. 2(a). The curves are obtained by inserting into Eqs. (10)–(13) the best values of the free parameters $|F_0|^2$, ρ_{00}, and ρ_{1-1} derived from the NSM ($M_1 - M_6$) for all events [Table I(a)].

at all t' values and the distribution has the following features: peripheral production consistent with meson exchange dominance peaked near $t'=0$ followed by a possible shoulder at $t'\sim 0.25$ GeV^2, and some backward (baryon-exchange) produced B ($4.8\pm 2.0\%$ of the total B signal) at $6<t'_{pp}<7$ GeV^2 which is equivalent to $u'_{pB^+}<0.8$ GeV^2.

V. DECAY DISTRIBUTIONS

We performed a sequential decay analysis of $B^+\to\omega\pi^+$, $\omega\to\pi^+\pi^-\pi^0$, using formulas and notations of Refs. 1 and 4. In this formalism the matrix element M for the decay of the B with spin and z projection (J, J_z) is given by

$$M(J,J_z)\sim\sum_{\lambda=0,\pm1}F_\lambda D^{J*}_{J_z\lambda}(\phi\theta 0)D^{1*}_{\lambda 0}(\psi\chi 0)\ , \qquad (3)$$

where F_λ are helicity amplitudes of the ω and $\sum_\lambda|F_\lambda|^2=1$. θ and ϕ are the polar and azimuthal angles, respectively, of the $\omega(\vec{p}_\omega)$ in the B rest frame. A right-handed coordinate system is chosen so that the z axis is either in the beam direction, i.e., Gottfried-Jackson (J) frame, or along the B direction in the c.m. system, i.e., helicity (H) frame; y is normal to the production plane, $\vec{y}=(\vec{\pi}_{\text{in}}\times\vec{B})$; χ and ψ are the polar and azimuthal angles, respectively, of the normal to the ω decay plane in the ω rest frame, measured in a system x', y', z', where $\vec{z}'=\vec{p}_\omega$ and $\vec{y}'=\vec{z}\times\vec{z}'$. In Fig. 3(c)–3(h) we plot the distributions of $\cos\chi$, ψ^J, $\cos\theta^J$, ϕ^J, $\cos\theta^H$, and ϕ^H. The upper histograms include all events in the B region [Fig. 2(a)], defined as $M(\omega\pi^+)=1.16$–1.32 GeV. Strong asymmetries are observed, mainly in the $\cos\theta$ plots, due to the Δ^{++} reflections. The lower histograms are plotted after subtracting the background distributions of the control regions A and C [Fig. 2(a)], defined between 0.92–1.08 and 1.40–1.56 GeV, respectively, with weights according to the fitted values of B and background in the B region. The subtracted distributions are quite symmetric within errors as expected for a well-defined J^P state.[12] These distributions are similar to others obtained by different methods of Δ^{++} removal, such as repopulation.[13] We thus justify this subtraction method as a tool to eliminate the strong Δ^{++} background.

From Eq. (3) the decay probability is given by[1,4]

$$\frac{d^4W}{d\cos\theta\, d\phi\, d\cos\chi\, d\psi}=\frac{3(2J+1)}{16\pi^2}\sum_{L,m,\lambda,m',\lambda'}(-1)^m\rho_{mm'}F^*_\lambda F_{\lambda'}C(JJL;\ -mm')C(JJL;\ -\lambda\lambda')D^L_{m'-m,\lambda'-\lambda}(\phi\theta\psi)\times d^1_{-\lambda 0}(\chi)d^1_{\lambda' 0}(\chi)\ , \qquad (4)$$

where $\rho_{mm'}$ refers to the density matrix of the B, and C's are Clebsch-Gordan coefficients.

In Figs. 2(b)–2(e) we present the dependence of the following moments on $M(\omega\pi)$:

$$M_1\equiv 5\langle d^2_{00}(\chi)\rangle=\tfrac{5}{2}\langle(3\cos^2\chi-1)\rangle=3|F_0|^2-1\ , \qquad (5)$$

$$M_2\equiv 5\langle D^2_{00}(\phi\theta\psi)\rangle=\tfrac{5}{2}\langle(3\cos^2\theta-1)\rangle=Q_J\left[\frac{|F_0|^2}{2|F_1|^2}+1-\frac{3}{J(J+1)}\right]\ , \qquad (6)$$

$$M_3\equiv 5\langle \operatorname{Re}D^2_{02}(\phi\theta\psi)\rangle=\tfrac{5}{4}\sqrt{6}\langle\sin^2\theta\cos 2\psi\rangle=-(-1)^J P(\tfrac{3}{8})^{1/2}Q_J\ , \qquad (7)$$

$$M_4\equiv-\tfrac{5}{4}\langle\sin^2\chi\cos 2\psi\rangle=\mp\tfrac{1}{2}|F_1|^2(3\rho_{00}-1)\quad\text{for } J^P=1^\pm\ . \qquad (8)$$

This is calculated by weighting various angular functions with the decay distribution (4). P is the parity of the B meson, and[1]

$$Q_J=\frac{5J(J+1)}{4J(J+1)-3}x\ ,$$

$$x=\left[1-\frac{3\langle J_z{}^2\rangle}{J(J+1)}\right]2|F_1|^2\ ,$$

$$\langle J_z{}^2\rangle=\sum_{m=-J}^{J}m^2\rho_{mm}\ . \qquad (9)$$

M_3 and M_4 are shown in the J frame, and M_2 in the H frame, since in these moments, structure is apparent[14] at the B region [Figs. 2(b)–2(e)], and thus we can use them, with appropriate background subtraction[12] as described above for Figs. 3(c)–3(h), to calculate the unknown parameters of (5)–(8). Since these moments are equal to the "symmetrized" moments of Chung *et al.*,[5] interference effects between opposite-parity states cancel out.

VI. SPIN-PARITY OF THE B

The helicity-zero decay probability of the ω derived from the normalized subtracted moment (NSM) M_1 is small [by averaging over the three methods of Table I (a)–(c), we obtain $|F_0|^2=0.8\pm 0.08$] in agreement with previous results.[1-5] This rules out $J^P=0^-$ for the B meson. Comparing the consistency of the results from moments M_2 and M_3 in the J frame, assuming different J^P assignments for the B meson, we obtain the follow-

TABLE I. Parameters for the sequential decay $B^+ \to \omega\pi^+$, $\omega \to \pi^+\pi^-\pi^0$ in various t' ranges obtained by different methods. 1. From normalized subtracted moments (NSM): (a) for all events; (b) for "repopulated" events (events with $\cos\theta^H > 0.65$ are excluded, and events with $\cos\theta^H < -0.65$ are taken twice); (c) for backward-hemisphere events (events in the hemisphere $\cos\theta^H > 0$ are excluded). 2. From fitting the lower histograms of Figs. 3(c)–3(h) to Eqs. (10)–(13) by the χ^2 method: (d) for the whole angular region; (e) with a cut (events with $\cos\theta^H > 0.6$ are excluded) to remove $\Delta^{++}\omega$ reflection. Errors are statistical only.

Parameter	Moment (Method of calculation)	χ^2 from Eq.	All t'	$t' < 0.1$	$0.1 < t' < 0.25$	$0.25 < t' < 0.45$	$0.45 < t' < 1$
	Number of B events		584 ± 70	110 ± 22	109 ± 27	130 ± 22	104 ± 27
$\lvert F_0\rvert^2$	M_1 (a)		0.01 ± 0.07	-0.09 ± 0.16	0.02 ± 0.15	0.06 ± 0.13	0.17 ± 0.17
	M_1 (b)		0.15 ± 0.07				
	M_1 (c)		0.09 ± 0.09				
		(10) (d)	0.01 ± 0.08				
ρ_{00}^J	M_3^J (a)		0.57 ± 0.08	0.50 ± 0.16	0.34 ± 0.17	0.54 ± 0.17	1.04 ± 0.25
	M_4^J (a)		0.61 ± 0.10				
		(11) (d)	0.56 ± 0.09				
		(12) (d)	0.88 ± 0.21				
ρ_{00}^H	M_2^H (a)		0.69 ± 0.18	0.98 ± 0.37	0.13 ± 0.37	0.97 ± 0.46	0.47 ± 0.75
	M_2^H (b)		0.80 ± 0.30				
	M_2^H (c)		0.85 ± 0.31				
	M_8^H (a)		0.33 ± 0.17	0.70 ± 0.37	-0.33 ± 0.41	0.69 ± 0.32	0.02 ± 0.44
		(12) (d)	0.59 ± 0.16	1.35 ± 0.63	0.35 ± 0.46	0.65 ± 0.33	0.37 ± 0.25
		(12) (e)	0.64 ± 0.16	1.54 ± 0.86	0.49 ± 0.54	0.71 ± 0.20	0.40 ± 0.32
ρ_{1-1}^J	M_5^J, M_6^J (a)		-0.06 ± 0.13				
		(13) (d)	-0.03 ± 0.09				
ρ_{1-1}^H	M_5^H, M_6^H (a)		-0.07 ± 0.14				
		(13) (d)	-0.06 ± 0.14				
$\mathrm{Re}\rho_{10}^J$	M_7^J (a)		-0.22 ± 0.12				
$\mathrm{Re}\rho_{10}^H$	M_7^H (a)		0.27 ± 0.12				

ing results in agreement with Refs. 1–5 (see Table II; similar results were obtained in the H frame): (a) $J^P = 1^-$, and the series $2^-, 3^+, \ldots$ are excluded due to disagreement between M_2 and M_3; (b) the series $2^+, 3^-, \ldots$ is acceptable but improbable since it gives exceptionally high $\langle J_z \rangle$ projections, in contrast with the nature of a peripheral reaction [Fig. 3(a)]. This series could be excluded provided $|F_0|^2$ were significantly different from zero (Chung *et al.*, in Ref. 5). However, this is not the case in our data (Table I).

VII. PRODUCTION MECHANISM

Assuming $J^P = 1^+$ as the most probable assignment for the B meson, we calculate from the normalized subtracted moments[13] the spin density matrix elements of the B, shown in Table I, for all B events and for various t' regions. Integrating Eq. (4) with respect to all but one variable at a time yields[4,5]

$$\frac{dW}{d\cos\chi} = \tfrac{1}{2}[1 + \tfrac{1}{2}(3|F_0|^2 - 1)(3\cos^2\chi - 1)] , \qquad (10)$$

$$\frac{dW}{d\psi} = \frac{1}{2\pi}[1 + |F_1|^2(3\rho_{00} - 1)\cos 2\psi] , \qquad (11)$$

$$\frac{dW}{d\cos\theta} = \frac{3}{2}\left[\frac{1 - 3|F_0|^2}{4}(1 - 3\rho_{00})\cos^2\theta + \tfrac{1}{4}(1 + |F_0|^2 + \rho_{00}(1 - 3|F_0|^2))\right] , \qquad (12)$$

TABLE II. Comparison between moments M_2^J and M_3^J and the spin projection $\langle J_z^2\rangle^{1/2}$ of the B meson for various J^P assignments. Errors are statistical only. x and $\langle J_z^2\rangle$ are defined in Eq. (9) and calculated from NSM for all events [Table I(a)]. χ^2 is given by $[x(M_2^J)-x(M_3^J)]^2/[(\Delta x(M_2^J))^2+(\Delta x(M_3^J))^2]$.

J^P	$x(M_2^J)$	$x(M_3^J)$	χ^2	x_{av}	$\langle J_z^2\rangle^{1/2}$
1^+	0.52 ± 0.24	0.35 ± 0.12	0.4	0.44 ± 0.11	0.61 ± 0.07
2^-	-0.70 ± 0.32	0.49 ± 0.17	10.8	...	...
3^+	-0.50 ± 0.23	0.53 ± 0.18	12.4	...	...
(∞)	-0.40 ± 0.18	0.56 ± 0.20	12.8	...	...
1^-	0.52 ± 0.24	-0.35 ± 0.12	9.2	...	...
2^+	-0.70 ± 0.32	-0.49 ± 0.17	0.3	-0.60 ± 0.15	1.80 ± 0.09
3^-	-0.50 ± 0.23	-0.53 ± 0.18	0.0	-0.52 ± 0.14	2.48 ± 0.12
(∞)	-0.40 ± 0.18	-0.56 ± 0.20	0.4	-0.48 ± 0.13	$(0.70\pm0.03)J$

$$\frac{dW}{d\phi}=\frac{1}{2\pi}\left[1+(1-3|F_0|^2)\rho_{1-1}\cos 2\phi\right] . \tag{13}$$

Inserting the best values of $|F_0|^2$, ρ_{00}, and ρ_{1-1} calculated from NSM for all events [Table I(a)], into (10)–(13) we obtain, after normalizing to the number of events, the smooth curves of Fig. 3(c)–3(h) in good agreement with the experimental distributions with background subtraction as described above (lower histograms).

The following features can be seen from Table I for all t's: (a) For the moments M_3^J, M_4^J, and M_2^H which show structure[14] in the B region [Figs. 2(c)–2(e)], high values of $\rho_{00}^J\sim0.6$ and $\rho_{00}^H\sim0.7$–0.8 are obtained. The first one is in agreement with Refs. 1, 2, 4, and 7; the second one is fairly consistent with Ref. 5 ($\rho_{00}^H=0.55\pm0.05$), but larger than that of Ref. 4 ($\rho_{00}^H=0.2\pm0.1$). (b) ρ_{1-1} is calculated as an average of the moments[4] $M_5\equiv\langle\sin^2\theta\cos2\phi\rangle=-0.4\,M_1\rho_{1-1}(J=1)$ and $M_6\equiv\langle\cos2\phi\rangle=-0.5M_1\rho_{1-1}(J=1)$, which do not show structure at the B region. It is small and slightly negative for both J and H frames. (c) $\mathrm{Re}\rho_{10}$ calculated from the moment $M_7\equiv\langle\sin2\theta\cos\phi\rangle=-0.4\sqrt{2}M_1\mathrm{Re}\rho_{10}(J=1)$ is quite large (~-0.25 and ~0.25 for the J and H frames, respectively). (d) The contribution of the unnatural-exchange part to the B production in the H frame, calculated from M_2^H and M_5^H, M_6^H (Table I), is $\sigma_1=(\rho_{11}+\rho_{1-1})^H=0.09\pm0.17$.

The possible exchanges in the peripheral reaction (1) are ω and A_2, which are believed[15] to contribute dominantly to helicity nonflip ($\Delta\lambda_B=0$) and flip ($\Delta\lambda_B=1$), respectively, at the baryon vertex. The distinct peak in the forward direction ($t'<0.1$ GeV^2) for the background-substracted B meson [Fig. 3(a)] precludes a strong contribution from the net helicity-flip amplitudes $\Delta\lambda\neq0$ due to parity angular momentum conservation.[16] Moreover, the high ρ_{00}^H value near $t'=0$ (Table I, column 5) is consistent with a dominant helicity-nonflip contribution at the meson vertex ($\Delta\lambda_M=0$), thus implying that ω exchange ($\Delta\lambda_B=0$) is the main contributor to reaction (1).

Further evidence for this conclusion can be obtained within the framework of the dual absorptive model (DAM)[15] by looking at the t' dependence of ρ_{00}^H. Using[14] the NSM M_2^H for all events [Table I(a)] to calculate ρ_{00}^H, one can see (Table I, column 6) substantial depletion at the region $0.1<t'<0.25$ GeV^2. This tendency is also seen when ρ_{00}^H is calculated from the related moment

$$M_8^H\equiv2.5\langle(3\cos^2\theta-1)(2.5\sin^2\chi-1)\rangle$$
$$=Q_J[1-3/J(J+1)] ,$$

where no structure is observed in the B region, as well as from fitting the lower histogram of Fig. 3(e) to Eq. (12) by the χ^2 method [Table I (d) and (e)]. In Fig. 3(b) we show, using M_2^H, the helicity-nonflip contribution at the meson vertex ($\Delta\lambda_M=0$) of the differential cross section $\rho_{00}^H dN/dt'$ for the background-subtracted B meson. The dip at ~0.2 GeV^2 as well as the forward peak are consistent with a strong contribution of $|J_0(R\sqrt{t'})|^2$, $R\approx1$ fermi, to the B^+ cross section, which in DAM comes from a net helicity-nonflip contribution $\Delta\lambda=0$, implying again $\Delta\lambda_B=0$ (ω exchange).

These results are inconsistent with Fox[17] who claims that the spin-flip contribution dominates reaction (1) at 5 GeV/c. In particular we do not agree with the conclusion of Ref. 17 that the peak near $t'=0$ is due to $\omega\pi(1^-)$ background underneath the B, produced by π exchange, rather than to the B itself, since the peak in our data, contrary to previous experiments,[4,5] comes from a background-subtracted procedure. Moreover, substantial contamination of π exchange in the B signal originating from $J^P=1^-$ yields $\rho_{00}^J=0.10\pm0.08$ and $\rho_{00}^J=0.05\pm0.09$ from M_3^J and M_4^J, respectively, which strongly contradicts the value of ~0.6 obtained from M_3^J and M_4^J with $J^P=1^+$ and from M_2^J which is parity-independent (see also Table II). We thus conclude that if the B structure is due to a combination of two objects[18]: $\alpha(J^P=1^-)+(1-\alpha)(J^P=1^+)$, then (a) if $\alpha\geq0.5$, $\rho_{00}(1^+)$ turns to be unphysical; (b) for $\alpha<0.5$, $\rho_{00}(1^+)\gg\rho_{00}(1^-)$, contrary to the result $\rho_{00}(1^+)\approx\rho_{00}(1^-)$ of Chung *et al.*[5]; (c) for $\rho_{00}(1^+)=\rho_{00}(1^-)$ the most probable value for α is zero with a 1-s.d. upper limit of $\alpha<0.2$. Similar results were obtained also for the region $t'<0.1$ GeV^2. The shape of Fig. 3(f) is also inconsistent with pure one-pion exchange (OPE) ($\rho_{00}^J=1$) originating from $J^P=1^-$ which should yield a ψ distribution [see Eqs. (8) and (11)] proportional to $(1-\cos2\psi)$. We also claim that π exchange originating from 1^- background is small in the vicinity of the B region since it should yield[1,4] $|F_0|^2=0$, thus widening the typical structure in the M_1 moment. We do not see such an effect and the width of the M_1 structure [Fig. 2(b)] is consistent with the width of the B [Fig. 2(a)].

VIII. FRACTION OF D WAVE

The fraction of D wave to S wave in the decay $B^+ \to \omega\pi^+$ was calculated by using the relations $F_0 = S - \sqrt{2}\,D$, $F_1 = S + D/\sqrt{2}$, and the expression (Lynch, Ref. 5)

$$3|F_0|^2 - 1 = [(D/S)^2 \mp 2\sqrt{2}(D/S)]/[1+(D/S)^2]\ ,$$

where D and S must be relatively real for a resonant state. Using our average value for $|F_0|^2 = 0.08 \pm 0.08$ we obtain two solutions for the D-wave fraction $F_D = |D|^2/(|D|^2+|S|^2)$: 0.11 ± 0.14 and 0.61 ± 0.14. The ambiguity between the solutions can be resolved if the sign of the interference term between F_0 and F_1 is known. From the value of $\mathrm{Re}F_0^* F_1$ calculated from the relevant moments[2,4] we have found a better consistency with a positive phase, in agreement with Refs. 5 and 7, thus preferring the first solution with the small F_D value.

IX. SEARCH FOR $B^0\Delta^{++}$ PRODUCTION

To get more information on the B production mechanism, we have looked at the $I_z = 0$ $\omega\pi^0$ state, where the B cannot be produced by ω exchange, in reaction (2) which contains two neutrals. Due to the narrowness of the ω, we can obtain a better estimate of the cross section by using simple kinematical considerations to constrain the channel:

$$\pi^+ p \to \Delta^{++}\pi^+\pi^-\mathrm{MM},\quad \Delta^{++}\to p\pi^+,\quad \mathrm{MM} \geq 2m_{\pi^0}\ . \tag{14}$$

Assuming that (a) we have only two π^0's: π^0_ω and π^0_2, and (b) the ω has zero width,[19] one can express[20] in the $\pi^+\pi^-$MM or equivalently in the $\omega\pi^0$ frame the absolute value of the momentum of each π^0 as well as the cosine of the angle between the two π^0's in terms of measurable quantities:

$$|\vec{P}_{\pi^0_2}|^2 \equiv |\vec{P}_\omega|^2 = \frac{M(\omega\pi^0)^2}{4} + \frac{(m_\omega{}^2 - m_{\pi^0}{}^2)^2}{4M(\omega\pi^0)^2} - \frac{m_\omega{}^2 + m_{\pi^0}{}^2}{2}\ , \tag{15}$$

$$|\vec{P}_{\pi^0_\omega}|^2 = [E_{\mathrm{MM}} - (|\vec{P}_{\pi^0_2}|^2 + m_{\pi^0}{}^2)^{1/2}]^2 - m_{\pi^0}{}^2, \tag{16}$$

$$\cos(\vec{\pi}^0_\omega, \vec{\pi}^0_2) = \frac{|\vec{P}_{\mathrm{MM}}|^2 - |\vec{P}_{\pi^0_\omega}|^2 - |\vec{P}_{\pi^0_2}|^2}{2|\vec{P}_{\pi^0_\omega}|\,|\vec{P}_{\pi^0_2}|}\ , \tag{17}$$

where E_{MM} and $\vec{P}_{\mathrm{MM}}$ are the missing energy and 3-momentum in reaction (14). The component $\omega\pi^0_2$ in the effective-mass combination $M(\pi^+\pi^-\mathrm{MM})$ is thus enhanced by requiring the cuts

$$|\vec{P}_{\pi^0_2}|^2 > 0,\quad |\vec{P}_{\pi^0_\omega}|^2 > 0,\quad |\cos(\vec{\pi}^0_\omega, \vec{\pi}^0_2)| \leq 1\ . \tag{18}$$

The $(\pi^+\pi^-\mathrm{MM})$ mass plot of reaction (14) for events satisfying the above-mentioned cuts[21] is shown in Fig. 4(a), where we have imposed a t' cut between the target and the Δ^{++} of 1.0 GeV^2 and a Δ^{++} cut of 1.16–1.28 GeV. A significant signal (~6 s.d.) is seen at a mass (1274 ± 7 MeV) higher than the mass of the B and is probably due to the f^0 decaying into $\pi^+\pi^-\pi^0\pi^0$, which is not removed by the ω cuts (18) since the $M(\pi^+\pi^-\pi^0)$ coming from the f^0 decay strongly overlaps with the ω mass. Other possibilities are that the signal is due to (a) $D \to \eta_N\pi^+\pi^-$ ($\eta_N \to$ neutrals), but when we plot the MM for the 1300-MeV signal we do not see any η_N; (b) $A_2^0 \to \eta_c\pi^0(\eta_c \to \pi^+\pi^-\pi^0)$, but since the method used to enhance the $\omega\pi^0$ final state can also be used to enhance the $\eta_c\pi^0$ final state, we have looked at the overlapping region between the two, and no signal at 1300 MeV can be seen. Thus, the signal comes most probably from the f^0 and/or B^0.

Since we see an $f^0 \to \pi^+\pi^+\pi^-\pi^-$ signal in the final state

$$\pi^+ p \to \Delta^{++}\pi^+\pi^-\pi^+\pi^-,\quad \Delta^{++}\to p\pi^+ \tag{19}$$

we have faked the $\omega\pi^0$ cuts (18) on this final state, assuming that two identical pions are unmeasured, and fitted it to an f^0 resonance plus background. Assuming a ratio[22] of $(f \to \pi^+\pi^-\pi^0\pi^0)/(f \to \pi^+\pi^+\pi^-\pi^-) = 2$, we have subtracted the appropriate amount of

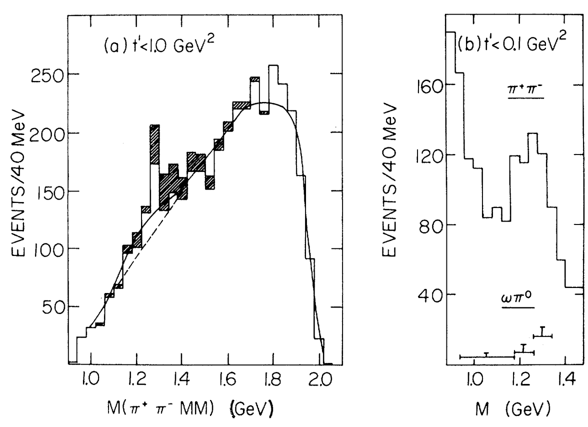

FIG. 4. (a) $\pi^+\pi^-$MM spectrum of reaction (14) for events with $t'_{p\Delta} < 1$ GeV^2 consistent with having an $\omega\pi^0$ final state according to the cuts (18) described in text. Events in shaded histograms are due to $f^0 \to \pi^+\pi^-\pi^0\pi^0$ (see text). Solid curve is fit of the unshaded events to B meson plus background which is estimated by the dashed line. (b) Effective mass distribution of $\pi^+\pi^-$ in the final state $\Delta^{++}\pi^+\pi^-$ (upper histogram) compared with upper limit for $\omega\pi^0$ events (lower part) extracted from the final state $\Delta^{++}\pi^+\pi^-$MM as described in text. Both distributions are for the π-exchange dominated region $t'_{p\Delta} < 0.1$ GeV^2.

f^0 from the $\pi^+\pi^-$MM channel, as shown in the shaded part of Fig. 4(a). Only a small residual signal is apparent and the unshaded histogram was further fitted to a B meson resonance with fixed M, Γ values as found in reaction (1) plus hand-drawn background. The solid curve in Fig. 4(a) describes the over-all fit, and the dashed line gives the background estimate. We thus obtain an estimate for reaction (2) for $t'_{p\Delta} < 1$ GeV^2 of 69 ± 58 events, corresponding to a cross section[11] of 15 ± 12 μb, which is smaller but not inconsistent with that given in Ref. 6. The errors include systematic uncertainties in the estimate of the background under the B^0. Comparing with the number of B^+ events of reaction (1) for $t'_{pp} < 1$ GeV^2 (Table I) we obtain 0.19 ± 0.16 for the ratio of $\Delta^{++}B^0/pB^+$.

X. $\pi\pi \to \pi\omega$

We have seen earlier that B^+-resonance production is dominant in the low-mass $\omega\pi$ system in reaction (1) thus masking any π-exchange background underneath it. A better place to study the π-exchange contribution to the $\omega\pi$ system near threshold is in reaction (14), where the B^0 production was found to be small. Since the $\omega\pi$ system in the reaction

$$\pi^+ \text{“}\pi^-\text{”} \to \omega\pi^0 \tag{20}$$

can be coupled only to $J^P = 1^-, 3^-, \ldots,$ it turns out[1,4] that $|F_0|^2 = 0$.

Following the cuts (18) which were imposed to enhance the $\omega\pi^0$ content in reaction (14), we can boost π^0_ω from the $\omega\pi^0_2$ to the ω rest frame and obtain the angle between π^0_ω and the ω direction: $\cos(\vec{\pi}^0_\omega, \vec{\omega})_\omega$. This quantity was calculated[20] and found to have a well-defined distribution for events with $|F_0|^2 = 0$:

$$W[\cos(\vec{\pi}^0_\omega, \vec{\omega})_\omega] = 0.32[1 + 1.7\cos^2(\vec{\pi}^0_\omega, \vec{\omega})_\omega] \; . \tag{21}$$

Comparing the experimental $\cos(\vec{\pi}^0_\omega, \vec{\omega})_\omega$ distributions for various $\omega\pi^0$ mass slices with the predicted one (21), we get after appropriate subtraction of the $f^0 \to 4\pi$ signal a better upper limit for the number of $\omega\pi^0$ events[23] produced with $|F_0|^2 = 0$. This upper limit near the $\omega\pi$ threshold region is shown for the π-exchange dominated region $t'_{p\Delta} < 0.1$ GeV^2 in the lower part of Fig. 4(b) as compared with the "elastic" π^+"π"$\to \pi^+\pi^-$ off-mass-shell reaction produced in the final state $\Delta^{++}\pi^+\pi^-$ with the same t' cut.

This comparison can be further converted into an upper limit for reaction (20) on the mass shell by assuming that the extrapolation to the pion pole is the same for both reactions. Using the extrapolated values obtained by Ref. 24 for the reaction $\pi^+\pi^- \to \pi^+\pi^-$, we obtain upper limits for $\sigma(\pi^+\pi^- \to \omega\pi^0)$ of $\sigma \leq 0.68$, 1.37, and 3.53 mb for $E_{\text{c.m.}}(\pi^+\pi^- \to \omega\pi^0)$ averaged over the intervals 0.92–1.18, 1.18–1.26, and 1.26–1.34 GeV, respectively.

The low cross section of reaction (20) and its slow rise contradicts previous works that have considered it as a main contributor to the background under the $B^\pm$,[17] and to the fast rise of the $\pi^+\pi^-$MM mass spectra[24] near threshold in reaction (14) as compared to the slow rise of $M(\pi^+\pi^-\pi^+\pi^-)$ in reaction (19). We thus conclude that this fast rise comes mainly from other final states rather than from $\omega\pi^0$.

To further check our result, we have looked for the SU(3) symmetric reaction $\pi^+\pi^- \to \eta\rho^0$ that can be obtained from $\pi^+p \to \Delta^{++}\eta_c\pi_1^+\pi_1^-$; $\eta_c \to \pi_2^+\pi_2^-\pi^0$, where clear η_c and Δ^{++} signals have been seen[9]; however, when we plot the $\pi_1^+\pi_1^-$ mass spectra after selecting events in the η_c and Δ^{++} regions, no ρ^0 signal is seen, thus supporting our $\omega\pi^0$ result.

The upper limit for reaction (20) in the first $\omega\pi^0$ mass slice can be compared with the number of $\rho^0 \to \pi^+\pi^-$ events in the final state $\Delta^{++}\pi^+\pi^-$ for the same mass and $t'_{p\Delta}$ slices after appropriate subtraction of S and D waves.[25] We then get a lower limit for the $I=1$, $J^P = 1^-$ partial-wave elasticity of $\eta_1^1 \geq 0.92$ for the $\omega\pi^0$ mass interval 0.92–1.18 GeV, in agreement with the value $\eta_1^1 = 0.98 \pm 0.05$ of Protopopescu *et al.*.[24] However, in Ref. 24, a large inelasticity is obtained for the $\pi^+\pi^- \to \pi^+\pi^-$ F wave ($J^P = 3^-$) above the $\omega\pi$ threshold. Our small upper limit for reaction (20) in the first mass slice indicates that this result cannot be connected with the $\omega\pi^0$ channel and is possibly due to other effects.

XI. SUMMARY AND CONCLUSIONS

We have studied the production of the B meson in the reaction $\pi^+p \to p\pi^+\omega$ at 5 GeV/c. Strong contamination of the quasi-two-body final state $\Delta^{++}\omega$ is apparent, but does not seem to seriously disturb the analysis of the B, since background subtraction yields fairly symmetric angular distributions which are similar to results obtained by repopulation and other methods. We get a cross section of 98 ± 16 μb for the final state pB^+, and peripheral production angular distribution consistent with dominant meson exchange. A small backward produced B^+ also exists and will be discussed at a later stage with improved statistics. The helicity-zero decay probability of the ω, $|F_0|^2$, is small ($\sim 0.08 \pm 0.08$) in agreement with previous results. The favored spin-parity assignment for the B is $J^P = 1^+$ although the natural series $2^+, 3^-, \ldots$ cannot be ruled out, and the fraction of D wave is 0.11 ± 0.17. The forward part of the reaction is consistent with a dominant ω-exchange contribution, since ρ_{00} is large, dN/dt' has a distinct forward peak, and $\rho_{00}^H\, dN/dt'$ has a shape similar to the $|J_0|^2$ Bessel function, implying $\Delta\lambda = \Delta\lambda_M = \Delta\lambda_B = 0$. The unnatural-exchange contribution σ_1 of the B production, found to be consistent with zero, indicates that the contribution of cuts to σ_1 is small, since no known pole of the unnatural series can be exchanged.

The suppression of the A_2 exchange part is further substantiated in the study of the final state $B^0\Delta^{++}$ by using the kinematical constraints of the $\omega\pi^0$ part in the $\pi^+\pi^-$MM spectrum. We obtain for $t'_{p\Delta} < 1$ GeV^2 an estimate of 15 ± 12 μb for $B^0\Delta^{++}$, as compared with 38 ± 14 μb at 7 GeV/c inferred from the reaction[6] $\pi^- n \to B^-\Delta^0$ which is $\frac{2}{3}$ of our reaction by isospin conservation.[26] This yields a ratio of 0.19 ± 0.16 for $\Delta^{++}B^0/pB$ at 5 GeV/c, remarkably different from ratios such as $\Delta^{++}\rho^0/p\rho^+$ or $\Delta^{++}A_2^0/pA_2^+$ which are[27] of the order of 1. The upper limit obtained for the reaction π^+"π^-"$\to \pi^0\omega$ near the threshold region is also smaller than expected from previous works.[17,24]

ACKNOWLEDGMENTS

We wish to thank SLAC and the 82-in. HBC crew for their assistance in obtaining the exposure, and LBL for their help in the construction of our Spiral Reader. We are grateful to our engineers, technicians, programmers, and scanners for their devoted efforts in operating the Spiral Reader and the data reduction system.

[1] G. Ascoli, H. B. Crawley, D. W. Mortara, and A. Shapiro, Phys. Rev. Lett. 20, 1411 (1968).

[2] A. Werbrouck, G. Rinaudo, R. T. Van de Walle, D. J. Schotanus, C. L. Pols, N. Stief, G. Gidal, and D. Brown, Nuovo Cimento Lett. 4, 1267 (1970).

[3] I. A. Erofeev *et al.*, Yad. Fiz. 11, 805 (1970) [Sov. J. Nucl. Phys. 11, 450 (1970)].

[4] M. Afzal *et al.*, Nuovo Cimento 15A, 61 (1973).

[5] R. L. Ott, Ph.D. thesis, LBL Report No. LBL-1547, 1972 (unpublished); and preliminary reports by G. R. Lynch [LBL report (unpublished)] and S. U. Chang *et al.* [BNL Report No. 18340, 1973 (unpublished)].

[6] D. Cohen, T. Ferbel, and P. Slattery, Phys. Rev. D 8, 23 (1973).

[7] V. Chaloupka, CERN Report No. CERN/D.Ph. II/PHYS 73-33, 1973 (unpublished).

[8] G. Goldhaber, S. Goldhaber, J. A. Kadyk, and B. C. Chen, Phys. Rev. Lett. 15, 118 (1965); S. U. Chung, O. I. Dahl, J. Kirz, and D. H. Miller, Phys. Rev. 165, 1491 (1968).

[9] Z. Carmel *et al.*, report at the XVI International Conference on High Energy Physics, Chicago-Batavia, 1972 (unpublished); Wis-72/28-Ph Report No. (unpublished); Y. Eisenberg *et al.*, paper submitted to the Second Aix-en-Provence International Conference on Elementary Particles, 1973 (unpublished).

[10] Events ambiguous between this channel and other final states do not contribute to low momentum transfer ($t_{p\Delta}$) events relevant to this study.

[11] The B^+ and B^0 cross sections in reactions (1) and (2) are corrected for the tails outside the ω cut by factors of 1.23 and 1.05 [see Ref. 19(b)] respectively, and for the other decay modes of the ω by a factor of 1.12 [Particle Data Group, Rev. Mod. Phys. 45, S1 (1973)]. The B^0 cross section is also corrected for the Δ^{++} tails by the factor 1.5. The results of fitting reaction (1) are insensitive to the exact shape of the resonance [Breit-Wigner or Jackson-type shape; see J. D. Jackson, Nuovo Cimento 34, 1644 (1964)].

[12] Our subtraction method assumes that the structure in the B region is due to a unique spin-parity state. Recently, more refined analyses have been done (Refs. 5 and 7), where the various partial waves of the $\omega\pi$ system have been separated. The results in both methods for the same data (Chung *et al.* and Lynch, Ref. 5) were found to be very similar, indicating that the assumption of a unique J^P state is reasonable.

[13] Similar results were obtained by repeating the angular analysis with the repopulation method [P. Eberhard and M. Pripstein, Phys. Rev. Lett. 10, 351 (1963)]. See also G. R. Lynch and Chung *et al.*, in Ref. 5, where events with $\cos\theta^H > 0.65$ are excluded and events with $\cos\theta^H < -0.65$ are given weight of two as well as by confining the analysis to the region $\cos\theta^H < 0$ [Table I (b) and (c)]. Consistent results are also obtained by fitting the lower histograms of Figs. 3(c)–3(h) to Eqs. (10)–(13) by the χ^2 method, for the whole angular region and for $\cos\theta^H < 0.6$, where there is no $\Delta^{++}\omega$ reflection [Table I (d) and (e)].

[14] The structure in the B region in the unnormalized moment M_2^H [Fig. 2(c)] is somewhat marginal; however, it is much stronger in the normalized moment and also in the t' region where ρ_{00}^H is high ($t' < 0.1$ and $0.25 < t' < 0.45$ GeV^2; see Table I) in both the normalized and unnormalized moments.

[15] See, for example, H. Harari, Phys. Rev. Lett. 26, 1400 (1971); H. Harari, Ann. Phys. (N.Y.) 63, 432 (1971); H. Harari and A. Schwimmer, Phys. Rev. D 5, 2780 (1972).

[16] The turnover in t' distributions for reactions dominated by $\Delta\lambda = \pm 1$ amplitudes is typically at $t' \sim 0.1$–0.15 GeV^2 (e.g., $\pi^+ p \to \eta\Delta^{++}$ or $\eta'\Delta^{++}$, Ref. 9).

[17] G. C. Fox, in *Experimental Meson Spectroscopy*, proceedings of the third international conference on experimental meson spectroscopy, Philadelphia, 1972, edited by Kwan-Wu Lai and Arthur H. Rosenfeld (A.I.P., New York, 1972); Nucl. Phys. B56, 386 (1973).

[18] P. Frenkiel *et al.*, Nucl. Phys. B47, 61 (1972).

[19] (a) By comparing the number of e^+e^- pairs in the 1C channel to that of the 0C, we obtain for the latter $\langle n_{\pi^0} \rangle \approx 2.2$. (b) Less than 5% of the true ω's are lost due to the experimental width in the ω region in the MM

channel.

[20]G. Mikenberg, Phys. Rev. D 10, 3889 (1974).

[21]The above-mentioned cuts reduce the number of events of reaction (14) from 10230 to 4443 events.

[22]G. Ascoli *et al.*, Phys. Rev. Lett. 21, 1712 (1968); J. C. Anderson *et al.*, *ibid.* 31, 562 (1973).

[23]Note that $\omega\pi^0$ states with $J^P = 2^+, 4^+, \ldots$ are also enhanced by the requirement $|F_0|^2 = 0$, but they cannot be produced by pion exchange.

[24]S. D. Protopopescu *et al.*, Phys. Rev. D 7, 1279 (1973).

[25]Y. Eisenberg, B. Haber, U. Karshon, J. Mikenberg, S. Pitluck, E. E. Ronat, A. Shapira, and G. Yekutieli, Phys. Lett. 48B, 354 (1974).

[26]Note, however, that the extraction of $B^-\Delta^0$ in Ref. 6 from the final state $\omega\pi^-\pi^-p$ is difficult, since their Δ^0 signal [Fig. 2(b) of Ref. 6] is very narrow (one bin of 40-MeV width).

[27]D. J. Schotanus *et al.*, Nucl. Phys. B22, 45 (1970); C. L. Pols *et al.*, *ibid.* B25, 109 (1970).