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A Spin-Parity Analysis of the B Meson

D. Mortara, G. Ascoli, H. B. Crawley, and A. Shapiro

Department of Physics, University of Illinois, Urbana, Illinois

We report here on a study of the $\omega \pi^+ p$ final state produced by
5 BeV/c π^- mesons in the 72" HBC. The sample consists of 1571 events which
fit the reaction (1)

Candidates for reaction (1) were first obtained by fitting 4-prong events
to the reaction (2)

Providing this fit was successful, a two-step fit to ω production was
attempted, yielding a 2-constraint χ^2 . An event was considered an ω candidate
if the confidence level for the 1-constraint fit to reaction (2) was less than
3 times the corresponding confidence level for the 2-constraint fit to
reaction (1). The factor of 3 reflects the ratio of ω production to back-
ground 3 pion masses in the region of the ω . The actual ratio is approximately
4 or 5. All ω candidates were screened on the basis of ionization consistency.

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Remaining ambiguities with the various other possible final states were resolved on the basis of χ^2 . [The most prominent feature of Reaction (1) is the production of the B-meson, which can be seen from the $\omega\pi$ mass spectrum/ in Figure 1. The B has had a somewhat tangled history. Early in its history, there was an apparent anomaly in the Dalitz plot distribution of ω 's resulting from B decays.^{1/} No indications of this effect have been observed in our experiment. Later its status as a resonant state was questioned,^{2/} and then reconfirmed by observation of B production in $\bar{p}p$ annihilations.^{3/} We also have observed B production independent of overlap with N^{*0} 's decaying into $p\pi^-$, and at large momentum transfers, although there is some indication that interference with N^{*0} production contributes substantially to B production. For this reason we do not attempt to quote either a mass or width for the B.

A number of attempts to establish a spin-parity for the B have been made, but no previous experiment has succeeded in accomplishing this. We have determined the spin-parity of the B to be 1^+ or 2^+ , 3^- , 4^+ ... with a reasonable degree of confidence using a moment analysis of the decay angular distributions. The apparent absence of a $\pi\pi$ decay mode of the B plus some prejudices about the density matrix make a 1^+ assignment a strong choice. The axes of the $B \rightarrow \omega\pi$ decay are the standard Gottfried-Jackson axes, and the angles (θ_1, ϕ_1) refer to the direction of the ω with respect to these axes. The helicity axis of the ω is used in the ω decay. The angles (θ_2, ϕ_2) refer to the direction of the ω decay plane normal with respect to the decay axes. The amplitude for the decay of a state $|jm\rangle$ into $\omega + \pi$ can be written

$$A_m = \sqrt{\frac{2j+1}{4\pi}} M_\lambda D_{m\lambda}^{j*}(\phi_1, \theta_1, 0) \sqrt{\frac{3}{4\pi}} D_{\lambda 0}^{1*}(\phi_2, \theta_2, 0) \quad (1)$$

where λ is the helicity of the ω . The complete decay angular distribution is then

$$W(\theta_1, \phi_1, \theta_2, \phi_2) = \sum_{mm'} \sum_{\lambda} A_m \rho_{mm'}^{(B)} A_m^* \quad (2)$$

where $\rho_{mm'}^{(B)}$ is the density matrix for the B. $W(\theta_1, \phi_1)$ can be expressed in terms of the moments $\langle D_{MO}^L(\phi_1, \theta_1, 0) \rangle = A_{LM}$ by

$$W(\theta_1, \phi_1) = \sum_{LM} \frac{2L+1}{4\pi} A_{LM} D_{MO}^{L*}(\phi_1, \theta_1, 0) \quad (3)$$

where $L \leq 2j$. Similar moments (B_{LM}) can be calculated for the ω decay distribution. The moments relevant to our discussion are shown in Figure 2. Normalized moments can be obtained from the unnormalized ones shown by dividing by A_{00} . A_{00} is obtained from the $\omega\pi$ mass distribution by counting the number of events in the B region (1.16 - 1.36 BeV) above the free-hand estimate of the background. Similarly the higher moments are obtained by counting events above (below) smooth background curves. The statistically significant moments obtained in the B region are:

$$A_{00} = 146$$

$$A'_{20} = A_{20}/A_{00} = -.13$$

$$B'_{20} = B_{20}/A_{00} = -.17$$

$$\text{Re}(B'_{22}) = \text{Re}(B_{22})/A_{00} = +.10$$

We first note that the non-zero A_{20} moment requires $j \geq 1$.

If the expression (2) for $W(\theta_1, \phi_1, \theta_2, \phi_2)$ is integrated over the angles θ_1, ϕ_1 and ϕ_2 we obtain for $W(\theta_2)$,

$$W(\theta_2) = \frac{3}{4} \left[\sin^2 \theta_2 + \frac{|M_0|^2}{|M_1|^2} \cos^2 \theta_2 \right] / \left(1 + \frac{|M_0|^2}{2|M_1|^2} \right)$$

Comparison with the expansion of $W(\theta_2, \phi_2)$ in the moments B_{LM}

$$W(\theta_2, \phi_2) = \sum \frac{2L+1}{4\pi} B_{LM} D_{MO}^{L*}(\phi_2, \theta_2, 0) \quad (4)$$

shows that

$$|M_0|^2 / |M_1|^2 = 2(1 + 5 B'_{20}) / (2 - 5 B'_{20}) = .10.$$

If $W(\theta_1, \phi_1, \theta_2, \phi_2)$ is integrated over θ_1, ϕ_1 , and θ_2 , one obtains

$$W(\phi_2) = \frac{1 + \alpha \cos 2\phi_2}{2\pi}$$

$$\alpha = \sum_{L \text{ even} \geq 2} \frac{2(2L+1)A'_{LO}}{(L+2)(L-1)} \frac{1}{1 - \frac{L(L+1)}{2j(j+1)} + \frac{|M_0|^2}{2|M_1|^2}} \quad (5)$$

$$M_{-\lambda} = \epsilon M_{\lambda}$$

$$\epsilon = \eta_B (-1)^{j-1} \quad (\eta_B = \text{parity of } B)$$

Thus the sign of α is related to the parity of the B. Comparison with (4) shows that

$$\alpha = \frac{10}{\sqrt{6}} \operatorname{Re} (B'_{22}) = +.41$$

We tabulate α/ϵ for a few values of j (obtained from Eq. (5), with $A_{60} = 0$).

j	α/ϵ	α/ϵ for $M_0 = 0$
1	.95	.85
2	-.77	-.85
3	-.53	-.57
4	-.47	-.50

The sign of α suggests that J^P for the $B = 1^+, 2^+, 3^-, 4^+ \dots$. We note that for the $2^+, 3^-, 4^+ \dots$ spin-parity series, parity conservation requires $M_0 \equiv 0$. The uncertainty in α prevents any further distinction of the spin on the basis of α . We can however calculate elements of the B density matrix for additional indications of the B spin. The solution for diagonal elements ρ_{mm} in terms of the moments A_{LM} can be written as

$$\rho_{mm} = \frac{1}{2j+1} \sum_{L \text{ even}} (-1)^m \frac{\langle LO | jj \ m-m \rangle}{\langle LO | jj \ 00 \rangle} \frac{(2L+1) \left(1 + \frac{|M_0|^2}{2|M_1|^2} \right)}{1 - \frac{L(L+1)}{2j(j+1)} + \frac{|M_0|^2}{2|M_1|^2}} A_{LO} \quad (6)$$

The results for the first 3 values of j are

$$j = 1 \quad \rho_{00} = 1.0, \quad \rho_{11} = 0$$

$$= 2 \quad \rho_{00} = -.14, \quad \rho_{11} = .03, \quad \rho_{22} = .54$$

$$= 3 \quad \rho_{00} = .01, \quad \rho_{11} = .02, \quad \rho_{22} = .14, \quad \rho_{33} = .34$$

where M_0 has been set = 0 for $j = 2, 3$. Aside from the negative (unphysical) value of ρ_{00} for $j = 2$ which is probably not statistically significant, we note that for $j \geq 2$, ρ_{jj} is the largest element of the density matrix. Although we have not calculated the uncertainties of the ρ_{mn} , we note that ρ_{jj} is always of the form

$$\rho_{jj} = \frac{1}{2j+1} \left[1 - \gamma A'_{20} \right]$$

where $\gamma \geq 0$. A glance at the moment distributions assures us that $A'_{20} < 0$ with some degree of certainty. We conclude that the large values of ρ_{jj} are significant. Since it is difficult to conceive of a production process yielding such density matrices, we have a strong prejudice that $j \geq 2$ hypotheses for the spin of the B must be discarded. This prejudice is further reinforced by the lack of observation of a 2π decay mode of the B. Since the positive value of α indicates a positive parity for $j = 1$, we conclude that the B has $J^P = 1^+$. It is interesting to note that the A_{20} moment shows that the decay is not s-wave, but rather is a mixture of s and d-waves.

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