# DETERMINATION OF THE G-PARITY AND ISOSPIN OF $\psi(3095)$ BY STUDY OF MULTIPION DECAYS* 

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ABSTRACT

We present here a measurement of six branching ratios of $\psi(3095)$ corresponding to the decays $\psi(3095) \longrightarrow \rho \pi, 2\left(\pi^{+} \pi^{-}\right)$, $2\left(\pi^{+} \pi^{-}\right) 1 \pi^{\circ}, 3\left(\pi^{+} \pi^{-}\right), 3\left(\pi^{+} \pi^{-}\right) 1 \pi^{\circ}$ and $4\left(\pi^{+} \cdot \pi^{-}\right) 1 \pi^{\circ}$. From this study, the isospin and G-parity quantum numbers are found to be $I^{G}=0^{-}$.
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We report here the analysis of multipion decays: of the $\psi(3095)$. ${ }^{(1,2)}$ found among 50,000 events collected by the SLAC/LBL magnetic detector at SPEAR ${ }^{(3)}$. By using only the information from the detected charged tracks, it is possible to observe either totally charged modes ( $e^{+} e^{-} \rightarrow n\left(\pi^{+} \pi^{-}\right), n=1,2,3 \ldots$ ) or modes involving one missing neutral ( $e^{+} e^{-} \rightarrow n\left(\pi^{+} \pi^{-}\right)+\pi^{0}$ ). The comparison between the multipion production on-resonance and offresonance enables us to determine the G-parity of $\psi(3095)$. Furthermore, the measurement of the channel $\psi(3095) \rightarrow \rho \pi$, where the $\rho \pi$ system is observed in the three charge states, unambiguously determines the isospin.

A series of cuts are applied to select a clean sample of events. First, the sum of the charges of all reconstructed tracks is required to be zero. A 2 standard deviation cut on the reconstructed longitudinal vertex position reduces beam gas background to less than $0.1 \%$ A cut on the minimum angle between any pair of particles $\left(<10^{\circ}\right)$ removes events having a photon converted in the vacuum pipe or in the first scintillation counter. This cut also removes events with a $\delta$ ray associated with a track. Events having one or more particles striking any of the internal support posts of the detector have been discarded.

The same cuts previously defined are put into the Monte Carlo program which calculates the detection efficiencies. A Lorentz invariant phase space distribution reproduces fairly well both the angular and the momentum distribution of the observed multipion events.

The $n\left(\pi^{+} \pi^{-}\right)$events are selected by requiring the missing momentum to be less than $0.100 \mathrm{GeV} / \mathrm{c}$. The distribution of the total energy observed, assuming pion masses, is then fitted by a Monte Carlo distribution which includes the contributions coming from all known sources of events. In the case of $2\left(\pi^{+} \pi^{-}\right)$shown in Fig. 1 , the fit takes into account three possible contaminating channels: $\pi \pi \mathrm{KK}, \mathrm{K}_{\mathrm{s}}^{0} \mathrm{~K} \pi$ and $2\left(\pi^{+} \pi^{-}\right) 1 \pi^{\circ}$.

For the $n\left(\pi^{+} \pi^{-}\right) 1 \pi^{\circ}$ events a missing momentum greater than 0.200 $\mathrm{GeV} / \mathrm{c}$ is required. The missing mass squared distribution is fitted taking into account the known contaminating channels. Figure $2 b$ shows the fit obtained for $2\left(\pi^{+} \pi^{-}\right) 1 \pi^{\circ}$. The background events observed under the peak come mainly from higher charged multiplicity states $\left(3\left(\pi^{+} \pi^{-}\right), 3\left(\pi^{+} \pi^{-}\right)+\pi^{0}\right)$ and from $K_{s}^{\mathrm{O}^{+}} \pi^{+} \pi^{\mathrm{o}}$ or $2\left(\pi^{+} \pi^{-}\right) 2 \pi^{\circ}$.

Only runs within $\pm 1 \mathrm{MeV}$ of the peak energy are used. They represent about $75 \%$ of the data and amount to an integrated Iuminosity of $\int \mathscr{Q d t}=35.6 \pm 3.5 \mathrm{nb}^{-1}$. Table 1 gives the branching ratios obtained for all the channels investigated so far. An overall correction of $7 \%$ takes into account the events lost by scattering in the material preceding the first chamber or not found by the tracking program. A $10 \%$ systematic error has been added in quadrature to the statistical errors.

Assuming that the $\psi(3095)$ couples to the lepton pairs via an intermediate photon, we expect ${ }^{(4)}$ about $17 \%$ of the hadronic events produced at $\psi(3095)$ to come from the second order electromagnetic decay $\psi(3095) \rightarrow \boldsymbol{\gamma} \rightarrow$ hadrons. Those states which are coupled to the $\psi_{\text {only }}$ via virtual photon should exhibit the same properties on-
and off- resonance. Off-resonance, $\mathrm{R}_{\mathrm{OFF}}=\sigma_{\mathrm{OFF}}^{\mathrm{F}} / \sigma_{\mathrm{OFF}}^{\mu \mu}$ measures the ratio of the cross section to produce a given hadronic final state F to the $\mu$-pair cross section (both produced via a virtual photon). On-resonance, the $\mu$-pairs are still produced via a virtual photon, but the observed hadrons can either come from a direct decay $(\psi \rightarrow F)$ or be produced via a virtual photon $(\psi \rightarrow \gamma \rightarrow F)$. In the latter case, $\mathrm{R}_{\mathrm{ON}}=\sigma_{\mathrm{ON}}^{\mathrm{F}} / \sigma_{\mathrm{ON}}$ and $\mathrm{R}_{\mathrm{OFF}}$ will be equal.

The off-resonance data were taken at $3.0 \mathrm{GeV} .\left(\int \mathbb{R} \mathrm{dt}=195 \pm 15 \mathrm{nb}{ }^{-1}\right)$. In this sample, the $2\left(\pi^{+} \pi^{-}\right)$and $3\left(\pi^{+} \pi^{-}\right)$are well identified, but due to the very low statistics, background events and signal cannot be well separated for $\rho \pi, 5 \pi$ or $7 \pi$ (see Fig. 2 a ). Therefore, no subtraction has been made and only an upper limit for $R_{O F F}$ is obtained for these channels.

It is convenient to study the quantity

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\alpha=\frac{\mathrm{R}_{\mathrm{ON}}}{\mathrm{R}_{\mathrm{OFF}}}=\frac{\mathrm{N}_{\mathrm{ON}}^{\mathrm{F}}}{\mathrm{~N}_{\mathrm{OFF}}^{\mathrm{F}}} \times \frac{\mathrm{N}_{\mathrm{OFF}}^{\mu \mu}}{\mathrm{N}_{\mathrm{ON}}^{\mu \mu}} \times \frac{\epsilon_{\mathrm{OFF}}^{\mathrm{F}}}{\epsilon_{\mathrm{ON}}^{\mathrm{F}}} \times \frac{\epsilon_{\mathrm{ON}}^{\mu \mu}}{\epsilon_{\mathrm{OFF}}^{\mu \mu}} ;
$$

$\alpha$ will be equal to one if only a second order electromagnetic decay occurs and greater than one if there are also direct decays. The detection efficiencies $\epsilon_{\mathrm{OFF}}$ and $\epsilon_{\mathrm{ON}}$, calculated by the Monte Carlo simulation, differ only by about $10 \%$. Since the hadronic events and the $\mu$-pairs are selected $O F F-$ and $O N$-resonance in the same way, most of the systematic errors cancel out in the computation of $\alpha$. Figure 3 shows $\alpha$ versus the pion multiplicity. Both channels with an even number of pions are consistent with a second order electromagnetic decay, whereas, all three channels with an odd number of
pions are considerably enhanced. The observation that $\boldsymbol{\alpha}$ is consistent. with unity for the $2\left(\pi^{+} \pi^{-}\right)$and $3\left(\pi^{+} \pi^{-}\right)$states is evidence that $\psi(3095)$ couples to lepton via an intermediate photon. The G-parity selection rule appears to work strikingly well and is consistent with the assignment $G=-1$. Thus, the isospin, $I$, which is related to $G$ by $G=C(-1)^{I}$, must be even.

This result could be affected if $\psi(3095)$ decayed radiatively to $\mathrm{n}\left(\pi^{+} \pi^{-}\right) \gamma$. Although a small contribution of such decays is not ruled out, the missing mass squared distributions agree very well with the distributions expected for a missing $\pi^{\circ}$ (see Figure $2 b$ for example). Furthermore, we observe exclusive channels such as $\rho \pi\left(>70 \%\right.$ of $\left.\pi^{+} \pi^{-} \pi^{\circ}\right)$, $\omega \pi \pi\left(20 \%\right.$ of $\left.2\left(\pi^{+} \pi^{-}\right) 1 \pi^{0}\right), \quad \rho \pi \pi \pi\left(30 \%\right.$ of $\left.2\left(\pi^{+} \pi^{-}\right) 1 \pi^{\circ}\right)$. They
represent a significantly large fraction of the decays and lead us to conclude that most of the direct decays of $\psi(3095)$ into multipions include a $\pi^{\circ}$.

Direct determination of the isospin may be obtained by studying the decay $\psi(3095) \rightarrow \rho_{\pi} . \quad$ To study this mode it is necessary to introduce an additional requirement on event selection, viz that the two prongs be noncoplanar with the beam by at 1 east $15^{\circ}$ in order to eliminate radiatively degraded elastic events (e.g., $e^{+} e^{-} \rightarrow e^{+} e^{-} \boldsymbol{\gamma}$ ). Furthermore, the proper angular distributions for the cascade decay of $\psi(3095)$ into three pions, via $\rho \pi$, were used in the Monte Carlo. The detection efficiency for $\rho^{\circ} \pi^{\circ}$ is 0.135 , and for $\rho^{ \pm} \pi^{\mp}, 0.084$. The selected events are shown in the Dalitz plot in Figure 4. The three $\rho$ bands are clearly seen. For events with $0.600<M_{\pi \pi}<0.950 \mathrm{GeV} / \mathrm{c}^{2}$,
the residual contamination is found to be negligible for $\rho^{\circ} \pi^{\circ}$ and on the order of $4 \%$ for $\rho^{ \pm} \pi^{+}$. The ratio between the production of neutral and charged modes $\sigma_{\rho^{\circ} \pi^{o}} /\left(\sigma_{\rho^{+} \pi^{-}}{ }^{+} \sigma_{\rho^{-} \pi^{+}}\right)$should be equal to 0.5 for $I=0$, or equal to 2 for $I=2$. The experimental ratio is $0.59 \pm 0.17$ which clearly favors the assignment $I=0$.

In conclusion the branching ratios for multipion final states strongly indicate odd G-parity for the direct hadronic decays of the $\psi(3095)$. The analysis of the $\rho \pi$ decay channel leads to the result $\mathrm{I}=0$. We conclude, therefore, that the $\psi(3095)$ has quantum numbers $I^{G}=0^{-}$.

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## References

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4. A. M. Boyarski et al., Phys. Rev. Lett. 34, 1357 (1975).
5. The direction of the $\rho$ has an angular distribution of $1+\cos ^{2} \theta$ with respect to the beam axis. The angular distribution of the $\pi^{\prime} \mathrm{s}$ from the $\rho$ decay is $\sin ^{2} \theta_{\mathrm{cm}}$ with respect to the $\rho$ 's direction in the center of mass of the $\rho$. The normal to the plane containing the three pions of the final state is distributed like $\sin ^{2} \theta_{N}$ with respect to the beam axis.

## Figure Captions

1. Total energy of the charged tracks observed in 4-prong events with a momentum imbalance of less than $0.100 \mathrm{GeV} / \mathrm{c}$ and a total charge equal to zero, assuming all particles are pions. The curve is a Monte Carlo fit to the data.
2. Distribution of the 4 -prong events with a momentum imbalance greater than $200 \mathrm{MeV} / \mathrm{c}$ and a total charge zero at
(a) C.M. energy of 3.0 GeV
(b) $\psi(3095)$ - The curve shows the Monte Carlo fit to the data.
3. Comparison of the ratio of multipion to $\boldsymbol{\mu}$-pair production onresonance and off-resonance, for various multipion channels.
4. Dalitz plot for the $\pi^{+} \pi^{-} \pi^{0}$ decay of $\psi(3095)$.

TABLE 1

Branching Ratios for Some Multipion Decay Channels of the $\psi(3095)$

| Mode | Branching <br> Ratio (\%) | No. of Events <br> Observed |
| :---: | :---: | :---: |
| $\rho \pi$ | $1.3 \pm 0.3$ | $153 \pm 13$ |
| $2 \pi^{+} 2 \pi^{-}$ | $0.4 \pm 0.1$ | $76 \pm 9$ |
| $2 \pi^{+} 2 \pi^{-} \pi^{\circ}$ | $4.0 \pm 1.0$ | $675 \pm 40$ |
| $3 \pi^{+} 3 \pi^{-}$ | $0.4 \pm 0.2$ | $32 \pm 7$ |
| $3 \pi^{+} 3 \pi^{-} \pi^{\circ}$ | $2.9 \pm 0.7$ | $181 \pm 26$ |
| $4 \pi^{+} 4 \pi^{-} \pi^{\circ}$ | $0.9 \pm 0.3$ | $13 \pm 4$ |



Figure 1


Figure 2


Figure 3


Figure 4

