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Partial Wave Analysis of $J/\psi \to \gamma(\pi^+\pi^-\pi^+\pi^-)$

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BES data on $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$ have been analyzed into partial waves. We fit with resonances having $J^{PC} = 2^{++}$ at 1275 MeV, 0^{++} at 1500 MeV, 2^{++} at 1565 MeV, 0^{++} at 1740 MeV, 2^{++} at 1940 MeV and 0^{++} at 2104 MeV, plus a broad 0^-. The 0^{++} resonances decay dominantly to $\sigma\sigma$, while 2^{++} resonances in the high mass region decay mainly to $f_2(1270)\sigma$ and $\sigma\sigma$; 2^{++} resonances from the low mass region decay dominantly to $\rho\rho$.

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MARK III and DM2 reported their data on $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$ in 1986 and 1989 respectively [1,2]. They found that the dominant component of the spectrum below 2 GeV was due to $J/\psi \to \gamma\rho\rho$ with spin-parity 0^- in the $\rho\rho$ system, where the two ρ appear in a relative P-wave. MARK III claimed a pseudoscalar resonance at 1.55 GeV/c^2. This was supported by DM2, and in addition they claimed that structures at 1.80 and 2.10 GeV/c^2 were also $J^{PC} = 0^{-+}$.

Later, E760 found three structures in the $\eta\eta$ [3] with masses and widths very similar to those observed in $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$. However, the quantum numbers 0^{-+} are forbidden to $\eta\eta$.

Both MARK III and DM2 analyzed their data in term of $J/\psi \to \gamma\rho\rho \to \gamma\pi^+\pi^-\pi^+\pi^-$, but they did not consider $J/\psi \to \gamma\sigma\sigma \to \gamma\pi^+\pi^-\pi^+\pi^-$. Here σ means the full $\pi-\pi$ S-wave amplitude, parametrized up to 1800 MeV. In 1995, Bugg *et al.* reanalyzed MARK III data [4] and added the $\sigma\sigma$ decay mode to $\rho\rho$. Inclusion of this decay identified two of the peaks as $I = 0$ scalar resonances decaying exclusively via $\sigma\sigma$. Those states have masses in the region $M = 1500$ and 2100 MeV/c^2. An additional scalar state was required at $M = 1750$ MeV/c^2, decaying dominantly to $\sigma\sigma$, but also with significant decays via $\rho\rho$.

We present here an analysis of BES data on $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$ into partial waves. In this analysis, the full Monte Carlo simulation of the BES detector is used; the analysis of Bugg *et al.* used only a simplified Monte Carlo simulation, since the full Monte Carlo simulation of the Mark III detector was then no longer available. The full Monte Carlo simulation allows an improved study of the main background channel $J/\psi \to \pi^0\pi^+\pi^-\pi^+\pi^-$. Results are similar to those of Ref. [4], except that additional 2^+ amplitudes are required in the mass region around 2 GeV.

The Beijing Spectrometer(BES) has collected 7.8×10^6 J/ψ triggers, used here. Details of the detector are given in Ref. [5]. We describe briefly those detector elements playing a crucial role in the present

measurement. Tracking is provided by a 10 superlayer main drift chamber (MDC). The momentum resolution is $\sigma_P/P = 1.7\%\sqrt{1+P^2}$, where P is the momentum of charged tracks in GeV/c. The resolution of the dE/dx measurement is $\sim \pm 9\%$, providing good π/K separation for momenta up to 600 MeV/c. An array of 48 scintillation counters surrounding the MDC measures the time-of-flight (TOF) of charged tracks with a resolution of $330ps$ for hadrons. Outside the TOF system is an electromagnetic calorimeter having a z positional resolution of 4 cm. The energy resolution scales as $\sigma_E/E = 22\%/\sqrt{E}$, where E is the energy in GeV.

Candidates for the decay $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$ are selected by requiring exactly four charged tracks with a good helix fit in the polar angle range $-0.8 < \cos\theta < 0.8$ and a transverse momentum > 60 MeV/c. The number of neutral clusters maybe up to five, but only one reconstructed γ is required in the barrel shower counter. A minimum energy cut of 50 MeV is imposed on the photons. Showers associated with charged tracks are also removed. Four-constraint kinematic fits are performed to the final states $\gamma\gamma 4\pi$, $\gamma 4\pi$ and 4π. The value of $\chi^2(\gamma 4\pi)$ is required to be the smallest one. The probability of $\chi^2(\gamma 4\pi)$ is required to be larger than 5%, in order to achieve good resolution and to select a good photon.

Further cuts are as follows. To remove the main background $J/\psi \to \pi^0\pi^+\pi^-\pi^+\pi^-$, the probability $Prob(\chi^2(\gamma 4\pi))$ larger than $Prob(\chi^2(\gamma\gamma_{miss}4\pi))$ is required, where γ_{miss} means this photon is missing. If the two photons in $J/\psi \to \gamma\gamma_{miss}\pi^+\pi^-\pi^+\pi^-$ are from a π^0 decay, $Prob(\chi^2(\gamma\gamma_{miss}4\pi))$ is required to be $< 1\%$. Next, $\mid U_{miss} \mid = \mid E_{miss} - P_{miss} \mid < 0.12$ GeV/c^2 is required in order to reject events containing more than one photon or containing charged kaons; here, E_{miss} and P_{miss} are, respectively, the missing energy and missing momentum of all charged particles. The transverse momentum of the 4π system $P^2_{t\gamma} = 4 \mid P_{miss} \mid^2 \sin^2(\theta_{m\gamma}/2) < 0.005$ (GeV/c)^2 is required in order to remove the background $J/\psi \to \pi^0\pi^+\pi^-\pi^+\pi^-$; here $\theta_{m\gamma}$ is the angle between the missing momentum and the photon direction. Background $J/\psi \to \omega\pi^+\pi^-$ events are eliminated by the cut $\mid M_{\pi^+\pi^-\pi^0} - M_\omega \mid > 25$ MeV, in the $\pi^0\pi^+\pi^-\pi^+\pi^-$ hypothesis with only one photon detected and the π^0 associated to the missing momentum. To remove the small background due to $J/\psi \to \gamma K^0_s K^0_s$ events, a double cut on the two $\pi^+\pi^-$ invariant masses is performed, $\mid M_{\pi^+\pi^-} - M_{K^0_s} \mid > 25$ MeV. The BES data show a small signal due to $f_1(1285)$; this is not of concern in this analysis, so, in order to remove it, an additional cut is applied to discard events within the mass region between 1.24 and 1.32 GeV/c^2.

The estimated background is 31%, purely from $J/\psi \to \pi^0(\pi^+\pi^-\pi^+\pi^-)$, and is included in the fits. It includes a small signal (visible in Fig. 3(c) and (d) below) for $a_2(1320) \to \rho\pi$, originating from $J/\psi \to a_2\rho$. When this $a_2(1320)$ signal is combined with a fourth pion, it does not correlate with any peak in the 4π mass spectrum. Otherwise, the 4π and 3π mass distributions in the background lie very close to phase space and are parametrised by phase space distributions.

Fig. 1 shows the 2π invariant mass distribution; strong signals of ρ, σ and $f_2(1270)$ are seen. The 4π invariant mass distribution of $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$ is shown in Fig. 2; the amplitude analysis resolves structures from 1.50 to 2.30 GeV/c^2. For our final fit, we used 2004 events below a 4π mass of 2.4 GeV.

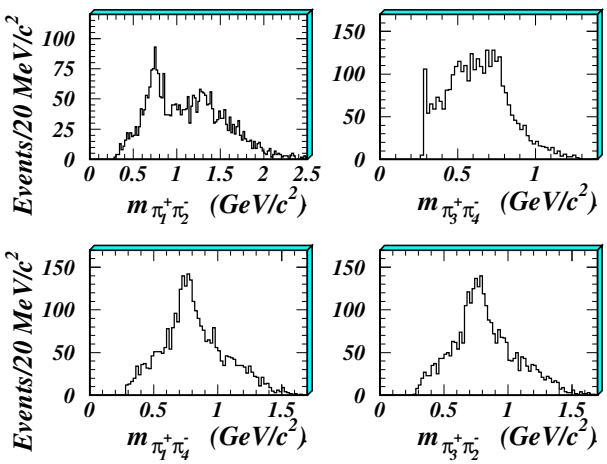

FIG. 1. The 2π mass spectrum of $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$, taking $P(\pi_1^+) > P(\pi_3^+)$ and $P(\pi_2^-) > P(\pi_4^-)$.

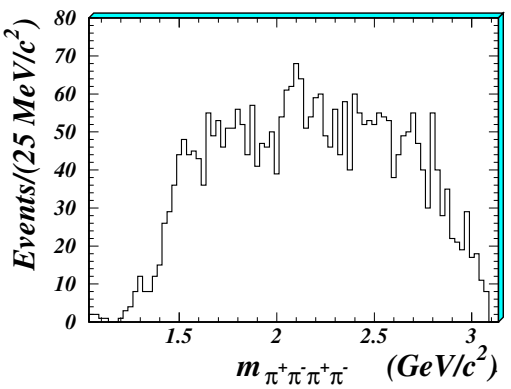

FIG. 2. The 4π mass spectrum of $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$.

We have carried out a partial wave analysis using amplitudes constructed from Lorentz-invariant combinations of the 4-vectors and the photon polarization for J/ψ initial states with helicity ± 1. Cross sections are summed over photon polarizations. The relative magnitudes and phases of the amplitudes are determined by a maximum likelihood fit. We use ℓ to denote the orbital angular momentum between the photon from J/ψ decay and the resonance in the production process; we use L to denote the orbital angular momentum in the decay of the resonance to final states $\rho\rho$, $\sigma\sigma$ and $f_2(1270)\sigma$, with L

restricted ≤ 2. Because production is via an electromagnetic transition, the same phase is used for amplitudes with different ℓ but otherwise the same final state.

We now discuss resonances and possible decay modes which have been included in the fit. Spin-parity assignments up to $J = 4$ have been tried. In Ref. [4], the only decays of 2^{++} resonances which were included were to $\rho\rho$; we have added the $f_2(1270)\sigma$ mode above 1.8 GeV. We have tried to include $\pi - \pi(1300)$ or $\pi - a_1(1260)$ decay modes for 0^+ resonance. There are two decay modes of $\pi(1300)$ and $a_1(1260)$: $\rho\pi$ and $\sigma\pi$. From the PDG [6], $\pi(1300)$ and $a_1(1260)$ decay mainly to $\rho\pi$. When putting this constraint into the fit, we found the contributions of the $\pi - \pi(1300)$ and $\pi - a_1(1260)$ decay modes are negligible. The resonances and decay modes which make significant improvements in log likelihood are listed in Table I. Amplitudes are constructed in terms of the combined spin S of the decay photon and the J/ψ system. Table I also summarizes the significance level of each resonance. It indicates that the $f_2(1270)$, 0^-, $f_0(1500)$, $f_2(1565)$, $f_0(1740)$, $f_2(1950)$ and $f_0(2100)$ should be included in the fit.

The dominant component in the fit is 0^-. We find that this may be parametrized in two alternative ways. The one used for the fit reported here is a simple Breit-Wigner amplitude of mass 1435 MeV and width 245 MeV. It is much wider than $\eta(1440)$ and is therefore not to be identified with that state. The rapidly increasing phase space for decays to $\rho\rho$ with $L = 1$ results in a very broad 0^- signal, illustrated below in Fig. 4(a). An alternative more complicated parametrization is given in a recent coupled channel analysis of many J/ψ decay modes [7]; it gives results almost indistinguishable from those presented here.

The width of $f_2(1270)$ cannot be fitted with any precision. Statistics of data in the $f_2(1270)$ mass region are very low because the $f_1(1285)$ has been removed by a cut in this mass region. Hence the mass and width of the $f_2(1270)$ are constrained to the PDG value [6]. Some 2^+ component is definitely required in the mass range 1500–1700 MeV, as is illustrated below in Fig. 4(c). This may probably be attributed to $f_2(1565)$, which sits at the $\rho\rho$ and $\omega\omega$ threshold and can decay into 4π. In the final fit, the mass of $f_2(1565)$ has been fixed at 1565 MeV, which is well determined by data from other sources [8–10].

Comparisons with data are shown in Fig. 3 summed from $M(4\pi) = 1.0$ to 2.4 GeV for $M_{\pi^+\pi^-\pi^+\pi^-}$, $M_{\pi^+\pi^-}$, $M_{3\pi}$, $M_{\rho\pi}$, $\cos\theta_{\pi^+}$; here θ_{π^+} is the angle of π^+ with respect to the $\pi^+\pi^-$ pair in their rest frame, and χ is the azimuthal angle between the planes of $\pi^+\pi^-$ pairs in the rest frame of the resonance X. The contributions of the various components in this fit are shown in Fig. 4; crosses are data and histograms the fit.

Branching fractions are given in Table II. The branching fraction for $M_{4\pi} < 3.0$ GeV/c^2 is $Br(J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-) = (3.8 \pm 0.3 \pm 1.3) \times 10^{-3}$. The first error is statistical and the second systematic.

Fig. 2 seems to require a narrow resonance $f_j(2220)$ near 2.2 GeV, we have therefore tried adding to the fit a narrow 0^-, 0^+, 2^+ or 4^+ resonance with width 20 MeV to 70 MeV. We have found it possible to improve the fit only slightly by superposing a narrow 2^+ resonance at M = 2210 MeV. The improvement is only 2.5σ effect. Alternative 0^-, 0^+ or 4^+ resonances give smaller improvements. The BES data on $J/\psi \to \gamma K^+K^-$ [11] show two possible resonance in the 1.7 GeV region: a scalar with mass 1781 MeV, a tensor 1696 MeV. We have therefore tried adding to the fit a tensor resonance in this mass region. We have found no significant production of spin 2 is observed in the $\gamma\pi^+\pi^-\pi^+\pi^-$ channel.

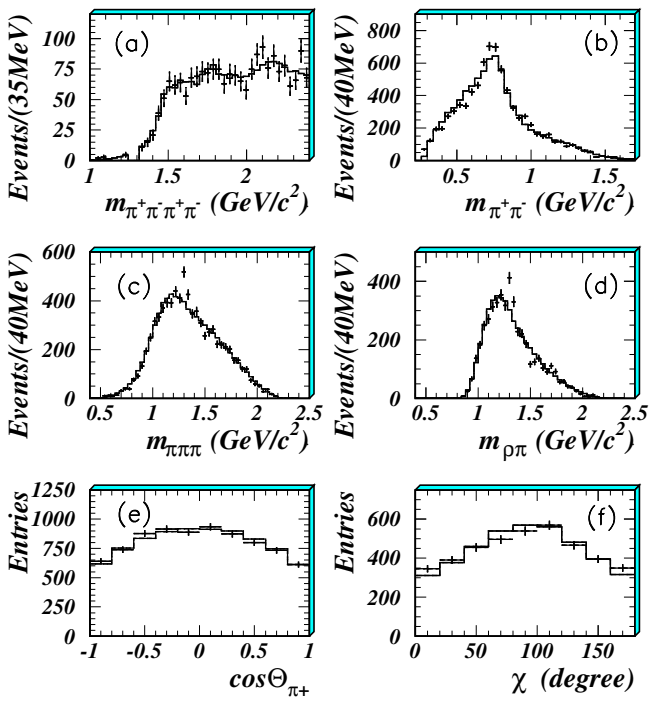

FIG. 3. The comparison between data and final full fit.

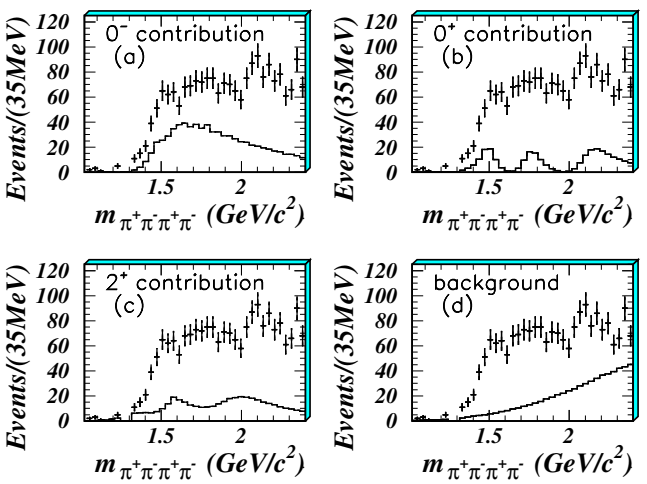

FIG. 4. component contribution.

TABLE I. Resonances fitted to the BES data and decay modes used in the final fit.

J^P	Resonance	Measured Mass (MeV)	Measured Γ (MeV)	Used in final fit Mass (MeV)	Used in final fit Γ (MeV)	Significance level	decays	ℓ or $^{2S+1}\ell_2$
2^+	$f_2(1270)$	1285^{+35}_{-25}		1275	185	4.5σ	$\rho\rho$	$^1D_2$ $^3D_2$
0^-		1435^{+20}_{-20}	245^{+25}_{-25}	1435	245	$>6.0\sigma$	$\rho\rho$	$\ell = 1$
0^+	$f_0(1500)$	1505^{+15}_{-20}	125^{+35}_{-30}	1500	112	4.9σ	$\sigma\sigma$	$\ell = 0$
2^+	$f_2(1565)$	1500^{+20}_{-20}	160^{+30}_{-30}	1565	160	$>6.0\sigma$	$\rho\rho$	$^5S_2$
0^+	$f_0(1740)$	1740^{+30}_{-25}	135^{+40}_{-35}	1740	135	4.8σ	$\sigma\sigma$	$\ell = 0$
2^+	$f_2(1950)$	1940^{+60}_{-50}	$350^{+100}_{-\ 60}$	1940	350	$>6.0\sigma$	$f_2(1270)\sigma$	$^5S_2$
							$\sigma\sigma$	$^1D_2$ $^3D_2$
0^+	$f_0(2100)$	2065^{+30}_{-30}	$225^{+100}_{-\ 75}$	2104	215	4.1σ	$\sigma\sigma$	$\ell = 0$

TABLE II. Branching ratios for various final states in J/ψ decays, integrated up to $M(4\pi) = 2400$ MeV.

Process	Branching ratios
$Br(J/\psi \to \gamma f_2(1270)) \times Br(f_2(1270) \to \pi^+\pi^-\pi^+\pi^-)$	$(1.5 \pm 0.1 \pm 0.5) \times 10^{-4}$
$Br(J/\psi \to \gamma 0^-) \quad \times Br(0^- \to \pi^+\pi^-\pi^+\pi^-)$	$(1.3 \pm 0.1 \pm 0.5) \times 10^{-3}$
$Br(J/\psi \to \gamma f_0(1500)) \times Br(f_0(1500) \to \pi^+\pi^-\pi^+\pi^-)$	$(2.9 \pm 0.2 \pm 1.0) \times 10^{-4}$
$Br(J/\psi \to \gamma f_2(1565)) \times Br(f_2(1565) \to \pi^+\pi^-\pi^+\pi^-)$	$(4.0 \pm 0.2 \pm 1.4) \times 10^{-4}$
$Br(J/\psi \to \gamma f_0(1740)) \times Br(f_0(1740) \to \pi^+\pi^-\pi^+\pi^-)$	$(3.4 \pm 0.2 \pm 1.2) \times 10^{-4}$
$Br(J/\psi \to \gamma f_2(1950)) \times Br(f_2(1950) \to \pi^+\pi^-\pi^+\pi^-)$	$(4.5 \pm 0.3 \pm 1.6) \times 10^{-4}$
$Br(J/\psi \to \gamma f_0(2100)) \times Br(f_0(2100) \to \pi^+\pi^-\pi^+\pi^-)$	$(4.0 \pm 0.2 \pm 1.4) \times 10^{-4}$

The results are summarized as follows: The 0^{++} resonances decay dominantly to $\sigma\sigma$, while the 2^{++} resonances in the low mass region decay dominantly to $\rho\rho$, and those in the high mass region decay to $f_2(1270)\sigma$, $\sigma\sigma$.

The BES data on $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$ show a dominant scalar resonance at 1740 MeV, a possible candidate for $f_J(1710)$. The $f_0(1500)$ and $f_0(1740)$ are produced significantly in $J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$; according to the criteria of determining the gluonic content of resonance in radiative J/ψ decays proposed by Close *et al.* [12], they may therefore contain significant glueball components.

The BES results are approximately consistent with the results from the earlier re-analysis of MARK III data [4]. But the BES data favour more 2^+ in the high mass region. A possible cause of this difference is that a better background function for BES data is available and a full Monte Carlo simulation is employed in BES analysis. An important conclusion is that a broad 2^+ resonance $f_2(1950)$ is needed around 2 GeV. This is where the 2^+ glueball may be expected, and J/ψ radiative decays are supposed to be one of the best places to search for the glueballs. Recently, the WA102 group found a broad 2^+ resonance at 1920 MeV in their 4π mass spectrum [13]; this agrees with our observation.

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* Deceased.

† Data analyzed were taken prior to the participation of U.S. members of the BES Collaboration.

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