Search for a Vector Glueball by a Scan of the J/ψ Resonance

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The cross section for $e^+e^- \to \rho\pi$ has been measured by the BES detector at BEPC at center-of-mass energies covering 40 MeV interval spanning the J/ψ resonance. The data are used to search for the vector gluonium state hypothesized by Brodsky, Lepage and Tuan as an explanation of the $\rho\pi$ puzzle in charmonium physics. The shape of the $\rho\pi$ cross section is compatible with that of the total hadronic cross section. No distortions indicating the presence of a vector glueball are seen.

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There is a well known mystery in charmonium physics, the so-called "$\rho\pi$ puzzle". According to quantum chromodynamics, the J/ψ and $\psi(2S)$ resonances are S-wave $c\bar{c}$ bound states that decay to hadrons via three gluons or, with a smaller probability, via a single direct photon. In either case the partial decay width is proportional to $|\Psi(0)|^2$, the square of the $c\bar{c}$ wave function at the origin. Expectations based on perturbative QCD are that for any specific final hadronic state h:

$$
\begin{aligned}
Q_h \equiv \frac{B(\psi(2S) \to h)}{B(J/\psi \to h)} &\cong \frac{B(\psi(2S) \to e^+e^-)}{B(J/\psi \to e^+e^-)} \\
&= 0.147 \pm 0.023 \text{ [1]}.
\end{aligned}
\tag{1}
$$

While this rule appears to be satisfied for most hadronic channels, there are startling exceptions that occur for the

$\rho\pi$ and $K^*\bar{K}$ final states. These are dominant hadronic channels for J/ψ decays but are not seen in $\psi(2S)$ decays; the present experimental limits [1] are

$$Q_{\rho\pi} < 0.0028 \quad \text{and} \quad Q_{K^*\bar{K}} < 0.011. \tag{2}$$

An intriguing possible explanation for this anomaly was provided by Brodsky, Lepage and Tuan [2] based on a refinement of an idea of Hou and Soni [3]. They assume the general validity of the perturbative QCD theorem that total hadron helicity is conserved in high-momentum-transfer exclusive processes, in which case the decays to $\rho\pi$ and $K^*\bar{K}$ are forbidden for both the J/ψ and the $\psi(2S)$. The observed J/ψ decays to these channels are mediated by an intermediate gluonium state O with quantum number $J^{PC} = 1^{--}$ and a mass near that of the J/ψ. The experimental limits given by Eq.(2) imply that the O mass is within 80 MeV of the mass of the J/ψ and its total width is less than 160 MeV [2].

Experimentally, the search for such a vector gluonium state could be carried out using sources of three gluons occurring in certain hadronic decays of the $\psi(2S)$, such as $\psi(2S) \to \pi\pi + X, \eta + X, \eta' + X$, where X decays into vector-pseudoscalar (VP) final states [3]. A more direct way to verify the existence of O is to scan the $e^+e^- \to VP$ cross secection across the J/ψ resonance [4]. The O, being close in mass to the J/ψ and having decay width Γ_O substantially larger than $\Gamma_{J/\psi}$, should interfere with the J/ψ, producing a distortion of the shape of the J/ψ obtained from the $e^+e^- \to VP$ cross section compared to that of the total hadronic or lepton pair cross section. In this paper, we report on such a search based on an energy scan done with the BES detector [5] at the BEPC e^+e^- collider.

Cross section measurements were performed at 29 different energy points covering a 40 MeV interval spanning the J/ψ resonance. The original purpose of the scan was measurements of the total and lepton partial widths of the J/ψ, the results of which are published elsewhere [6]. The data sample corresponds to a total integrated luminosity of 238 nb^{-1}. In this energy region the uncertainty in the c.m. energy of the BEPC collider is ± 0.07 MeV, and the rms c.m. energy spread is 1 MeV [5]. A summary of the energy points at which data were taken is provided in Table I.

In this analysis, the candidate events for $e^+e^- \to \rho\pi$ are required to have exactly two, oppositely charged and well reconstructed tracks, and between two and six neutral energy clusters in the shower counters. Each charged track is identified as a pion using a combination of the time-of-flight and dE/dx information. In order to remove lepton pair events, we require the opening angle between the two charged tracks to be less than 170°, the total energy deposit in the calorimeter associated with the two charged tracks to be less than 1.6 GeV, and at least one charged track *not* identified as a muon by the muon counters. The events are required to have at least two "good" photons, which are defined as neutral energy deposits that are larger than 80 MeV and are separated from the nearest charged track by more than 8°. The selected events are kinematically fitted to the $\pi^+\pi^-\gamma\gamma$ hypothesis by imposing the energy and momentum constraints corresponding to each scan point. For events where the number of good photons exceeds two, all two-photon combinations are fitted, and the combination with the minimum χ^2 and $P(\chi^2) > 0.01$ is retained. Finally, the mass cuts $|M_{\gamma\gamma} - M_{\pi^0}| < 50$ MeV/c^2 and $|M_{\pi\pi} - M_\rho| < 200$ MeV/c^2 are also applied. The number of $\rho\pi$ candidates found in each scan point is listed in the last column of Table I.

The $\rho\pi$ scan data are analyzed using a maximum likelihood method. The likelihood function is a product of Poission distributions, one for each center-of-mass energy W_i. At each scan point i, the number of expected events ν_i is given by

$$\nu_i = [\epsilon\sigma_{\rho\pi}(W_i) + \sigma_b(W_i)]\mathcal{L}_i; \tag{3}$$

ϵ is the overall efficiency for identifying $\rho\pi$ events; $\mathcal{L}_i$ is the integrated luminosity; $\sigma_{\rho\pi}(W_i)$ is the corresponding cross section for $\rho\pi$ production; and $\sigma_b(W_i)$ is the background cross section. The efficiency combines the trigger efficiency, which is estimated to be 98.4% for two prong hadron events [6], and the reconstruction and selection efficiency, which is determined from Monte Carlo simulations to be 13.1% and virtually independent of energy over the scan region. Backgrounds come from $e^+e^- \to J/\psi \to \pi^+\pi^-\pi^0$(direct), $K^+K^-\pi^0$, etc. Assuming that the shape of the background is compatible with the shape of $e^+e^- \to J/\psi \to hadrons$, the background cross section can be written as

$$\sigma_b(W) = \sum_k \epsilon_k B_k \sigma_{tot}(W), \tag{4}$$

where ϵ_k is the overall efficiency for a specific background process k; B_k is the corresponding branching fraction; $\sigma_{tot}(W)$ is the total observed cross section of the J/ψ resonance in which radiative corrections and collider c.m. energy spread are taken into account. For $\pi^+\pi^-\pi^0$(direct) and $K^+K^-\pi^0$, the main background processes, Monte Carlo simulations yield the efficiencies for reconstruction and selection to be 5.86% and 0.75%, respectively.

The $\rho\pi$ cross section $\sigma_{\rho\pi}(W)$ is the sum of a nonresonant direct-channel contribution from nonresonant virtual photon annihilation and a resonant term that is convoluted with a Gaussian function describing the c.m. energy spread of the collider

$$\sigma_{\rho\pi}(W) = R_{\rho\pi}\sigma_{\mu\mu}(W) + \frac{1}{\sqrt{2\pi}\Delta}\int_0^\infty dW' e^{-\frac{(W-W')^2}{2\Delta^2}}\sigma(W'). \tag{5}$$

Here $\sigma_{\mu\mu}$ is the pure QED $e^+e^- \to \mu\mu$ cross section and $R_{\rho\pi}$ is the fractional nonresonant direct-channel cross section for $\rho\pi$ production; Δ is the standard deviation of the Gaussian function; $\sigma(W)$ is the Breit-Wigner cross section due to the J/ψ and O propagators for the process $e^+e^- \to \rho\pi$. Taking into account radiative corrections [7], $\sigma(W)$ can be expressed as

$$\begin{aligned}
\sigma(W) = {} & [1 + \frac{3}{4}\beta + \frac{\alpha}{\pi}(\frac{\pi^2}{3} - \frac{1}{2}) - \beta^2(\frac{\pi^2}{12} - \frac{9}{32})]\int_0^1 dx\beta x^{\beta-1} \\
& (\frac{|B|^2}{(W^2(1-x) - M_{J/\psi}^2)^2 + M_{J/\psi}^2\Gamma_{J/\psi}^2} + \frac{|D|^2}{(W^2(1-x) - M_O^2)^2 + M_O^2\Gamma_O^2} \\
& + \frac{2Re\{DB[W^2(1-x) - M_O^2 - iM_O\Gamma_O][W^2(1-x) - M_{J/\psi}^2 + iM_{J/\psi}\Gamma_{J/\psi}]\}}{[(W^2(1-x) - M_O^2)^2 + M_O^2\Gamma_O^2][(W^2(1-x) - M_{J/\psi}^2)^2 + M_{J/\psi}^2\Gamma_{J/\psi}^2]}) \\
\equiv {} & \sigma_{J/\psi}(W) + \sigma_{O+I}(W),
\end{aligned} \tag{6}$$

where $\beta = \frac{2\alpha}{\pi}(ln\frac{W^2}{m_e^2} - 1)$; B is the J/ψ partial width to e^+e^- (denoted as $\Gamma_{J/\psi}^{ee}$) and $\rho\pi$ (denoted as $\Gamma_{J/\psi}^{\rho\pi}$) in the form $|B|^2 = 12\pi\Gamma_{J/\psi}^{ee}\Gamma_{J/\psi}^{\rho\pi}$; $D = |D|\exp(i\theta)$ is the contribution from the O with θ denoting a possible relative complex phase; $M_{J/\psi}, \Gamma_{J/\psi}$ are the mass and total width of the J/ψ; M_O, Γ_O are the mass and total width of the O. For the analysis in this work, $\sigma(W)$ is decomposed into two parts: $\sigma_{J/\psi}(W)$ is the first term in Eq.(6) and corresponds to the normal J/ψ resonance; and $\sigma_{O+I}(W)$ is the sum of the second and third term due to the O and its interference with the J/ψ.

In fitting the cross section $\sigma_{\rho\pi}$ in Eq.(5) to the results listed in Table I, $|B|$, $|D|$ and $R_{\rho\pi}$ are treated as free, independent parameters. Different sets of input values of M_O, Γ_O and θ are taken within the ranges suggested by Ref. [2]: M_O is varied from $M_{J/\psi} - 80$ MeV to $M_{J/\psi} + 80$ MeV, Γ_O from 10 to 160 MeV, and θ from 0 to 90 degrees. For $M_{J/\psi}$, $\Gamma_{J/\psi}$, $\Gamma_{J/\psi}^{ee}$ and Δ, the values determined from the same set of the scan data [6] are used here as well as in the background expression of Eq.(4). The fits yield an upper limit on the cross section ratio of

$$\frac{\sigma_{O+I}}{\sigma_{J/\psi}} < 2.2 \times 10^{-3} \ \ (90\% \ C.L.) \tag{7}$$

at $W = M_{J/\psi}$.

For the model proposed in Ref. [2], the $\sigma_{J/\psi}$ contribution should observe the perturbative QCD relation of Eq.(1), namely

$$\frac{B(\psi(2S) \to \rho\pi)}{\sigma_{J/\psi}/\sigma_{tot}} = 0.147, \tag{8}$$

while the anomalous $J/\psi \to \rho\pi$ decay mode is the contribution from σ_{O+I}, modifying Eq.(8) to become

$$\frac{B(\psi(2S) \to \rho\pi)}{(\sigma_{J/\psi} + \sigma_{O+I})/\sigma_{tot}} = Q_{\rho\pi}. \tag{9}$$

Combining Eq.(8) and Eq.(9) and using the experimental limit of $Q_{\rho\pi}$ in Eq.(2), we find

$$\frac{\sigma_{O+I}}{\sigma_{J/\psi}} = 0.147/Q_{\rho\pi} - 1 > 51.5, \tag{10}$$

in clear contradiction with the obtained upper bound in Eq.(7).

On the other hand, if we define λ to be the ratio of $L(H_0)$, the maximum value of the likelihood function for the null hypothesis ($|D| = 0$ in Eq.(6)), to $L(H_1)$, the maximum value of the likelihood function for the vector glueball hypothesis, we find $-2\ln\lambda = 0.84$. In the limit where the distribution of $-2\ln\lambda$ is the χ^2 distribution for 1 degree of freedom, the 90% confidence level expectation is $-2\ln\lambda < 2.71$. This indicates that our results are in good agreement with the null hypothesis and there is no evidence for the vector glueball hypothesis.

In the case of no contribution from the O, $\sigma_{\rho\pi}(W)$ can be simply expressed as

$$\sigma_{\rho\pi}(W) = R_{\rho\pi}\sigma_{\mu\mu}(W) + B_{\rho\pi}\sigma_{tot}(W), \tag{11}$$

and fitting the data allowing both $B_{\rho\pi}$ and $R_{\rho\pi}$ to be free parameters yields

$$B_{\rho\pi} = B(J/\psi \to \rho\pi) = (1.21 \pm 0.20)\%. \tag{12}$$

The error includes the statistical and the systematic errors added in quadrature. This is the first measurement of the $B_{\rho\pi}$ for the J/ψ from the scan across the resonance, and the result is consistent with the Particle Data Group value [1], which comes from the data taken at the J/ψ resonance peak. The measured $\rho\pi$ cross sections are shown as a function of c.m. energy in Fig. 1. The curve in this figure is the result of the likelihood fit to the null hypothesis. For comparison, the measured total hadronic cross section and the fitted curve from Ref. [6] are shown in Fig. 2. The quality of the fit in Fig. 1 is checked by forming the likelihood ratio λ with the result $-2\ln\lambda = 22.0$. In the large statistics limit, this should obey a χ^2 distribution for 27 degrees of freedom, further indicating that the fit with the null hypothesis is acceptable.

In conclusion, the data from a scan of the $\rho\pi$ cross section over a 40 MeV interval spanning the J/ψ resonance have been used to search for the vector gluonium state O that was hypothesized to explain the $\rho\pi$ puzzle in J/ψ and $\psi(2S)$ physics. No evidence was found to support the existence of such a vector gluonium state. The shape of the $\rho\pi$ curve is found to be consistent with the shape of the total hadronic curve with no distortion observed within the experimental uncertainties. The $J/\psi \to \rho\pi$ branching fraction obtained from fitting the shape of the scan data yields the result $(1.21 \pm 0.20)\%$. The $\rho\pi$ puzzle in charmonium physics remains a puzzle.

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FIGURES

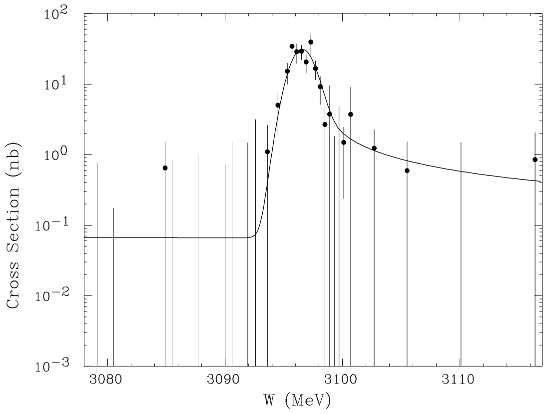

FIG. 1. The center-of-mass energy dependence of the $\rho\pi$ cross section resulting from the likelihood fit (curve), compared to the data corrected for the efficiency and background.

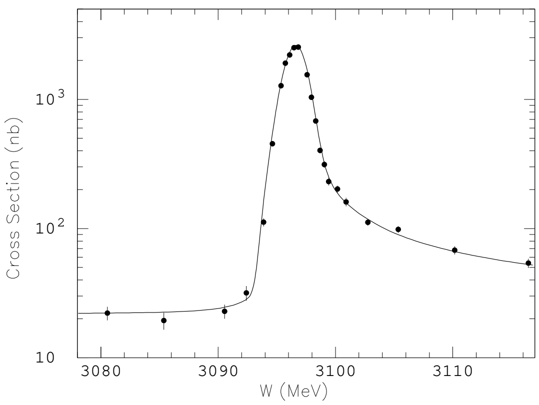

FIG. 2. The total cross section for $e^+e^- \to hadrons$.

TABLES

TABLE I. A summary of the data of the $\rho\pi$ scan.

Scan point	W (MeV)	$\mathcal{L}$ (nb^{-1})	N
1	3079.1	11.434	0
2	3080.5	51.378	0
3	3084.9	12.086	1
4	3085.5	10.767	0
5	3087.7	9.142	0
6	3090.0	12.318	0
7	3090.6	5.801	0
8	3091.9	6.019	0
9	3092.6	2.826	0
10	3093.6	6.866	1
11	3094.5	5.715	4
12	3095.3	5.498	12
13	3095.7	5.459	26
14	3096.1	3.353	14
15	3096.5	5.617	24
16	3096.9	5.414	17
17	3097.3	1.833	10
18	3097.7	6.161	15
19	3098.1	5.853	8
20	3098.5	4.384	2
21	3098.9	1.818	1
22	3099.3	4.036	0
23	3099.7	1.738	0
24	3100.1	13.470	3
25	3100.7	1.990	1
26	3102.7	11.376	2
27	3105.5	11.226	1
28	3110.1	5.659	0
29	3116.4	8.709	1