Branching fractions for $\psi(2S) \to \gamma\eta'$ and $\gamma\eta$

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We report first measurements of the branching fractions:

- $\mathcal{B}(\psi_{2S} \to \gamma\eta') = (1.54 \pm 0.31 \pm 0.23) \times 10^{-4}$ and
- $\mathcal{B}(\psi_{2S} \to \gamma\eta) = (0.53 \pm 0.31 \pm 0.08) \times 10^{-4}$.

The $\psi(2S) \to \gamma\eta'$ result is consistent with expectations of a model that considers the possibility of η'-η_c mixing. The ratio of the $\psi(2S) \to \gamma\eta'$ and $\psi(2S) \to \gamma\eta$ rates are used to determine the pseudoscalar octet-singlet mixing angle.

I. INTRODUCTION

In contrast to the J/ψ, experimental results on radiative decays of the $\psi(2S)$ to non-charmonium hadrons are scarce; in the latest Particle Data Group tables, only upper limits for a few decay modes are listed [1]. Moreover, it is found experimentally that, while decays to $\rho\pi$ and $K^*\overline{K}$ Vector Pseudoscalar (VP) final states are significant ($\sim 1\%$) for the J/ψ, hadronic decays of the $\psi(2S)$ to these same VP final states are strongly suppressed [2,3]. This longstanding mystery of charmonium physics is referred to in the literature as the $\rho\pi$ puzzle [4]. The processes $J/\psi \to \gamma\eta'(958)$ and $\gamma\eta$ are radiative VP channels that have been measured by several experiments [1]. It is of interest to see if the same radiative VP decays of the $\psi(2S)$ are suppressed to the same extent as the hadronic $\rho\pi$ and $K^*\overline{K}$ decays.

Recently, the CLEO experiment has reported an anomalously large branching fraction for the inclusive production of η' in the B-meson decay $B \to \eta' X_s$, where X_s denotes an inclusive hadronic system containing a strange quark [5]. One possible interpretation is the presence of an intrinsic charm component of the η' meson induced by the strong coupling of the η' to gluons via the QCD axial anomaly [6]. The resulting η'-η_c mixing has been proposed as the dominant mechanism for the OZI forbidden radiative charmonium decays such as $\psi(nS) \to \gamma\eta'$ and $\gamma\eta$. In this case, the branching fraction for $\psi(2S) \to \gamma\eta'$ is estimated to be in the range $(1.0 \sim 2.7) \times 10^{-4}$ [7].

The ratio of the $\gamma\eta'$ and $\gamma\eta$ decay rates of the $J^{PC} = 1^{--}$ charmonium states is sensitive to the pseudoscalar octet-singlet mixing angle θ_p. Neglecting SU(3)-breaking effects, one has the simple relation [8]

$$\frac{\Gamma(\psi_{nS} \to \gamma\eta')}{\Gamma(\psi_{nS} \to \gamma\eta)} = \left(\frac{p_{\eta'}}{p_\eta}\right)^3 \frac{1}{\tan^2\theta_p}, \qquad (1)$$

where p_η ($p_{\eta'}$) is the momentum of the η (η') in the $\psi(nS)$ rest frame. The measured J/ψ branching fraction values [1] imply a mixing angle of $|\theta_p| = 22^\circ \pm 1^\circ \pm 4^\circ$, (the second error is theoretical), which agrees well with the value determined from other processes [9]. Measurements of the corresponding branching fractions for the $\psi(2S)$ provide a consistency check of this relation. (Since the corrections to the relation given in Eqn. 1 are expected to be independent of the radial quantum number n [10], this form is convenient for comparing $\psi(2S)$ and J/ψ results.)

In this report we present the first measurement of the branching fractions for $\psi(2S) \to \gamma\eta'$ and $\psi(2S) \to \gamma\eta$ using 3.7×10^6 $\psi(2S)$ decays collected using the Beijing Spectrometer (BES) detector located at the Beijing Electron-Positron Collider (BEPC) at the Beijing Institute of High Energy Physics.

II. THE BES DETECTOR

The BES is a large solid-angle magnetic spectrometer that is described in detail in ref. [11]. Charged particle momenta are determined with a resolution of $\sigma_p/p = 2.1\%\sqrt{1+p^2(GeV^2)}$ in a 40-layer cylindrical drift chamber. Radially outside of the drift chamber is a 12-radiation-length barrel shower counter (BSC) comprised of gas proportional tubes interleaved with lead sheets. The BSC measures the energies and directions of photons with resolutions of $\sigma_E/E \simeq 22\%/\sqrt{E(GeV)}$, $\sigma_\phi = 4.5$ mrad, and $\sigma_\theta = 12$ mrad. The iron flux return of the magnet is instrumented with three double layers of counters that are used to identify muons.

For this analysis we use charged tracks with momentum greater than 80 MeV/c that are well fit to a helix originating near the interaction point. Candidate γ's are associated with energy clusters in the BSC that have more than three hit tubes in at least two readout layers. We only use charged tracks and γ's that are within the polar angle region $|\cos\theta| < 0.8$. We reject tracks that are identified as muons, or that produce high energy showers in the BSC that are characteristic of electrons. When computing energies, each charged tracks is assigned the pion mass.

III. DETERMINATION OF $\mathcal{B}(\psi(2S) \to \gamma\eta')$

For the $\psi(2S) \to \gamma\eta'$ measurement we investigate the decay chains

$$\psi_{2S} \to \gamma\,\eta' \quad \text{and} \quad \psi_{2S} \to \gamma\,\eta'$$
$$\gamma\,\rho^o \qquad\qquad \pi^+\pi^-\eta$$
$$\pi^+\pi^- \qquad\qquad 2\gamma.$$

It follows that the reactions of interest are $\psi(2S) \to \pi^+\pi^-\gamma\gamma$ for the $\rho^0\gamma$ mode, and $\psi(2S) \to \pi^+\pi^-\gamma\gamma\gamma$ for the $\pi^+\pi^-\eta$ decays.

A. The $\psi(2S) \to \gamma\eta' \to \gamma\gamma\rho^0$ measurement

For the measurement using the $\eta' \to \gamma\rho^0$ mode, we require two oppositely charged tracks with an opening angle $\theta_{open} < 130^\circ$ and at least two candidate γ's that are more that 10 degrees away from the nearest charged track. The events where the total energy of the two charged tracks is less than 2.1 GeV are subjected to a four-constraint kinematic fit to the hypothesis $\psi(2S) \to \pi^+\pi^-\gamma\gamma$ and required to have $\chi^2 < 15$. The $\pi^+\pi^-\gamma$ mass distribution for events with $M_{\pi^+\pi^-}$ within 0.15 GeV of M_ρ and a $\gamma\gamma$ opening angle greater than 110° is plotted in Fig. 1, where a peak at the mass of the $\eta'(958)$ is apparent. The curve in Fig. 1 is the result of a fit to the measured mass distribution with the $\eta(958)$ represented as a Gaussian and a third-order polynomial background function. The width of the Gaussian is fixed at the Monte-Carlo determined experimental resolution of $\sigma = 0.01$ GeV. The fitted Gaussian has a peak position at $M_{\eta(958)}$ and $N_{evts} = 28.1 \pm 7.2$ events. Events from the cascade decays $\psi(2S) \to anything + J/\psi$ where $J/\psi \to \gamma\eta'$ or $J/\psi \to \pi^0\rho^0$ also can give a peak at $M_{\eta'(958)}$. Using Monte Carlo simulated events, we estimate the contamination from this source to be $N_{bkg} = 1.4 \pm 0.5$ events.

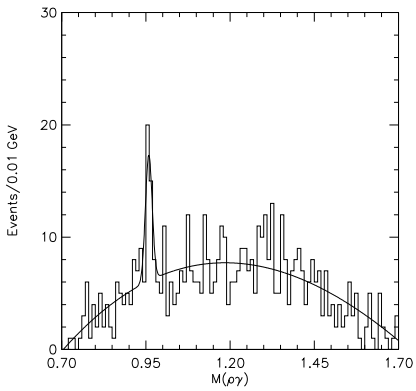

FIG. 1. The $\pi^+\pi^-\gamma$ invariant mass distribution for selected events.

We use Monte Carlo simulated events to determine the acceptance. The events are generated with a $1 + \cos^2\theta$ angular distribution for the $\psi(2S) \to \gamma\eta'$ decays, anisotropic distribution for the $\eta' \to \gamma\rho^0$ decays, followed

by helicity ± 1 $\rho^0 \to \pi^+\pi^-$ decays. The acceptance determined in this way is $\epsilon_{\rho\gamma} = 0.18 \pm 0.02$, where the error includes both Monte Carlo statistics and uncertainties in the simulation program.

The $\psi(2S) \to \gamma\eta'$ branching ratio is determined from the relation

$$\mathcal{B}(\psi_{2S} \to \gamma\eta') = \frac{N_{evts} - N_{bkg}}{N_{\psi_{2S}}\mathcal{B}(\eta' \to \gamma\rho)\epsilon_{\rho\gamma}} = (1.36 \pm 0.37 \pm 0.20) \times 10^{-4}. \quad (2)$$

Here the first error is statistical, and the second is the systematic error due primarily to uncertainties in $N_{\psi_{2S}}$ and the acceptance.

B. The $\psi(2S) \to \gamma\eta' \to \gamma\pi^+\pi^-\eta$ measurement

For the measurement using the $\eta' \to \pi^+\pi^-\eta$ mode, we require two oppositely charged tracks with an opening angle $\theta_{open} < 70°$, and at least three candidate γ's that are more than five degrees away from the nearest charged track. We select events with a total energy for the two charged tracks that is less than 1.2 GeV, and require them to satisfy a four-constraint kinematic fit to the hypothesis $\psi(2S) \to \pi^+\pi^-\gamma\gamma\gamma$ with $\chi^2 < 12$. We identify $\gamma\gamma$ pairs with an invariant mass within 0.03 GeV of M_η as candidate η's. The $\pi^+\pi^-\eta$ mass distribution for selected events is plotted in Fig. 2. There is a peak in the data at the mass of the $\eta'(958)$.

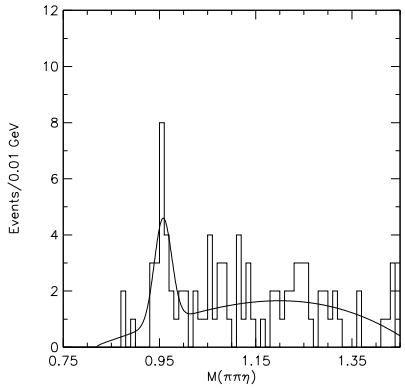

FIG. 2. The $\pi^+\pi^-\eta$ invariant mass distribution for selected events.

The curve in Fig. 2 is the result of a fit to the measured mass distribution with the $\eta(958)$ represented as a Gaussian and a polynomial background function that is forced to zero at the $\pi^+\pi^-\eta$ threshold. The width of the Gaussian is fixed at $\sigma = 0.018$ GeV, the resolution value determined from the MC simulation. The fitted Gaussian has $N_{evts} = 16.8 \pm 4.9$ events. The Monte Carlo estimate of backgrounds from $\psi(2S) \to J/\psi$ cascade decays is $N_{bkg} = 0.35 \pm 0.03$. The MC determined acceptance for this mode is 0.14 ± 0.015, and the corresponding $\psi(2S) \to \gamma\eta'$ branching fraction is

$$\mathcal{B}(\psi_{2S} \to \gamma\eta') = (2.00 \pm 0.59 \pm 0.29) \times 10^{-4}. \quad (3)$$

The agreement with the result determined for the $\eta' \to \gamma\rho^0$ mode is reasonable.

IV. THE $\psi(2S) \to \gamma\eta$ MEASUREMENT

For the $\psi(2S) \to \gamma\eta$ measurement, we use the $\eta \to \pi^+\pi^-\pi^0$ decay mode. This corresponds to the same $\psi(2S) \to \pi^+\pi^-\gamma\gamma\gamma$ reaction as for the $\eta' \to \pi^+\pi^-\eta$ measurement.

We require two oppositely charged tracks with total energy less than 1.7 GeV and at least three candidate γ's that are more than five degrees away from the nearest charged track. The events are required to satisfy a four-constraint kinematic fit to the hypothesis $\psi(2S) \to \pi^+\pi^-\gamma\gamma\gamma$ with $\chi^2 < 12$. We identify $\gamma\gamma$ pairs with an invariant mass within 0.025 GeV of m_{π^0} as candidate π^0's. The $\pi^+\pi^-\pi^0$ mass distribution for events where $m_{\pi^+\pi^-} < 0.42$ GeV is plotted in Fig. 3. Here small clusters of events appear at the mass of the $\eta(547)$ and the $\omega(780)$.

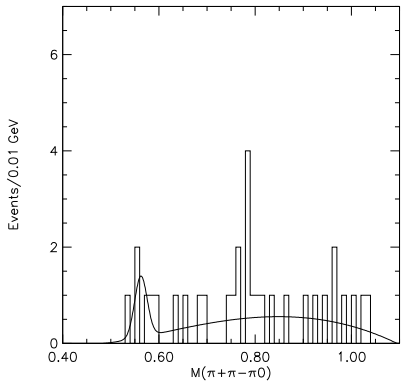

FIG. 3. The $\pi^+\pi^-\pi^0$ invariant mass distribution for selected events.

The curve in Fig. 3 is the result of a fit to the measured mass distribution with the η represented as a Gaussian and a polynomial background function. The width of the Gaussian is fixed at $\sigma = 0.013$ GeV, the value determined from the MC simulation. The $\omega(780)$ mass region is excluded from the fit. The fitted Gaussian has a peak position at $M_{\pi^+\pi^-\pi^0} = 0.56 \pm 0.01$, which is one standard deviation above M_η, and an area of $N^\eta_{evts} = 4.1 \pm 2.4$ events. The MC-determined acceptance for this channel is 0.10 ± 0.012.

The $\psi(2S) \to \gamma\eta$ signal has a statistical significance corresponding to a little less than 2σ. If we treat the 4.1 observed events as a real signal, the $\psi(2S) \to \gamma\eta$ branching fraction is determined to be

$$\mathcal{B}(\psi_{2S} \to \gamma\eta) = (0.53 \pm 0.31 \pm 0.08) \times 10^{-4}. \quad (4)$$

The 4.1 events from the fit imply a 90% confidence level (c.l.) upper limit of 7.2 events; this corresponds to a

90% c.l. limit on the $\psi(2S) \to \gamma\eta$ branching fraction of 0.9×10^{-4}.

V. DISCUSSION

Combining the two results for $\mathcal{B}(\psi(2S) \to \gamma\eta')$ from the different η' decay modes gives

$$\mathcal{B}(\psi_{2S} \to \gamma\eta') = (1.54 \pm 0.31 \pm 0.23) \times 10^{-4}, \qquad (5)$$

which is within the range expected for the case where $\eta' - \eta_c$ mixing is important [7]. To compare with J/ψ decays, we use the ratio

$$Q_{\gamma\eta'} = \frac{\mathcal{B}(\psi_{2S} \to \gamma\eta')}{\mathcal{B}(J/\psi \to \gamma\eta')} = 0.036 \pm 0.009. \qquad (6)$$

This low value for $Q_{\gamma\eta'}$ indicates that this $\psi(2S)$ decay mode is suppressed relative to di-lepton decays, where the corresponding ratio $Q_{\ell\ell} = 0.147 \pm 0.023$ [1], but not as severely as in the case of $\rho\pi$, where $Q_{\rho\pi} < 0.002$, or $K^{*+}K^-$, where $Q_{K^{*+}K^-} < 0.006$ [3]. Pinsky relates the processes $\psi(2S) \to \gamma\eta'$ to the hindered $M1$ transition $\psi(2S) \to \gamma\eta_c$ [12]. He predicts $Q_{\gamma\eta'} = 0.002$, which is well below our measured value.

The suppression of $J/\psi \to \gamma\eta$ relative to $J/\psi \to \gamma\eta'$ decays appears to also occur for the $\psi(2S)$:

$$\frac{\mathcal{B}(J/\psi \to \gamma\eta)}{\mathcal{B}(J/\psi \to \gamma\eta')} = 0.200 \pm 0.023 \text{ (PDG)}; \qquad (7)$$

$$\frac{\mathcal{B}(\psi(2S) \to \gamma\eta)}{\mathcal{B}(\psi(2S) \to \gamma\eta')} = 0.34 \pm 0.22 \text{ (this expt)}. \qquad (8)$$

Our results provide an independent evaluation of the mixing angle of $|\theta_p| = 28^{\circ}{}^{+7^{\circ}}_{-10^{\circ}}$, which is consistent with other determinations, albeit with larger errors.

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