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

J. Z. Bai[1], J. G. Bian[1], I. Blum[11], Z. W. Chai[1], G. P. Chen[1], H. F. Chen[10], J. Chen[3], J. C. Chen[1], Y. Chen[1], Y. B. Chen[1], Y. Q. Chen[1], B. S. Cheng[1] X. Z. Cui[1], H. L. Ding[1], L. Y. Ding[1], L. Y. Dong[1], Z. Z. Du[1], W. Dunwoodie[7], S. Feng[1], C. S. Gao[1], M. L. Gao[1], S. Q. Gao[1], P. Gratton[11], J. H. Gu[1], S. D. Gu[1], W. X. Gu[1], Y. F. Gu[1], Y. N. Guo[1], S. W. Han[1], Y. Han[1], F. A. Harris[8], J. He[1], J. T. He[1], M. He[5], D. G. Hitlin[2], G. Y. Hu[1], H. M. Hu[1], J. L. Hu[1], Q. H. Hu[1], T. Hu[1], X. Q. Hu[1], J. D. Huang[1], Y. Z. Huang[1], J. M. Izen[11], C. H. Jiang[1], Y. Jin[1], Z. J. Ke[1], M. H. Kelsey[2], B. K. Kim[11], D. Kong[8], Y. F. Lai[1], P. F. Lang[1], A. Lankford[9], C. G. Li[1], D. Li[1], H. B. Li[1], J. Li[1], P. Q. Li[1], R. B. Li[1], W. Li[1], W. D. Li[1], W. G. Li[1], X. H. Li[1], X. N. Li[1], H. M. Liu[1], J. Liu[1], J. H. Liu[1], R. G. Liu[1], Y. Liu[1], X. C. Lou[11], B. Lowery[11], F. Lu[1], J. G. Lu[1], J. Y. Lu[1], L. C. Lu[1], C. H. Luo[1], A .M .Ma[1], E. C. Ma[1], J. M. Ma[1], R. Malchow[3], H. S. Mao[1], Z. P. Mao[1], X. C. Meng[1], J. Nie[1], S. L. Olsen[8], J. Oyang[2], D. Paluselli[8], L. J. Pan[8], J. Panetta[2], F. Porter[2], N. D. Qi[1], X. R. Qi[1], C. D. Qian[6], J. F. Qiu[1], Y. H. Qu[1], Y. K. Que[1], G. Rong[1], M. Schernau[9], Y. Y. Shao[1], B. W. Shen[1], D. L. Shen[1], H. Shen[1], X. Y. Shen[1], H. Y. Sheng[1], H. Z. Shi[1], X. F. Song[1], J. Standifird[11], F. Sun[1], H. S. Sun[1], S. Q. Tang[1], W. Toki[3], G. L. Tong[1], F. Wang[1], L. S. Wang[1], L. Z. Wang[1], M. Wang[1], Meng Wang[1], P. Wang[1], P. L. Wang[1], S. M. Wang[1], T. J. Wang[1†], Y. Y. Wang[1], M. Weaver[2], C. L. Wei[1], Y. G. Wu[1], D. M. Xi[1], X. M. Xia[1], P. P. Xie[1], Y. Xie[1], Y. H. Xie[1], W. J. Xiong[1], C. C. Xu[1], G. F. Xu[1], S. T. Xue[1], J. Yan[1], W. G. Yan[1], C. M. Yang[1], C. Y. Yang[1], J. Yang[1], W. Yang[3], X. F. Yang[1], M. H. Ye[1], S. W. Ye[10], Y. X. Ye[10], K. Yi [1], C. S. Yu[1], C. X. Yu[1], Y. H. Yu[4], Z. Q. Yu[1], Z. T. Yu[1], C. Z. Yuan[1], Y. Yuan[1], B. Y. Zhang[1], C. C. Zhang[1], D. H. Zhang[1], Dehong Zhang[1], H. L. Zhang[1], J. Zhang[1], J. L. Zhang[1], J. W. Zhang[1], L. S. Zhang[1], Q. J. Zhang[1], S. Q. Zhang[1], X. Y. Zhang[5], Y. Zhang[1], Y. Y. Zhang[1], D. X. Zhao[1], H. W. Zhao[1‡], J. W. Zhao[1], M. Zhao[1], W. R. Zhao[1], Z. G. Zhao[1], J. P. Zheng[1], L. S. Zheng[1], Z. P. Zheng[1], G. P. Zhou[1], H. S. Zhou[1], L. Zhou[1], Q. M. Zhu[1], Y. C. Zhu[1], Y. S. Zhu[1], B. A. Zhuang[1]

(BES Collaboration)

[1] *Institute of High Energy Physics, Beijing 100039, People's Republic of China*
[2] *California Institute of Technology, Pasadena, California 91125*
[3] *Colorado State University, Fort Collins, Colorado 80523*
[4] *Hangzhou University, Hangzhou 310028, People's Republic of China*
[5] *Shandong University, Jinan 250100, People's Republic of China*
[6] *Shanghai Jiaotong University, Shanghai 200030, People's Republic of China*
[7] *Stanford Linear Accelerator Center, Stanford, California 94309*
[8] *University of Hawaii, Honolulu, Hawaii 96822*
[9] *University of California at Irvine, Irvine, California 92717*
[10] *University of Science and Technology of China, Hefei 230026, People's Republic of China*
[11] *University of Texas at Dallas, Richardson, Texas 75083-0688*

(July 6, 1998)

We report first measurements of the branching fractions:

- $\mathcal{B}(\psi_{2S} \to \gamma\eta') = (1.54 \pm 0.31 \pm 0.20) \times 10^{-4}$ 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'-$\eta_c(2S)$ mixing. The ratio of the $\psi(2S) \to \gamma\eta'$ and $\psi(2S) \to \gamma\eta$ rates is 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'-$\eta_c(nS)$ 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 the case where η'-$\eta_c(2S)$ mixing is important, the branching fraction for $\psi(2S) \to \gamma\eta'$ is estimated to be in the range $(1.0 - 2.7) \times 10^{-4}$ [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. Assuming that the process occurs primarily through radiation of the photon from one of the initial state c-quarks and the applicability of SU(3) symmetry for the decay amplitudes, one has the simple relation [8]

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

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 $|\theta_p| = 22° \pm 1° \pm 4°$, (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.

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 3.44×10^6 $\psi(2S)$ decays [10] collected using the Beijing Spectrometer (BES) 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 $\sigma_p/p = 1.7\%\sqrt{1+p^2(GeV^2)}$ 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 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 track 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

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

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 $\theta_{open} < 130°$ and at least two candidate γ's that are more than 10 degrees away from the nearer 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.

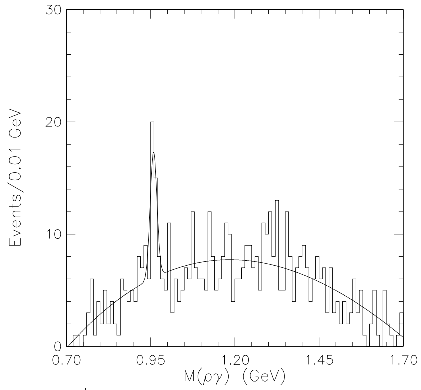

FIG. 1. The $\pi^+\pi^-\gamma$ invariant mass distribution for selected events.

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 [12]. 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 $M_{\eta'(958)}$. We subject a sample of Monte Carlo simulated events equivalent to ten times the $\psi(2S)$ data set to the same selection and fitting procedure. The resulting estimate of the contamination from this source is $N_{bkg} = 1.4 \pm 0.5$ events, where the error is statistical and comes from the fit.

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, an isotropic 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 $\epsilon_{\rho\gamma} = 0.19 \pm 0.02$, where the error includes both Monte Carlo statistics (7%) and uncertainties in the simulation program (8%) [13] added in quadrature.

The $\psi(2S) \to \gamma\eta'$ branching fraction 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 to uncertainties in $N_{\psi_{2S}}$ (9%), the acceptance (11%) and the $\eta' \to \gamma\rho$ branching fraction (4%) added in quadrature.

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 nearer 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 the selected events is plotted in Fig. 2. There is a peak in the data at the mass of the $\eta'(958)$.

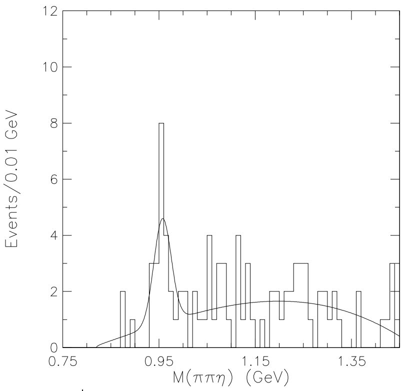

FIG. 2. The $\pi^+\pi^-\eta$ invariant mass distribution for selected events.

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 nearer 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 is plotted in Fig. 3. Here small clusters of events appear at the mass of the $\eta(547)$ and the $\omega(780)$.

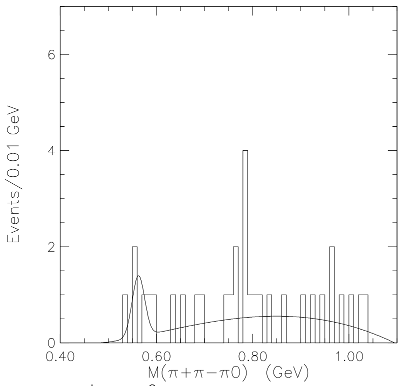

FIG. 3. The $\pi^+\pi^-\pi^0$ invariant mass distribution for selected events. The region near the $\omega(785)$ is excluded from the fit.

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.

As a check, we used the events in the π^0 sidebands of the $\gamma\gamma$ invariant mass distribution as an experimental estimate of our background. Here we find no events within $\pm3\sigma$ of M_η and a fit to the sideband-subtracted $M_{\pi^+\pi^-\pi^0}$ distribution yields 6.0 ± 2.5 η events.

The $\psi(2S) \to \gamma\eta$ signal has a statistical significance corresponding to a little less than 2σ [14]. If we treat the 4.1 observed events as a real signal, the $\psi(2S) \to \gamma\eta$ branching fraction is determined to be

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

(The MC-determined acceptance for this channel is 0.10 ± 0.012.) 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 [15]

$$\mathcal{B}(\psi_{2S} \to \gamma\eta') = (1.54 \pm 0.31 \pm 0.20) \times 10^{-4}, \tag{5}$$

which is within the range expected for the case where $\eta' - \eta_c(2S)$ mixing is important [7]. To compare with J/ψ decays, we use the ratio

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

This low value for $Q_{\gamma\eta'}$ indicates that this $\psi(2S)$ decay mode is suppressed relative to e^+e^- decays, where the corresponding ratio $Q_{e^+e^-} = 0.146 \pm 0.022$ [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 [16] relates the processes $\psi(2S) \to \gamma\eta'$ to the hindered $M1$ transition $\psi(2S) \to \gamma\eta_c$. 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 $\psi(2S)$:

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

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

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.

VI. ACKNOWLEDGEMENTS

We acknowledge the strong efforts of the BEPC staff and the helpful assistance we received from the members of the IHEP computing center. We also thank K-T. Chao for a number of helpful discussions.

---

† Deceased.

‡ Present address: Beijing University, Beijing, China.

† Work supported in part by the National Natural Science Foundation of China under Contract No. 19290400 and the Chinese Academy of Sciences under contract No. KJ85 (IHEP), and by the Department of Energy under Contract Nos. DE-FG03-92ER40701 (Caltech), DE-FG03-93ER40788 (Colorado State University), DE-AC03-76SF00515 (SLAC), DE-FG03-91ER40679 (UC Irvine), DE-FG03-94ER40833 (U Hawaii), DE-FG03-95ER40925 (UT Dallas).

[1] R.M. Barnett *et al.* (Particle Data Group), Phys. Rev. **D54**, 1 (1996).

[2] M.E.B. Franklin *et al.* (Mark II Collaboration), Phys. Rev. Lett. **51**, 963 (1983).

[3] Y.S. Zhu (representing the BES Collaboration), *Recent $\psi(2S)$ and χ_C results from BES*, paper submitted to the XXVIIIth International Conference on High Energy Physics, Warsaw, Poland, July 1996.

[4] See, for example, W.-S. Hou and A. Soni, Phys. Rev. Lett. **50**, 569 (1983) and S.J. Brodsky, G.P. Lepage and S.F. Tuan Phys. Rev. Lett. **59**, 621 (1987).

[5] T.E. Browder *et al.* (CLEO Collaboration), submitted to Physical Review Letters.

[6] F. Yuan and K-T. Chao, Phys. Rev. **D56**, 2495 (1997); I. Halperin and A. Zhitnitsky, hep-ph/9704412; I. Halperin and A. Zhitnitsky hep-ph/9705251; and E. Shuryak and A. Zhitnitsky hep-ph/9706316.

[7] K-T. Chao, private communication; see also Nuclear Physics **B317**, 597 (1989); **B335**, 101 (1990).

[8] R.N. Cahn and M.S. Chanowitz, Phys. Lett **B59**, 277 (1975); T.F. Walsh, Lett Nuovo Cimento **14**, 290 (1975); and H. Fritzsch and J.D. Jackson, Phys. Lett **B66**, 365 (1977).

[9] F.J. Gilman and R. Kauffman, Phys. Rev. **D36**, 2761 (1987).

[10] This is a subset of the BES group's total sample of 3.78×10^6 $\psi(2S)$ events.

[11] J.Z. Bai *et al.* (BES Collaboration), Nucl. Instr. Meth. **A344**, 319 (1994).

[12] The resolution parameters in the simulation program have been tuned and checked with data from high statistics processes. For example, the measured width of the ~400 event $\omega \to \pi^+\pi^-\pi^0$ peak in $\psi(2S) \to \pi^+\pi^-\omega$ decays ($\sigma = 16.1 \pm 1.1$ MeV) agrees well with the MC expectation ($\sigma_{MC} = 16.6$ MeV).

[13] The systematic error on the MC efficiency is mostly due to uncertainties in the modeling of the photon shower clustering. These are studied using $J/\psi \to \pi^+\pi^-\pi^0$ events.

[14] The area under the background function for the interval $M_\eta \pm 3\sigma$ is 0.8 event. The probability that this can fluctuate to the observed signal plus background is ~3.5%.

[15] All components of the systematic error calculations for the two η' decay modes are common except for the MC statistics.

[16] S.S. Pinsky, Phys. Lett. **B236**, 479 (1990).