Recent results on η_c and $\eta_c(2S)$ from BaBar

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This contribution reports the results of the studies on the pseudoscalar states of the charmonium ($c\bar{c}$) spectrum, η_c and $\eta_c(2S)$, performed by the BABAR Collaboration. The results are based on a sample of data collected with the BABAR detector [1] at a center-of-mass energy equal to the $\Upsilon(4S)$ mass, and corresponding to an integrated luminosity of about $90\,\mathrm{fb}^{-1}$.

1 Measurement of the η_c and $\eta_c(2S)$ resonance parameters

The mass and width of the η_c meson, the lowest lying state of charmonium, are not well established after almost 30 years from its first observation. In particular, the most recent measurements of the the total width [2] point to values substantially larger than the current world average [3]. The first radial excitation of the η_c, the $\eta_c(2S)$, has recently been observed by Belle in exclusive $B^+ \to \eta_c(2S)K^+$, $\eta_c(2S) \to K^0_S K^+\pi^-$ decays [4] [5] and in the J/ψ recoil spectrum in e^+e^- annihilations [6], at a mass significantly higher than what originally reported by the Crystal Ball experiment [7].

The η_c is known to be coupled to two photons ($\mathcal{B}(\eta_c \to \gamma\gamma) \sim 5 \cdot 10^{-4}$). An estimate of the two-photon production rate of $\eta_c(2S)$ suggests that also the radial excitation could be identified in the current e^+e^- B-factory [8]. At BABAR, $\gamma\gamma$ interactions result from virtual photons emitted by electrons and positrons in the colliding beams: the cross section is highly peaked at small angles, so that in most cases the electron and positron remain undetected and the momentum of detected particles is balanced in the transverse plane.

In the analysis [9], $K^0_S K^+\pi^-$ final states are considered. Events are selected by requiring four charged particles with total transverse momentum $p_{\mathrm{T}} < 0.5\,\mathrm{GeV}/c$ and total energy in the laboratory frame $E_{tot} < 9\,\mathrm{GeV}$, in order to suppress $e^+e^- \to q\bar{q}$ events. One track is required to be identified as a kaon and pairs of oppositely charged tracks are used to reconstruct $K^0_S \to \pi^+\pi^-$ decays. The $K^0_S K^+\pi^-$ vertex is fitted, with the K^0_S mass constrained to the world average value.

Figure 1 (a) shows the resulting $K^0_S K^+ \pi^-$ invariant mass spectrum. The presence of a peak at the J/ψ mass is due to initial state radiation events, where a photon is emitted in the initial state, and a backward-going J/ψ is produced, its decay products falling into the detector acceptance because of the Lorentz boost of the center of mass. A fit to this distribution with a sum of a smooth background shape, a Gaussian function for the J/ψ peak and the convolution of a non-relativistic Breit-Wigner shape with a Gaussian resolution function for the η_c peak, gives: $m(J/\psi) - m(\eta_c) = (114.4 \pm 1.1)$ MeV/c^2, $m(J/\psi) = (3093.6 \pm 0.8)$ MeV/c^2, $\Gamma(\eta_c) = (34.3 \pm 2.3$ MeV/$c^2)$, $\sigma(J/\psi) = (7.6 \pm 0.8)$ MeV/c^2. The numbers of η_c and J/ψ events are respectively 2547 ± 90 and 358 ± 33.

The η_c mass resolution $\sigma(\eta_c)$ is constrained by the close J/ψ peak; the small difference (0.8 MeV/c^2) observed between $\sigma(J/\psi)$ and $\sigma(\eta_c)$ in the simulation is taken into account in the fit to data. The simulation is also used to check for possible bias in the fitted masses. The η_c and J/ψ mass peaks are shifted by the same amount (1.1 MeV/c^2) in the simulation, therefore the bias does not affect the mass difference and the η_c mass is determined by subtracting 114.4 MeV/c^2 from the world-average value of the J/ψ mass. The systematic error on the mass accounts for an uncertainty on $m(J/\psi) - m(\eta_c)$ due to the background subtraction, and for an uncertainty associated to the different angular distributions of the J/ψ and the η_c. The systematic error on the width is dominated by the uncertainty in the

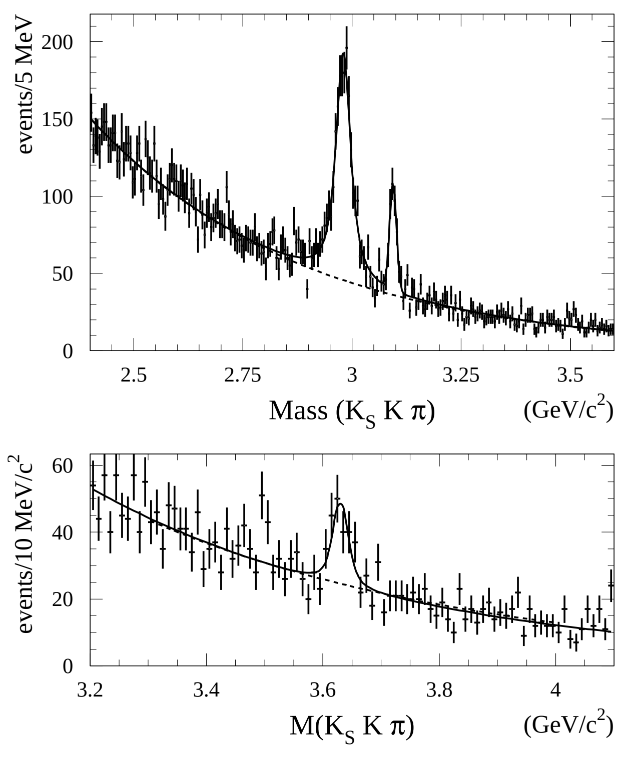

Figure 1: The $K^0_S K^+ \pi^-$ invariant mass spectrum for selected events: (a) the η_c (and J/ψ) region; (b) detail of the $\eta_c(2S)$ region, with results from the fit superimposed.

background-subtraction and in the mass resolution. The final results for the η_c mass and width are

$$m(\eta_c) = (2982.5 \pm 1.1(\text{stat}) \pm 0.9(\text{syst}))\,\text{MeV}/c^2, \quad (1)$$

$$\Gamma(\eta_c) = (34.3 \pm 2.3(\text{stat}) \pm 0.9(\text{stat}))\,\text{MeV}/c^2. \quad (2)$$

A detail of the highest part of the spectrum is shown in Fig. 1 (b): an enhancement corresponding to the $\eta_c(2S)$ peak is clearly visible. A fit similar to the previous one is applied to these data, which yields 112 $\pm$ 24 $\eta_c(2S)$ events. The final results are:

$$m(\eta_c(2S)) = (3630.8 \pm 3.4(\text{stat}) \pm 1.0(\text{syst}))\,\text{MeV}/c^2, \quad (3)$$

$$\Gamma(\eta_c(2S)) = (17.0 \pm 8.3(\text{stat}) \pm 2.5(\text{stat}))\,\text{MeV}/c^2. \quad (4)$$

Systematic errors are evaluated as for the η_c. In addition, they include a contribution due to the maximum variation on the mass (0.1 MeV/c^2) and width (0.7 MeV/c^2) which can be induced by five $\psi(2S)$ events, corresponding to the estimated upper limit for the ISR production of this higher resonance.

The deduced mass splitting is $m(\psi(2S)) - m(\eta_c(2S)) = (55.2 \pm 4.0)$ MeV/c^2.

2 Production in B decays: $B \to \eta_c K$ and η_c branching fractions

The decay $B \to \eta_c K$ is studied at BABAR to measure the CP violating parameter sin2β, but it is also interesting dinamically. The ratio of its decay rate to that of $B \to J/\psi K$ reflects the underlying strong dynamics and can be used to check models of heavy quark systems.

In the analysis [10] η_c mesons are reconstructed in the $K_S^0 K^\pm \pi^\mp$, $K^+K^-\pi^0$, $K^+K^-K^+K^-$ and $\phi\phi$ decay modes. Candidates for K_S^0 are identified through the decay $K_S^0 \to \pi\pi$, ϕ candidates through $\phi \to K^+K^-$ and π^0 candidates through $\pi^0 \to \gamma\gamma$. Note that η_c decays to $K^+K^-K^+K^-$ include both non-resonant and resonant ($\phi\phi$, ϕK^+K^-) components, so the $K^+K^-K^+K^-$ sample partially overlaps to the $\phi\phi$ sample.

A significant signal is observed in all modes. In the largest sample ($\eta_c \to K_S^0 K^\pm \pi^\mp$) the η_c width $\Gamma(\eta_c)$ can be determined from a simultaneous fit to neutral and charged B data, shown in Fig. 2 for all modes. In the fit, the mass of the η_c is fixed to the world-average value and the width is determined to be $\Gamma(\eta_c) = 39.7 \pm 6.6\,\text{MeV}/c^2$, where the error is statistical only. Since this value is consistent with the two-photon measurement, the most precise two-photon result is used in the individual fits to determine the branching-fractions.

The results on the products of the branching fractions for each mode are listed in Table 1. The systematic error comprises the uncertainties on the signal efficiency, on the number of $B\overline{B}$ pairs, on the extracted yield, and on the secondary branching fractions for the $K_S^0 \to \pi\pi$, $\pi^0 \to \gamma\gamma$ and $\phi \to K^+K^-$ decays. The dominant error is due to particle identification and tracking efficiency.

The decay amplitudes for $\eta_c \to K^+K^-\pi^0$ and $\eta_c \to K^0K^-\pi^+$ are related by isospin symmetry. Therefore, they are combined to obtain

$$\mathcal{B}(B^+ \to \eta_c K^+) \times \mathcal{B}(\eta_c \to K\bar{K}\pi) = (7.40 \pm 0.50 \pm 0.70) \times 10^{-5} \quad (5)$$

and

$$\mathcal{B}(B^0 \to \eta_c K^0) \times \mathcal{B}(\eta_c \to K\bar{K}\pi) = (6.48 \pm 0.85 \pm 0.71) \times 10^{-5}. \quad (6)$$

The $\eta_c \to 2(K^+K^-)$ and $\eta_c \to \phi\phi$ results can be expressed in terms of ratios to the best-measured branching fractions of $\eta_c \to K\bar{K}\pi$, thereby cancelling all fully-correlated systematic uncertainties. The average on charged B decays and neutral B decays, which takes into account correlations in the systematic uncertainties, is $\mathcal{B}(K^+K^-K^+K^-)/\mathcal{B}(\eta_c \to K\bar{K}\pi) = (2.3 \pm 0.7 \pm 0.6) \times 10^{-2}$ and $\mathcal{B}(\eta_c \to \phi\phi)/\mathcal{B}(\eta_c \to K\bar{K}\pi) = (5.5 \pm 1.4 \pm 0.5) \times 10^{-2}$. These results can be translated into η_c branching fractions:

$$\mathcal{B}(K^+K^-K^+K^-) = (1.3 \pm 0.4 \pm 0.3 \pm 0.4) \times 10^{-3}$$

$$\mathcal{B}(\eta_c \to \phi\phi) = (3.0 \pm 0.8 \pm 0.3 \pm 0.9) \times 10^{-3},$$

where the third error is due to the uncertainty of $\mathrm{B}(\eta_c \to K\bar{K}\pi)$. Note that about half of the $\eta_c \to 2(K^+K^-)$ events are due to $\eta_c \to \phi\phi$, $\phi \to K^+K^-$ decays. These branching fractions for $\eta_c \to 2(K^+K^-)$ and $\eta_c \to \phi\phi$ are consistent with recent results from Belle and

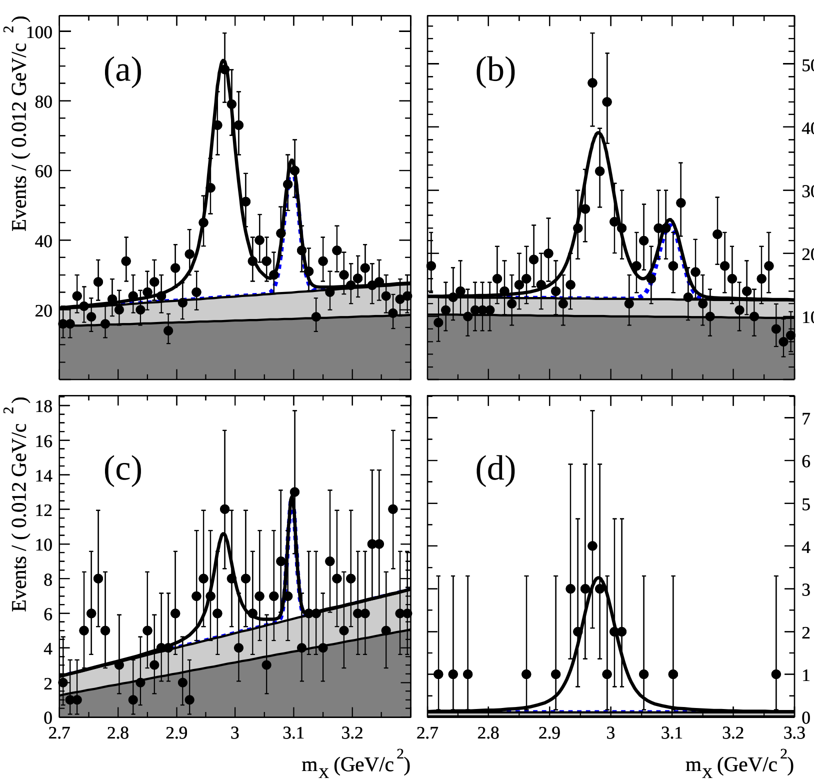

Figure 2: Distribution of the mass of the charmonium system for charged and neutral B candidates: (a) $\eta_c \to K^0_S K^{\pm}\pi^{\mp}$; (b) $\eta_c \to K^+K^-\pi^0$; (c) $\eta_c \to 2(K^+K^-)$; and (d) $\eta_c \to \phi\phi$. The fit result is overlaid as a solid curve.

Table 1: Measured branching-fraction products $B(B \to \eta_c K) \times B(\eta_c \to X)$ (10^{-6}). The first error is statistical and the second is the total systematic uncertainty.

η_c decay channel	$B^+ \to \eta_c K^+$	$B^0 \to \eta_c K^0$
$\eta_c \to K^0 K^- \pi^+$	$48.6 \pm 3.9 \pm 4.9$	$42.6 \pm 6.8 \pm 5.2$
$\eta_c \to K^+ K^- \pi^0$	$12.9 \pm 1.7 \pm 1.6$	$11.1 \pm 2.6 \pm 1.3$
$\eta_c \to 2(K^+ K^-)$	$2.0 \pm 0.6 \pm 0.4$	$0.9 \pm 0.9 \pm 0.4$
$\eta_c \to \phi\phi$	$4.7 \pm 1.2 \pm 0.5$	$2.4 \pm 1.4 \pm 0.3$

BES [11, 12] and are smaller than those of earlier experiments [3] by a factor twenty and two, respectively.

A similar analysis is performed to search for a new η_c decay mode, $\eta_c \to p\bar{p}\pi^+\pi^-$, in exclusive $B \to \eta_c K$ decays. A significant signal is observed for charged B decays. The measured product of branching-fractions is

$$\mathcal{B}(B^+ \to \eta_c K^+) \times \mathcal{B}(\eta_c \to p\bar{p}\pi^+\pi^-) = (7.6^{+1.7}_{-1.6} \pm 0.9) \times 10^{-6} \tag{7}$$

Using the BaBar value of $\mathcal{B}(B^+ \to \eta_c K^+) \times \mathcal{B}(\eta_c \to K\bar{K}\pi) = (7.40 \pm 0.50 \pm 0.70) \times 10^{-5}$, we obtain $\mathcal{B}(\eta_c \to p\bar{p}\pi^+\pi^-)/\mathcal{B}(\eta_c \to K\bar{K}\pi) = 0.103 \pm 0.024 \pm 0.016$ and $\mathcal{B}(\eta_c \to p\bar{p}\pi^+\pi^-) = (0.57 \pm 0.13 \pm 0.09 \pm 0.17)$ % where the third error is due to the uncertainty of $B(\eta_c \to K\bar{K}\pi)$. This result is still preliminary.

BaBar results are compared with Belle results in Table 2.

Table 2: Comparison of BaBar and Belle results.

	BaBar	Belle	PDG(2003)
$m(\eta_c)$(MeV/c^2)	$2982.5 \pm 1.1 \pm 0.9$	$2979.6 \pm 2.3 \pm 1.6$ [2]	2979.2 ± 1.3
$\Gamma(\eta_c)$ (MeV/c^2)	$34.3 \pm 2.3 \pm 0.9$	$29 \pm 8 \pm 6$ [2]	$16.1^{+3.1}_{-2.8}$
$m(\eta_c(2S))$(MeV/c^2)	$3630.8 \pm 3.4 \pm 1.0$	$3654 \pm 6 \pm 8$ [4]	3654 ± 10
$\Gamma(\eta_c(2S))$ (MeV/c^2)	$17.0 \pm 8.3 \pm 2.5$	<55 [4]	-
$B(B^+ \to \eta_c K^+)$ $\times 10^{-3}$	$1.34 \pm 0.09 \pm 0.13 \pm 0.41$	$1.25 \pm 0.14^{+0.10}_{-0.12} \pm 0.38$ [2]	0.9 ± 0.27
$B(B^0 \to \eta_c K^0)$ $\times 10^{-3}$	$1.18 \pm 0.16 \pm 0.13 \pm 0.37$	$1.23 \pm 0.23^{+0.12}_{-0.16} \pm 0.38$ [2]	1.2 ± 0.4
$B(\eta_c \to 2(K^+K^-))$ $\times 10^{-3}$	$1.3 \pm 0.4 \pm 0.3 \pm 0.4$	$1.4^{+0.5}_{-0.4} \pm 0.6$ [11]	21 ± 12
$B(\eta_c \to \phi\phi)$ $\times 10^{-3}$	$3.0 \pm 0.8 \pm 0.3 \pm 0.9$	$1.8^{+0.8}_{-0.6} \pm 0.7$ [11]	7.1 ± 2.8

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