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Charmonium and charmonium-like results from BaBar

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Summary. — We present new results on charmonium and charmonium-like states from the BABAR experiment located at the PEP-II asymmetric energy e^+e^- collider at the SLAC National Accelerator Laboratory.

PACS 13.66.Bc – Production by electron-positron collisions.
PACS 14.40.Lb – Charmed mesons.
PACS 14.40.Pq – Heavy quarkonia.
PACS 13.25.Gv – Decays of hadronic quarkonia.

1. – Charmonium spectroscopy

The charmonium spectrum consists of eight narrow states below the open charm threshold (3.73 GeV) and several tens of states above the threshold. Below the threshold almost all states are well established. On the other hand, very little is known above the threshold, there are several new "Charmonium-like" states that are very difficult to accommodate in the charmonium spectrum.

The B-factories are an ideal place to study charmonium since charmonium states are produced in four different processes:

- B decays, charmonium states of any quantum numbers can be produced.
- Two photon production: in this process two virtual photons are emitted by the colliding e^+e^- pair ($e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-(c\bar{c})$), charmonium states with $J^{PC} = 0^{\pm+}, 2^{\pm+}, 4^{\pm+}, \ldots, 3^{++}, 5^{++} \ldots$ can be produced.
- Initial State Radiation (ISR): where a photon is emitted by the incoming electron or positron ($e^+e^- \to \gamma c\bar{c}$), only states with $J^{PC} = 1^{--}$ are formed.
- Double charmonium production: in this process a J/ψ or a $\psi(2S)$ is produced together with another charmonium state.

TABLE I. – *Branching fraction measurements where the first uncertainty is statistical and the second is systematic.*

B channel	Branching fraction ($\times 10^{-5}$)
$B^+ \to J/\psi K^+K^-K^+$	$6.05 \pm 0.33 \pm 0.24$
$B^+ \to J/\psi \phi K^+$	$4.57 \pm 0.32 \pm 0.13$
$B^0 \to J/\psi K^+K^-K^0_S$	$3.55 \pm 0.57 \pm 0.15$
$B^0 \to J/\psi \phi K^0_S$	$2.53 \pm 0.35 \pm 0.09$

2. – Study of $B \to J/\psi K^+K^-K$ and search for $B^0 \to J/\psi\phi$

The CDF experiment in 2009 studied the decay $B \to J/\psi\phi K$ [1] and they observed the Y(4140) resonance in the $J/\psi\phi$ invariant mass distribution with a significance of 3.8σ (where σ corresponds to one standard deviation). They confirmed it in a later analysis [2] with more that 5σ with the additional observation of a bump around $4270\,\mathrm{MeV}/c^2$ (Y(4270)). In 2012, the LHCb experiment studied [3] the $B^+ \to J/\psi\phi K^+$ decay and did not confirm the Y(4140), in disagreement at 2.4σ with the CDF experiment. However, CMS in 2013 [4] and D0 in 2014 [5], confirmed the presence of the Y(4140) with 5σ and 3.1σ respectively, with hints for a state around $4270\,\mathrm{MeV}/c^2$.

BABAR study the decays $B \to J/\psi K^+K^-K$ [6], where B and K are either charged or neutral. The ϕ is reconstructed via its decay to K^+K^- and the J/ψ is reconstructed in the channels e^+e^- and $\mu^+\mu^-$. The selection is based on invariant masses of intermediate particles (J/ψ, ϕ and K^0_S), on the difference between the reconstructed energy of the B candidate and the beam energy ΔE, and on the vertex reconstruction of the J/ψ and ϕ particles. Clear signals are observed in the beam-energy-substituted mass m_{ES} for the charged and neutral channels. Fits to the m_{ES} distribution are performed to obtain the branching fractions reported in table I. These values are in good agreement with the previous measurement performed by BABAR [7]. The ratios of the resonant and non-resonant branching fractions are in good agreement with predicitions from spectator quark model.

The study of the $J/\psi\phi$ invariant mass is then performed using the decay $B \to J/\psi\phi K$. The invariant mass is fitted using two incoherent Breit-Wigner distributions where the parameters are fixed to the CDF values. A two-dimensional efficiency map is produced and taken into account in the fit. The background is described by a phase-space uniform distribution. The results of the fits are shown in fig. 1 for the charged mode. A fit which includes the two resonances seen by CDF returns a χ^2/ndf of 17.2/13 while a fit with no resonance returns 24.0/15. If we assume the presence of the two resonances, we obtain the fractions of the Y(4140) and Y(4270) resonances to be, respectively, $(7.3 \pm 2.5 \pm 3.8)\%$ and $(7.7 \pm 3.7 \pm 5.2)\%$. The upper limits at 90% confidence level on these fractions are respectively 12.1% and 16.4%. In conclusion, the hypothesis that the events are distributed uniformly on the Dalitz plot gives a worse description of the data, although, in order to access the presence of resonant behavior, higher statistics and a full Dalitz plot analysis are needed.

Finally, a search for the decay $B^0 \to J/\psi\phi$ is performed. This decay is expected to be strongly suppressed in the standard model. A m_{ES} fit of this channel is shown in fig. 1. The signal yield is measured to be 6 ± 4 events, giving a limit at 90% confidence level on the $B^0 \to J/\psi\phi$ branching fraction of 0.101×10^{-5}.

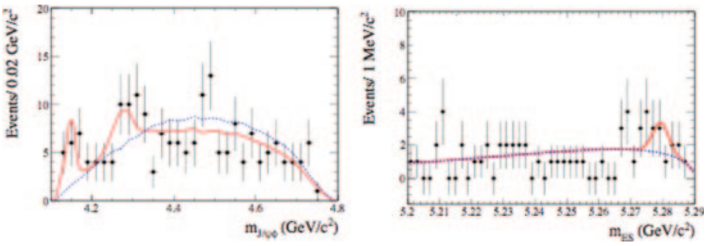

Fig. 1. – Left: distribution of the invariant mass of the $J/\psi\phi$ system for the decay $B^+ \to J/\psi\phi K^+$. The yellow histogram corresponds to the background estimated from the data side-band. The red line represents the fit result when including two resonances, while the blue dashed line represents the fit result with no resonance included. Right: fit to the m_{ES} distribution for the decay $B^0 \to J/\psi\phi$. The red continuous line is the total fit while the dashed blue line corresponds to the background contribution.

3. – Dalitz plot analyses of $\eta_c \to K^+K^-\eta$ and $\eta_c \to K^+K^-\pi^0$ in two-photon interactions

Using 529 fb^{-1}, we study [8] the reactions $\gamma^*\gamma^* \to K^+K^-\eta$ with $\eta \to \gamma\gamma$, $\pi^+\pi^-\pi^0$, and $\gamma^*\gamma^* \to K^+K^-\pi^0$. The photons are quasi-real photons, and the outgoing e^+ and e^- are produced at low angle and are not detected. This two-photon reaction can produce, among other particles, the η_c or $\eta_c(2S)$ $c\bar{c}$ resonances. Many η_c and $\eta_c(2S)$ decays are still missing or are studied with low statistics. Only 20% and less than 5% of the decays of the η_c and $\eta_c(2S)$ are known at present. This study brings also more information on poorly known scalar states and is sensitive to new gluonic states.

After the selection and the reconstruction of the events, the invariant mass of the $K^+K^-\eta$ system shows a prominent peak due to the η_c particle and a smaller contribution due to the $\eta_c(2S)$. The fit to the invariant mass yields 1145 events, which constitutes the first observation of the decay mode $\eta_c \to K^+K^-\eta$. 47 events are observed for $\eta_c(2S) \to K^+K^-\eta$ which is the first evidence of this decay. A fit to the $K^+K^-\pi^0$ invariant mass distribution gives 4518 η_c and 178 $\eta_c(2S)$ events. The resonances are described in the fits by Breit-Wigner functions convolved with the corresponding resolution functions. The parameter values are presented in table II.

The branching ratios between the decay modes are computed and found to be:

$$\mathcal{R}(\eta_c) = \frac{\mathcal{B}(\eta_c \to K^+K^-\eta)}{\mathcal{B}(\eta_c \to K^+K^-\pi^0)} = 0.571 \pm 0.025 \pm 0.051, \quad (1)$$

$$\mathcal{R}(\eta_c(2S)) = \frac{\mathcal{B}(\eta_c(2S) \to K^+K^-\eta)}{\mathcal{B}(\eta_c(2S) \to K^+K^-\pi^0)} = 0.82 \pm 0.21 \pm 0.27. \quad (2)$$

The first value can be compared to the measurement performed by BESIII [9] of 0.46 ± 0.23.

Full Dalitz plot analyses of the decays $\eta_c \to K^+K^-\eta$ and $\eta_c \to K^+K^-\pi^0$ are performed for the first time. The η_c signal region is defined in the range 2922–3036 MeV/c^2. The Dalitz plots and their projections are presented in figs. 2 and 3. Fits of the Dalitz planes are performed and reveal in the $\eta_c \to K^+K^-\eta$ channel the presence of the scalar resonances $f_0(980)$, $f_0(1500)$, $f_0(1710)$, and $f_0(2200)$ in the K^+K^- invariant mass. The states $f_0(1500)$ and $f_0(1710)$ are in particular possible gluonium candidates. In the

Table II. – *Fitted η_c and $\eta_c(2S)$ parameter values, where the first uncertainty is statistical and the second systematic.*

Resonance	Mass (MeV/c^2)	Γ (MeV)
$\eta_c \to K^+K^-\eta$	$2984.1 \pm 1.1 \pm 2.1$	$34.8 \pm 3.1 \pm 4.0$
$\eta_c \to K^+K^-\pi^0$	$2979.8 \pm 0.8 \pm 3.5$	$25.2 \pm 2.6 \pm 2.4$
$\eta_c(2S) \to K^+K^-\eta$	$3635.1 \pm 5.8 \pm 2.1$	11.3 (fixed)
$\eta_c(2S) \to K^+K^-\pi^0$	$3637.0 \pm 5.7 \pm 3.4$	11.3 (fixed)

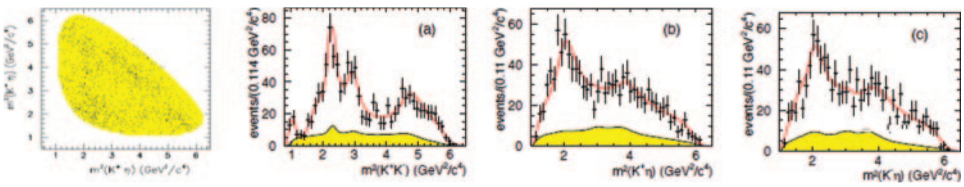

Fig. 2. – Left: Dalitz plot for the $\eta_c \to K^+K^-\eta$ events in the signal region. (a-c): The $\eta_c \to K^+K^-\eta$ Dalitz plot projections. The red curve shows the projection of the Dalitz fit and the shaded regions show the background estimates.

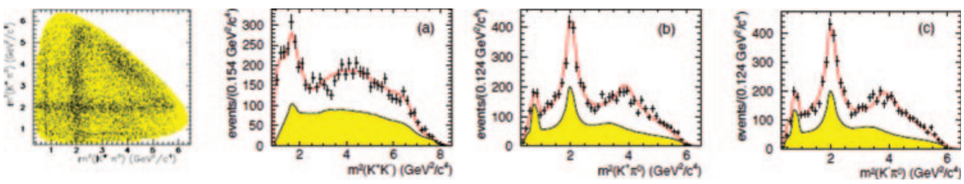

Fig. 3. – Left: Dalitz plot for the $\eta_c \to K^+K^-\pi^0$ events in the signal region. (a-c): The $\eta_c \to K^+K^-\pi^0$ Dalitz plot projections. The red curve shows the projection of the Dalitz fit and the shaded regions show the background estimates.

$\eta_c \to K^+K^-\pi^0$ channel, the K^+K^- invariant mass exhibits predominantly a peak at the $a_0(1450)$ position. In the $K^\pm\eta$ invariant mass (fig. 2b, c), a clear signal is seen for $K_0^*(1430) \to K^\pm\eta$, which constitutes the first observation for this decay mode. We notice also in fig. 3b, c that the $K^\pm\pi^0$ mass spectrum is dominated by the $K_0^*(1430)$ resonance. Interestingly, the observation of the $K_0^*(1430)$ is the first time this particle is seen as a peak (compared to its observation by LASS [10]).

A likelihood scan is performed in the Dalit plot analysis of $\eta_c \to K^+K^-\pi^0$ which allows to obtain the mass and width of the $K_0^*(1430)$ resonance. We obtain $M(K_0^*(1430)) = 1438 \pm 8 \pm 4\,\mathrm{MeV}/c^2$ and $\Gamma(K_0^*(1430)) = 210 \pm 20 \pm 12\,\mathrm{MeV}$. The mass value is in good agreement with the result from LASS [10], but the width is 3σ lower than the LASS result. The branching ratio between the two modes is calculate and found to be $\frac{\mathcal{B}(K_0^*(1430))\to K\eta}{\mathcal{B}(K_0^*(1430))\to K\pi} = 0.092 \pm 0.025^{+0.010}_{-0.025}$.

4. – Summary

In summary, the BaBar collaboration study the process $B \to J/\psi K^+K^-K$ and measure the branching fractions of these modes. A search is performed for the X(4140) and X(4270) resonances in the $J/\psi\phi$ invariant mass for the channel $B \to J\psi\phi K$. No definitive conclusion on their existence can be reach with this data sample. In addition, no significant signal is found for the decay $B \to J/\psi\phi$.

We also present results on $\gamma^*\gamma^* \to K^+K^-\eta$ and $\gamma^*\gamma^* \to K^+K^-\pi^0$ decays. We observe a large signal in both channels, with the first observation of the decay $\eta_c \to K^+K^-\eta$ and a first evidence for the decay $\eta_c(2S) \to K^+K^-\eta$. A Dalitz plot analysis has been performed, where we observe a large contribution from $\eta_c \to f_0(1500)\eta$, and with the first observation of the decay $K_0^*(1430) \to K^\pm\eta$.

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