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Study of $\phi(2170)$ at BESIII

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In e^+e^- collisions between 2 and 3 GeV, excited states of ρ, ω and ϕ can be produced directly. Especially the resonances around 2 GeV like $\rho(2000)$, $\rho(2150)$ and $\phi(2170)$ are not fully understood yet. Theorists describe the $\phi(2170)$ as a traditional $s\bar{s}$ state, an $s\bar{s}$ gluon hybrid, a tetraquark state, a $\Lambda\bar{\Lambda}$ bound state, or a ϕKK resonance. The predicted decay widths vary strongly depending on the assumed nature of $\phi(2170)$. With energy scan data collected by the BESIII collaboration between 2.0 GeV and 3.08 GeV, the properties of $\phi(2170)$ are studied systematically in its expected decay modes, such as $e^+e^- \to K^+K^-$, $K^0_SK^0_L$, $\phi K^+K^-/K^+K^-K^+K^-$, $\phi\eta$, $\phi\eta'$, $\omega\eta$ and $K^+K^-\pi^0\pi^0$.

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1. Introduction

Hadron spectroscopy provides a way to understand the dynamics of the strong interaction. Experimental data on hadron spectroscopy plays an important role on various theoretical models, since the failure of perturbation expansions for QCD at low energy. Charmonium ($c\bar{c}$) and botomonium $b\bar{b}$ states have been studied abundantly since many decades. There are many XYZ exotic sates with charm quarks and bottom quarks. The multitude of results from heavier quarkonia leads to the obvious question whether similar states exist in the strange sector. However, the spectrum of strangeonium ($s\bar{s}$) is a terra incognita. The $\phi(2170)$ is an ideal candidate of exotic hadron with strange quarks.

The $\phi(2170)$ was first observed by *BABAR* [1] and subsequently confirmed by BESIII and Belle in several experiments [2–7]. The internal constituents of the $\phi(2170)$ are still unknown, which has stimulated extensive theoretical discussions. Possible interpretations of the $\phi(2170)$ include a conventional 3^3S_1 or 2^3D_1 $s\bar{s}$ state [8–11], an $s\bar{s}g$ hybrid [9, 12, 13], a tetraquark state [14–17], a $\Lambda\bar{\Lambda}(3^S_1)$ bound sate [18–20], or a ϕKK resonance state [21], etc., but no interpretation has yet been established. Studying the decay modes of the $\phi(2170)$ plays a key role in determining the internal structure of the $\phi(2170)$. BESIII has the capabilities to archive a direct investigation for $\phi(2170)$.

2. BESIII experiments

BESIII is a general-purpose detector located at the Beijing Electron Positron Collider (BEPCII) [22] and is designed for studies of hadron spectroscopy and τ-charm physics [23, 24]. BEPCII is a double-ring e^+e^- collider with a centerof-mass energy ranging from 2 to 5 GeV and a design luminosity of 10^{33} cm^{-2}s^{-1} at a beam energy of 1.89 GeV. More details about the design and performance of the detector are given in Ref. [23]. In the study of the $\phi(2170)$ resonance, the main data set is located in 2.0 and 3.08 GeV with an integrated luminosity about 650 pb^{-1}.

3. Results of $\phi(2170)$ at BESIII

Several exclusive processes have been studied to investigate the properties of the $\phi(2170)$ resonance.

3.1 $e^+e^- \to K^+K^-/K_SK_L$

The Born cross sections of $e^+e^- \to K^+K^-$ are measured with much improved precision [25] compared to BABAR's results [26, 27]. A clear structure is observed in the line shape of the measured cross section, and a fit yields a mass of $2239.2 \pm 7.1 \pm 11.3$ MeV/c^2, and a width of $139.8 \pm 12.3 \pm 20.6$ MeV for this structure. From the Particle Data Group [1], possible candidates for the observed structure may be the $\rho(2150)$ or $\phi(2170)$. Although the measured parameters agree within 2σ with those from some individual experiments, the results obtained in Ref. [25] differ from the world average parameters of$\rho(2150)$ and $\phi(2170)$ by more than 3σ in mass and more than 2σ in width. For the $\phi(2170)$ case, the result deviates from almost all individual measurements in the e^+e^- annihilation process, disfavoring the reaction $e^+e^- \to \phi(2170) \to K^+K^-$. Thus, the

coupling of $\phi(2170) \to K^+K^-$ is also disfavored, and this may help to veto the model that treats $\phi(2170)$ as a 2^3D_1 state of the $s\bar{s}$ system.

In Ref. [28], the Born cross sections of the process $e^+e^- \to K_SK_L$ measured by BESIII are consistent within 2σ with previous *BABAR* measurements [29] in the overlap region from 2.00 to 2.54 GeV, and the Born cross sections from 2.54 to 3.08 GeV are reported for the first time.

3.2 $e^+e^- \to \phi K^+K^-/K^+K^-K^+K^-$

BESIII has measured the Born cross sections of the process of $e^+e^- \to K^+K^-K^+K^-$ and its dominant submode $e^+e^- \to \phi K^+K^-$ [30]. An enhancement at $\sqrt{s} = 2.232$ GeV is observed in the cross section lineshape of both processes, which is very close to the $\Lambda\bar{\Lambda}$ threshold. If the enhancement is a resonance, the width would be less than 20 MeV, which is much smaller than the width of the intriguing $\phi(2170)$.

3.3 $e^+e^- \to \phi\eta$ and $\phi\eta'$

The process $e^+e^- \to \phi\eta'$ has been studied for the first time by BESIII [31, 32]. A resonance with quantum numbers $J^{PC} = 1^{--}$ is observed with mass $M = 2177.5 \pm 4.8 \pm 19.5$ MeV/c^2 and width $\Gamma = 149.0 \pm 15.6 \pm 8.9$ MeV. In the cross section lineshape of $e^+e^- \to \phi\eta$, a resonant structure around 2.175 GeV is observed with mass $M = 2163.5 \pm 6.2 \pm 3.0$ MeV/c^2 and width $\Gamma = 31.1^{=21.1}_{-11.6} \pm 1.1$ MeV. The observed resonances in $e^+e^- \to \phi\eta$ and $\phi\eta'$ are compatible with the $\phi(2170)$. For the 2^3D_1 $s\bar{s}$ excited state and the $\Lambda\bar{\Lambda}$ bound states in the molecular scenario, the decay mode of $\phi(2170) \to K^+K^-$ is favored. Assuming that the observed resonance is the $\phi(2170)$, the ratio $\frac{\mathcal{B}^{\phi(2170)}_{\phi\eta}\Gamma^{\phi(2170)}_{ee}}{\mathcal{B}^{\phi(2170)}_{\phi\eta'}\Gamma^{\phi(2170)}_{ee}}$ is estimated to be $0.03^{+0.02}_{-0.01}$ or $1.42^{+0.56}_{-0.46}$, which is smaller than the prediction of the $s\bar{s}g$ hybrid models by several orders of magnitude [33–36], and casts severe doubt on the validity of these models.

3.4 $e^+e^- \to \omega\eta$

A resonant structure is observed in the cross section of the $e^+e^- \to \omega\eta$ process [37]. The mass, width and $\mathcal{B}^R_{\omega\eta} \cdot \Gamma^R_{ee}$ of the structure are measured to be $M = (2176 \pm 24 \pm 3)$ MeV/c^2, $\Gamma = (89 \pm 50 \pm 5)$ MeV, $\mathcal{B}^R_{\omega\eta} \cdot \Gamma^R_{ee} = (0.43 \pm 0.15 \pm 0.04)$ eV or $(1.25 \pm 0.48 \pm 0.18)$ eV, respectively. The observed structure agrees well with the properties of the $\phi(2170)$ resonance, which indicates the first observation of the decay $\phi(2170) \to \omega\eta$.

3.5 $e^+e^- \to K^+K^-\pi^0\pi^0$

A PWA of the process $e^+e^- \to K^+K^-\pi^0\pi^0$ is performed for data samples with c.m. energies from 2.000 to 2.644 GeV [38]. The Born cross sections for the two-body processes $e^+e^- \to K^+(1460)K^-$, $e^+e^- \to K_1^+(1400)K^-$, $e^+e^- \to K_1^+(1270)K^-$ and $e^+e^- \to K^{*+}(892)K^{*-}(892)$ are measured individually. A simultaneous fit on the four lineshapes results in a structure with mass $M = (2126.5 \pm 16.8 \pm 12.4)$ MeV/c^2, width $\Gamma = (106.9 \pm 32.1 \pm 28.1)$ MeV. Assuming the observed structure is $\phi(2170)$, this measurement implies that the $\phi(2170)$ has a sizeable partial width to $K^+(1460)K^-$, $K_1^+(1400)K^-$, and $K_1^+(1270)K^-$, but a much smaller partial width to $K^{*+}(892)K^{*-}(892)$ and $K^{*+}(1410)K^-$. According to Ref. [9], the 3^3S_1 $s\bar{s}$ state mainly decays to $K^{*+}(892)K^{*-}(892)$ and $K^{*+}(1410)K^-$, but has a much smaller partial width to $K_1^+(1410)K^-$ and

$K^+(1460)K^-$. On the other hand, the 2^3D_1 $s\bar{s}$ state has an expected partial width to $K_1^+(1400)K^-$ smaller than that to $K^{*+}(1410)K^-$ by a factor of 2–5 [9, 10]. A hybrid state is expected to decay dominantly into $K_1^+(2170)K^-$ and $K_1^+(1400)K^-$, while it should be highly suppressed in the modes $K^{*+}(892)K^{*-}(892)$ and $K^+(1460)K^-$ [12]. None of the above theoretical expectations are in good agreement with the $e^+e^- \to K^+K^-\pi^0\pi^0$ measurements at BESIII.

4. Summary and discussion

BESIII has measured various processes in the studying of $\phi(2170)$. Figure1 summarized the mass and width of the $\phi(2170)$ from BESIII measurements, as well as results from other experioments. These experimental results contribute profitable information in comprehension of the $\phi(2170)$. Still, the $\phi(2170)$ remains fascinating. More studies, both experimentally and theoretically, are needed in the future.

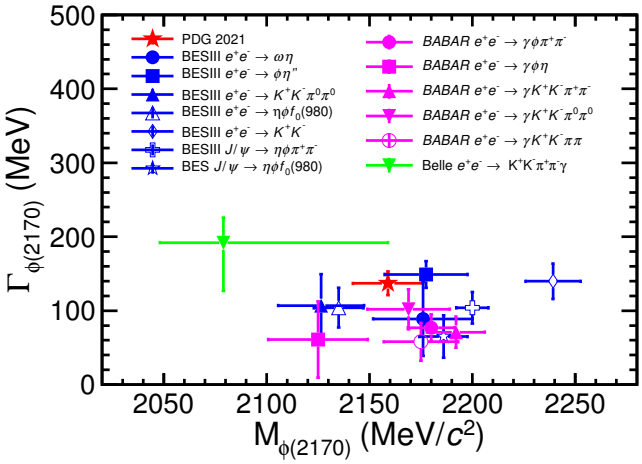

Figure 1: Mass and width of the $\phi(2170)$ resonance from experimental measurements.

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