Newest results on XYZ states at BESIII

F. Nerling
on behalf of the BESIII Collaboration

Institut für Kernphysik, Goethe Universität Frankfurt,
and GSI Darmstadt, Germany

The BESIII experiment at BEPCII at IHEP in Beijing/China has collected the world largest data sets in the τ-charm region and it is well suited to cover a rich hadron physics programme, including charmonium and open-charm spectroscopy, R-scan or electromagnetic form factor measurements, and many more. In particular, the unique data sets between 3.8 and 4.6 GeV allow for discoveries and precision measurements of the interesting charmonium-like (exotic) “XYZ” states. The recently published precision cross-section measurement for Y states is discussed as well as the first observation of the X(3872) in radiative decays, also the completion of the two observed isospin triplets Zc(3900) and Zc(4020) is briefly summarised.

1 Introduction

The discovery of the J/ψ in 1974[1] triggered investigations in the charmonium region, where the c ¯c states can successfully described using potential models, for a recent overview see e.g.[2]. Especially below the open-charm threshold, excellent agreement is achieved between theory and experiment — all the predicted states have been observed with the expected properties. The situation above the open-charm threshold appears more complicated. There are still many predicted states that have not yet been discovered, and, surprisingly, there are quite some unexpected states that have been observed since 2003. Well known examples of these so-called charmonium-like (exotic) “XYZ” states are the X(3872) observed by Belle in 2003[3], the Y(4260) and the Y(4360), both discovered by BaBar[4,5], or the manifestly exotic charged state Zc(3900)± discovered by BESIII in 2013[6], and shortly after confirmed by Belle[7].

The BESIII experiment[8] at BEPCII is the latest incarnation of the Beijing Spectrometer (BES) at the Beijing Electron-positron Collider (BEPC) that started in 1989, it begun operation in March 2008 after the major upgrades were finalised. The multi-purpose detector is well suited to cover a broad hadron physics programme, including charmonium and open-charm spectroscopy, R scan measurements or electromagnetic form factors, and many others. It has collected the world largest data sets in the τ-charm mass region, and in the “XYZ” region above 3.8 GeV, BESIII has accumulated unique high-luminosity data sets of about 5 fb−1 in total to explore the still-unexplained XYZ states.

*Email: F.Nerling@gsi.de
2 Newest results on XYZ states

The BESIII experiment is ideally suited to study conventional as well as charmonium-like (exotic) XYZ states. We have direct access to $Y$ states ($J^{PC} = 1^{--}$) in the $e^+e^-$ annihilation, $X$ states are accessed in radiative decays, and also, we can study charged as well as neutral $Z_c$ states.

2.1 The $Y$ states — $e^+e^-$ production of the $J/\psi \pi^+\pi^-$, the $\psi(2S)\pi^+\pi^-$ and the $h_c\pi^+\pi^-$ systems

The $Y(4260)$ and the $Y(4360)$ had been firstly observed using initial state radiation (ISR) decaying to $J/\psi \pi^+\pi^-$ and $\psi(2S)\pi^+\pi^-$, respectively, by BABAR\cite{4,5}. Based on increased statistics by about a factor of two, the $Y(4260)$ appears to show a somewhat asymmetric shape\cite{9}. In agreement with their previous result based on lower statistics, confirming the $Y(4260) \rightarrow J/\psi \pi^+\pi^-$ discovered by BABAR\cite{2}, and in contradiction to the BABAR result, Belle claims a lower mass peak, the “$Y(4008)$”, that needs a second coherent resonance (Breit-Wigner) shape in addition to the $Y(4260)$ and some incoherent background in order to describe their data\cite{7}.

Based on the “high luminosity” (< 40 pb$^{-1}$ at each energy point $E_{cms}$, total integrated luminosity of 8.2 fb$^{-1}$) and the “low luminosity” (~ 7-9 pb$^{-1}$ at each energy point $E_{cms}$, total integrated luminosity of 0.8 fb$^{-1}$) XYZ data, we performed a precision measurement of the energy dependent cross-section $\sigma(e^+e^- \rightarrow J/\psi \pi^+\pi^-)$ in the energy range of $3.77 < E_{cms} < 4.60$ GeV recently published\cite{10}. The result obtained by a simultaneous fit to both data sets is shown in Fig.\cite{1}. The signal yields are determined using an unbinned maximum-likelihood fit.

Figure 2: Left: The reconstructed $\psi(2S)\pi^+\pi^-$ invariant mass spectrum from Belle shows clear indications of the $Y(4360)$ and the $Y(4660)$, however, no evidence for the $Y(4260)$ resonance, for details see text. Right: Comparison of the $e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$ cross-section shape measured at BESIII to those provided by BABAR and Belle — the $Y(4360)$ line shape is found in consistency for the three different experiments.

Figure 1: Precision cross-section measurement of the $J/\psi \pi^+\pi^-$ production in $e^+e^-$ annihilation as obtained from a simultaneous fit to both, the “high luminosity” XYZ data (left) and the “low luminosity” scan data (right).
Figure 3: Cross-section measurement of $h_c\pi\pi$ versus $J/\psi\pi\pi$ production in $e^+e^-$ annihilation, based on the “high luminosity” $XYZ$ data (left) and based on the “low luminosity” scan data (right).

(“high luminosity” $XYZ$ data) and a simple counting method (“low luminosity” scan data), for the latter the background counts from sidebands are subtracted. First of all, the cross-section appears inconsistent with a single peak just for the $Y(4260)$ — two resonances to describe two peaks is favoured over one by the data at high statistical significance of more than $7\sigma$. Moreover, two fit models have been used to describe the data. “Fit I” comprises three resonances, namely $Y(4008)$, $Y(4260)$ and the $Y(4360)$, whereas in “Fit II”, the first resonance in terms of the low mass $Y$ state claimed by Belle has been replaced by an interfering non-resonant exponential shape. Since both models deliver identical fit quality, we can not confirm the $Y(4008)$ as it is not needed to describe the BESIII data. It should be emphasised that the parameters of the third resonance ($m = 4326.8\pm10.0$ MeV, $\Gamma = 98.2^{+25.4}_{-19.6}$ MeV) are consistent within errors with the $Y(4360)$ observed decaying to $\psi(2S)\pi^+\pi^-$ previously, while the $Y(4260)$ is observed with a significantly smaller width ($\Gamma=44.1\pm3.8$ MeV). Given the much larger statistics by BESIII, the $Y(4260)$ and the $Y(4360)$ are resolved here for the first time, and the $Y(4360)$ is first observed decaying to $J/\psi\pi^+\pi^-$. Interestingly, coming back to the $e^+e^-$ production of the $\psi(2S)\pi^+\pi^-$ system, a result by Belle obtained using ISR (Fig. 2, left) gives clear indication of the $Y(4360)$ and the $Y(4660)$ decaying to $\psi(2S)\pi^+\pi^-$. However, there is no evidence for the $Y(4260)$ being present in the data. When trying to accommodate it coherently, in addition to the other two $Y$ states, the statistical significance turns out to be well below $3\sigma$, so that Belle omitted the $Y(4260)\rightarrow \psi(2S)\pi^+\pi^-$ from their best fit\textsuperscript{11}. The preliminary result on the cross-section shape for direct $\psi(2S)\pi^+\pi^-$ production in $e^+e^-$ annihilation as observed at BESIII is compared to the ones from BABAR and Belle in Fig. 2 (right). The preliminary measurement by BESIII confirms the $Y(4360)$ line shape reported previously, they are all three found in good agreement. More data for a thorough study of the mass region 4.2–4.3 GeV is currently taken at IHEP/Beijing.

Finally, the cross-section shapes for $e^+e^-\rightarrow h_c\pi^+\pi^-$ production as measured at BESIII and CLEO-c are compared to the one for $e^+e^- \rightarrow J/\psi\pi^+\pi^-$ from Belle in Fig. 3 (left), and we find the $h_c\pi^+\pi^-$ differs in shape from the $J/\psi\pi^+\pi^-$ system. Based on more statistics (Fig. 3 right), the new BESIII result\textsuperscript{12} shows evidence for two resonant structures (at 4.22 and 4.39 GeV/$c^2$) that we call “$Y(4220)$” and “$Y(4390)$”, respectively. A fit with a coherent sum of two Breit-Wigner functions results in a mass of $(4218.4 \pm 4.0 \pm 0.9)$ MeV/$c^2$ and a width of $(66.0 \pm 0.9 \pm 0.4)$ MeV/$c^2$ for the “$Y(4220)$”, and a mass of $(4391.6 \pm 6.3 \pm 1.0)$ MeV/$c^2$ and a width of $(139.5 \pm 16.1 \pm 0.6)$ MeV/$c^2$ for the “$Y(4390)$”. The statistical significance of “$Y(4220)$” and “$Y(4390)$” is 10 $\sigma$ over the one resonance assumption.

More work and especially higher statistics data is needed to further sort out these exclusive cross-sections of highest interest.
2.2 The $X$ states — First observation of $e^+ e^- \rightarrow \gamma X(3872)$

The $X(3872)$ is the first of the $XYZ$ states observed, it was discovered by Belle in the $J/\psi \pi^+ \pi^-$ decay mode. At BESIII, we studied $e^+ e^- \rightarrow \gamma X(3872) \rightarrow \gamma J/\psi \pi^+ \pi^-$ at four centre of mass energies $E_{\text{c.m.}} = (4.009, 4.229, 4.260, 4.360) \text{ GeV/c}^2$. The combined reconstructed $J/\psi \pi^+ \pi^-$ invariant mass spectrum (Fig. 4, left) shows an even though tiny accumulation of events in form of a nice narrow peak on top of a rather low background. The resonance parameters obtained from the fit ($m = (3872.9 \pm 0.7 \pm 0.2) \text{ MeV/c}^2$, $\Gamma < 2.4 \text{ MeV/c}^2$) are consistent with those of previous observations of the $X(3872)$. This is the first observation of the $X(3872)$ in radiative decays, the statistical significance is 6.3 $\sigma$. The corresponding cross-sections at the four centre-of-mass energies together with different fit attempts (Fig. 4, right) already hint to the production via a $Y$ state, however, more data is clearly also needed here.

2.3 The $Z$ states — Two established isospin triplets $Z_c(3900)$ and $Z_c(4020)$

The $Z_c(3900)^\pm$ discovered by BESIII, shortly after confirmed by Belle, is (due to the charge) a manifestly exotic state, corresponding to a strong hint for the first four-quark state being observed. The neutral partner $Z_c(3900)^0$ decaying to $J/\psi \pi^0$ has been observed also in the BESIII data, at 10.4 $\sigma$, confirming earlier evidence reported by CLEO-c, and establishing an $Z_c(3900)^{\pm,0}$ isospin triplet (Fig. 5, left). Furthermore, also a second isospin triplet $Z_c(4020)^{\pm,0}$ has meanwhile been established in the BESIII data (Fig. 5, right). Despite this remarkable progress, the nature of these states is still unclear, especially one question still is, whether the different decays the $Z_c$ states have been observed in (hidden versus open charm) are decay modes of the same state observed. Clearly, also further decay channels via other charmonia (than $J/\psi$ and $h_c$) need to be investigated, and possible multiplets need to be completed by high spin states, which can only be accessed by future experiments like e.g. PANDA at FAIR.

2.4 Summary and outlook

The BESIII experiment at BEPCII is successfully operating since 2008. We have collected the world largest data set in the $\tau$-charm region as well as unique data sets to study $XYZ$ states. It is ideally suited to explore transitions and decays of $Y$ states. We have the first two $Z_c$ isospin triplets established, the $X(3872)$ observed for the first time in radiative decays, and we have recently published a precision measurement of the cross-section in the $Y$ energy range, resolving for the first time structures overseen in previous measurements. As an outlook, BESIII is continuing collecting data, helping and needed to resolve the $XYZ$ puzzle.
Figure 5: The two established isospin triplets $Z_c(3900)^{\pm,0}$ (left) and $Z_c(4020)^{\pm,0}$ (right). Shown are the observation plots of the charged (left) and neutral (right) partners, as observed in hidden charm (top) and open charm (bottom) decays.

References

1. J.-E. Augustin et al., Phys. Rev. Lett. 33 (1974) 1406.
2. R.F. Lebedev, R.E. Mitchell and E.S. Swanson, arXiv:1610.04528v2[hep-ex].
3. S.K. Choi et al. (Belle Collaboration), Phys. Rev. Lett. 91 (2003) 262001.
4. B. Aubert et al. (BABAR Collaboration), Phys. Rev. Lett. 95 (2005) 142001.
5. B. Aubert et al. (BABAR Collaboration), Phys. Rev. Lett. 98 (2007) 212001.
6. M. Ablikin et al. (BESIII Collaboration), Phys. Rev. Lett. 110 (2013) 252001.
7. Z.Q. Liu et al. (Belle Collaboration), Phys. Rev. Lett. 110 (2013) 252002.
8. M. Ablikin et al. (BESIII Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 614 (2010) 345.
9. B. Aubert et al. (BABAR Collaboration), Phys. Rev. D 86 (2012) 051102.
10. M. Ablikin et al. (BESIII Collaboration), Phys. Rev. Lett. 118 (2017) 092001.
11. Z.Q. Liu et al. (Belle Collaboration), Phys. Rev. D 91 (2015) 112007.
12. M. Ablikin et al. (BESIII Collaboration), Phys. Rev. Lett. 118 (2017) 092002.
13. M. Ablikin et al. (BESIII Collaboration), Phys. Rev. Lett. 112 (2014) 092001.
14. T. Xiao, S. Dobbs, A. Tomaradze and Kamal K. Seth, Phys. Lett. B 727 (2013) 366.
15. W. Erni et al. (PANDA Collaboration), Panda Performance Report (2009), arXiv:0903.3905[hep-ex].