The $p\bar{p}$ mass threshold structure in $\psi(3686)$ radiative decay revisited

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The near-threshold behavior of the $p\bar{p}$ invariant mass spectrum from the $\psi(3686)\rightarrow \gamma p\bar{p}$ decay reported recently by the BESIII Collaboration is analyzed. The enhancement in the $p\bar{p}$ invariant mass spectrum near threshold is nicely reproduced by the $p\bar{p}$ final-state interaction based on the isospin averaged $^1S_0$ partial-wave amplitude as predicted by the Jülich nucleon-antinucleon model. Contributions from the $f_2(1910)$ or $f_2(1950)$ mesons, as promoted in earlier works, are not needed.

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Recently, the BESIII Collaboration presented data with improved statistics on the $p\bar{p}$ invariant mass spectrum for the reaction $J/\psi \rightarrow \gamma p\bar{p}$, but also a first high-statistics measurement of the $\psi(3686)\rightarrow \gamma p\bar{p}$ decay $^1$. The new $J/\psi \rightarrow \gamma p\bar{p}$ measurement confirmed the spectacular near-threshold enhancement in the $p\bar{p}$ invariant mass, found in an earlier experiment by the BES Collaboration $^2$, which has been seen as evidence for a $p\bar{p}$ bound state or baryonium $^3,^4$. For exotic glueball states $^5,^6$, but also simply as manifestation of the final-state interaction (FSI) between the outgoing proton and antiproton $^7,^8$. A significant near-threshold enhancement of the $p\bar{p}$ invariant mass was seen also in the $\psi(3686)$ decay, although less pronounced than in the $J/\psi$ case.

The BESIII Collaboration themselves interpreted their $J/\psi$ decay data in terms of the $p\bar{p}$ FSI proposed by us $^9$, but folded with a Breit-Wigner type resonance at around 1835 MeV presuming that the structure at the $p\bar{p}$ threshold might be related to the $X(1835)$ resonance that had been observed in the reaction $J/\psi \rightarrow \gamma \pi^+\pi^-\eta'$ $^9,^10,^11$, see also the comments in Ref. $^11$. This object is called $X(pp)$ in Ref. $^11$. For the description of the $\psi(3686)$ decay the same $X(pp)$ amplitude is used but sizeable additional contributions from the $f_2(1910)$ resonance had to be invoked. Contributions of a tensor meson, but in this case of the $f_2(1950)$, were also advocated in the work of the CLEO collaboration $^12$, which had published data on the reaction $\psi(3686)\rightarrow \gamma p\bar{p}$ decay prior to BESIII, though with lower statistics. In both cases an isoscalar meson with a larger mass ($f_0(2100)$ and $f_2(2150)$, respectively) has been added to explain the $p\bar{p}$ spectrum at higher invariant masses.

In this report we take a closer look at those $\psi(3686)\rightarrow \gamma p\bar{p}$ data from the BESIII Collaboration. Specifically, we provide an alternative interpretation of the near-threshold enhancement solely in terms of the $p\bar{p}$ FSI, i.e. without resorting to any resonance contributions like the $f_2(1910)$ or $f_2(1950)$ (or the $X(1835)$), based on the very same $NN$ interaction used by us previously in the explanation of the enhancement in the $J/\psi$ decay $^9$.

Conservation laws for parity, charge-conjugation and total angular momentum severely restrict the partial waves in the $p\bar{p}$ system $^9$ for such decay processes. Specifically, the partial-wave analysis for the $J/\psi$ decay performed in $^1$ suggests that the near-threshold enhancement is dominantly in the $J^{PC}=0^{-+}$ state, which means that the $p\bar{p}$ system should be in the $^1S_0$ partial wave (we use here the standard nomenclature $^{2S+1}L_J$ where $S$ is the total spin and $L$ the orbital angular momentum). However, since the decay of the $J/\psi$ and $\psi(3686)$ to the $\gamma p\bar{p}$ system involves electromagnetic processes, isospin is not conserved so that, in principle, any combination of the isospin $I=0$ and $I=1$ components is allowed. Indeed, while the $p\bar{p}$ invariant mass for $J/\psi$ decay can be understood in terms of the FSI generated by the isospin $I=1$ component of the $NN$ amplitude in the $^1S_0$ state alone – at least in our work $^9$ – the $I=1$ and $I=0$ channels can occur with different weights in case of the $\psi(3686)$ decay.

The $\psi(3686)\rightarrow \gamma p\bar{p}$ decay rate is given by $^9$

$$d\Gamma = \frac{|A|^2}{2\pi s\rho^2_{\psi}} \lambda^{1/2}(m_\psi^2, M^2, m_{\rho}^2) \times \lambda^{1/2}(M^2, m_p^2, m_{\rho}^2) \, dM \, d\Omega_p \, d\Omega_{\gamma},$$

(1)

where the Källén function $\lambda$ is defined by $\lambda(x, y, z) = ((x - y - z)^2 - 4yz)/4x$, $M = M_{\rho\rho}$ is the invariant mass of the $p\bar{p}$ system, $\Omega_p$ is the proton angle in that system, while $\Omega_{\gamma}$ is the angle in the $\psi(3686)$ rest frame. After averaging over the spin states and integrating over the angles, the differential decay rate is

$$\frac{d\Gamma}{dM} = \frac{(m_\psi^2 - M^2) \sqrt{M^2 - 4m_p^2}}{2\pi^3 m_\psi^3} |A|^2. $$

(2)

The quantity $A$ in Eqs. $^1$ and $^2$ stands for the total $\psi(3686)\rightarrow \gamma p\bar{p}$ reaction amplitude and is dimensionless.

We assume again the validity of the Watson-Migdal $^12,^20$ approach for the treatment of the FSI effect. It suggests that the reaction amplitude for a production and/or decay reaction that is of short-ranged nature can be factorized in terms of an elementary (basically constant) production amplitude $A_0$ and the $p\bar{p}$ scattering
data from Ref. [1]. As expected from the curves predominantly dominated by the $^1S_0$ curve are corresponding results using the normalized to the data, cf. Eq. (3). The dashed (dash-dotted) $^1N$ the Ref. [9] for further details. As in our investigation of where $^1N$ amplitude squared ($|A|^2$). For notation of curves, see Fig. 1.

The circles show experimental results of the BES Collaboration 1. The solid line is a calculation using the $^1N$ model A(OBE) published in Refs. [21, 22], and those curves were normalized so that they all coincide at $M_{p\bar{p}} - 2m_p \approx 60$ MeV.

FIG. 1: The $p\bar{p}$ mass spectrum from the decay $\psi(3686) \rightarrow \gamma p\bar{p}$. The circles show experimental results of the BES Collaboration 1. The solid line is a calculation using the $^1N$ model A(OBE) published in Refs. [21, 22], and those curves were normalized so that they all coincide at $M_{p\bar{p}} - 2m_p \approx 60$ MeV in order to facilitate comparison of the differences in the energy dependence. The latter is obtained by using a constant amplitude $A$ in Eq. (2). The $\chi^2$ value for the pure $I = 0$ amplitude is 11.9. The one for the phase-space curve amounts to 60 which is a clear indication that the measured invariant mass spectrum does not exhibit a phase-space behaviour near threshold. All those curves are normalized to the solid curve at $M_{p\bar{p}} - 2m_p \approx 60$ MeV in order to facilitate a comparison of the differences in the energy dependence.

Based on those findings we do not see any need here to invoke further more substantial contributions coming from any $f_2(1910)$ or $f_2(1950)$ mesons, say, as done in Refs. [1, 18], in order to explain the data.

In Fig. 2 our results are compared with the data obtained by the CLEO Collaboration 15. For notation of curves, see Fig. 1 (a) for further details. As in our investigation of the $J/\psi$ decay we employ the amplitudes predicted by the $N\bar{N}$ model A(OBE) published in Refs. [21, 22], and we assume that the FSI effects in the $\psi(3686)$ decay are likewise dominated by the $^1S_0$ partial wave.

Our results are presented in Fig. 1 together with the data from Ref. 1. As expected from the curves presented in Fig. 3 of Ref. 1, the $N\bar{N}$ amplitude in the $I = 1$ channel, which successfully describes the rather strong enhancement detected in the reaction $J/\psi \rightarrow \gamma p\bar{p}$ 4, overestimates the energy dependence seen in the $\psi(3686)$ case, cf. the dashed curve. On the other hand, the result based on the isospin averaged amplitude, $(T_{I=1} + T_{I=0})/2 \equiv T_{p\bar{p}}$, shown in Fig. 1 by the solid line, agrees rather nicely with the energy dependence found in the experiment. With an appropriately chosen normalization, cf. Eq. (3), the data are well reproduced from the $p\bar{p}$ threshold up to excess energies of about 150 MeV. In particular, the $\chi^2$ is 8.7 for the 15 data points shown in Fig. 1 while it is 22.2, i.e. more than twice as large, for the pure $I = 1$ amplitude. We also include the result based on FSI effects due to the $p\bar{p}$ amplitude in the $I = 0$ channel alone (dash-dotted curve) and we indicate the pure phase-space behaviour by the dotted curve.

Finally, in Fig. 3 the results for BESIII are displayed again, however this time in terms of the modulus squared of the amplitude $A$. Here the curves correspond directly to the $^1S_0$ partial-wave. The symbols indicate the experimental values of $|A|^2$, obtained from the BESIII data 1 via dividing the latter by the kinematical factors according to Eq. (2).

In summary, we have analyzed the near-threshold behavior of the $p\bar{p}$ invariant mass spectrum from the $\psi(3686) \rightarrow \gamma p\bar{p}$ decay reported recently by the BESIII Collaboration within the Watson-Migdal approach. Although in this reaction there is definitely an enhancement in the near-threshold region as compared to the phase-space behavior, it is much less pronounced than what was found for the corresponding reaction $J/\psi \rightarrow \gamma p\bar{p}$. The enhancement is nicely reproduced by the $p\bar{p}$ final-state interaction based on the isospin averaged $^1S_0$ partial-wave.
particular, any more substantial contributions from tensor mesons like $f_2(1910)$ or $f_2(1950)$, as advocated in earlier works [1, 18], are not required.

Note that we have used here the same $N\bar{N}$ amplitudes as in our study of the $J/\psi$ decay [9]. In the $J/\psi$ case the FSI provided by the $I = 1$ component alone led to an agreement with the measured near-threshold $p\bar{p}$ invariant mass spectrum. Clearly, the mechanisms for the decay of the $J/\psi$ and $\psi(3686)$ mesons into $\gamma p\bar{p}$ should be different so that different admixtures of the two isospin components in the final $p\bar{p}$ state have to be expected. Only dedicated microscopic calculations, which hopefully will be performed in the future, can allow to shed light on the details of the reaction mechanisms.

FIG. 3: Invariant $\psi(3686)\rightarrow\gamma p\bar{p}$ amplitude $|A|^2$ as a function of the $p\bar{p}$ mass. The circles symbolize the experimental values of $|A|^2$ extracted from the BES data [1] via Eq. (2). The curves are the appropriately normalized scattering amplitude squared, $|T|^2$, predicted by the $N\bar{N}$ model A(OBE) [21, 22] for the $^1S_0$ partial wave. For notation of curves, see Fig. 1. amplitude as given by the Jülich $N\bar{N}$ model. In particular, any more substantial contributions from tensor mesons like $f_2(1910)$ or $f_2(1950)$, as advocated in earlier works [1, 18], are not required.

Note that we have used here the same $N\bar{N}$ amplitudes as in our study of the $J/\psi$ decay [9]. In the $J/\psi$ case the FSI provided by the $I = 1$ component alone led to an agreement with the measured near-threshold $p\bar{p}$ invariant mass spectrum. Clearly, the mechanisms for the decay of the $J/\psi$ and $\psi(3686)$ mesons into $\gamma p\bar{p}$ should be different so that different admixtures of the two isospin components in the final $p\bar{p}$ state have to be expected. Only dedicated microscopic calculations, which hopefully will be performed in the future, can allow to shed light on the details of the reaction mechanisms.

Acknowledgments

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