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Near threshold $p\bar{p}$ enhancement in the $J/\psi \to \omega p\bar{p}$ decay

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ABSTRACT

The near-threshold behavior of the $p\bar{p}$ invariant mass spectrum from the $J/\psi \to \omega p\bar{p}$ decay reported recently by the BES Collaboration is analyzed. Our study demonstrates that there is indeed a clear enhancement in the $p\bar{p}$ invariant mass spectrum near threshold as compared to the phase-space behavior. Moreover, this enhancement is nicely reproduced by the final state interaction in the relevant $(^{11}S_0)$ $p\bar{p}$ partial wave as given by the Jülich nucleon–antinucleon model. Therefore, contrary to the statement by the BES Collaboration, their new data on $J/\psi \to \omega p\bar{p}$ decay in fact strongly support the FSI interpretation of the $p\bar{p}$ enhancement, seen also in other decay reactions.

The study of the decays of mesons like the J/ψ, $\psi(2S)$, B, and Υ as pursued by the BES, Belle, BaBar and CLEO Collaborations is a rather powerful tool for examining systematically the spectrum of light as well as heavier hadrons. Specifically, exclusive measurements of decays into three-meson or meson–baryon–antibaryon channels play a very important role and have already led to the identification of several new structures.

Among the various three-particle channels explored those involving the proton–antiproton ($p\bar{p}$) system in the final state have caused considerable attention in the community. The excitement was initiated by the observation of a significant near-threshold enhancement in the $p\bar{p}$ invariant mass spectrum for the reaction $J/\psi \to \gamma p\bar{p}$ in a high-statistics and high-mass-resolution experiment by the BES Collaboration [1]. Furthermore, a first indication for a near-threshold enhancement in the $p\bar{p}$ invariant mass spectrum from the $B^+ \to K^+ p\bar{p}$ and $\bar{B}^0 \to D^0 p\bar{p}$ decays were reported by the Belle Collaboration [2,3] but with much lower statistics and mass resolution. More recently the Belle Collaboration [4,5] found also a near-threshold $p\bar{p}$ enhancement in the decays $B^+ \to \pi^+ p\bar{p}$, $B^0 \to K^0 p\bar{p}$ and $B^+ \to K^{*+} p\bar{p}$, while the CLEO Collaboration detected such an enhancement in (the unsubtracted) data for $\Upsilon(1S) \to \gamma p\bar{p}$ [6] and the BES Collaboration in $\psi(2S) \to \gamma p\bar{p}$ [7]. Finally, the BaBar Collaboration presented measurements of the $B^+ \to K^+ p\bar{p}$, $B^0 \to \bar{D}^0 p\bar{p}$ and $B^0 \to \bar{D}^{*0} p\bar{p}$ decays [8,9] confirming the presence of a near-threshold enhancement in the $p\bar{p}$ invariant mass.

The high-statistics data by the BES Collaboration triggered several theoretical speculations where the observed enhancement in the invariant $p\bar{p}$ mass spectrum was interpreted as evidence for a $p\bar{p}$ bound state or baryonium [10–13], or for exotic glueball states [14,15]. Alternatively, we [16,17] but also others [18–23] demonstrated that the near-threshold enhancement in the $p\bar{p}$ invariant mass spectrum from $J/\psi \to \gamma p\bar{p}$ and other decays leading to a final $p\bar{p}$ system could be simply due to the final state interaction (FSI) between the outgoing proton and antiproton. Specifically, our calculation based on the realistic Jülich nucleon–antinucleon ($N\bar{N}$) model [24,25], the one by Loiseau and Wycech [21], utilizing the Paris $N\bar{N}$ model, and those of Entem and Fernández [22], using a $N\bar{N}$ interaction derived from a constituent quark model, explicitly confirmed the significance of FSI effects estimated in the initial studies [18–20] within the effective range approximation. Interestingly, the same FSI mechanism explains the near threshold enhancement of the data on $e^+e^- \leftrightarrow \bar{N}N$ from the PS170 Collaboration, from the FENICE Collaboration and from BaBar utilizing radiative return, see [26,27].

Very recently the BES Collaboration presented a high-statistics measurement of the $J/\psi \to \omega p\bar{p}$ decay [28] where, according to their own words, "no obvious near-threshold $p\bar{p}$ mass enhancement is observed". This supposed lack of any enhancement in the $\omega p\bar{p}$ channel is then seen as a hint that the FSI interpretation of the $p\bar{p}$ enhancement in $J/\psi \to \gamma p\bar{p}$ is disfavoured [28].

In the present Letter we want to take a closer look at those $J/\psi \to \omega p\bar{p}$ data by the BES Collaboration. As we already argued in our first work on the $p\bar{p}$ enhancement [16], this specific decay channel is rather interesting for clarifying the role of the $p\bar{p}$ FSI effects, because here the conservation laws for parity, charge-conjugation and total angular momentum severely restrict the par-

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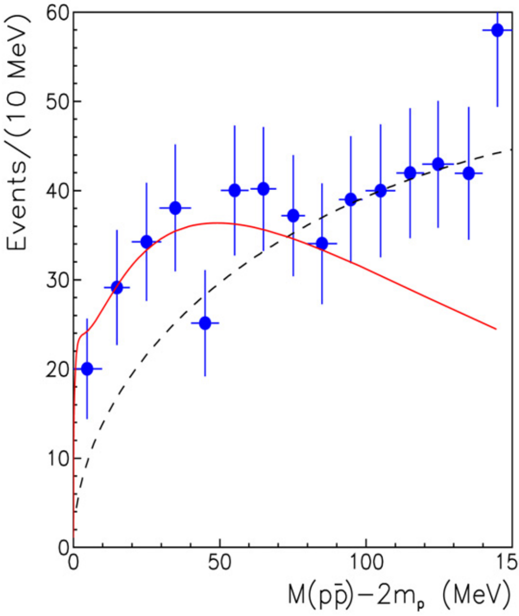

Fig. 1. The $p\bar{p}$ mass spectrum from the decay $J/\psi \to \omega p\bar{p}$. The circles show experimental results of the BES Collaboration [28], while the dashed line is the spectrum obtained from Eq. (2) by assuming a constant reaction amplitude A which was normalized to the data at $M(p\bar{p}) - 2m_p \approx 110$ MeV. The solid line is a calculation using the scattering amplitude squared ($|T|^2$) predicted by the $N\bar{N}$ model A(OBE) [24] for the ${}^{11}S_0$ partial wave, normalized to the data, cf. Eq. (3).

tial waves in the $p\bar{p}$ system. In particular, near threshold the $p\bar{p}$ system can only be in the ${}^{11}S_0$ state. We use here the standard nomenclature ${}^{(2I+1)(2S+1)}L_J$ where I and S are the total isospin and spin, respectively. In contrast, for the extensively discussed $J/\psi \to \gamma p\bar{p}$ decay any combination of the $I = 0$ and $I = 1$ amplitudes is allowed because isospin is not conserved in electromagnetic processes.

Like in our earlier papers [16,17,26], besides the directly measured $p\bar{p}$ invariant mass spectrum, we utilize also the total spin-averaged (dimensionless) $J/\psi \to \omega p\bar{p}$ reaction amplitude A because that allows us to get rid of trivial kinematical factors. The $J/\psi \to \omega p\bar{p}$ decay rate is given in terms of A by [29]

$$d\Gamma = \frac{|A|^2}{2^9\pi^5 m_{J/\psi}^2}\lambda^{1/2}\left(m_{J/\psi}^2, M^2, m_\omega^2\right) \times \lambda^{1/2}\left(M^2, m_p^2, m_p^2\right) dM\, d\Omega_p\, d\Omega_\omega, \tag{1}$$

where the Källén function λ is defined by $\lambda(x, y, z) = ((x - y - z)^2 - 4yz)/4x$, $M \equiv M(p\bar{p})$ is the invariant mass of the $p\bar{p}$ system, Ω_p is the proton angle in that system, while Ω_ω is the ω angle in the J/ψ rest frame. After averaging over the spin states and integrating over the angles, the differential decay rate is

$$\frac{d\Gamma}{dM} = \frac{\lambda^{1/2}(m_{J/\psi}^2, M^2, m_\omega^2)\sqrt{M^2 - 4m_p^2}}{2^6\pi^3 m_{J/\psi}^2}|A|^2. \tag{2}$$

We use Eq. (2) for extracting $|A|^2$ from the data of the BES Collaboration. The original data [28] are reproduced in Fig. 1 while the extracted values for $|A|^2$ are shown in Fig. 2.

We assume again the validity of the Watson–Migdal 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 and the $p\bar{p}$ scattering amplitude T of the particles in the final state so that

$$A\big(M(p\bar{p})\big) \approx N \cdot T\big(M(p\bar{p})\big), \tag{3}$$

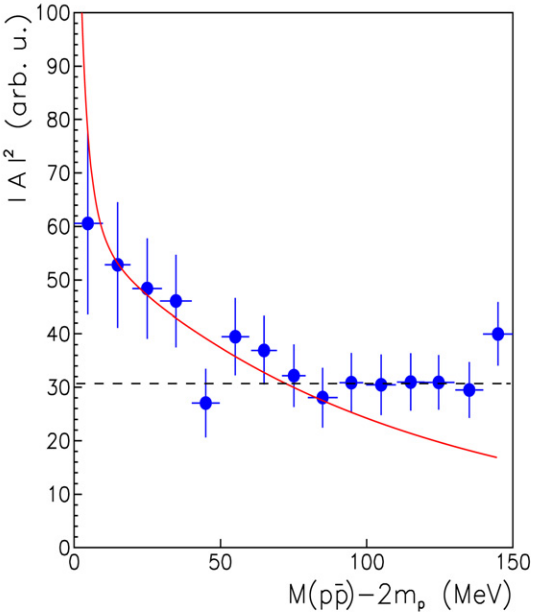

Fig. 2. Invariant $J/\psi \to \omega p\bar{p}$ amplitude $|A|^2$ as a function of the $p\bar{p}$ mass. The circles symbolize the experimental values of $|A|^2$ extracted from the BES data [28] via Eq. (2). The solid curve is the appropriately normalized scattering amplitude squared ($|T|^2$) predicted by the $N\bar{N}$ model A(OBE) [24] for the ${}^{11}S_0$ partial wave. The dashed curve represents the constant reaction amplitude used for generating the dashed curve in Fig. 1.

(cf. Ref. [16] for further details). Thus, we compare the extracted amplitude $|A|^2$ with the suitably normalized scattering amplitudes $|T|^2$ that result from the Jülich $N\bar{N}$ model [24] for the ${}^{11}S_0$ partial wave. Interestingly, that scattering amplitude reproduces the dependence of the experimental $|A|^2$ on the invariant mass almost perfectly in the near-threshold region, cf. the solid curve in Fig. 2. It should be noted that this result is actually a prediction of the model and not a fit. The dashed line represents a constant reaction amplitude and corresponds to the pure phase-space behavior. Obviously the BES data show a clear enhancement as compared to the phase-space behavior in the near-threshold region. This can be also seen from Fig. 1, where the measured $p\bar{p}$ mass spectrum is shown directly. The normalization of the phase space is done in the region $M(p\bar{p}) - 2m_p \approx 100$–140 MeV, where the data indeed follow the phase-space distribution. In principle, one could have also normalized the dashed curve to the lowest data points. Then the first four data points would still be roughly in line with a phase-space behavior, at least within the error bars, but one would end up with a gross overestimation of the data at higher invariant masses and, consequently, be in a situation that one sees and has to explain a suppression in the experimental data in that invariant-mass region.

The BES Collaboration describes the $p\bar{p}$ mass distribution with the polynomial $f(\varepsilon) = N\sqrt{\varepsilon}(1 + a_1\varepsilon + a_2\varepsilon^2)$ with $\varepsilon = M(p\bar{p}) - 2m_P$ (so that the first (constant) term corresponds to the phase-space behavior) and coefficients a_1, a_2 fitted to the data. The polynomial is meant to represent contributions of non-resonant $\omega p\bar{p}$ events and background, where the latter is suggested to come mainly from the decays of $J/\psi \to \pi^+\Lambda\bar{\Sigma}^-$ (+ c.c.) and $\pi^0\Delta^{++}\bar{\Delta}^{--}$ [28]. Since the data exhibit a significant dependence on ε near the threshold, cf. Figs. 1 and 2, it is obvious that the polynomial likewise produces a significant dependence on the $p\bar{p}$ excess energy ε. Thus, we believe that this polynomial simply parameterizes the $p\bar{p}$ FSI effects. It would be hard to understand if any background, unrelated to the $p\bar{p}$ system, depends so strongly on the $p\bar{p}$ excess energy ε.

Note that the disagreement of our model results with the experiment for invariant masses beyond $M(p\bar{p}) - 2m_p \approx 100$ MeV is not a reason of concern and, in particular, does not discredit the interpretation of the data in terms of FSI effects. At those energies we expect that contributions from higher partial waves, not considered here, should start to play a more prominent role.

In summary, we have analyzed the near-threshold data on the $p\bar{p}$ invariant mass spectrum from the $J/\psi \to \omega p\bar{p}$ decay reported recently by the BES Collaboration. Our study demonstrates that not only in $J/\psi \to \gamma p\bar{p}$ but also in this reaction there is indeed a noticeable enhancement in the $p\bar{p}$ invariant mass spectrum near threshold as compared to the phase-space behavior. Moreover, this enhancement is nicely reproduced by the final state interaction in the relevant $({}^{11}S_0)$ $p\bar{p}$ partial wave as given by the Jülich $N\bar{N}$ model [24]. Accordingly, the present result is completely in line with our previous investigations of the $p\bar{p}$ invariant mass spectrum from the $J/\psi \to \gamma p\bar{p}$ decay [16] measured by the BES Collaboration and the $B^+ \to K^+ p\bar{p}$ decay [17] measured by the BaBar Collaboration. In particular, and contrary to the statement by the BES Collaboration [28], their new data on $J/\psi \to \omega p\bar{p}$ decay, in fact, strongly support the FSI interpretation of the $p\bar{p}$ enhancement seen in other decay reactions. It goes without saying that, the FSI effects for the various decay reactions should not be expected to be *quantitatively the same* because due to the different quantum numbers and conservation laws as well as different reaction mechanisms in those decay channels, the final $p\bar{p}$ system can and must be in different partial waves.

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