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Near threshold $p\bar{p}$ enhancement in B and J/Ψ decay

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The near-threshold enhancement in the $p\bar{p}$ invariant mass spectrum from the $B^+ \to K^+ p\bar{p}$ decay reported recently by the *BABAR* Collaboration is studied within the Jülich $N\bar{N}$ model. We illustrate that the invariant mass dependence of the $p\bar{p}$ spectrum close to the threshold can be reproduced by the final state interactions. This explanation is in line with our previous analysis of the $p\bar{p}$ invariant mass spectrum from the $J/\Psi \to \gamma p\bar{p}$ decay measured by the BES Collaboration. We also comment on a structure found recently in the $\pi^+\pi^-\eta'$ mass spectrum of the radiative J/Ψ decay by the BES Collaboration. In particular we argue that one should be rather cautious in bringing this structure in connection with the enhancement found in the $p\bar{p}$ invariant mass spectrum or with the existence of $N\bar{N}$ bound states.

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A first indication for a near-threshold enhancement in the proton-antiproton $p\bar{p}$ 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 [1,2]. Soon afterwards a much more significant evidence of a $p\bar{p}$ enhancement, i.e. with high statistics and high mass resolution, was observed by the BES Collaboration [3] in the reaction $J/\Psi \to \gamma p\bar{p}$. More recently the Belle Collaboration [4] found also a near-threshold $p\bar{p}$ enhancement in the decays $B^+ \to \pi^+ p\bar{p}$, $B^+ \to K^+ p\bar{p}$, $B^0 \to K^0 p\bar{p}$ and $B^+ \to K^{*+} p\bar{p}$, while the CLEO Collaboration detected such an enhancement in (the unsubtracted) data for $\Upsilon(1S) \to \gamma p\bar{p}$ [5]. However, in all these cases the results are marred by low statistics. Very recently the *BABAR* Collaboration presented a new measurement with high mass resolution of the $B^+ \to K^+ p\bar{p}$ decay [6] confirming the threshold peaking in the $p\bar{p}$ invariant mass, see also [7].

The high statistics data by the BES Collaboration triggered a number of 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 [8], or for exotic glueball states [9,10]. Alternatively, we [11] but also others [12–15] demonstrated that the near-threshold enhancement in the $p\bar{p}$ invariant mass spectrum from the $J/\Psi \to \gamma p\bar{p}$ decay could be simply due to the final state interactions (FSI) between the outgoing proton and antiproton. Specifically, our calculation based on the realistic Jülich $N\bar{N}$ model [16,17] and the one by Loiseau and Wycech [15], utilizing the Paris $N\bar{N}$ model, explicitly confirmed the significance of FSI effects estimated in the initial studies [12–14] within the effective range approximation.

In the present paper we want to investigate whether the near-threshold enhancement in the $p\bar{p}$ invariant mass spectrum, visible in the data on the reaction $B^+ \to K^+ p\bar{p}$, cf. Fig. 1, can likewise be understood in terms of the $p\bar{p}$ FSI. In our study of the $J/\Psi \to \gamma p\bar{p}$ decay we considered the $p\bar{p}$ FSI interaction in the ${}^1S_0$ and ${}^3P_0$ partial waves and the $I = 0$ and $I = 1$ isospin channels. Other $p\bar{p}$ S- and P-waves are ruled out by conservation laws for parity, charge-conjugation and total angular momentum together with the measured photon angular distribution from the $J/\Psi \to \gamma p\bar{p}$ decay, which agrees with that expected from the $p\bar{p}$ state being in both ${}^1S_0$ and ${}^3P_0$ states. We found that the mass dependence of the $p\bar{p}$ spectrum close to the threshold can be reproduced by the S-wave $p\bar{p}$ FSI in the isospin $I = 1$ state. In case of the $B^+ \to K^+ p\bar{p}$, the weak interaction is involved. As a consequence, the selection rules are less rigid and now other $p\bar{p}$ S- and P-waves are allowed too and could produce FSI effects in the near-

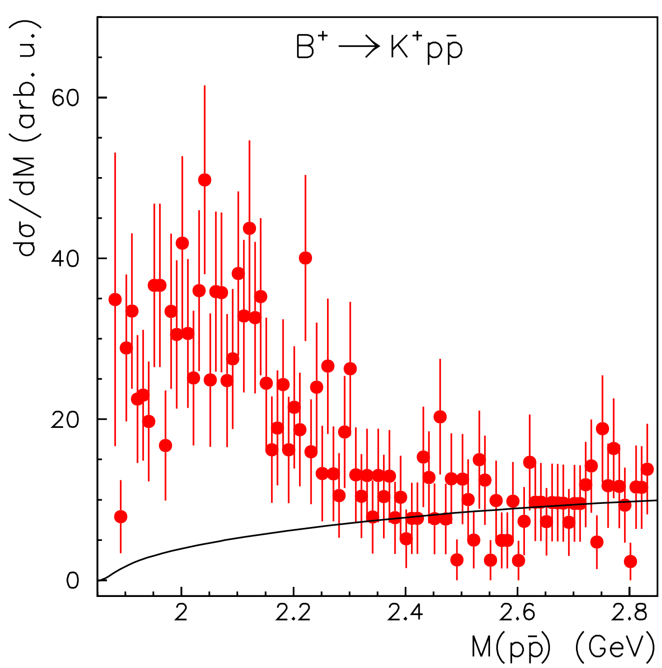

FIG. 1 (color online). The $p\bar{p}$ mass spectrum from the decay $B^+ \to K^+ p\bar{p}$. The circles show experimental results of the *BABAR* Collaboration [6,7], while the solid line is the spectrum obtained from Eq. (2) by assuming a constant reaction amplitude A which was normalized to the data at $M(p\bar{p}) \approx 2.7$ GeV.

threshold region. Thus, besides the effects resulting from the ${}^1S_0$ and ${}^3P_0$ partial waves we explore here also those of the ${}^3S_1$ and ${}^3P_1$ states.

Like in our earlier paper we utilize the total spin-averaged (dimensionless) $B^+ \to K^+ p\bar{p}$ reaction amplitude A and not directly the measured $p\bar{p}$ invariant mass spectrum, because that allows us to get rid of trivial kinematical factors. The $B^+ \to K^+ p\bar{p}$ decay rate is given in terms of A by [18]

$$d\Gamma = \frac{|A|^2}{2^9\pi^5 m_{B^+}^2}\lambda^{1/2}(m_{B^+}^2, M^2, m_{K^+}^2)\lambda^{1/2}(M^2, m_p^2, m_p^2) \times dMd\Omega_p d\Omega_K, \quad (1)$$

where the Kallen 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_K is the K^+ angle in the B^+ rest frame. After averaging over the spin states and integrating over the angles, the differential decay rate is

$$\frac{d\Gamma}{dM} = \frac{\lambda^{1/2}(m_{B^+}^2, M^2, m_{K^+}^2)\sqrt{M^2 - 4m_p^2}}{2^6\pi^3 m_{B^+}^2}|A|^2. \quad (2)$$

We use Eq. (2) for extracting $|A|^2$ from the data of the *BABAR* Collaboration. The corresponding results are shown in Fig. 2 by the filled circles.

We assume again the validity of the Watson-Migdal approach for the treatment of FSI effects. 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

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

(cf. Ref. [11] 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. The curves shown in Fig. 2 correspond to the $p\bar{p}$ scattering amplitude squared calculated for the ${}^1S_0$, ${}^3S_1$, ${}^3P_0$ and ${}^3P_1$ partial waves, where the solid lines are the results for the isospin $I = 0$ channel, while the dashed lines are for the $I = 1$ channel.

As can be seen from Fig. 2, the enhancement of the near-threshold $p\bar{p}$ invariant mass spectrum from the $B^+ \to K^+ p\bar{p}$ decay, as observed in the new *BABAR* experiment [6,7], is fully in line with our previous results [11]. Figure 2 contains also the $J/\Psi \to \gamma p\bar{p}$ reaction amplitude, evaluated via

$$\frac{d\Gamma}{dM} = \frac{(m_{J/\Psi}^2 - M^2)\sqrt{M^2 - 4m_p^2}}{2^7\pi^3 m_{J/\Psi}^3}|A_{J/\Psi}|^2, \quad (4)$$

again suitably normalized to facilitate an easy comparison

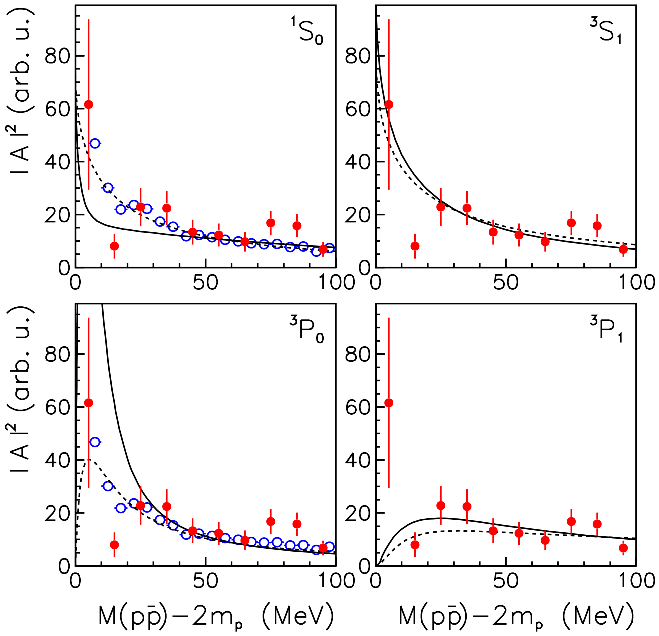

FIG. 2 (color online). Invariant $B^+ \to K^+ p\bar{p}$ amplitude $|A|^2$ as a function of the $p\bar{p}$ mass. The filled circles represent the experimental values of $|A|^2$ extracted from the *BABAR* data [6,7] via Eq. (2). The curves are the scattering amplitude squared ($|T|^2$) predicted by the $N\bar{N}$ model A(OBE) [16] for the ${}^1S_0$, ${}^3S_1$, ${}^3P_0$, and ${}^3P_1$ partial waves and the $I = 0$ (solid) and $I = 1$ (dashed) channels, respectively. Note that the latter results have been normalized to $|A|^2$ at $M(p\bar{p}) - 2m_p = 50$ MeV. For comparison reasons we show also the corresponding results extracted from the data on $J/\Psi \to \gamma p\bar{p}$ [3] (open circles).

of the dependence on the $p\bar{p}$ invariant mass. Obviously the data from both considered decay reactions are in reasonable agreement as far as the dependence on $M(p\bar{p})$ is concerned. As already mentioned, while for the $J/\Psi \to \gamma p\bar{p}$ data the final $p\bar{p}$ system is restricted to the ${}^1S_0$ and ${}^3P_0$ partial waves in the near-threshold region, due to selection rules and the measured photon angular distribution [3], the $B^+ \to K^+ p\bar{p}$ reaction allows also for other partial waves. But also here a measurement of the K^+ angular distribution could clarify whether the ${}^1S_0$ or ${}^3P_0$ partial waves are responsible for the $p\bar{p}$ enhancement, as for the J/Ψ, or rather the ${}^3S_1$, ${}^3P_1$ or ${}^1P_1$ states. Conservation of the total angular momentum requires the K^+ to be either in a relative s wave to the $p\bar{p}$ system (for the ${}^1S_0$ or ${}^3P_0$ partial waves) or in a p wave (for ${}^3S_1$, ${}^3P_1$ or ${}^1P_1$). We note that the invariant amplitude for the ${}^1P_1$ wave looks very similar to the one for ${}^3P_1$.

Recently the CLEO Collaboration published results on the radiative decays of the $\Upsilon(1S)(9460)$ to the $p\bar{p}$ system [5]. Interestingly, also in this reaction one can see an enhancement in the $p\bar{p}$ invariant mass spectrum near threshold, cf. Fig. 6 in that paper. The authors presented also results of a reference measurement for the reaction $e^+e^- \to \gamma p\bar{p}$ at the energy $\sqrt{s} = 10.56$ GeV where a similar near-threshold enhancement in the $p\bar{p}$ mass spectrum is detected. We do not show corresponding results here because the accuracy and the mass resolution of those data is too low for allowing a meaningful comparison. However, we would like to comment on a conclusion drawn in Ref. [5]. In order to remove possible continuum background contributions the CLEO Collaboration subtracted the (scaled) $e^+e^- \to \gamma p\bar{p}$ mass spectrum from the one measured for the $\Upsilon(1S)$ radiative decay. The "corrected" $\Upsilon(1S) \to p\bar{p}$ data do not show an enhancement in the $p\bar{p}$ spectrum anymore. We believe that this is not surprising and, in fact, must be expected if the near-threshold enhancement comes indeed from the FSI in the $p\bar{p}$ system. Then, the same or a similar FSI must be present in $e^+e^- \to \gamma p\bar{p}$ as well as in $\Upsilon(1S) \to \gamma p\bar{p}$ and it must cancel to a large degree in a subtraction like the one performed in Ref. [5]. Accordingly, from our point of view there is no contradiction between the results of CLEO and those of the BES Collaboration for $J/\Psi \to \gamma p\bar{p}$ as suggested in Ref. [5]. Rather the CLEO results even strengthen the conjecture that the near-threshold enhancement in the $p\bar{p}$ spectrum seen in J/Ψ, B^+, $\Upsilon(1S)$ etc. decays is due to the $p\bar{p}$ FSI.

Next, let us reflect on the present results in view of the earlier consideration concering the J/Ψ decays. In our work on the $J/\Psi \to \gamma p\bar{p}$ spectrum we admitted that, because of our poor knowledge of the $N\bar{N}$ interaction near threshold and for some other reasons [11], explanations for the enhancement other than final state interactions cannot be ruled out at the present stage. Specifically, we discussed [11] that intermediate pseudoscalar ($J^{PC} = 0^{-+}$) meson resonances, for instance the $\pi(1800)$ resonance but also the $\eta(1760)$ [19], could couple to the $p\bar{p}$ channel and thus could play a role. In fact, we showed that the presence of these resonances in the decay $J/\Psi \to \gamma p\bar{p}$ is, in principle, in line with the BES data [3] once FSI effects are taken into account.

In this context it is interesting to note that recently the BES Collaboration reported [20] a resonance in the $J/\Psi \to \gamma\pi^+\pi^-\eta'$ mode with mass 1833.7 ± 6.1 MeV and width of 67.7 ± 20.3 MeV obtained by fitting a Breit-Wigner function to the $\pi^+\pi^-\eta'$ invariant spectrum. This resonance was denoted as a new $X(1835)$ state, arguing that it is not compatible with any of the meson resonance listed in Ref. [19].

Following our prescription [11] the authors of Ref. [20] refitted the $J/\Psi \to \gamma p\bar{p}$ spectrum including a pseudoscalar resonance and the $I = 0$ $^1S_0$ $p\bar{p}$ FSI of the Jülich $N\bar{N}$ model A(OBE) [16]. The fit yielded a mass of 1831 ± 7 MeV and a $\Gamma < 153$ MeV and led them to the conclusion that the $X(1835)$ properties as found in $J/\Psi \to \gamma\pi^+\pi^-\eta'$ are consistent with expectations for the state that produces the strong $p\bar{p}$ mass threshold enhancement observed in the $J/\Psi \to \gamma p\bar{p}$ decay [20].

Though the authors of Ref. [20] admitted in the summary that other possible interpretations of the $X(1835)$ that have no relation to the observed near-threshold $p\bar{p}$ enhancement are not excluded, we think its worthwhile to elaborate further on that issue. Dividing the average total $J/\Psi \to \gamma p\bar{p}$ reaction amplitude $|A_{J/\Psi}|^2$, which is related to the differential decay rate via Eq. (4), by the $p\bar{p}$ scattering amplitude $|T|^2$ [11,16] one can easily obtain the FSI corrected data as a function of the $p\bar{p}$ invariant mass $M(p\bar{p})$, cf. Fig. 3. Here we use the $^1S_0$ scattering amplitudes in the $I = 0$ and $I = 1$ isospin states.

In our experience the data do not allow one to fix uniquely the resonance properties if the mass, width and the strength of the resonant contribution are unknown. In order to illustrate that we show the squared Breit-Wigner amplitudes for the $X(1835)$, the $\eta(1760)$ and $\pi(1800)$ with their properties given by the BES Collaboration [20] and the PDG [19], respectively. We only vary the coupling strength of the 0^{-+} state to the $p\bar{p}$ channel in order to reproduce the BES data [3]. Since the $X(1835)$ might be a $I^G(J^{PC}) = 0^+(0^{-+})$ resonance [20] one can certainly speculate whether it is the same object as the $\eta(1760)$ listed by the PDG [19]. In fact, the $\eta(1760)$ was also established in radiative J/Ψ decays, namely, in the reaction $J/\Psi \to \gamma\rho\rho$ [21]. While the PDG cites only an averaged value, a glance into the original paper [21] makes clear that the mass as well as the width of the $\eta(1760)$ could not be reliably established from the data. Indeed, one of the six solutions with comparable χ^2 given in Ref. [21]

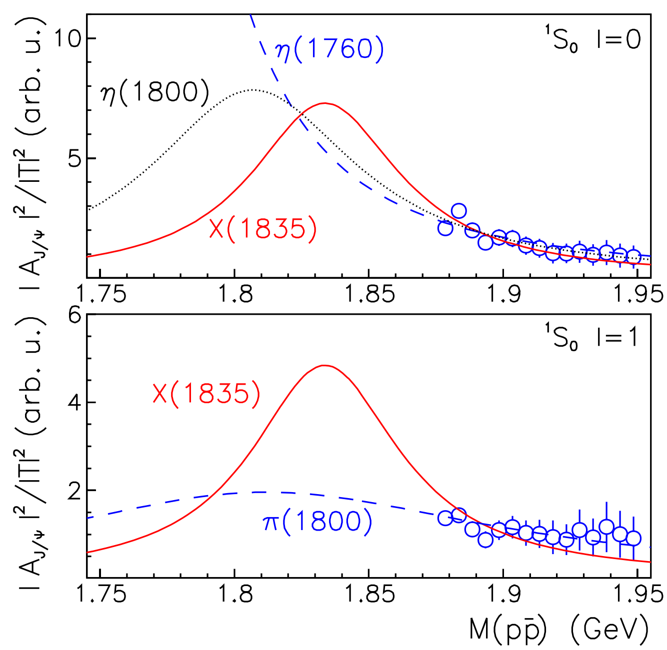

FIG. 3 (color online). Invariant FSI corrected $J/\Psi \to \gamma p\bar{p}$ amplitude $|A_{J/\Psi}|^2/|T|^2$ as a function of the $p\bar{p}$ mass. The squares show the values of $|A_{J/\Psi}|^2$ extracted from the BES data [3] via Eq. (2) and divided by the $^1S_0$ scattering amplitude squared for the $I = 0$ and $I = 1$ isospin states. The lines show the squared Breit-Wigner amplitudes for the $X(1835)$ [20], $\eta(1800)$ [21] and $\pi(1800)$ and $\eta(1760)$ [19] states.

(in Table IV) yields a mass and width of 1807 ± 10 MeV and 94 ± 12 MeV, which is not that far away from the values obtained by the BES Collaboration. We show also results based on the above resonance parameters in Fig. 3. It is obvious that there is practically no difference between the $X(1835)$ of Ref. [20] and the $\eta(1800)$ of Ref. [21] as far as the description of the $p\bar{p}$ invariant mass spectrum is concerned.

Anyway, the properties of the $X(1835)$ are indeed consistent with the measured near-threshold enhancement in the $p\bar{p}$ spectrum of the reaction $J/\Psi \to \gamma p\bar{p}$. On the other hand, one has to concede that this enhancement as such does not provide any reliable additional support for the existence of the $X(1835)$ resonance, and likewise not for the existence of $p\bar{p}$ bound states or baryonia. With regard to the latter we want to remind the reader that our model calculations [11] as well as those of Loiseau and Wycech [15] are able to reproduce the $p\bar{p}$ spectrum. However, while the $N\bar{N}$ model used in [15] generates a near-threshold bound state (at $E \approx -5 - i50$ MeV) in the relevant $^{11}S_0$ state no such state is present in our $^{31}S_0$ amplitude (which describes the data equally well) and the one in the $^{11}S_0$ (at $E \approx -104 - i413$ MeV [22]) is too wide to have an influence in the physical region.

We believe that it will be rather difficult to establish experimentally a direct connection between the $X(1835)$ and the $p\bar{p}$ system. On the other hand, it would be still interesting to investigate whether this resonance is also visible in $p\bar{p}$ annihilation. The $X(1835)$ could be searched for in reactions like $p\bar{p} \to \pi^+\pi^- X$, $X \to \pi^+\pi^-\eta'$, etc. [23]. Measurements to get more information on these issues could be performed using the PANDA detector at the future FAIR project.

In this context let us also remind the reader that standard quark-model calculations like those in Refs. [24–26] do predict radial excitations of the η, η' around the $\eta(1800)$ mass. Thus, a very conventional interpretation of the structure found by the BES Collaboration should be also taken into consideration before speculating excessively on exotic explanations.

In summary, we have analyzed the near-threshold enhancement in the $p\bar{p}$ invariant mass spectrum from the $B \to Kp\bar{p}$ decay reported recently by the *BABAR* Collaboration within the Jülich $N\bar{N}$ model. Our study shows that the mass dependence of the $p\bar{p}$ spectrum close to the threshold can be reproduced by the final state interaction. This explanation is in line with our previous investigation of the $p\bar{p}$ invariant mass spectrum from the $J/\Psi \to \gamma p\bar{p}$ decay measured by the BES Collaboration.

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