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Antiproton-proton channels in J/ψ decays

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The recent measurements by the BES Collaboration of J/ψ decays into $\gamma p\bar{p}$ indicate a strong enhancement at $p\bar{p}$ threshold not observed in the decays into $\pi^0 p\bar{p}$. Is this enhancement due to a $p\bar{p}$ quasibound state or a baryonium? A natural explanation follows from a traditional model of $p\bar{p}$ interactions based on the G-parity transformation. The observed $p\bar{p}$ structure is due to a strong attraction in the $^1S_0$ state and possibly to a near-threshold quasibound state in the $^{11}S_0$ wave.

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A point of interest in the antiproton interactions is the question of existence or nonexistence of exotics in the nucleon-antinucleon ($N\bar{N}$) systems: quasibound, virtual, resonant, multiquark, or baryonium states [1]. Such states, if located close to the threshold, may be indicated by large scattering lengths for a given spin and isospin state. For this purpose, scattering experiments are apparently the easiest to perform with good precision. However, a clear separation of quantum states is not easy. Complementary measurements of the x-ray transitions in antiprotonic hydrogen are useful to select some partial waves. These are particularly valuable when the fine structure of levels is resolved. Such a resolution has been achieved for the $1S$ states [2] and partly for the $2P$ states [3]. Another method to reach selected states are formation experiments. In this way a resonantlike behavior was recently observed by BES Collaboration in the radiative decay $J/\psi \to \gamma p\bar{p}$ close to the $p\bar{p}$ threshold [4]. On the other hand, a clear threshold suppression is seen in the pionic decay channel $J/\psi \to \pi^0 p\bar{p}$. To better understand the nature of the enhancement, one should look into the $p\bar{p}$ subthreshold-energy region. This may be achieved indirectly in the $\bar{p}d$ low-energy scattering or $\bar{p}d$ atoms. Such atomic experiments were performed, but the fine structure resolution has not been achieved so far [5].

The purpose of this paper is to discuss the physics of slow $p\bar{p}$ pairs produced in the J/ψ decays. The J^{PC} conservation reduces the number of $p\bar{p}$ final states to several partial waves. These, denoted by $^{2I+1\,2S+1}L_J$, differ by their isospin I, spin S, angular momenta L, and total spin J. Close to the $p\bar{p}$ threshold, quite different behavior of scattering amplitudes is expected in different states. In the $1S$ state of antiprotonic hydrogen, it is the $^1S_0 = (^{11}S_0 + {}^{31}S_0)/2$ and $^3S_1 = (^{13}S_1 + {}^{33}S_1)/2$ waves which are studied [2]. While atomic experiments determine the scattering lengths, the BES experiment allows us to extend this knowledge into a broad energy region above the threshold. As will be shown, the radiative J/ψ decay involves also the $^{11}S_0 + {}^{31}S_0$ combination. The understanding of this and other involved states should be based on the experience gained in studies of elastic and inelastic $\bar{N}N$ scattering. We use the Paris potential model [6–9] for this purpose.

To our present knowledge, none of the available related works [10–14] on the BES radiative and pionic J/ψ decays have given a comprehensive explanation of the BES experimental spectra. Only two of these papers [10,12] compare their results to the data. The Jülich $N\bar{N}$ model is used in [10] to show that within the Watson-Migdal approach, the isospin 1 S wave can reproduce the low-energy part of the $p\bar{p}$ spectrum in the radiative decay. The same spectrum is fitted with a constant scattering length in Ref. [12]. The length obtained in this way is larger than the lengths calculated in potential models. In Ref. [11], more realistic but spin averaged constant lengths are shown to generate some low-energy enhancement for the BES radiative decays. A K matrix, calculated with the one-pion exchange in the Born approximation, is considered in Ref. [14]. An enhancement is seen, but this model is too simple to describe the $N\bar{N}$ interactions. The formation mechanisms in the radiative decays are discussed qualitatively in Ref. [13], where the quantum numbers of final states are listed with the recommendation to look into decay modes of the $p\bar{p}$ systems.

In the present work, the following results are obtained. The set of allowed final $p\bar{p}$ states is limited to three partial waves in the photon channel and two waves in the pion channel. Among the three possible $p\bar{p}$ states in the $p\bar{p}\gamma$ channel, one is dominated at very low energies by the well-known $p\bar{p}(^{13}P_0)$ resonance, formed as a result of attractive one-pion exchange forces. However, this state as well as another allowed $^3P_1$ state cannot explain the experimental spectrum. The final $p\bar{p}\gamma$ state is dominated by the $p\bar{p}(^1S_0)$ wave. A strong attraction arises in this wave as a result of coherent one- and two-pion exchange forces. It produces broad, deeply bound states, difficult to detect. However, the recent version of the model [6], adapted to hydrogen atom data, generates a near-threshold state in the related $p\bar{p}(^{11}S_0)$ wave. This state is about 50 MeV wide and bound by 5 MeV.

In the $p\bar{p}\pi^0$ decay channel, two $p\bar{p}$ waves, $^{33}S_1$ and $^{31}P_1$, are allowed. These indicate distinctly different threshold behavior. The S wave is ruled out by the experiment and the $p\bar{p}(^{31}P_1)$ leads to a natural explanation of the BES spectrum. These findings can be unified in a qualitative model for both decay modes.

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TABLE I. States of low-energy $p\bar{p}$ pairs allowed in the $J/\psi \to \gamma p\bar{p}$ and $J/\psi \to \pi^0 p\bar{p}$ decays. The first column gives the decay modes to the specified internal state of the $p\bar{p}$ pair. Well-established, two-particle analogs are indicated in the second column [15]. The third column gives J^{PC} for the light spectator particles, photons or pions. The fourth column gives J^{PC} for the internal $p\bar{p}$ system; the last column gives the relative angular momentum of the light particle vs the pair. $J^{PC} = 1^{(--)}$ for J/ψ.

Decay mode	Analog	$J^{PC}(\gamma$ or $\pi^0)$	$J^{PC}(p\bar{p})$	Relative l
$\gamma p\bar{p}(^1S_0)$	$\gamma\eta(1444)$	1^{--}	0^{-+}	1
$\gamma p\bar{p}(^3P_0)$	$\gamma f_0(1710)$	1^{--}	0^{++}	0
$\gamma p\bar{p}(^3P_1)$	$\gamma f_1(1285)$	1^{--}	1^{++}	0
$\pi^0 p\bar{p}(^{31}P_1)$		0^{-+}	1^{+-}	0
$\pi^0 p\bar{p}(^{33}S_1)$	$\pi^0\rho$	0^{-+}	1^{--}	1

The J^{PC} conservation limits the number of slow $p\bar{p}$ final states. The latter are understood as $p\bar{p}$ pairs with small $M_{p\bar{p}} - 2m_p$, where $M_{p\bar{p}}$ is the pair invariant mass. The allowed states are listed in Table I, and a few possibilities exist for each channel. The BES experiment provides an angular distribution for the photons. With θ denoting the angle between the γ emission and the beam direction, the angular distributions $(\cos^2\theta + 1)$ and $\sin^2\theta$ were tested against the data in Ref. [4]. These indicated a preference for radiative transitions to $^3P_0$ or $^1S_0$ states, but a transition to the $^3P_1$ state is not excluded.

Any multichannel system can be conveniently parametrized by a K matrix which guarantees unitarity of the description. The transition amplitude from a channel i to a two-body channel f may be presented in the form

$$T_{if} = \frac{A_{if}}{1 + iqA_{ff}}, \tag{1}$$

where A_{if} is a transition length, A_{ff} is the scattering length in the channel f, and q is the momentum in this channel (see, e.g. [16]). Both lengths can be expressed in terms of energy-dependent K-matrix elements. The same formalism describes the scattering amplitude in channel f as

$$T_{ff} = \frac{A_{ff}}{1 + iqA_{ff}}. \tag{2}$$

In the process of interest the formation amplitude A_{if} is unknown, but A_{ff} is calculable in $N\bar{N}$ interaction models constrained by other experiments. For slow $p\bar{p}$ pairs, the final state interactions in the $\pi^0 p\bar{p}$ and $\gamma p\bar{p}$ systems are dominated by interactions in the $p\bar{p}$ subsystem. Formal manipulation of Eqs. (1) and (2) yields

$$T_{if} = \frac{A_{if}}{A_{ff}} T_{ff} = \left(\frac{A_{if}q^L}{A_{ff}}\right)\left(\frac{T_{ff}}{q^L}\right), \tag{3}$$

which defines a quantity $C_{if} \equiv A_{if}q^L/A_{ff}$. For S waves, the standard final state dominance assumption (Watson-Migdal) is equivalent to a weak energy dependence in C_{if}. This is usually true in a small energy range where the denominator in Eq. (1) provides all the energy dependence. In the $p\bar{p}$ states, such an approximation is correct for q up to about 0.5 fm^{-1}. It fails at higher momenta, since A_{ff} is energy dependent. On the other hand, A_{if} stems from a short-range $c\bar{c}$ annihilation process. The annihilation range is of the order of $1/m_c$ [17], and only a weak energy dependence is expected in A_{if}. We assume $A_{if} = A_{if}(0)/[1 + (r_oq)^2]$ with a range parameter r_o well below 1 fm. For P-wave final states, the low-energy behavior gives $A_{if} \approx A^1_{if}q$, $A_{ff} \approx A^1_{ff}q^2$, where the A^1_{if} are parameters and A^1_{ff} the scattering volumes. The latter are energy dependent as a result of medium-ranged π exchange forces. This dependence is particularly strong in waves that involve resonances. The Watson approximation is not appropriate there, and Eq. (1) must be used. The transition length is parametrized as $A_{if} = A^1_{if}(0)q/[1 + (r_oq)^2]^2$.

The advantage of K-matrix formalism is clear in the analysis of low-energy final state interactions since it isolates the kinematic singularity into a definite form given by Eq. (1). The two functions A_{ff} and A_{if} depend only on q^2. Hence, close to the threshold, a constant scattering length approximation in Eq. (3) may well indicate some subthreshold phenomena. This approximation has been used in Refs. [11,12]. In the $p\bar{p}$ system, the energy dependence in A_{ff} is strong, as pointed out in Ref. [10] on the basis of a one-boson exchange version of Bonn potential. A similar behavior is seen with the Paris model, although these two potentials differ strongly in the two-pion sector. As shown below, Eq. (3) with a constant C_{if} and realistic $A_{ff}(q^2)$ describes a too narrow energy range. The selection of the best $p\bar{p}$ partial wave requires Eq. (1). This equation offers also an explicit and unique dependence on the on-shell A_{ff} [or T_{ff} since $1/(1 + iqA_{ff}) = 1 - iqT_{ff}$]. An off-shell A_{ff} may be involved in A_{if} if one attempts to construct a model for the $p\bar{p}$ formation.

There exists substantial phenomenological control over A_{ff}. Here these scattering lengths are calculated in terms of the Paris $N\bar{N}$ potential model, and the same procedure is applied to both decay modes $J/\psi \to \pi^0 p\bar{p}$ and $J/\psi \to \gamma p\bar{p}$. Figures 1 to 3 present the results obtained with Eqs. (3) and (1) for three of the five states of interest calculated for the four versions of the Paris model [6–9] which evolved over the last 20 years. This evolution followed the increasing data basis. The last version [6] is based on 3934 data which includes the recent antiproton-hydrogen widths and shifts [2,3] and the total $\bar{n}p$ cross sections of Ref. [18]. Study of the energy dependence of different $N\bar{N}$ observables does not indicate the existence of quasibound states or resonances in any of the four versions. It is necessary to look for poles of the S matrix in a given partial wave [8]. The Coulomb interactions yield enhancements of the S waves at very low energies due to Gamov factors. These affect the final state interaction for $q < 0.15$ fm^{-1} and produce spikes. Since the amplitudes are weighted by the phase space factor q, these become unessential. The q factor represents a residual piece of the full three-body phase space [15]. Note that (figures not shown here) the $p\bar{p}(^{33}S_1)$ wave is not consistent with the BES pionic decays and that the $p\bar{p}(^3P_1)$ wave cannot reproduce the BES radiative data.

Let us now consider a plausible qualitative model. As exemplified by the final state calculations, the BES findings are most consistent with a $p\bar{p}(^{31}P_1)$ wave in the $\pi^0 p\bar{p}$ channel and

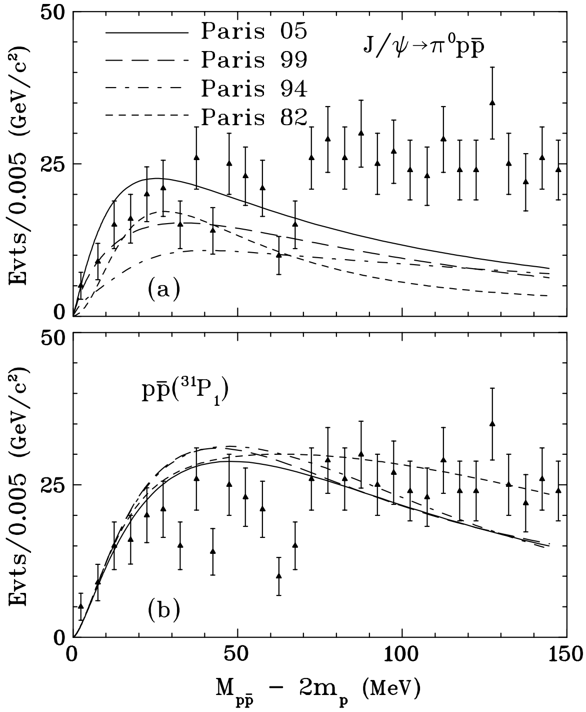

FIG. 1. $\pi^0 p\bar{p}(^{31}P_1)$ decay channel. Experimental data are from Fig. 2(a) of Ref. [4]. (a) Final state factor $q\,|T_{ff}/q\,|^2$ (Watson approximation). Constant C_{if} of Eq. (3) is chosen to fit the low-energy part of the data. Four versions of the Paris potential model [6–9] are used. This approximation fails for $M_{p\bar{p}} - 2m_p > 40$ MeV ($q > 1$ fm^{-1}). (b) Rate $q\,|T_{if}\,|^2$ of Eq. (1). Constant $A^1_{if}(0)$ and formation range parameter $r_o = 0.55$ fm are chosen to obtain a good fit to the data. All four potentials give equivalent fits, eventhough a 118 MeV wide state bound by 15 MeV is generated in version [6] in the $^{31}P_1$ wave.

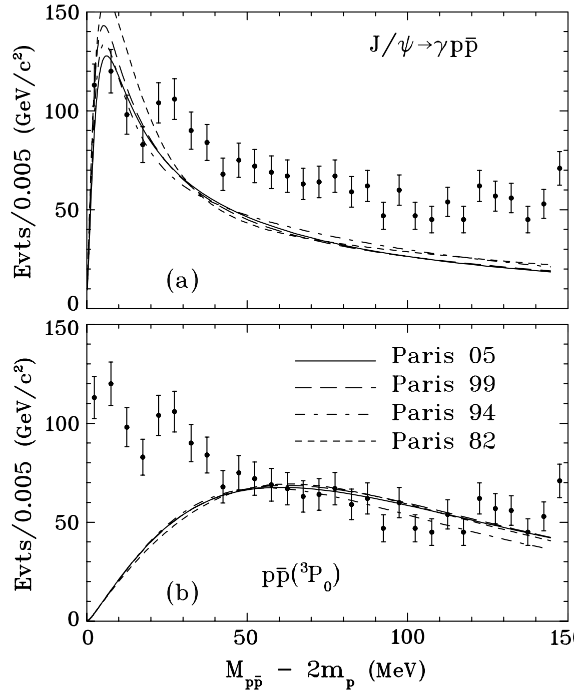

FIG. 2. $\gamma p\bar{p}(^3P_0)$ decays. Experimental data extracted from Fig. 3(a) of Ref. [4]. (a) Final state factor $q\,|T_{ff}/q\,|^2$ of Eq. (3). The low energy part is dominated by the resonance in the $^{13}P_0$ wave at 1876 MeV, of 10 MeV width, present in all models. However, for $q > 1$ fm^{-1} this approximation fails to fit the data. (b) Rate $q\,|T_{if}\,|^2$ of Eq. (1) with $r_o = 0.55$ fm. This rate can describe only the $q > 1$ fm^{-1} part of the spectrum. This wave is not consistent with the BES data.

a $p\bar{p}(^1S_0)$ wave in the $\gamma p\bar{p}$ channel. Therefore, the experiment leads us to a simple picture of the slow $p\bar{p}$ formation.

The initial heavy $c\bar{c}$ quarks in the J/ψ state of $J^{PC} = 1^{--}$ annihilate into a $N\bar{N}$ pair. As argued in Refs. [17,19], that process is mediated by three gluon exchange. Due to isospin conservation, the baryon pair is formed in an $I = 0$ state of $n\bar{n} + p\bar{p}$ as indicated by experiment [20] and calculations of Ref. [17]. The pair inherits the J/ψ quantum numbers $J^{PC} = 1^{--}$ and forms a $^3S_1$ state. Next, the emission of a pion or a photon takes place. The π_0 emission proceeds via the standard $\pi N\bar{N}$ coupling $(f_{\pi NN}/2m_\pi)\,\mathbf{q}\cdot\boldsymbol{\sigma}$. It requires one nucleon to flip spin and change angular momentum, which leads to the final $p\bar{p}(^{31}P_1)$ state. The photon may be produced as magnetic or as electric. The relevant formation amplitudes are given by the transition operator $(e/2m_p)$ $[2\ \boldsymbol{\epsilon}^\gamma\cdot\mathbf{q} + i\ \boldsymbol{\sigma}\cdot(\mathbf{k}^\gamma\times\boldsymbol{\epsilon}^\gamma)]$, $\mathbf{k}^\gamma$ and $\boldsymbol{\epsilon}^\gamma$ being the photon momentum and polarization vector, respectively. In the final states, q is small. In the intermediate states, it is not necessarily small, but any formation mechanism would favor small momenta. Since $|\,\mathbf{k}^\gamma\,|$ is large, we conclude that it is the magnetic transition which is more likely to occur. It favors formation of the final $\gamma p\bar{p}(^1S_0)$ state which arises in a most natural way. In the initial $p\bar{p}(^3S_1)$ wave, the proton and antiproton magnetic moments are opposite and the transition to $p\bar{p}(^1S_0)$ involves spin and magnetic moment flips. Large moments create large radiative amplitudes. The emission model indicated above yields comparable branching ratios of the γ and π^0 channels, as found in the experiment. This ratio follows roughly the ratio of the coupling constants $f^2_{\pi NN}/(4e^2) \approx 2.8$, while the experimental ratio is ≈ 3 [15].

The final $p\bar{p}$ state involves the isospin 1 plus isospin 0 combination. The pair may be also formed in the $n\bar{n}$ state and undergo a transition to $p\bar{p}$ in the final state. That process is expected to be suppressed, since that transition implicates the $T_{ff}(I = 1) - T_{ff}(I = 0)$ amplitude, which is about an order of magnitude smaller than the elastic $T_{ff}(I = 1) + T_{ff}(I = 0)$ one. The simple model of final photon radiation discussed above would reduce the neutron channel even further, because of different charges and magnetic moments.

We have shown that the new results of the BES Collaboration find a natural explanation in a fairly traditional model of $p\bar{p}$ interactions based on the G-parity transformation, dispersion relations to calculate two-pion exchange and semiphenomenological absorptive and short-range potentials. This model predicts quasibound states close to the threshold, in particular in the $p\bar{p}(^{33}P_1)$ and $p\bar{p}(^{11}S_0)$ waves and a resonance in the $p\bar{p}(^{13}P_0)$ wave. The first two indicate a strong dependence on the model parameters and, so far, are

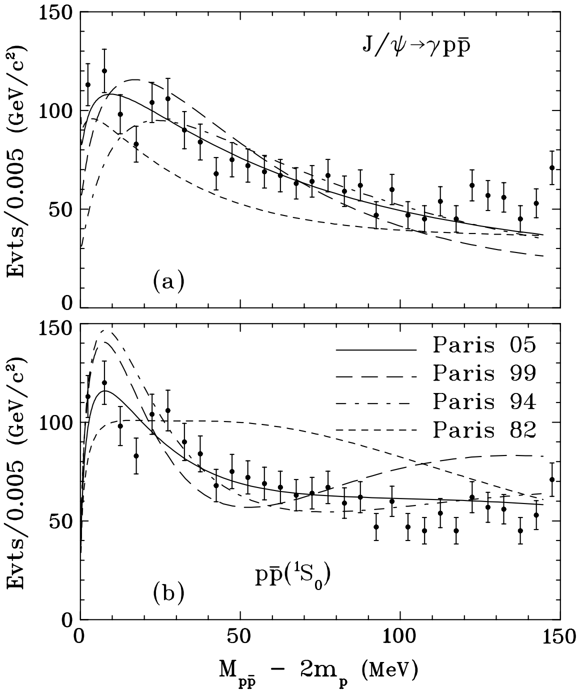

FIG. 3. $\gamma p\bar{p}(^1S_0)$ decays. Data as in Fig. 2. (a) The final state factor $q\,|T_{ff}|^2$ of Eq. (3). At higher momenta ($q > 2$ fm^{-1}), this approximation begins to fail. (b) The rate $q|T_{if}^2|$ of Eq. (1) with $r_o = 0.55$ fm. The latest Paris model [6] offers the best fit to the data with an $^{11}S_0$ wave involving a quasibound state located very close to threshold, of 53 MeV width and 5 MeV binding.

not confirmed in other experiments. The third one, the resonant state, is well established.

It is the $^1S_0$ state that reproduces the $\gamma p\bar{p}$ spectrum found by the BES collaboration. This wave is dominated by a strong attraction due to the pion exchange forces. This attraction generates broad, deeply bound states. The recent atomic and scattering data indicate that such a state in the $^{11}S_0$ wave is located close to the threshold. The BES data offer some support for the existence of such a state. The actual energy level and its width are affected by interactions at distances of less then 1 fm. These are not fully understood and only partly controlled through phenomenology.

To better discern the nature of the $^{11}S_0$ state, one should look directly under the $p\bar{p}$ threshold. This could be done with measurements of the invariant mass of few meson systems coupled to $p\bar{p}$ just below the threshold. The selectivity in partial waves is necessary, and a convenient way to reach that is the $J/\psi \to \gamma$ mesons decay. Another, indirect method is to achieve a fine resolution of energy levels in antiprotonic atoms. Some anomalies were found in atoms with nuclei characterized by weakly bound valence protons [21]. These anomalies may reflect a resonant behavior of the $p\bar{p}$ scattering amplitudes in the region of $p\bar{p}$ quasibound states. More systematic measurements are necessary to pinpoint the $p\bar{p}$ wave responsible for these effects.

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