Antiproton-Proton Channels in J/ψ Decays

B. Loiseau and S. Wycech

1 LPNHE, Groupe Théorie, Université P. & M. Curie, 4 Pl. Jussieu, F-75252 Paris, France
2 Soltan Institute for Nuclear Studies, Warsaw, Poland

(Dated: March 26, 2022)

PACS numbers: 12.39.Pn, 13.20.Gd, 13.60.le, 13.75.Cs, 14.65Dw

Abstract

The recent measurements by the BES Collaboration of J/ψ decays into γp¯p indicate a strong
enhancement at pp threshold not observed in the decays into π⁰p¯p. Is this enhancement due to a
p¯p quasi-bound state or a baryonium? A natural explanation follows from a traditional model of
p¯p interactions based on G-parity transformation. The observed p¯p structure is due to a strong
attraction in the 1S₀ state, and possibly to a near-threshold quasi-bound state in the 1S₀ wave.

A point of interest in the antiproton interactions is the question of existence or non-existence of exotics in the
nucleon-antinucleon (NN) systems: quasi-bound, 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 the scattering experiments are apparently the easiest to perform with a 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 is to observe resonant-like behavior was recently observed by BES Collaboration in the radiative decay

\[ J/\psi \rightarrow \gamma p\bar{p} \]  \hspace{1cm} (1)

close to the p\bar{p} threshold [4]. On the other hand, a clear threshold suppression is seen in the pionic decay channel

\[ J/\psi \rightarrow \pi^0 p\bar{p}. \]  \hspace{1cm} (2)

To understand better the nature of the enhancement, one should look into the p\bar{p} sub-threshold-energy region. This may be achieved, indirectly, in the pd low-energy scattering or p\bar{d} atoms. Such atomic experiments were performed, but the fine structure resolution has not been achieved so far [3].

The purpose of this letter 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 2J+1LJ, 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 1S₀ = (1S₀ + 3S₁)/2 and 3S₁ = (3S₁ + 3S₁)/2 waves which are studied [2]. While atomic experiments determine the scattering lengths, the BES experiment allows to extend this knowledge into a broad energy region above the threshold. As will be shown, the radiative J/ψ decay involves also the 1S₀ + 3S₁ combination. The understanding of this and other involved states should be based on the experience gained in studies of elastic and inelastic NN scattering. We use the Paris potential model [7, 8, 9] for this purpose.

To our present knowledge, none of the available related works [10, 11, 12, 13, 14] on the J/ψ decays [1] and [2] 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 NN 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 length calculated in potential models. In Ref. [11], more realistic but spin averaged constant lengths are shown to generate some low-energy enhancement in reaction [1]. 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 NN 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 to two waves in the pion channel. Among the three possible p\bar{p} states in the p\bar{p}γ channel one is dominated, at very low energies, by the well known p\bar{p}(13P₀) resonance, formed as a result of attractive one-pion exchange force. However, this state as well as another allowed 13P₁ state cannot explain the experimental spectrum. The final p\bar{p}γ state is dominated by the p\bar{p}(1S₀) wave. A strong attraction arises in this

1 Unité de Recherche des Universités Paris 6 et Paris 7, associée au CNRS
2 Electronic address: loiseau@ip2p.fr
3 Electronic address: wycech@fuw.edu.pl
TABLE I: States of low energy $p\bar{p}$ pairs allowed in the $J/\psi \rightarrow \gamma p\bar{p}$ and $J/\psi \rightarrow \pi^0 p\bar{p}$ 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. 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 $J/\psi$.

| Decay mode | Analog | $J^{PC}[\gamma or \pi^0]$ | $J^{PC}[p\bar{p}]$ | Relative 1
|------------|--------|--------------------------|------------------|-----
| $\gamma p\bar{p}(S_0)$ | $\gamma_0(1444)$ | $1^-$ | $0^-$ | 1
| $\gamma p\bar{p}(P_0)$ | $\gamma_f(1710)$ | $1^-$ | $0^+$ | 0
| $\gamma p\bar{p}(P_3)$ | $\gamma_f(1285)$ | $1^-$ | $1^+$ | 0
| $\pi^0 p\bar{p}(31 P_1)$ | $0^+$ | $1^-$ | 0
| $\pi^0 p\bar{p}(33 S_1)$ | $0^+$ | $1^-$ | 0

wave as a result of coherent one-pion and two-pion exchange forces. It produces broad, deeply bound states, distinctly different threshold behavior. The $S$-wave is ruled out by the experiment and the $P$-wave can be unified in a qualitative model for both decay modes.

The allowed final states. 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. The specific situation of $e^-e^+$ scattering is that the projectiles are polarized perpendicular to the beam direction and the $J/\psi$ spin direction follows that of the beam. The angular distribution can be measured within a limited range. It offers a hint which in principle permits to further reduce the number of allowed final states. For completeness, the angular distributions of the photon in the states of interest is calculated below. The simplest Lorentz invariant couplings which are also gauge invariant are given in Table I. The $p\bar{p}$ pair is described as a single scalar $(S_0)$, pseudoscalar $(S_1)$ or pseudovector $(P_1)$ particle. This picture is expected to work for the pairs of small center of mass (CM) system energies. Next, the appropriate couplings are reduced to the $J/\psi$ CM system and the corresponding angular distributions are calculated. The couplings given in Table I follow from Hamiltonians that couple the electromagnetic field $f_{\sigma\rho}$ to the $J/\psi$ field $F_{\sigma\rho} = \partial_\sigma V_\rho - \partial_\rho V_\sigma$ and to the corresponding scalar $\varphi^s$, pseudoscalar $\varphi^{ps}$ and pseudovector $\varphi^{pv}$ fields describing the low energy $p\bar{p}$ pairs. These gauge invariant Hamiltonians are $H^s = \langle eK^{ps}/2M_J \rangle \int f_{\sigma\rho} F^{\sigma\rho} \varphi^s$, $H^{ps} = \langle eK^{ps}/4M_J \rangle \int f_{\rho\sigma} F^{\sigma\rho} \varphi^{ps}$ and $H^{pv} = e \int f_{\rho\sigma} V^{\rho\sigma} \varphi^{pv}$, where $K^{ps}$ are the magnetic moments for the transitions. The vector nature of the fields, expressed by $\nabla^2 \varphi^{pv} = 0$, leads to the results given in Table I. The first two angular distributions are well known [17]. $\theta$ denoting the angle between the $\gamma$ emission direction and the beam direction, the angular distributions $(\cos^2 \theta + 1)$ and sin$^2 \theta$ were tested against the data in Ref. [4]. These have indicated a preference for the first choice, i.e. radiative transitions to $^3P_0$ or $^1S_0$ states. However, as can be seen in Table I a transition to $^3P_1$ state is not excluded.

Final state interactions. Any multichannel system can be conveniently parameterized 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

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

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. [18]). Both lengths can be expressed in terms of energy dependent $K$ matrix elements. The same formalism describes the scattering amplitude in the channel $f$ as

$$T_{ff} = \frac{A_{ff}}{1 + iqA_{ff}}.$$
TABLE II: Radiative couplings of low energy $p\bar{p}$ pairs to $\gamma$ $J/\psi$ and angular distributions of the final photon with respect to the $J/\psi$ spin direction, $J$ denotes the $J/\psi$ and $h$ the $p\bar{p}$ pair. The second line specifies the transformation property of $p\bar{p}$ pair. The third line gives the invariant couplings and the fourth line presents these in the $J/\psi$ to the $\gamma$ for the three different cases. The photon energy is denoted by $\omega$, that of $p\bar{p}$ pair by $E_h$ and the $J/\psi$ mass by $M_J$. For $E_h = 2m_p : \omega/E_h = 0.46$.

| decay mode $h(p\bar{p})$ | $\gamma p\bar{p}$ | $\gamma p\bar{p}$ | $\gamma p\bar{p}$ |
|--------------------------|------------------|------------------|------------------|
| coupling in CM $|\epsilon\rangle$ | $e^{\alpha\beta\sigma\rho}k_{\alpha}e_{\beta}\gamma_{\rho}/M_J$ | $(k_{\beta}e_{\alpha} - k_{\alpha}e_{\beta})F_{\sigma\rho}/M_J$ | $e^{\alpha\beta\sigma\rho}k_{\alpha}e_{\beta}\gamma_{\rho}\epsilon_h$ |
| angular profile | $e^{(\epsilon^{+}\wedge\epsilon^{-})\cdot k}$ | $\omega_{\epsilon^{+},\epsilon^{-}}$ | $\omega_{\epsilon^{+},\epsilon^{-}}$ |
| $1 + \cos^2\theta$ | $1 + \cos^2\theta$ | $2\sin^2\theta + [(1 + \omega/E_h)/(1 - \omega/E_h)](1 + \cos^2\theta)$ |

![Graph](image1.png)

FIG. 1: $p\bar{p}(31P_1)$ decay channel. Experimental data have been extracted from Fig. 2(a) of Ref. [4]. (a) Final state factor $q | T_{ff} |^2$ (Watson approximation). Constant $C_{ff}$ of Eq. [5] is chosen to fit the low-energy part of the data. Four versions of the Paris potential model [5, 6, 8, 9] are used. This approximation fails for $M_{p\bar{p}} - 2m_p > 40$ MeV ($q > 1$ fm$^{-1}$). (b) The rate $q | T_{ff} |^2$ of Eq. [5]. Constant $A_{ff}(0)$ 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 $31P_1$ wave.

![Graph](image2.png)

FIG. 2: $p\bar{p}(33S_1)$ decays. Data as in Fig. 1. (a) Final state factor $q | T_{ff} |^2$ of Eq. [5]. (b) Rate $q | T_{ff} |^2$ of Eq. [5]. This wave is not consistent with the BES data whatever the choice of $p\bar{p}$ potential version, of $C_{ff}$ in (a) or $A_{ff}(0)$ and $r_o$ in (b).

there, and Eq. [5] must be used. The transition length is parameterized as $A_{ff} = A_{ff}(0)/q[1 + (r_0q)^2]^2$.

The advantage of K matrix formalism is clear in the analyzes of low-energy final state interactions since it isolates the kinematic singularity into a definite form given by Eq. [5]. The two functions $A_{ff}$ and $A_{ff}$ depend only on $q^2$. Hence, close to the threshold, a constant scattering length approximation in Eq. [5] may well indicate some sub-threshold 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 an 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. [5] with a constant $C_{ff}$ and realistic $A_{ff}(q^2)$ describes a too narrow energy range. The selection of the best $p\bar{p}$ partial wave
FIG. 3: \(\gamma p p(\mathbf{3}P_0)\) decays. Experimental data have been extracted from Fig. 3(a) of Ref. 4. (a) Final state factor \(q | T_{ff}/q |^2\) of Eq. 4. The enhancement in Paris 05 solution \(4\) is related to a 18 MeV wide state bound by 5 MeV in the \(\mathbf{3}P_1\) wave. (b) Rate \(q | T_{ff}|^2\) of Eq. 4. This wave cannot reproduce the BES data whatever the choice of \(p\bar{p}\) potential version, of \(C_{ff}\) in (a) or \(A_{ff}(0)\) and \(r_o\) in (b).

requires Eq. 3. This equation offers also an explicit and unique dependence on the 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 \(A_{ff}\) if one attempts to construct a model for the \(p\bar{p}\) formation.

**Results.** 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 5 present the results obtained with Eq. 4 and Eq. 5 for the five states of interest calculated for the four versions of Paris model \(4, 7, 8, 9\) which evolved over the last 20 years. This evolution followed the increasing data basis. The last version \(9\) is based on 3934 data which includes the recent antiproton-hydrogen widths and shifts \(8, 8\) and the total \(p\bar{p}\) cross sections of Ref. \(20\). The Coulomb interactions yield enhancements of the \(S\) waves at very low energies due to Gamov factors. These affect the final state interaction for \(q < 0.15 \text{ fm}^{-1}\) 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 \(13\).

A qualitative model. As exemplified by the final state calculations, the BES findings are most consistent with a \(p\bar{p}(\mathbf{3}P_1)\) wave in the \(\pi^0 p\bar{p}\) channel and a \(p\bar{p}(\mathbf{3}S_0)\) wave in the \(\gamma p\bar{p}\) channel. Therefore the experiment leads us to a simple picture for the slow \(p\bar{p}\) formation.

The initial heavy \(c\bar{c}\) quarks in the \(J/\psi\) state of \(J^{PC} = 1^{--}\) annihilate into a \(N\bar{N}\) pair. As argued in Refs. \(13, 21\), 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 \(22\) and calculations of Ref. \(10\). The pair inherits the \(J/\psi\) quantum numbers \(J^{PC} = 1^{--}\) and forms a \(3S_1\) state. Next, the emission of a pion or a photon takes place. The \(\pi_0\) emission proceeds via the standard \(\pi NN\) coupling \(f_{\pi NN}/2m_\pi\) \(q \cdot \sigma\). It requires one nucleon to flip spin and change angular momentum, which leads to the final \(pp\) state. The photon may be produced as a magnetic one or as an electric one. The relevant formation amplitudes are given by the transition operator \((e/2m_\pi) [2 \epsilon^\gamma \cdot q + i \sigma \cdot (k^\gamma \times \epsilon^\gamma)]\). In the final states \(q\) is small. In the intermediate states it is not necessarily so, but any formation mechanism would favor small momenta. Since \(|k^\gamma|\) is large we conclude that it is the magnetic transition which is more likely to occur. It fa-
The emission model indicated above, yields comparable flips. Large moments create large radiative amplitudes. In the initial \( p\bar{p} \) wave involving a quasi-bound state located very close to threshold, in particular in the \( p\bar{p}(33_{1}) \) and \( p\bar{p}(13_{0}) \) waves and a resonance in the \( p\bar{p}(13_{0}) \) wave. The first two indicate a strong dependence on the model parameters and, so far, are not confirmed in other experiments. The third one, the resonant state, is well established.

It is the \( 1_{S_{0}} \) state which 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 \( 1_{S_{0}} \) 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 less than 1 fm. These are not fully understood and only partly controlled through phenomenology.

In order to better see the nature of the \( 1_{S_{0}} \) 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 \( J/\psi \rightarrow \gamma \) 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 [23]. These anomalies may reflect a resonant behavior of the \( p\bar{p} \) scattering amplitudes in the region of \( p\bar{p} \) quasi-bound states. More systematic measurements are necessary to pinpoint the \( p\bar{p} \) wave responsible for these effects.

We acknowledge useful discussion on the angular distribution with J.-M. Levy and W. Kloet. We thank M. Lacome and B. El-Bennich for helpful collaboration on the \( p\bar{p} \) Paris potential. B. L. is grateful to S. Jin and P. N. Shen for important informations and enlightening comments. This work was performed in the framework of the IN2P3-Polish Laboratories Convention.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5}
\caption{\( \gamma p\bar{p}(1_{S_{0}}) \) decays. Data as in Fig. 3. (a) Final state factor \( q \mid T_{ff} \mid^{2} \) of Eq. 6. At higher \( q > 2 \text{ fm}^{-1} \) momenta this approximation begins to fail. (b) Rate \( q \mid T_{ff} \mid^{2} \) of Eq. 6 with \( r_{o} = 0.55 \text{ fm} \). The latest Paris model [2] offers the best fit to the data with an \( 1_{S_{0}} \) wave involving a quasi-bound state located very close to threshold, of 53 MeV width and 5 MeV binding.}
\end{figure}
[4] BES collaboration J. Z. Bai et al., Phys. Rev. Lett. 91, 022001 (2003): Observation of a Near-Threshold Enhancement in the $p\bar{p}$ Mass Spectrum from Radiative $J/\psi \rightarrow \gamma p\bar{p}$ Decays.

[5] D. Gotta et al., Nucl. Phys. A660, 283 (1999): Balmer $\alpha$ transitions in antiprotonic hydrogen and deuterium.

[6] M. Lacombe, B. Loiseau, R. Vinh Mau, S. Wycech, The Paris $NN$ potential constrained by recent $\bar{n}p$ total cross section and antiproton-atom data, in preparation.

[7] B. El-Bennich, M. Lacombe, B. Loiseau, R. Vinh Mau, Phys. Rev. C59, 2313 (1999): Refining the inner core of the Paris $NN$ potential.

[8] M. Pignone, M. Lacombe, B. Loiseau, R. Vinh Mau, Phys. Rev. C50, 2710 (1994): Paris $NN$ potential and recent proton-antiproton low energy data.

[9] J. Côté, M. Lacombe, B. Loiseau, B. Moussallam, R. Vinh Mau, Phys. Rev. Lett. 48, 1319 (1982): On the Nucleon-Antinucleon Optical Potential.

[10] A. Sibirtsev, J. Haidenbauer, S. Krewald, Ulf-G. Meissner and A. W. Thomas, Phys. Rev. D71, 054010 (2005): Near threshold enhancement of the $p\bar{p}$ mass spectrum in $J/\psi$ decay.

[11] B. Kerbikov, A. Stavinsky and V. Fedotov, Phys. Rev. C69, 055205 (2004): Low-mass proton-antiproton enhancement: BELLE and BES results, premises of LEAR and expectations from CLAS.

[12] D. V. Bugg, Phys. Lett. B598, 8 (2004): Reinterpreting several narrow 'resonances' as threshold cusps.

[13] Chong-Shou Gao and Shi-Lin Zhu, Commun. Theor. Phys. 42, 844 (2004): Understanding the Possible Proton Antiproton Bound State Observed by BES Collaboration.

[14] B. S. Zou, H.C. Chiang, Phys. Rev. D69, 034004 (2004): One-pion-exchange final-state interaction and $p\bar{p}$ near threshold enhancement in $J/\psi \rightarrow \gamma p\bar{p}$ decays.

[15] Particle Data Group, S. Eidelman et. al., Review of Particle Physics, Phys. Lett. B592, 1 (2004).

[16] M. Gourdin, in Hadronic interactions of electrons and photons, p. 395, Acad. Press 1971, Ed. J. Cumming and H. Osborn.

[17] F. M. Renard, Basics of electron positron collisions, Éditions Frontières, 1981, p. 116.

[18] H. Pilkuhn, Interaction of Hadrons, North Holland P. C., 1967, p. 213, Eq. 3.7.

[19] J. Bolz and P. Kroll, Eur. Phys. J. C 2, 545 (1998): Exclusive $J/\Psi$ and $\Psi'$ decays into baryon-antibaryon pairs.

[20] OBELIX Collaboration, F. Iazzi et al., Phys. Lett. B475, 378 (2000): Antineutron-proton total cross-section from 50 to 400 MeV/c.

[21] S. J. Brodsky and G. P. Lepage, Phys. Rev. D24, 2848 (1981): Helicity selection rules and tests of gluon spin in exclusive quantum-chromodynamic processes.

[22] FENICE Collaboration, A. Antonelli et al., Phys. Lett. B301, 317 (1993): A new measurement of $J/\Psi \rightarrow n\bar{n}$.

[23] A. Trzcinska et al. Nucl. Phys. A692, 176c (2001): Information on anti-protonic atoms and the nuclear periphery from the PS209 experiment; S. Wycech, Nucl. Phys. A692, 29c (2001): Optical potential for anti-proton nucleus interactions.