In search of baryonium

S.Wycech
National Centre for Nuclear Studies, Warsaw, Poland
E-mail: wycech@fuw.edu.pl

J.P. Dedonder
Laboratoire de Physique Nucléaire et de Hautes Énergies, Groupe Théorie, IN2P3-CNRS,
Universités Pierre & Marie Curie et Paris-Diderot, France
E-mail: Jean-pierre.dedonder@univ-paris-diderot.fr

B. Loiseau
Laboratoire de Physique Nucléaire et de Hautes Énergies, Groupe Théorie, IN2P3-CNRS,
Universités Pierre & Marie Curie et Paris-Diderot, France
E-mail: loiseau@lpnhe.in2p3.fr

Abstract. Recent experimental hints of the existence of nucleon-antinucleon quasi-bound states are presented and discussed. One, very broad and weakly bound $S$ wave state is indicated in two decay modes of the $J/\Psi$ meson. It finds additional support in the level widths measured in light antiprotonic atoms. Another, a narrow $P$-wave state, is found instrumental in the understanding of several results obtained in heavy antiprotonic atoms. Both states have a natural explanation in a fairly traditional Paris potential model of the $NN$ interactions.

1. Introduction
The concept of baryonium - a state coupled strongly to a nucleon antinucleon system - emerged when it was realized that the attraction due to pion exchange may be particularly strong in this system. The special role of the pion is due to the G-parity transformation which changes the sign of the pion mediated interaction in $NN$ systems as compared to $N\bar{N}$ systems [1]. There is no Pauli principle in the $N\bar{N}$ system and strong attraction may exist in the states which are not allowed in the $NN$ systems. In some of such states there arises strong coherence of pion and heavier meson exchange forces. Initial expectations indicated possibilities of very deeply bound states. Later on baryonium was also understood as any meson system coupled to $N\bar{N}$.

Experimental attempts to find these exotic objects started some 30 years ago. However, there has been two obstacles in the way. First, the detection in scattering or formation experiments is difficult as the measurements involve large number of partial waves. Second, the annihilation process is very fast and if such bound states exists they are expected to be very broad. No evidence for such states exists as the result of a long series of CERN experiments performed in the last century. Let us mention two results which offer definite limits. A measurement [2] of $p\bar{p} \rightarrow \pi + X$ performed at 1.3 GeV/c antiproton momentum found no signal of baryonium in the 1.6-2 GeV energy range. The possibility of a narrow 4 MeV wide baryonium is limited to...
8 μb/sr cross section. This work contains references to earlier experiments claiming discoveries in particular findings of baryonia in the radiative transitions. The latest of these radiative transition studies involving antiprotons stopped in hydrogen performed at LEAR [3] excludes baryonium of widths $\Gamma < 25$ MeV and energies $E < 1770$ MeV.

Apparently, broad baryonia close to the $NN$ threshold or states weakly coupled to $NN$ have not been excluded. To test these possibilities new experiments are required which select specific partial waves. Recently, such selectivity, has to a certain extent become accessible due to the fine structure resolution of antiprotonic atomic levels. It has also been obtained by the BES Collaboration [4, 5] in the studies of radiative $J/\psi$ decays

$$J/\psi \rightarrow \gamma p\bar{p},$$

and

$$J/\psi \rightarrow \gamma \pi^+\pi^-\eta'.$$

Reaction (1) indicates an enhancement at the $p\bar{p}$ threshold, which may be related to a strong attraction or to a quasi-bound state. The allowed $p\bar{p}$ states are restricted by CP conservation to three partial waves. An analysis [6] performed in terms of Paris $NN$ potential model [7] reaches consistency of the data with a 52 MeV wide $11S_0$ quasi-bound state located at 4.8 MeV below threshold. On the other hand, there is no quasi-bound state in the Jülich potential model [8] which also explains the data. To resolve the difference, one has to look below the $NN$ threshold. Two ways are open nowadays: the selective mesonic decay mode (2) and non-selective widths of the $\bar{p}$ atomic levels. The latter are determined by the absorptive $NN$ amplitudes at negative energies and indicate absorption increasing with the increasing nucleon binding energies. It is consistent with the $11S_0$ quasi-bound state. The mesonic decay mode shows a distinct peak at 40 MeV below threshold, the X(1835), which apparently is also related to the $11S_0$ quasi-bound state. The actual shape of the X(1835) may be roughly reproduced by an interference of the $11S_0$ state with a background amplitude [9].

The exotic states indicated by the BES and the atomic results find a natural explanation in a fairly traditional Paris model of the $NN$ interactions based on dispersion relations, G-parity transformation, correlated two-pion exchanges and semi-phenomenological absorptive and short-range potentials.

The text that follows is divided into four sections:

- Section II, the $J/\Psi$ evidence, examines and discusses reactions (1) and (2).
- In section III, we present the atomic evidence which contains indications of a broad $S$-wave state, and a narrow $P$-wave one.
- Section IV summarizes the description in terms of the Paris potential.
- Some perspectives are outlined in a brief section V."

At this moment, the experimental and model indications suggest existence of two quasi-bound states: a broad $11S_0$ state, and a narrow $33P_1$ one.

2. The $J/\Psi$ evidence

The measurements by the BES collaboration [4] of the $J/\psi \rightarrow \gamma p\bar{p}$ decays indicated an enhancement at $p\bar{p}$ threshold which however is not present in the $J/\psi$ decays into $\pi p\bar{p}$. The explanation is due in part to the CP invariance and in part to the properties of the final state interactions in the $p\bar{p}$ system. First the CP invariance limits the radiative transitions to three possible final $p\bar{p}$ states. These are given in table 1.

Models of final state nucleon-antinucleon interaction allow to pinpoint the proper final state. The standard way of reaction parametrization in multichannel systems is a $K$-matrix which
Table 1. Low partial wave states of $p\bar{p}$ allowed in the $J/\psi \rightarrow \gamma p\bar{p}$ and $J/\psi \rightarrow \pi^0 p\bar{p}$ decays. The first column gives decay modes to the specified internal state of the $p\bar{p}$ pair. Spectroscopic notation $2^{T+1} S^{L+1} J_J$ is used with isospin $T$, spin $S$, angular momenta $L$ and total spin $J$. The notation $2S+1 L_J$ implies all possible isospin components contribute. Two particle analogs are indicated in the second column [10]. The third column gives $J^{PC}$ for the light spectator particles, photons or $\pi$ mesons. 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   | analogue   | $J^{PC}[\gamma \text{ or } \pi^0]$ | $J^{PC}[p\bar{p}]$ | relative $l$ |
|--------------|------------|----------------------------------|-------------------|--------------|
| $\gamma p\bar{p}(^1 S_0)$ | $\gamma \eta(1405)$ | $1^-$ | $0^+$ | 1 |
| $\gamma p\bar{p}(^3 P_0)$ | $\gamma f_0(1710)$ | $1^-$ | $0^+$ | 1 |
| $\gamma p\bar{p}(^3 P_1)$ | $\gamma f_1(1285)$ | $1^-$ | $1^+$ | 0 |
| $\pi^0 p\bar{p}(^3 S_1)$ | $\pi^0$ | $0^+$ | $1^+$ | 0 |
| $\pi^0 p\bar{p}(^3 S_1)$ | $\pi^0$ | $0^+$ | $1^-$ | 1 |

guarantees unitarity of the description. The transition amplitude from a channel $i$ to a two-body channel $f$ may be presented in the form

$$T_{if} = \frac{A_{if}}{1 + iqA_{ff}}$$  \hspace{1cm} (3)

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. [11]). 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

$$T_{ff} = \frac{A_{ff}}{1 + iqA_{ff}}.$$  \hspace{1cm} (4)

In the decay of interest the final state interaction is assumed to occur in the proton-antiproton state $f$ which emerges after the boson emission. 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 $p\bar{p}$ sub-system. The formation amplitude $A_{if}$ is unknown, but $A_{ff}$ is calculable in terms of $N\bar{N}$ interaction models constrained by other experiments. The results obtained with a plausible form $A_{if} = C/(1 + (r_o q)^2)$, where $C$ is a constant and $r_o = .55$ fm is a best fit length, are shown in Fig. 1. Only one partial wave the $^1 S_0$ is consistent with the data and this result seems fairly independent on the latest versions of the potential. In particular the enhancement generated in both the Paris and the Jülich-Bonn potential models is due to strong attraction in the isospin zero $^1 S_0$ component of the proton-antiproton wave function. In this partial wave the Paris potential [7] generates a 52 MeV broad quasi-bound state at 4.8 MeV below threshold. A similar conclusion has been reached by the Jülich group although the Bonn-Jülich potential does not generate a bound state in the $^1 S_0$ partial wave [8].

To understand better the nature of the $p\bar{p}$ states involved, one should look directly into the subthreshold energy region. This may be achieved in the antiproton-deuteron or the antiproton-helium atoms or very low energy scattering. Another way is the detection of $N\bar{N}$ decay products. The decay mode (2) has been studied by the BES collaboration [5]. This reaction is attributed by BES to an intermediate $p\bar{p}$ configuration in the $J^{PC}(p\bar{p}) = 0^{+-}$ state which corresponds to spin singlet $S$ wave. A peak in the invariant mass of the mesons is observed. It has been interpreted as a new baryon state and named X(1835).
Figure 1. The $\gamma p\bar{p}(1S_0)$ decays. The final state factor $q | T_{if} |^2$. The latest Paris model [7] offers the best fit to the BES data with an $^{11}S_0$ wave involving a 4.8 MeV quasi-bound state of 52 MeV width.

Under the assumption that all mesons are produced in relative $S$ waves, reaction (2), if attributed to an intermediate $p\bar{p}$ is even more restrictive than reaction (1). It allows only one intermediate state the $p\bar{p} \ 1S_0$, which coincides with the previous findings. The intermediate state of $p\bar{p}$ in reaction (2) is possible but not warranted. In Ref. [9] a more consistent interpretation is obtained with the dominance of the $^{11}S_0$ state which is a mixture of $p\bar{p}$ and $n\bar{n}$ pairs. It has been argued there that the peak is due to an interference of the quasi-bound, isospin 0, $NN$ state with a background amplitude. The results are plotted in Fig. 2. Both Figs. 2 and 1 indicate that the agreement is semi-quantitative and a more involved decay model is necessary to clarify the understanding.

Figure 2. The distribution of the invariant meson mass from reaction (2) measured by BES. Calculations are performed with Paris potential and the curve is due to interference od direct decay and an intermediate $NN$ interaction amplitude. The latter is dominated by the $^{11}S_0$ quasi-bound state, $r_f$ is the size of the initial $NN$ source.
3. The evidence from antiprotonic atoms

Antiprotonic atom X ray measurements may provide shifts and widths of atomic levels which are generated by strong interactions (see review [12]). In the lightest atoms Hydrogen and Helium experiments test the $1S$, $2P$ and $3D$ levels. The widths and shifts are related to low energy antiproton-nucleon scattering amplitudes

$$f(E) = a + 3 \, b \, \mathbf{q} \cdot \mathbf{q}'$$

where $a$ are scattering lengths and $b$ are scattering volumes. The atomic physics opens a method to test the subthreshold $NN$ energy region as both nucleons and antiprotons are bound. The scattering amplitudes relevant to atomic states $f(-E_{binding} - E_{recoil})$ involve binding as well as recoil energies. In light atoms the accessible energies span the region from - few keV (Hydrogen) to about - 40 MeV (Helium). As fine structure is not fully resolved one can extract only spin and isospin averaged absorptive parts of $a$ and $b$. The results are given in Fig. 3.

![Graph showing Im a and Im b](image)

**Figure 3.** The spin and isospin averaged, $N\bar{p}$ amplitudes in the sub-threshold region extracted from light antiprotonic atoms: circles - absorptive parts of length, squares - absorptive parts of volumes. The curves present Im $a$, Im $b$ calculated with the Paris potential.

The energy dependence extracted in this way indicates a sizable increase of the $S$ wave absorption in the subthreshold region consistent with the existence of an $S$ wave $NN$ quasi-bound state [13]. In addition, the deuteron atomic level widths indicate enhanced absorption in a $P$ wave which occurs at energies very close to the threshold. The result obtained in deuteron coincides with certain anomalies observed in antiproton annihilation on a single nucleon studied in heavy nuclei by radiochemical methods (so called cold capture). The method discussed in Ref. [14] is devoted to studies of the neutron distribution at the surface of nuclei. One can test the frequency of antiproton capture on neutrons relative to the frequency of capture on protons and in this way infer the ratio of neutron to proton densities at the site of capture. The capture site is different in two atomic levels (a lower one and an upper one) tested by X-ray method. The site tested by cold capture is much more peripheral. Nuclear densities involved
are \( \sim 10\% \), \( \sim 3\% \) and \( \sim 0.1\% \) of central density correspondingly. Nuclear physics expects the neutron/proton ratio to increase along the way out of the nucleus. This behavior is observed in almost a hundred of tested nuclei. Three examples are given in the upper part of table 2. However, there are anomalous cases indicated in lower part of the table. These are characterized by a low \( \sim 7 \text{ MeV} \) proton separation energies and larger \( \sim 11 \text{ MeV} \) neutron separation energies. In the cold capture one tests essentially the valence nucleons and these respond differently to the narrow resonance. Thus the anomalous cases are not related to any "proton halos" in these nuclei but to the different chances to form a narrow \( N\bar{N} \) state very close to the threshold.

### Table 2. Ratios of \((n\bar{p})\) and \((p\bar{p})\) capture rates from atomic states. The last column shows experimental numbers from radiochemical experiments. Other columns give ratios calculated with optical potential and plausible nuclear densities [13] based on experimental results from [14].

| atom | lower  | upper   | radiochemistry |
|------|--------|---------|----------------|
| \(^{96}\text{Zr}\) | 0.95(9) | 1.53(29) | 2.6(3)         |
| \(^{116}\text{Cd}\) | 1.63(49) | 2.65(61) | 5.00(21)       |
| \(^{124}\text{Sn}\) | 1.79(10) | 2.44(39) | 5.0(6)         |
| \(^{106}\text{Cd}\) | 1.64(80) | 2.10(80) | 0.5(1)         |
| \(^{112}\text{Sn}\) | 1.90(13) | 2.43(49) | 0.79(14)       |

4. The Paris potential model

The 1982 Paris \( N\bar{N} \) optical potential was itself readjusted in 1994, 1999 and 2008 [7]. For all these potentials the \( N\bar{N} \) interaction is described by an energy dependent optical potential

\[
V_{N\bar{N}}(r, T_{Lab}) = U_{N\bar{N}}(r, T_{Lab}) - i W_{N\bar{N}}(r, T_{Lab}),
\]

where the non-locality of the real \( U_{N\bar{N}} \) and imaginary \( W_{N\bar{N}} \) potentials are accounted for by a linear energy dependence in the kinetic energy \( T_{Lab} \). Meson exchanges explain in a satisfactory way the \( NN \) force for large and medium distances between the nucleons. Therefore the long and intermediate range real parts, i.e., those for inter \( NN \) distances \( r \geq 1 \text{ fm} \), are obtained by the \( G \)-parity transformation of the corresponding parts of the Paris \( NN \) potential. These real potentials contain, besides the one-pion exchange, the two-pion exchange and the \( \omega \) and \( A_1 \) meson exchanges as parts of the three-pion exchange. For \( r < 1 \text{ fm} \) heavier meson exchanges and/or other degrees of freedom, such as quarks and gluons take place but the available theoretical calculations are not free from phenomenological parameters (see for instance Ref. [12]. Consequently, following the choice made in the case of the Paris \( NN \) potential an empirical short range real potential is used.

For \( r < 1 \text{ fm} \) the phenomenological radial potentials are expanded in powers of \( r \) and matched to the theoretical ones in the vicinity of 1 fm. Then, above 1 fm the theoretical potentials are entirely preserved. For each isospin state, the spin structure of the \( N\bar{N} \) interaction requires five independent invariant with five radial potentials. All together it leads to nine parameters representing the strength of the different empirical potentials. These parameters are fitted to about 4000 scattering data and four complex scattering lengths obtained from hydrogen atoms.

The central potentials essential to generate the \( S \) state are plotted in Figs. 4 and 5, and the two quasi-bound states given in this model are shown in table 3. The values of the recent model are consistent with the experimental data discussed above.
Figure 4. The real part of the central potential which dominates the attraction in the singlet wave.

Figure 5. Absorptive part of central potential.

Table 3. Binding energy in MeV of the close to threshold quasi-bound states of the Paris 08 [7] and of the Paris 99 potential [15].

| \(2T+1 \ 2S+1 \ L_J\) | Paris 08 | Paris 99 |
|-----------------------|---------|---------|
| \(1^1 S_0\)           | -4.8-i26|         |
| \(3^3 P_1\)           | -4.5-i9.0| -17-i6.5|
5. Conclusions
The arguments for the existence of two nucleon-nucleon quasi-bound states were presented. These are based on experimental measurements performed with antiprotonic atoms and $J/\Psi$ decay studies as well as potential interaction models. We believe that a further confirmation is necessary. It may be achieved with several experiments feasible with the new FAIR / PANDA project:

- resolution of the fine structure in lightest antiprotonic atoms, in particular in the antiprotonic deuterium.
- repetition of the CERN $(\bar{p}, \pi)$ and $(\bar{p}, \gamma)$ experiments performed in flight with polarized antiproton and polarized targets.
- repetition of the CERN studies of the atomic radiative transition from the atomic to baryonium states.

The quasi-bound nuclear states of antiprotons constitute a separate branch of this research. In general such states are too broad to be detected easily. However, certain states of antiprotons bound loosely in the region of nuclear surface are likely to exist.

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