In search of Baryonia

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Stranu: hot topics in STRANngeness NUclear and atomic physics
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Merci Slawek pour cette collaboration enrichissante et fructueuse

Introduction

- → Fruitful collaboration with Slawek.
- ⇒ Where to search for nucleon-antinucleon (quasi-)bound states or baryonia?

1) Formation experiments

- ⋆ $J/\psi \to \mathcal{B}p\bar{p}$, $\mathcal{B} = \gamma(\omega, \phi, \pi)$
- ⋆ $M_{p\bar{p}}$ distribution compared BES III histogram data of $J/\psi \to \gamma p\bar{p}$
- ⋆ Summary and outlook

2) Experiments testing sub-threshold energy region

- ∗ Analysis of anti-protonic hydrogen and helium atoms
- ∗ Results with the Paris potential models
- ∗ Ratios of neutron over proton capture rates
- ∗ Concluding remarks and outlook

Fruitfull collaboration with Slawek

Started in the late nineties, being both invited by Torleif Ericson at Uppsala. Since then, we have collaborated within the French-Polish IN2P3-COPIN agreement program.

Publications not involving nucleon-antinucleon:

- B. Loiseau , S. Wycech, $\pi\Lambda\Sigma$ coupling extracted from hyperonic atoms, Phys. Rev. C **63**, 034003 (2001); arXiv: nucl-th/0012005.
- T.E.O. Ericson, B. Loiseau, S. Wycech, A phenomenological $\pi^- p$ scattering length from pionic hydrogen, Phys. Letters B **594**, 76 (2004); arXiv: hep-ph/0310134.

Publications related to possible nucleon-antinucleon (quasi-)bound states or baryonia:

→ B. Loiseau, S. Wycech, Antiproton-Proton Channels in J/Psi decays Phys. Rev. C **72**, 011001(R) (2005); arXiv: hep-ph/0501112.

→ B. El-Bennich, M. Lacombe, B. Loiseau, S. Wycech, Paris $N\bar{N}$ potential constrained by recent antiprotonic atom data and $\bar{n}p$ total cross sections, Phys. Rev C **79**, 054001 (2009); arXiv:0807.4454 [nucl-th].

→ B. El-Bennich, J-P. Dedonder ,B. Loiseau, S. Wycech, Structure of the X(1835), Phys. Rev. C **80**, 045207 (2009); arXiv:0904.2163 [hep-ph].

→ E. Friedman, A. Gal, B. Loiseau, S. Wycech, Antiproton-nucleus interaction near threshold from the Paris nucleon-antinucleon potential, Nucl. Phys. A **943**, 101 (2015); arXiv:1506.06965 [nucl-th].

⇒ J. -P. Dedonder, B. Loiseau, S. Wycech, Photon or meson formation in J/ψ decays into $p\bar{p}$, Phys. Rev. C **97**, 065206 (2018); arXiv:1802.00763 [hep-ph].

⇒ B. Loiseau, S. Wycech, Extraction of baryonia from the lightest anti-protonic atoms, Phys. Rev. C **102**, 034006 (2020); arXiv:2007.01775 [nucl-th].

Where to search for nucleon-antinucleon (quasi-)bound states or baryonia?

Search in $N\bar{N}$ since the beginnings of LEAR era at CERN but nothing found as:

- these states are broad due to fast annihilation processes and experiments confronted with heavy backgrounds,
- exclusion principle not operative and a large number of partial waves may be formed in the $N\bar{N}$ systems.

1) Specific $N\bar{N}$ states can be reached in formation experiments.

→ $J/\psi \to \gamma p\bar{p}$: enhancement close to the $p\bar{p}$ threshold observed by the BES Collaboration [Phys. Rev. Lett. **108**, 112003 (2012)].

→ J/ψ meson and photon: $J^{PC} = 1^{--} \Rightarrow$ only ${}^1S_0$, ${}^3P_1$, and ${}^3P_0$ final $p\bar{p}$ states allowed by P and C conservations in the $\gamma p\bar{p}$ channel.

→ Semi-quantitative description of $J/\psi \to \gamma p\bar{p}$ [B. Loiseau, S. Wycech, PRC**72**, 011001(R) (2005)] with final $\gamma p\bar{p}$ state dominated by the ${}^{11}S_0$ partial wave where Paris potential [B. El-Bennich, J-P. Dedonder ,B. Loiseau, S. Wycech, PRC **79**, 054001 (2009)] has a 52 MeV broad quasi-bound state at 4.8 MeV below threshold.

${}^{2S+1}L_J$ or ${}^{2I+1,2S+1}L_J \to S, L, J, I$: spin, angular momentum, total momentum, isospin (1 or 0) of $p\bar{p}$.

⇒ Study of $J/\psi \to \mathcal{B} p\bar{p}$ decays, $\mathcal{B} = \gamma, (\omega, \phi, \pi)$ [J. -P. Dedonder, B. Loiseau, S. Wycech, PRC **97**, 065206 (2018)]

2) Experiments testing sub-threshold energy region: atomic levels in very light atoms:

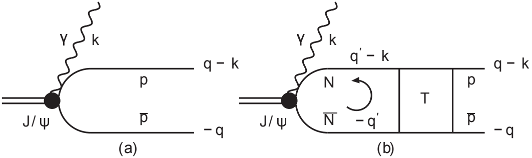
→ Useful atoms to study baryonia: antiprotonic deuterium and antiprotonic helium - experimental data exist - relatively simple nuclear structure - study $\bar{p}N$ interaction at different sub-threshold energies.

⇒ Analysis of anti-protonic hydrogen and helium atoms [B. Loiseau, S. Wycech, PRC **102**, 034006 (2020)].

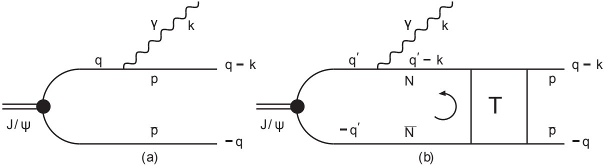
1) $J/\psi \to \mathcal{B}p\bar{p}$, $\mathcal{B} = \gamma(\omega, \phi, \pi)$ [J. -P. Dedonder, B. Loiseau, S. Wycech, PRC **97**, 065206 (2018)]

Two processes (DWBA) to describe the BES Collaboration data on γ (or ω).

a) Direct Emission (DE):



b) Emission from Baryonic Current (BC):

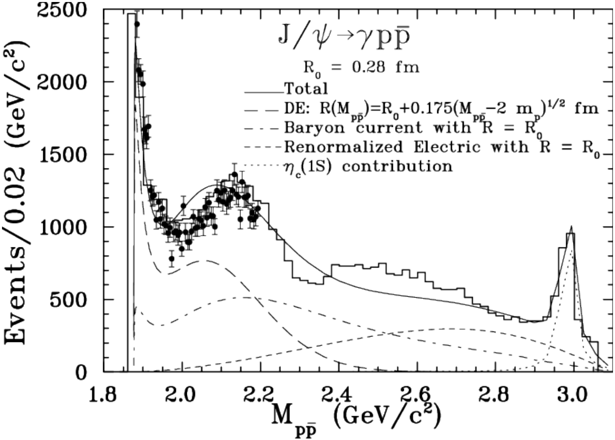


=●: J/ψ source, phenomenological Gaussian function with radius $R(M_{p\bar{p}}) = R_0 + \beta\sqrt{M_{p\bar{p}} - 2m} \longrightarrow R_0 = 0.28$ fm, $\beta = 0.175$ fm$^{3/2}$ represent the data fairly well.

(a) Born term, (b) T: Final State Interaction (FSI) with *S*-wave half-off shell function from Paris $N\bar{N}$ potential [B. El-Bennich, M. Lacombe, B. Loiseau, S. Wycech, PRC **79**, 054001 (2009)]

$M_{p\bar{p}}$ distribution compared BES III histogram data of $J/\psi \to \gamma p\bar{p}$ [PRL **108**, 112003 (2012)]

Peak related to strong nucleon-antinucleon attraction essentially in the $N\bar{N}$ $^{11}S_0$ state



Baryonic current peak: strongly suppressed due to interference of intermediate $p\bar{p}$, $n\bar{n}$ channels.

→ 7 free parameters,

i) normalization source function fixed by $J/\psi \to p\bar{p}$ decay rate,

ii) magnetic and electric amplitudes calculated independently for DE and BC emission modes,

iii) emission rates added and the normalizations of the DE and BC rates fixed to reproduce the experimental ratio $\mathcal{R} = \Gamma(p\bar{p}\gamma)/\Gamma(p\bar{p})$ and the invariant mass distribution,

iv)Electric contribution (*P*-wave) is renormalized,

v) the $\eta_c(2983)$ formation is fitted by a relativistic Breit-Wigner.

Summary and outlook of $J/\psi \to \mathcal{B}p\bar{p}$, $\mathcal{B} = \gamma(\omega, \phi, \pi)$

Summary: BES Collaboration data on $J/\psi \to \gamma(\omega)p\bar{p}$ is described by two processes.

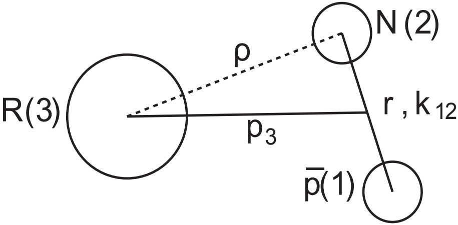
1) Direct emission process before formation of final baryons.
   $\star$ FSI for $\gamma \Rightarrow$ 2 resonant states:
   a) a very sharp peak close to threshold due to a baryonium - broad 52 MeV wide quasi-bound state at 4.8 MeV below threshold in $^{11}S_0$ wave of Paris potential,
   b) a resonant state at 2170 MeV - shape resonance in the same partial wave.
   $\star$ For (ω) Born contribution describes full ω spectrum at large $M_{p\bar{p}}$ and $M_{\omega p}$.
   $\star$ For γ (or ω) weak energy dependence for the source radius is necessary.
2) Emission from baryonic current. Occurs after J/ψ decay into an $N\overline{N}$ pair.
   $\star$ For γ not sufficient to reproduce final resonant states $\Rightarrow$ need DE model.
   $\star$ For $(\omega, \pi, \phi$, not shown here) the Born term is the dominant mode.
   $\star$ But the ω mass distribution $M_{p\bar{p}}$ needs a strong reduction in the lower mass region: obtained by introducing a FSI involving a $N^*(3/2)$ or $\overline{N}^*(3/2)$ resonance created by an ω-p (ω-$\bar{p}$) interaction via an ω exchange between $\bar{p}$-p (p-$\bar{p}$) pairs.

Outlook

- J/ψ and $\psi(2S)$ different internal structure: DE$\Rightarrow$ no peak in $\psi(2S)$ formation.
- Paris potential fits data $M_{p\bar{p}} \lesssim 2.1$ GeV but produces reasonable results beyond.
- Present approach could be applied with other interaction like the χEFTN^{3}LO [Ling-Yun Dai, J. Haidenbauer, U.-G. Meissner, JHEP **07**, 078 (2017)]
- Present work $\Rightarrow$ related $\bar{p}p \to J/\psi +$ *meson* reaction on nuclei sooner or later at FAIR (Facility for Antiproton and Ion Research), at GSI, Darmstadt, Germany.

2) Analysis of anti-protonic hydrogen and helium atoms [B. Loiseau, S. Wycech, PRC **102**, 034006 (2020)]

Level shifts and width for ^{2}H($2P$), ^{3}He($2P$, $3D$), ^{4}He($2P$, $3D$) expressed in terms of $\bar{p}N$ sub-threshold scattering lengths and volumes.



Quasi-three-body system, 1: antiproton, 2: nucleon, 3: residual system.
Jacobi coordinates, momentum: $\boldsymbol{p}_3, \boldsymbol{k}_{12}$, space: $\boldsymbol{\rho}, \boldsymbol{r}$.

Outline for the S-wave interaction:

$$V_{\bar{p}N}(E_{cm}, S) = \frac{2\pi}{\mu} \widetilde{T}_0(r, E_{cm})$$

$$\widetilde{T}_0(r, E) = \frac{\mu_{N\bar{N}}}{2\pi} V_{N\bar{N}}(r, E) \frac{\Psi(r, E, k'(E))}{\psi_o(r, k'(E))}$$

$\to E < 0$, $V_{N\bar{N}}(r, E)$: Paris model, $k'(E) = \sqrt{2\mu_{N\bar{N}}E}$, regular free wave: $\psi_o(r, k) = \sin(rk)/(rk)$, $\Psi(r, E, k'(E))$ solution of the Lippman-Schwinger equation: $\Psi = \psi_o + G^+ V \Psi$.

$\Rightarrow$ If $\bar{p}$ bound into an atomic orbital, energy shifts of upper levels (levels of small atomic-nucleus overlap) generated by perturbation and at leading order:
$\Delta E_{nL} - i\Gamma_{nL}/2 = \Sigma_j \langle \psi_L\, \varphi | V_{\bar{p}N_j}(E, S) | \varphi\, \psi_L \rangle$, Σ_j over all nucleons of the nucleus.
$\varphi(\boldsymbol{\rho})$: wave function of the struck nucleon; $\psi_L(\beta\boldsymbol{\rho})$: Coulomb-atomic-wave functions of given angular momentum L with $\beta = \frac{M_R}{M_R+M_N}$.

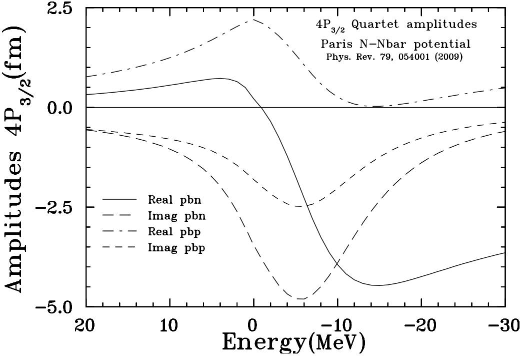
Results with the Paris potential models for antiprotonic deuterium, ^{2}H, atoms

order	Shift	Width
S wave	100{113}	210{145}
P wave	-9{58}	365{206}
Sum	91{171}	575{341}
Data [1, 2]	243±26	489±30

[1] D. Gotta, Prog.Part.Nuc.Phys. **52**, 133 (2004).

[2] D. Gotta *et al.*, NPA **660**, 283 (1999).

Results for 2P-deuterium level corrections in meV calculated with the spin averaged amplitudes of the Paris 2009 potential. Numbers curly brackets are results with the Paris 1999 potential.



Subthreshold amplitudes generating the $4P_{3/2}$ hyperfine structure in deuterium. With Paris 09 solution it is strongly dominated by the resonant $a(^{33}P_1)$ at -4.8 MeV. Relevant $\bar{p}N$ c.m. energies fall in the region -7.6 ± 1 MeV. Downward shift of the resonance position by a -4 MeV or more will strongly reduce the attraction calculated in this component. In this way the hyperfine structure splitting is practically nullified.

Results with the Paris potential models for antiprotonic ^{3}He atoms

	2P shift	2P width	3D width
S wave	6.68{9.22}	17.5{11.5}	0.69{0.49}
P wave	-6.36{1.44}	15.0{26.9}	1.46{2.08}
Sum	0.31{10.71}	32.5{38.4}	2.15{2.57}
Data [3]	17±4	25±9	2.14 ±0.18

[3] M. Schneider *et al.*, Zeit. Phys. A **338**, 217 (1991).

Leading order calculations in eV for $2P$ and in meV for $3D$ (widths only) level corrections in ^{3}He obtained with the spin averaged amplitudes of the Paris 2009 potential. Numbers in curly brackets are obtained with the Paris 1999 potential.

	2P shift	2P width
S wave	6.66{7.83}	12.3{7.70}
P wave	-5.20{4.75}	19.1{22.13}
Sum	1.46{12.59}	31.4{29.8}
Data [3]	17±4	25±9

As in the above Table but only for $2P$ level including higher order corrections. Now the contribution of the *P* wave interaction depends also on *S* wave interaction as a result of multiple scattering summation method.

Results with the Paris potential models for antiprotonic ^{4}He atoms

	2P shift	2P width	3D width
S wave	9.72{17.6}	26.0{19.8}	0.66{0.50}
P wave	-9.01{-10.4}	14.9{14.8}	0.91{0.91}
Sum	0.708{7.2}	40.9{34.6}	1.57{1.41}
Data [3]	18±2	45±5	2.36 ±0.10

[3] M. Schneider *et al.*, Zeit. Phys. A **338**, 217 (1991).

Leading order calculations in eV for $2P$ and in meV for $3D$ (widths only) level corrections in ^{4}He obtained with the spin averaged amplitudes of the Paris 2009 potential. Numbers in curly brackets are obtained with the Paris 1999 potential.

	2P shift	2P width
S wave	8.94{12.3}	14.7{10.4}
P wave	-8.71{-10.9}	19.0{18.6}
Sum	0.23{1.4}	33.7{29.0}
Data [3]	18±2	45±5

As in the above Table but only for $2P$ level including higher order corrections. Now the contribution of the P wave interaction depends also on S wave interaction as a result of multiple scattering summation method.

The Ratios of neutron over proton capture rates from atomic states: $R_{n/p} = N(\bar{p}n)/N(\bar{p}p)$.

atom	$N(\bar{p}n)/N(\bar{p}p)$
^{96}Zr [4]	2.6±0.3
^{124}Sn [4]	5.0±0.6
^{106}Cd [4]	0.5±0.1
^{112}Sn [4]	0.79±0.14

[4] P. Lubiński, J. Jastrzębski, A. Trzcińska, W. Kurcewicz, F. J. Hartmann, W. Schmid, T. vonEgidy, R. Smolańczuk, S. Wycech, Composition of the nuclear periphery from antiproton absorption, PRC **57**, 2962 (1997).

The ratios of $N(\bar{p}n)$ and $N(\bar{p}p)$ capture rates from atomic states. The second column gives the experimental numbers obtained in radiochemical experiments [4]. Two normal cases ^{96}Zr and ^{124}Sn: neutron haloes.
Anomalous results for ^{106}Cd and ^{112}Sn, partly due to a sizable differences ($\sim$ 3 MeV) in p and n separation energies valence nucleons. Additional explanation: fairly narrow N-$\bar{N}$ quasibound state boosting $\bar{p}$-p absorptions over $\bar{p}$-n ones.

Atom	Experiment	Paris 09	Paris 99
$\bar{p}\ ^2$H [5]	0.81±0.03	1.09 $\{0.55\rangle$	0.84 $\{0.61\}$
$\bar{p}\ ^2$H [6]	0.749±0.018	1.09 $\{0.55\rangle$	0.84 $\{0.61\}$
$\bar{p}\ ^3$He [7]	0.70±0.14	.65	1.00
$\bar{p}\ ^4$He [7]	0.48±0.03	.48	0.59

[5] R. Bizzari *et al.*, Nuovo Cim. **22A**, 225 (1974)

[6] T. E. Kalogeropoulos and G.S Tsanakos, PRD **22**, 2585 (1980).

[7] F. Balestra *et al.*, Nucl. Phys. **A474**, 651 (1987).

$R_{n/p}$ ratios. Second column: experimental results from $\bar{p}$ stopped in bubble chambers. Third and fourth columns Paris potential calculation It is assumed that capture occurs from nP atomic levels. Results for captures in deuterons from nS states: curly brackets.

Concluding remarks and outlook

Antiprotonic atomic levels characterized with very small nuclear-atom overlap are a powerful method to study $\bar{p}N$ amplitudes below the threshold, down to some -40 MeV.

- Paris 2009: S-wave $\bar{p}N$ amplitudes dominated by a broad ${}^{11}S_0$ quasibound state, E =-4.8 MeV, $\Gamma = 50$ MeV, → strong repulsion levels in the light atoms.
- P-wave interactions are attractive and balance with S wave →uncertain position of the ${}^{33}P_1$-quasibound state predicted by Paris 2009 and 1999.
- Repulsion from the ${}^{11}S_0$ wave not strong enough: → new phenomenon below -40 MeV - In Paris 2009: I=1 quasibound S-wave state at -80 MeV - Data requires a shift to -60 MeV. ★ Medium and heavy atoms - higher nuclear densities and level shifts far from Born approximations - require attraction.
- Consistency with the ^{2}H , ^{3}He atomic levels + understanding of the $R_{n/p}$ anomalies require the ${}^{33}P_1$ quasibound state (-17 MeV in Paris 99; -4.5 MeV in Paris 09) to be located in the [-11, -9] MeV region.
- In antiprotonic deuterium measurement of the $4P_{3/2}$ fine structure would be valuable and would fix the energy of ${}^{33}P_1$ quasibound state.

⇒ Paris 2009 versus Paris 1999: level shifts Paris 99 better (strongly bound ${}^{33}P_1$); Paris 09 fits on additional $\bar{n}p$ and capture rates $R_{n/p}$ better → advantage PUMA project at CERN; Paris 09 better for the BES Collaboration enhancement results.

★ **Outlook** Paris 09 starting point for successful description of atomic, bubble chamber, radiochemical data if P-wave baryonium position shifted down by few MeV + deeply bound S state pushed up by some 20 MeV.
⇒ Update of this potential model, work is in progress.

MERCI POUR VOTRE ATTENTION

BACKUP MATERIAL

→ Related works to formation experiments

Related works to formation experiments and baryon-antibaryon interactions

- A first indication that the near threshold $p\bar{p}$ enhancement observed by the BES collaboration in $J/\psi \to \gamma p\bar{p}$ is in an $I = 0$ state was obtained in a simple quark model by A. Datta and P. J. O'Donnell [A new state of baryonium, PLB **567**, 273 (2003)]
- Near-threshold peak formed in the 1S0 wave reached by:
  - the Jülich group, although the Bonn-Jülich potential does not generate a bound state in this wave [Haidenbauer, U.-G. Meißner, A. Sibirtsev, Near threshold $p\bar{p}$ enhancement in B and J/ψ decays, PRD **74**, 017501 (2006).]
  - G. Y. Chen, H. R. Dong, J.P. Ma, [Near threshold enhancement of $p\bar{p}$ system and $p\bar{p}$ elastic scattering, PLB **692**,136 (2010)] in the framework of an effective NN interaction model.
- Another study of the near-threshold enhancement → quasibound state [A. I. Milstein, S. G. Salnikov, Interaction of real and virtual $p\bar{p}$ pairs in $J/\psi \to p\bar{p}\gamma(\rho, \omega)$ decays, NPA **966**, 54 (2017).]
- The Bonn-Jülich group, good threshold behavior description in all mesic channels with a chirally motivated *NN* potential, conclusion similar to that of the Paris potential: ⇒ quasibound state [X.-Y. Kang, J. Haidenbauer, U.-G. Meißner, Near threshold $p\bar{p}$ invariant mass spectrum measured in J/ψ and ψ' decays, PRD **91**, 074003 (2015).]
- Analysis on baryon-antibaryon in the low relative momentum region in *pp* collisions, performed by Valentina Mantovani Sarti within The Alice collaboration, S. Acharya *et al.* [Investigating the role of strangeness in baryon-antibaryon annihilation at the LHC, arXiv: 2105.05190v1 [nucl-ex]]