Antibaryon interactions with the nuclear medium

Jaroslava Hrtánková

Nuclear Physics Institute, Řež, Czech Republic

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Introduction

- study of $\bar{B}$ ($\bar{p}$, $\bar{\Lambda}$, $\bar{\Sigma}$, $\bar{\Xi}$) bound states in selected nuclei:
  - behavior of $\bar{B}$ in the nuclear medium including its absorption
  - core polarization effect due to $\bar{B}$
- testing models of (anti)hadron–hadron interactions
- knowledge of $\bar{B}$–nucleus interaction for future experiments (PANDA@FAIR)

RMF approach

- Nucleons – Dirac fields interacting via the exchange of meson fields
- Dirac equation for nucleons and antibaryon

$$[-i\vec{\alpha}\vec{\nabla} + \beta(m_j + S_j) + V_j]\psi_j^\alpha = \epsilon_j^\alpha \psi_j^\alpha \ , \quad j = N, \bar{B} \ ,$$

$$S = g_{\sigma j}\sigma, \quad V_j = g_{\omega j}\omega_0 + g_{\rho j}\rho_0\tau_3 + e_j \frac{1+\tau_3}{2} A_0 \ ,$$

- Klein-Gordon equations for meson fields

$$\begin{aligned}
(-\triangle + m_\sigma^2)\sigma &= -g_{\sigma N}\rho_S - g_{\sigma\bar{B}}\rho_{S\bar{B}} \\
(-\triangle + m_\omega^2)\omega_0 &= g_{\omega N}\rho_V + g_{\omega\bar{B}}\rho_{V\bar{B}} \\
(-\triangle + m_\rho^2)\rho_0 &= g_{\rho N}\rho_I + g_{\rho\bar{B}}\rho_{I\bar{B}} \\
-\triangle A_0 &= e\rho_p + e_{\bar{B}}\rho_{\bar{B}}.
\end{aligned}$$

Baryon-nucleus interaction

- Nucleon-meson couplings obtained by fitting nuclear matter and finite nuclei properties
- Hyperon-meson coupling constants:
  - for ω and ρ field obtained from SU(6) symmetries,
  - for σ field obtained from fits to experimental data (Λ hypernuclei, Σ atoms, Ξ production in (K^+, K^-) reactions)

$$
\begin{aligned}
g_{\sigma\Lambda} &= 0.621 g_{\sigma N}, & g_{\omega\Lambda} &= 2/3 g_{\omega N}, & g_{\rho\Lambda} &= 0\ , \\
g_{\sigma\Sigma} &= 0.5 g_{\sigma N}, & g_{\omega\Sigma} &= 2/3 g_{\omega N}, & g_{\rho\Sigma} &= 2/3 g_{\rho N}\ , \\
g_{\sigma\Xi} &= 0.299 g_{\sigma N}, & g_{\omega\Xi} &= 1/3 g_{\omega N}, & g_{\rho\Xi} &= g_{\rho N}
\end{aligned}
$$

$\bar{B}$-nucleus interaction

- $BN \to \overline{B}N$ interaction – G-parity transformation $\hat{G} = \hat{C}e^{i\pi I_1}$

$$g_{\sigma\bar{B}} = g_{\sigma B}, \quad g_{\omega\bar{B}} = -g_{\omega B}, \quad g_{\rho\bar{B}} = g_{\rho B}$$

- G-parity valid for the long and medium range $\bar{B}N$ potential
$\to$ 750 MeV deep $\bar{p}$ potential in the nucleus
- Nuclear medium + short range interaction – possible deviations from the G-parity
- Antiprotonic atoms and $\bar{p}$ scattering off nuclei at low energies
$\to$ $\mathrm{ReV}_{\bar{p}} \sim 100 - 300$ MeV deep
- Reduced $\bar{B}$ coupling constants

$$g_{\sigma\bar{B}} = \xi\, g_{\sigma B}, \quad g_{\omega\bar{B}} = -\xi\, g_{\omega B}, \quad g_{\rho\bar{B}} = \xi\, g_{\rho B} \ ,$$

where parameter $\xi = 0.2 - 0.3$

Antibaryon potential

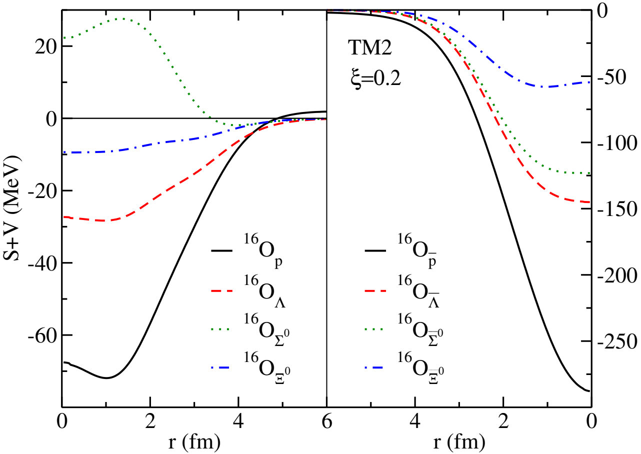

Fig.1: The B–nucleus (left) and $\bar{B}$–nucleus (right) potentials in ^{16}O.

Antibaryon spectrum

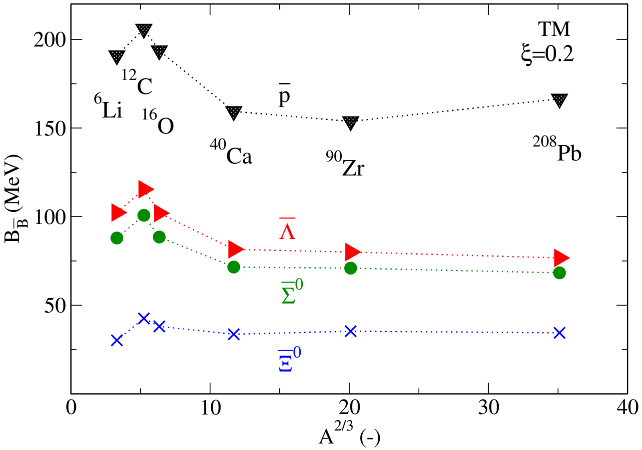

Fig.2: The A dependence of $\bar{B}$ 1s binding energies, calculated dynamically in the TM model for $\xi = 0.2$.

$\bar{p}$ absorption

- $\bar{p}$–nucleus potential:

$$\mathrm{Re}\,V_{\bar{p}} = \xi\, V_{\mathrm{RMF}}$$

$$\mathrm{Im}\,V_{\bar{p}} = \sum_{channel} f_s(\sqrt{s}) B_r \,\mathrm{Im}\, b_0\, \rho$$

$\xi = 0.2$, $\mathrm{Im}\, b_0 = 1.9$ fm

- $s = (E_N + E_{\bar{p}})^2 - (\vec{p}_N + \vec{p}_{\bar{p}})^2$

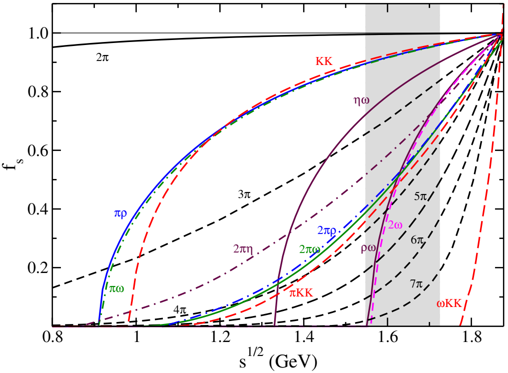

Fig.3: The phase space suppression factor f_s as a function of the center-of-mass energy $\sqrt{s}$.

Energy available for annihilation

- CMS frame $\rightarrow \sqrt{s} = \; m_{\bar{p}} + m_N - B_{\bar{p}} - B_N$ (M)
- $\bar{p}$ absorption in a nucleus $\rightarrow \vec{p}_N + \vec{p}_{\bar{p}} \neq 0$
  (*A. Cieplý, E. Friedman, A. Gal, D. Gazda, J. Mareš, PLB 702, 402 (2011)*)

$$\sqrt{s} = E_{th}\left(1 - \frac{2(B_{\bar{p}} + B_{Nav})}{E_{th}} + \frac{(B_{\bar{p}} + B_{Nav})^2}{E_{th}^2} - \frac{1}{E_{th}} T_{\bar{p}} - \frac{1}{E_{th}} T_{Nav}\right)^{1/2}, \quad \text{(J)}$$

where $T_j = -\frac{\hbar^2}{2m_j^*}\triangle$ and $m_j^* = m_j - S_j,\; j = N, \bar{p}$

1s $\bar{p}$ energies and widths in nuclei

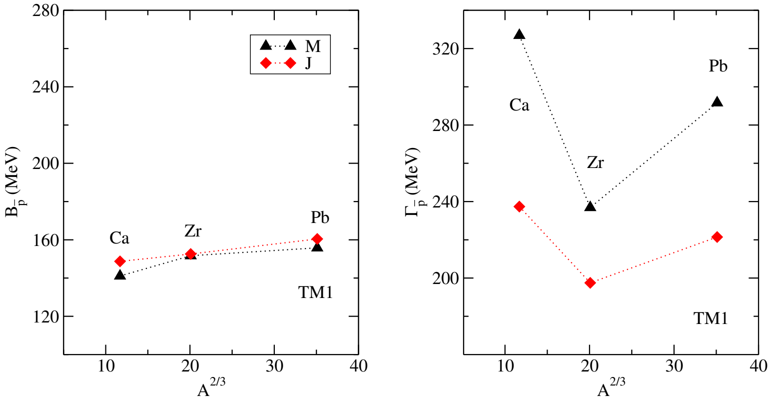

Fig.4: Binding energies (left panel) and widths (right panel) of 1s $\bar{p}$-nuclear states in selected nuclei, calculated dynamically using the TM1 model for different $\sqrt{s}$.

Paris $\bar{N}N$ potential

- Microscopic $\bar{N}N$ Paris potential constrained by scattering and antiproton atom data

  (B. El-Bennich, M. Lacombe, B. Loiseau, S. Wycech, PRC 79 (2009) 054001.)
- Recently used to describe the $\bar{p}$-atom data and low energy $\bar{p}$ scattering off nuclei

  (E. Friedman, A. Gal, B. Loiseau, S. Wycech, NPA 934 (2015) 101)
- S-wave $\bar{p}$-nucleus optical potential in a 'tρ' form

$$2E_{\bar{p}}V_{\rm opt} = -4\pi\frac{\sqrt{s}}{m_N}\left(F_0\frac{1}{2}\rho_p + F_1\left(\frac{1}{2}\rho_p + \rho_n\right)\right)$$

In-medium Paris S-wave amplitudes

- In-medium amplitudes F_0 and F_1 obtained from free-space amplitudes by multiple scattering approach (WRW)

  (T. Wass, M. Rho, W. Weise, NPA 617 (1997) 449)

$$F_1 = \frac{f_{\bar{p}n}(\delta\sqrt{s})}{1 + \frac{1}{4}\xi_k \frac{\sqrt{s}}{m_N} f_{\bar{p}n}(\delta\sqrt{s})\rho}\,,\; F_0 = \frac{[2f_{\bar{p}p}(\delta\sqrt{s}) - f_{\bar{p}n}(\delta\sqrt{s})]}{1 + \frac{1}{4}\xi_k \frac{\sqrt{s}}{m_N}[2f_{\bar{p}p}(\delta\sqrt{s}) - f_{\bar{p}n}(\delta\sqrt{s})]\rho}\,,$$

where $\delta\sqrt{s} = \sqrt{s} - E_{\rm th}$, $\xi_k = \frac{9\pi}{p_f^2}\, 4\int_0^\infty \frac{dt}{t}\exp(iqt) j_1^2(t)$ and $q = \frac{1}{p_f}\sqrt{E_{\bar{p}}^2 - m_{\bar{p}}^2}$

In-medium Paris S-wave amplitudes

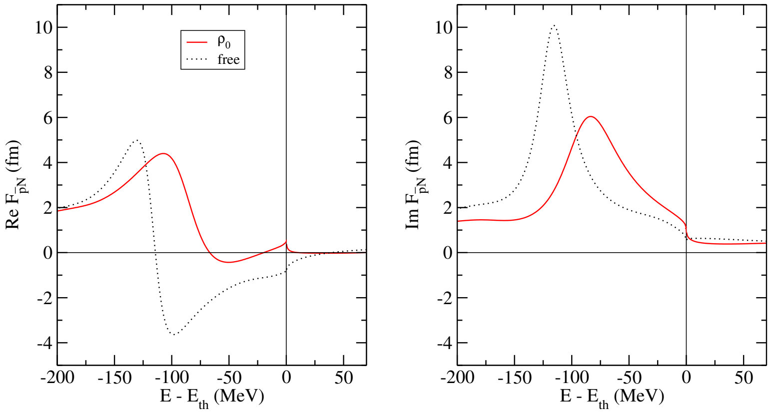

Fig.5: Energy dependence of the Paris 09 $\bar{p}N$ S-wave amplitudes: Pauli blocked amplitude for $\rho_0 = 0.17$ fm^{-3} (solid lines) compared with free-space amplitude (dotted lines).

1s $\bar{p}$ energies and widths

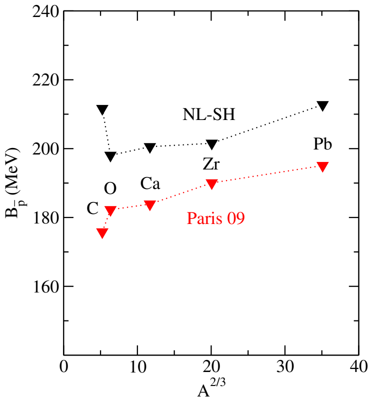

Fig.6: Binding energies (left panel) and widths (right panel) of 1s $\bar{p}$-nuclear states in selected nuclei, calculated dynamically for $\sqrt{s} = \mathrm{J}$ using the Paris $\bar{N}N$ S-wave potential (red) and phenomenological approach within the NL-SH model (black).

$\bar{p}$ spectrum in ^{16}O

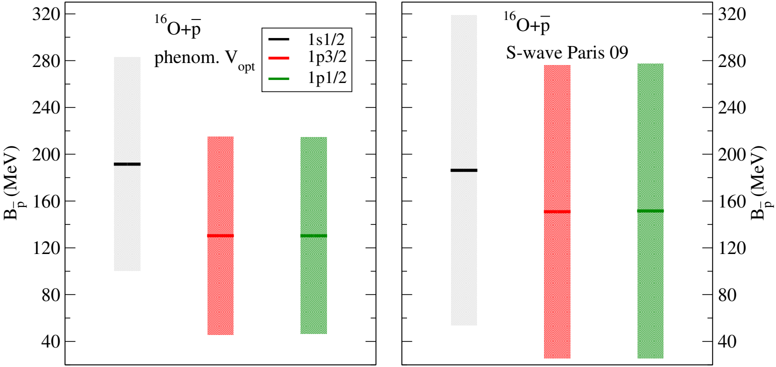

Fig.7: 1s and 1p binding energies (lines) and widths (boxes) of $\bar{p}$ in ^{16}O calculated dynamically within the TM2 model for $\sqrt{s}$ = J with phenomenological $\bar{p}$ optical potential (left) and S-wave Paris potential (right).

Conclusions

- Antibaryons deeply bound in the nuclear medium within the RMF + G-parity approach
- $\bar{p}$ absorption in a nucleus – $\bar{p}$ widths are reduced due to significant contribution from $T_{\bar{p}}$ and T_N to $\Gamma_{\bar{p}}$, but still remain large for potentials consistent with $\bar{p}$–atom data
- $\bar{p}$-nucleus quasibound states calculated with the Paris $\bar{N}N$ potential
  - S-wave potential yields smaller 1s $\bar{p}$ energies and larger $\bar{p}$ widths then the RMF approach
  - the P-wave interaction to be included