Calculations of antibaryon nuclear bound states

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ECT* workshop, Trento, October 27 - 31, 2014

Introduction

- study of antibaryon ($\bar{p}$, $\bar{\Lambda}$, $\bar{\Sigma}$, $\bar{\Xi}$) bound states in selected nuclei:
  - behavior of antibaryons in the nuclear medium
  - changes of the binding energy, single particle energies and density distributions in the nuclear core
  - $\bar{p}$ absorption in a nucleus

- knowledge of $\bar{p}$–nucleus and $\bar{Y}$–nucleus interaction for future experiments (PANDA@FAIR)
- testing models of (anti)hadron–hadron interactions
- possibility of long living $\bar{p}$ in the nuclear medium due to phase space suppression? (*I.N. Mishustin et al, Phys. Rev. C 71 (2005)*)

RMF approach

- Baryons treated as Dirac fields interacting via the exchange of meson fields
  - isoscalar-scalar field σ, isoscalar-vector field ω_μ, isovector-vector field $\vec{\rho}_\mu$, and massless vector field A_μ.
- The standard RMF models TM and density dependent model TW99

$$g_{iN}(\rho_{VN}) = g_{iN}(\rho_{sat}) f_i(x) \ , \quad i = \sigma, \omega, \rho \ ,$$

where ρ_{VN} is a vector baryon density and $x = \rho_{VN}/\rho_{sat}$

(*S. Typel, H.H. Wolter, Nucl. Phys. A 656 (1999) 331*)

RMF approach

- Dirac equation for nucleons and antibaryon

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

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

$$\Sigma_{\mathrm{R}} = \frac{\partial g_{\omega N}}{\partial \rho_{\mathrm{V}N}}\rho_{\mathrm{V}N}\omega_0 + \frac{\partial g_{\rho N}}{\partial \rho_{\mathrm{V}N}}\rho_{\mathrm{I}N}\rho_0 - \frac{\partial g_{\sigma N}}{\partial \rho_{\mathrm{V}N}}\rho_{\mathrm{S}N}\sigma \ .$$

- Klein-Gordon equations for meson fields

$$(-\triangle + m_\sigma^2)\sigma = -g_{\sigma N}(\rho_{\mathrm{V}N})\rho_S - g_{\sigma\bar{B}}(\rho_{\mathrm{V}N})\rho_{S\bar{B}}$$

$$(-\triangle + m_\omega^2)\omega_0 = g_{\omega N}(\rho_{\mathrm{V}N})\rho_V + g_{\omega\bar{B}}(\rho_{\mathrm{V}N})\rho_{V\bar{B}}$$

$$(-\triangle + m_\rho^2)\rho_0 = g_{\rho N}(\rho_{\mathrm{V}N})\rho_I + g_{\rho\bar{B}}(\rho_{\mathrm{V}N})\rho_{I\bar{B}}$$

$$-\triangle A_0 = e\rho_p + e_{\bar{B}}\rho_{\bar{B}} \ .$$

B-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)

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

$\bar{B}$-nucleus interaction

- $NN \rightarrow \bar{N}N$ interaction – G-parity + optical potential
- B-nucleus $\rightarrow \overline{B}$-nucleus interaction – G-parity transformation

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

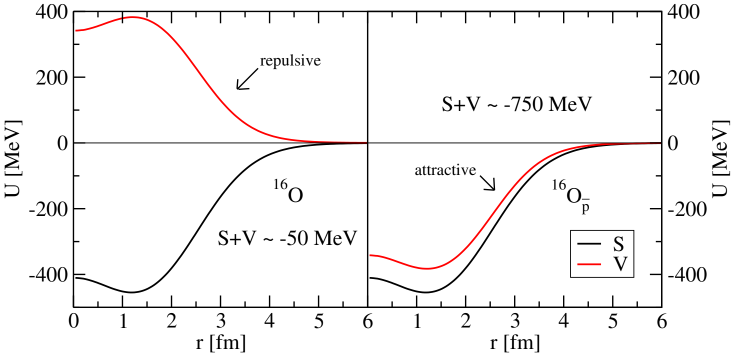

Fig.1: The scalar and vector potential acting on nucleon in ^{16}O (left) and $\bar{p}$ in ^{16}O$_{\bar{p}}$ (right), calculated statically in the TM2 model.

$\bar{p}$-nucleus interaction

- Antiprotonic atoms and $\bar{p}$ scattering off nuclei at low energies $\rightarrow$ the depth of $\mathrm{ReV}_{\bar{p}} \sim \mathbf{100} - \mathbf{300}$ MeV
- Reduced $\bar{p}$ coupling constants

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

  where parameter ξ is from $\langle 0, 1\rangle$
- large polarization effects confirmed (*I.N. Mishustin et al, Phys. Rev. C 71 (2005)*)

The issue of the $\bar{p}$ self-interaction

KG equations for a meson field acting on nucleons:

$$(-\triangle + m_M^2)\Phi_N = g_{MN}\rho_{MN} + g_{M\bar{p}}\rho_{M\bar{p}}$$

acting on $\bar{p}$:

$$(-\triangle + m_M^2)\Phi_{\bar{p}} = g_{MN}\rho_{MN} \cancel{+ g_{M\bar{p}}\rho_{M\bar{p}}}$$

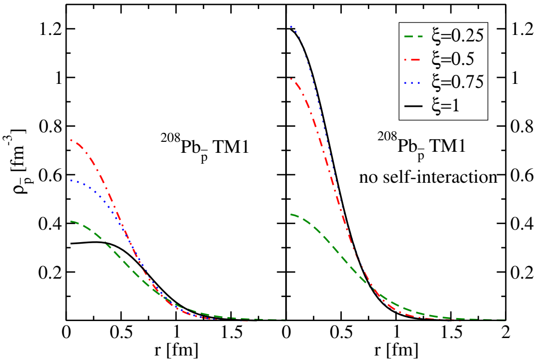

Fig.2: The $\bar{p}$ density in ^{208}Pb$_{\bar{p}}$, calculated with and without the $\bar{p}$ self-interaction.

Density-dependent vs. standard RMF model

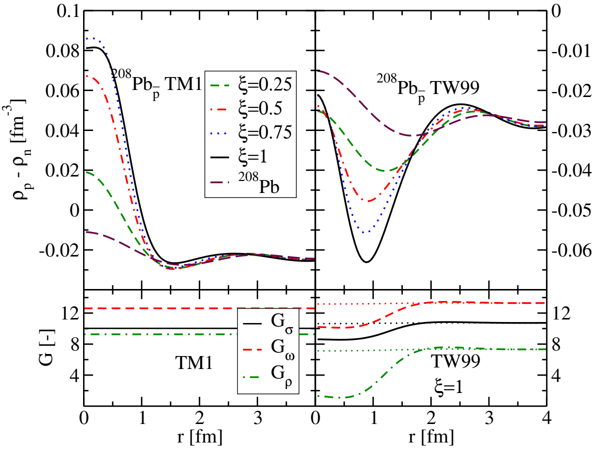

Fig.3: The isovector density in $^{208}Pb_{\bar{p}}$, calculated within the TM1 and TW99 model.

Antibaryon potential

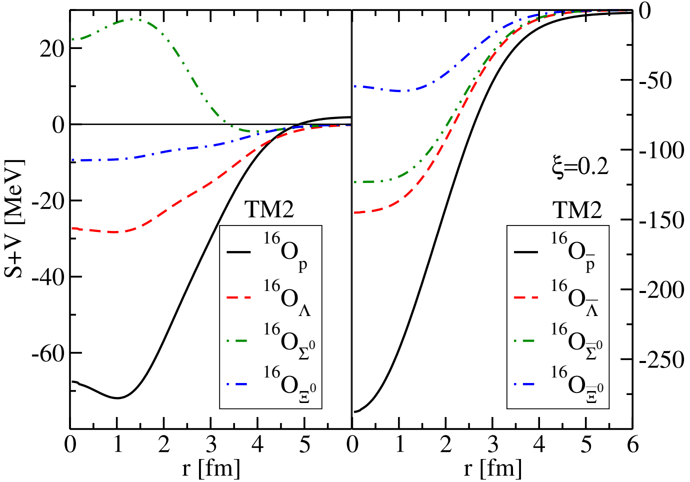

Fig.4: The B–nucleus (left) and $\bar{B}$–nucleus (right) potentials in ^{16}O.

Antibaryon spectrum

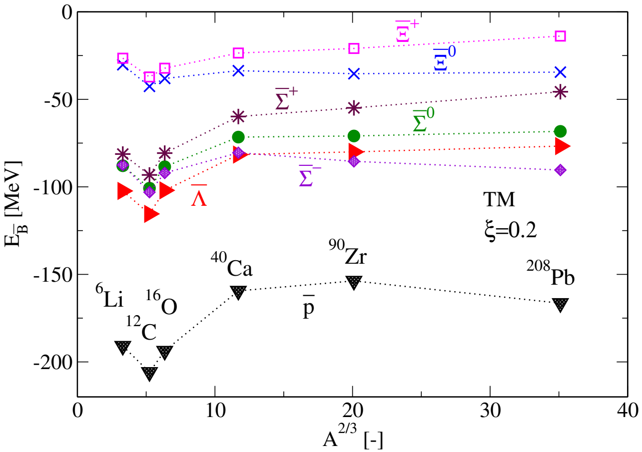

Fig.5: The A dependence of $\bar{B}$ single particle energies, calculated in TM model for $\xi = 0.2$.

Baryon vs. antibaryon s.p. energies

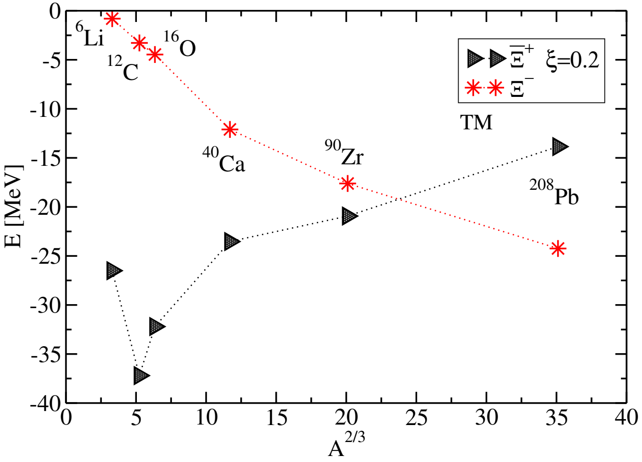

Fig.6: Single particle energies of Ξ^- and $\bar{\Xi}^+$ for $\xi = 0.2$ in various nuclei, calculated dynamically in the TM model.

The $\bar{p}$ absorption

- $\bar{p}$–nucleus optical potential:

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

$$\mathrm{Im}V_{\bar{p}} = \sum_{channel} f_s B_r \mathrm{Im}b_0 \rho_{\mathrm{RMF}} \ ,$$

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

- $\sqrt{s} = 2m_N - B_{\bar{p}} - B_N$

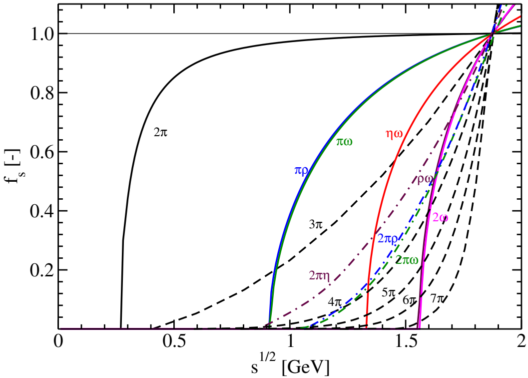

Fig.7: The phase space suppression factor f_s as a function of the center-of-mass energy $\sqrt{s}$.

The $\bar{p}$ absorption

Table 1: The 1s single particle energies $E_{\bar{p}}$ and widths $\Gamma_{\bar{p}}$ (in MeV) in $^{16}O_{\bar{p}}$, calculated dynamically (Dyn) and statically (Stat) with the real, complex and complex with f_s potentials (TM2 model), consistent with $\bar{p}$–atom data.

	Real		Complex		Complex + f_s	
	Dyn	Stat	Dyn	Stat	Dyn	Stat
$E_{\bar{p}}$	193.7	137.1	175.6	134.6	190.2	136.1
$\Gamma_{\bar{p}}$	-	-	552.3	293.3	232.5	165.0

CMS vs LAB frame

- $\bar{p}$ absorption in a nucleus → non-negligible contribution from the momentum dependent term in

$$s = (E_N + E_{\bar{p}})^2 - (\vec{p}_N + \vec{p}_{\bar{p}})^2 \ , \quad \vec{p}_N + \vec{p}_{\bar{p}} \neq 0,$$

where $E_i = m_i - B_i$ for $i = N, \bar{p}$.

(A. Cieply et al., Phys. Lett. B 702, 402 (2011))

Table 2: The 1s single particle energies $E_{\bar{p}}$ and widths $\Gamma_{\bar{p}}$ (in MeV) in $^{16}O_{\bar{p}}$, calculated dynamically in TM2 model with different approach to $\sqrt{s}$, consistent with $\bar{p}$–atom data.

	CMS	LAB
$E_{\bar{p}}$	190.2	191.6
$\Gamma_{\bar{p}}$	232.5	179.9

Spin symmetry in $\bar{p}$ spectrum

- relativistic symmetry of Dirac Hamiltonian when V=S+const
  J.N. Ginocchio, Phys. Rep. 414, 165 - 261 (2005)
- spin doublets - states with $j = \ell \pm \frac{1}{2}$ are degenerate
- upper components of $\bar{p}$ wave function are equal $g_{n_r,\ell+1/2}(r) = g_{n_r,\ell-1/2}(r)$
- lower components are related by the equation

$$\left(\frac{\partial}{\partial r} + \frac{\ell+2}{r}\right) f_{n_r,\ell+1/2}(r) = \left(\frac{\partial}{\partial r} - \frac{\ell-1}{r}\right) f_{n_r,\ell-1/2}(r)$$

- spin symmetry is well preserved in antinucleon spectra
  X.T. He, S.G. Zhou, J. Meng, E.G. Zhao and W. Scheid, Eur. Phys. J. A 28, 265 - 269 (2006)

Spin symmetry

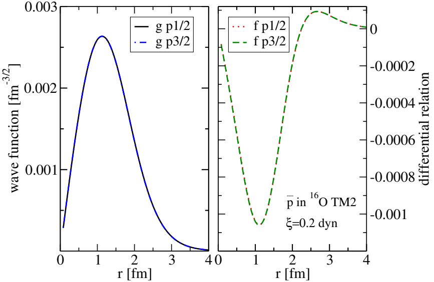

Fig.8: Upper (g) and lower (f) components of the $\bar{p}$ wave function in $^{16}O_{\bar{p}}$ TM2, calculated dynamically.

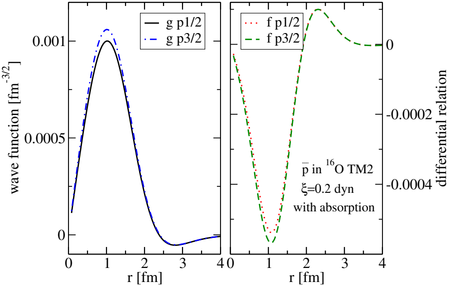

Fig.9: Upper (g) and lower (f) components of the $\bar{p}$ wave function in $^{16}O_{\bar{p}}$ TM2, calculated dynamically with $\bar{p}$ absorption in the nucleus.

Conclusions

- antibaryons are deeply bound in the nuclear medium
- large polarization effects of the nuclear core due to $\bar{B}$ confirmed
- $\bar{p}$ absorption in a nucleus – $\bar{p}$ widths are suppressed due to the phase space reduction, but still remain large for potentials consistent with $\bar{p}$–atom data
- significant contribution from $\vec{p}_{\bar{p}}$ and $\vec{p}_N$ to $\Gamma_{\bar{p}}$
- spin symmetry in $\bar{p}$ spectrum is preserved even if the polarization effects in the nucleus and the $\bar{p}$ absorption are taken into account