

Interaction of antiproton with nuclei

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Introduction

- study of \bar{p} bound states in selected nuclei:
 - behavior of \bar{p} in the nuclear medium
 - changes of the nuclear binding energy, single particle energies and density distributions
 - \bar{p} absorption in a nucleus
- previous study *I.N. Mishustin et al., Phys. Rev. C 71 (2005)*
 - possibility of long living \bar{p} in the nuclear medium?
- testing models of (anti)hadron–hadron interactions
- knowledge of \bar{p} –nucleus interaction for future experiments (PANDA@FAIR)

RMF approach

- Nucleons 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

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

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

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

RMF approach

- Dirac equation for nucleons and antiproton

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

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

$$\Sigma_R = \frac{\partial g_{\omega N}}{\partial \rho_{VN}} \rho_{VN} \omega_0 + \frac{\partial g_{\rho N}}{\partial \rho_{VN}} \rho_{IN} \rho_0 - \frac{\partial g_{\sigma N}}{\partial \rho_{VN}} \rho_{SN} \sigma.$$

- Klein-Gordon equations for meson fields

$$(-\Delta + m_\sigma^2)\sigma = -g_{\sigma N}(\rho_{VN})\rho_S - g_{\sigma \bar{p}}(\rho_{VN})\rho_{S\bar{p}}$$

$$(-\Delta + m_\omega^2)\omega_0 = g_{\omega N}(\rho_{VN})\rho_V + g_{\omega \bar{p}}(\rho_{VN})\rho_{V\bar{p}}$$

$$(-\Delta + m_\rho^2)\rho_0 = g_{\rho N}(\rho_{VN})\rho_I + g_{\rho \bar{p}}(\rho_{VN})\rho_{I\bar{p}}$$

$$-\Delta A_0 = e\rho_p + e_{\bar{p}}\rho_{\bar{p}}.$$

\bar{p} -nucleus interaction

- $NN \rightarrow \bar{N}N$ interaction – G-parity transformation $\hat{G} = \hat{C}e^{i\pi I_1}$

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

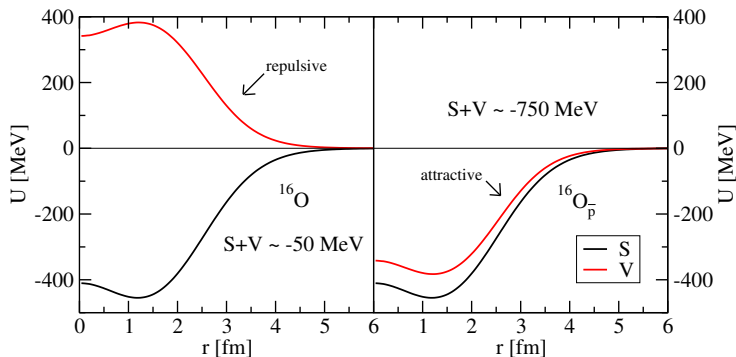


Fig.1: The scalar and vector potential acting on nucleon in ^{16}O (left) and \bar{p} in $^{16}\text{O}_{\bar{p}}$ (right), calculated statically in the TM2 model.

\bar{p} -nucleus interaction

- Antiprotonic atoms: energy shifts and widths due to the strong interaction \rightarrow the depth of $\text{Re}V_{\bar{p}} \sim \mathbf{100 - 300}$ MeV
(*E. Friedman, A. Gal, J. Mares, Nucl. Phys. A 761, 283 (2005)*)
- 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)*)
- density dependent model TW99 - similar results as TM model

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

KG equations for a meson field acting on nucleons:

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

acting on \bar{p} :

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

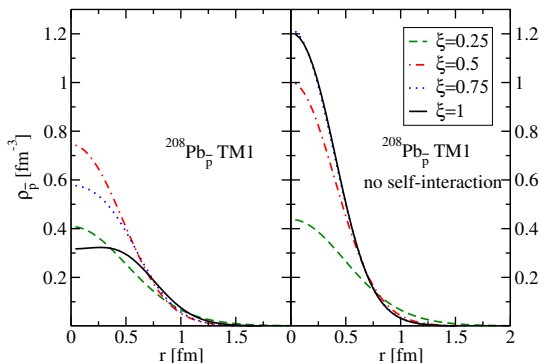


Fig.2: The \bar{p} density in $^{208}\text{Pb}_{\bar{p}}$, calculated with and without the \bar{p} self-interaction.

The \bar{p} absorption

- \bar{p} -nucleus optical potential:

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

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

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

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

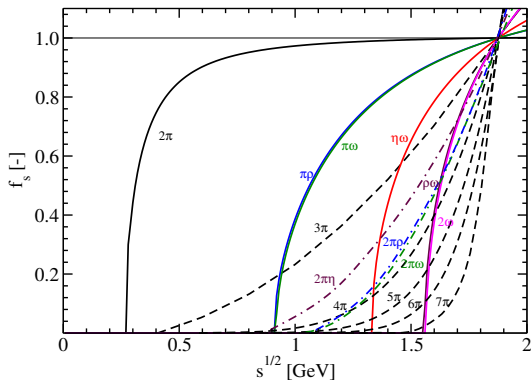


Fig.3: The phase space suppression factor f_s as a function of the center-of-mass energy \sqrt{s} .

The \bar{p} absorption

Table 1: The $1s$ single particle energies $E_{\bar{p}}$ and widths $\Gamma_{\bar{p}}$ (in MeV) in $^{16}\text{O}_{\bar{p}}$, 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 \rightarrow 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 $^{16}\text{O}_{\bar{p}}$, 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 $V=S+\text{const}$
(*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

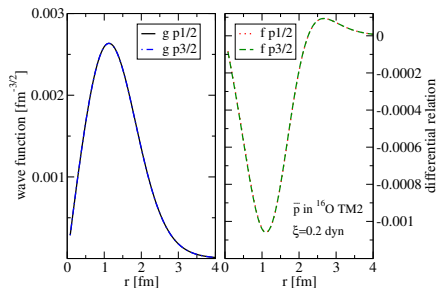


Fig.5: Upper (g) and lower (f) components of the \bar{p} wave function in $^{16}\text{O}_{\bar{p}}$ TM2, calculated dynamically.

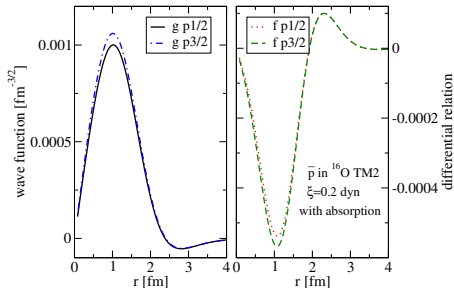


Fig.6: Upper (g) and lower (f) components of the \bar{p} wave function in $^{16}\text{O}_{\bar{p}}$ TM2, calculated dynamically with \bar{p} absorption in the nucleus.

Extension of conventional RMF model

- standard RMF models - scaling factor for antiproton couplings
- Non-linear derivative (NLD) model for nuclear matter
(*T. Gaitanos, M. Kaskulov, Nucl. Phys. A 899, 133 - 169 (2013)*)
- NLD model applied to antiproton interaction in nuclear matter \rightarrow much shallower $\text{Re}V_{\bar{p}}$ for the G-parity
(*T. Gaitanos, M. Kaskulov, H. Lenske, Phys. Lett. B 703, 193-198 (2011)*)
- application of the NLD model to finite nuclei

Conclusion

- large polarization effects of the nuclear core due to \bar{p} 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
- further study of the \bar{p} interaction with nuclei is needed