acta physica slovaca vol. 56 No. 2, 95 – 98 April 2006

KAONIC NUCLEI[1]

J. Mareš,[2,*] E. Friedman,[‡] A. Gal [‡]
[*] *Nuclear Physics Institute ASCR, 25068 Řež, Czech Republic*
[‡] *Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*

Received 6 December 2005, in final form 3 January 2006, accepted 23 January 2006

Limits on the possible existence of narrow K^- nuclear states and on their widths are explored. Deeply bound K^- nuclear states are generated dynamically. Substantial polarization of the core nucleus is found for light K^- nuclei. The widths of the states are mostly determined by the phase-space suppression on top of the increase provided by the density of the compressed nuclei. The behaviour of the calculated widths as function of the K^- binding energy provides useful guidance for the interpretation of recent experimental results.

PACS: 13.75.Jz, 25.80.Nv, 36.10.Gv

1 Introduction

The strong-interaction shifts and widths in kaonic-atom levels [1] indicate that the K^--nucleus interaction is strongly attractive. It is not established yet, however, how strong it is. Attractive K^--nucleus potentials as deep as 150-200 MeV were proposed by models, based on fitting to K^- atomic data and extrapolating into the nuclear interior [2]. More microscopical in-medium $\bar{K}N$-interaction models favor moderately attractive K^--nucleus potentials of about 50 MeV depth [3, 4]. All of these potentials are very absorptive.

Is the K^--nucleus interaction strong enough to bind K^- meson in nuclei and are such deeply bound states sufficiently narrow to allow their observation? This issue has attracted considerable attention recently [4–7]. Several (K^-, N) experiments on light nuclei have found evidence for peaks that are assigned to relatively narrow ($\Gamma < 25$ MeV) and deep K^- nuclear states bound by over 100 MeV [8, 9]. New results from DAΦNE suggest deep binding for K^- mesons in light nuclei such as Li and C [10].

In this work, we explore limits on the possible existence of narrow K^- nuclear states and on their widths using the relativistic mean field (RMF) model for a system of nucleons and one $\bar{K}$ meson which interact via scalar (σ) and vector (ω) meson fields [11]. Deeply bound K^- nuclear states are generated dynamically by allowing the K^- to polarize the nucleons, and vice versa. The K^- absorption modes are included within a $t\rho$ optical-model approach, where the density ρ plays a dynamical role, and the constant t which is constrained near threshold by K^--atom data follows the phase-space reduction for K^- absorption from deeply bound states.

[1]Presented at 15-th Conference of Czech and Slovak Physicist, Košice, Slovakia, September 5–8, 2005
[2]E-mail address: mares@ujf.cas.cz

2 Model

In our model [11], the nucleonic sector is described by a standard RMF Lagrangian $\mathcal{L}_{\rm N}$. The (anti)kaon interaction with the nuclear medium is incorporated by the additional Lagrangian density $\mathcal{L}_{\rm K}$:

$$\mathcal{L}_{\rm K} = \mathcal{D}^*_\mu \bar{K} \mathcal{D}^\mu K - m^2_{\rm K} \bar{K} K - g_{\sigma {\rm K}} m_{\rm K} \sigma \bar{K} K \ , \quad \text{where } \mathcal{D}_\mu = \partial_\mu + i g_{\omega {\rm K}} \omega_\mu \ . \tag{1}$$

Whereas appending $\mathcal{L}_{\rm K}$ to the original Lagrangian $\mathcal{L}_{\rm N}$ does not affect the form of the corresponding Dirac equation for nucleons, the presence of $\bar{\rm K}$ leads to subsequent source terms in the equations of motion for the meson fields σ and ω_0 to which the $\bar{\rm K}$ couples:

$$\left(-\Delta + m^2_\sigma\right) \sigma \quad = \quad -g_{\sigma {\rm N}} \rho_{\rm S} - g_{\sigma {\rm K}} m_{\rm K} \bar{K} K + \left(-g_2\, \sigma^2 - g_3\, \sigma^3\right) \ , \tag{2}$$

$$\left(-\Delta + m^2_\omega\right) \omega_0 \quad = \quad +g_{\omega {\rm N}} \rho_{\rm V} - 2 g_{\omega {\rm K}} (\omega_{\rm K} + g_{\omega {\rm K}} \omega_0) \bar{K} K \ . \tag{3}$$

Here, $\omega_{\rm K} = \sqrt{m^2_{\rm K} + g_{\sigma {\rm K}} m_{\rm K} \sigma + p^2_{\rm K}} - g_{\omega {\rm K}} \omega_0$ is the $\bar{\rm K}$ energy in the nuclear medium and $\rho_{\rm S}$ and $\rho_{\rm V}$ denote the nuclear scalar and vector densities, respectively. The presence of $\bar{\rm K}$ in the nuclear system affects the scalar and vector potentials which enter the Dirac equation for nucleons. This leads to the rearrangement of the nuclear core. The Klein Gordon (KG) equation of motion for the $\bar{\rm K}$ is considered in the form [4]:

$$\left[\Delta - 2\mu(B + V_{\rm opt} + V_{\rm c}) + (V_{\rm c} + B)^2\right] \bar{K} = 0 \quad (\hbar = c = 1). \tag{4}$$

Here, $V_{\rm c}$ denotes the Coulomb potential for the $\bar{\rm K}$, μ is the $\bar{\rm K}$-nucleus reduced mass, and $B = B_{\rm K} + {\rm i}\Gamma_{\rm K}/2$ is the complex binding energy. The real part of the $\bar{\rm K}$ optical potential $V_{\rm opt}$ is then given by

$$\text{Re } V_{\rm opt} = \frac{m_{\rm K}}{\mu} \left[\frac{1}{2} S - \left(1 - \frac{B_{\rm K}}{m_{\rm K}}\right) V - \frac{V^2}{2 m_{\rm K}}\right] \quad , \tag{5}$$

where $S = g_{\sigma {\rm K}} \sigma$ and $V = g_{\omega {\rm K}} \omega_0$ are the scalar and vector potentials.

The imaginary part of the potential, ${\rm Im}\, V_{\rm opt}$ is taken in a phenomenological $t\rho$ form. Its depth was fitted to the K^- atomic data [2]. Note that the nuclear density ρ in our model is a *dynamical* entity affected by the $\bar{\rm K}$ interacting with the nucleons. The resulting compressed density leads to increased widths, particularly for deeply bound states. On the other hand, the phase space available for $\bar{\rm K}$ absorption from deeply bound states is reduced, which will act to decrease the calculated widths. Therefore, suppression factor f multiplying ${\rm Im}\ V_{\rm opt}$ was introduced. Two absorption channels were considered, $\bar{\rm K}{\rm N} \to {\rm Y}\pi \quad ({\rm Y} = \Sigma,\ \Lambda)$ and $\bar{\rm K}{\rm NN} \to {\rm YN}$, and the corresponding density-independent suppression factors f_1 and f_2 were evaluated [11]. For the combined suppression factor we assumed $f = 0.8\, f_1 \ + \ 0.2\, f_2$, where the branching ratios were adopted from bubble-chamber experiments.

The coupled system of equations for nucleons, meson mean fields and $\bar{\rm K}$ was solved self-consistently using an iterative procedure. The requirement of self-consistency appeared crucial for the proper evaluation of the dynamical effects of the $\bar{\rm K}$ on the nuclear core and vice versa.

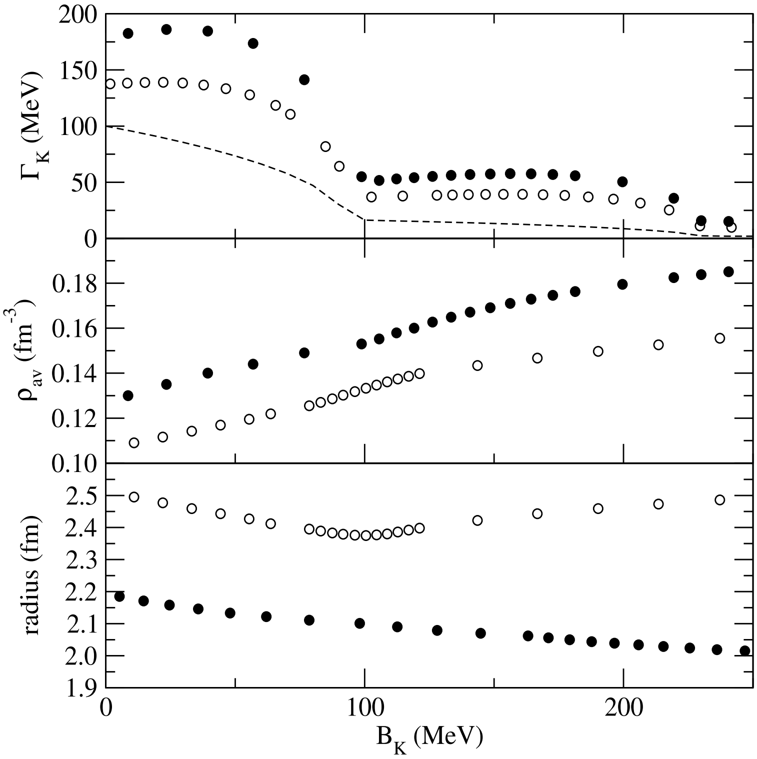

Fig. 1. The width of the $1s$ K$^-$- nuclear state, dimensionless phase-space suppression factor f (x100) for Im $V_{\rm opt}$ (top, dashed line), average nuclear density $\rho_{\rm av}$ and nuclear rms radius in ^{12}C (solid circles) and ^{16}O (open circles) as function of the K$^-$ binding energy.

3 Results

The main objective of the present calculations of K$^-$-nucleus bound states was to establish correlations between various observables such as the K$^-$ binding energy, width and macroscopic nuclear properties. Varying the K$^-$ coupling constants $g_{\sigma\rm K}$ and $g_{\omega\rm K}$ (eq.1) we covered a wide range of binding energies in order to evaluate widths of possible strongly bound K$^-$ nuclear states. Furthermore, in order to study effects of the nuclear polarization, we calculated rms radii and average densities of the nuclei involved and, in some cases, also single particle energies. We present here only results of calculations for ^{12}C and ^{16}O, nuclei that had been discussed earlier in the context of strongly bound K$^-$ states [5, 9].

Figure 1 shows, in its upper part, calculated widths $\Gamma_{\rm K}$ as function of the binding energy $B_{\rm K}$ for $1s$ states in $^{16}_{\rm K^-}$O (open circles) and $^{12}_{\rm K^-}$C (solid circles). The dimensionless suppression factor f (dashed line, multiplied by 100) is presented here as well. It is clearly seen that the widths of the K$^-$ nuclear state follow the dependence of the suppression factor (dashed line) on the binding energy and that, except for binding energies smaller than 50 MeV, the dependence of the width on the binding energy follows almost a universal curve. We note that the widths calculated in the range $B_{\mathrm{K}} \sim 100 - 200$ MeV assume values 40 ± 5 MeV, which are considerably larger than what the suppression factor would suggest.This is largely related to the dynamical nature of the RMF calculation whereby the nuclear density is increased by the polarization effect of the K^-. The middle and lower parts of Fig.1 show the calculated average nuclear density $\rho_{\mathrm{av}} = \frac{1}{A} \int \rho^2 d\mathbf{r}$ and the nuclear rms radius, respectively. It is interesting to note that the increase in the nuclear rms radius of $_{\mathrm{K}^-}^{16}\mathrm{O}$ for large values of B_{K} is the result of the reduced binding energy of the $1p_{1/2}$ state, due to the increased spin-orbit term. The substantial increase of ρ_{av} and the change of the nuclear rms radius point out to a significant polarization of the nuclear core by the $1s$ K^-.

4 Conclusions

In the present work we studied *dynamical* effects for K^- nuclear states, particularly in the range of binding energy $B_{\mathrm{K}} \sim 100 - 200$ MeV [8,9], and the widths anticipated for such deeply bound states. The theoretical framework here adopted is the RMF model for a system of nucleons and one $\bar{\mathrm{K}}$ meson interacting through the exchange of scalar (σ) and vector (ω) boson fields which are treated in the mean-field approximation. Absorption modes are also included dynamically. It is to be noted that the relatively shallow chirally-motivated K^--nucleus potentials [3,4] are of no use in this context, since they cannot yield binding energy greater than the potential depth of about 50 MeV.

Substantial polarization of the core nucleus was found in the light nuclei for deeply bound K^- nuclear states. The widths are mostly determined by the phase-space suppression factors on top of the increase provided by the compressed nuclear density. The present results already provide useful guidance for the interpretation of recent experimental results [9] by placing a lower limit $\Gamma_{\mathrm{K}} \sim 35 - 40$ MeV on K^- states in $^{16}\mathrm{O}$ bound in the range $B_{\mathrm{K}} \sim 100 - 200$ MeV. For lighter nuclear targets such as $^4\mathrm{He}$, where the RMF approach becomes unreliable but where nuclear polarization effects are found larger using few-body calculational methods [6,7], we anticipate larger widths for K^- deeply bound states, if such states do exist.

Acknowledgement: This work was supported by the GA AVCR grant IAA1048305.

References

[1] C.J. Batty, E. Friedman, A. Gal: *Phys. Rep.* **287** (1997) 385
[2] E. Friedman, A. Gal, J. Mareš, A. Cieplý: *Phys. Rev. C* **60** (1999) 024314
[3] A. Ramos, E. Oset: *Nucl. Phys. A* **671** (2000) 481
[4] A. Cieplý, E. Friedman, A. Gal, J. Mareš: *Nucl. Phys. A* **696** (2001) 173
[5] T. Kishimoto: *Phys. Rev. Lett.* **83** (1999) 4701
[6] Y. Akaishi, T. Yamazaki: *Phys. Rev. C* **65** (2002) 044005
[7] A. Doté, H. Horiuchi, Y. Akaishi, T. Yamazaki: *Phys. Lett. B* **590** (2004) 51 ; *Phys. Rev. C* **70** (2004) 044313
[8] M. Iwasaki *et al.*: nucl-ex/0310018
[9] T. Kishimoto: *Nucl. Phys. A* **754** (2005) 383c
[10] M. Agnello *et al.*: *Phys. Rev. Lett.* **94** (2005) 212303
[11] J. Mareš, E. Friedman, A. Gal: *Phys. Lett. B* **606** (2005) 295