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Widths of $\bar{K}$-nuclear deeply bound states in a dynamical model

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Abstract

The relativistic mean field (RMF) model is applied to a system of nucleons and a $\bar{K}$ meson, interacting via scalar and vector boson fields. The model incorporates the standard RMF phenomenology for bound nucleons and, for the $\bar{K}$ meson, it relates to low-energy $\bar{K}N$ and K^- atom phenomenology. Deeply bound $\bar{K}$ nuclear states are generated dynamically across the periodic table and are exhibited for ^{12}C and ^{16}O over a wide range of binding energies. Substantial polarization of the core nucleus is found for these light nuclei. Absorption modes are also included dynamically, considering explicitly both the resulting compressed nuclear density and the reduced phase space for $\bar{K}$ absorption from deeply bound states. The behavior of the calculated width as function of the $\bar{K}$ binding energy is studied in order to explore limits on the possible existence of narrow $\bar{K}$ nuclear states.

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1. Introduction

The $\bar{K}N$ interaction near threshold is strongly attractive, in agreement with the existence of the unstable bound state $\Lambda(1405)$ below the K^-p threshold. The $\bar{K}$-nucleus interaction is also strongly attractive, as derived from the strong-interaction shifts and widths in kaonic-atom levels across the periodic table [1]. It is not established yet how strong the $\bar{K}$-nucleus potential is: 'deep' (150–200 MeV [2,3]) or relatively 'shallow' (50–60 MeV [4,5])? Is it possible to bind *strongly* $\bar{K}$ mesons in nuclei and are such potentially deep bound states sufficiently narrow to allow observation and identification? These issues have received considerable phenomenological and theoretical attention recently [4–8], and some experimental evidence for candidate states in the $(K^-_{\rm stop}, n)$ and $(K^-_{\rm stop}, p)$ reactions on

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^{4}He (KEK-PS E471, [9,10] respectively) and in the (K^-, n) in-flight reaction on ^{16}O (BNL-AGS, parasite E930 [11]) has been presented very recently. New experiments have been approved at KEK, using (K^-, N) reactions to search for $\bar{K}$ nuclear bound states [12]. (K^-, π^-) reactions [13] were also suggested in this context.

A prime concern in searching for $\bar{K}$ nuclear bound states is the anticipated large width due to pionic conversion modes on a single nucleon:

$$\bar{K}N \to \pi\Sigma,\ \pi\Lambda\ (\sim 80\%), \tag{1}$$

with thresholds about 100 and 180 MeV, respectively, below the $\bar{K}N$ total mass, and also due to non-pionic multi-nucleon absorption modes, say

$$\bar{K}NN \to YN\ (\sim 20\%), \tag{2}$$

with thresholds about $m_\pi = 140$ MeV lower than the single-nucleon thresholds. The branching ratios in parentheses are known from bubble-chamber experiments [14].

The aim of the present work is to study *dynamical* effects for $\bar{K}$ nuclear states in the range of binding energy $B_K \sim 100$–200 MeV [9–11] and in particular the width anticipated for such deeply bound states. The relatively shallow chirally-motivated $\bar{K}$-nucleus potentials [4,5] which followed the microscopic construction by Ramos and Oset [15] are of no use in this context, since they cannot yield binding energy greater than the potential depth of about 50 MeV. One must therefore depart from the microscopic approach in favor of a more phenomenologically inclined model which is constrained by data other than two-body $\bar{K}N$ observables. The theoretical framework here adopted is the relativistic mean field (RMF) model for a system of nucleons and one $\bar{K}$ meson interacting through the exchange of scalar (σ) and vector (ω) boson fields which are treated in the mean-field approximation. By allowing the $\bar{K}$ to polarize the nucleons, and vice versa, this dynamical calculation is made self consistent. $\bar{K}$ 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 in reactions Eqs. (1) and (2) for a deeply bound $\bar{K}$. A wide range of binding energies may be explored in the RMF calculation simply by scanning over the coupling constants of the $\bar{K}$ meson to the σ and ω boson fields. Detailed calculations were done by us across the periodic table. In this Letter we demonstrate the essential points and conclusions for ^{12}C and ^{16}O where the dynamical polarization effects are extremely important for the energies of the $\bar{K}$ bound states as well as for their widths. Akaishi et al. [7,8] too have found large polarization effects in lighter nuclei using few-body variational techniques. The RMF is a systematic approach used across the periodic table beyond the very light elements explored by other techniques, and it can be used also to study multi-$\bar{K}$ configurations and to explore the $\bar{K}$ condensation limit [16,17]. Similar RMF calculations have been recently reported for $\bar{N}$ states in nuclei [18,19].

2. Methodology

In the calculations described below, the standard RMF Lagrangian $\mathcal{L}_N$ with the linear (L) parameterization of Horowitz and Serot [20] as well as the nonlinear (NL) parameterization due to Sharma et al. [21] are used for the description of the nucleonic sector. The (anti)kaon interaction with the nuclear medium is incorporated by adding to $\mathcal{L}_N$ the Lagrangian density $\mathcal{L}_K$ [16,17]:

$$\mathcal{L}_K = \mathcal{D}^*_\mu \bar{K} \mathcal{D}^\mu K - m_K^2 \bar{K} K - g_{\sigma K} m_K \sigma \bar{K} K. \tag{3}$$

The covariant derivative $\mathcal{D}_\mu = \partial_\mu + i g_{\omega K} \omega_\mu$ describes the coupling of the (anti)kaon to the vector meson ω. The vector field ω is then associated with a conserved current. The coupling of the (anti)kaon to the isovector ρ meson is here excluded due to considering $N = Z$ nuclear cores in this initial report.

Whereas adding $\mathcal{L}_K$ to the original Lagrangian $\mathcal{L}_N$ does not affect the form of the corresponding Dirac equation for nucleons, the presence of $\bar{K}$ leads to additional source terms in the equations of motion for the meson fields σ