K fragments

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The $KNNN$ bound states recently discovered at KEK are studied. It is shown that the $\Lambda(1405)$ and $\Sigma(1385)$ resonant states coupled to the KN system may generate an attraction strong enough to form such bound states.

1 Introduction

The bound $KNNN$ states, discovered at KEK [1], open up a new sector of strange nuclei. The state found in the K^-pnn system is bound by 195 MeV. A related K^-ppn state bound by some 20 MeV less is reported to this conference [2]. These states live fairly long and decay into a hyperon and two nucleons. Nuclear states of kaons were expected, since early studies of kaonic atoms indicated that the nuclear potential for K^- mesons is attractive, see review [3]. However, the (K, π) conversion is very rapid and such states would be difficult to detect due to large ($\approx$ 100 MeV) widths. One way to form states of longer lifetime would be to block the main decay channels. That may happen if the K^- is bound very strongly. Such a possibility was indicated to exist in the nuclear matter situation, [4]. Akaishi and Yamazaki predicted the existence of narrow states also in light nuclei such as He, [5], and this prediction led to the experiment of Ref. [1]. In both cases the mechanism of attraction was attributed to the resonant $\Lambda(1405)$ $I = 0$ state coupled to $K^-p + K^0n$.

The actual experiment [1] shows that the attraction due to the $\Lambda(1405)$ apparently plays an important role but is not strong enough to generate the binding as observed [6]. Both predictions [4] and [5] were based on a sizeable proton component in the nucleus and that is not the case in the K^-pnn system. One line of explanation is given at this conference, in terms of a contraction of the nuclear system [7]. Here, it is shown that, under fairly standard nuclear conditions another possibility exists. Two resonant states $\Lambda(1405)$ and $\Sigma(1385)$ coupled to the KN system may generate the attraction required to produce the strong binding. This happens under two basic conditions

- the $\Lambda(1405)$ and $\Sigma(1385)$ in a nuclear medium are located above the KN threshold.
- the binding of K^- is strong enough to block the main $\pi\Sigma$ and $\pi\Lambda$ decay modes.

Such conditions may be fulfilled also in heavier nuclei, but the state generated with this interaction will be similar everywhere. The meson is bound in a restricted small area in a region of the highest neutron density.

2 The origin of K^- attraction to nuclei

Let the $KN, I = 0$ S-wave scattering amplitude be described by a simple resonance formula

$$f_o = \frac{\gamma_o^2}{E_{KN} - E_o + i\Gamma_o/2}, \tag{1}$$

where E_{KN} is the energy in the KN channel and E_o is the $\Lambda(1405)$ energy. This amplitude is normalised to the scattering length at the threshold. For kaons in a nuclear medium it generates an optical potential $U_o = 2m_K V_o$ with

$$V_o(r) = \frac{4\pi}{2\mu_{KN}}\rho(r) f_o, \tag{2}$$

where μ_{KN} is the KN reduced mass and $\rho(r)$ is the nuclear density. The resonant situation produces an attractive potential when $E_{KN} - E_o < 0$ and a repulsive one otherwise. One question to settle is the value of the actual energy of the resonance in the nuclear medium. Emulsion studies of K^- absorption at the nuclear surface indicate an upward shift of some 10 MeV, [11]. Nuclear matter calculations generate an upward shift of some 50-100 MeV at central densities as a result of Pauli blocking, [9], [10],[11]. This creates the $E_{KN} - E_o < 0$ situation which results in an attractive potential.

The other resonance, $\Sigma(1385)$, coupled to the KN $I = 1$, P wave is located far below the threshold. In atomic states $\Sigma(1385)$ seems to play little role. However, in deeply bound states it becomes the dominant factor. The scattering amplitude $f_\Sigma = 2\mathbf{p}\mathbf{p}' A_\Sigma$ is given by a resonant-like volume

$$A_\Sigma = \frac{\gamma_{\Sigma KN}^2}{E_{KN} - E_\Sigma + i\Gamma_\Sigma/2}\ , \tag{3}$$

where $\mathbf{p}, \mathbf{p}'$ are the relative momenta and $\gamma_{\Sigma KN}$ is a coupling constant. The $\Sigma(1385)$ width is composed of three terms $\Gamma_\Sigma/2 = \Sigma_i\ p_i^3 \gamma_i^2(p_i^2)$ and the sum extends over the channels : $\pi\Sigma, \pi\Lambda, KN$. The resonance decays mostly (0.87 %) to the $\pi\Lambda$ channel and an experimental width of 36 MeV gives $\gamma_{\Sigma\pi\Lambda}^2$. The corresponding coupling to the KN channel is related by SU(3) $\gamma_{\Sigma KN}^2/\gamma_{\Sigma\pi\Lambda}^2 = 2/3$, while an experimental ratio of 0.51±0.18 has been obtained in K^-D capture [14]. Inside the nuclear medium f_Σ yields an optical potential

$$U_G = \overleftarrow{\nabla}\ U_\Sigma(E_{KN})\ \overrightarrow{\nabla}\ , \tag{4}$$

where $U_\Sigma = [2m_K 4\pi/(2\mu_{KN})]2\rho A_\Sigma$. It produces a dramatic effect on the kinetic energy of the meson. The dispersion law in nuclear matter becomes

$$E_K^2 - m_K^2 = p^2[1 + U_\Sigma(E_{KN})] + U_o\ , \tag{5}$$

where $E_K = m_K - E_B$. For energies E_{KN} close to, but less than E_Σ, the U_Σ term may dominate the kinetic energy and make negative the p^2 term in the dispersion formula (5). That happens for energy separations $\mid E_{KN} - E_\Sigma \mid < 140$ MeV at central nuclear densities. In the nuclear matter case it may generate a quasi-collapse which, however, is removed by the resonance denominator. An increased binding generates larger $E_{KN} - E_\Sigma$ and a weaker attraction. At the end a finite saturation energy is obtained. The latter depends on the position of E_Σ in the nuclear medium. An experiment reported at this meeting [8] indicates that it stays at its free value.

3 The K^-NNN system

In the K^-pnn situation the $\Lambda(1405)$ may be formed on the proton. Following the nuclear matter calculations we use an upward shift of some 40 MeV for the position E_o. The $\Sigma(1385)$ is formed more frequently as it involves mostly neutrons and also E_Σ is apparently not modified [8]. With the K^- bound by some 180 MeV the relative separation of the KN threshold and the $\Lambda(1405)$ position amounts to 190 MeV and an extrapolation of the scattering amplitudes to this region is necessary. The K-matrix parametrization of A.Martin[12] ($K_{NN} = -1.65 fm, R_{NN} = 0.18 fm$) is used here, but it is supplemented by a separable model of Ref.[13] to obtain a smooth subthreshold extrapolation. This procedure generates the $I = 0$ scattering amplitude of $f_0 = 1.4$ fm, a fairly standard result in this energy region. As the energy of KN is so low, the pionic decay channels are closed and the scattering amplitudes are real. For AMG the $K^-n, I = 1$ amplitude the solution from Ref. [12] is used ($K_{NN} = 1.07$ fm) which produces $f_1 = 0.34$ fm. These values generate the potential $V_o = -105$MeV (–130 MeV for K^-ppn) for a K^- at the centre of the tritium nucleus. An additional, and in fact dominant, attraction comes from the $\Sigma(1385)$. We look for the variational solution for the kaonic energy level, $\epsilon = E_K^2 - m_K^2$,

$$\epsilon = Min \int d\mathbf{r} \Psi(r)[p^2 + \overleftarrow{\nabla} U_\Sigma(E_{KN}) \overrightarrow{\nabla} + U_o]\Psi(r). \tag{6}$$

The results are given in the Table 1 with details of the test function Ψ being found in [15].

Table 1: The binding energies E_B, in MeV, of the K^-pnn and K^-ppn systems. The first line is based on the $SU(3)$ value for the $KN\Sigma(1385)$ coupling. In the second line this coupling is enhanced by 20%.

$\gamma^2_{\Sigma KN}/\gamma^2_{\Sigma\pi\Lambda}$	K^-pnn	K^-ppn
2/3	164	147
1.2*2/3	187	167

In summary:

• The $\Lambda(1405)$ and $\Sigma(1385)$ states coupled to the KN system may generate the strong binding of K^- mesons, as is observed. Such states, under normal nuclear density tend to be localised close to the nuclear centres to maximize the P-wave attraction.

• This model requires obvious refinements (1) a better knowledge of the extrapolated scattering amplitudes, (2) the value of the $\gamma_{\Sigma KN}$ coupling, (3) corrections for NNN excitations.

• This model stresses the strengths of the K^-n interaction. The search for K^-nn, K^-nnn and other objects of neutron excess could be helpful. This project is financed by the European Community Human potential Program HPRN-2002-00311 EURIDICE.

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