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Conventional view versus FINUDA claims of a deeply bound K^-pp state

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Abstract. We critically revise the recent claims of a deeply bound K^-pp state associated to a peak seen in the Λp invariant-mass spectrum following nuclear K^- absorption reactions measured by the FINUDA Collaboration. An explicit theoretical simulation shows that the peak is simply generated from a two-nucleon absorption process, like $K^-pp \to \Lambda p$, followed by final-state interactions of the produced particles with the residual nucleus.

PACS. 25.80.Nv Kaon-induced reactions – 13.75.Jz Kaon-baryon interactions – 21.45.+v Few-body systems – 21.80.+a Hypernuclei

1 Introduction

Over the last years, the study of the interactions of antikaons with nuclei has revealed many interesting aspects that have triggered various speculations on the existence of new exotic phenomena.

The possible appearance of a condensate of antikaons in neutron stars was postulated after examining the sizable attractive properties of the chiral $\bar{K}N$ interaction at tree level [1]. Phenomenological fits to kaonic atoms fed the idea because a solution where antikaons would feel strongly attractive potentials of the order of -200 MeV at the center of the nucleus [2] was preferred. However, a deeper understanding of the antikaon optical potential demands it to be linked to the elementary $\bar{K}N$ scattering amplitude which is dominated by the presence of a resonance, the $\Lambda(1405)$, located only 27 MeV below threshold. This makes the problem to be a highly non-perturbative one. In recent years, the scattering of $\bar{K}$ mesons with nucleons has been treated within the context of chiral unitary methods [3]. The explicit incorporation of medium effects, such as Pauli blocking, was shown to be important [4] and it was soon realized that the influence of the resonance demanded the in-medium amplitudes to be evaluated self-consistently [5]. The resulting antikaon optical potentials were quite shallower than the phenomenological one, with depths between -70 and -40 MeV [6], but gave an acceptable description of the kaonic atom data [7].

More recently, variational calculations of few-body systems using a simplified phenomenological $\bar{K}N$ interaction predicted extremely deep kaonic states in ^{3}He and ^{4}He, reaching densities of up to ten times that of normal nuclear matter [8,9]. Motivated by this finding, experiment KEK-E471 used the ^{4}He(stopped K^-, p) reaction and reported [10] a structure in the proton momentum spectrum, which was denoted as the tribaryon $S^0(3115)$ with strangeness $S = -1$. If interpreted as a (K^-pnn) bound state, it would have a binding energy of 194 MeV. However, in a recent work [11] strong criticisms to the theoretical claims of refs. [8,9] have been put forward and, in addition, a reinterpretation of the KEK proton peak has been given in terms of two-nucleon absorption processes, $K^-pn \to \Sigma^-p$, $K^-pp \to \Sigma^0(\Lambda)p$, where the rest of the nucleus acts as a spectator. We note that deficiencies in the efficiency corrections were revealed in the last *HYP2006 Conference*, and the new reanalyzed KEK proton momentum spectrum does not show evidence of this peak [12], although the conditions of the analysis (cuts and coincidences with other charged particles) were not the same as in the previous one. In contrast, a FINUDA proton momentum spectrum from K^- absorption on ^{6}Li [13] does show a peak, which is interpreted with the two-nucleon absorption mechanism advocated in ref. [11].

Another experiment of the FINUDA Collaboration has measured the invariant-mass distribution of Λp pairs [14]. The spectrum shows a narrow peak at 2340 MeV, which corresponds to the same signal seen in the proton momentum spectrum, namely K^- absorption by a two-nucleon

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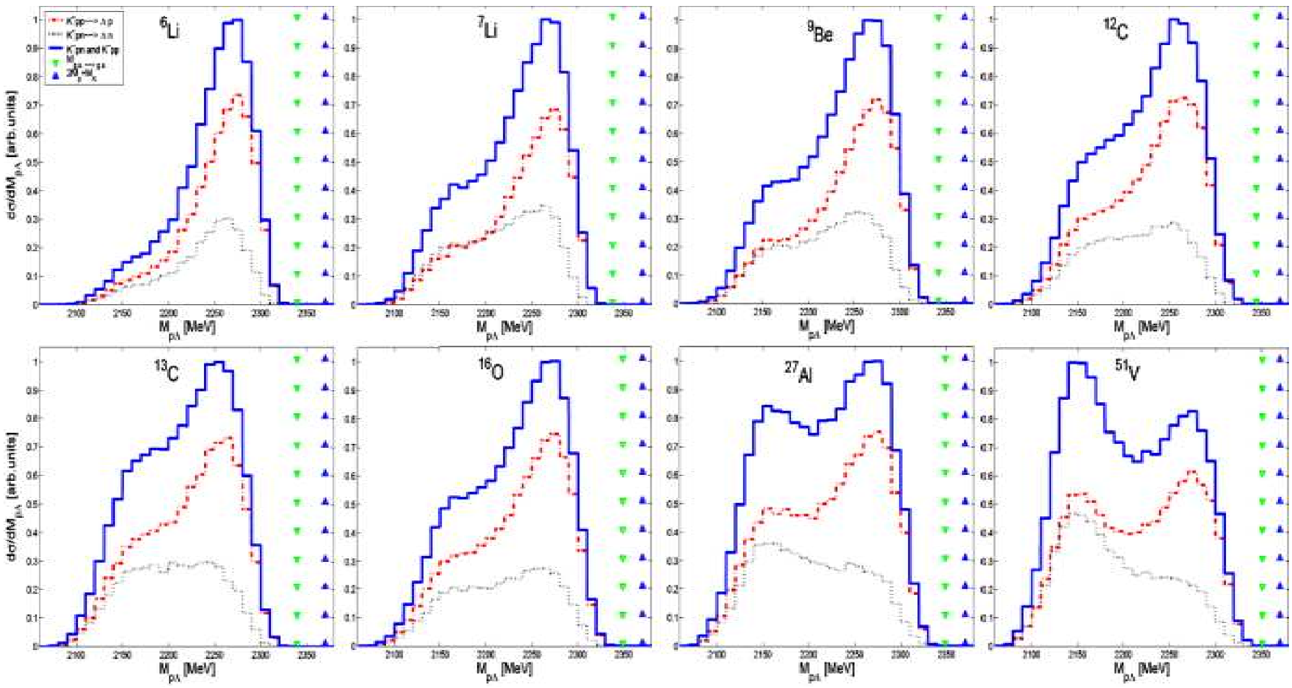

Fig. 1. Λp invariant-mass distribution after K^- absorption in several nuclei imposing $P_\Lambda > 300\,\mathrm{MeV}/c$ and $\cos\Theta_{\boldsymbol{p}_\Lambda \boldsymbol{p}_p} < -0.8$.

pair leaving the daughter nucleus in its ground state. Another wider peak is also seen at around 2255 MeV, which is interpreted in ref. [14] as being a $K^- pp$ bound state with $B_{K^- pp} = 115^{+6}_{-5}(\mathrm{stat})^{+2}_{-3}(\mathrm{syst})\,\mathrm{MeV}$ and having a width of $\Gamma = 67^{+14}_{-11}(\mathrm{stat})^{+2}_{-3}(\mathrm{syst})\,\mathrm{MeV}$. In a recent work [15] we showed that this peak is generated from the interactions of the Λ and the nucleon, produced after K^- absorption, with the residual nucleus. We here present some additional results, improved by the use of more realistic ΛN scattering probabilities, and summarize the present status of the field.

2 Theoretical model

The reaction $(K^-)_{\mathrm{stopped}}\ A \to \Lambda p A'$ proceeds by capturing a slow K^- in a high atomic orbit of the nucleus, which later cascades down till the K^- reaches a low-lying orbit, from where it is finally absorbed. We assume that the absorption of the K^- takes place from the lowest level where the energy shift for atoms has been measured, or, if it is not measured, from the level where the calculated shift [7] falls within the measurable range.

The width for K^- absorption from pN pairs in a nucleus with mass number A is given, in Local Density Approximation (LDA) by

$$\Gamma_A \propto \int \mathrm{d}^3\boldsymbol{r} |\Psi_{K^-}(\boldsymbol{r})|^2 \int \frac{\mathrm{d}^3\boldsymbol{p}_1}{(2\pi)^3} \int \frac{\mathrm{d}^3\boldsymbol{p}_2}{(2\pi)^3} \Gamma_m(\boldsymbol{p}_1, \boldsymbol{p}_2, \boldsymbol{p}_K, \boldsymbol{r}), \tag{1}$$

where $|\Psi_{K^-}(\boldsymbol{r})|^2$ is the probability of finding the K^- in the nucleus, $|\boldsymbol{p}_1|, |\boldsymbol{p}_2| < k_F(r)$ with $k_F(r) = \left(3\pi^2\rho(r)/2\right)^{1/3}$ being the local Fermi momentum and $\Gamma_m(\boldsymbol{p}_1, \boldsymbol{p}_2, \boldsymbol{p}_K, \boldsymbol{r})$ is the in-medium decay width for the $K^- pN \to \Lambda N$ process. The structure of the integrals determining Γ_m,

$$\Gamma_m \propto \int \mathrm{d}^3\boldsymbol{p}_\Lambda \mathrm{d}^3\boldsymbol{p}_N \ldots K(\boldsymbol{p}_\Lambda, \boldsymbol{r}) K(\boldsymbol{p}_N, \boldsymbol{r}), \tag{2}$$

allows us to follow the propagation of the produced nucleon and Λ through the nucleus after K^- absorption via the kernel $K(\boldsymbol{p}, \boldsymbol{r})$. The former two equations describe the process in which a kaon at rest is absorbed by two nucleons (pp or pn) within the local Fermi sea emitting a nucleon and a Λ. The primary nucleon (Λ) is allowed to re-scatter with nucleons in the nucleus according to a probability per unit length given by $\sigma_{N(\Lambda)}\rho(r)$, where $\sigma_{N(\Lambda)}$ is the experimental $NN(\Lambda N)$ cross-section at the corresponding energy, while in [15] a simpler parameterization for the Λ, of the type $\sigma_\Lambda = 2\sigma_N/3$ was employed. The angular distribution of the re-scattered particles are also generated according to experimental differential cross-sections. We note that particles move under the influence of a mean-field potential, of Thomas-Fermi type. After several possible collisions, one or more nucleons and a Λ emerge from the nucleus and the invariant mass of all possible Λp pairs, as well as their relative angle, are evaluated for each Monte Carlo event. See ref. [15] for more details.

3 The Λp invariant-mass spectrum

Absorption of a K^- from a nucleus leaving the final daughter nucleus in its ground state gives rise to a narrow peak in the Λp invariant-mass distribution, as it is observed in the spectrum of [14]. We note that our local density formalism, in which the hole levels in the Fermi sea form a continuum of states, cannot handle properly transitions to discrete states of the daughter nucleus, in particular to the ground state. For this reason, we will remove in our calculations those events in which the p and Λ produced after K^- absorption leave the nucleus without having suffered a secondary collision. However, due to the small overlap between the two-hole initial state after K^- absorption and the residual $(A-2)$ ground state of the daughter nucleus, as well as to the limited survival probability for both the p and the Λ crossing the nucleus without any collision, this strength represents only a moderate fraction, estimated to be smaller than 15% in ^{7}Li [15]. This means, in practice, that the excitation of the nucleus will require the secondary collision of the p or Λ after the K^-pp absorption process, similarly as to what happens in (p,p') collisions, where the strength of the cross-section to elastic or bound excited states is very small compared to that of nuclear breakup producing the quasi-elastic peak.

Our invariant-mass spectra requiring at least a secondary collision of the $p(n)$ or Λ after the $K^-pp(np)$ absorption process are shown in fig. 1 for several nuclei, where we have applied the same cuts as in the experiment, namely $P_\Lambda > 300\,\mathrm{MeV}/c$ (to eliminate events from $K^-p \to \Lambda\pi$) and $\cos\Theta_{\boldsymbol{p}_\Lambda \boldsymbol{p}_p} < -0.8$ (to filter Λp pairs going back-to-back). Actually, the calculated angular distribution shown in ref. [15] demonstrates that, even after collisions, a sizable fraction of the events appear at the back-to-back kinematics. These events generate the main bump at 2260–2270 MeV in all the Λp invariant-mass spectra shown in fig. 1, about the same position as the main peak shown in the inset of fig. 3 of [14]. We note that, since one measures the Λp invariant mass, the main contribution comes from $K^-pp \to \Lambda p$ absorption (dot-dashed lines), although the contribution from the $K^-pn \to \Lambda n$ reaction followed by $np \to pn$ (dotted line) is non-negligible. It is interesting to observe that the width of the distribution gets broader with the size of the nucleus, while the peak remains in the same location, consistently to what one expects for the behavior of a quasi-elastic peak. Let us point out in this context that the work of [16] shows that the possible interpretation of the FINUDA peak as a bound state of the K^- with the nucleus, not as a K^-pp bound state, would unavoidably lead to peaks at different energies for different nuclei. We finally observe that the spectra of heavy nuclei develop a secondary peak at lower invariant masses due to the larger amount of re-scattering processes. It is slightly more pronounced than that shown in our earlier work [15], due to the use here of a realistic ΛN scattering cross-section.

In summary, we have seen how the experimental Λp invariant-mass spectrum of the FINUDA Collaboration [14] is naturally explained in our Monte Carlo simulation as a consequence of final-state interactions of the particles produced in nuclear K^- absorption as they leave the nucleus, without the need of resorting to exotic mechanisms like the formation of a K^-pp bound state. Together with the interpretation of the proton momentum spectrum given in refs. [11,13], it seems then clear that there is at present no experimental evidence for the existence of deeply bound kaonic states. Theoretically, a major step forward has been given by recent few-body calculations, either solving Faddeev equations [17] or applying variational techniques [18], using realistic $\bar{K}N$ interactions and short-range nuclear correlations. These works predict few-nucleon kaonic states bound by 50–70 MeV but having large widths of the order of 100 MeV, thereby disclaiming the findings of refs. [8,9]. It remains to be explored whether the larger attraction expected in much heavier kaonic nuclear systems is enough to block the decaying channels, thus opening the possibility of narrow, hence measurable, deeply bound kaonic states.

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References

1. D.B. Kaplan, A.E. Nelson, Phys. Lett. B **175**, 57 (1986); **179**, 409 (1986)(E).
2. E. Friedman, A. Gal, C.J. Batty, Nucl. Phys. A **579**, 518 (1994).
3. N. Kaiser, P.B. Siegel, W. Weise, Nucl. Phys. A **594**, 325 (1995); E. Oset, A. Ramos, Nucl. Phys. A **635**, 99 (1998); J.A. Oller, U.G. Meissner, Phys. Lett. B **500**, 263 (2001); M.F.M. Lutz, E.M. Kolomeitsev, Nucl. Phys. A **700**, 193 (2002); C. Garcia-Recio, J. Nieves, E. Ruiz Arriola, M.J. Vicente Vacas, Phys. Rev. D **67**, 076009 (2003); D. Jido, J.A. Oller, E. Oset, A. Ramos, U.G. Meissner, Nucl. Phys. A **725**, 181 (2003); B. Borasoy, R. Nissler, W. Weise, Eur. Phys. J. A **25**, 79 (2005); J.A. Oller, J. Prades, M. Verbeni, Phys. Rev. Lett. **95**, 172502 (2005).
4. V. Koch, Phys. Lett. B **337**, 7 (1994).
5. M. Lutz, Phys. Lett. B **426**, 12 (1998).
6. A. Ramos, E. Oset, Nucl. Phys. A **671**, 481 (2000).
7. S. Hirenzaki, Y. Okumura, H. Toki, E. Oset, A. Ramos, Phys. Rev. C **61**, 055205 (2000); A. Baca, C. Garcia-Recio, J. Nieves, Nucl. Phys. A **673**, 335 (2000).
8. Y. Akaishi, T. Yamazaki, Phys. Rev. C **65**, 044005 (2002).
9. Y. Akaishi, A. Dote, T. Yamazaki, Phys. Lett. B **613**, 140 (2005).
10. T. Suzuki *et al.*, Phys. Lett. B **597**, 263 (2004).
11. E. Oset, H. Toki, Phys. Rev. C **74**, 015207 (2006).
12. M. Iwasaki, invited talk at the *IX International Conference on Hypernuclear and Strange Particle Physics, Mainz, October 10-14, 2006*.
13. FINUDA Collaboration (M. Agnello *et al.*), Nucl. Phys. A **775**, 35 (2006).
14. FINUDA Collaboration (M. Agnello *et al.*), Phys. Rev. Lett. **94**, 212303 (2005).
15. V.K. Magas, E. Oset, A. Ramos, H. Toki, Phys. Rev. C **74**, 025206 (2006).
16. J. Mares, E. Friedman, A. Gal, Nucl. Phys. A **770**, 84 (2006).
17. N.V. Shevchenko, A. Gal, J. Mares, Phys. Rev. Lett. **98**, 082301 (2007).
18. A. Dote, contributed talk at the *IX International Conference on Hypernuclear and Strange Particle Physics, Mainz, October 10-14, 2006*.