Kaon absorption in flight and the binding of $\bar{K}$ in nuclei.

E. Oset*, V.K. Magas, A. Ramos†, J. Yamagata-Sekihara** and S. Hirenzaki‡

*Dep. de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Apartado 22085, 46071 Valencia, Spain
†Departament d’Estructura i Constituents de la Materia, Universitat de Barcelona, Diagonal 647, 08028 Barcelona, Spain
**Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan
‡Department of Physics, Nara Women’s University, Nara 630-8506, Japan

Abstract. We make a theoretical study of the kaon absorption in flight on nuclei with a kaon beam of 1 GeV momentum, paying special attention to the forward and energetic emitted protons, which were used to claim a deep kaon nucleus optical potential in a recent experiment. We perform a Monte Carlo simulation of this reaction, which allows to account not only for quasi-elastic $K^-p$ scattering, but also for the other processes which contribute to the proton spectra and which are not taken into account by the ordinary Green’s function method analysis. The experiment looks for fast protons, but in coincidence with at least one charged particle in a decay counters sandwiching the target. The coincidence requirement is assumed not to distort the shape of the proton spectra, but we show that this is not the case and as a consequence the conclusions drawn from the experimental analysis do not hold.

Keywords: Kaon-nucleon interaction, Monte Carlo simulations, antikaon absorption in nuclei

The issue of the kaon interaction in the nucleus has stimulated much work in recent years. From the study of kaon atoms one knows that the $K^-\text{-nucleus}$ potential is attractive [2], however, there is a strong debate over how attractive it is, and whether it can accommodate deeply bound kaon atoms (kaonic nuclei), which could be observed in direct reactions.

Chiral unitary dynamics has brought some light into the issue and all modern potentials based on this dynamics for the $KN$ interaction [3, 4, 5, 6, 7] lead to moderate potentials of the order of 60 MeV attraction at normal nuclear density. In addition, they also have a large imaginary part, making the width of the bound states much larger than the energy separation between the levels, which would rule out the experimental observation of these states.

Deep $K^-\text{-N}$ optical potentials are preferred by the phenomenological fits to kaon atoms data. But a best fit to all data of $K^-\text{ atoms}$ conducted in [8] concludes that an excellent agreement with the data can be obtained with small changes of the order of 20 % in the theoretical potential of [4]. One of the extreme cases of these type is a highly attractive phenomenological potential with about 600 MeV strength in the center of the nucleus, introduced in [9, 10]. In these picture such an attractive $K^-$ leads to a shrinkage of the nucleus, generating a new very compact object - kaonic nucleus - with central density about ten times larger than normal nuclear density. Such super-deep potentials were criticized in [11, 12, 13, 14]. They are also ruled out by the new precise experiment of the $^4\text{He}K^-\text{ atom}$ in [15].

Several claims of observed deeply bound $K^-$ states have been made. However the first one, about $K^-\text{ pnn}$ state bound by 195 MeV from the experiment at KEK [16], is now withdrawn after a new more precise experiment [17]. Originally a narrow peak was reported in [16] which was associated to kaon absorption by two nucleons in [11]. This latter paper predicted that the peak should be seen in medium size nuclei and gradually disappear for heavier nuclei, and this was confirmed in [18]. The revision of the experiment of [16] in [17], showed that the original peak became a broad bump, in agreement with the estimated theoretical width reported in [13, 14].

The peaks seen by FINUDA and originally interpreted in terms of deeply bound $K^-\text{ pp}$ [19] and $K^-\text{ pnn}$ [20] clusters, are now put under the question, because in Refs. [21, 22, 23, 24] these peaks found explanations based on conventional reactions that unavoidably occur in the process of kaon absorption.

There is however one more experiment where the authors claim the evidence for a strong kaon-nucleons potential, with a depth of the order of 200 MeV [1]. The experiment looks for fast protons emitted from the absorption of in flight kaons by $^{12}\text{C}$ in coincidence with at least one charge particle in a decay counters sandwiching the target. The data analysis in [1] is based on the assumption that the coincidence requirement does not change the shape of the final spectra. But we have seen that this assumption doesn’t hold and the interpretation of the data requires a more thorough
One of the limitations of Ref. [1] comes from using the Green's function method [25] to analyze the data. The only mechanism considered in Ref. [1] for the emission of fast protons is the $\bar{K}p \to \bar{K}p$ process, taking into account the optical potential for the slow kaon in the final state. However, there are other mechanisms that contribute to generate fast protons, like multi-scattering reactions, and kaon absorption by one nucleon, $K^-N \to \pi \Sigma$ or $K^-N \to \pi \Lambda$ or by a pair of nucleons, $\bar{K}NN \to \Sigma N$ and $\bar{K}NN \to \Lambda N$, followed by decay of $\Sigma$ or $\Lambda$ into $\pi N$. The contributions from these processes were also suggested in Ref. [26].

In a recent paper [27], we take into account all the above mentioned reactions by means of a Monte Carlo simulation [28]. The select the reaction which occurs at a certain point in the nucleus one chooses a step size $\delta l$ and calculates, by means of $\sigma_\rho \delta l$, the probabilities that any of the possible reactions takes place $i = \text{Quasi-elastic, } 1N \text{ absorption, } 2N \text{ absorption}; \rho$ is nucleon density. The size of $\delta l$ is small enough such that the sum of probabilities that any reaction occurs is reasonably smaller than unity. A random number from 0 to 1 is generated and a reaction occurs if the number falls within the corresponding segment of length given by its probability. If the random number falls outside the sum of all segments then this means that no reaction has taken place and the kaon is allowed to proceed one further step $\delta l$. This procedure is iterated till all the produced particles leave the nucleus. To adapt the calculations to the experimental of [1] we select "good events" with fast protons that emerge within an angle of 4.1 degrees in the nuclear rest frame (lab frame). As in [1] we plot our obtained $^{12}\text{C}(K^-,p)$ spectrum as a function of a binding energy of the kaon, $E_B$, should the process correspond to the trapping of a kaon in a bound state and emission of the fast proton.

If there is a quasi-elastic collision at a certain point, then the momentum of the $K^-$ and that of the nucleon, which is randomly chosen within the Fermi sea, are boosted to their CM frame. The direction of the scattered momenta is determined according to the experimental cross section. A boost to the lab frame determines the final kaon and nucleon momenta. The event is kept if the final nucleon momentum is larger than the local Fermi momentum. We also take into account secondary collisions and consider the reaction $K^-p \to K^0n$ and $K^-n \to K^-n$ with their corresponding cross sections.

Once primary nucleons are produced they are also followed through the nucleus taking into account the probability that they collide with other nucleons, losing energy and changing their direction, see [21, 22, 23, 24] for more details.

We also follow the rescattered kaon on its way through the nucleus. In the subsequent interaction process we let the kaon experience whichever reaction of the three that we consider (quasi-elastic, one-body absorption, two-body absorption) according to their probabilities. This procedure continues until kaon is absorbed or leaves of the nucleus.

Apart from following the kaons and nucleons, our calculations also need to consider the quasi-elastic scattering of $\Lambda$'s and $\Sigma$'s (produced in the kaon absorption reactions) on their way through the residual nucleus. Given the uncertainties in the hyperon-nucleon cross sections, we may use for $\Sigma N$ scattering the relation $\sigma_{\Sigma N} = 2\sigma_{NN}/3$, based on a simple non-strange quark counting rule. In the case of $\Lambda N$ scattering, we use the refined parameterization of Ref. [29], as was also done in Ref. [23].

One nucleon $K^-$ absorption leads to $K^-N \to \pi \Lambda$ or $K^-N \to \pi \Sigma$, with all the possible charge combinations. The elastic and inelastic two-body $\bar{K}N$ cross sections for kaons are taken from the Particle Data Group [30].

The kaon absorption by two nucleons requires further work. For this one takes into account the following processes: $K^-NN \to \Lambda N$ or $K^-NN \to \Sigma N$ with all possible charge combinations. In these reactions an energetic nucleon is produced, as well as a $\Lambda$ or a $\Sigma$. Both the nucleon and the hyperon are followed through the nucleus as discussed above. Once out of the nucleus, the hyperons are let to decay weakly into $\pi N$ pairs. Therefore, the two-body absorption process provides a double source of fast protons, those directly produced in two nucleon absorption reaction and those coming from hyperon decays.

We assume a total two body absorption rate to be 20% that of one body absorption at about nuclear matter density, something that one can infer from data of $^4\text{He}$ [31].

The different partial processes that can take place in a two-nucleon absorption reaction are: $K^-pp \to p\Lambda$, $p\Sigma^0$, $n\Sigma^+$; $K^-pn \to n\Lambda$, $n\Sigma^0$, $p\Sigma^-$; $K^-nn \to n\Sigma^-$. In the work of [27] one assigns equal probability to each of the above reactions, a sufficiently realistic approach for the limited contribution of these process. However, by noting that the chance of the kaon to find a $pn$ pair is twice as large as that for $pp$ or $nn$ pairs, we finally assign a probability of 3/10 for having a $p\Sigma$ pair in the final state, 4/10 for $n\Sigma$, 1/10 for $p\Lambda$ and 2/10 for $n\Lambda$.

We also take into account a kaon optical potential $V_{\text{opt}} = \text{Re}V_{\text{opt}} + i \text{Im}V_{\text{opt}}$, which will influence the kaon propagation through the nucleus, especially when it will acquire a relatively low momentum after a high momentum transfer quasi-elastic collision. In the present study we take the strength of the potential as predicted by chiral models: $\text{Re}V_{\text{opt}} = -60\rho/\rho_0$ MeV [3, 4, 5, 6, 7]; $\text{Im}V_{\text{opt}} \approx -60\rho/\rho_0$ MeV, as in the experimental paper [1] and the theoretical study of [4].
In the Monte Carlo simulation we implement this distribution by generating a random kaon mass $\tilde{M}_K$ around a central value, $M_K + \text{Re} V_{\text{opt}}$, within a certain extension determined by the width of the distribution $\Gamma_K = -2\text{Im} V_{\text{opt}}$. The probability assigned to each value of $\tilde{M}_K$ follows the Breit-Wigner distribution given by the kaon spectral function:

$$S(M_K) = \frac{1}{\pi} \frac{(\tilde{M}_K - M_K - 2M_K \text{Re} V_{\text{opt}})^2 + (2M_K \text{Im} V_{\text{opt}})^2}{\Gamma_K^2}.$$  

In Fig. 1 we show the results of the Monte Carlo simulation obtained with an optical potential $V_{\text{opt}} = (-60,-60)\rho/\rho_0$ MeV: first, taking into account only quasi-elastic processes; and then taking into account all the discussed mechanisms. We can see that there is some strength gained in the region of "bound kaons" due to the new mechanisms. Although not shown separately in the figure, we have observed that one nucleon absorption and several rescatterings contribute to the region $-E_B > -50$ MeV. To some extent, this strength can be simulated by the parametric background used in [1]. However, this is not true anymore for the two nucleon absorption process, which contributes to all values of $-E_B$, starting from almost as low as $-300$ MeV.

As mentioned above, in the spectrum of [1] the outgoing forward protons were measured in coincidence with at least one charged particle in the decay counters which surround the target.

Although we are studying many processes and following many particles in our Monte Carlo simulation, which is not the case in the Green function method used in the data analysis [1], we cannot fully simulate precisely the real coincidence effect.

However, we can do a good approximate job by eliminating the processes which, for sure, will not produce a coincidence, this can be called minimal coincidence requirement. If the kaon in the first quasi-elastic scattering produces an energetic proton falling into the peaked region of the spectra, then the emerging kaon will be scattered backwards. In our Monte Carlo simulations we can select events were neither the proton, nor the kaon will have any further reaction after such a scattering. In these cases, although there is a "good" outgoing proton, there are no charged particles going out with the right angle with respect to the beam axis to hit the decay counter, since the $K^-$ escapes undetected in the backward direction. Therefore, this type of events must be eliminated for comparison with the experimental spectra.

It is clear from Fig. 1 that the main source of the energetic protons for $^{12}\text{C}(K^-, p)$ spectra is $K^-$ $p$ quasi-elastic scattering, however many of these events will not pass the coincidence condition. Implementing the minimal coincidence requirement, as discussed above, we will cut off a substantial part of the potentially "good" events, and drastically change the form of the final spectrum, as illustrated in Fig. 2.

To further simulate the coincidence requirement we introduce additional constant suppression factors to the obtained spectrum - see Fig. 3. Comparing our results with the experimental data we can conclude that in the "bound" region, $-E_B < 0$ MeV, these additional suppression is about $\sim 0.7$ and more or less homogeneous, while in the continuum the suppression weakens and for $-E_B > 50$ MeV it is negligible. This picture is natural from the physical point of view, because the r.h.s. of the spectrum, Fig. 3, with relatively low momentum protons is mostly populated by many particle final states, which have a good chance to score the coincidence.
FIGURE 2. Calculated $^{12}\text{C}(K^-, p)$ spectra with $V_{\text{opt}} = (-60, -60)\rho/\rho_0$ MeV taking into account all contributing processes (dash-dotted line). Then we impose minimal coincidence requirement (full line). Data points are from [1].

FIGURE 3. Calculated $^{12}\text{C}(K^-, p)$ spectrum with $V_{\text{opt}} = (-60, -60)\rho/\rho_0$ MeV with minimal coincidence requirement - solid line; and with additional suppression factors - dash-dotted and dotted lines. Experimental points are from [1].

Although due to the limitations to implement theoretically the coincidence requirement we cannot state that the data of Ref. [1] supports $\text{Re} V_{\text{opt}} = -60\rho/\rho_0$ MeV rather than $-200\rho/\rho_0$, one certainly can conclude that this experiment is not appropriate for extracting information on the kaon optical potential. Indeed, contrary to what is assumed in Ref. [1], we clearly see, Fig. 2, that the spectrum shape is largely affected by the required coincidence. Since the shape of this spectrum, without normalization, was used in Ref. [1] to make the claims for a deep kaon potential, we can certainly state here that these claims were unfounded. The experimental data without the coincidence requirement would be a more useful observable, although, as we have mentioned, there are many processes which contribute to the proton spectra and some uncertainties will inevitably have to be assumed.

Acknowledgments. This work is partly supported by the contracts FIS2006-03438, FIS2008-01661 from MICINN (Spain), by CSIC and JSPS under the Spain-Japan research Cooperative program, and by the Generalitat de Catalunya contract 2009SGR-1289. We acknowledge the support of the European Community-Research Infrastructure Integrating Activity “Study of Strongly Interacting Matter” (HadronPhysics2, Grant Agreement n. 227431) under the Seventh Framework Programme of EU. J.Y. is a Yukawa Fellow and this work is partially supported by the Yukawa Memorial Foundation.
REFERENCES