The $(K^-,p)$ reaction on $^{12}$C at KEK

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We study the $(K^-,p)$ reaction on $^{12}$C with a kaon beam of 1 GeV momentum, paying a special attention to the region of emitted protons having kinetic energy above 600 MeV, which was used to claim a deep kaon nucleus optical potential [1]. The experiment looks for fast protons emitted from the absorption of in flight kaons by nuclei, but in coincidence with at least one charged particle in the decay counters sandwiching the target. The analysis of the data is done in [1] assuming that the coincidence requirement does not change the shape of the final spectra. However our detailed calculations show that this assumption doesn’t hold, and, thus, the final conclusion of this experiment is doubtful.

We perform Monte Carlo simulation of this reaction. The advantage of our method with respect to Green’s function method used in [1] is that it allows to account not only for quasi-elastic $K^-p$ scattering, but also for the other processes which contribute to the proton spectra. We investigated the effect of the multi-scatterings and of the $K^-$ absorptions by one and two nucleons ($K^-N \rightarrow \pi Y$ and $K^-NN \rightarrow YN$) followed by the decay of the hyperon in $\pi N$. We show that all these mechanisms allow us to explain reasonably well the observed spectrum with standard shallow kaon nucleus optical potential, obtained in chiral models.

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The issue of the kaon interaction in the nucleus has attracted much attention in past years. Although from the study of kaon atoms one knows that the $K^-$-nucleus potential is attractive [2], the discussion centers on how attractive the potential is and whether it can accommodate deeply bound kaon atoms (kaonic nuclei), which could be observed in direct reactions.

All modern potentials based on underlying chiral dynamics of the $KN$ interaction [3, 4, 5, 6, 7] lead to moderate potentials of the order of 60 MeV attraction at normal nuclear density. 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 $K^-$-N optical potentials are preferred by the phenomenological fits to kaon atoms data. One of the most known extreme cases of these type is a highly attractive phenomenological potential with about 600 MeV strength in the center of the nucleus, introduced in [8, 9]. In these picture such an attractive $K^-$, inserted inside the nucleus, would lead to a shrinkage of the nucleus, generating a new very compact object - kaonic nucleus - with central density which can be 10 times larger than normal nuclear density. Such superdeep potentials were criticized in [10, 11, 12, 13].

It is important to keep in mind that in kaon atoms the $K^-$ is primary bound by the Coulomb force. These are extended systems, and therefore their properties cannot directly tell us about the $K^-$-N potential at short distances. From the experimental side the search for bound $K^-$ states with nucleons is a most direct and clear way to
answer whether the $K^-$-nucleon potential is deep or shallow, because only deep potential may generate states sufficiently narrow to be observed experimentally. Experimental attempts to resolve this situation are made since 2004, but the situation is still very unclear.

Several claims of observed deeply bound $K^-$ states have been made. However the first one, about $K^-pnn$ state bound by 195 MeV from the experiment at KEK [14], is now withdrawn after a new more precise experiment [15]. The peaks seen by FINUDA and originally interpreted in terms of deeply bound $K^-pp$ [16] and $K^-pnn$ [17] clusters, are now put under the question, because in Refs. [18, 19, 20, 21] these peaks found explanations based on conventional reactions that unavoidably occur in the process of kaon absorption.

There are also claims (with very low statistical significance) of $K^-pp$ and $K^-ppn$ bound states from $\bar{p}$ annihilation in $^4$He at rest measured by OBELIX@CERN [22]. And the recent claim of $K^-pp$ bound state, seen in $pp \to K^+X$ reaction, from DISTO experiment [23]. These experimental claims are under investigation now. Before calling in new physics one has to make sure that these data cannot be explained with conventional mechanisms.

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 $^{12}$C in coincidence with at least one charge particle in the 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. We shall see that this assumption doesn’t hold and the interpretation of the data requires a more thorough approach than the one used in that work.

One of the shortcomings of Ref. [1] stems from employing the Green’s function method [24] 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. We shall show that there are other mechanisms that contribute to generate fast protons, namely 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. [25].

In the present work, we take into account all the above mentioned reactions by means of a Monte Carlo simulation [26]. The election of which reaction occurs at a certain point in the nucleus is done as usual. One chooses a step size $\delta l$ and calculates, by means of $\sigma_\rho \delta l$, the probabilities that any of the possible reactions happens $i = \text{Quasi-elastic, } 1N \text{ absorption, } 2N \text{ absorption; } \rho$ 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 $\delta l$. The simulation of one event is over when all the produced particles leave the nucleus. To adapt the calculations to the experiment 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 $^{12}$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 as long as the size of the nucleon momentum is larger than the local Fermi momentum. Since we take into account secondary collisions we also consider the reaction $K^-p \to K^0 n$ 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 [18, 19, 20, 21] 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 Λ’s and Σ’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 ΣN scattering the relation $\sigma_{\Sigma N} = 2\sigma_{NN}/3$, based on a simple non-strange quark counting rule. In the case of ΛN scattering, we use the refined parameterization of Ref. [27], as was also done in Ref. [21].

One nucleon $K^-$ absorption leads to $K^-N \rightarrow \pi\Lambda$ or $K^-N \rightarrow \pi\Sigma$, with all possible charge combinations. The elastic and inelastic two-body $KN$ cross sections for kaons are taken from the Particle Data Group [28].

The kaon absorption by two nucleons is a bit more tricky. Here we take into account the following processes: $K^-NN \rightarrow \Lambda N$ or $K^-NN \rightarrow \Sigma N$ with all possible charge combinations. In these reactions an energetic nucleon is produced, as well as a Λ or a Σ. 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 $K^-$ absorption in $^4$He [29]. In practice, this is implemented in the following way. The probability per unit length for two nucleon absorption is proportional to the square of the nucleon density: $\mu_{K^-NN}(\rho) = C_{abs}\rho^2$. We assume that $\mu_{K^-NN}(\rho) = C_{abs}(\rho^2) = 0.2\mu_{K^-N}$, $0.2\sigma_{K^-N}^{tot}$ accounts for the total one nucleon absorption cross section and, in symmetric nuclear matter it is given by: $\sigma_{K^-N}^{tot} = (\sigma_{K^-p}^{tot} + \sigma_{K^-n}^{tot} - \sigma_{K^-p-K^-n}^{tot} - \sigma_{K^-K^-n-K^-n})/2$. Taking $\langle\rho\rangle = \rho_0/2$, where $\rho_0 = 0.17$ fm$^{-3}$ is normal nuclear matter density, we obtain $C_{abs} \approx 6$ fm$^5$.

The different partial processes that can take place in a two-nucleon absorption reaction are: $K^-pp \rightarrow p\Lambda$, $p\Sigma^0$, $n\Sigma^+$; $K^-pn \rightarrow n\Lambda$, $n\Sigma^0$, $p\Sigma^-$; $K^-nn \rightarrow n\Sigma^-$. Ideally, their corresponding branching ratios should be obtained from relevant microscopic mechanisms, however in the present exploratory work, we will consider a much simpler approach consisting of assigning equal probability to each of the above reactions. 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 $V_{\text{opt}} = ReV_{\text{opt}} + i\text{Im}V_{\text{opt}}$, 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: $ReV_{\text{opt}} \approx -60\rho/\rho_0$ 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 $M_K$ around a central value, $M_K + ReV_{\text{opt}}$, 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 $M_K$ follows

![FIG. 1: Calculated $^{12}C(K^-,p)$ spectra with $V_{\text{opt}} = (-60,-60)\rho/\rho_0$ MeV, taking into account only quasi-elastic processes (dash-dotted line), and including all the contributing processes (full line).](image)

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the Breit-Wigner distribution given by the kaon spectral function:

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

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.

It is very important to keep in mind that in the spectrum of [1] the outgoing forward protons were measured in coincidence with at least one charged particle in the decay counters sandwiching the target. Obviously, the real simulation of such a coincidence experiment is tremendously difficult, practically impossible with high accuracy, because it would require tracing out all the charged particles coming out from all possible scatterings and decays. 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 simulate precisely the real coincidence effect.

The best we can do is to eliminate 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 a 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 \(^{12}C(K^-, p)\) 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.

To conclude, the main point of our analysis is not to state that the data of Ref. [1] supports \( \text{Re} V_{\text{opt}} = -60\rho/\rho_0 \) MeV rather than \(-200\rho/\rho_0\). We want to make it clear that trying to simulate these data one necessarily introduces large un-
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![Graph](image)

**FIG. 3:** Calculated \(^{12}\)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].

Contrary to what it is assumed in Ref. [1], we clearly see, Fig. 2, that the spectrum shape is affected by the required coincidence. The experimental data without the coincidence requirement would be a more useful observable.

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