The (K^-, p) reaction on nuclei with in-flight kaons

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Abstract

We perform a theoretical study of the spectrum of protons with kinetic energies of around 600 MeV, emitted following the interaction of 1 GeV/c kaons with nuclei. A recent experimental analysis of this (K^-, p) reaction on ^{12}C, based on the dominant quasielastic process, has suggested a deeply attractive kaon nucleus potential. Our Monte Carlo simulation considers, in addition, the one-and two-nucleon K^- absorption processes producing hyperons that decay into πN pairs. We find that this kaon in-flight reaction is not well suited to determine the kaon optical potential due, essentially, to the limited sensitivity of the cross section to its strength, but also to unavoidable uncertainties from the coincidence requirement applied in the experiment. A shallow kaon nucleus optical potential obtained in chiral models is perfectly compatible with the observed spectrum.

Key words: (K^-, p) reaction, antikaon optical potential, deeply bound antikaon states
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1. Introduction

The study of the interactions of antikaons with nuclei has received much attention in past years. Although kaonic-atom data favor an attractive K^--nucleus interaction [1, 2], the discussion centers on whether it can accommodate deeply bound antikaon states which could be observed in direct reactions. Potentials based on underlying chiral dynamics of the kaon-nucleon interaction [3, 4, 5, 6, 7] show a moderate attraction of the order of 60 MeV at nuclear matter density and have a sizable imaginary part, which would rule out the experimental observation of peaks. Nevertheless, the theoretical shallow potentials reproduce satisfactorily data of kaonic atoms [8], and best fits including an additional phenomenological component [9] indicate deviations of at most 20% from the theoretical potential of [4]. Recently, the lightest $\bar{K}NN$ system has also been the subject of strong debate [10, 11, 12, 13].

At the other extreme, highly attractive phenomenological potentials having a strength of about 600 MeV at the center of the nucleus, leading to nuclear densities ten times that of normal nuclear matter, and favoring the existence of deeply bound kaon nuclear states, have been advocated [14, 15], but have received strong criticisms [16, 17, 18]. Furthermore, the claimed experimental evidences of deeply bound states using *stopped* kaon reactions at KEK [19] and FINUDA [20, 21] have to be looked at with caution, especially after the reanalysis of the KEK

experiment [22] which makes it consistent with the spectra measured in [23], interpreted there on the basis of the two-nucleon absorption mechanism pointed out in [16]. The calculations of Refs. [24, 25] explain also the FINUDA peaks [20, 21] in terms of conventional two- and three-nucleon absorption mechanisms, consistently with recent KEK data [26, 27].

There is yet another experiment, measuring fast protons emitted from the reaction of *in flight* kaons with nuclei [28], from which evidence for a very strong kaon-nucleus potential, with a depth of the order of 200 MeV, was claimed. The data was analyzed in terms of the Green's function method of Refs. [29, 30, 31] considering only the dominant quasielastic $K^- p \to K^- p$ process. In this contribution we will show that one- and two-nucleon absorption reactions also contribute to the spectrum, the shape of which is, moreover, strongly affected by the experimental coincidence requirements, making this reaction not well suited to extract information on the depth of the kaon optical potential.

2. Monte Carlo simulation of the (K^-, p) reaction

Our Monte Carlo simulation of the (K^-, p) reaction [32, 33] considers the nucleus as a density distribution of nuclear matter, through which the kaon and all other produced particles propagate. As sources of fast protons we consider the quasielastic processes ($\bar{K}N \to \bar{K}N$), as well as kaon absorption by one nucleon ($\bar{K}N \to \pi\Lambda$, $\bar{K}N \to \pi\Sigma$) or two nucleons ($\bar{K}NN \to \Sigma N$ and $\bar{K}NN \to \Lambda N$), followed by the weak decay of the Σ or the Λ into πN pairs. Each reaction occurs according to the probability $\sigma_i \rho(r) \delta l$ (i = qe, 1N, 2N), where $\rho(r)$ is the local density and δl a small enough step size. The values of the cross sections, taken from the Particle Data Group [34], are explicitly listed in Ref. [32].

In case of a quasielastic collision, the direction of the scattered kaon and nucleon is determined according to the experimental differential cross section, checking always that the size of the nucleon momentum is larger than that of the local Fermi sea. The nucleon then propagates through the nucleus colliding with other nucleons, losing energy, changing its direction, and generating new secondary nucleons. The rescattered kaon is also followed, letting it experience different interaction mechanisms (scattering or absorption) according to their respective probabilities. In one-nucleon absorption processes of the type $K^- N \to \pi\Lambda$ and $K^- N \to \pi\Sigma$, we let the Λ or the Σ propagate undergoing quasielastic collisions with the nucleons and, once they leave the nucleus, they are allowed to decay weakly into πN pairs, providing in this way a source of protons in the energy region of interest. The simulation also accounts for two-nucleon absorption processes $K^- NN \to \Lambda N$ or $K^- NN \to \Sigma N$ with all possible charge combinations. According to ⁴He data [35], the probability per unit length for two-nucleon absorption, $\mu_{K^- NN} \equiv C_{\text{abs}} \rho^2$, is taken to be 20% that of one-body absorption, which determines a value $C_{\text{abs}} \simeq 6$ fm⁵. The two-body absorption reactions provide a double source of fast protons, those produced directly in the absorption process and those coming from the decay of the hyperon into πN pairs.

We also implement the effect of a kaon optical potential, $V_{\text{opt}} = \text{Re} V_{\text{opt}} + \text{i} \text{Im} V_{\text{opt}}$, which will influence the kaon propagation, especially after a high momentum transfer quasi-elastic collision when the kaon will acquire a relatively low momentum.

At the end of the simulation, we keep the events containing a proton in a kinetic energy range of $500 - 700$ MeV, within an angle of 4.1 degrees in the lab frame, as in the experiment. To facilitate comparison with experiment, the missing invariant mass is translated into a kaon binding energy, E_B, according to:

$$\sqrt{(E_K + M_{^{12}\text{C}} - E_p)^2 - (\vec{P}_p - \vec{P}_K)^2} = M_{^{11}\text{B}} + M_K - E_B \,, \tag{1}$$

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where $E_p, \vec{P}_p$ are the energy and momentum of the observed proton and $E_K, \vec{P}_K$ are the energy and momentum of the initial kaon.

3. Results and Discussion

Our results for an optical potential $V_{\text{opt}} = (-60, -60)\rho/\rho_0$ MeV are shown in Fig. 1, including only quasi-elastic reactions (dash-dotted line) and considering also one- and two-nucleon absorption processes (solid line). A non-negligible amount of strength is gained in the region of "bound kaons" due to the new mechanisms. Although not shown separately, we find that one-nucleon absorption and multi-scattering processes contribute to the region $-E_B > -50$ MeV whereas the two-nucleon absorption reactions contribute to all values of $-E_B$, starting from values as low as -300 MeV.
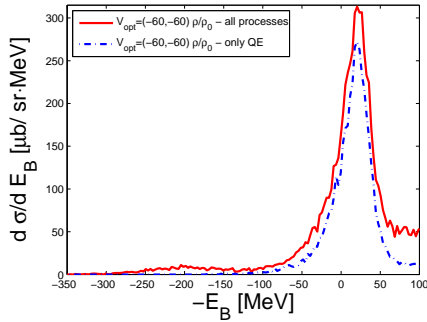

Fig.1. Proton spectra for quasi-elastic processes (dash-dotted line), and including all processes (solid line), using $V_{\text{opt}} = (-60, -60)\rho/\rho_0$ MeV.
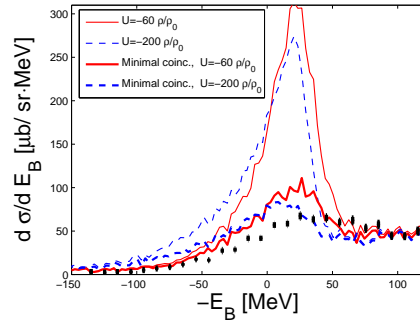
Fig. 2. Proton spectra without (thin lines) and with (thick lines) the minimal coincidence requirement, using $V_{\text{opt}} = (-60, -60)\rho/\rho_0$ MeV (solid lines) and $V_{\text{opt}} = (-200, -60)\rho/\rho_0$ MeV (dashed lines). Experimental data are from [28].

We must keep in mind that the outgoing forward protons were measured in coincidence with at least one charged particle in the decay counters surrounding the target [28] and the analysis assumed the shape of the spectrum not to change under that requirement. Whereas a detailed simulation of these experimental conditions is prohibitive, we can at least study their consequences by applying a minimal coincidence requirement [32, 33], which eliminates the events that, for sure, will not produce a coincidence. These are the ones that, after a primary quasi-elastic collision producing a fast forward proton and a backward kaon, neither particle suffer any further reaction and, therefore, no charged particle will have the chance of hitting the decay counters. This minimal coincidence requirement changes the shape of the spectrum considerably, as seen in Fig. 2 upon comparing the bare spectrum obtained with a kaon potential depth of 60 MeV (solid thin line) with that obtained after the coincidence cut (solid thick line). The distribution becomes wider because many "good events" generated from the dominant quasielastic processes are eliminated. The figure also shows the spectra corresponding to a potential depth of 200 MeV, before (dashed thin line) and after the minimal coincidence cut (dashed thick line). We clearly see that the sensitivity of the bound region to the optical potential is essentially lost when the coincidence requirement is applied.

We finally note that our implementation of the experimental conditions should actually lead to a spectrum that overshoots the data, as it keeps some events that might not produce a coincidence signal. The amount of discrepancy should be smaller or inexistent in the continuum region, populated by lower momentum protons produced in many particle final states, which have a better chance of hitting the decay counters. Having this in mind, the spectrum obtained with a kaon nucleus potential of $V_{\text{opt}} = (-60, -60)\rho/\rho_0$ MeV is compatible with the experimental data, as one can see in Fig. 2.

Our results demonstrate the limited capability of the (K^-, p) reaction with in-flight kaons to infer the depth of the kaon optical potential. On the one hand, there are more processes beyond quasielastic reactions that populate the spectrum in the region of interest and, on the other hand, large uncertainties are introduced when trying to simulate the conditions of the experimental set up [28]. Contrary to what it is assumed in the analysis of Ref. [28], we have clearly seen that the spectrum shape is affected by the required coincidence. Certainly, the bare spectrum would be a much more valuable observable to learn about the kaon nucleus optical potential.

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