RPA calculation of $K^+$-nucleus
cross-sections with a density-dependent
Brueckner-Hartree-Fock NN interaction

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Abstract

In the calculation of the $K^+$-nucleus cross sections, the coupling of the mesons exchanged between the $K^+$ and the target nucleons to the polarization of the Fermi and Dirac seas has been taken into account. This polarization has been calculated in the one-loop approximation but summed up to all orders (RPA approximation). For this calculation a density-dependent Brueckner-Hartree-Fock NN interaction providing a good description of both nuclear matter and finite nuclei has been used. The agreement with experiment is considerably improved.
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These last years, significant progress have been made towards a better understanding of the properties of both nuclear matter and finite nuclei starting from a free-space nucleon-nucleon interaction. Using a relativistic Brueckner-Hartree-Fock theory with a one-boson-exchange potential where coupling constants and form factors were obtained from the NN scattering data, Brockmann and Machleidt\cite{1} reproduced the saturation properties of nuclear matter nearly quantitatively. The scalar and vector fields they obtained have then been introduced as input in a relativistic density-dependent Hartree approach for finite nuclei by Brockmann and Toki\cite{2} who obtained a good agreement with experiment for both the binding energy and the mean-square radius in $^{16}O$ and $^{40}Ca$. This result solves an old outstanding problem of nuclear physics.

Another longstanding problem is the continuing discrepancy between experimental results and theoretical predictions for $K^+$-nucleus total cross-sections. Since the $K^+$ interact very weakly (at the hadronic scale) with nucleons\cite{3}, they reach the dense central regions of nuclei and thus should be sensitive to the in-medium modifications of the nucleons and mesons.

Different types of such medium effects have been studied. Historically, the first one has been the swelling of the nucleons in nuclear matter\cite{4}. This possible swelling has then been related to a decreasing of the mesons effective mass in the cloud around the nucleon core. This scaling of the mesons mass with density leads to improved $K^+$-nucleus cross sections\cite{3, 5}. Let us mention that an improvement has also been obtained, but to a lesser extent, taking into account the
decreasing of the nucleon effective mass by the scalar nuclear field in the target, decreasing which modifies the KN amplitude in the medium[7].

The second type of medium effects which has been considered is the possibility for the $K^+$ to scatter on the mesons exchanged between the target nucleons[8, 9]. Although these calculations seem not completely under control since the exchanged mesons are well off-shell[10], they seem to lead also to a small improvement[8].

About these medium effects, the most important arises from the modification of the properties of the mesons exchanged between the $K^+$ and the target nucleons. Since they are well off-mass-shell, it is not sufficient to consider that the only modification in their propagation is the change of their effective mass. For example, since they are space-like, they can produce particle-hole excitations, and thus acquire also a width. To go beyond this effective mass approximation, we can consider that, at the hadronic level, this modification of the mesons propagation in nuclear matter arises from the coupling of these mesons with particle-hole and nucleon-antinucleon excitations. Since the interaction is strong, this coupling must be summed up to all orders and thus the choice of the NN interaction which will be used is very important if we want the final result might have a chance to be realistic. The question arises if the relativistic Brueckner-Hartree-Fock interaction we spoke about, which reproduces the properties of nuclear matter and finite nuclei, could also give a good description of the polarization of nuclear matter (at least in the region of small energy-momentum transfer) and thus lead to improved $K^+$-nucleus cross-sections.
In this work, we have calculated the $K^+$-nucleus cross-sections using a KN amplitude in which the mesons exchanged are coupled to the polarization of the medium in the RPA approximation. This polarization has been obtained using the relativistic Brueckner-Hartree-Fock NN interaction of Brockmann and Machleidt[1].

We have analyzed these effects on the ratio $R_T$ of $K^+-^{12}C$ to $K^+-d$ total cross sections which has been measured[11, 12, 13] from 400 MeV/c to 900 MeV/c.

$$R_T = \frac{\sigma_{tot}(K^+-^{12}C)}{6 \cdot \sigma_{tot}(K^+-d)}$$  \hspace{1cm} (1)

As emphasized by many authors, this ratio is less sensitive to experimental and theoretical uncertainties than, for example, differential cross sections, and thus more transparent to the underlying physics.

The total $K^+$-nucleus cross section has been obtained from the forward scattering amplitude using the optical theorem. The optical potential we used to calculate the $K^+$-nucleus amplitude has been built by folding the in-medium KN amplitude by the nuclear density. The point-like proton distribution of the $^{12}C$ nucleus required in the present analysis is that deduced, after the proton finite-size correction has been made, from the electron-scattering charge density of Sick and McCarthy[14] and we have chosen equal n and p-distributions. For the $K^+$-nucleon amplitude in free space, we have used here the full Bonn boson exchange model[13] which is actually one of the more elaborate descriptions of
the KN interaction. In nuclear matter, this amplitude has been modified in order to take into account the coupling of the $\sigma$ and $\omega$ mesons, whose exchange provides the dominant part of the medium-range KN interaction, to the polarization of the Fermi and Dirac seas. This polarization, calculated in the one-loop approximation, has been summed up to all orders in the mesons propagators (RPA approximation) using the NN interaction of Brockmann and Machleidt. Details of the method will appear elsewhere\cite{16}. The heavier particles exchanged lead to very short-ranged processes less influenced by the nuclear environment. A Pauli blocking for the nucleon intermediate states has been introduced in the integral equation generating the in-medium KN amplitude from the boson-exchange kernel. For the calculation of the $K^+$-deuteron cross section, since the densities involved are small\cite{17} and since in a nucleus made up of two nucleons it is not possible to excite more than one particle-hole pair, we have used the free-space KN interaction. To be consistent, we have thus also used the free-space KN interaction in the $K^{+}$-$^{12}C$ calculation for densities lower than half the saturation density and we have verified that a variation of this cutoff around this value doesn’t change significantly the results.

The ratio $R_T$ obtained when the polarization of the nuclear medium is taken into account as indicated above, is shown fig.1, curve b. We can see that this effect is important since the $R_T$ ratio is now, in average, $\sim 5\%$ higher than that calculated using the free-space KN interaction (curve a) and that the agreement with experiment is considerably improved over the full energy range. We have
used here the potential B of ref.\cite{1} for the NN interaction but potentials A and C lead to very similar results.

Therefore, it seems that the relativistic Brueckner-Hartree-Fock NN interaction obtained by Brockmann and Machleidt from a free-space boson exchange model, which gives a good description of nuclear matter and of finite nuclei, leads also to a polarization of nuclear matter good enough to reproduce realistically the dressing of the $\sigma$ and $\omega$ mesons, at least in the small energy-momentum space-like region which is the dominant one for forward projectile-nucleus scattering.

To our knowledge, this is the first time that such an agreement for the $R_T$ ratio is obtained from a fully microscopic (at the hadronic level) calculation. We believe that this result, obtained without any free parameter, clearly shows that the main part of the physical content of the $K^+\text{-nucleus}$ interaction in the forward direction has been understood.
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Figure captions

Fig.1: Ratio $R_T$ of the $K^+ - ^{12}C$ and $K^+ - d$ total cross sections as a function of $p_{lab}$ calculated, curve (a): with the free-space $K^+ N$ interaction, curve (b): with a density-dependent $K^+ N$ interaction taking into account the coupling of the $\sigma$ and $\omega$ mesons with the polarization of nuclear matter calculated in the RPA approximation. The experimental points are taken from ref.[11] (squares), from ref.[12] (circles) and from ref.[13] (triangles).
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