MESONIC EXCHANGE CURRENT CONTRIBUTION TO K^+ NUCLEUS SCATTERING*

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A microscopical many-body calculation of the self-energy of a positive kaon interacting with a nucleus is carried out for kinetic energies T_K up to 500 MeV. On top of the well known contribution of the impulse approximation, we have considered the kaon coupling to the pions in the nucleus. Previous approximations for the pionic cloud contribution, specially on the imaginary part, are shown to be inadequate. We also find and evaluate new contributions to the imaginary part from the pionic cloud which were not previously considered. The results for the total and differential cross sections are satisfactory after these new contributions are included, but uncertainties remain in the real part.

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1. Introduction

The diffusion of positive kaons by nuclei has been experimentally carried out recently [1, 2]. There have been theoretical attempts [3, 4] to explain the experimental differential cross-sections in terms of the KN scattering amplitudes, nuclear distributions of nucleons in nuclei considering Pauli corrections and nuclear correlations. But it looks like systematic discrepancies remain despite those efforts. Some attempts have been done at explaining the discrepancies as a consequence of an increased size of the nucleons in the nucleus [3, 5].

A recent paper [6] pointed out that the interaction of the kaon with the modified pionic cloud surrounding the nucleons in nuclei is responsible for those discrepancies. Estimations of such effects on the kaon selfenergy show a qualitative improvement of the agreement between data and calculation. Ref. [6] approximates the effect as the kaon-pion $t_{K\pi}$-matrix (evaluated at certain average values for kinematic variables) times the excess number of pions in nuclei. There the excess number of pions has been taken from previous works [7] in nuclear matter. Recently a work by Jiang and Koltun [8] has analyzed more carefully the contribution of the excess of pions in the nucleus to the kaon-nucleus scattering. In that work a certain momentum distribution of pions in the nucleus is assumed, and a $t_{K\pi}$-matrix depending on momentum is considered, then the kaon-selfenergy is obtained by integrating over all three-momenta. This is an improvement over previous works, but still a static approximation is made for the $t_{K\pi}$-matrix to be able to factorize the pion three-momentum distribution. We show that this approximation is not justified when the available phase space is properly taken into account. In Section 2 we discuss the standard meson exchange current (MEC) contribution, already considered in [6, 8]. In Section 3, new MEC contributions are considered. Finally in Section 4, calculations are presented for the differential and total cross sections.

The two main novelties of the present work with respect to that of Jiang and Koltun are: first that in the latter work the pion energy is set to zero in $t_{K\pi}$, whereas in our case the pion energy dependence is explicitly taken into account. And second, we have found new relevant mechanisms which enhance the contribution of the pion cloud. The details will be presented elsewhere [9].

2. Standard MEC contribution to K^+-nucleus selfenergy

The standard MEC contribution to the K^+-nucleus optical potential or self-energy is shown in the diagram in Fig. 1. There the incoming K^+ interacts with a pion of the nuclear medium. This contribution is dealt with in nuclear matter and applied to finite nuclei through a local density approximation. The contribution of the excess of pions to the kaon selfenergy in nuclear matter is given by

$$\Pi_K(k) = \frac{3}{2} i \int \frac{d^4q}{(2\pi)^4} \left[D_\rho(q) - D_0(q) - \rho \left(\frac{\partial D_\rho(q)}{\partial \rho} \right)_{\rho=0} \right] t_{K\pi}(k,q;k,q) \tag{1}$$

$t_{K\pi}(k,q)$ is the $t_{K\pi}$-matrix corresponding to a kaon with four-momentum $(k^0, \vec{k})$ and a pion with four-momentum $(q^0, \vec{q})$. D_ρ is the full pion propagator in a nuclear medium of density ρ, whereas D_0 is the free pion propagator. In the pion propagator we have included the pion selfenergy coming from ph and Δh excitations as well as the short range correlations among these, accounted for by the phenomenological Landau parameter g'. Note the combination $D_\rho - D_0 - \rho D'_0$ appearing in the kaon selfenergy. The part independent of the density, D_0, is already included in the kaon mass and hence it has been subtracted. Similarly the part linear in the nuclear density, $\rho D'_0$, is included in the impulse approximation. There are large cancellations due to these subtractions in the pion propagator.

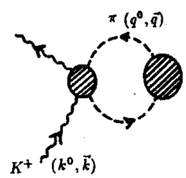

Fig. 1

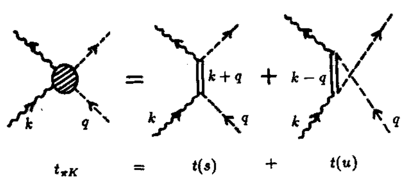

Fig. 2

We deal with the calculation of the selfenergy by taking into account the analytical properties of propagators and $t_{K\pi}$-matrix. As a result, the imaginary part of the self-energy is given by integrals in a finite range of energy and momentum, which is convenient for its numerical evaluation. This is not the case for the real part.

The pion propagator satisfies the following dispersion relation:

$$D_\rho(q^0, \vec{q}) = \int_0^\infty d\omega \frac{-2\omega}{\pi} \frac{\text{Im}\, D_\rho(\omega, \vec{q})}{q^{0\,2} - \omega^2 + i\varepsilon}. \tag{2}$$

For the $t_{K\pi}$-matrix we have used the model of Ref. [8], which (for the case of momentum transfer zero) has the structure:

$$t_{K\pi}(k,q;k,q) = t(s) + t(u), \qquad s = (k+q)^2, \qquad u = (k-q)^2\,, \tag{3}$$

as represented in Fig. 2. Then, $t(x)$ verifies the following subtracted dispersion relation [10]:

$$t(x) = P(x) + (x - x_0) \int_{x_0}^{\infty} \frac{dx'}{\pi} \frac{\mathrm{Im}\; t(x')}{(x - x' + i\varepsilon)(x_0 - x' + i\varepsilon)}\,, \tag{4}$$

where $P(x)$ is a polynomial of real coefficients and $x_0 = (m_K + m_\pi)^2$. Using these explicit analytical structures in Eq. (1) and doing integrations in energies in the complex plane, we obtain an expression of the kaon selfenergy only in terms of Im D_ρ, Im t and P. The result for the imaginary part is:

$$\mathrm{Im}\,\Pi_K(k) = -3 \int \frac{d^3\vec{q}}{(2\pi)^3} \int_0^{k^0 - E(x_0)} \frac{dq^0}{\pi} \mathrm{Im}\left[D_\rho(q) - D_0 - \rho\left(\frac{\partial D_\rho}{\partial \rho}\right)_0\right] \mathrm{Im}\, t(u), \tag{5}$$

with $E(x_0) = \sqrt{x_0 + (\vec{k} - \vec{q})^2}$. Note that for the imaginary part, *i.e.* the reaction channels of the kaon optical potential, the pion energy q^0 is restricted to the interval $0 < q^0 < k^0 - E(x_0)$, since Im $t(u) = 0$ for $u < x_0$. The static approximation, by neglecting the q^0 dependence in $t_{K\pi}$, allows the q^0 integral to go up to ∞, hence introducing unphysical contributions. Note also that the $t_{K\pi}$-matrix in the integral no longer depends on s but only on the u variable.

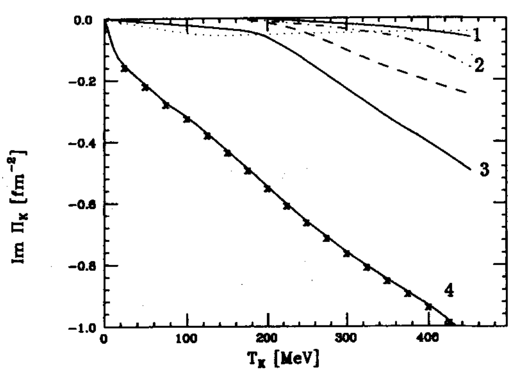

Fig. 3

In Fig. 3 we present the imaginary part of the K^+ selfenergy as a function of its kinetic energy for normal nuclear density $\rho = \rho_0$. The solid curve labeled by 1 is the exact calculation of the diagram in Fig. 1. Curve 2 shows the same diagram using the static approximation. They differ by an approximate factor of two.

3. New MEC contributions to the K$^+$-nucleus selfenergy

We observe that Im $t(u)$ comes from the process $K\pi \to K\pi$ in the u-channel. So the imaginary part of diagram of Fig. 1 is the imaginary part of the diagram $d1a$ of Fig. 4. But the pion which is hidden in Im $t_{K\pi}$ has also a self-energy which should be taken into account. Actually both pions in the process $K \to K\pi\pi$ can be modified by the medium. To account for this up to second order in density, we have considered the contributions of all the diagrams in Fig. 4.

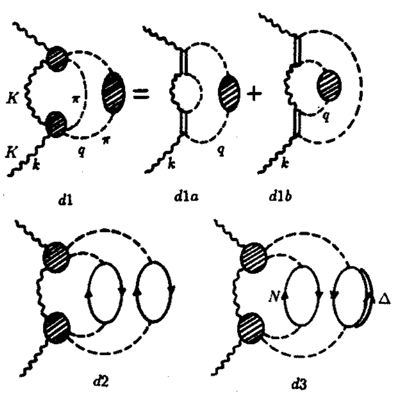

Fig. 4

Diagram $d1 = d1a + d1b$ corresponds to the process $K \to K\pi ph$, with threshold $T_K > m_\pi$. Diagram $d2$ corresponds to $K \to Kphph$, so its threshold is $T_K > 0$. Diagram $d3$ corresponds to $K \to Kph\pi ph$ (where $\pi ph \equiv \Delta h$) and it is allowed for $T_K > m_\pi$. So we have the new contributions $d1b$, $d2$ and $d3$ to be added to the "standard" one $d1a$.

The imaginary part is quadratically dependent on ρ, and we can write for finite nuclei:

$$\text{Im}\,\Pi_K^{MEC}(\vec{r}) = \text{Im}\,\Pi_K^{MEC}(\rho_0)\left(\frac{\rho(\vec{r})}{\rho_0}\right)^2 , \tag{6}$$

where Im $\Pi_K^{MEC}(\rho_0)$ is calculated in nuclear matter at density ρ_0, which only depends on kaon energy.

In Fig. 3, curve 3 shows the total MEC contributions The total result is about seven times larger that the only contribution which had been previously considered, although as discussed above this contribution was then overestimated. Curve 4 displays, for comparison, the impulse approximation contribution to Im Π_K.

We do not discuss the real part here because its energy and momentum integration range is not bound and thus the result depends strongly on the values of the $t_{K\pi}$-matrix for large and off-shell four-momenta. By using several off-shell extrapolations, results for the real part where obtained in Ref. [8] which differed by a factor of 5. In our approach we can not avoid having the same uncertainties as in Ref. [8] Given these large uncertainties in the terms induced by MEC, we have restricted ourselves to the impulse approximation for the real part.

4. Results

We have solved the Klein-Gordon equation for a K^+ scattered by a nucleus using the K^+ selfenergy given by the impulse approximation (IA) and the one including IA plus the pionic cloud effects (IA+MEC).

The differential cross-section for a K^+ with kinetic energy of 450 MeV scattered by a nucleus of ^{40}Ca is presented in Fig. 5. The dashed line corresponds to IA, the solid line to IA+MEC, with MEC effects as calculated in previous section. The Coulomb effects have not been included. The improvement due to MEC effects is surprising. Similar results are found for K^+ over ^{12}C, [9]. The experimental data are taken from Ref. [11].

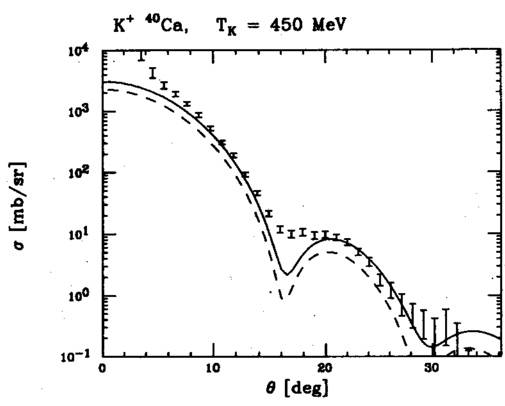

Fig. 5

The total cross-sections for different energies of the K^+ over ^{12}C are shown in Fig. 6. The data with a cross are from Ref. [2], the data with a

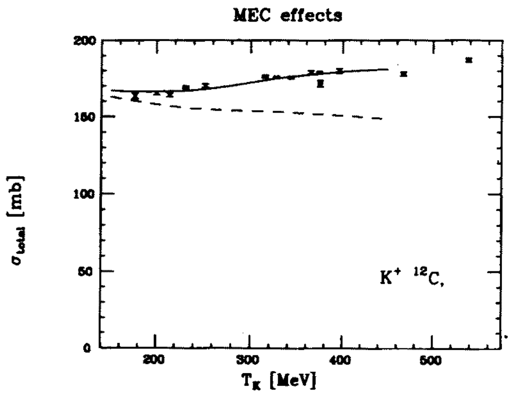

Fig. 6

circle are from Ref. [12]. The dashed line presents the results with IA, and the solid line comes from IA plus MEC effects on the imaginary part of K^+ selfenergy. The agreement of experiment with the calculation of IA+MEC is remarkably good. This suggests that the real part from MEC and other sources should be small. The verification of this is an interesting problem which is completely open.

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