The kaon optical potential modified by $\Theta^+$ Pentaquark excitation

D. Cabrera\footnote{1}, L. Tolós\footnote{2}, A. Ramos\footnote{3}, and A. Polls\footnote{3}

1Cyclotron Institute and Physics Department, Texas A&M University, College Station, Texas 77843-3366, USA.
2Gesellschaft für Schwerionenforschung, Planckstrasse 1, D-64291 Darmstadt, Germany.
3Departament d’Estructura i Constituents de la Matèria, Universitat de Barcelona, Diagonal 647, 08028 Barcelona, Spain.

Received: date / Revised version: date

Abstract. We study the kaon nuclear optical potential including the effect of the $\Theta^+$ pentaquark in a self-consistent approach, starting from an extension of the Jülich meson-exchange potential as bare kaon-nucleon interaction. Significant differences between a fully self-consistent calculation and the low-density $T\rho$ approximation are observed. Whereas the influence of the $K\pi$ system is neglected due to the small $\Theta^+ K\pi$ coupling, the two-nucleon mechanism ($KNN \rightarrow \Theta^+ N$), estimated from the two-meson coupling of the pentaquark, provides the necessary additional kaon absorption to reconcile with data the systematically low theoretical $K^+$ nuclear reaction cross sections.

PACS. 13.75.Jz – 25.75.-q – 21.30.Fe – 21.65.+f – 12.38.Lg – 14.40.Ev – 25.80.Nv

1 Introduction

The possible existence of the $\Theta^+$ pentaquark with positive strangeness $^{1,2}$ and a very small width has attracted renewed interest on the properties of the $K N$ interaction $^{1,2,3,4}$. The medium properties of kaons are of particular interest as they are considered suited probes of the hot and dense matter created in heavy ion collisions and of partial restoration of chiral symmetry in dense matter. The in-medium $K N$ interaction, believed to be smooth in the absence of baryonic resonances with $S = +1$, has been usually implemented in a $T\rho$ approximation, leading to a repulsive single-particle kaon potential of around 30 MeV at normal nuclear matter density $\rho_0$ ($^{5,6,7,8}$) (the more recent self-consistent approach in $^7$ showing a kaon mass shift of 36 MeV at $\rho = \rho_0$). However, calculations of the kaon optical potential based on the $T\rho$ approximation share a common lack of success in reproducing $K^+$–nucleus total and reaction cross sections (see $^8$ and references therein), underestimating the data by about 10–15%, a problem which remains unsolved although a wide variety of mechanisms has been explored $^{9,10,11,12}$.

In this work we start by comparing the $T\rho$ approximation of the kaon optical potential to a fully self-consistent approach, starting from an extension of the Jülich meson-exchange potential as bare kaon-nucleon interaction $^{13}$. The latter, based on the Jülich meson-exchange model including the coupling of the $\Theta^+$ to the $K N$ system $^{13}$, allows us to investigate the changes on the kaon optical potential due to the one-nucleon induced excitation of the $\Theta^+$ in the medium. In addition, following the suggestion of $^{13}$, in which substantially improved fits to the data were obtained by incorporating $K^+$ absorption by nucleon pairs ($KNN \rightarrow \Theta^+ N$), we evaluate a microscopic calculation of this mechanism according to the model of Ref. $^{14}$ for the $\Theta^+$ interaction with a $K\pi$ cloud, where the pion couples to particle-hole ($ph$) and Delta-hole ($\Delta h$) excitations, and the kaon optical potential and obtain improved $K^+$ nuclear cross sections in close agreement with the experimental data $^{15}$.

2 In-medium $K N$ interaction

We evaluate the in-medium $K N$ interaction in a $G$–matrix approach, including Pauli blocking on the nucleonic intermediate states and the dressing of the $K$ meson and nucleon. Schematically,

$$\langle KN | G | KN \rangle = \langle KN | V | KN \rangle + \langle KN | V | KN \rangle \frac{Q_{KN}}{\Omega - E_K - E_N + i\eta} \langle KN | G | KN \rangle.$$  \hspace{1cm} (1)

The bare interaction, $V$, is obtained from the meson-exchange Jülich model for $K N$ scattering with a $\Theta^+$ pole term $^{13}$. The $\Theta^+$ bare mass and coupling to $K N$ are chosen as to reproduce the physical $\Theta^+$ mass and a width of 5 MeV in free space (widths higher than a few MeV have been excluded by recent analysis of the $K^+ N$ and $K^+ d$ data $^{16,17,18,19}$). The kaon single-particle energy in Eq. (1) is obtained self-consistently as $E_K(q;\rho) = \sqrt{m_K^2 + q^2} + \text{Re} \ U_K(E_K, q; \rho)$, with $U_K$ the complex single-particle potential which, in the Brueckner–Hartree–Fock approach, is given by

$$U_K(E_K, q; \rho) = \sum_{N \leq F} \langle KN | G_{KN \rightarrow KN} (\Omega = E_N + E_K) | KN \rangle,$$  \hspace{1cm} (2)
Gin absence of the coupling to $\Theta$ Kaon absorption from $T\rho$

as diagrammatically represented in Fig. 1. The nucleon single-particle energies are taken from a relativistic $\sigma - \omega$ model with density-dependent scalar and vector coupling constants [20], which provides an attraction of $-80$ MeV at saturation density.

We show in Fig. 2 the kaon optical potential at $\rho = \rho_0$ in absence of the coupling to $\Theta^+$, for the self-consistent $G$-matrix calculation and a $T\rho$ approximation (replacing $G$ in Eq. 2 by the free amplitude $T$). The latter, which ignores in-medium effects on the $KN$ interaction as well as on the $K, N$ energies, leads to a kaon optical potential (at zero momentum) 10 MeV less repulsive than the $G$-matrix result, which amounts to 39 MeV. The imaginary part of the potential indicates kaon widths of about 18 MeV at about 400 MeV/c momentum. The selfconsistent implementation of medium effects generates relevant features of the $KN$ interaction which reflect on the kaon properties in the nuclear medium in comparison with the $T\rho$ approximation.

3 Kaon absorption from $\Theta^+$ excitation

Turning on the $KN\Theta^+$ coupling incorporates the effect of one-body $\Theta^+$ excitation in the effective $KN$ interaction. Interestingly, the $G$-matrix exhibits the expected structure associated to the $\Theta^+$ with practically unchanged properties (mass and width) up to $\rho = \rho_0$ as compared to the free $T$-matrix amplitude, except for the in-medium modified $KN$ threshold. This result is highly non-trivial since the properties of the $\Theta^+$ in this approach result from multiple rescattering in the $T$-matrix equation and interference between the polar and non-polar terms of the $KN$ interaction. The selfconsistent kaon optical potential (Fig. 8) exhibits rather small changes (starting above 300 MeV/c momentum) from the $KN \rightarrow \Theta^+$ mechanism, which is related to a small $KN\Theta^+$ coupling (as implied by the small $\Theta^+$ width).

The kaon optical potential may also receive contributions from the two-nucleon process $KNN \rightarrow \Theta^+ N$ which can be realized from the $\Theta^+$ coupling to $K\pi$ with subsequent absorption of the pion by a $ph$ or $\Delta h$ excitation (Fig. 3). The $\Theta^+ K\pi N$ coupling was evaluated in a study of the two-meson cloud effects on the baryon antidecuplet binding in vacuum [14] and latter applied in a calculation of the $\Theta^+$ self-energy in nuclear matter [21]. Its contribution to the kaon optical potential can be obtained from the kaon self-energy diagram in Fig. 1 (right),

$$\Pi_{KN}(q^0, q; \rho) = i \int \frac{d^4k}{(2\pi)^4} \left[ D_\pi^{(0)}(k) \right]^2 \Pi_{\rho}(k; \rho) \times (-9) \sum_{j=S,V} | t^{(j)}(k, q) |^2 U_\rho(q - k; \rho), \quad (3)$$

where $D_\pi^{(0)}(k)$ is the free pion propagator, $\Pi_{\rho}(k; \rho)$ stands for the $ph + \Delta h$ contribution to the pion self-energy including short range correlations, $U_\rho(q - k; \rho)$ represents the pentaquark-hole Lindhard function and $t^{(j)}$ denotes the scalar ($S$) and vector ($V$) $\Theta^+ K\pi N$ amplitudes [14]. The contribution of this mechanism to the imaginary part of the kaon optical potential is shown in Fig. 8 as a function of the density for a kaon momentum of 500 MeV/c, exhibiting the expected $\rho^2$ dependence of a two-nucleon process and a significant size, comparable to the one-nucleon mechanisms depicted in Fig. 2.

4 $K$-nucleus cross section

We calculate kaon nuclear cross sections in the eikonal formalism according to

$$\sigma = \int d^2b \left[ 1 - \exp \left( -\int_{-\infty}^{\infty} -\frac{1}{q} \Im \Pi(q; \rho(b, z)) dz \right) \right], \quad (4)$$

where $\Pi$ is given by the two-nucleon component of the kaon self-energy ($\Pi_{KN}^{(2)}$) for the absorption cross section ($\sigma_{abs}$), or by the total self-energy including as well the contribution of the one-nucleon mechanisms for the reaction cross section ($\sigma_R$), respectively. In Fig. 6 the calculated cross sections per nucleon in $^6$Li, $^{12}$C, $^{28}$Si and $^{40}$Ca are compared to experimental data. The results for $\sigma_R/A$ from the $G$-matrix calculation of the kaon optical potential including the one-nucleon $\Theta^+$ excitation mechanism underestimate the data by about 15% (dashed lines). On the other hand, the absorption cross sections per nucleon obtained from the 2N mechanism (Figs. 4 and 5) are about 2-3 mb, right below the upper bound of 3.5 mb established.
The kaon optical potential modified by $\Theta^+$ Pentaquark excitation

**Fig. 3.** Kaon optical potential for $\frac{0}{2}^+\rho_0$ (left panels) and $\rho_0^+$ (right panels), without $\Theta^+$ (dashed lines) and including a $\Theta^+$ resonance with a width of 5 MeV (solid lines).

**Fig. 4.** Two-nucleon kaon absorption mechanism by excitation of $\Theta^+$ (left) and corresponding manybody diagram (right).

**Fig. 5.** Imaginary part of the two-nucleon contribution to the kaon optical potential as a function of the density for a kaon momentum of 500 MeV/c.

in Ref. [13]. The reaction cross sections per nucleon obtained with the complete imaginary part of the kaon self-energy, including both the one- and two-nucleon processes, lie very close to the experimental data (upper solid line). Our model for the two-nucleon kaon absorption mechanism provides the required strength to bring the reaction cross sections in agreement with experiment, thereby giving a possible answer to a long-standing anomaly in the physics of kaons in nuclei.

**5 Acknowledgments**

We thank J. Haidenbauer for providing us with the extended Jülich code, and L. Roca and M.J. Vicente-Vacas for fruitful discussions. L.T. acknowledges support from the Alexander von Humboldt Foundation and D.C. from Ministerio de Educación y Ciencia (Spain). This work is partly supported by DGICYT contract BFM2002-01868, the Generalitat de Catalunya contract SGR2001-64, and the E.U. EURIDICE network contract HPRN-CT-2002-00311. This research is part of the EU Integrated Infrastructure Initiative Hadron Physics Project under contract number RI3-CT-2004-506078.

**References**

1. T. Nakano et al. [LEPS Collaboration], Phys. Rev. Lett. 91, 012002 (2003).
2. www.rcnp.osaka-u.ac.jp/~hyodo/research/Thetapub.html
3. J. Haidenbauer and G. Krein, Phys. Rev. C 68, 052201 (2003).
4. A. Sibirtsev et al., Phys. Lett. B 599, 230 (2004); *ibid* Eur. Phys. J. A23, 491 (2005).
5. N. Kaiser et al., Nucl. Phys. A 594, 325 (1995); N. Kaiser et al., Nucl. Phys. A 612, 297 (1997).
6. E. Oset and A. Ramos, Nucl. Phys. A 635, 99 (1998).
7. C. L. Korpa and M. F. M. Lutz, Acta Phys. Hung. A 22, 21 (2005).
8. E. Friedman et al., Phys. Rev. C 55, 1304 (1997); E. Friedman et al., Nucl. Phys. A625, 272 (1997).
9. P.B. Siegel et al., Phys. Rev. C 30, 1256 (1984); P.B. Siegel et al., Phys. Rev. C 31, 2184 (1985).
10. G.E. Brown et al., Phys. Rev. Lett. 60, 273 (1988).
11. M.F. Jiang and D.S. Koltun, Phys. Rev. C 46, 2462 (1992).
12. C. Garcia-Recio et al., Phys. Rev. C 51, 237 (1995).
13. A. Gal and E. Friedman, Phys. Rev. Lett. 94, 072301 (2005); *ibid* Phys. Rev. C 73 (2006) 015208.
14. A. Hosaka et al., Phys. Rev. C 71, 045205 (2005).
15. L. Tolos et al., Phys. Lett. B 632 (2006) 219.
16. D. Diakonov et al., Z. Phys. A 359, 305 (1997).
17. S. Nussinov, arXiv [hep-ph/0307357]
18. R. A. Arndt et al., Phys. Rev. C 68, 042201 (2003).
19. W. R. Gibbs, Phys. Rev. C 70, 045208 (2004).
20. R. Machleidt, Adv. Nucl. Phys. 19, 189 (1989).
21. D. Cabrera et al., Phys. Lett. B 608 (2005) 231.