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GROSS PROPERTIES OF THE PION- AND KAON-NUCLEUS INTERACTION*

E. FRIEDMAN

Racah Institute of Physics, The Hebrew University
Jerusalem 91904, Israel

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Gross properties of the interaction of pions, K^+ and K^- with nuclei are reviewed. The pion-nucleus interaction below 200 MeV is related to the mean free path of pions in nuclei and the difference between the region below and above 50 MeV is emphasized. At zero energy the 'missing' s-wave repulsion in pionic atoms is still an open problem. Kaonic atoms have been analysed with a density dependent interaction that connects smoothly at low densities to the repulsive interaction expected for free nucleons. Total cross sections for K^+ nucleus interaction have been analysed with various prescriptions and improved fits have been obtained when an explicit p-wave term is included and the s-wave term is enhanced in the nuclear medium.

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1. Introduction

In this talk I will present a brief survey of some gross properties of the interaction of pions and kaons with nuclei. With well over a decade of intensive operation of the three "pion factories" (LAMPF, PSI/SIN and TRIUMF) there is a wealth of experimental results that enable very detailed analysis. The richness of the observed phenomena makes it natural to split the topic of pion–nucleus interactions into several sub topics, and the present talk will be confined to gross properties of the pion-nucleus interaction. Consequently the talk will not cover applications where the quantum numbers of the pion make it a selective probe of nuclear processes nor will it include single and double charge exchange reactions. Likewise, the present

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talk will not deal with the various unique excitations of collective states and giant resonances. The treatment of the pion–nucleus interaction will focus on gross properties and open problems of this interesting interaction.

The situation is different regarding the interaction of K^- and K^+ with nuclei where the experimental data is rather scarce and where it is probably true that only gross properties of the interaction are known. The K^- nucleus interaction will be discussed at zero energy as evidenced by the strong interaction shifts and widths of levels in kaonic atoms. For the K^+ meson, analysis of the recent measurements of total cross sections on several nuclei in the range of 400 to 700 MeV/c will be presented.

2. Pion scattering and pionic atoms

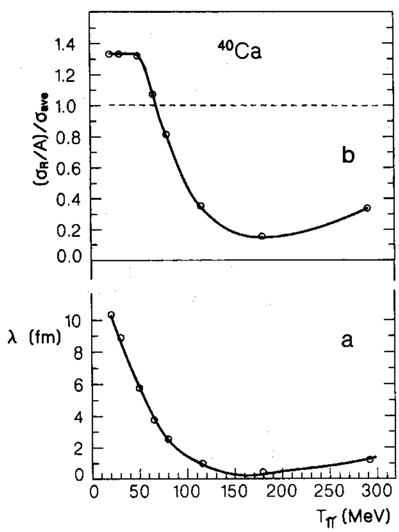


Fig. 1. Average ($\pi^{\pm}$) mean free path of pions in nuclear matter (a) and the average total reaction cross section per nucleon (for ^{40}Ca) divided by the average pion-nucleon total cross section (b).

An instructive approach to the pion–nucleus interaction is to look at the mean free path of pions in nuclei. Figure 1(a) demonstrates the well known dependence of $\lambda = 1/\sigma\rho$ on energy, where σ is the average total cross section (for π^+ and π^-) for the pion–nucleon interaction and ρ is the density of nuclear matter (0.16 fm^{-3}). Figure 1(b) shows the average total reaction cross section on ^{40}Ca per nucleon divided by the average total π-N cross section. Comparing the two parts of the figure we notice that as long as the mean free path is larger than the nuclear radius (3.5 fm

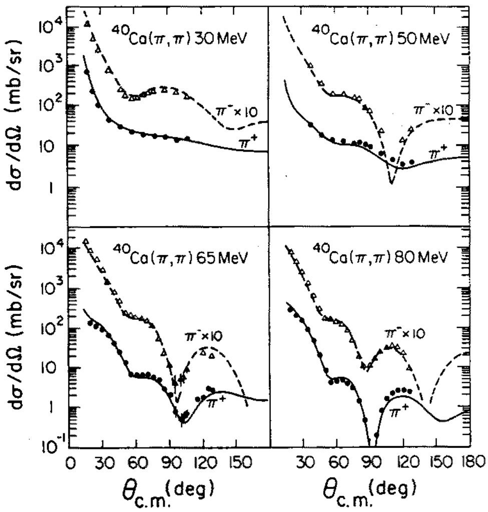


Fig. 2. Angular distribution of elastically scattered pions by ^{40}Ca showing the transition towards strong absorption conditions as the energy increases. (from Ref. [1]).

in this case) the nucleus is indeed transparent to pions, *i.e.* all its nucleons contribute to the interaction. As soon as λ becomes smaller than the nuclear radius the number of effective nucleons decreases. The total reaction cross sections in Fig. 1(b) are experimental up to 80MeV [1] and are calculated from fits to elastic scattering data at higher energies [2]. It is seen that around 50–65MeV a change in the character of the interaction is expected and Fig. 2 demonstrates that this is indeed so by showing how the shapes of the angular distributions change with energy [1]. It is clear from these two figures that above 100 MeV the interaction of pions with nuclei should be rather similar to that of strongly absorbed particles such as protons or α particles. Indeed Satchler [3] showed that at these energies one could well describe the pion–nucleus interaction by a conventional local potential, contrary to the Kisslinger type potential required by the data [4] at lower energies.

By relating the pion–nucleus potential to the nuclear densities using a modified Kisslinger potential [1, 5] one may obtain information on nuclear densities from analyses of elastic scattering data. This theoretically-motivated phenomonological potential may be written as [1]

$$2\omega V_N(r) = q(r) + \nabla \cdot \alpha(r) \nabla \,, \tag{1}$$

where ω is the total pion energy in the pion–nucleus system. The s-wave

(q) and p-wave (α) parts of the potential are given by ($\pm$ apply to $\pi^{\mp}$)

$$q(r) = -4\pi\left[\left[1+\frac{\omega}{m}\right]\left[b_o\left(\rho_n+\rho_p\right)\pm b_1\left(\rho_n-\rho_p\right)\right] + \left[1+\frac{\omega}{2m}\right]4B_o\rho_n\rho_p\right] + \Delta q_{at}(r)\,, \tag{2}$$

$$\alpha(r) = \frac{\alpha_1(r)}{1+\frac{1}{3}\xi\alpha_1(r)} + \alpha_2(r)\,, \tag{3}$$

with $\Delta q_{at}(r)$ the so-called angle-transformation term,

$$\Delta q_{at}(r) = -4\pi\frac{\omega}{2m}\left[\left[1+\frac{\omega}{m}\right]^{-1}\nabla^2\left[c_0(\rho_n+\rho_p)\pm c_1(\rho_n-\rho_p)\right] + \left[1+\frac{\omega}{2m}\right]^{-1}2C_0\nabla^2(\rho_n\rho_p)\right], \tag{4}$$

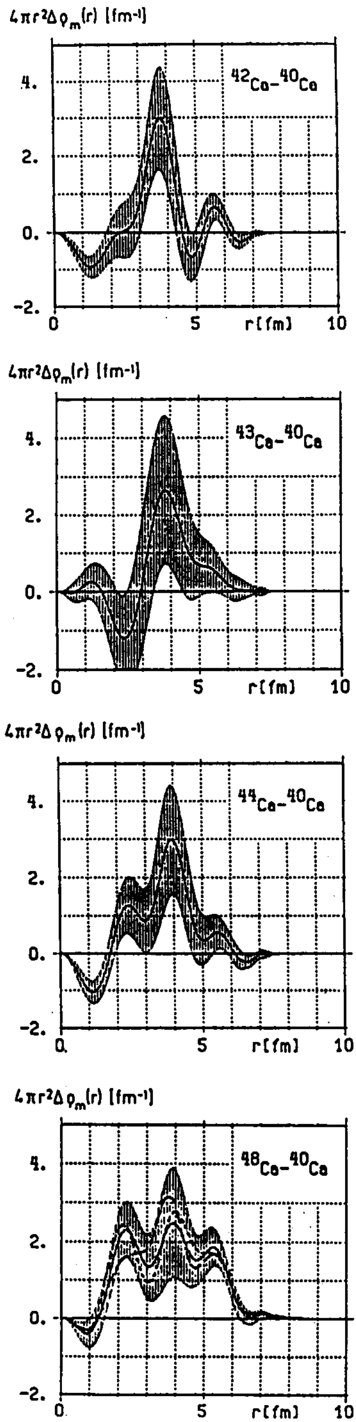
and

$$\alpha_1(r) = 4\pi\left[1+\frac{\omega}{m}\right]^{-1}\left[c_0(\rho_n+\rho_n)\pm c_1(\rho_n-\rho_p)\right]\,, \tag{5}$$

$$\alpha_2(r) = 4\pi\left[1+\frac{\omega}{2m}\right]^{-1}4C_0\rho_n\rho_p\,. \tag{6}$$

ρ_n and ρ_p are the nuclear densities normalized to N and Z, respectively, and m is the mass of the nucleon. An example of a recent application of pion scattering to the study of nuclear densities is given by Gibbs and Dedonder [6]. Figure 3 shows the densities of the excess neutrons in several calcium isotopes obtained by them in comparison with similar information derived from the analysis of the elastic scattering of alpha particles [7]. As expected on the basis of mean free path arguments, the results are quite similar, with one obvious difference, namely, that the non-pion authors show realistic errors! However, it is stressed that with pions one can use π^+ and π^- beams and make consistency checks with the help of charge distributions determined from electron scattering.

The energy range where these unique properties of pions are evident is 50–65 MeV. Figure 4 shows comparisons between calculation and experiment for the elastic scattering of 50 MeV π^+ and π^- by ^{48}Ca. The data is of Rozon *et al.* [8], and the calculations were made with the "J4" potential [1], for two different values of the rms radius of the neutron density distribution. The results for π^+ should not depend much on the neutron distribution but the π^- results should be sensitive to it, as is indeed observed. The rms radius deduced here for neutrons in ^{48}Ca agrees very well



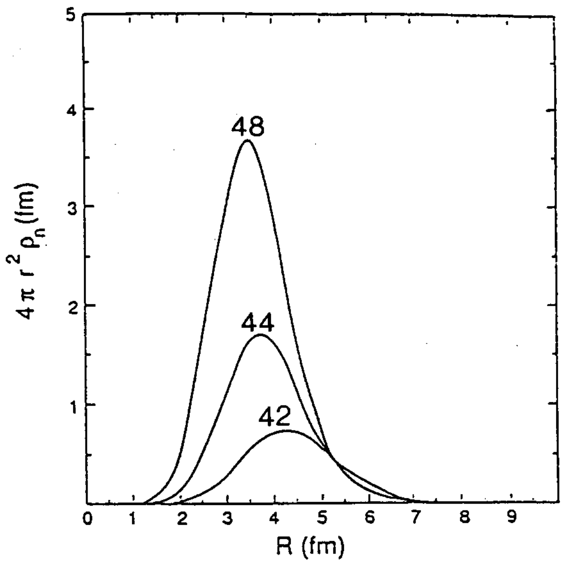


Fig. 3. Density distributions of the excess neutrons in calcium isotopes from alpha scattering (left side, Ref. [7]) and pion sacttering (Ref. [6]).

with that of Gibbs and Dedonder [6]. The use of 50 MeV pions in a "definitive experiment" to determine the neutron density in ^{48}Ca had been advocated before [9]; the present results show what is to be expected. However, note that some of the information comes from regions near minima in the angular distribution, where higher order effects might be important.

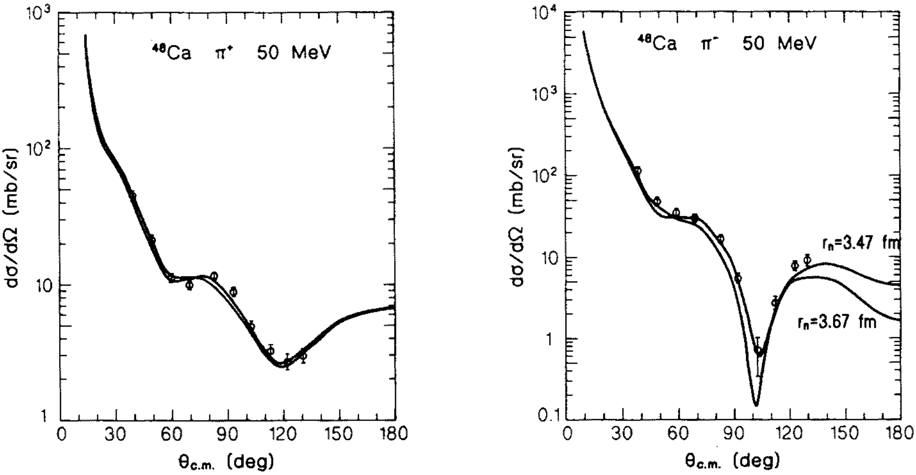


Fig. 4. Experimental results for the elastic scattering of 50 MeV pions by ^{48}Ca, compared with calculations using two different rms radii for the neutron density distribution (top curves for 3.47 fm).

Moving down in energy to pionic atoms, we note that the parameters b_0, b_1, c_0, c_1 become real. Although correlations exist between b_0 and $\mathrm{Re}B_0$, c_0 and $\mathrm{Re}C_0$ [10], it is found that almost unique results can be obtained when a χ^2 fit is made to a very large data base, containing *e.g.* 70 atoms [11]. One of the clear features of such fits is the fact that the real part of the s-wave term of the potential is found to be much more repulsive than expected [12]. One way of seeing that is by looking at $\mathrm{Re}B_0$. Table I summarizes values of parameters obtained from fits to broad data bases, where one sees this unusual large repulsion, *i.e.* $-\mathrm{Re}\,B_0 > \mathrm{Im}B_0$. Including explicitly the nucleon correlation term [5] in b_0 does not alter the picture regarding the "missing" repulsion. The excellent agreement between the different calculations is evident. Birbrair [13] and Leisi and co-workers [14] pioneered the idea that the extra repulsion needed by the data could result from the neglect of Dirac phenomenology nuclear effects. Gal *et al.* [15] who extended this analysis to a broad data base containing heavy nuclei, showed that including effects of in-medium spinors could lead to this repulsion, but in a non-unique fashion, thus leaving this mechanism at a speculative level.

TABLE I

Comparisons between several fits to pionic atoms

	"J5"	Konijn *et al.* [11]		
b_0	0.028 ± 0.016	0.024 ± 0.005	0.0250 ± 0.005	$[m_\pi^{-1}]$
b_1	-0.106 ± 0.007	-0.090 ± 0.005	-0.0940 ± 0.005	$[m_\pi^{-1}]$
c_0	$\underline{0.220}$	0.272 ± 0.016	0.2730 ± 0.020	$[m_\pi^{-3}]$
c_1	$\underline{0.152}$	0.107 ± 0.015	0.1840 ± 0.021	$[m_\pi^{-3}]$
$\mathrm{Re}B_0$	-0.300 ± 0.08	-0.261 ± 0.028	-0.2650 ± 0.026	$[m_\pi^{-4}]$
$\mathrm{Im}B_0$	0.058 ± 0.03	0.052 ± 0.013	0.0546 ± 0.012	$[m_\pi^{-4}]$
ξ	1.8*	0	1.0	

*LIFE in linear term only

Following Brown *et al.* [16], who suggested an alternative mechanism for the enhanced repulsion, (although in connection with the K^+), one may gain some extra repulsion in the s-wave term of the potential by assuming a density dependence to the masses of the vector component of the meson cloud of the nucleon. This leads to the replacement of the b_1 in Eq. (2) by

$$\frac{b_1}{(1-\frac{1}{2}\lambda\rho(r)/\rho_0)^2} \tag{7}$$

with $\lambda \approx 0.3$. This enhancement obviously does not apply to isoscalar nuclei but one could hope that it might provide the extra repulsion in heavy pionic atoms. Fits to a wide data base using the modification given by (7) fail to produce a significant change and the conclusion is that this isovector enhancement is unimportant in pionic atoms. We return to this mechanism later in connection with the K^+ nuclear interaction.

The "missing" repulsion revealed in pionic atoms remains a mystery, unless the relativistic effects mentioned above turn out to be the correct mechanism. It is expected that if deeply bound pionic states are observed in heavy nuclei [17, 18] then more light will be shed on the s-wave part of the pion–nucleus interaction and its dependence on the nuclear medium. The attempts to observe those states is, in my opinion, the most exciting development expected in this field in the next few years.

3. Kaonic atoms

A reasonably comprehensive set of data on the strong interaction effects in kaonic atoms has been in existence for years. A simple "$t\rho$" potential analogous to the s-wave part of Eq. (2) is quite successful [19] in describing the data, but, contrary to expectations based on the free $\overline{K}$ nucleon interaction one finds the real potential to be attractive, whereas the $\overline{K}N$ interaction at low energies is repulsive. This sign reversal has long been suspected to originate from the effect of the $\Lambda(1405)$ subthreshold resonance that is likely to affect the interaction in the nuclear medium. As the K^- nucleus interaction is expected to follow the free $\overline{K}N$ interaction at the extreme nuclear surface, a density dependence of the K^- nucleus interaction is to be expected. Very recently [20] we have studied this phenomenon by introducing a density dependent term into the optical potential that is written as

$$2\mu V_{\rm opt}(r) = -4\pi\left(1+\frac{\mu}{m}\right)\left[b + B\left(\rho(r)/\rho_0\right)^\alpha\right]\rho(r) \tag{8}$$

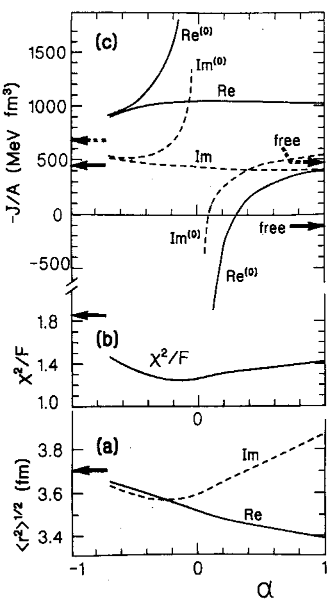


Fig. 5. χ^2/F for a broad data set of kaonic atoms as a function of the density dependent exponent α (b). Also shown are rms radii (a) and volume integrals of the potentials (c) for Ni, where the arrows on the left indicate the corresponding values for a $t_{\rm eff}\rho$ potential. Values with the superscript (0) refer to the linear component of Eq. (8) (see Ref. [20]).

with b and B complex parameters, α an empirical parameter and μ the K^- nucleus reduced mass. Figure 5 is a summary of the results of χ^2 fits to a comprehensive set of data covering the entire periodic table. It shows that a most significant improvement in the fit to the data is achieved with the density dependent potential (8) whose volume integrals and rms radii are well defined and change smoothly with α. In addition, one may impose the

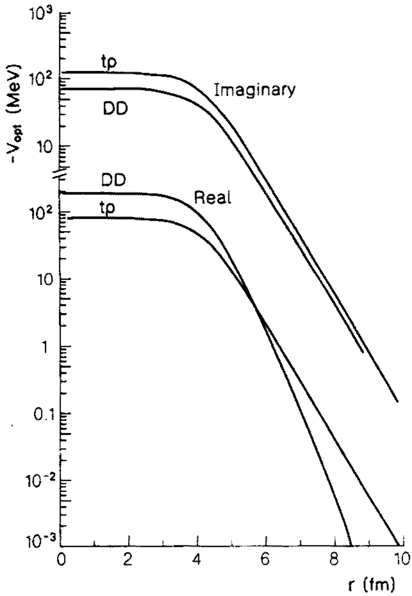


Fig. 6. Examples of a $t_{\rm eff}\rho$ potential and a density dependent potential for kaonic atoms of Ni whose linear part derives from $t_{\rm free}\rho$.

free $\overline{K}N$ value on the linear term (b) and still get χ^2 very close to the minimum. Figure 6 shows an example of the modified potentials in comparison to the "$t\rho$" ones, and together with the values of rms radii (Fig. 5) one notes that the potential is "compressed" in comparison to the nuclear density. This density dependence can be related to the $\Lambda(1405)$ resonance and is expected to dominate the interaction also at non-zero energies. Very little has been done so far on the elastic scattering of K^- by nuclei. An example at 800MeV/c shows [21] that at this energy the rms radius of the potential is very close to (but larger than) that of the point nucleon distribution.

4. K^+ nucleus total cross sections

The K^+ nucleus interaction is of a special interest due to the mean free path of K^+ in nuclear matter being larger than typical nuclear radii. Recent measurements of total K^+ cross sections on several nuclei between 500 and 700 MeV/c [22] were performed with the specific aim of observing nuclear medium effects on the basic KN interaction. In fact, analyses of earlier data on K^+ nucleus interaction by Brown *et al.* [16] suggested an enhancement of the interaction in nuclear matter (see Eq. (7)).

Figure 7 shows the results of several χ^2 fits of various potentials to the total cross sections of Piasetzki and collaborators [22]. In part (a) we see

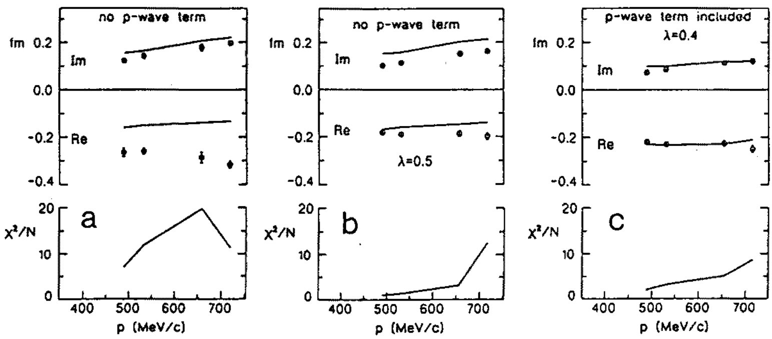


Fig. 7. χ^2/N, the free scattering amplitudes (smooth curves) and the effective scattering amplitudes (dots with error bars) obtained from fits to total cross sections of K^+ on nuclei: (a) for a $t_{eff}\rho$ potential, (b) including the isovector enhancement with $\lambda = 0.4$ (Eq. (7)) and (c) with the isovector enhancement and using explicitly the free KN p-wave term.

only a moderate fit with a "$t\rho$" potential and the t_{eff} (indicated by dots with error bars) disagrees with the free KN amplitude shown by the solid curves (particularly the real part). Figure 7(b) shows the results for an isovector enhancement (Eq. (7) applied to the entire potential in this case) with $\lambda = 0.4$, where the χ^2 values are smaller now and the t_{eff} comes closer to t_{free}. Note, however, that we find λ to be energy dependent and the choice of $\lambda = 0.4$ is a compromise. In Fig. 7(c) we have separated the p-wave part of the KN interaction and used a Kisslinger type potential (Eqs (2)-(5)) with linear terms only and $\xi=0$) where the p wave part was held fixed at the free KN values (as it is confined to the nuclear surface) and only the s wave part was varied. The $\lambda = 0.4$ enhancement was included too, and it is seen that now t_{eff} agrees very well with t_{free}. The exceptionally small errors quoted for the experimental results are partly responsible for values of χ^2/N being of the order of 5. These are only preliminary results but they are quite encouraging in showing the ability to connect the K^+ nucleus and KN interactions.

5. Summary

This review of gross properties of meson–nucleus interactions has inevitably been biased by the reviewer's taste and experience. Focusing only on global properties of the pion–nucleus interaction one notes that above 100MeV the pion is quite similar to other hadronic probes in its ability to supply information on the nucleus and its more unique properties become effective only around 50 MeV. (Note again, that we have not discussed special processes such as charge exchange). Pionic atoms supply unique information on the pion–nucleus potential at zero energy, where an unexpectedly large repulsion in its s-wave part is still largely unexplained. That could be one of the first cases where a modification of strong interaction within the nuclear medium has its origin in sub-nucleonic degrees of freedom. The prospects of experimental observations of the rather narrow deeply bound atomic states are quite exciting and could, in fact, be the only source of fundamental new information on the pion–nucleus interaction.

Turning to kaonic atoms, we showed that a recently introduced phenomenological density dependence produced greatly improved fits to the data while using the free $\bar{K}N$ interaction at large radii. This modified interaction in the nuclear medium can be explained by Fermi averaging of the effects of the $\Lambda(1405)$ subthreshold resonance and at this point it does not seem that sub-nucleonic effects are needed.

The modification of the KN interaction in the nuclear medium emerges as an important effect also in the K^+ nucleus interaction. We have shown that the recent measurements of total cross sections can be described by the free (s-wave and p-wave) KN interaction, enhanced by a density dependence of the mass of isovector mesons in the nucleon. This enhancement leads to compressed potentials, relative to the density, as is the case in kaonic atoms, although for completely different reasons.

Summarizing in one sentence all three cases, we converge on the study of the modification of meson-nucleon interactions within the nuclear medium, probably en route to the identification of sub-nucleonic effects at low energies.

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