Single- and two-nucleon antikaon absorption in nuclear matter with chiral meson-baryon interactions

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Introduction

- K^- multi-nucleon absorption fraction in the surface region of atomic nuclei represents about 20%

  NC 53 (1968) 313 (Berkeley), *NPB 35 (1971) 332 (BNL)*, *NC 39A (1977) 538 (CERN)*

- It was described mainly by phenomenological optical potential so far

  E. Friedman, A. Gal, NPA 959 (2017) 66

- Previous model for K^-NN absorption in nuclear matter using free-space chiral amplitudes by *T. Sekihara et al., PRC 86 (2012) 065205*

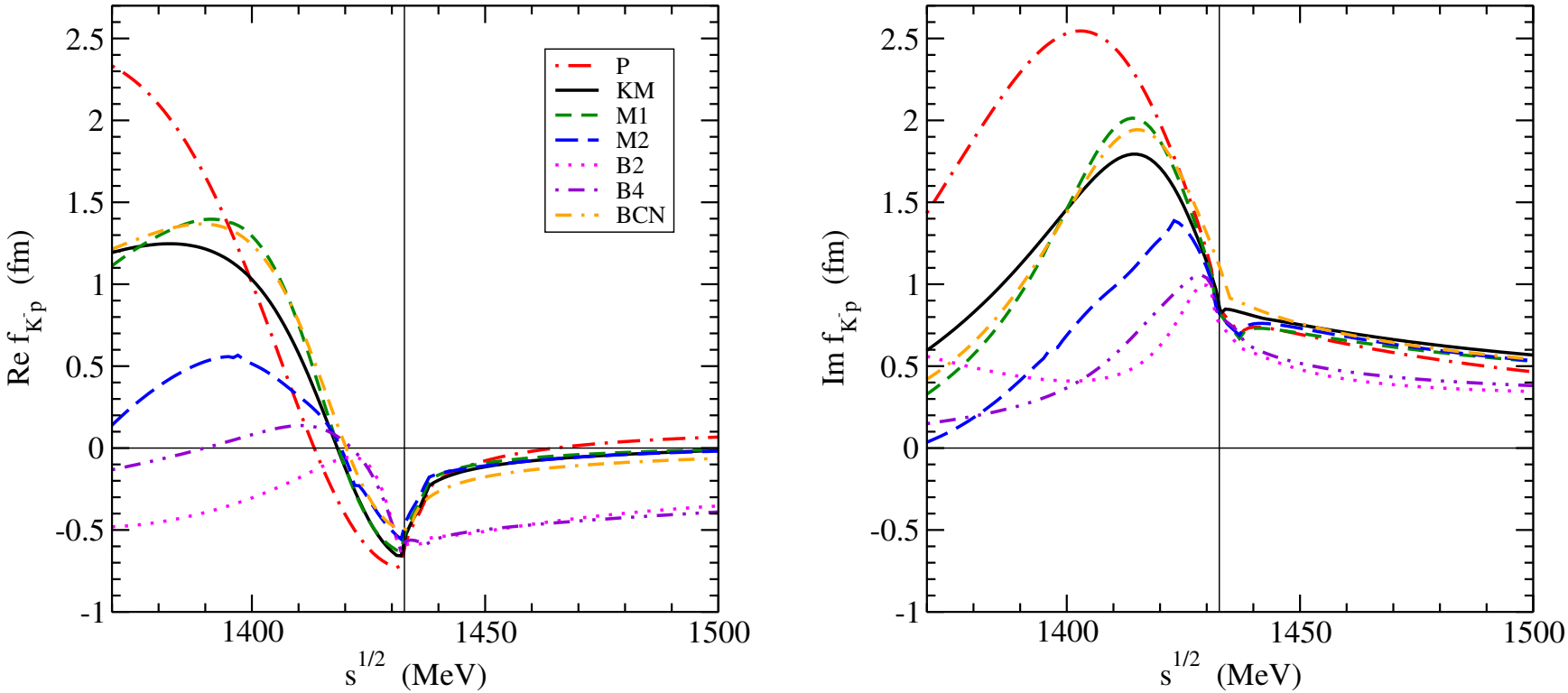
- New experimental data on K^-NN absorption (AMADEUS@DAΦNE)

  K. Piscicchia et al., PLB 782 (2018) 339

  R. Del Grande et al., EPJ C79 (2019) 190

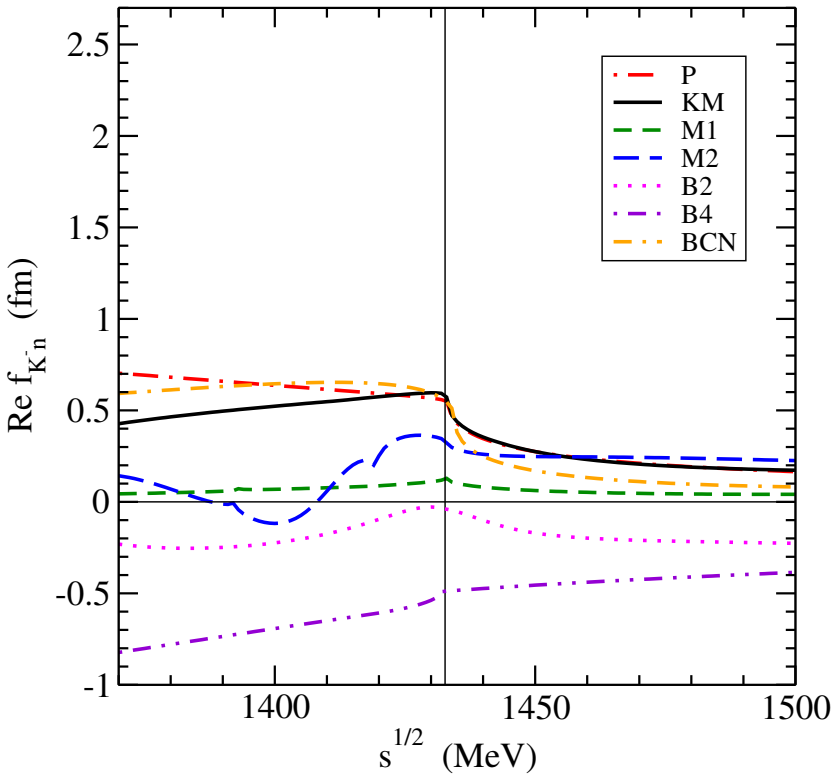
- Solid microscopic model for K^-NN absorption needed

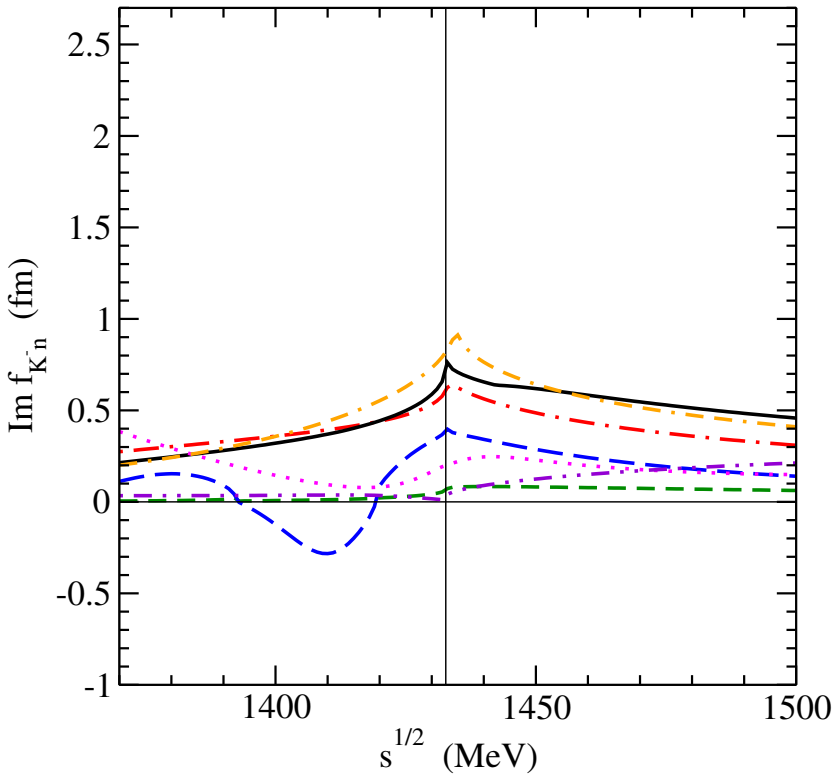
Free-space $K^- p$ amplitudes in various chiral models



Prague (P)	*A. Cieply, J. Smejkal, Nucl. Phys. A 881 (2012) 115*
Kyoto-Munich (KM)	*Y. Ikeda, T. Hyodo, W. Weise, Nucl. Phys. A 881 (2012) 98*
Murcia (M1 and M2)	*Z. H. Guo, J. A. Oller, Phys. Rev. C 87 (2013) 035202*
Bonn (B2 and B4)	*M. Mai, U.-G. Meißner, Nucl. Phys. A 900 (2013) 51*
Barcelona (BCN)	*A. Feijoo, V. Magas, A. Ramos, Phys. Rev. C 99 (2019) 035211*

Free-space $K^- n$ amplitudes





Kaonic atoms

- Info about $K^- N$ interaction below threshold provided by kaonic atoms

  65 data points (energy shifts, widths, yields=upper level widths) from CERN, Argonne, RAL, BNL

- Chirally motivated models fail to describe kaonic atom data

  E. Friedman, A. Gal, NPA 959 (2017) 66

Multinucleon processes

- Chiral models include only $K^- N \to \pi Y$ ($Y = \Lambda, \Sigma$) decay channel
- K^- interactions with two and more nucleons should be included, (e.g., $K^- + N + N \to Y + N$) - recent analysis of kaonic atom data

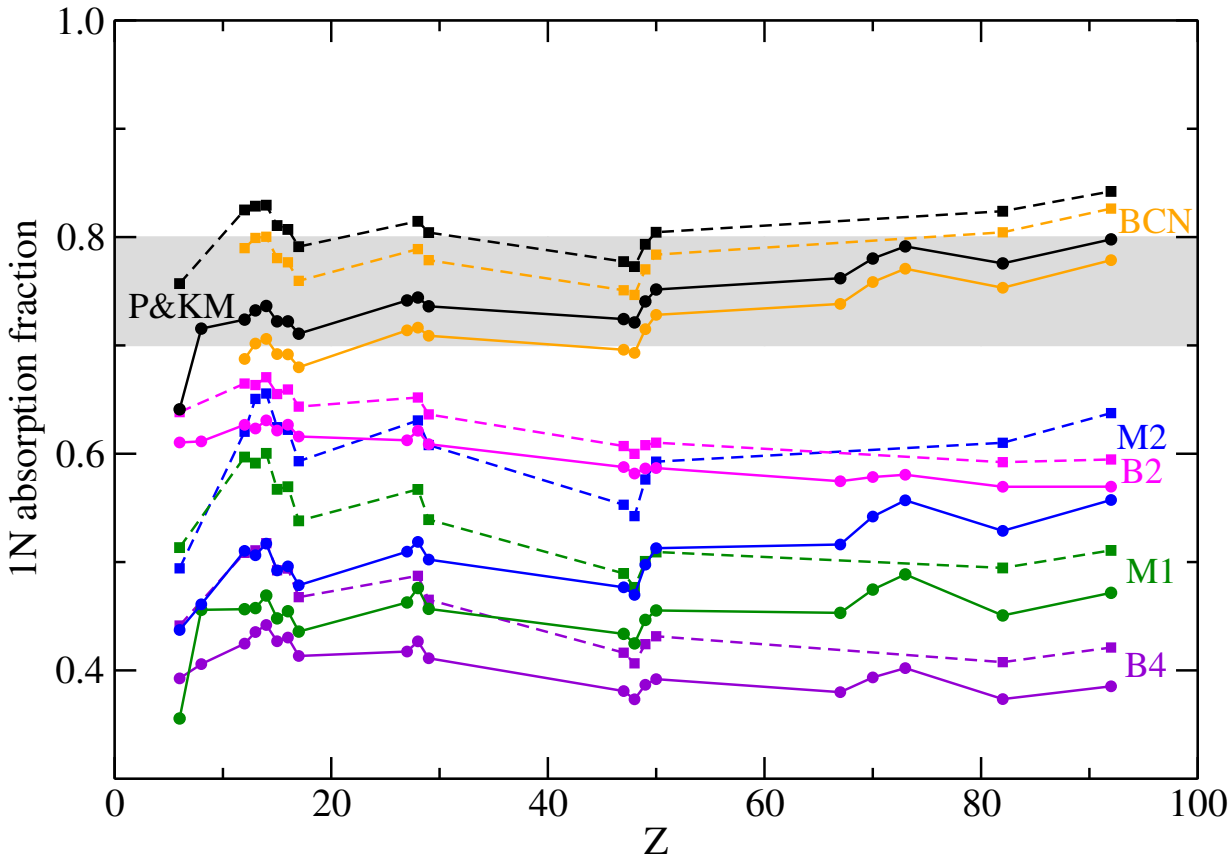
  E. Friedman, A. Gal, NPA 959 (2017) 66

$$2\mathrm{Re}(\omega_{K^-}) V_{K^-}^{(2)} = -4\pi B (\frac{\rho}{\rho_0})^{\alpha} \rho \ ,$$

where B is a complex amplitude, ρ is nuclear density distribution, ρ_0 is saturation density and α is positive

- Amplitude B fitted for each chiral model separately

Single- vs. multi-nucleon processes



- Fraction of *single-nucleon* absorption 0.75 ± 0.05 (average value) applied as an additional constraint.

$\rightarrow$ Only P, KM and BCN models found acceptable in kaonic atom analysis

E. Friedman, A. Gal, NPA 959 (2017) 66

Microscopic model for K^-NN absorption in nuclear matter

We have developed microscopic model for K^- two-nucleon absorption in symmetric nuclear matter

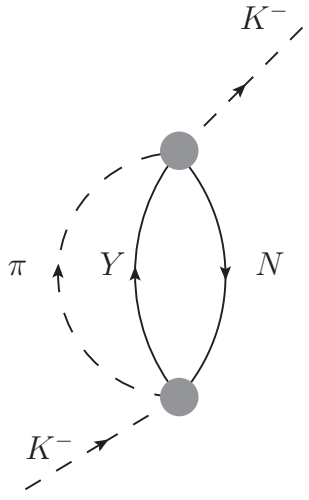
J. Hrtánková, À. Ramos, arXiv:1910.01336 [nucl-th], submitted to PRC

- based on a meson-exchange approach

  H. Nagahiro et al., PLB 709 (2012) 87.
- employing P and BCN chiral K^-N amplitudes
- considering Pauli correlations in the medium for K^-N amplitudes
- real part of the K^-NN optical potential evaluated as well
- K^-N optical potential derived within the same approach

K^-N absorption in nuclear matter

$$K^-N \to \pi Y \quad (Y = \Lambda, \Sigma)$$



- K^-N self-energy

$$\Pi_{K^-N\to\pi Y}(\vec{p}, p_0) = \mathrm{i}\,|t_{K^-N\to\pi Y}|^2 \int \frac{d^4q}{(2\pi)^4} U_{YN}(p-q) \frac{1}{q^2 - m_\pi^2 + \mathrm{i}\eta}$$

t - two-body t-matrix; U - Lindhard function

p - kaon 4-momentum; q - meson 4-momentum

K^-NN absorption in nuclear matter

$$K^- + N + N \to Y + N \quad (Y = \Lambda, \Sigma)$$

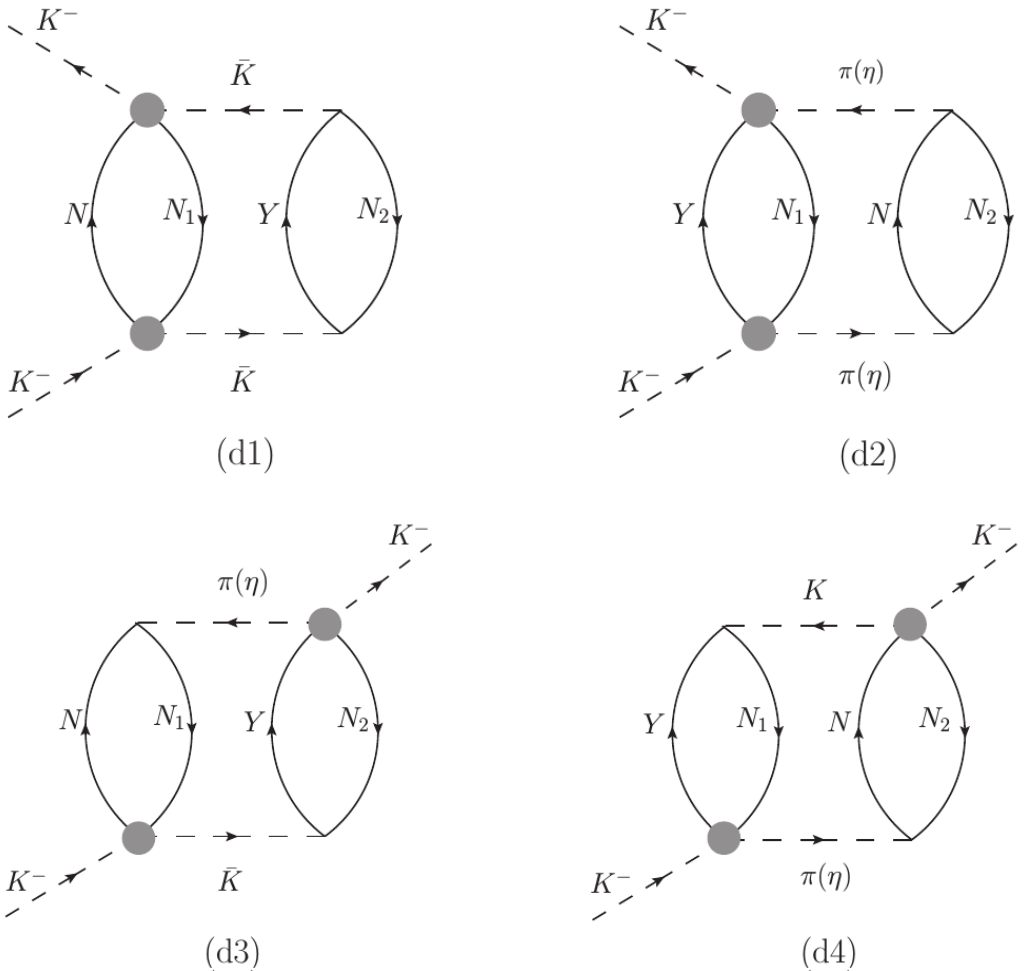


Fig.1: Two-fermion-loop (2FL) Feynman diagrams for non-mesonic K^- absorption on two nucleons N_1, N_2 in nuclear matter. The shaded circles denote the K^-N t-matrices derived from a chiral model.

K^-NN absorption in nuclear matter

- K^-NN self-energy from a direct 2FL diagram

$$\Pi^{\rm 2FL}_{K^-NN}(\vec{p},p_0) = -\,{\rm i}\,t_{B_1 x}\,t^*_{B_1 x}\,V_{B_2 N_2 x}\,V_{B_2 N_2 x}\int\frac{d^4q}{(2\pi)^4}\,U_{B_1 N_1}(p-q)\,U_{B_2 N_2}(q)$$
$$\times\,(-\vec{q}^{\,2})\,\frac{1}{q^2-m_x^2+{\rm i}\eta}\;\frac{1}{q^2-m_x^2+{\rm i}\eta}\;,$$

$x = K^-, \bar{K}^0, \pi,\ \eta$; t - two-body t-matrices; $B_1, B_2 = N, Y$

V - meson-baryon-baryon couplings; U - Lindhard function

p - kaon 4-momentum, q - meson 4-momentum

- Contributions from diagrams (d3) and (d4) are zero due to null trace over spins

K^-NN absorption in nuclear matter

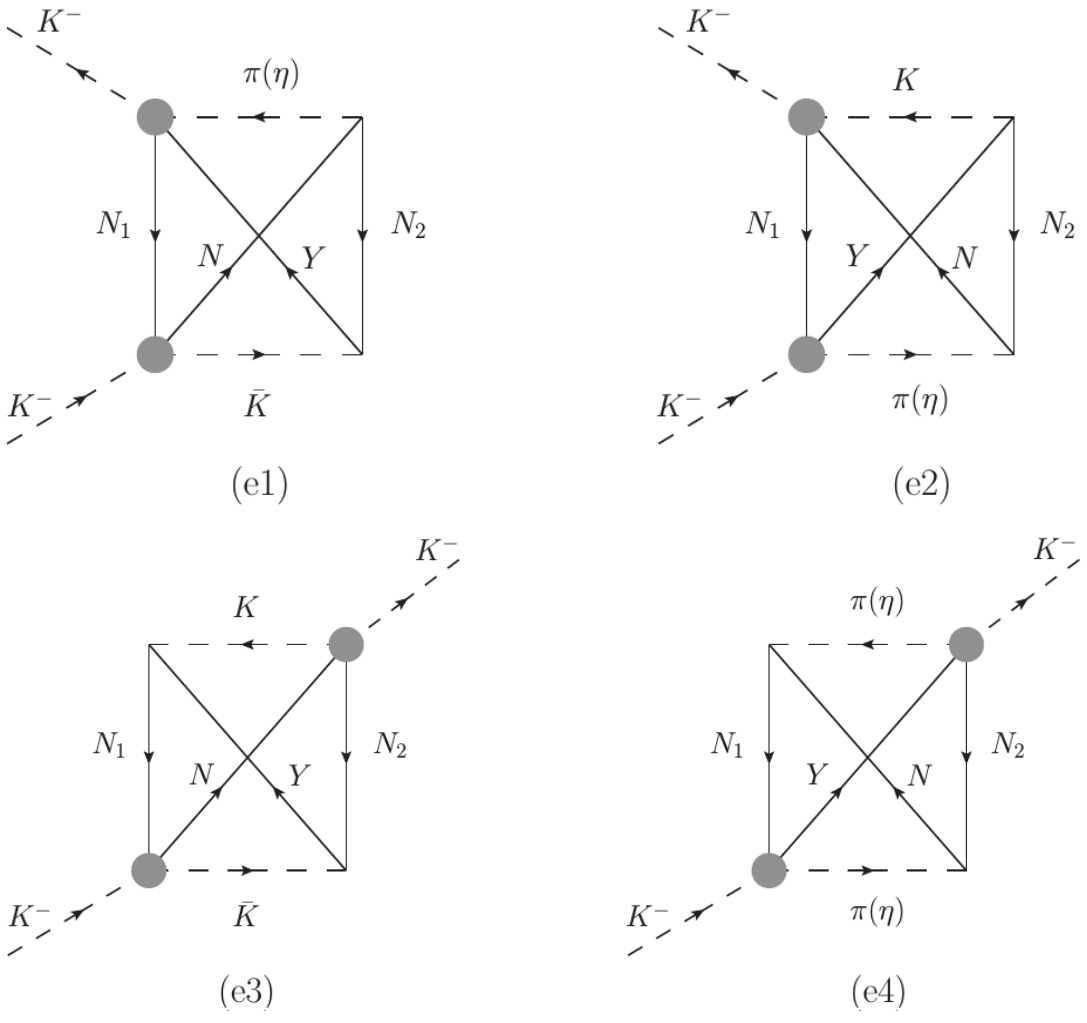


Fig.2: One-fermion-loop (1FL) Feynman diagrams for non-mesonic K^- absorption on two nucleons N_1, N_2 in nuclear matter. The shaded circles denote the K^-N t-matrices derived from a chiral model.

K^-NN absorption in nuclear matter

- K^-NN self-energy from an exchange 1FL diagram

$$\Pi^{1\mathrm{FLA}}_{K^-NN}(\vec{p},p_0) = -\,\mathrm{i}\,t_{B_1x_1}\,t^*_{B_2x_2}\,V_{B_2N_2x_1}\,V_{B_1N_2x_2}\int\frac{d^4q}{(2\pi)^4}(+2\vec{q}^{\,2})$$

$$\times\int\frac{d^4j}{(2\pi)^4}\,G_{N_1}(j)\,G_{B_1}(j+p-q)\int\frac{d^4k}{(2\pi)^4}\,G_{N_2}(k)\,G_{B_2}(q+k)$$

$$\times\frac{1}{q^2-m^2_{x_1}+\mathrm{i}\eta}\;\frac{1}{q'^{\,2}-m^2_{x_2}+\mathrm{i}\eta} =$$

$$=\mathrm{i}\,t_{B_1x_1}\,t^*_{B_2x_2}\,V_{B_2N_2x_1}\,V_{B_1N_2x_2}\,\frac{1}{2}\int\frac{d^4q}{(2\pi)^4}\,U_{B_1N_1}(p-q)\,U_{B_2N_2}(q)$$

$$\times\vec{q}^{\,2}\,\frac{1}{q^2-m^2_{x_1}+\mathrm{i}\eta}\;\frac{1}{q'^{\,2}-m^2_{x_2}+\mathrm{i}\eta}$$

G - baryon propagator in the medium; j,k - nucleon 4-momenta

$K^- NN$ absorption in nuclear matter

- K^- self-energy related to optical potential $V_{K^-} = \frac{\Pi_{K^-}}{2E_{K^-}}$
- $V_{K^-N} = \sum_{channels} V_{K^-N \to \pi Y}$
- $V_{K^-NN} = \sum_{\text{channels}} V^{\text{2FL}}_{K^-NN} + V^{\text{1FL}}_{K^-NN}$

  $\to$ contributions from 37 2FL and 28+33 1FL diagrams

Table 1: All considered channels for mesonic and non-mesonic K^- absorption in matter.

K^-N	$\to \pi Y$	$K^-N_1N_2$	$\to YN$
K^-p	$\to \pi^0\Lambda$	K^-pp	$\to \Lambda p$
	$\to \pi^0\Sigma^0$		$\to \Sigma^0 p$
	$\to \pi^+\Sigma^-$		$\to \Sigma^+ n$
	$\to \pi^-\Sigma^+$	$K^-pn(np)$	$\to \Lambda n$
K^-n	$\to \pi^-\Lambda$		$\to \Sigma^0 n$
	$\to \pi^-\Sigma^0$		$\to \Sigma^- p$
	$\to \pi^0\Sigma^-$	K^-nn	$\to \Sigma^- n$

K^-N free-space vs. Pauli blocked scattering amplitudes

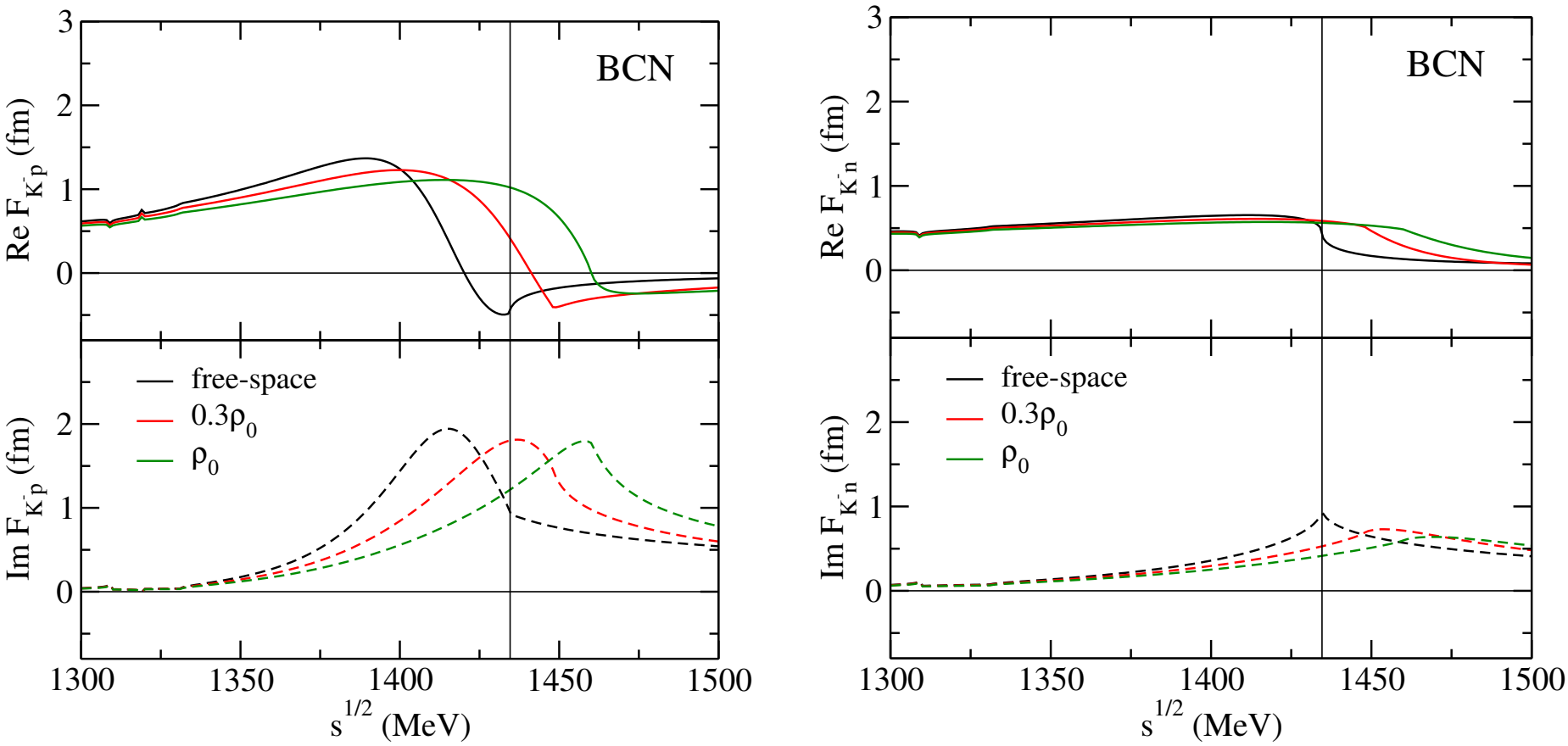
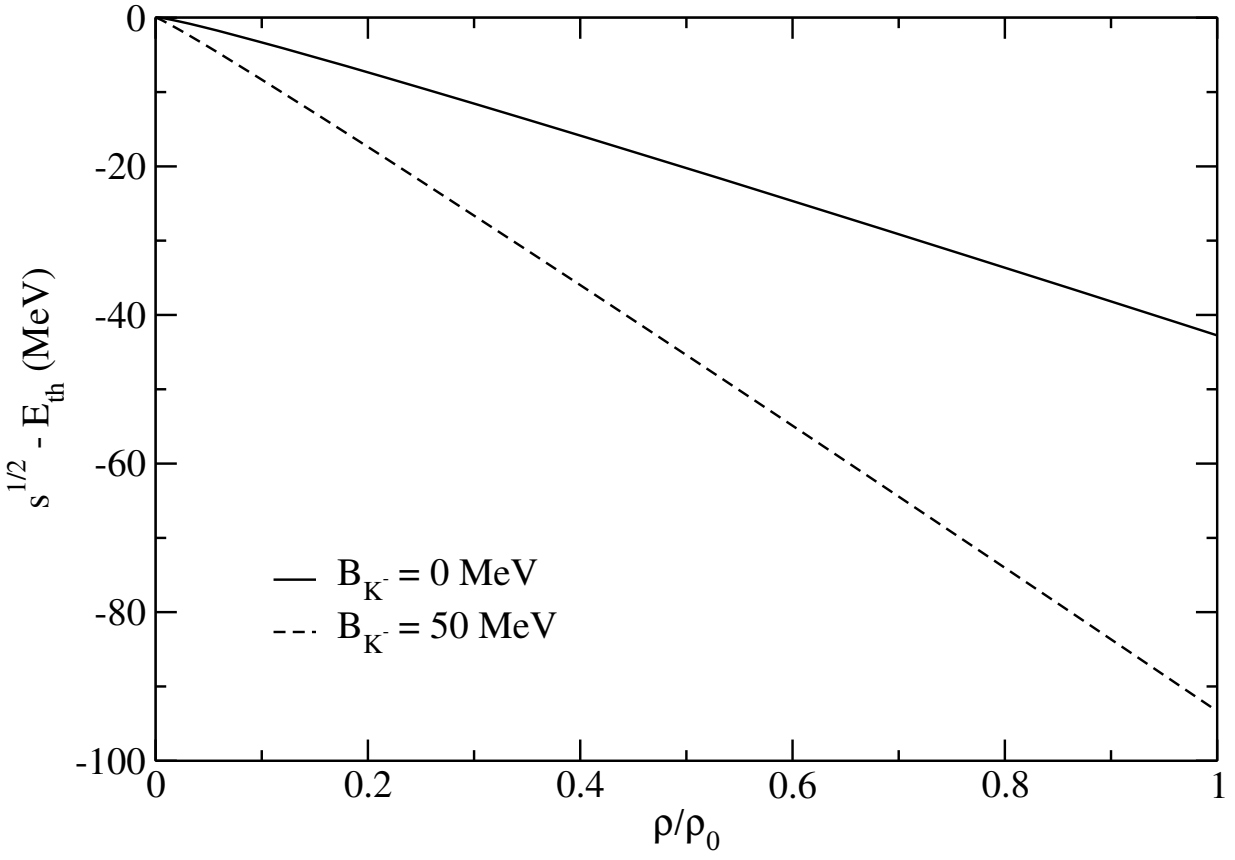


Fig.3: Comparison of K^-p and K^-n free-space (black) and Pauli blocked amplitudes at two different nuclear matter densities: $0.3\rho_0$ (red) and ρ_0 (green), calculated in the BCN model.

Energies probed below K^-N threshold

- Energy shift $\delta\sqrt{s} = \sqrt{s} - E_{\rm th}$ where $\sqrt{s} = \sqrt{(E_{K^-} + E_F)^2 - \frac{3}{5}k_F^2}$,

$E_F = \sqrt{m_N^2 + \frac{3}{5}k_F^2} + V_N \frac{\rho}{\rho_0}$ with $V_N = -50$ MeV, $E_{K^-} = m_{K^-} - B_{K^-}\frac{\rho}{\rho_0}$,
k_F - Fermi momentum, $\rho_0 = 0.169$ fm^{-3}, $E_{\rm th} = m_N + m_{K^-}$



K^- potential in nuclear matter - medium effects

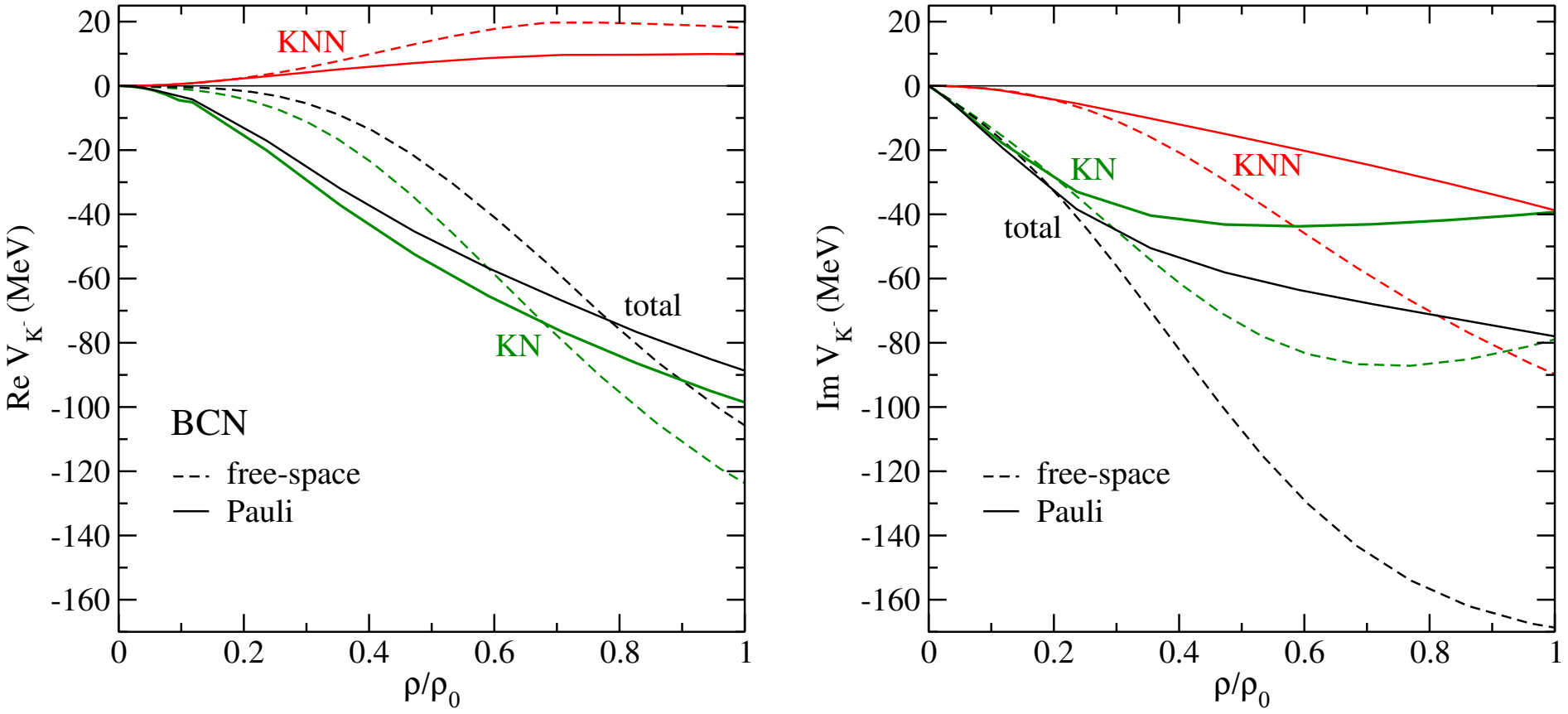


Fig.4: The real (left) and imaginary (right) parts of the K^-N, K^-NN, and total optical potentials as a function of relative density, calculated using the free-space (dashed) and Pauli blocked (solid) BCN amplitudes for $B_{K^-} = 0$ MeV.

K^-N and K^-NN absorption fractions

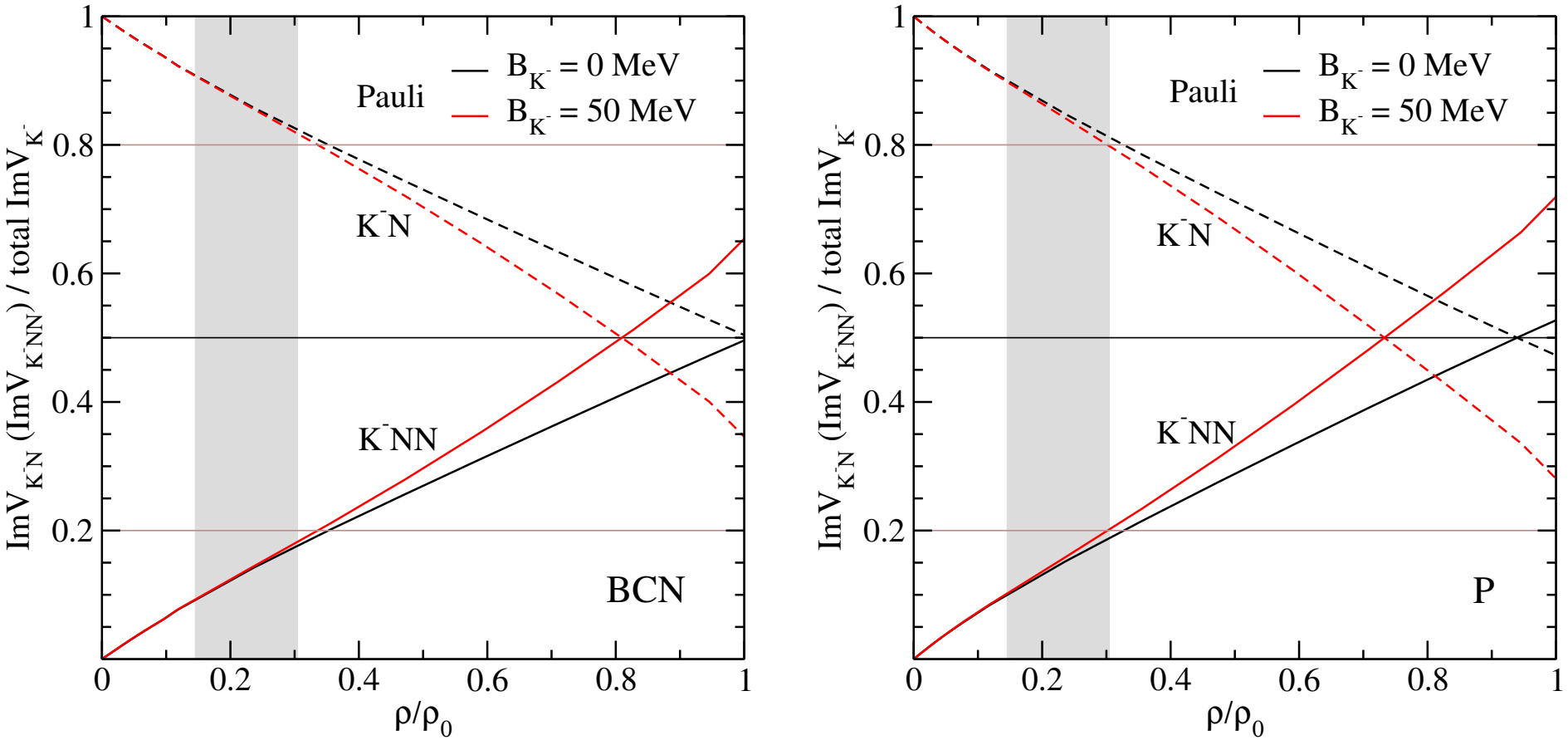


Fig.5: Ratio of K^- single-nucleon (K^-N) and two-nucleon (K^-NN) absorptive potentials to the total K^- absorptive potential as a function of relative density, calculated using the Pauli blocked amplitudes and for $B_{K^-} = 0$ and 50 MeV. The gray band denotes the region of densities probed in experiments with low-energy K^-.

AMADEUS data

- New measured ratio *R. Del Grande et al., EPJ C79 (2019) 190*

$$R = \frac{\mathrm{BR}(K^- pp \to \Lambda p)}{\mathrm{BR}(K^- pp \to \Sigma^0 p)} = 0.7 \pm 0.2(\mathrm{stat.})^{+0.2}_{-0.3}(\mathrm{syst.})$$

- Assumption that dominant contribution for $K^- pp \to \Lambda p$ and $K^- pp \to \Sigma^0 p$ channels comes from π^0 exchange leads to relation

$$\frac{\mathrm{BR}(K^- pp \to \Lambda p)}{\mathrm{BR}(K^- pp \to \Sigma^0 p)} = \frac{\mathrm{BR}(K^- p \to \pi^0 \Lambda)}{\mathrm{BR}(K^- p \to \pi^0 \Sigma^0)}$$

- However, the dominant contribution for $K^- pp \to \Lambda p$ channel comes from K^- exchange!

  T. Sekihara, D. Jido, Y. Kanada-En'yo, PRC 79 (2009) 062201(R)

  J. Hrtánková, À. Ramos, arXiv:1910.01336 [nucl-th], submitted to PRC

Ratio R for 2N absorption

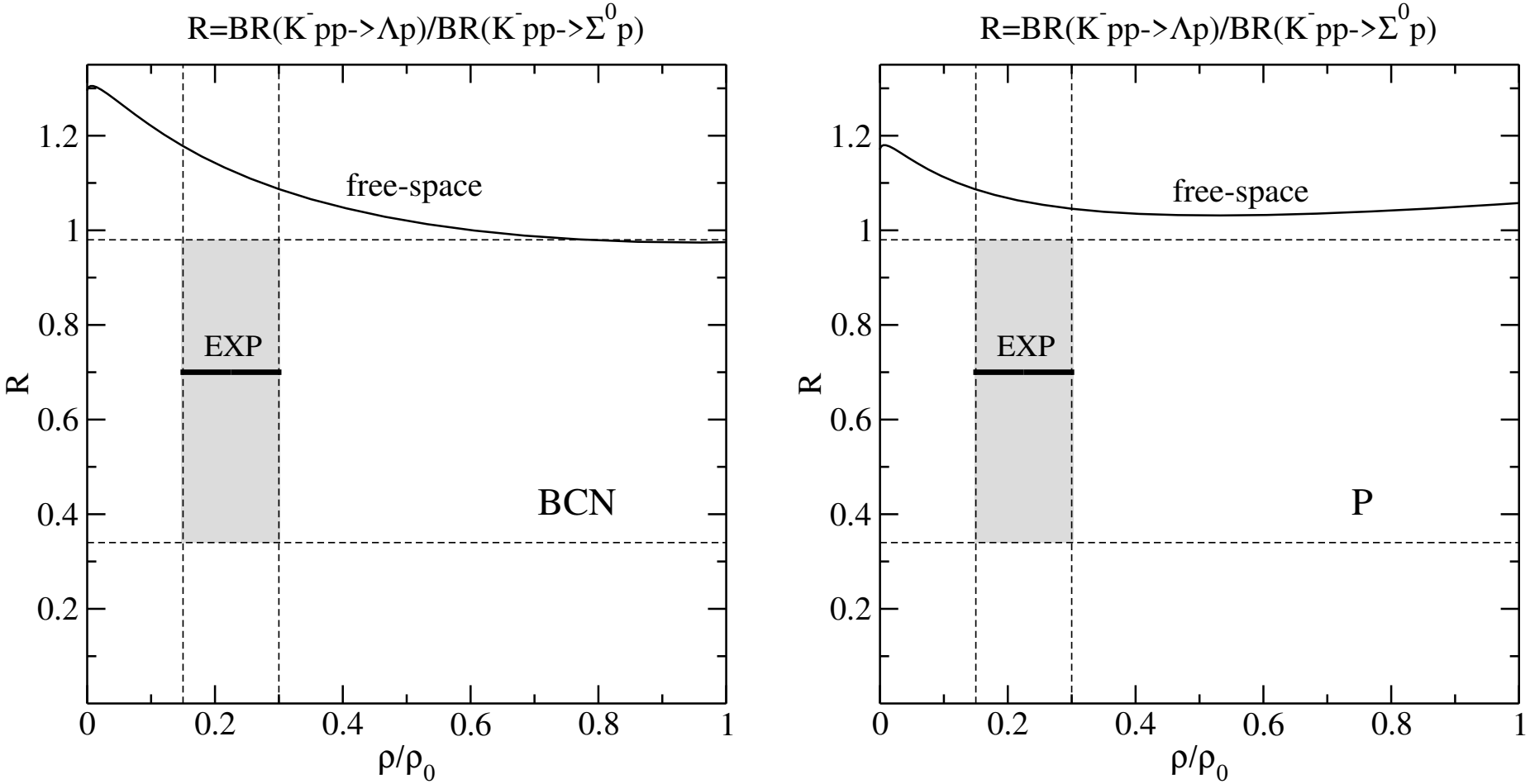


Fig.6: The ratio R as a function of relative density, calculated using the free-space amplitudes for $B_{K^-} = 0$ MeV. The dashed vertical lines denote the region of densities probed in experiments with low-energy K^- including the experimental value of the ratio with corresponding error bar.

Ratio R for 2N absorption

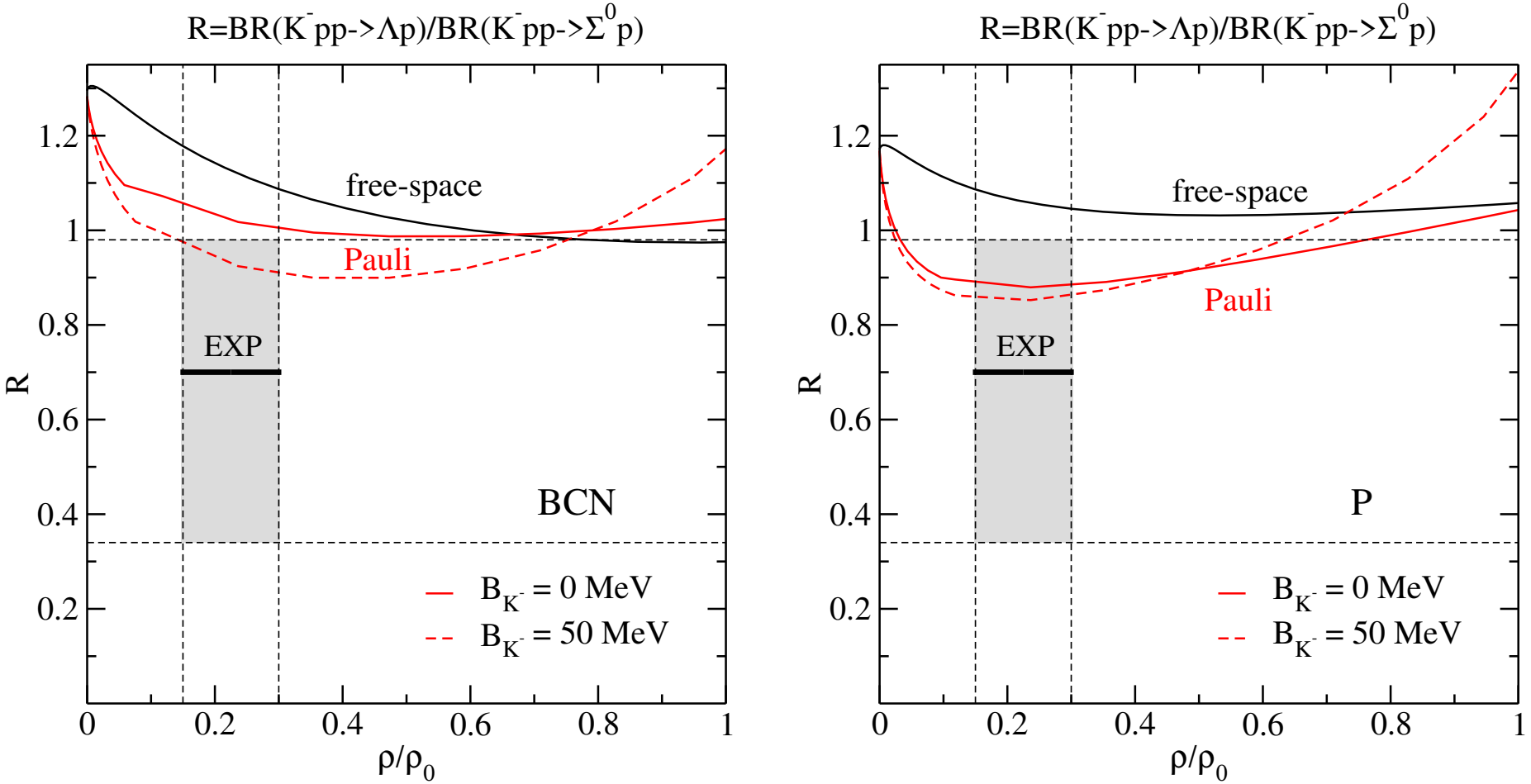


Fig.7: The ratio R as a function of relative density, calculated using the free-space and Pauli blocked amplitudes for $B_{K^-} = 0$ MeV and $B_{K^-} = 50$ MeV. The dashed vertical lines denote the region of densities probed in experiments with low-energy K^- including the experimental value of the ratio with corresponding error bar.

Ratio R^* for 1N absorption

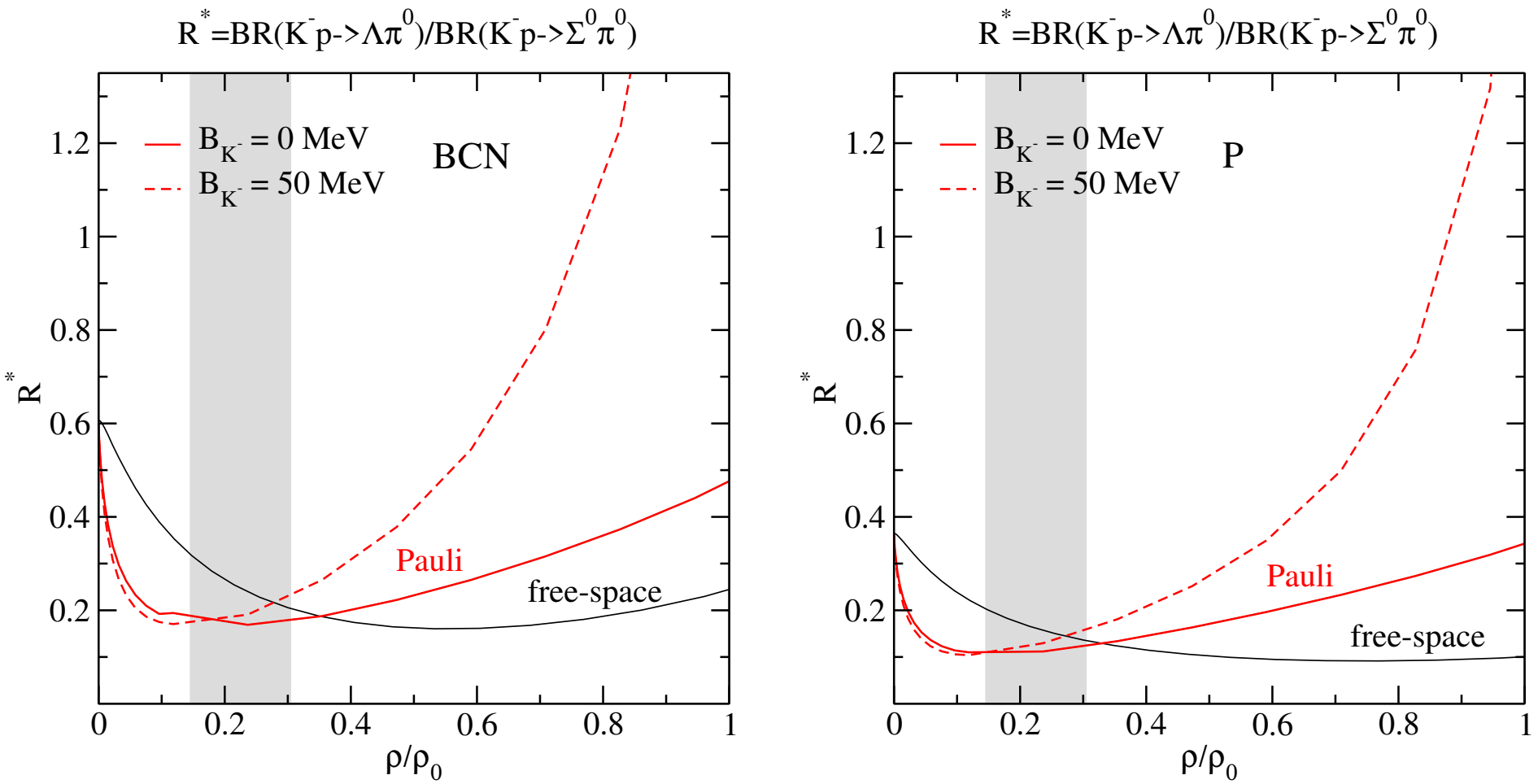


Fig.8: The ratio R^* as a function of relative density, calculated using the free-space and Pauli blocked amplitudes for $B_{K^-} = 0$ MeV and $B_{K^-} = 50$ MeV. The gray band denotes the region of densities probed in experiments with low-energy K^-.

Comparison with experimental data

Table 2: Primary-interaction ratios (in %) for mesonic absorption of K^- in nuclear matter, calculated with free-space and Pauli blocked BCN amplitudes for $B_{K^-} = 0$ MeV. The experimental data corrected for primary[a] interaction are shown for comparison.

BCN	$0.3\rho_0$		$0.5\rho_0$		Exp. [1]	
mesonic ratio	f.s.	Pauli	f.s.	Pauli	^{4}He	^{12}C
$\Sigma^+\pi^-/K^-$	19.0	28.0	21.4	27.6	31.2 ± 5.0	29.4 ± 1.0
$\Sigma^-\pi^0/K^-$	6.0	5.5	4.2	5.3	4.9 ± 1.3	2.6 ± 0.6
$\Sigma^-\pi^+/K^-$	21.3	14.4	15.8	9.3	9.1 ± 1.6	13.1 ± 0.4
$\Sigma^0\pi^-/K^-$	6.0	5.6	4.2	5.4	4.9 ± 1.3	2.6 ± 0.6
$\Sigma^0\pi^0/K^-$	17.6	18.7	16.9	16.0	17.7 ± 2.9	20.0 ± 0.7
$\Lambda\pi^0/K^-$	3.7	3.4	2.8	3.5	5.2 ± 1.6	3.4 ± 0.2
$\Lambda\pi^-/K^-$	7.4	6.8	5.6	7.2	10.5 ± 3.0	6.8 ± 0.3
total 1N ratio	81.0	82.4	70.9	74.3	83.5 ± 7.1	77.9 ± 1.6

[a] Corrected for secondary interactions of the primary particles created in the absorbing nucleus.

[1] *C. Vander Velde-Wilquet et al., Nuovo Cimento 39 A (1977) 538*

Comparison with experimental data

Table 3: Primary-interaction total ratios (in %) for non-mesonic and total (1N+2N) K^- absorption in matter and corresponding ratios corrected for Σ-Λ conversion with different conversion rates, a) - 60% for Σ^+-Λ, 22.5% for Σ^--Λ, 72% for Σ^0-Λ, b) - 50% for all Σ's, calculated with Pauli blocked BCN amplitudes for $B_{K^-} = 0$ MeV.

BCN	$0.3\rho_0$	$0.3\rho_0$+Σ-Λ conv.		Exp. [2]
non-mesonic ratio		a)	b)	^{4}He
$(\Lambda N + \Sigma^0 N)/K^-$	8.3	12.0	12.9	11.7 ± 2.4
$\Sigma^- N/K^-$	4.9	3.8	2.5	3.6 ± 0.9
$\Sigma^+ N/K^-$	4.3	1.7	2.2	1.0 ± 0.4
$\Sigma^0 N/K^-$	4.2	1.2	2.1	2.3 ± 1.0
total 2N ratio	17.6	17.6		16.4 ± 2.6
total ratio				
Σ^+/K^-	32.3	12.9	16.2	17.0 ± 2.7
Σ^-/K^-	24.8	19.2	12.4	13.8 ± 1.8
Σ^0/K^-	28.5	8.0	14.3	10.8 ± 5.0
Λ/K^-	14.3	59.8	57.2	58.4 ± 5.7
Σ^+/Σ^-	1.3	0.7	1.3	1.2 ± 0.2

[2] *P. A. Katz et al., PRD 1 (1970) 1267*

Conclusions

- Interaction of K^- with two and more nucleons important for realistic description of K^--nucleus interaction
- We have developed a microscopic model for K^-NN absorption in nuclear matter using scattering amplitudes derived from P and BCN chiral meson-baryon interaction models

  J. Hrtánková, À. Ramos, arXiv:1910.01336 [nucl-th], submitted to PRC
- Pauli blocked amplitudes included $\rightarrow$ medium effects non-negligible
- Calculated ratios in a good agreement with experimental data!
- Further application of the model in the calculations of kaonic atoms and K^--nuclear quasibound states

Backup

Backup slides

Free-space vs. Pauli blocked amplitudes

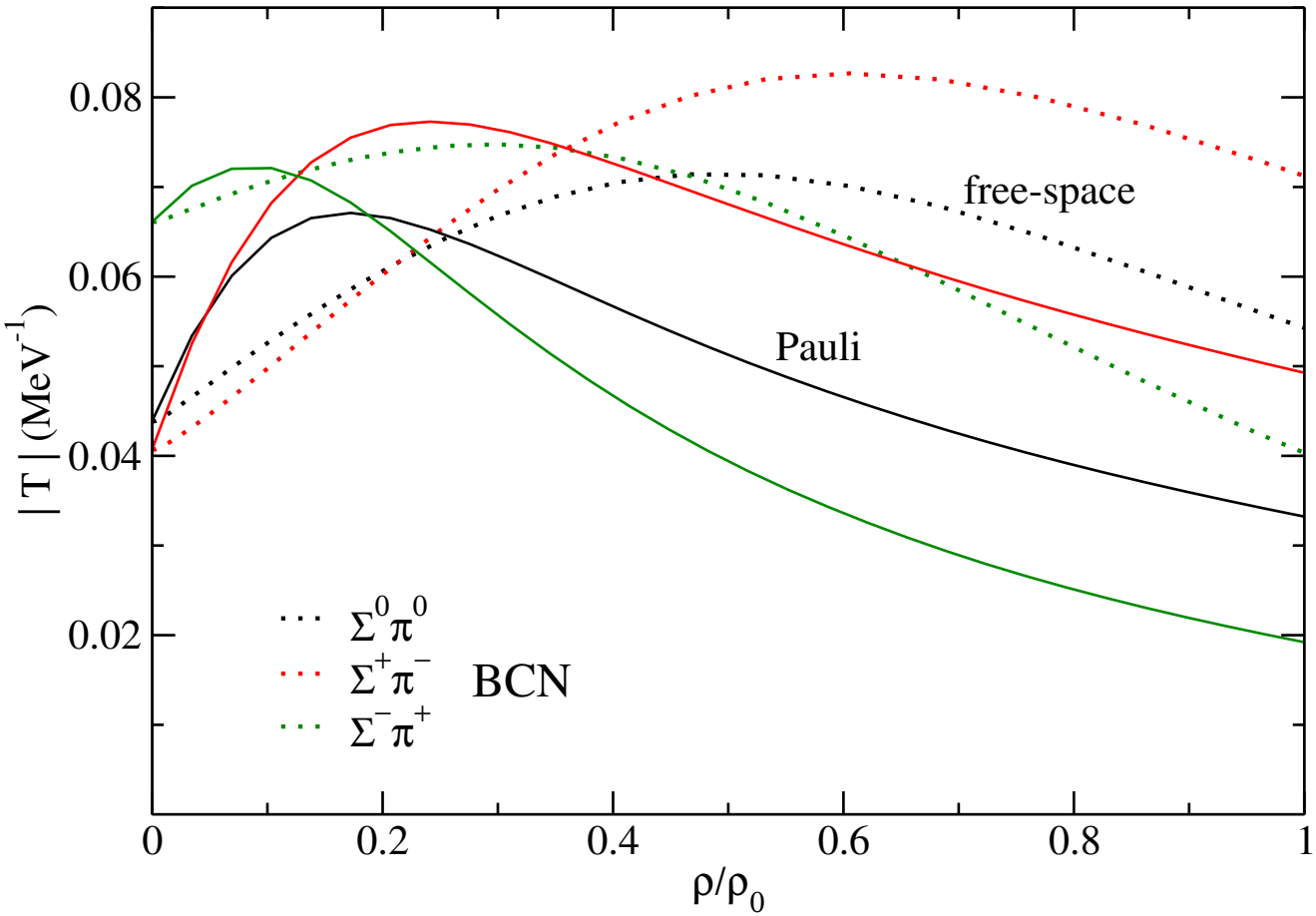


Fig.9: Absolute values of $\Sigma^0\pi^0$ (black), $\Sigma^+\pi^-$ (red), and $\Sigma^-\pi^+$ (green) free-space (dotted) and Pauli blocked (solid) BCN model t-matrices as functions of relative density ρ/ρ_0, printed for energy shift corresponding to $B_{K^-} = 0$ MeV.

K^- potential in nuclear matter

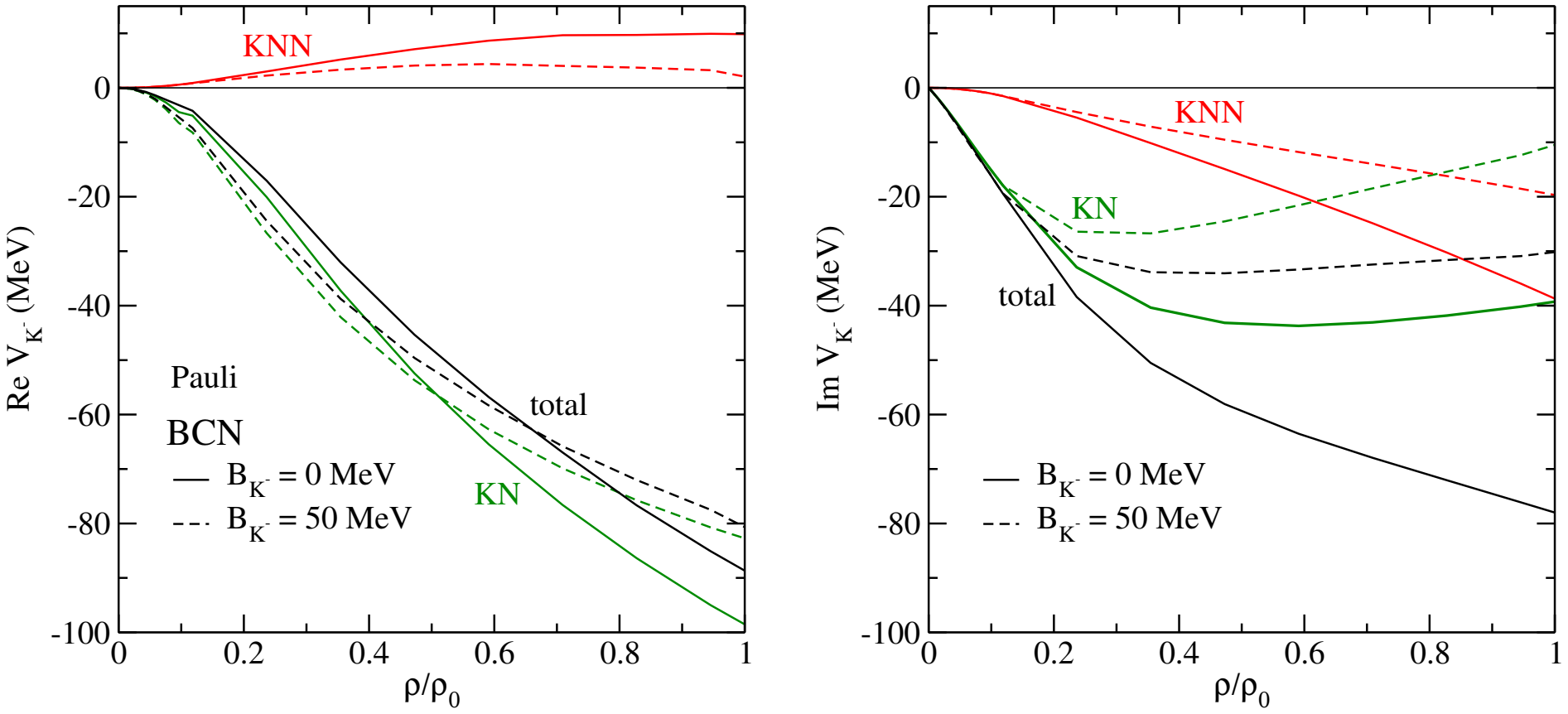


Fig.10: Real (left) and imaginary (right) parts of the K^-N, K^-NN, and total optical potential as a function of relative density, calculated using the Pauli blocked BCN amplitudes for $B_{K^-} = 0$ and 50 MeV.