Quark-model predictions for the ΞN interaction and the implications to Ξ hypernuclei

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- Importance of obtaining a realistic potential-model description for octet baryon-baryon interactions to understand properties of baryons and baryonic systems.
- At present, experimental data is scarce.
- Theoretical models play an important role.
  - OBEP, constituent quark model, chiral EFT, and …..
- The SU_6 quark model fss2 by the Kyoto-Niigata group is promising: reliable extension to the S=-1 and S=-2 sectors on the basis of the *NN*.
- Predictions of fss2 to hypernuclear properties. Especially Ξ hyperon.
  - Comparison of fss2 and the chiral EFT.

Kyoto-Niigata baryon-baryon interactions in the SU_6 quark model

- RGM description for three-quark clusters
  - effective one-gluon exchange

    ✚
  - scalar (ε, S*, δ, κ), pseudo-scalar (π, K), and vector (ω, ϕ, ρ, K*) meson exchanges between quarks
- most recent model: fss2
  - Y. Fujiwara et al., Phys. Rev. C 64, 054001 (2001).
  - Review: Y. Fujiwara, Y. Suzuki, and C. Nakamoto, Prog. Part. Nucl. Phys. 58 (2007) 439-520.
- no revision since 2001.

- To relate YN two-body bare interactions to empirical quantities, it is useful to calculate microscopically hyperon single-particle potentials in finite nuclei (and equivalent interactions in low-momentum space).

- Evaluate *G*-matrices in symmetric nuclear matter in the LOBT.

$$G_{YN}(k_F) = v + v\frac{Q(k_F)}{\omega - (T_{YN} + U_Y + U_N)}G_{YN}(k_F)$$

$$U_Y = \sum_h \langle Yh | G_{YN} | Yh \rangle$$

- Apply *G* to finite nuclei through LDA and spin-orientation average. ➡ Non-local potential (due to the exchange character of *YN* interaction).

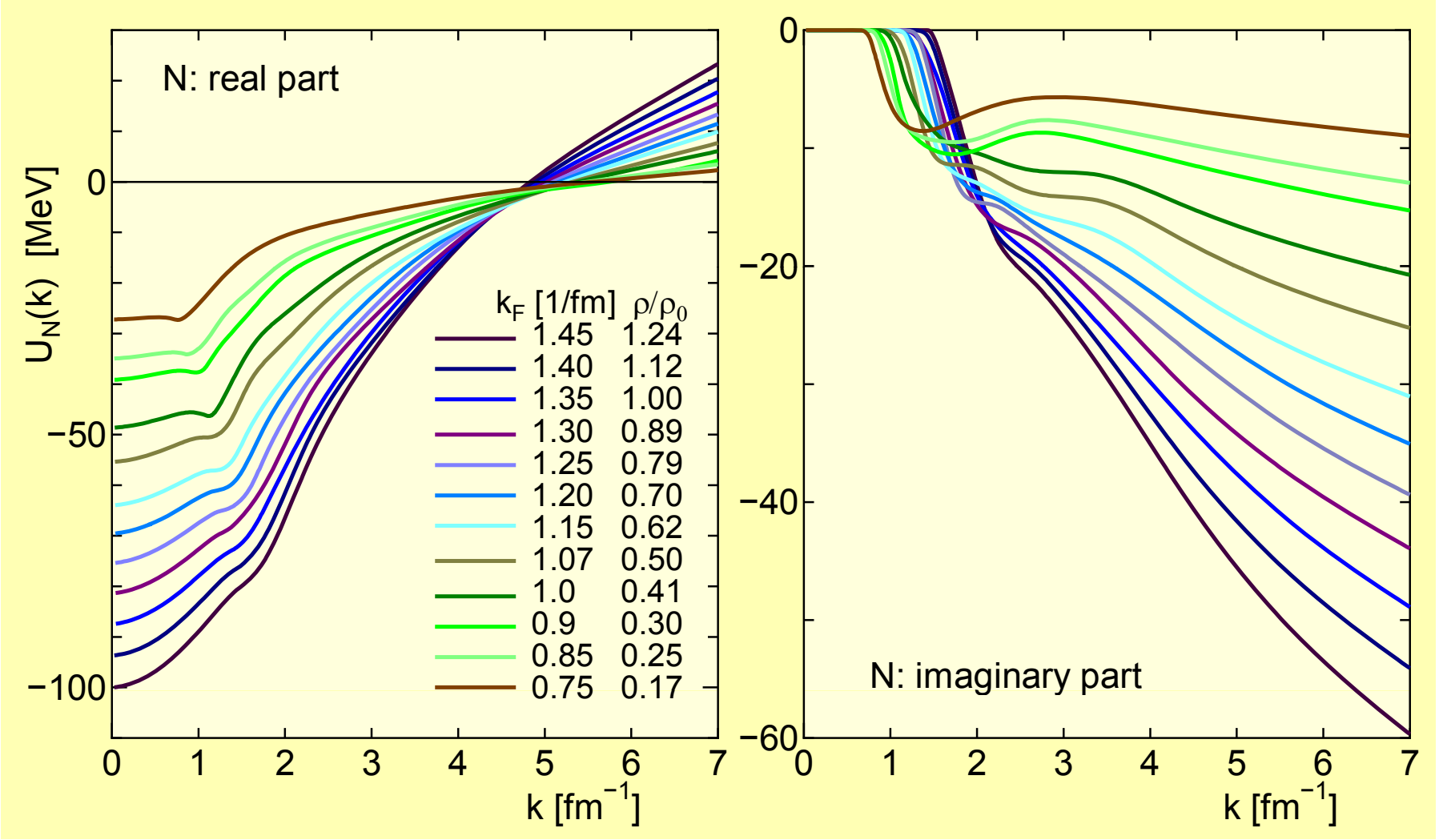
$$\langle j_Y | U_Y | j_Y \rangle = \sum_h \langle j_Y h | G_{YN}(k_F(r_1, r_2)) | j_Y h \rangle$$

- Localization by zero-momentum Wigner tf.

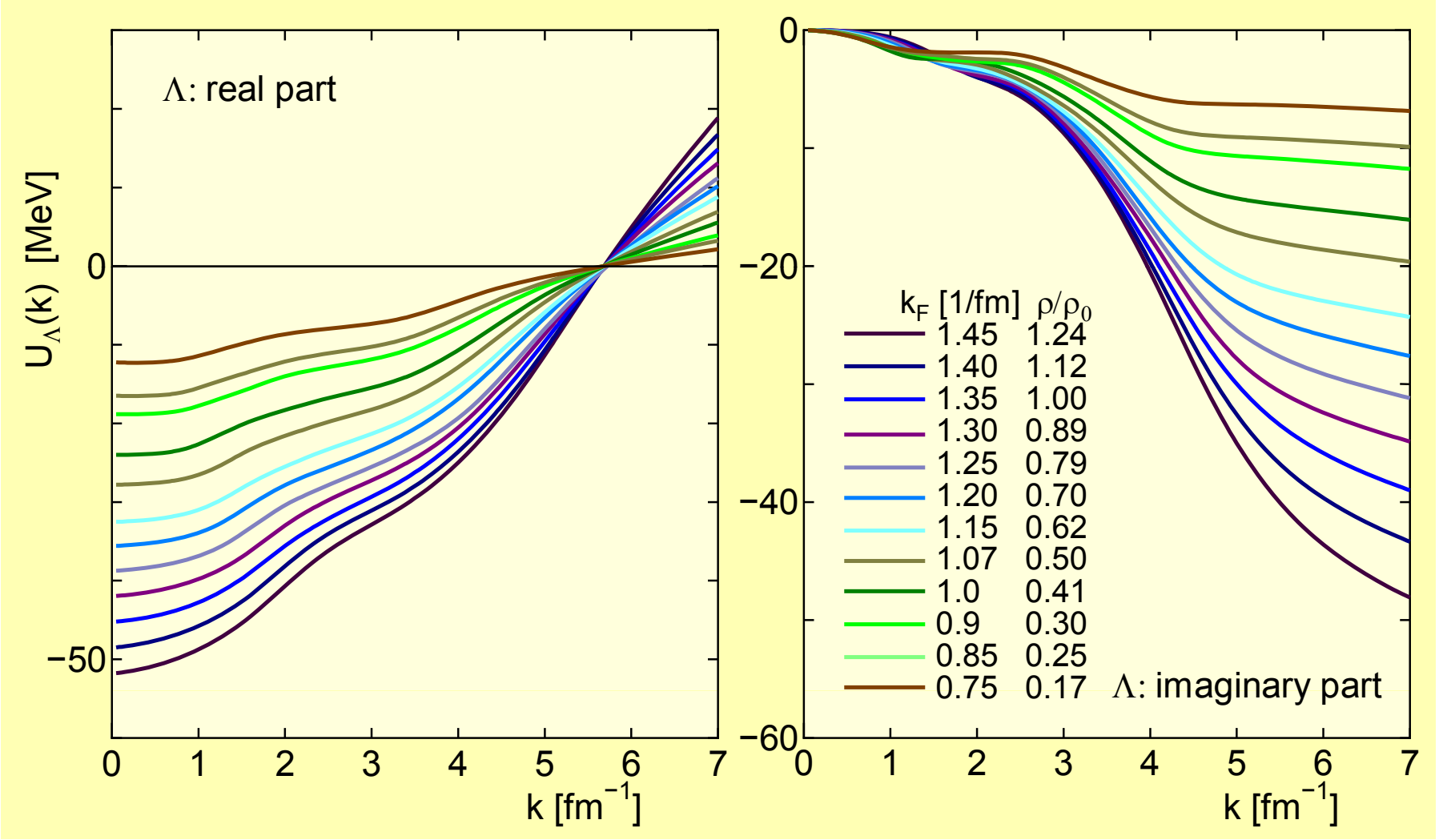
$$U_Y^W(\mathbf{R}, \mathbf{p}) = \int d\mathbf{s}\, e^{i\mathbf{p}\bullet\mathbf{s}} U_Y(\mathbf{R} + \tfrac{1}{2}\mathbf{s}, \mathbf{R} - \tfrac{1}{2}\mathbf{s}) \quad \Rightarrow \quad U_Y^W(\mathbf{R}, \mathbf{p} = 0)$$

- Calculations for ^{12}C, ^{16}O, ^{28}Si, ^{40}Ca, ^{56}Fe, ^{90}Zr .

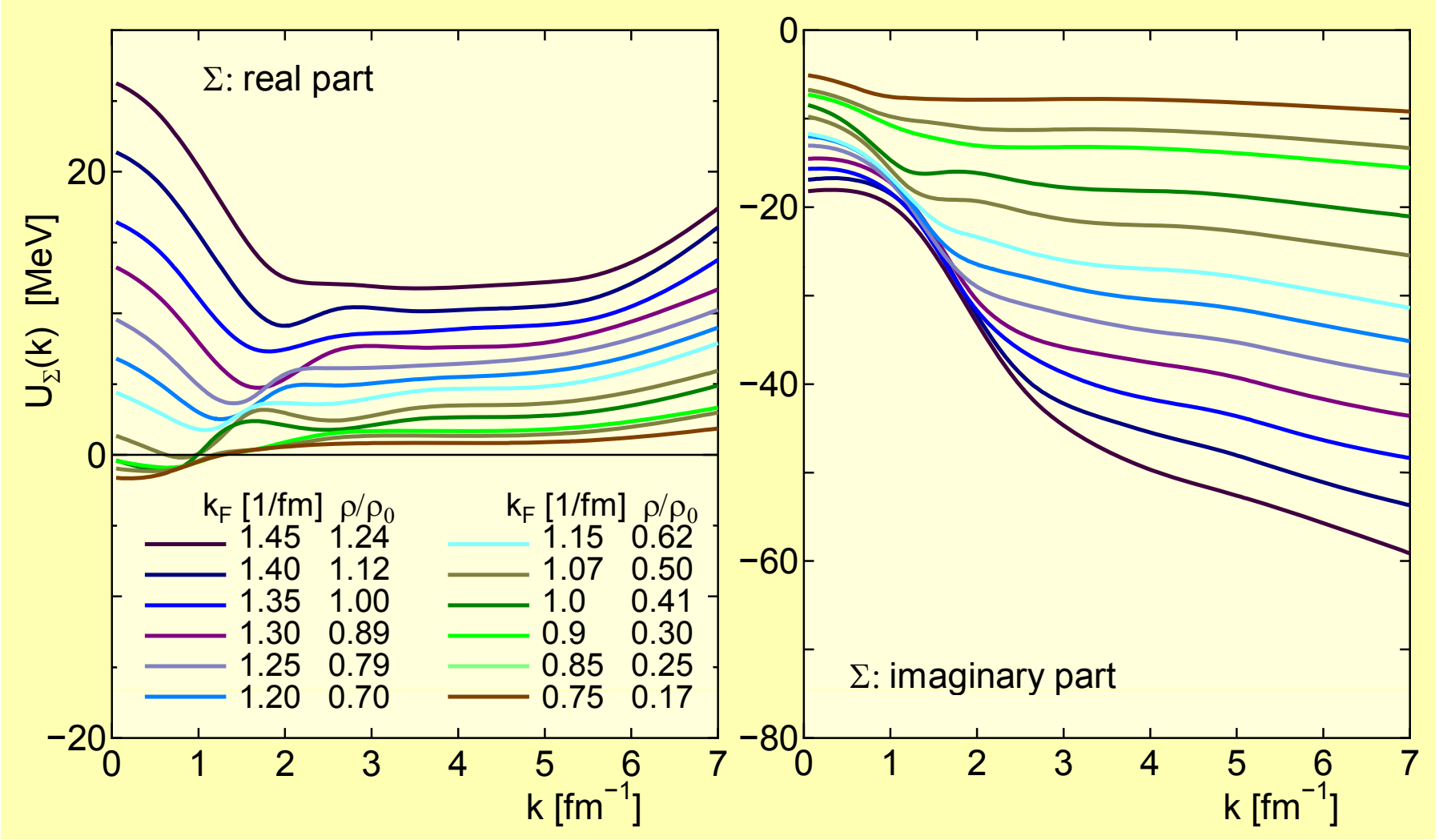
k -dependence of LOBT nucleon s.p. potential in symmetric nuclear matter with fss2.



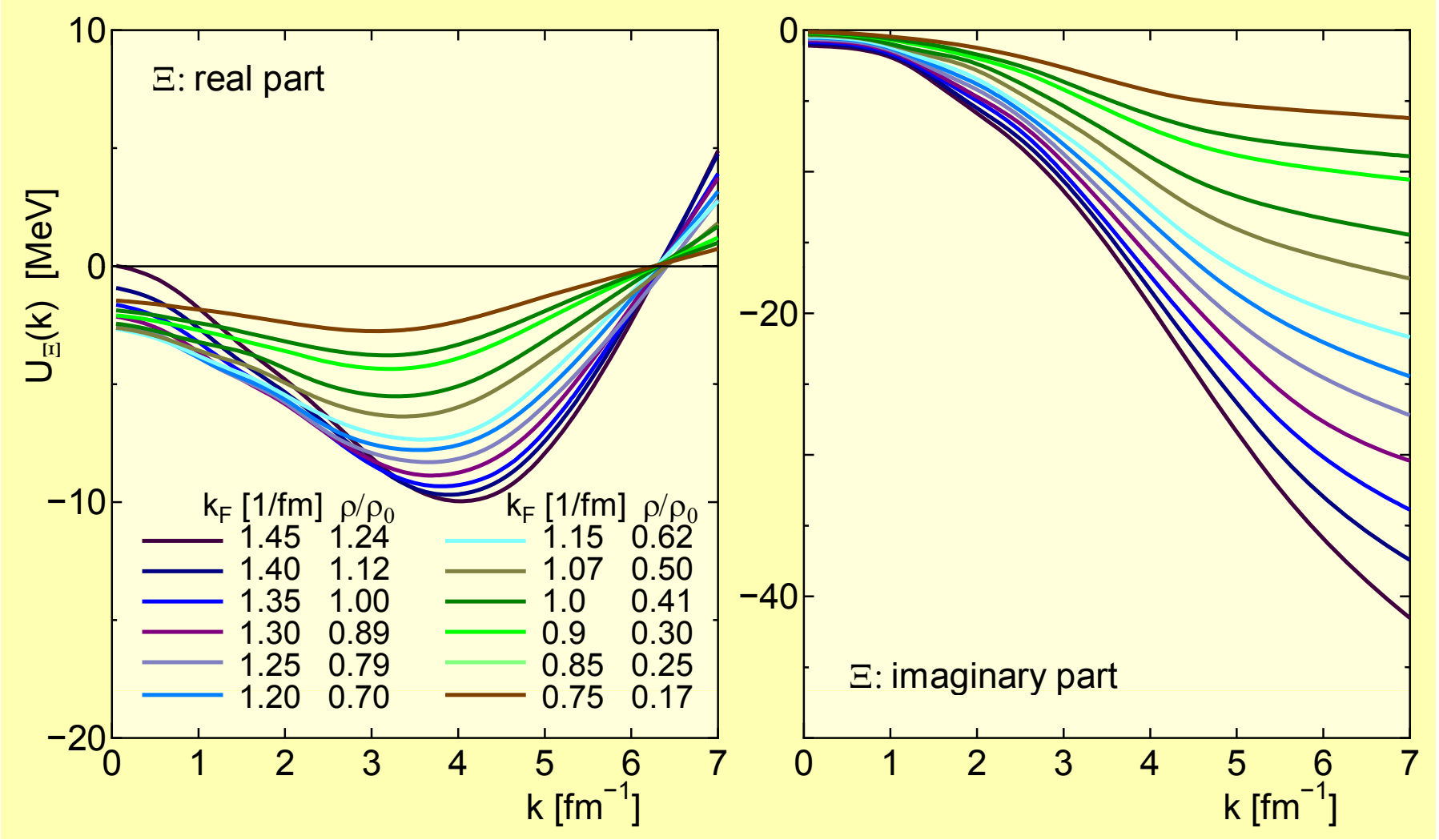
k -dependence of LOBT Λ s.p. potential in symmetric nuclear matter with fss2.



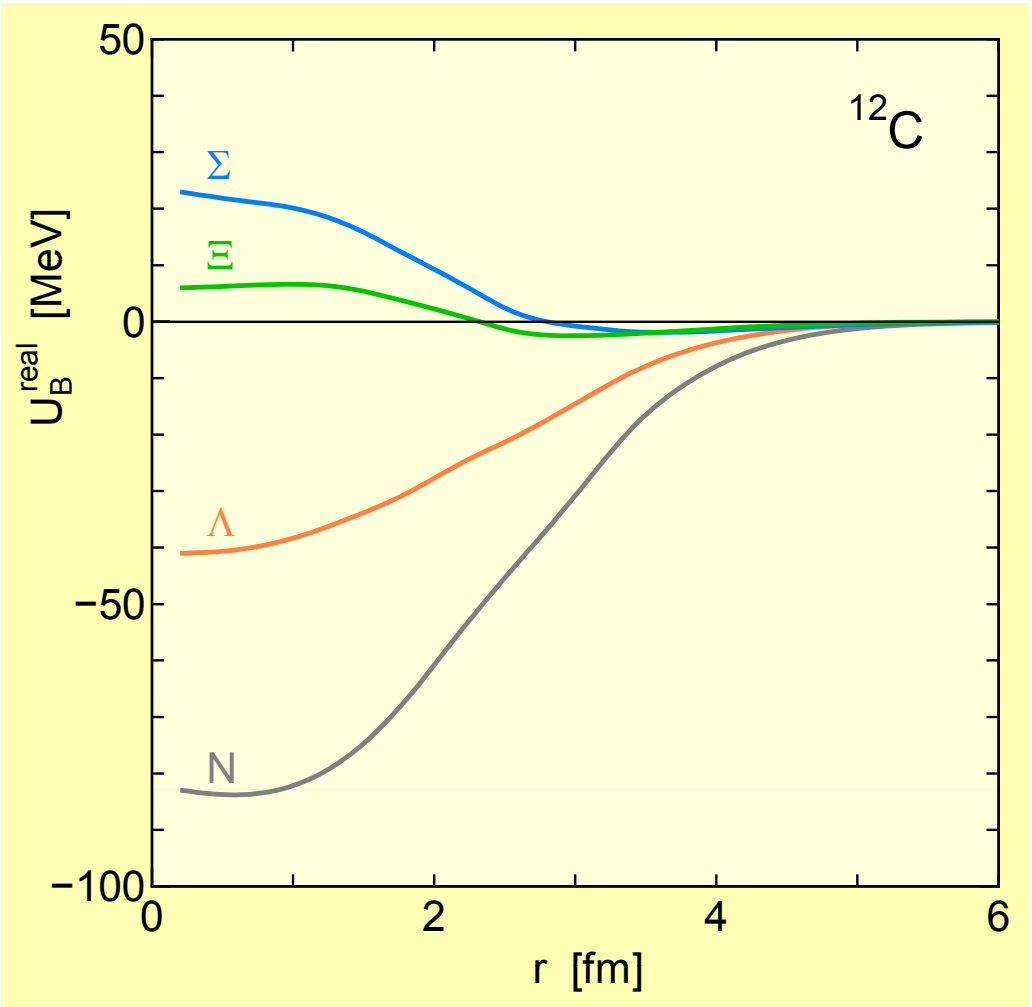
k -dependence of LOBT Σ s.p. potential in symmetric nuclear matter with fss2.

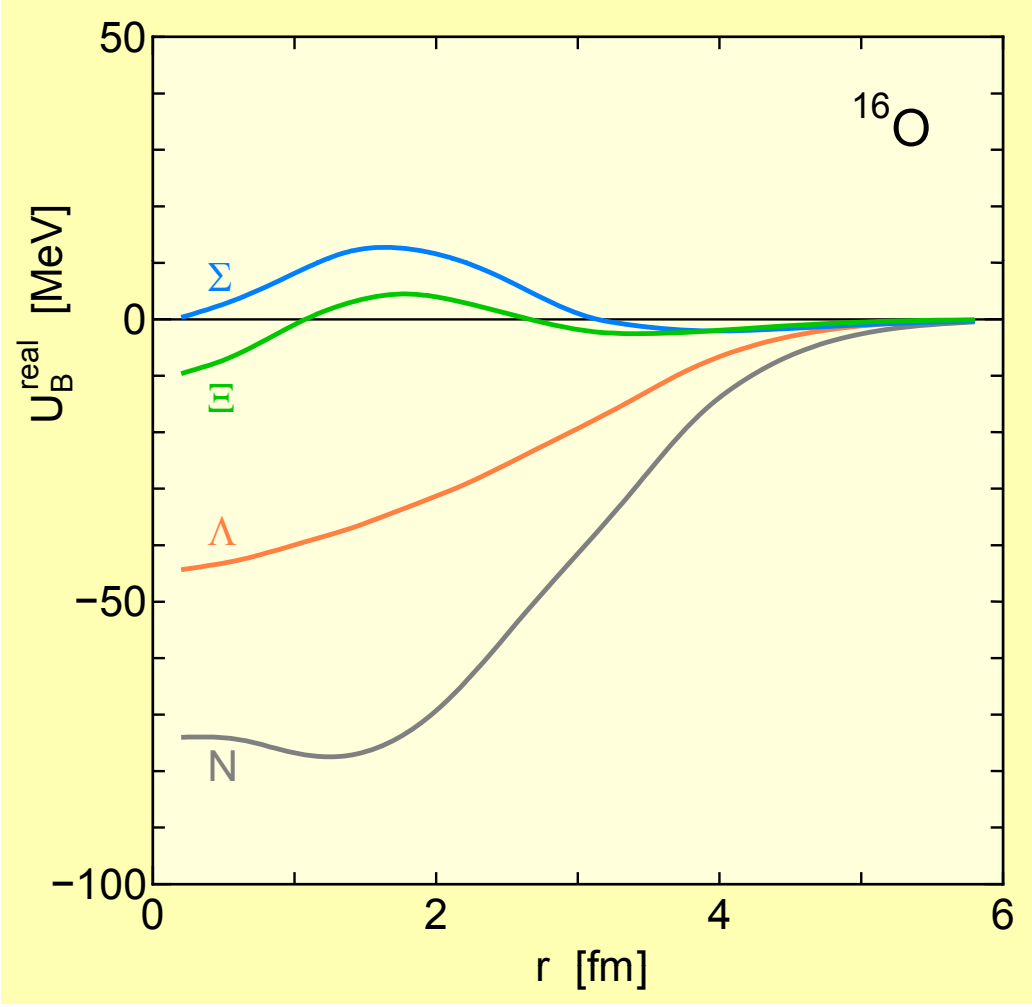


k -dependence of LOBT Ξ s.p. potential in symmetric nuclear matter with fss2.

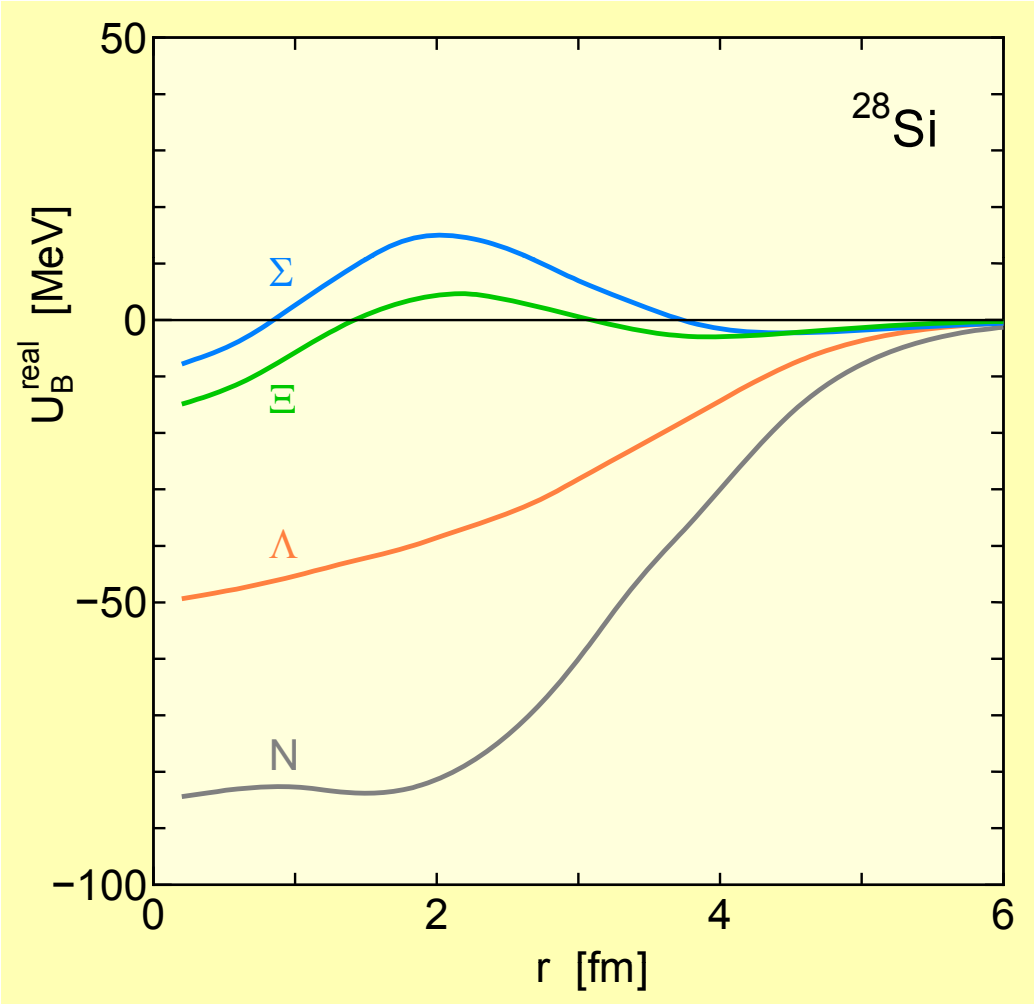


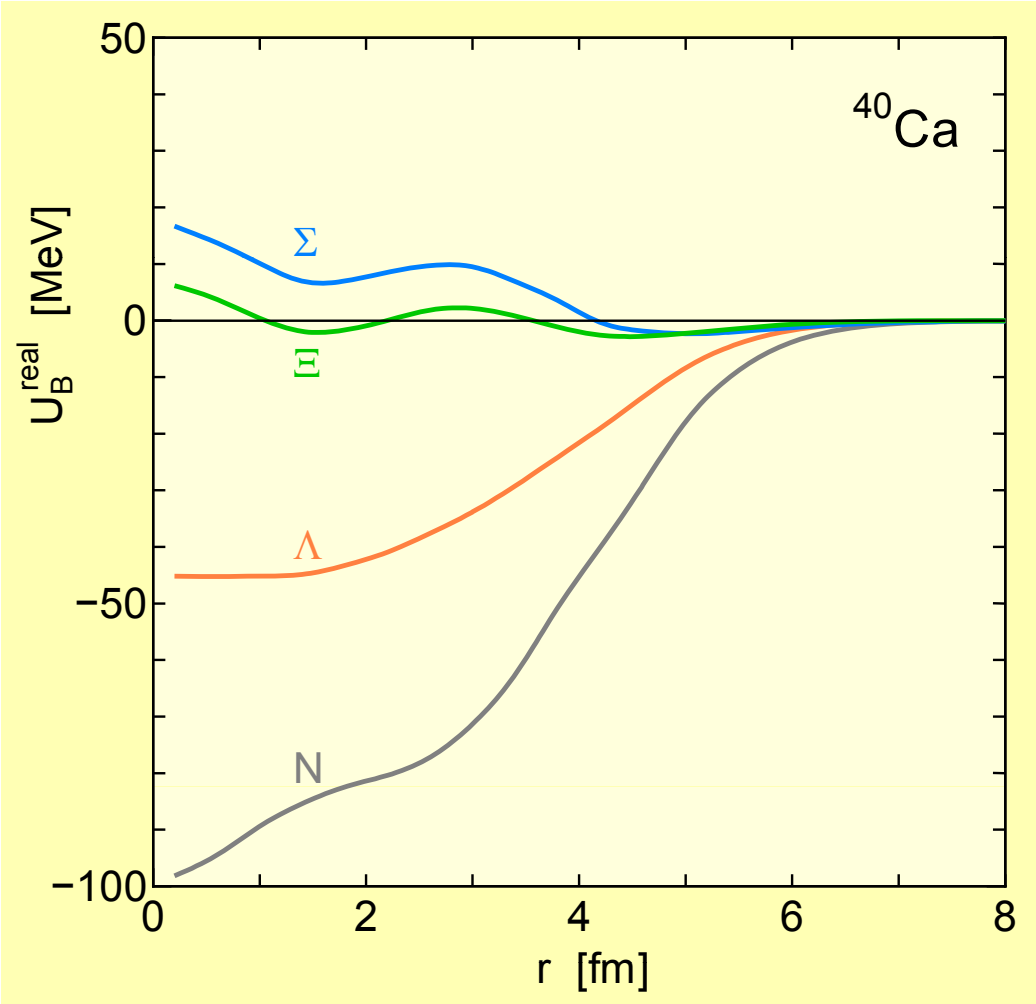
Real part of localized s.p. potentials for N, Λ, Σ and Ξ in ^{12}C and ^{16}O with fss2.



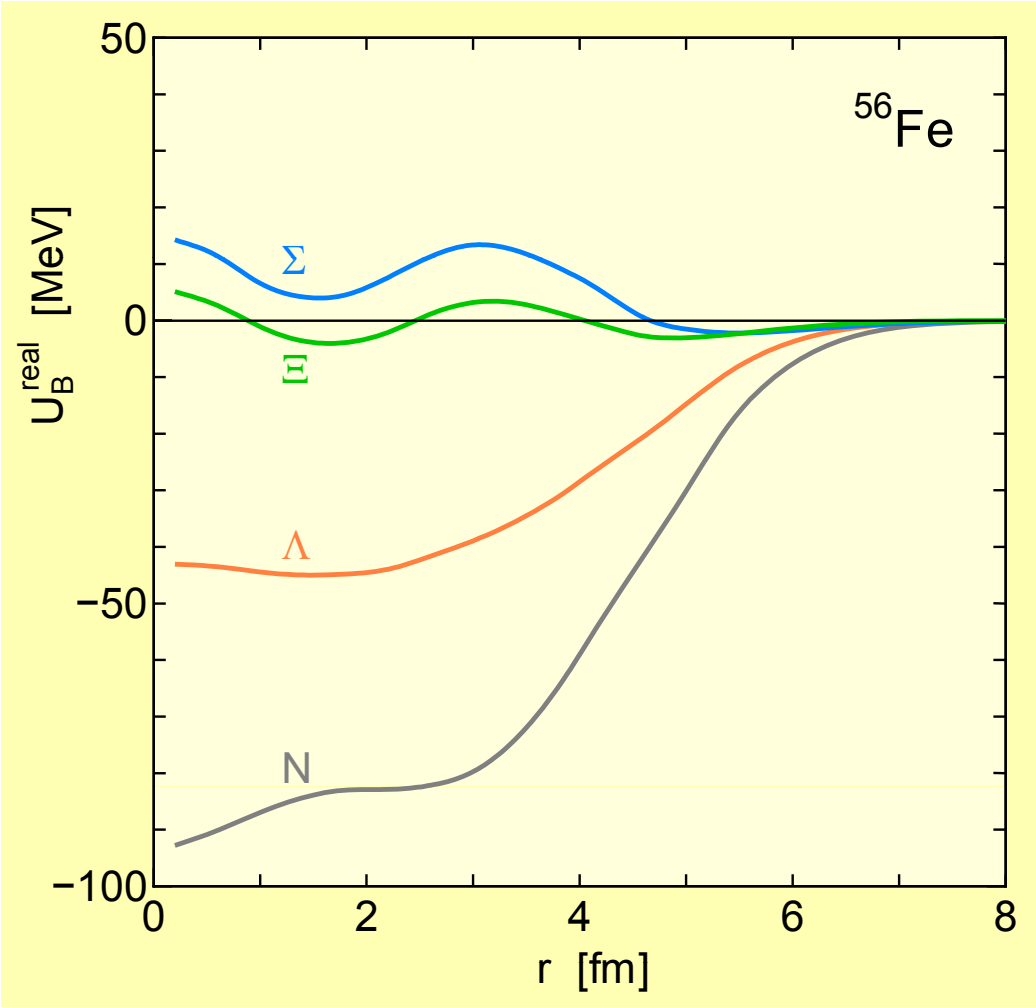


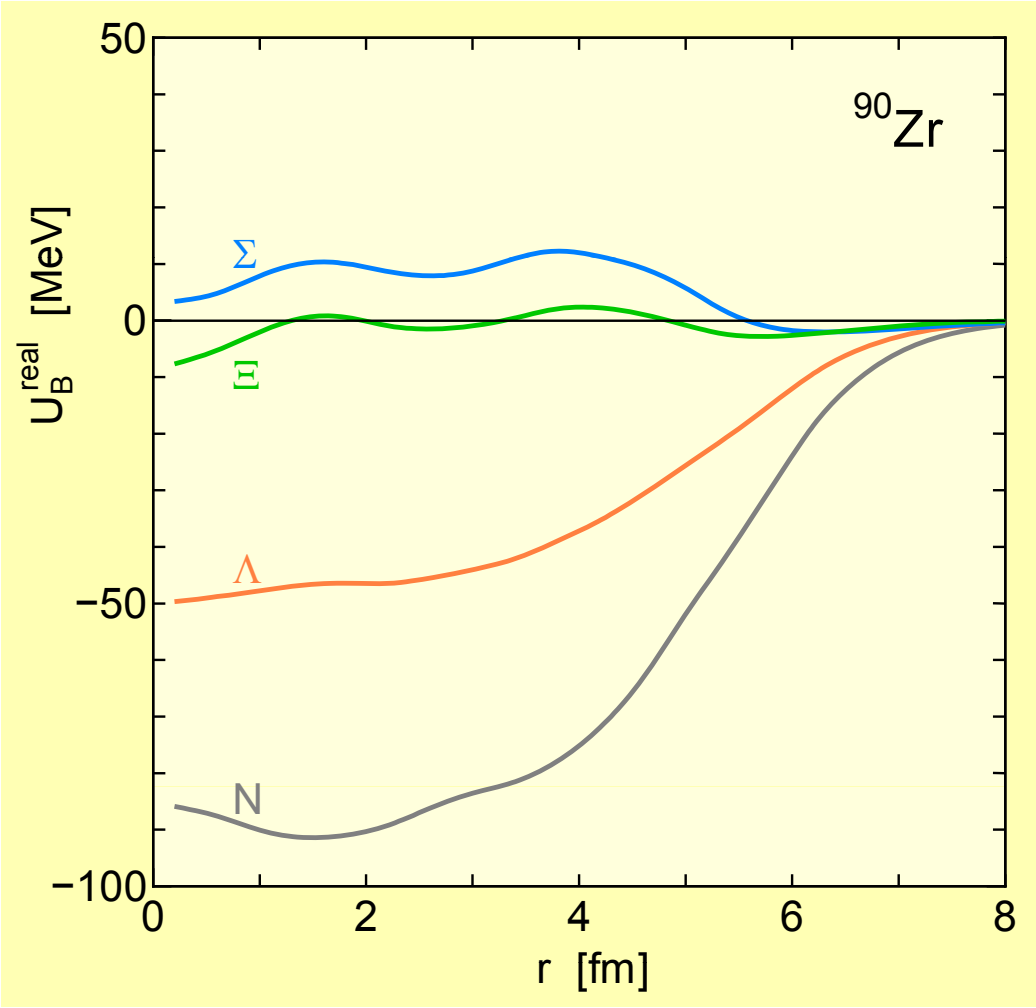
Real part of localized s.p. potentials for N, Λ, Σ and Ξ in ^{28}Si and ^{40}Ca with fss2.





Real part of localized s.p. potentials for N, Λ, Σ and Ξ in ^{56}Fe and ^{90}Zr with fss2.





Hypernuclear properties with fss2

- Λ hyperon: reasonable.
- Σ hyperon: microscopic calculations reproduce the subtle structure of the Σ-nucleus potential.
  - Weak attraction at the nuclear surface region.

    Shifts and widths of Σ^- atomic levels. Batty, Friedman, Gal, Phys. Lett. B335, 273('94)
  - Repulsion (a few tens MeV) inside a nucleus.

    (K^-, π^+) Σ^- production inclusive spectra. Noumi *et al*., P.R.L. 89, 072301 (2002)
- Then, results for Ξ hyperon (weak attraction at the surface and fluctuation around 0 inside) are believable.

  To be confronted with experiments.

Weak Ξ-nucleus potential is not inconsistent with the existing (K^-, K^+) spectrum by Khaustov *et al*. [Phys. Rev. C 61, 054602 (2000).

- At present, the canonical value of U_Ξ^0 is -14 MeV.
- However, our DWIA calculations in the SCDW method indicates that the almost zero potential suggested by fss2 is preferable.
- In that case, Ξ hypernuclear bound states are unlikely.
- Naturally, the present data is not accurate enough to give a conclusion.
- Data with better accuracy from J-PARC experiments.

P. Khaustov et al., Phys. Rev. C 61, 054603 (2000)

1.8 GeV/c K^-, (K^-, K^+) events on carbon

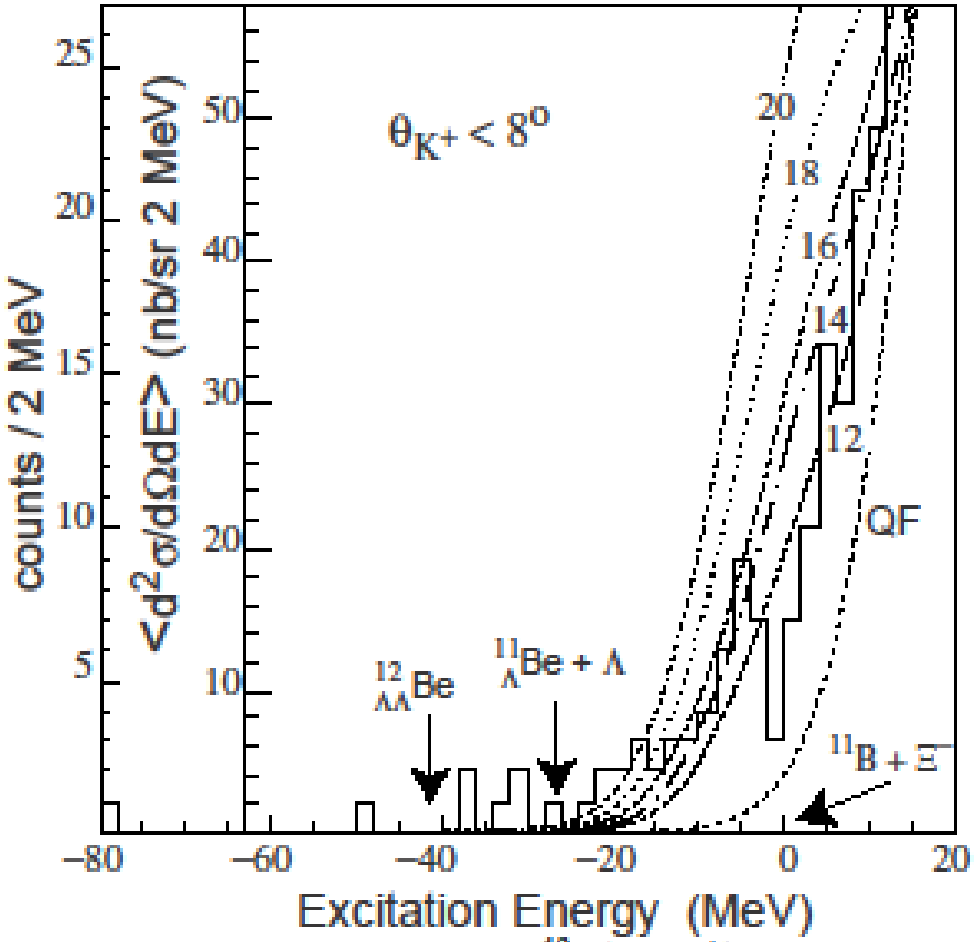
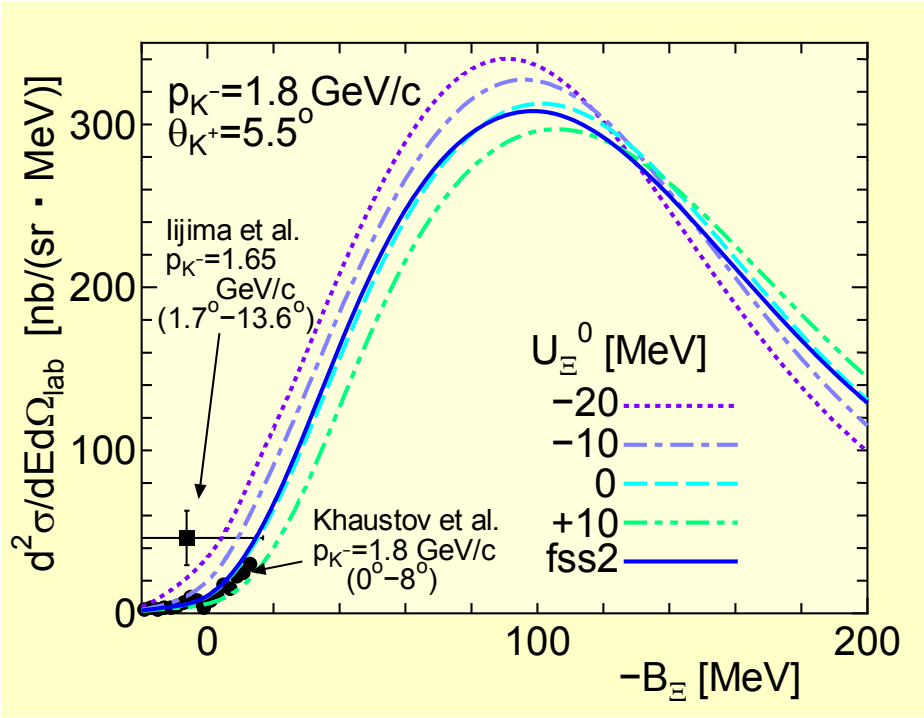
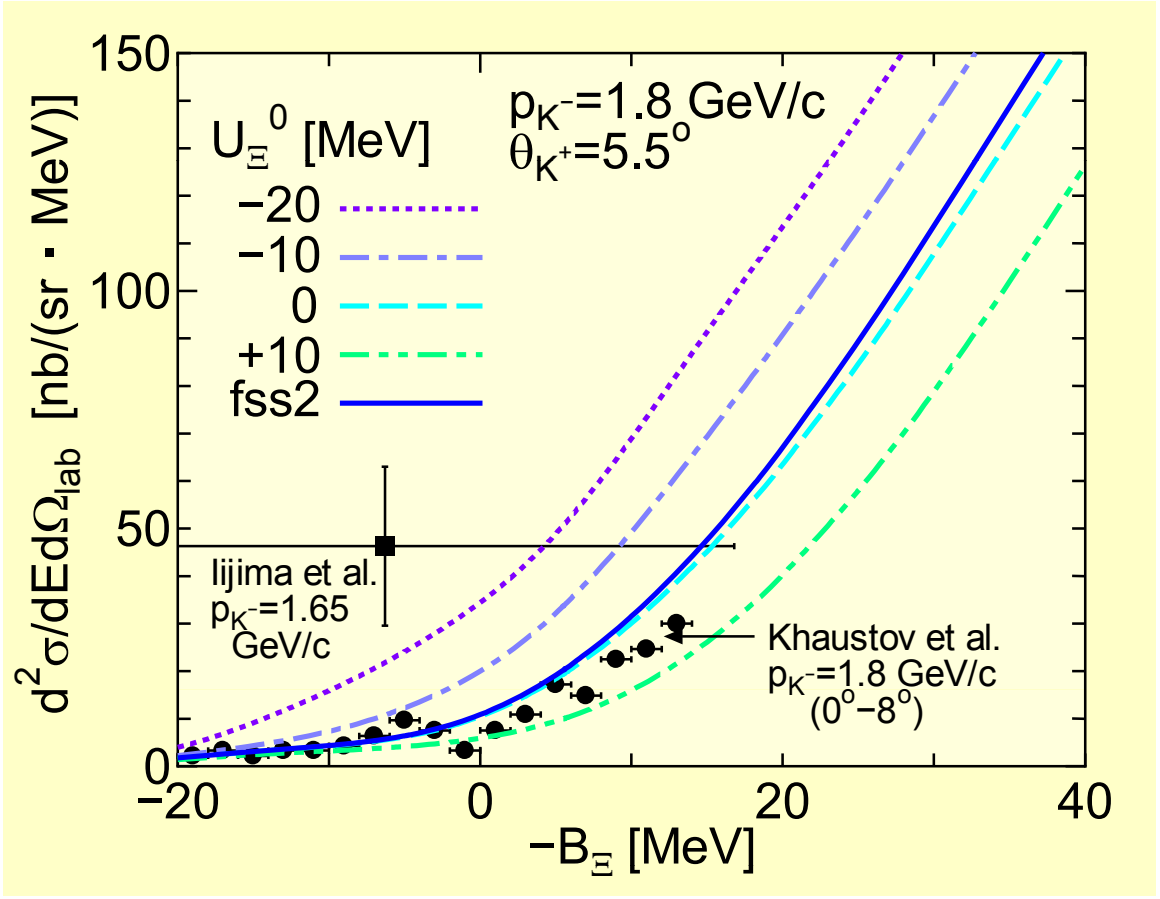


FIG. 6. Excitation-energy spectra from E885 for $^{12}C(K^-,K^+)X$ for θ_{K^+} <14° (top figure) and θ_{K^+} <8° (bottom figure) along with $^{12}_{\Xi}Be$ production theoretical curves for $V_{0\Xi}$ equal to 20, 18, 16, 14, and 12 MeV. The results of a quasi-free Ξ production calculation are also shown (curve QF). The expected location of the ground state of $^{12}_{\Lambda\Lambda}Be$ and the thresholds for $^{11}_{\Lambda}Be + \Lambda$ and $^{11}B + \Xi^-$ production are indicated with arrows.

Semi-Classical Distorted Wave model calculation of (K^-, K^+) Ξ^- production inclusive spectrum on ^{12}C.

M. Kohno and S. Hashimoto, nucl-th/0909.1385.





Energy shift and width of Σ^- and Ξ^- atomic orbits in ^{28}Si and ^{56}Fe

- Parameterize the calculated local s.p. potential in a 3-range Woods-Saxon form and calculate Σ^- and Ξ^- atomic orbits in ^{28}Si and ^{56}Fe.

Energy shift $\Delta E = E - E_C$ and width $\Gamma = -2\,\mathrm{Im}\,E$ of the Σ^- and Ξ^- atomic orbits in ^{28}Si and/or ^{56}Fe. Entries in eV.

Σ^-—^{28}Si	ΔE_{4f}	Γ_{4f}
Real only	-222	---
Real+Img*	-208	249
Exp.	-156∓36	220∓110

*W-S imaginary pot.:

W_0= -9 MeV,

r_0=1.1A$^{1/3}$,

a=0.67 fm.

Ξ^-—^{28}Si	ΔE_{4f}	Γ_{4f}
Real only	-346	---
Real+Img.	-345	16
Ref. W-S	-383	216

Ξ^-—^{56}Fe	ΔE_{4f}	Γ_{4f}
Real only	-1287	---
Real+Img.	-1281	88
Ref. W-S	-1675	1092

Ref. W-S pot.: U_0= -14 -3i MeV, r_0=1.1A$^{1/3}$ and a=0.67 fm.

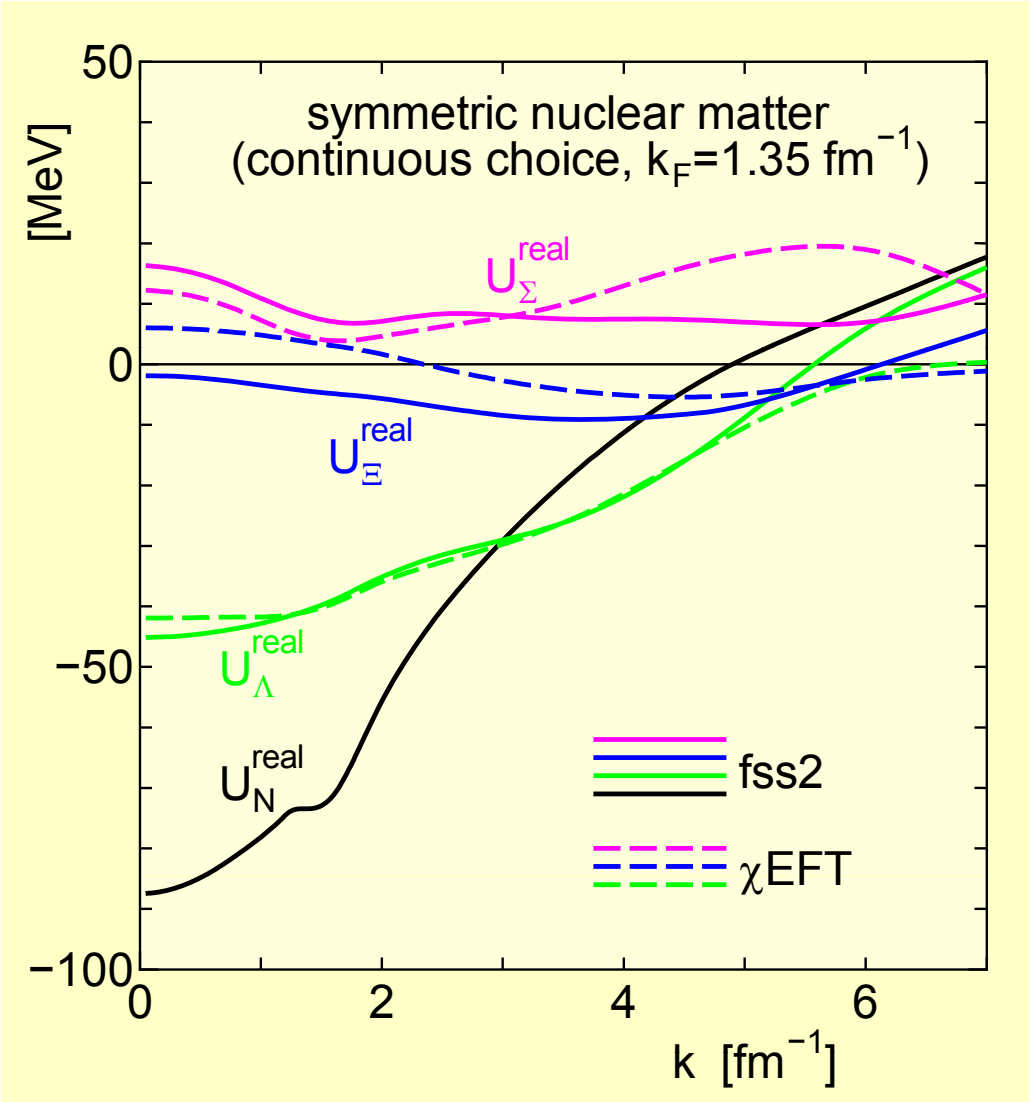
Summary

- Evaluate *N*, Λ, Σ, and Ξ s.p. potentials in finite nuclei using quark-model *YN* potential fss2.
  - Folding nuclear matter G-matrices in finite nuclei by LDA. (spin average and zero momentum Wigner tf.)
- Results for *N* and Λ ⇒ reliability of the method.
- Results for Σ ⇒ agree with empirical data.
  - Weak attraction at the nuclear surface and repulsion inside a nucleus.
- Results for Ξ ⇒ expect no bound states.
  - Weak attraction at the surface. Oscillate around 0 inside.（Not a Woods-Saxon type with a strength of 14MeV.）Consistent with (K^-, K^+) Ξ^- data by Khaustov.
  - Atomic energy shift: 1 keV（ 4g level in ^{56}Fe）.

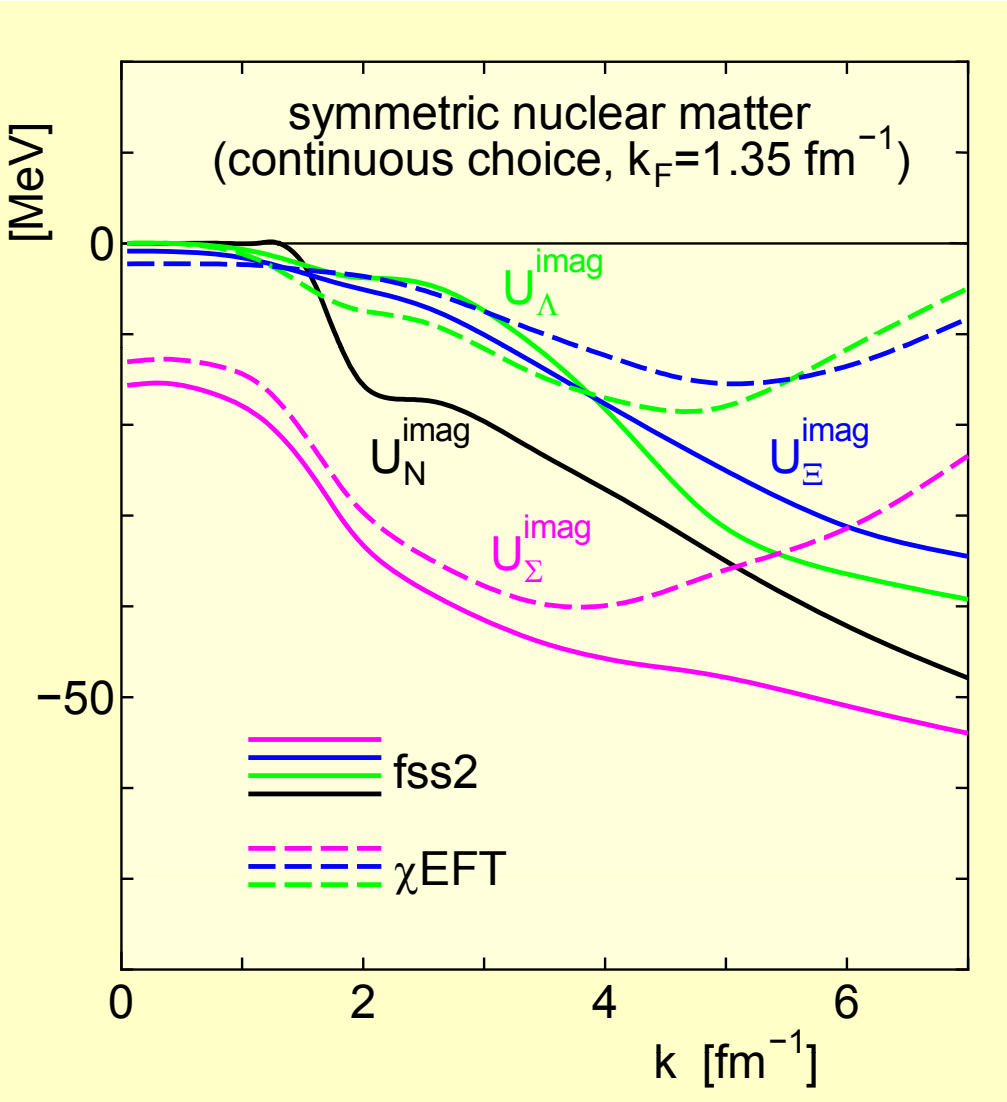
Additional remarks

- Comparison of the quark model potential fss2 and the chiral EFT potential.
  - H. Polinder, J. Haidenbauer, and Ulf-G. Meissner, Nucl. Phys. A779,244 (2006); Phys. Lett. B653, 29 (2007).
  - Pseudoscalar meson exchange + flavor SU3 invariant contact terms.
    - Parameters of the contact terms, 5 in number in the S=-1 sector and an additional one parameter in the S=-2 sector, are phenomenologically determined.
    - Regularization by a cut-off mass of around 600 MeV.
  - Different description from fss2 (short-range part).
- Similar results for Λ, Σ, and Ξ s.p. potentials as with fss2.

Λ, Σ and Ξ s.p. potentials in symmetric nuclear matter with k_F=1.35 fm^{-1} from continuous choice G-matrix calculations, using fss2 and Ch-EFT interactions.



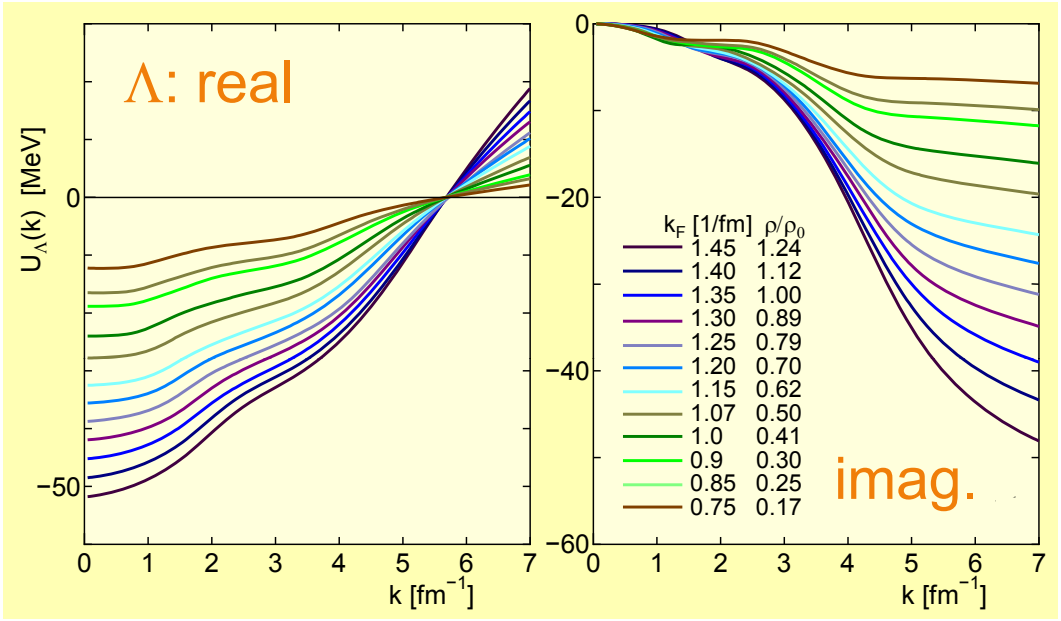
real part

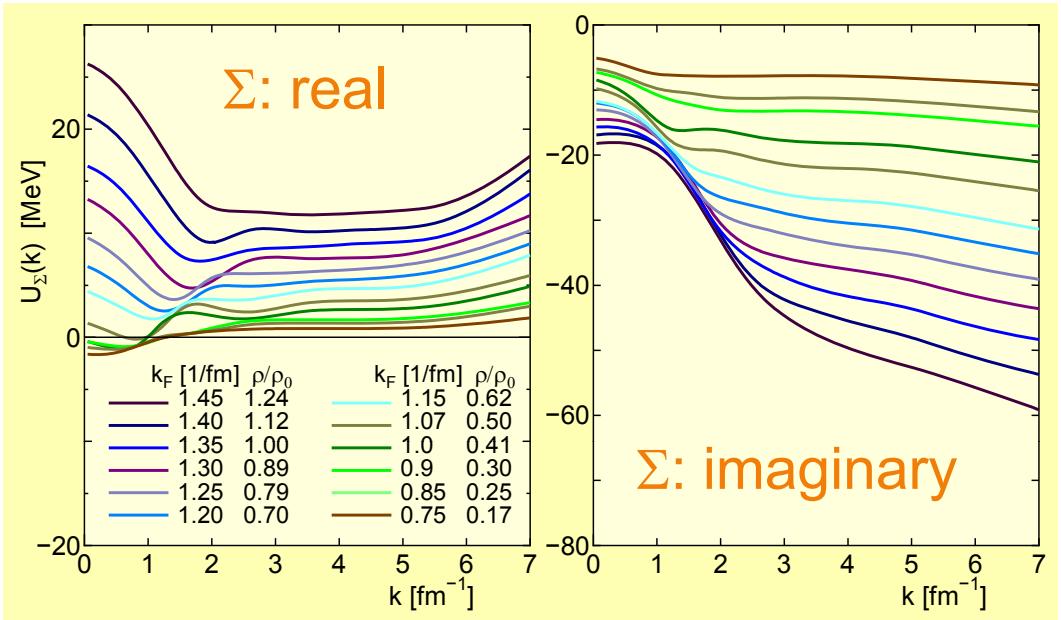


imaginary part

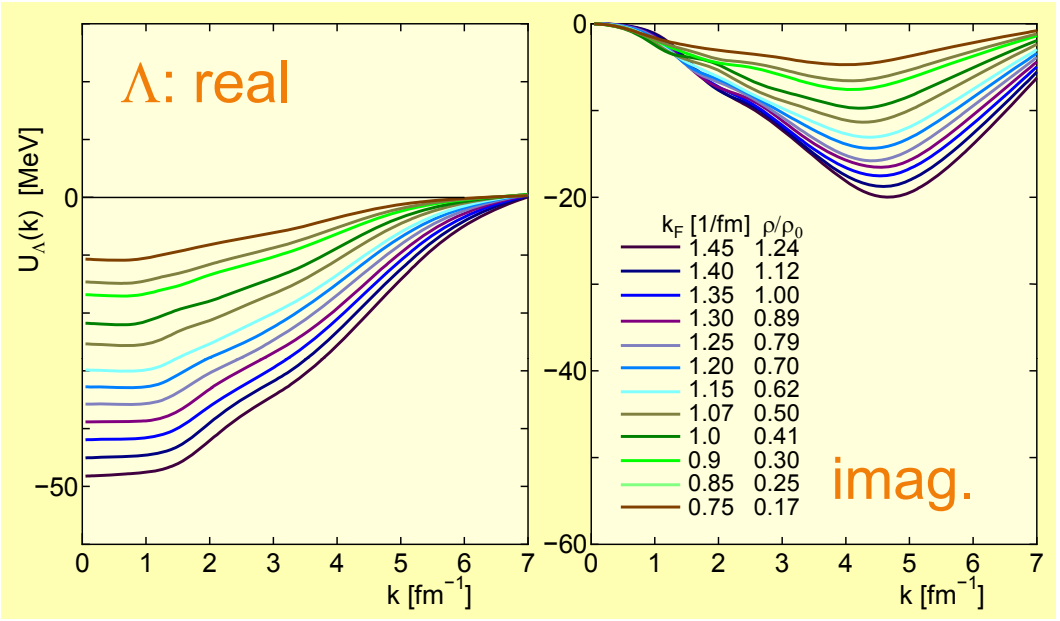
Λ and Σ s.p. potential in symmetric nuclear matter: comparison of fss2 and Ch-EFT

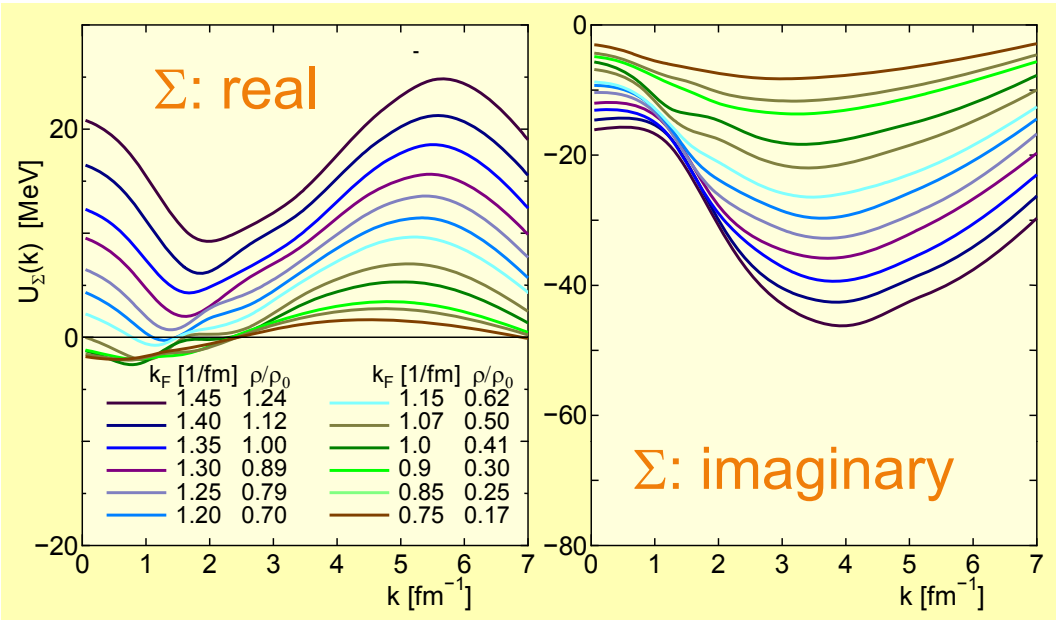
fss2





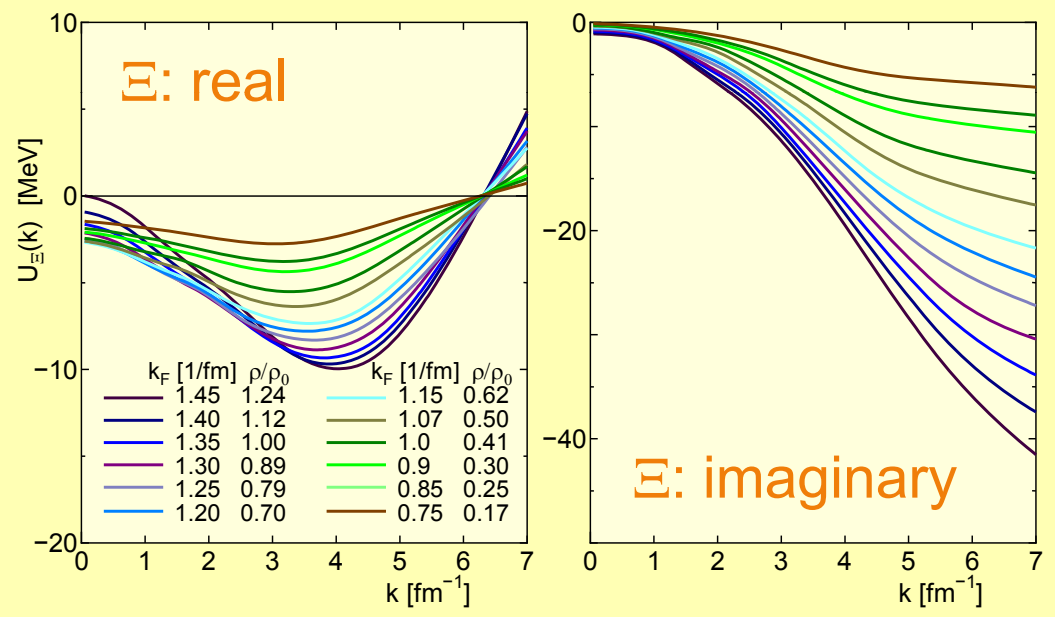
Ch-EFT



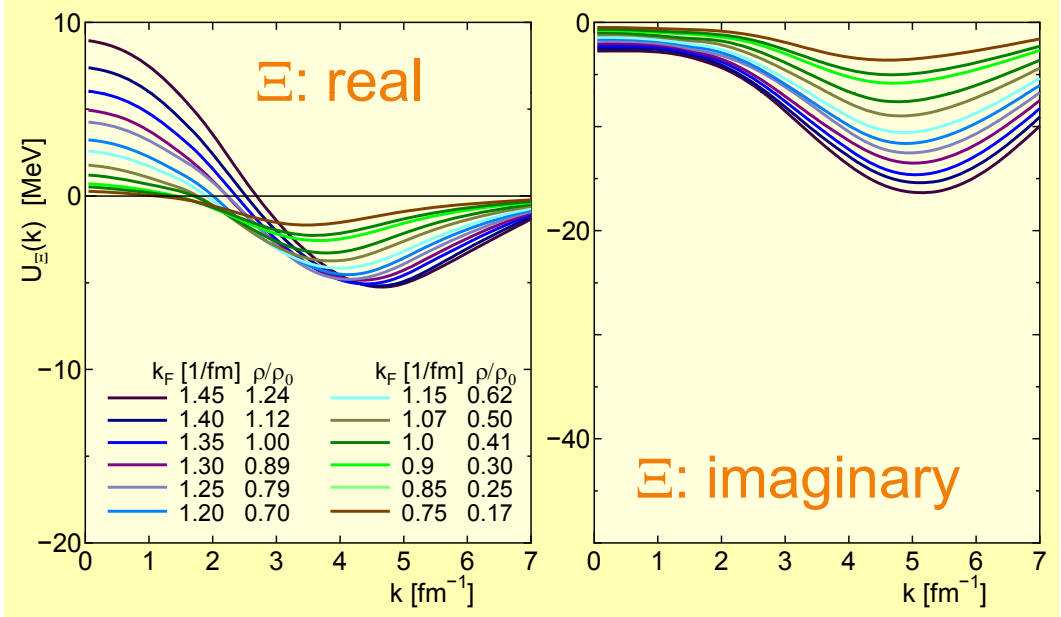


Ξ s.p. potential in symmetric nuclear matter : comparison of fss2 and Ch-EFT

fss2



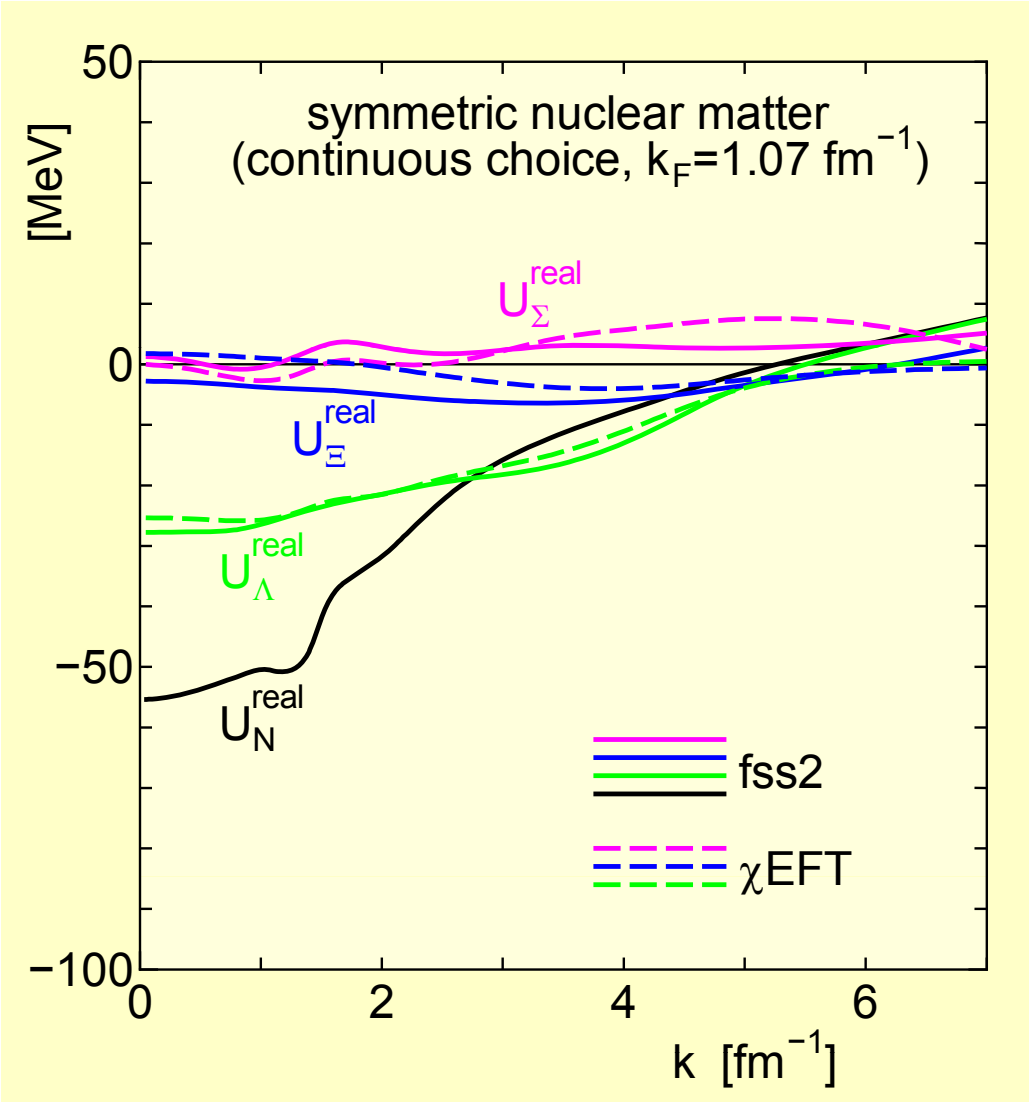
Ch-EFT



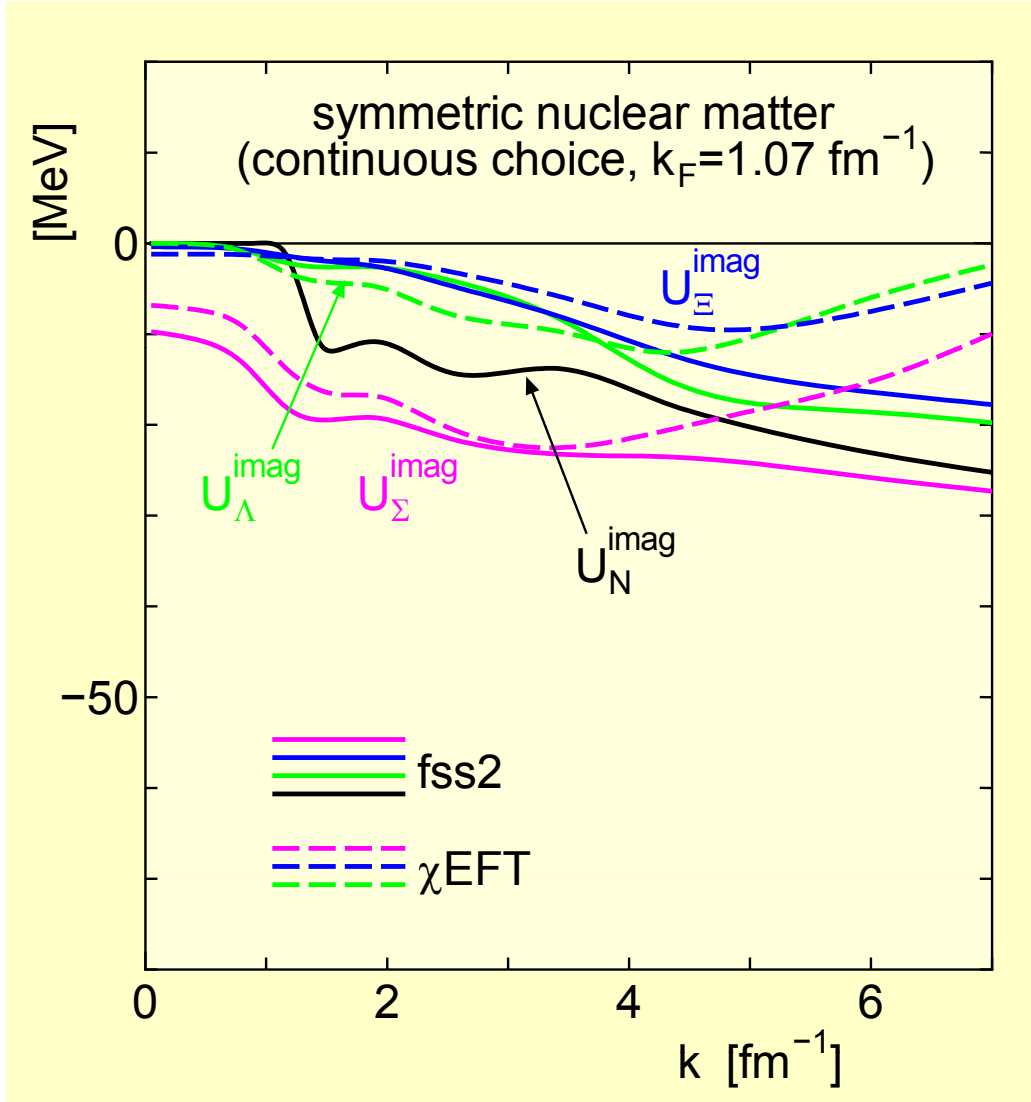
References

- quark-model potential fss2: Y. Fujiwara, Y. Suzuki, and C. Nakamoto, Prog. Part. Nucl. Phys. 58 (2007) 439-520.
- M. Kohno and Y. Fujiwara, Phys. Rev. C 79, 054318(2009): "Localized N, Λ, Σ, and Ξ single-particle potentials in finite nuclei calculated with SU_6 quark-model baryon-baryon interactions"
- M. Kohno and S. Hashimoto, nucl-th/0909.1385: "Ξ^--nucleus potential and (K^-,K^+) inclusive spectrum at Ξ^- production threshold region"

Λ, Σ and Ξ s.p. potentials in symmetric nuclear matter with k_F=1.07 fm^{-1} from continuous choice G-matrix calculations, using fss2 and Ch-EFT interactions.

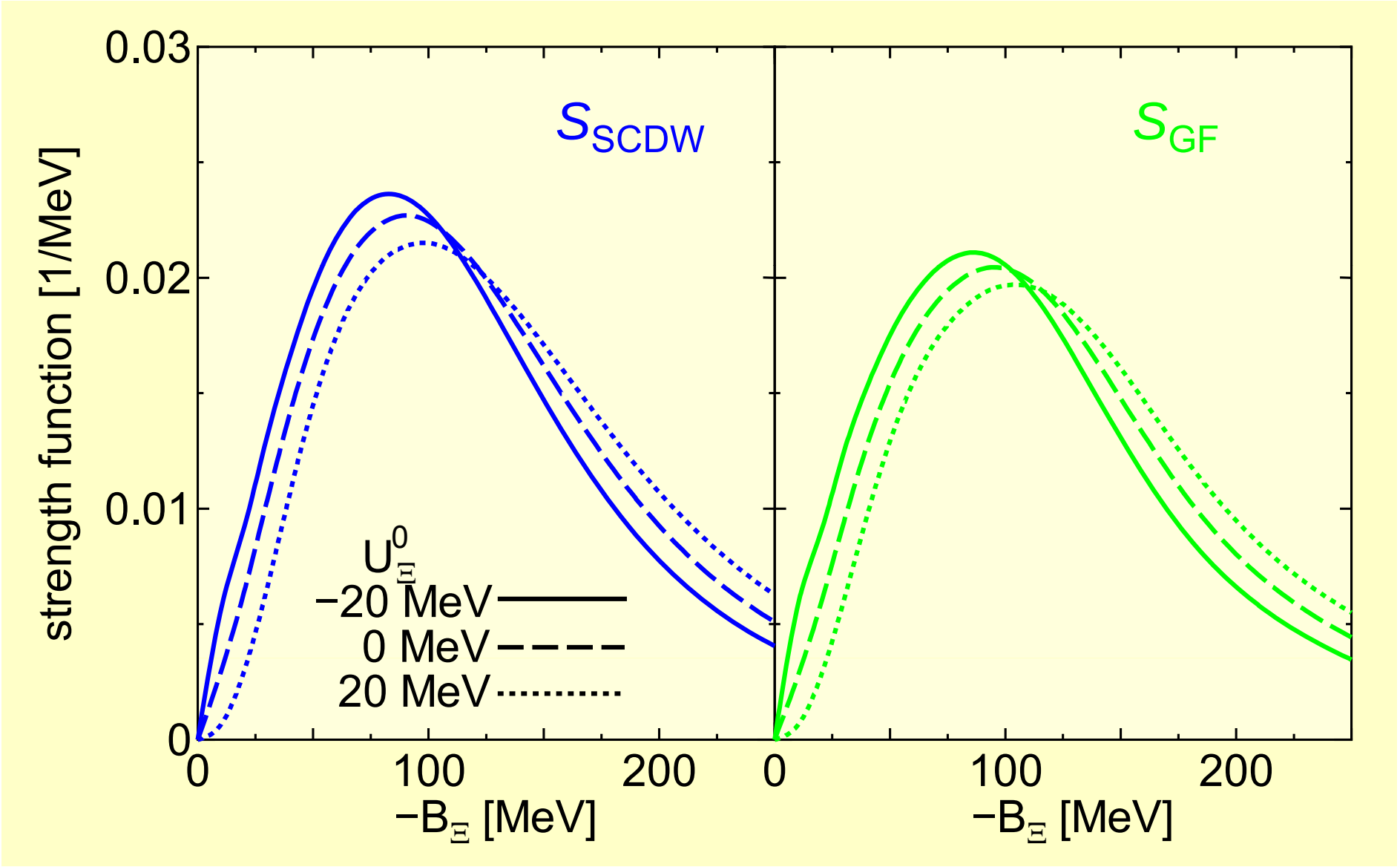


real part



imaginary part

Comparison of SCDW Green functions and precise Green functions corresponding to (K^-, K^+) at p_K-=1.8 GeV/c.



Energy shift $\Delta E = E - E_C$ and width $\Gamma = -2\,\mathrm{Im}\,E$ of the Σ^- atomic orbits in ^{28}Si and ^{56}Fe. Entries in eV.

Σ^-–^{28}Si		
	ΔE_{4f}	Γ_{4f}
Real only	-222	---
Real+Img*	-208	249
Exp.	-156∓36	220∓110
	ΔE_{5g}	Γ_{5g}
Real only	-0.8	---
Real+Img	-0.8	0.7
Exp.	---	0.41∓0.1

Σ^-–^{56}Fe		
	ΔE_{4f}	Γ_{4f}
Real only	-943	---
Real+Img*	-943	1205
	ΔE_{5g}	Γ_{5g}
Real only	-11	---
Real+Img	-11	8.3

*W-S img. Pot.: W_0= -9 MeV, r_0=1.1A$^{1/3}$ and a=0.67 fm.

Energy shift $\Delta E = E - E_C$ and width $\Gamma = -2\,\mathrm{Im}\,E$ of the Ξ^- atomic orbits in ^{28}Si and ^{56}Fe. Entries in eV.

Ξ^-—^{28}Si		
	ΔE_{4f}	Γ_{4f}
Real only	-346	---
Real+Img.	-345	16
Ref. W-S	-383	216
	ΔE_{5g}	Γ_{5g}
Real only	-6.9	---
Real+Img	-7.0	0.0
Ref. W-S	-1.4	0.5

Ξ^-—^{56}Fe		
	ΔE_{4f}	Γ_{4f}
Real only	-1287	---
Real+Img.	-1281	88
Ref. W-S	-1675	1092
	ΔE_{5g}	Γ_{5g}
Real only	-12	---
Real+Img	-12	1.0
Ref. W-S	-17	8.0

Ref. W-S pot.: U_0= -14 -3i MeV, r_0=1.1A$^{1/3}$ and a=0.67 fm.

Point nucleon distributions obtained from DDHF ground state wave functions.