轻反K介子核的相对论对称性破缺

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Outline

- Motivation
- Formulas and Method
- Relativistic symmetry breaking
- Neutron skin and symmetry energy
- Summary

Motivation

1. Novel structures in Kaonic nuclei

   Mares et.al., PLB 606, 295 (2005), NPA 770, 84 (2006)； Gazda, et.al., PRC 76, 055204 (2007);

   Zhong et al, PRC 74, 034321 (2006); Zhou, et.al., NPA 914, 332 (2013)

2. Investigate the density dependence of the symmetry energy at large density

   A strongly attractive K^- -nucleon interaction & Strong absorption

3. K^- - nucleon interaction is crucial for the properties of neutron stars

- Large uncertainties in the density dependence of the symmetry energy

non-relativistic theory **relativistic theory**

B.A. Li et al. / Physics Reports 464 (2008) 113–281 127

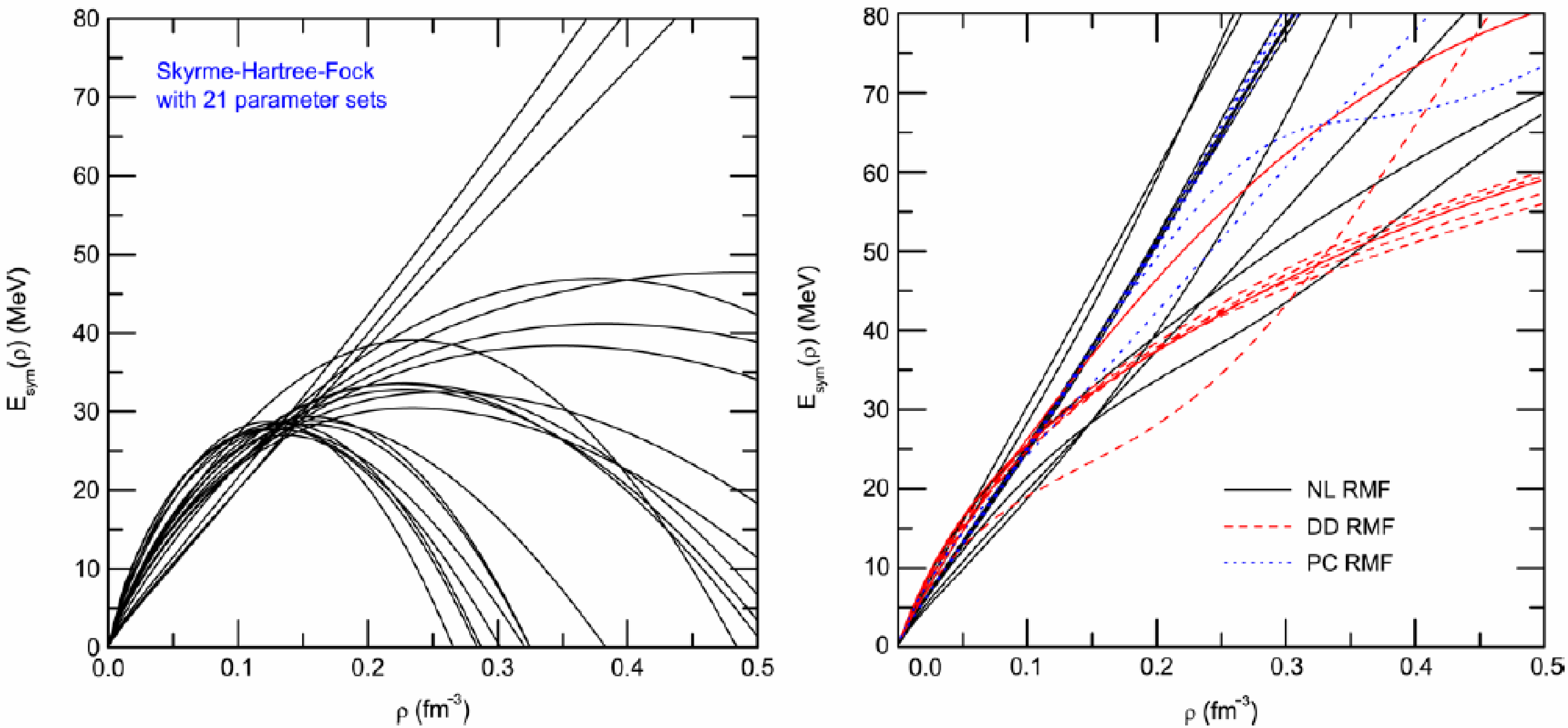


Fig. 8. Left window: Density dependence of the nuclear symmetry energy $E_{sym}(\rho)$ from SHF with 21 sets of Skyrme interaction parameters [71]. Right window: Same as left panel from the RMF model for the parameter sets NL1, NL2, NL3, NL-SH, TM1, PK1, FSU-Gold, HA, NLρ, and NL$\rho\delta$ in the nonlinear RMF model (solid curves); TW99, DD-ME1, DD-ME2, PKDD, DD, DD-F, and DDRH-corr in the density-dependent RMF model (dashed curves); and PC-F1, PC-F2, PC-F3, PC-F4, PC-LA, and FKVW in the point-coupling RMF model (dotted curves) [211].

PHYSICAL REVIEW C **74**, 034321 (2006)

Properties of kaonic nuclei in relativistic mean-field theory

X. H. Zhong,[1,2,*] G. X. Peng,[2,†] L. Li,[1] and P. Z. Ning[1,2,‡]

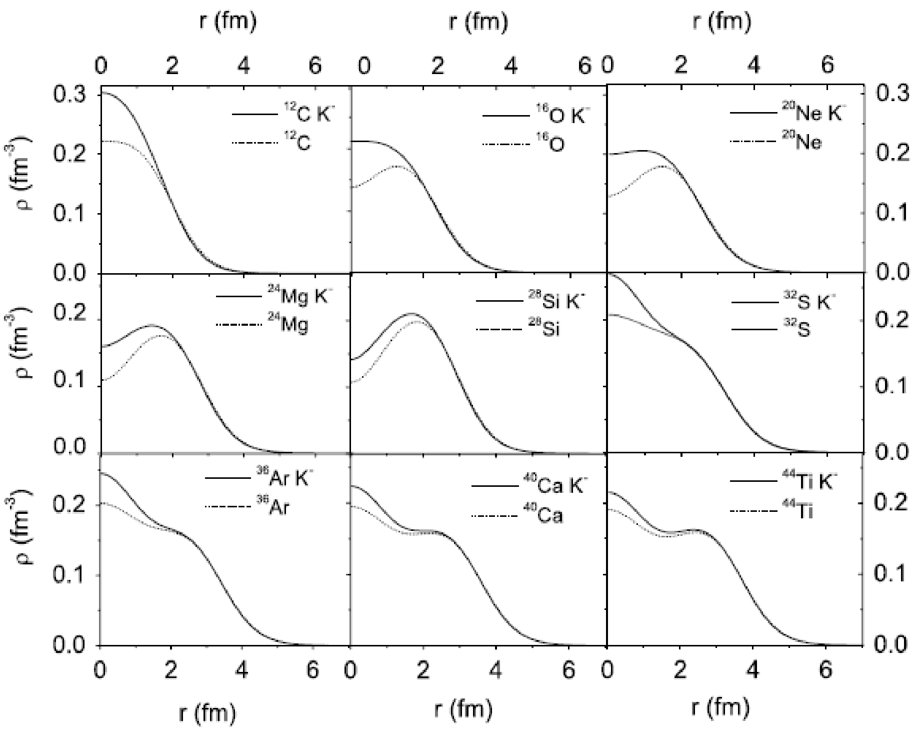


FIG. 1. Nucleon density as a function of nucleus radius. The solid and dotted curves represent kaonic nuclei and corresponding ordinary nuclei, respectively.

A lab to examine the symmetry energy at higher densities

II. Formulas

- The effective Lagrangian density:

$$\begin{aligned}\mathcal{L} &= \bar{\psi}_B[i\gamma_\mu\partial^\mu - M_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu\omega^\mu - g_{\rho B}\gamma_\mu\tau_3 b_0^\mu \\ &+ \frac{f_{\omega B}}{2M_N}\sigma_{\mu\nu}\partial^\nu\omega_0^\mu - e\frac{1}{2}(1+\tau_c)\gamma_\mu A^\mu]\psi_B - U(\sigma,\omega^\mu,b_0^\mu) \\ &+ \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu \\ &- \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}m_\rho^2 b_{0\mu}b_0^\mu - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} + \mathcal{L}_K\end{aligned}$$

$$\frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4 - \frac{1}{4}c_3(\omega_\mu\omega^\mu)^2 \\ -4g_{\rho N}^2(\Lambda_s g_{\sigma N}^2\sigma^2 + \Lambda_v g_{\omega N}^2\omega_\mu\omega^\mu)b_{0\mu}b_0^\mu$$

- For Kaon

$$\mathcal{L}_K = (\mathcal{D}_\mu K)^\dagger(\mathcal{D}^\mu K) - m_K^2 K^\dagger K + g_{\sigma K}m_K K^\dagger K\sigma$$

with $K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}$, $\quad K^\dagger = (K^-, \bar{K}^0)$

$$\mathcal{D}_\mu \equiv \partial_\mu + \mathrm{i}\, g_{\omega K}\omega_\mu + \mathrm{i}\, g_{\rho K}\tau_3\cdot b_{0\mu} + \mathrm{i}\, e\tfrac{1}{2}(1+\tau_3)A_\mu$$

D. Gazda et.al. PRC **76**, 055204 (2007)

- Equations of Motion In RMF:

$$\left(\frac{d^2}{dr^2}+\frac{2}{r}\frac{d}{dr}-m_\phi^2\right)\phi(r)=-s_\phi(r)$$

$$s_\phi(r)=\begin{cases} g_\sigma\rho_s+8g_\sigma^2g_\rho^2\Lambda_s\sigma b_0^2-g_2\sigma^2(r)-g_3\sigma^3(r)\boxed{+g_{\sigma K}m_K K^-K^+} & \sigma \\ g_\omega\rho_B-c_3\omega_0^3-8g_\omega^2g_\rho^2\Lambda_v\omega b_0^2\boxed{-g_{\omega K}\rho_{K^-}} & \omega \\ g_\rho\rho_3-8g_\rho^2b_0(g_\omega^2\Lambda_v\omega_0^2+g_\sigma^2\Lambda_s\sigma_0^2)\boxed{-g_{\rho K}\rho_{K^-}} & \rho \\ e\rho_c=e\sum_\alpha^A\frac{2j_\alpha+1}{4\pi r^2}\left(G_\alpha^2(r)+F_\alpha^2(r)\right)(1+t)/2\boxed{-e\rho_{K^-}} & \text{photon} \end{cases}$$

For anti-kaon

$$[-\nabla^2-E_{K^-}^2+m_K^2+\mathrm{Re}\,\Pi_{K^-}]K^-=0,$$

$$\boxed{\rho_{K^-}=2(E_{K^-}+g_{\omega K}\,\omega_0+g_{\rho K}\mathrm{b}_0+eA_0)K^-K^+}\qquad \int d^3x\rho_{K^-}=\kappa,$$

$$\mathrm{Re}\Pi_{K^-}=\boxed{-g_{\sigma K}m_K\sigma_0-2E_{K^-}}(g_{\omega K}\omega_0+g_{\rho K}\mathrm{b}_0+eA_0)-(g_{\omega K}\omega_0+g_{\rho K}\mathrm{b}_0+eA_0)^2.$$

Introduce Imaginary part of the potential (absorption)

pionic decay modes $\bar{K}N \to \pi\Sigma,\ \pi\Lambda\ (\sim 80\%)$

nonpionic decay modes $\bar{K}NN \to YN\ (\sim 20\%)$

the simple "$t\rho$" form $\mathrm{Im}\,\Pi_{K^-} = i\left[-2(\mathrm{Re}E)\,f\,V_0\,\frac{\rho}{\rho_0}\right]$

the phase-space suppression factors

KG Equation for K⁻

$$[-\nabla^2 - E_{K^-}^2 + m_K^2 + \Pi_{K^-}]K^- = 0$$

K^- binding energy $B_{K^-} = B[A, Z, \kappa K^-] - B[A, Z, (\kappa - 1)K^-]$

Spin and pseudospin symmetries

$$[\frac{d^2}{dr^2} + \frac{1}{U_G}\frac{d\triangle}{dr}\frac{d}{dr} + \frac{1}{U_G}\frac{d\triangle}{dr}\frac{\kappa}{r} - \frac{\kappa(\kappa+1)}{r^2} - U_G U_F]G_a(r) = 0,$$

$$[\frac{d^2}{dr^2} - \frac{1}{U_F}\frac{d\Sigma}{dr}\frac{d}{dr} + \frac{1}{U_F}\frac{d\Sigma}{dr}\frac{\kappa}{r} - \frac{\kappa(\kappa-1)}{r^2} - U_G U_F]F_a(r) = 0,$$

$$\Sigma = V(r) + S(r),\ \triangle = V(r) - S(r),$$

$$\Delta >> \Sigma$$

$$\kappa = \begin{cases} l, & j=l-\frac{1}{2}, \\ -(l+1), & j=l+\frac{1}{2}. \end{cases}$$

$j = l \pm \frac{1}{2}$, **spin-orbit splitting**

$$\left\{\begin{array}{c} (n, l, j = l+1/2),\ \text{e.g. } 2s_{1/2} \\ (n-1, l+2, j = l+3/2),\ \text{e.g. } 1d_{3/2} \end{array}\right.,$$ **pseudospin splitting**

Iteration for obtaining eigen energy

$$(-\frac{d^2}{dr^2}+\frac{l(l+1)}{r^2}+M_K^2+\Pi(r))K^-(r)=E^2K^-(r).$$

Match point, integration from ourward and inward; How to adjust Δ E?

$$E_{tr}^2=\int K_{tr}^{*-}(r)(-\frac{d^2}{dr^2}+\frac{l(l+1)}{r^2}+M_K^2+\Pi(r))K_{tr}^-(r)dr/\int K_{tr}^{*-}(r)K_{tr}^-(r)dr.$$

$$\begin{aligned}\Delta E_{tr}^2 &\approx \int_{r_m-\epsilon}^{r_m+\epsilon} -K_{tr}^{-*}(r)\frac{d^2K_{tr}^-(r)}{dr^2}dr/\int_0^\infty K_{tr}^{-*}(r)K_{tr}^-(r)dr \\ &\approx -K_{tr}^{-*}(r_m)[\frac{dK_{tr}^-(r_m+\epsilon)}{dr}-\frac{dK_{tr}^-(r_m-\epsilon)}{dr}]/\int_0^\infty K_{tr}^{-*}(r)K_{tr}^-(r)dr,\end{aligned}$$

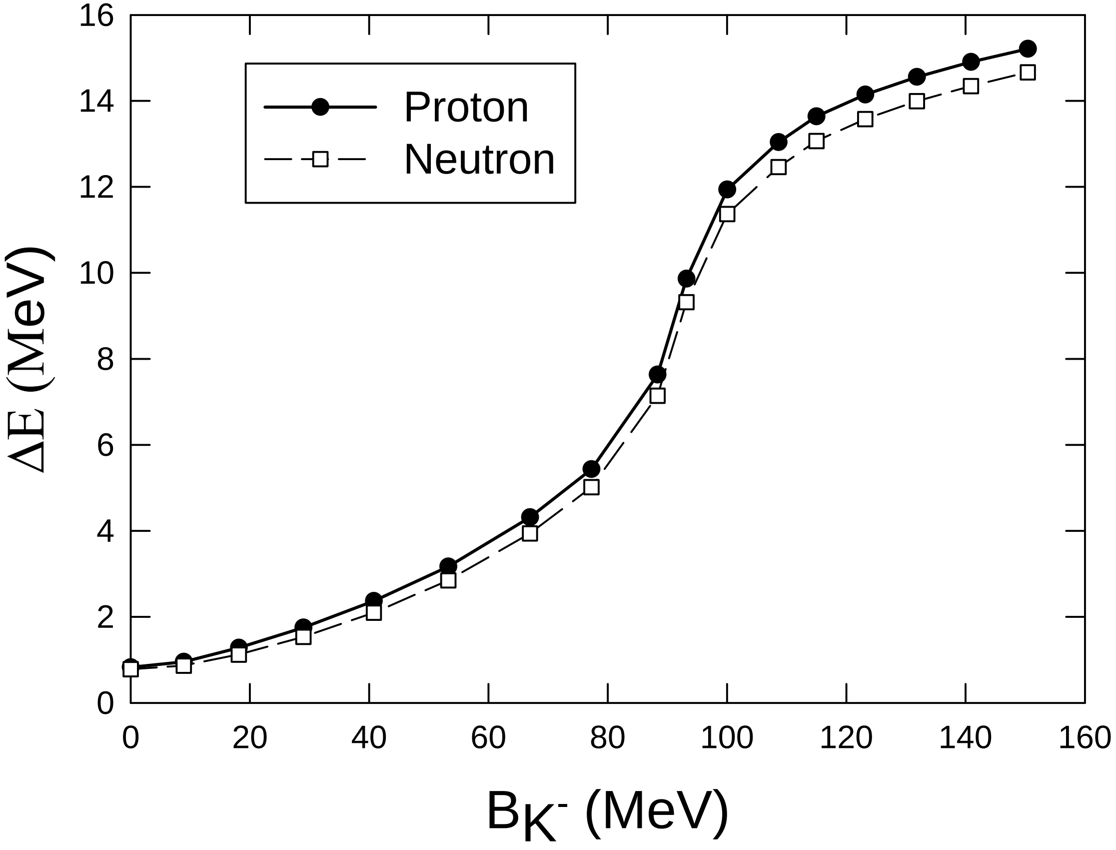
Pseudospin symmetry and its breaking

TABLE I: Single-neutron binding energies and splittings of the pseudospin and spin doublets in and the corresponding kaonic nuclei (in unit of MeV) with the NL3.

	$2S_{1/2}$	$1D_{3/2}$	△ (2S-1D)	$1D_{5/2}$	△ (1D)	$1P_{3/2}$	$1P_{1/2}$	△ (1P)
^{16}O	-	-	-	-	-	21.73	15.25	6.48
$^{16}_{K^-}$O	-	-	-	-	-	27.43	6.75	20.68
^{34}S	13.95	10.45	3.50	18.59	8.14	35.85	28.82	7.03
$^{34}_{K^-}$S	20.81	8.45	12.36	18.85	10.40	40.18	24.52	15.66
^{40}Ca	16.96	16.17	0.79	22.88	6.71	37.98	33.50	4.48
$^{40}_{K^-}$Ca	25.86	14.49	11.37	23.19	8.70	41.57	30.94	10.63
^{48}Ca	17.56	17.73	-0.17	23.88	6.15	38.94	35.63	3.31
$^{48}_{K^-}$Ca	21.36	16.77	4.59	25.00	8.23	42.61	36.48	6.13
^{52}Cr	20.21	21.89	-1.68	27.95	6.06	42.95	40.11	2.84
$^{52}_{K^-}$Cr	22.95	21.44	1.51	29.52	8.08	46.80	42.12	4.68
^{58}Ni	22.85	26.08	-3.23	31.38	5.30	45.71	43.67	2.04
$^{58}_{K^-}$Ni	25.10	26.22	-1.12	33.23	7.01	49.59	46.41	3.18
^{74}Se	25.63	29.42	-3.79	33.55	4.13	45.21	43.41	1.80
$^{74}_{K^-}$Se	28.05	29.78	-1.73	34.90	5.12	47.93	45.40	2.53
^{90}Zr	30.29	32.43	-2.14	36.32	3.89	48.38	46.56	1.82
$^{90}_{K^-}$Zr	33.35	32.62	0.73	37.46	4.84	51.02	48.14	2.88

More distinctive SB

Pesudospin-orbit splitting & antikaon binding energy

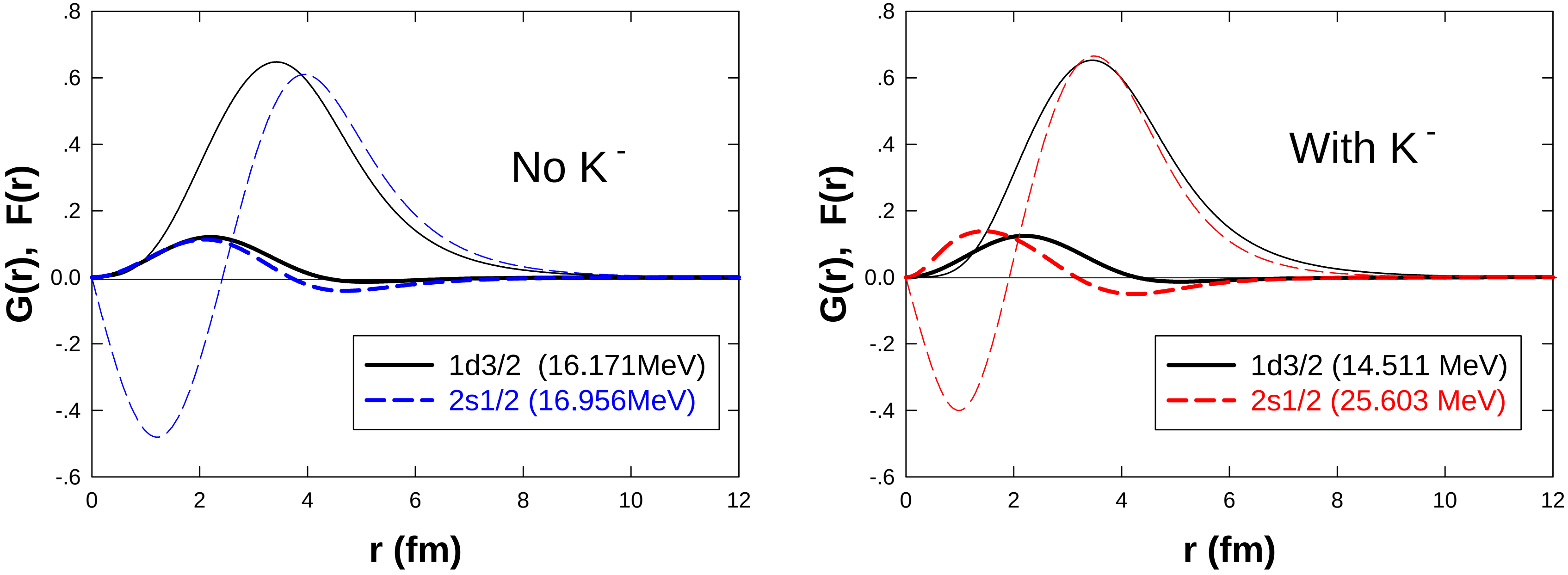


$\triangle E = \varepsilon[2S1/2] - \varepsilon[1D3/2]$ $B_{K^-} = B\ [\ 40Ca+K^-\ ] - B\ [\ 40Ca\ ]$

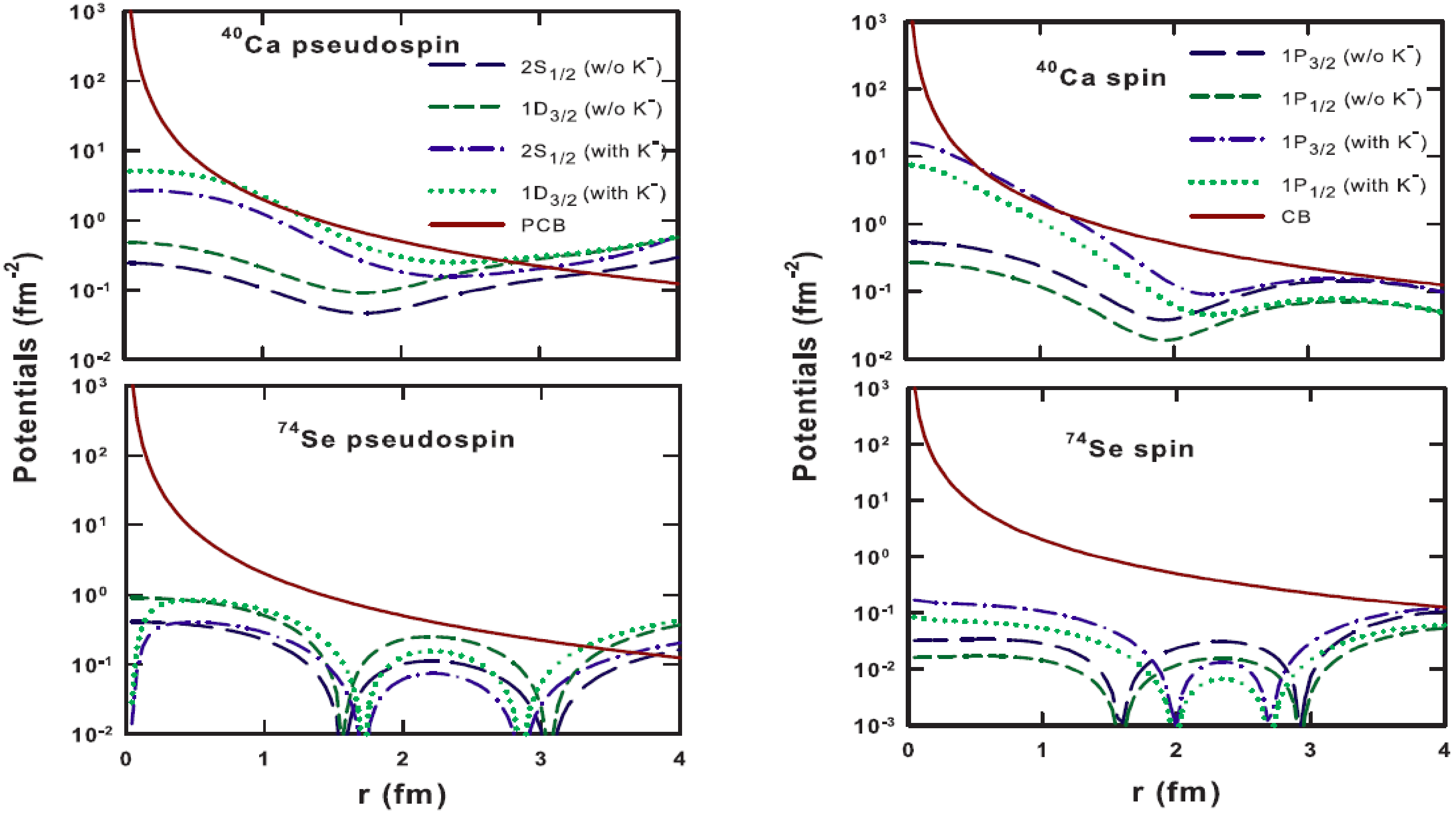
Radial wave function of the doublet

Pseudospin symmetry ⟷ similarity of small components

Neutron radial wave functions in ^{40}Ca

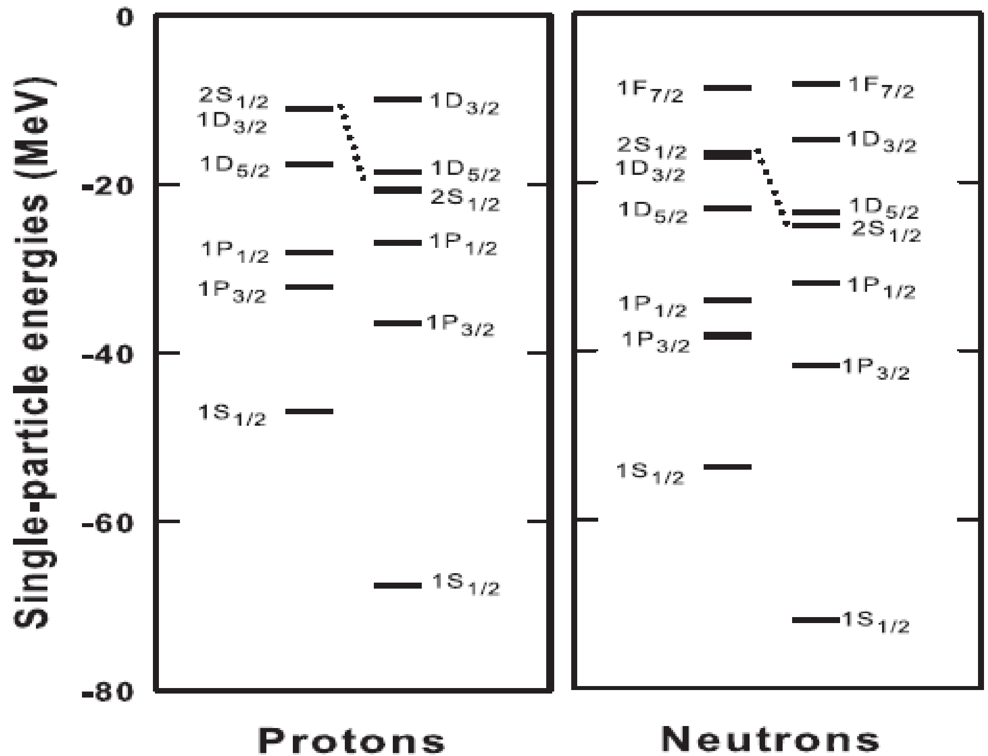


Potentials



^{40}Ca pseudospin
2S$_{1/2}$ (w/o K$^-$)
1D$_{3/2}$ (w/o K$^-$)
2S$_{1/2}$ (with K$^-$)
1D$_{3/2}$ (with K$^-$)
PCB
^{74}Se pseudospin
^{40}Ca spin
1P$_{3/2}$ (w/o K$^-$)
1P$_{1/2}$ (w/o K$^-$)
1P$_{3/2}$ (with K$^-$)
1P$_{1/2}$ (with K$^-$)
CB
^{74}Se spin
Potentials (fm^{-2})
r (fm)

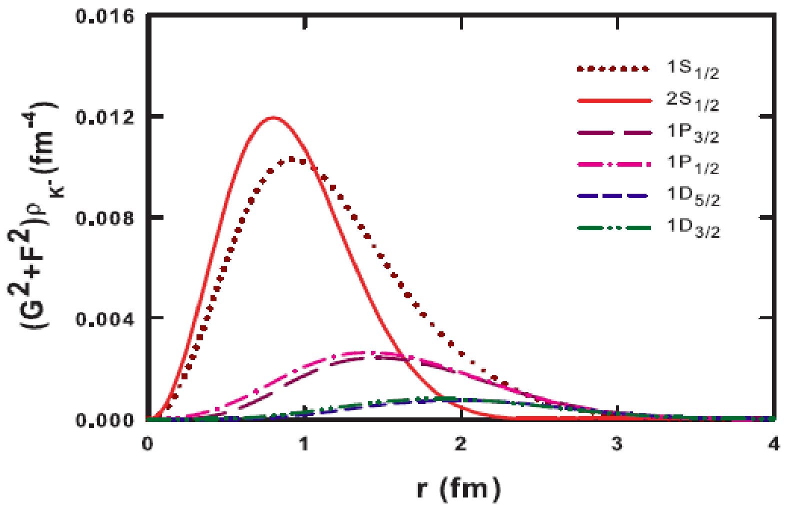
New magic number?

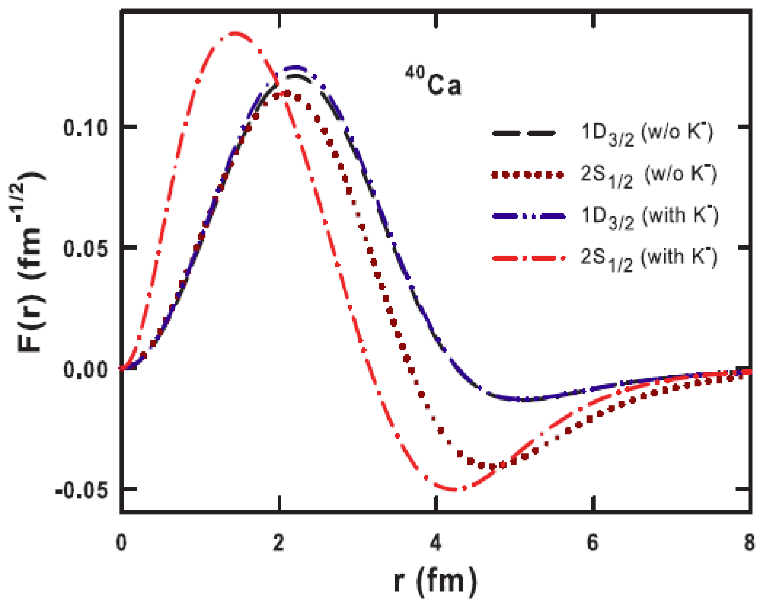


2, 8, 20, ... Not likely

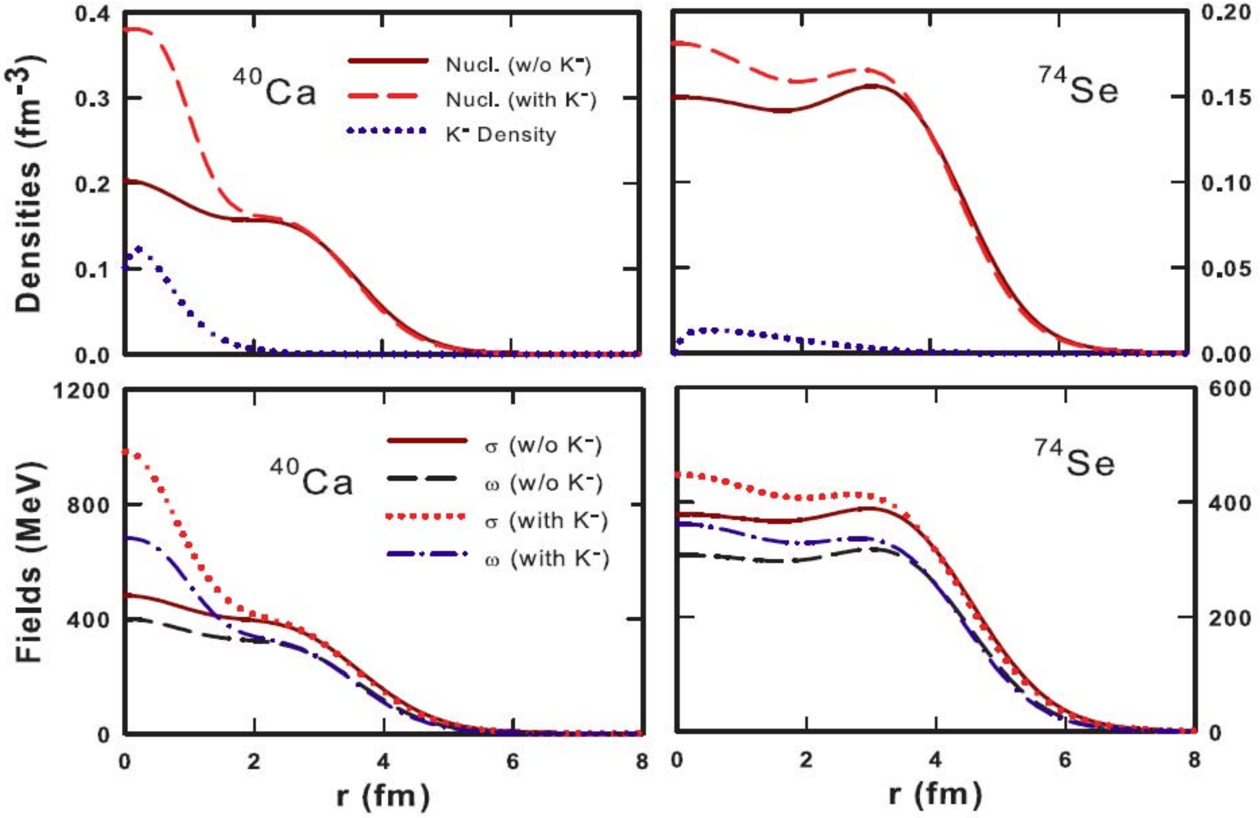
2, 6, 16, ... favored

Spatial proximity





Meson fields & Nuclear densities



RMS Radii (fm)

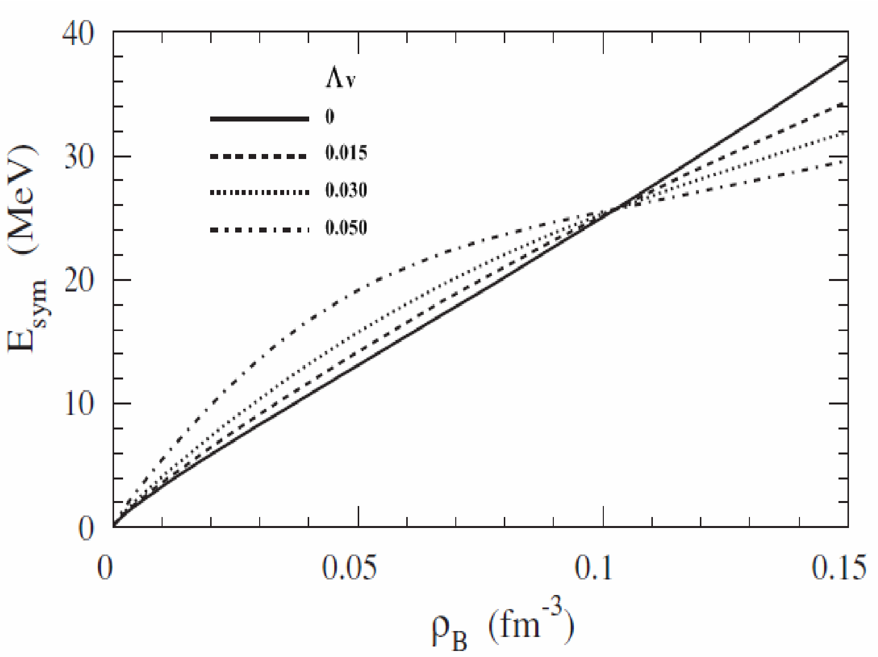
N 3.328 → 3.218 P 3.377 → 3.244 total 3.353 → 3.231

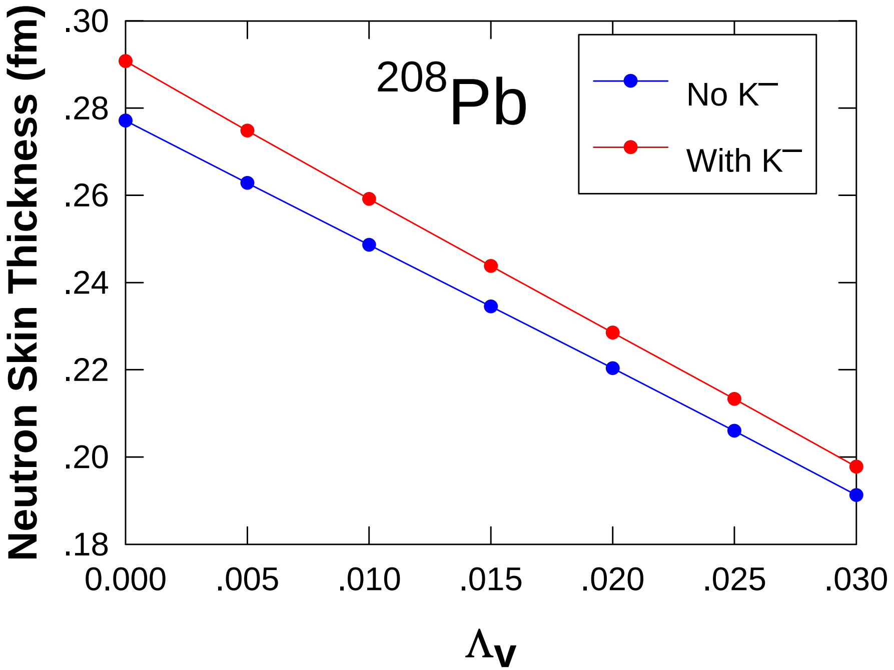
Neutron skin thickness & the symmetry energy

$$E_{sym}(\rho) = E_{sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho - \rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2$$

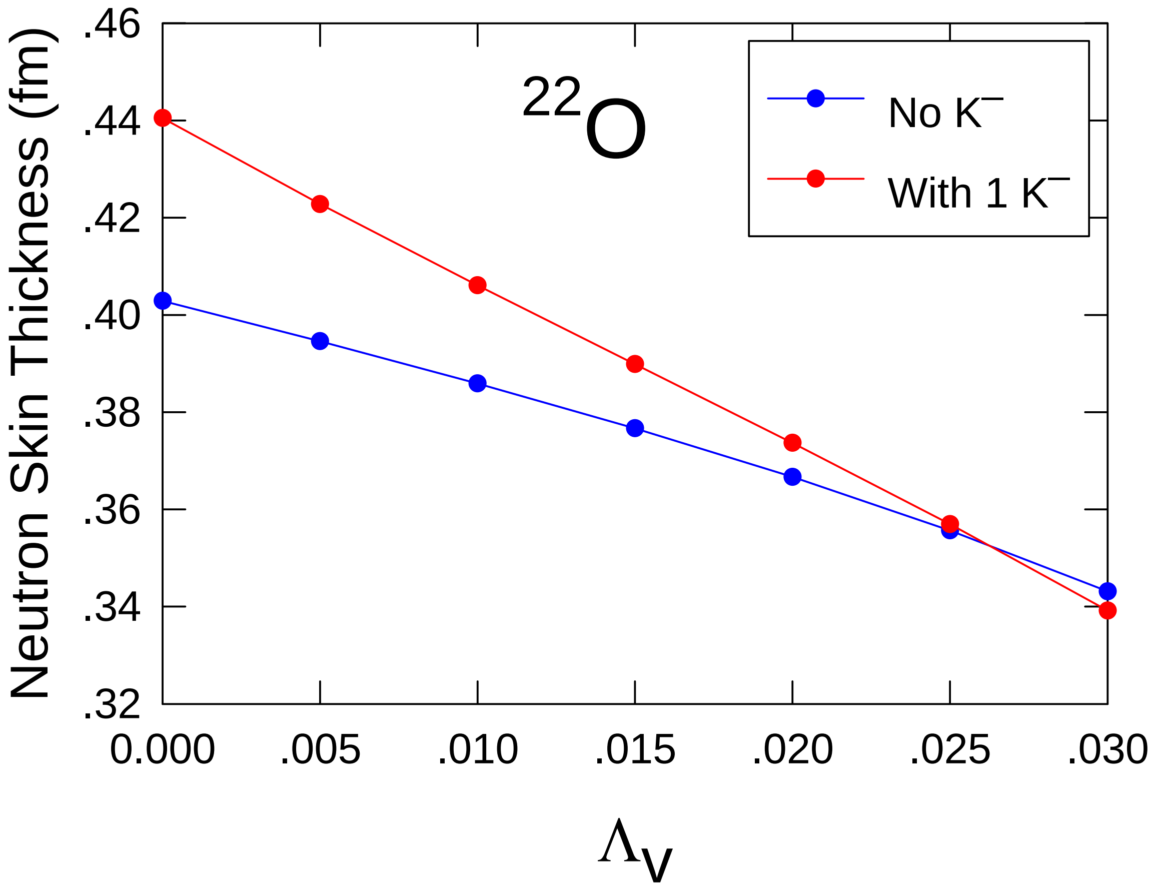
‘The slope parameter L has been found to be correlated linearly with the neutron-skin thickness of heavy nuclei’

B.A.Li et al./physics Reports 464, 113-281 (2008)



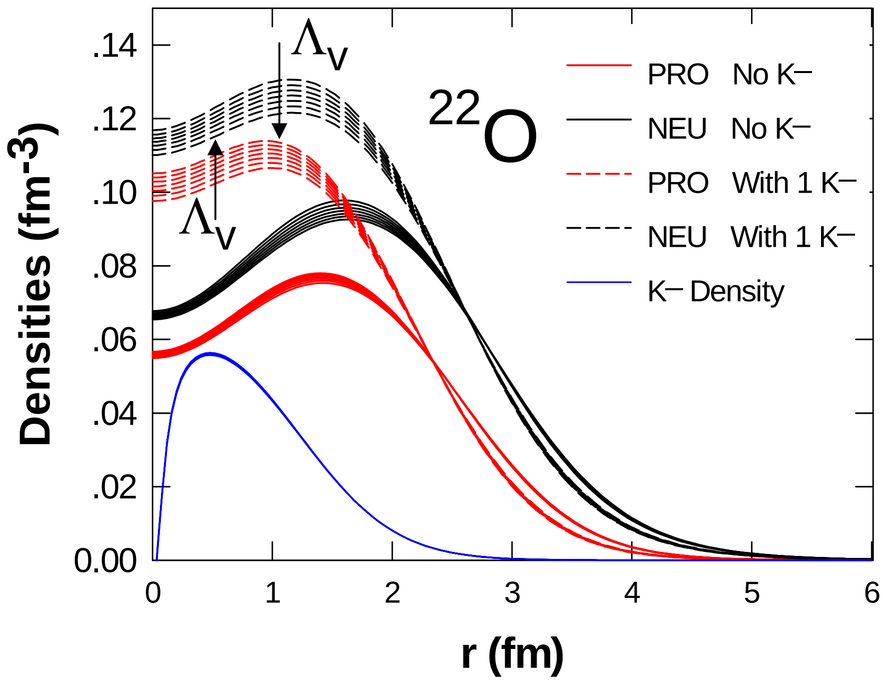


Neutron skin thickness for ^{22}O

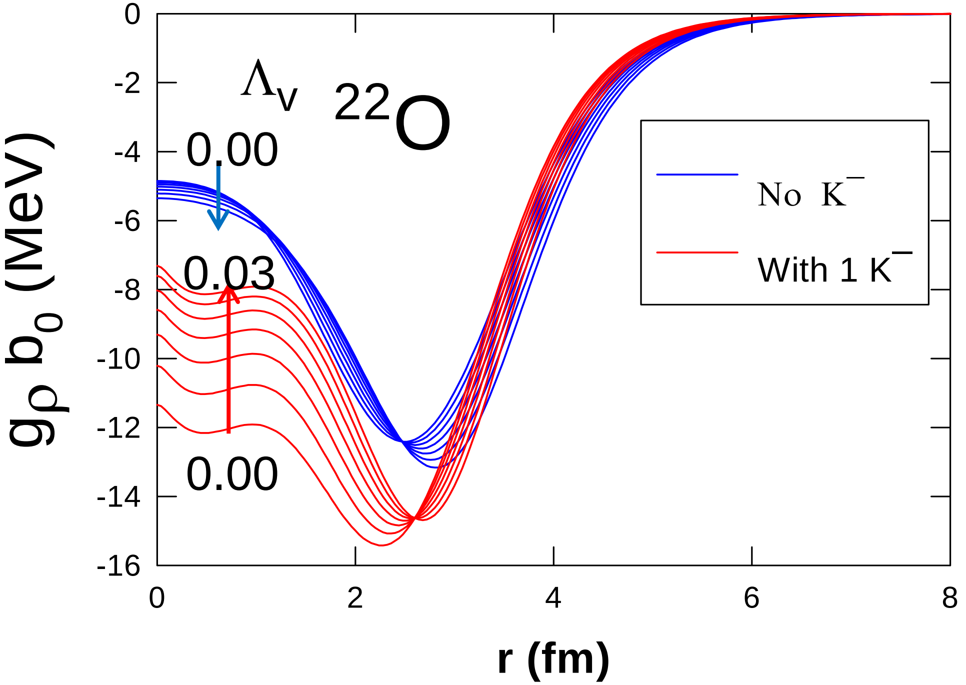


The one with K^- is much more sensitive to the symmetry energy

Proton and neutron Densities



Isovector field (ρ meson)



The isovector field relate to the symmetry energy

Summary

- ✓Properties of kaonic nuclei are investigated in RMF theory.

- ✓Pseudospin symmetry breaking and new magic numbers are found in light kaonic nuclei.

- ✓Neutron skin of light kaonic nuclei is sensitive to the difference in symmetry energies.

Thank you