Bulk properties of kaonic nuclei obtained by a RMF model

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Kaonic nuclei are intensively studied both experimentally and theoretically.

Due to the strong K^{-}-N attraction,

- possibility of ppK^{-} and pppK^{-} bound states,
- very high density ($\sim 10\rho_0$) by AMD calc

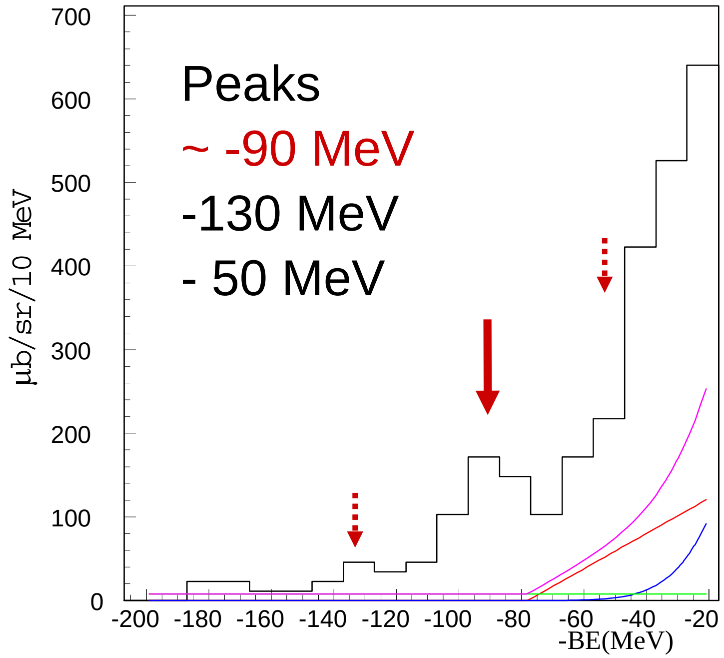
are suggested.

Kaon condensation at high density is also important for structure and dynamics of stellar objects. (K-con softens the EOS of matter, promotes the star cooling, causes inhomogeneous structure, etc.)

We study bulk properties of **kaonic nuclei** and the dependence on the K^{-}-N interaction by using a framework which reproduces properties of nuclear matter.

Experiments

- T.Kishimoto et al



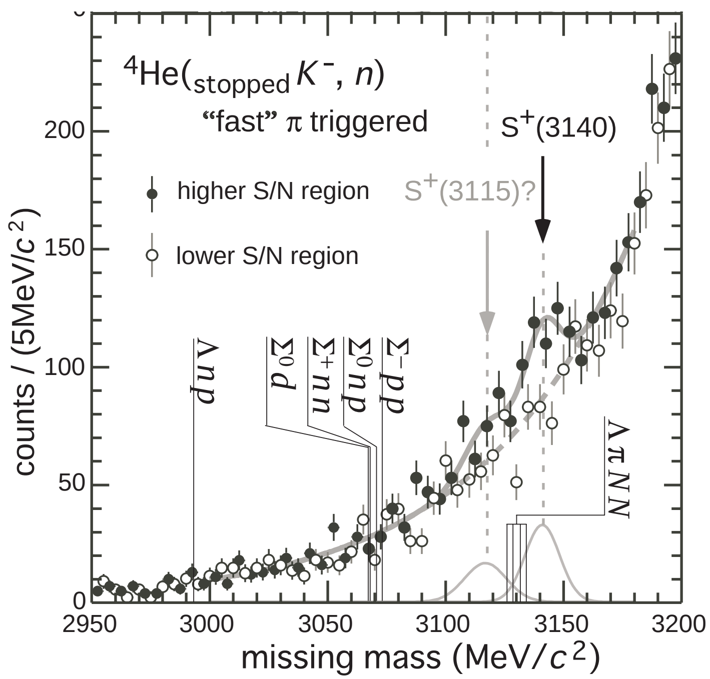
$^{16}\mathrm{O}(\mathrm{K}^-, \mathrm{n})$ reaction $\Rightarrow$

BE of $\mathrm{K}^- = (-130,) - 90, -50$ MeV

$\longrightarrow$ potential $U_{K^-} \sim (-200,) - 140$ MeV

- T.Suzuki et al, NPA754(2005)375

$^{4}\mathrm{He}(_{\mathrm{stopped}}\mathrm{K}^-, \mathrm{n})\underline{\mathrm{S}^+(3140)}$



Relativistic mean-field model with kaon

Thermodynamic potential

$$
\begin{aligned}
\Omega &= \Omega_B + \Omega_M + \Omega_K + \Omega_{\rm Coul} \\
\Omega_B &= \int d^3r \left[\sum_{i=p,n} \left(\int_0^{k_{Fi}} d^3k \sqrt{m_B^{*\,2} + k^2} - \rho_i \nu_i \right) \right] \\
\Omega_M &= \int d^3r \left[\frac{1}{2}(\nabla\sigma)^2 + \frac{1}{2} m_\sigma^2 \sigma^2 + U(\sigma) - \frac{1}{2}(\nabla\omega_0)^2 - \frac{1}{2} m_\omega^2 \omega_0^2 - \frac{1}{2}(\nabla R_0)^2 - \frac{1}{2} m_\rho^2 R_0^2 \right] \\
\Omega_K &= \int d^3r \left[-K^2 \left(-m_K^{*\,2} + \underline{(E_K - V_{\rm Coul} + g_{\omega K}\omega_0 + g_{\rho K} R_0)^2} \right) + (\nabla K)^2 \right] \\
\Omega_{\rm Coul} &= \int d^3r \left[-\frac{1}{8\pi e^2} (\nabla V_{\rm Coul})^2 \right]
\end{aligned}
$$

Thomas-Fermi approx.

Tomozawa-Weinberg term

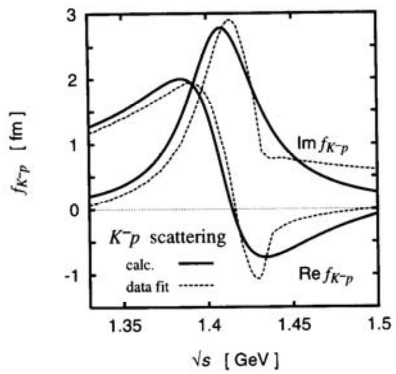
$$
\nu_p = \mu_p + V_{\rm Coul} - g_{\omega N}\omega_0 - g_{\rho K} R_0, \qquad \nu_n = \mu_n - g_{\omega N}\omega_0 + g_{\rho K} R_0,
$$

$$
m_B^* = m_B - g_{\sigma N}\sigma, \qquad m_K^{*\,2} = m_K^2 \underline{- 2 g_{\sigma K} m_K \sigma}
$$

K-N Σterm

Description of kaon

- Meson exchange model: linear approx of the chiral model.
  Reproduces KN scatt amplitude, etc.
- The chiral model is also presented late



Free K-N scattering amplitude by the chiral model. Phys.Rep.272(1996)255.

- Parameter: $U_K(\rho_0) = -80 - -180$ MeV [Batty et al] , $-76 - -92$ MeV ($\Sigma_{KN} = 290$–450 MeV) [Lattice QCD] ($U_K(\rho_0)$: real part of optical potential $g_{\sigma K}\sigma + g_{\omega K}\omega_0 + g_{\rho K} R_0$)
Here we use $U_K(\rho_0) = -80 - -120$ MeV.

EOM

From extremum conditions of thermodynamic pot $\frac{\delta\Omega}{\delta\phi_i(\mathbf{r})} = 0$,

$$
\begin{aligned}
-\nabla^2\sigma + m_\sigma^2\sigma &= -\frac{dU}{d\sigma} + g_{\sigma N}(\rho_n^{(s)} + \rho_p^{(s)}) - 4g_{\sigma K}m_K K^2 \\
-\nabla^2\omega_0 + m_\omega^2\omega_0 &= g_{\omega N}(\rho_p + \rho_n) + 2g_{\omega K}K^2(E_K - V_{\rm Coul} + g_{\omega K}\omega_0 + g_{\rho K}R_0) \\
-\nabla^2 R_0 + m_\rho^2 R_0 &= g_{\rho N}(\rho_p - \rho_n) + 2g_{\rho K}K^2(E_K - V_{\rm Coul} + g_{\omega K}\omega_0 + g_{\rho K}R_0) \\
\nabla^2 K &= \left[{m_K^*}^2 - (E_K - V_{\rm Coul} + g_{\omega K}\omega_0 + g_{\rho K}R_0)^2\right] K \quad \text{(linear approx)} \\
\nabla^2 V_{\rm Coul} &= 4\pi e^2\rho_{\rm ch} \quad \text{(charge density } \rho_{\rm ch} = \rho_p + \rho_K) \\
\mu_p &= \sqrt{k_{Fp}^2 + {m_B^*}^2} + g_{\omega N}\omega_0 + g_{\rho N}R_0 + V_{\rm Coul} \\
\mu_n &= \sqrt{k_{Fn}^2 + {m_B^*}^2} + g_{\omega N}\omega_0 - g_{\rho N}R_0 \\
\rho_K &= -2\,(E_K - V_{\rm Coul} + g_{\omega K}\omega_0 + g_{\rho K}R_0)\,K^2
\end{aligned}
$$

constraints:

$$\int \rho_{p,n}(\mathbf{r})d^3r = \text{given}, \qquad \int \rho_K(\mathbf{r})d^3r = -1, \qquad K(r\to\infty) = 0$$

Numerical procedure

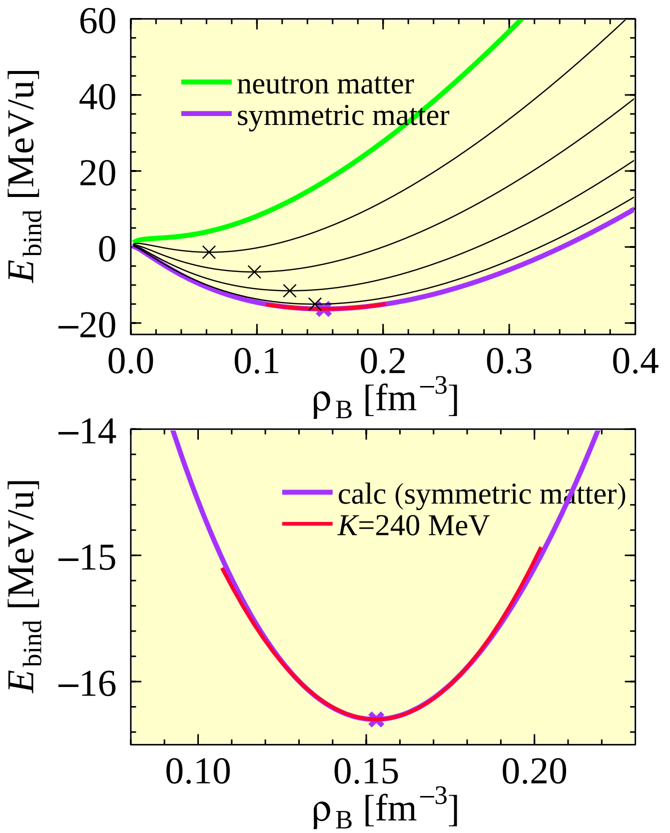
Numerically solve coupled EOMs of fields. Klein-Gordon (linear) or sine-Gordon (chiral) for kaon.

- Assume spherical symmetry. Divide space into grid points.
- Give initial ρ_p, ρ_n, σ, ω_0, R_0, K.
- Adjust all fields on grid points until they fulfill the above EOMs.

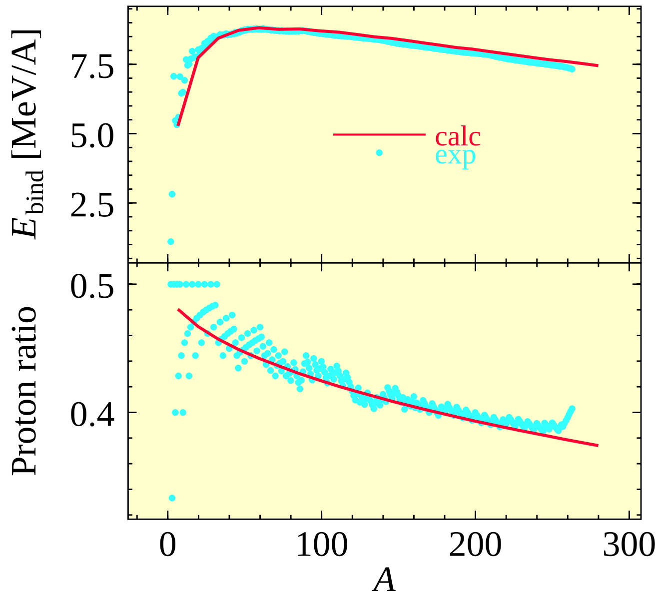
All densities and fields are consistent with each other.

Choice of parameters

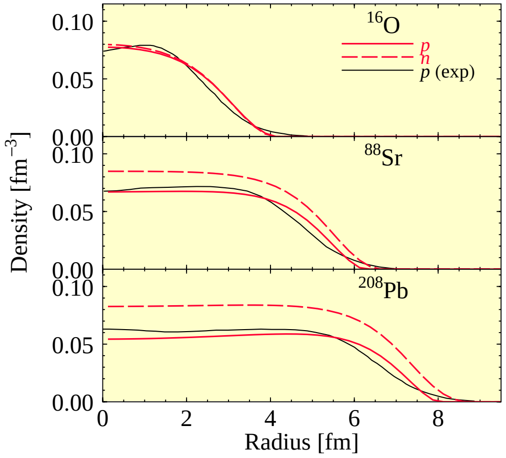
- Reproduce properties of both normal matter and normal nuclei.



Saturation of nuclear matter.



Binding energy of nuclei and proton mixing ratio.



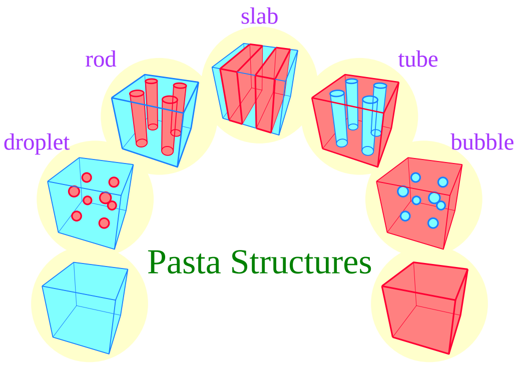
Examples of density profiles.

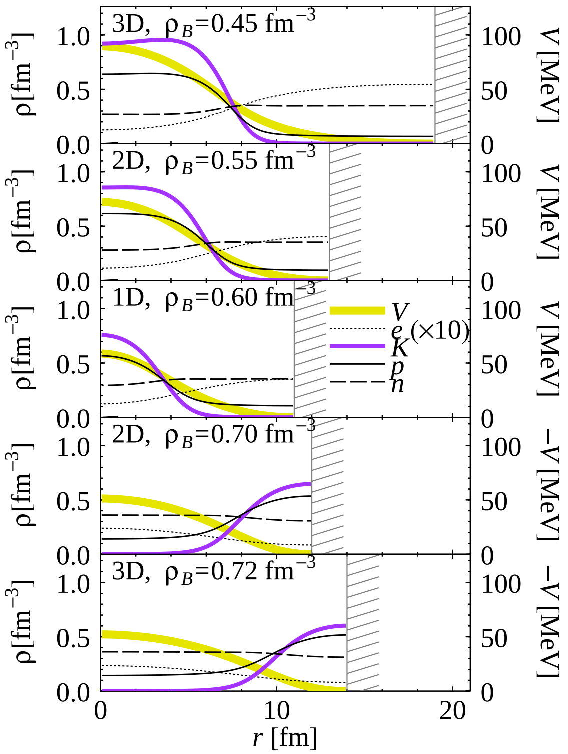
- Coupling constants for kaon

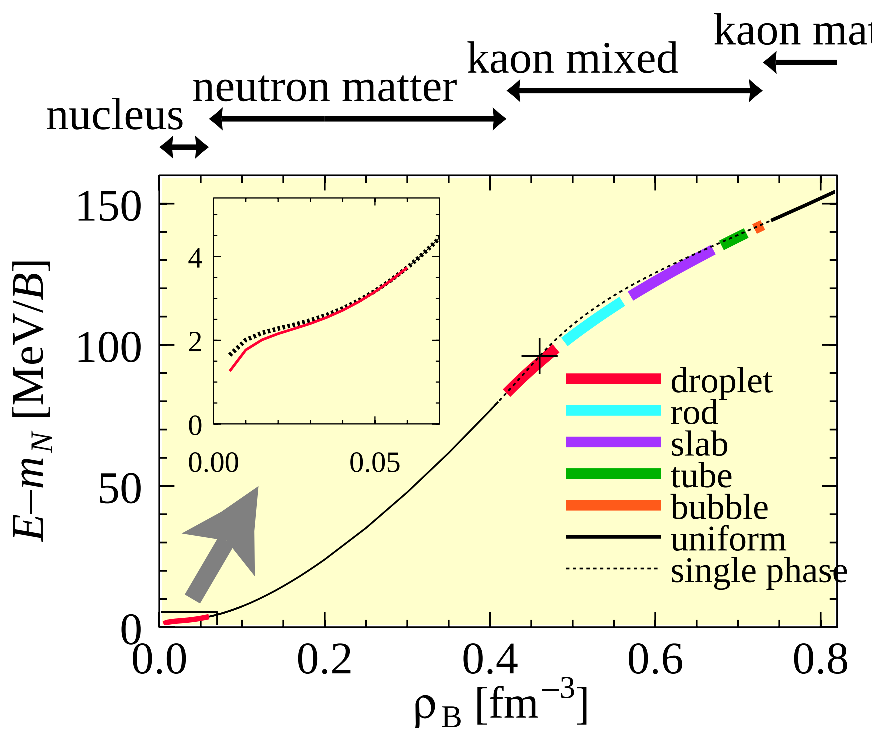
$$g_{\omega K} = \frac{1}{3} g_{\omega N}, \quad g_{\rho K} = g_{\rho N}, \quad g_{\sigma K} = 0.97 - 2.2 \qquad (U_K(\rho_0) = -80 - -120 \text{ MeV})$$

Related study: inhomogeneous structure of matter

Using the same (similar) framework, "pasta structure" of nuclear matter at subsaturation density, kaon condensed matter, and hadron-quark mixed phase are studied. [PRC72(2005)015802, PRC73(2006)035802, nucl-th/0605075].





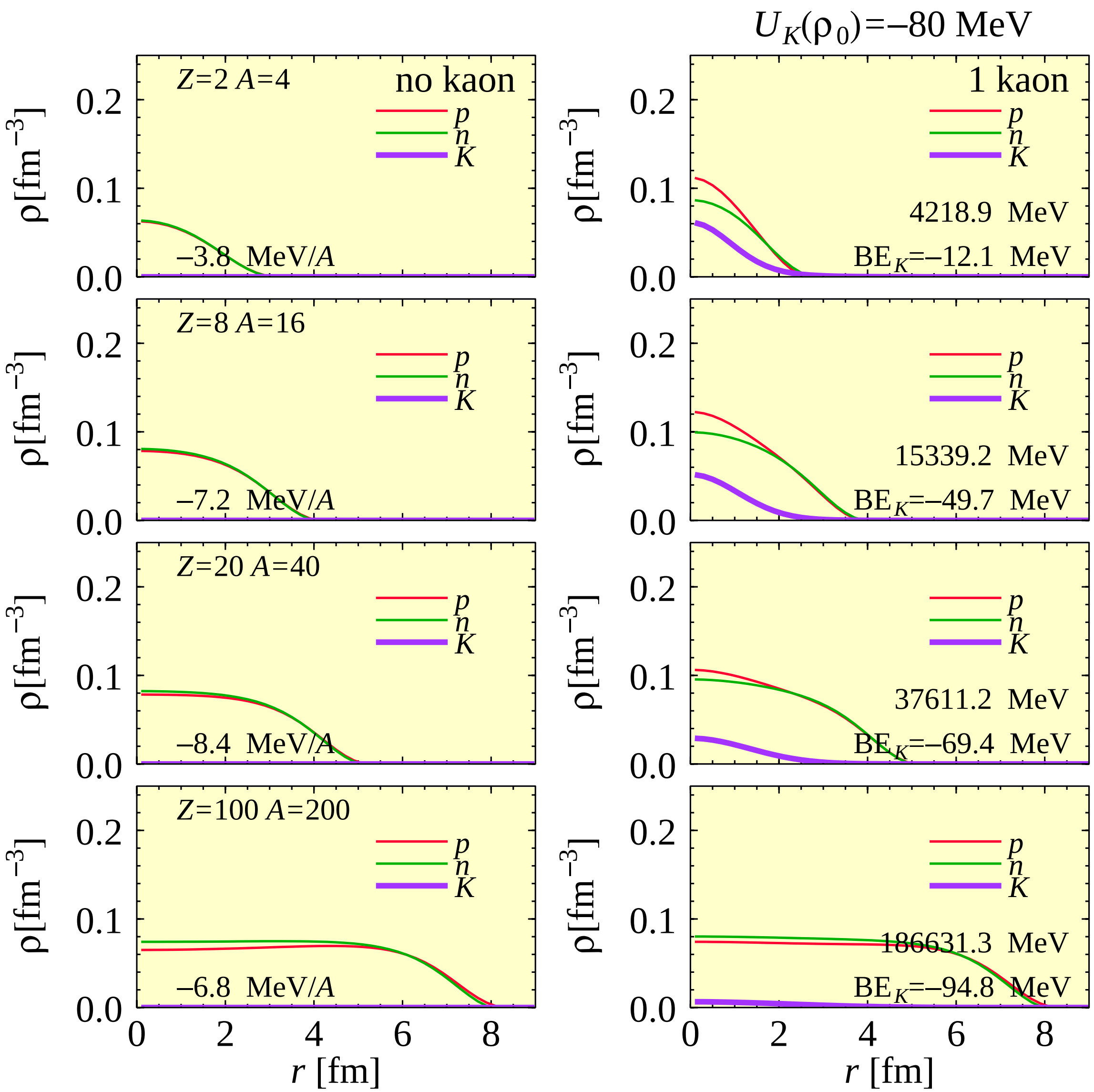


Phase diagram of neutron-star matter (charge neutral (with e) and beta equilibrium). $U_K(\rho_0) = -120$ MeV.

Kaonic pasta structure appears at high density.

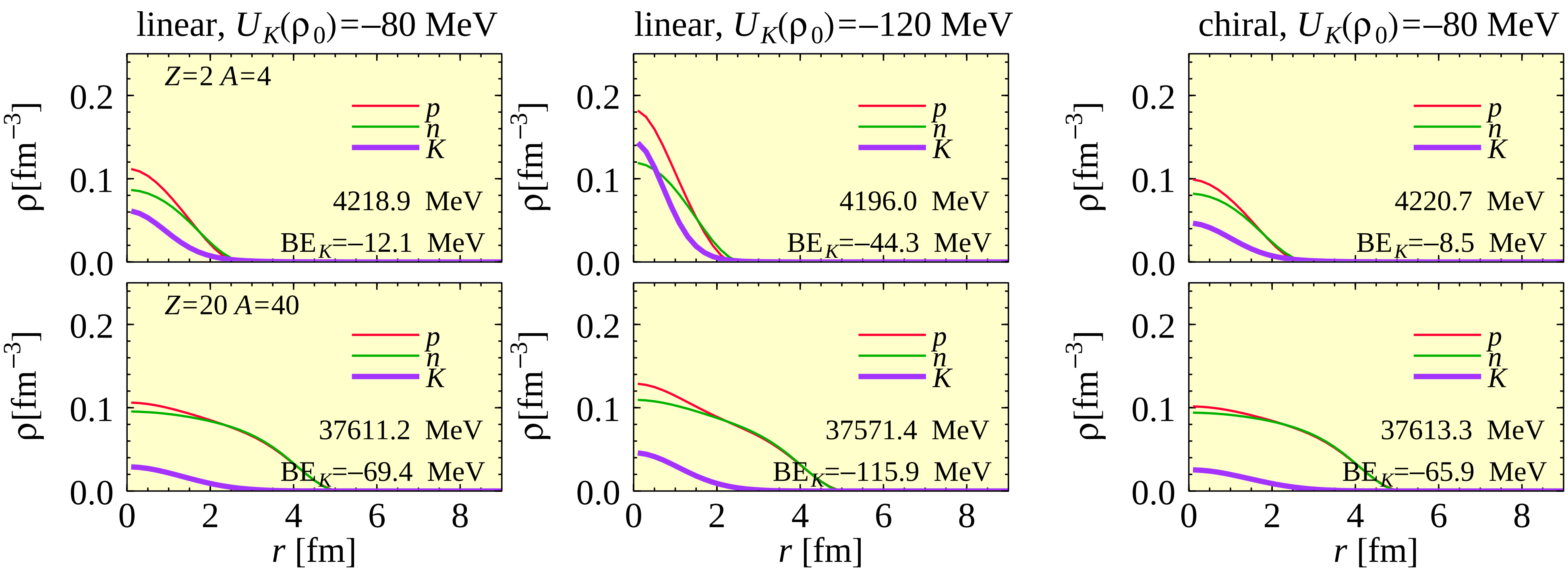
Charge screening effect is important.

Kaonic nuclei

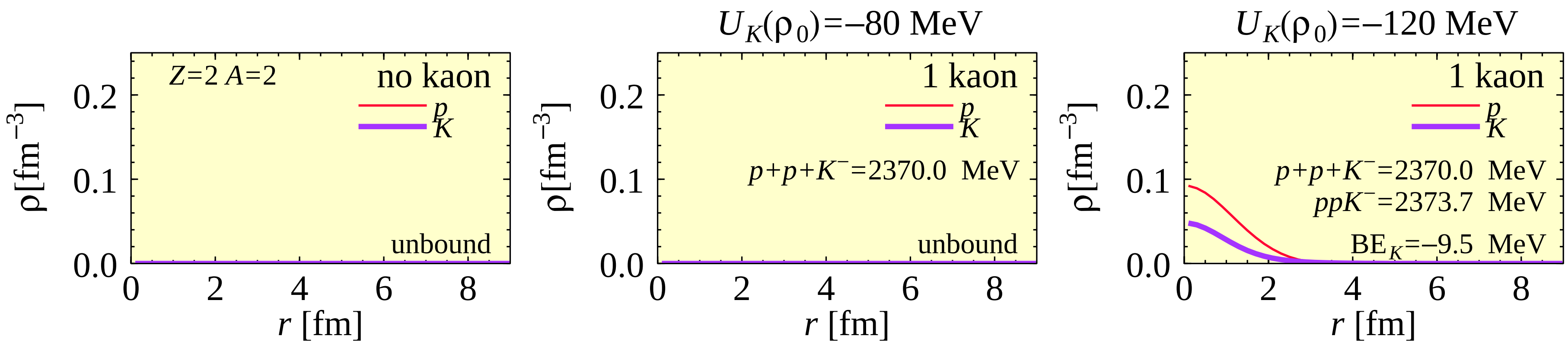


Comparison of normal nuclei and kaonic nuclei.

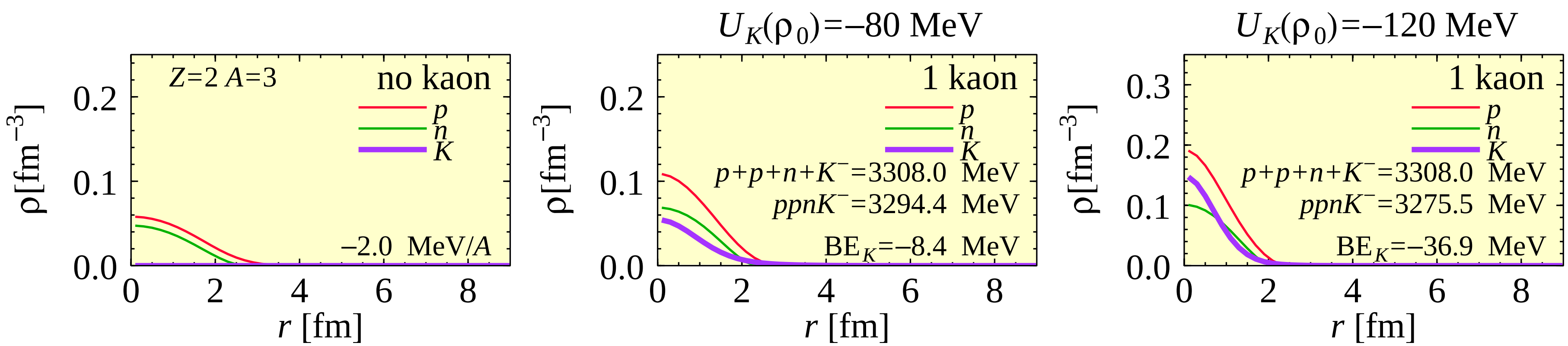
- Cluster-like correlation between kaon and protons.
- Higher density ($\rho_{\max} \sim 1.5\rho_0$) for light nuclei.
- Small effects for heavy nuclei.



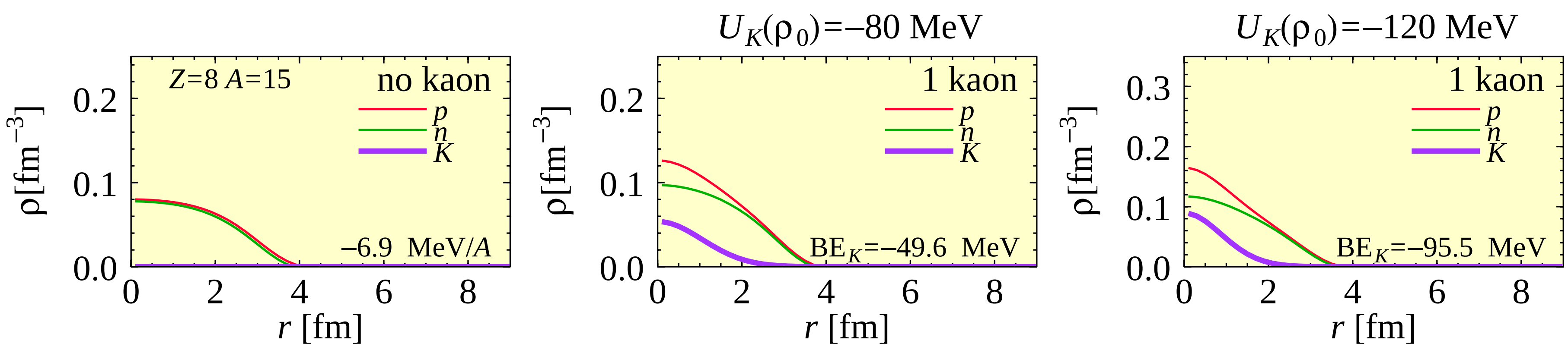
- The density depends on U_K. But the highest density is at most $2\rho_0$.
- The difference between the chiral model and the linear model is small.



ppK^- metastable for some cases.



$ppnK^-$ Shallower binding than S^+ (3140 MeV).



$^{15}OK^-$ Reasonable BE of kaonic nucleus for $U_K(\rho_0) = 120$ MeV.

nuclei	Kaon binding energy [MeV]		
	linear, $U_K = -80$ MeV	linear, $U_K = -120$ MeV	chiral, $U_K = -80$ MeV
pp	unbound	$+1.7$ $(+11.2-9.5)$	unbound
ppp	unbound	-0.4 $(+20.5-20.9)$	unbound
ppn	-7.7 $(+0.7-8.4)$	-26.5 $(+10.4-36.9)$	-6.2
^{15}O	-46.2 $(+3.4-49.6)$	-82.6 $(+12.9-95.5)$	-43.7
^{40}Ca	-66.9 $(+2.5-69.4)$	-106.6 $(+9.3-115.9)$	-64.7
^{100}50	-82.6 $(+1.9-84.5)$	-122.5 $(+6.3-128.8)$	-80.9
^{200}100	-93.2 $(+1.6-94.8)$	-131.4 $(+4.7-136.1)$	-91.8

Summary

• We have studied bulk properties (density profile and energy) of kaonic nuclei by a RMF model.

Results

For particular nuclei

• $\mathtt{ppK}^-$ is unbound or a metastable state (depends on the interaction).

• $\mathtt{ppnK}^-$ is more weakly bound than experimental $S^+(3140)$.

• BE of kaon in $^{15}\mathtt{OK}^-$ is -50 – -100 MeV.

General comments

• Cluster-like correlation between K^- and p.

• "High" density at the center. $\rho_{\max} \sim 2\rho_0$.

• Small effects of kaon for heavy nuclei.

What are missing in this calc

• Microscopic effects such as shell structure and clustering structure,

• description of excited states,

• decay width of kaon, etc.

But it's worth trying such a simple model to get a rough image.