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Dynamics of kaonic nuclei in an improved quark mass density-dependent model

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outline

1. Introduction to the improved quark mass density-dependent model
2. Theoretical framework for kaonic nuclei
3. Results and discussion
4. Summary

Introduction to the improved quark mass density-dependent model

Introduction to IQMDD

- **Self-consistent mean-field models for nuclear structure**
  - Hartree-Fock-Bogoliubov method (HFB)
    H. J. Mang, Phys. Rep. 18, 325 (1975).
  - Relativistic mean-field model (RMF)
    J. Walecka, Annals of Physics 83, 491 (1974).
    P. Ring, Prog. Part. Nucl. Phys. 37, 193 (1996).

- **Extended Relativistic mean-field models**
  - The quark-meson coupling model (QMC)
    P. A. M. Guichon, Physics Letters B 200, 235 (1988).
  - The quark mean field model (QMF)
    H. Toki, U. Meyer, A. Faessler, and R. Brockmann, Phys. Rev. C 58, 3749 (1998).

Introduction to IQMDD

According to the QMDD model, suggested by Fowler et al. , the masses of u, d quarks and strange quarks depend on the baryon number density n_B.

$$m_q = \frac{B}{3n_B}(q = u, d, \bar{u}, \bar{d}), \; m_{s,\bar{s}} = m_{s_0} + \frac{B}{3n_B}$$

G. N. Fowler et al., Z. Phys. C 9, 271 (1981)

The IQMDD Lagrangian density at hadronic level

$$L = \bar{\varphi}[i\gamma^{\mu}\partial_{\mu} - M_N^*(\sigma) - g_{\omega}\gamma^{\mu}\omega_{\mu} - \frac{g_{\rho}}{2}\gamma^{\mu}\tau\cdot\rho_{\mu} - \frac{e}{2}\gamma^{\mu}(1+\tau_3)A_{\mu}$$

$$+\frac{f_{\omega}g_{\omega}}{2M_N}\sigma^{\mu\nu}\partial_{\nu}\omega_{\mu}]\varphi + \frac{1}{2}\partial^{\mu}\sigma\partial_{\mu}\sigma - U(\sigma) - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2}m_{\omega}^2\omega^{\mu}\omega_{\mu}$$

$$-\frac{1}{4}G^{\mu\nu}G_{\mu\nu} + \frac{1}{2}m_{\rho}^2\rho^{\mu}\rho_{\mu} + \eta(g_{\rho}^2\rho_{\mu}\rho^{\mu})(g_{\omega}^2\omega_{\mu}\omega^{\mu}) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

Introduction to IQMDD

The effective nucleon mass is obtained from the bag energy which reads

$$M_N^* = \sum_q E_q = \sum_q \frac{4}{3}\pi R^3 \frac{\Gamma_q}{(2\pi)^3} \int_0^{K_F^q} \sqrt{m_q^{*2} + k^2} \left(\frac{dN_q}{dk}\right) dk$$

where, $m_q^* = m_q - g_\sigma^q \sigma$

The bag radius R can be determined by using the equilibrium condition for the nucleon bag

$$\frac{\delta M_N^*}{\delta R} = 0$$

Introduction to IQMDD

While the expression of M_N^* for RMF is taken as

$$\boxed{M_N^* = M_N - g_\sigma \sigma}$$

IQMDD model has a nonlinear relationship with the σ field rather than RMF model

$$\boxed{\left(\frac{\partial M_N^*}{\partial \sigma}\right)_R = -g_\sigma \times \begin{pmatrix} 1 \\ c(\sigma) \end{pmatrix} \quad \text{for} \quad \begin{pmatrix} \text{RMF(NL3,FSU,...)} \\ \text{IQMDD} \end{pmatrix}}$$

Theoretical framework for kaonic nuclei in IQMDD

Theoretical framework for kaonic nuclei

Formulas of the IQMDD model for kaonic nuclei

$$L = L_N + \partial_\mu \bar{K} \partial^\mu K - m_K^2 \bar{K} K + g_{\sigma K} m_K \bar{K} K \sigma$$
$$+ \left(i g_{\omega K} \omega_\mu + i g_{\rho K} \tau \cdot \rho_\mu + i \frac{e}{2} (1 + \tau_3) A_\mu \right) \left(K \partial^\mu \bar{K} - \bar{K} \partial^\mu K \right)$$
$$+ \left[g_{\omega K} \omega_\mu + g_{\rho K} \tau \cdot \rho_\mu + \frac{e}{2} (1 + \tau_3) A_\mu \right]^2 \bar{K} K$$

Using the Euler-Lagrange equation one obtains the Dirac equation for nucleons as follow

Theoretical framework for kaonic nuclei

$$\left[i\gamma^{\mu}\partial_{\mu} - M_N^* - g_{\omega}\gamma^0\omega_0 - \frac{g_{\rho}}{2}\gamma^0\tau_3\rho_0 + \frac{f_{\omega}g_{\omega}}{2M_N}\sigma^{0i}\partial_i\omega_0 - \frac{e}{2}\gamma^0\left(1+\tau_3\right)A_0 \right]\varphi = 0 \quad (1)$$

The equations of motion for the mesons and photon can be written as

$$\left(-\Delta + m_{\sigma}^2\right)\sigma = -\frac{\partial M_N^*}{\partial \sigma}\rho_s - b\sigma^2 - c\sigma^3 + g_{\sigma K}m_K\bar{K}K \quad (2)$$

$$\left(-\Delta + m_{\omega}^2\right)\omega_0 = g_{\omega}\rho_v + \frac{f_{\omega}g_{\omega}}{2M_N}\rho_0^T - g_{\omega K}\rho_{K^-} - 2\eta g_{\rho}^2 g_{\omega}^2 \rho_0^2 \omega_0 \quad (3)$$

Theoretical framework for kaonic nuclei

$$\left(-\Delta + m_\rho^2\right)\rho_0 = \frac{g_\rho}{2}\rho_3 - g_{\rho K}\rho_{K^-} - 2\eta g_\rho^2 g_\omega^2 \rho_0 \omega_0^2 \quad (4)$$

$$-\Delta A_0 = e\rho_p - e\rho_{K^-} \quad (5)$$

The density of K^- meson ρ_{K^-} is given by

$$\rho_{K^-} = 2\left[\mathrm{Re}\,E_{K^-} + g_{\omega K}\omega_0 + g_{\rho K}\rho_0 + eA_0\right]\bar{K}K \quad (6)$$

The integration of ρ_{K^-} over the whole volume is normalized to the number of antikaon, which is one in our calculation.

Theoretical framework for kaonic nuclei

The Klein-Gordon equation of motion for the K^- meson acquires the form

$$\left[-\Delta+(m_K^2-E_{K^-}^2)+\tilde{\Pi}\right]\bar{K}=0 \qquad (7)$$

- K^- **meson absorption in the nuclear medium**

To evaluate the K^- decay width, one allows the self-energy to become complex

$$\begin{aligned}\tilde{\Pi} &= \mathrm{Re}\,\tilde{\Pi}-i\,\mathrm{Im}\,\tilde{\Pi}\\ &= -g_{\sigma K}m_K\sigma-2\left(\mathrm{Re}\,E_{K^-}\right)\left[g_{\omega K}\omega_0+g_{\rho K}\rho_0+eA_0\right]\\ &-\left[g_{\omega K}\omega_0+g_{\rho K}\rho_0+eA_0\right]^2-i\,\mathrm{Im}\,\tilde{\Pi}\end{aligned}$$

Theoretical framework for kaonic nuclei

The complex eigenenergy is given as

$$E_{K^-} = \mathrm{Re}\, E_{K^-} - i\Gamma_{K^-} / 2$$

Two kinds of antikaonic absorption in the nuclear medium are considered.

$$\bar{K}N \rightarrow \pi\Sigma,\ \ \pi\Lambda; \qquad \bar{K}NN \rightarrow YN$$

Then the imaginary part of the potential $\mathrm{Im}\,\tilde{\Pi}$ is written as

$$\mathrm{Im}\,\tilde{\Pi} = \mathrm{Im}\,\tilde{\Pi}^{(1)} + \mathrm{Im}\,\tilde{\Pi}^{(2)} = 2\left(\mathrm{Re}\, E_{K^-}\right) f_1 V_0 \frac{\rho_\nu(r)}{\rho_0}$$

$$+2\left(\mathrm{Re}\, E_{K^-}\right) f_2 V_0 \frac{\rho_\nu{}^2(r)}{\rho_0{}^2}$$

Theoretical framework for kaonic nuclei

The mesonic and nonmesonic decay channels are dominated by the final Σ states

$$\boxed{f_1 = 0.8 f_{1\Sigma}, \quad f_2 = 0.2 f_{2\Sigma}}$$

$$\boxed{f_1 = 0.7 f_{1\Sigma} + 0.1 f_{1\Lambda}, \quad f_2 = 0.2 f_{2\Sigma}}$$

C. Vander Velde-Wilquet, J. Sacton, J. H.Wickens, D. N. Tovee, and D. H. Davis, *Nuovo Cimento A* **39**, 538 (1977).

J. Yamagata, H. Nagahiro, Y. Okumura et al., Prog. Theor. Phys. **114**, 301 (2005).

T. Sekihara, J. Yamagata-Sekihara, D. Jido, Y. Kanada-En'yo, Phys. Rev. *C* **86**, 065205 (2012).

Theoretical framework for kaonic nuclei

The imaginary potential depth V_0 strongly depends on the model adopted.

E. Friedman, A. Gal, C.J. Batty, Phys. Lett. B 308, 6 (1993).

E. Friedman, A. Gal, J. Mares, A. Cieply, Phys. Rev. C 60, 024314 (1999).

$\boxed{V_0 \sim 50\text{MeV}}$

A. Ramos et al., Nucl. Phys. A 691, 258 (2001).

$\boxed{V_0 \sim 15\text{MeV}}$

The imaginary potential depth V_0 is set to be in the range of 15 ~ 50 MeV.

Theoretical framework for kaonic nuclei

- K^- **optical potential**

The difference in K^- potential depths between different approaches

T.Waas, W. Weise, Nucl. Phys. A 625, 287 (1997).

$$U_{K^-}(\rho_0) \sim -120\mathrm{MeV}$$

V. Koch, Phys. Lett. B 337, 7 (1994).

$$U_{K^-}(\rho_0) \sim -100\mathrm{MeV}$$

A. Cieply, E. Friedman, A. Gal, and J. Mares, Nucl. Phys. A 696, 173 (2001)

$$U_{K^-}(\rho_0) \approx -60 \sim -50\mathrm{MeV}$$

Theoretical framework for kaonic nuclei

- The ω-K and ρ-K coupling constants are adopted from the SU(3) relation assuming ideal mixing

$$2g_{\omega K} = 2g_{\rho K} = 6.04$$

J. Schaffner, I.N. Mishustin, Phys. Rev. C 53, 1416 (1996).

- The σ-K coupling is fixed by varying the optical potential from −80MeV to −120MeV.

A. Martinez Torres, K.P. Khemchandani, E. Oset, Eur. Phys. J. A 36, 211 (2008)

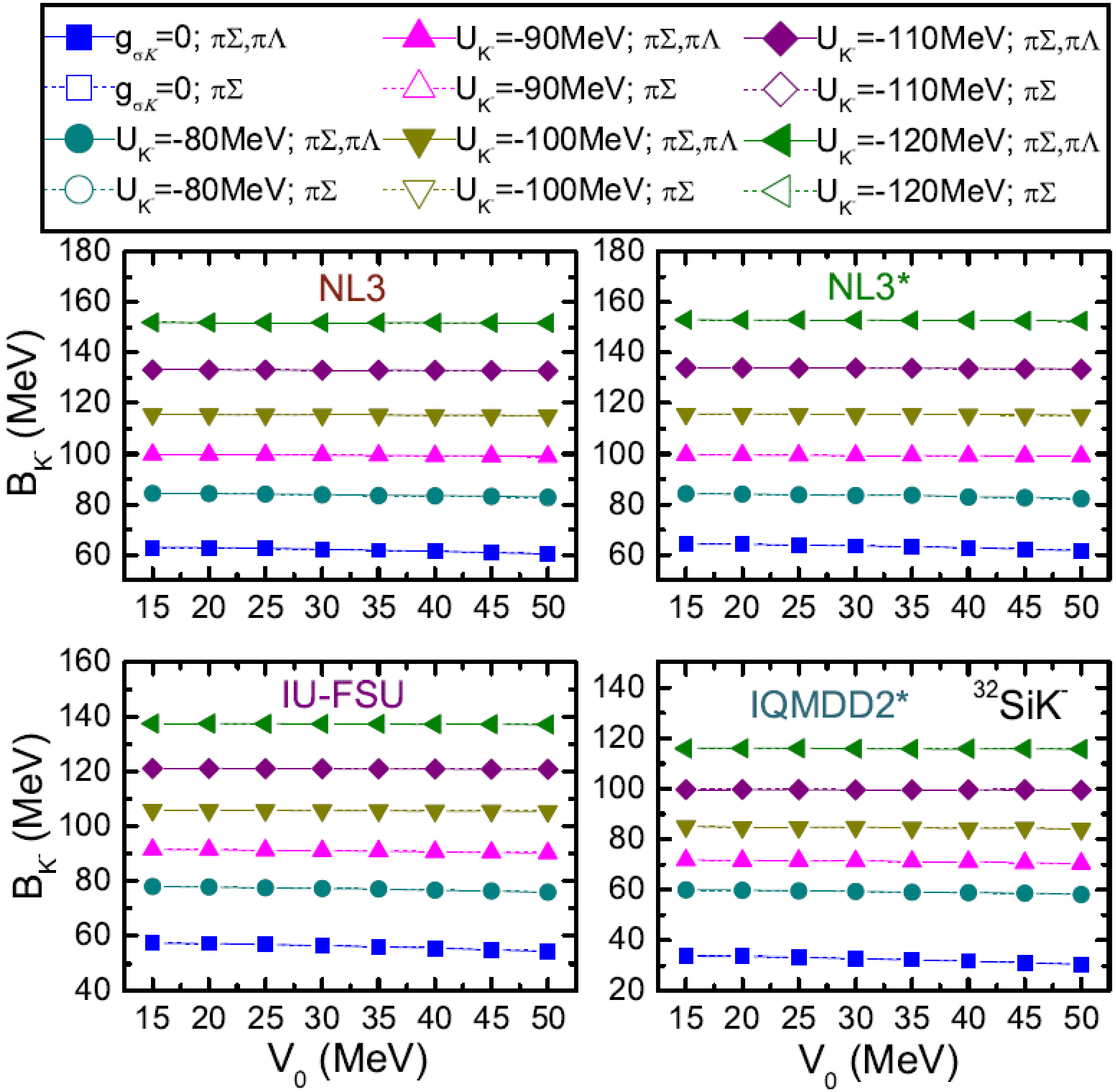
$$g_{\sigma K} = 0$$

$$U_{K^-}(\rho_0) \approx -70 \sim -50\mathrm{MeV}$$

(NL3, NL3*, IU-FSU,IQMDD2*)

Results and discussion

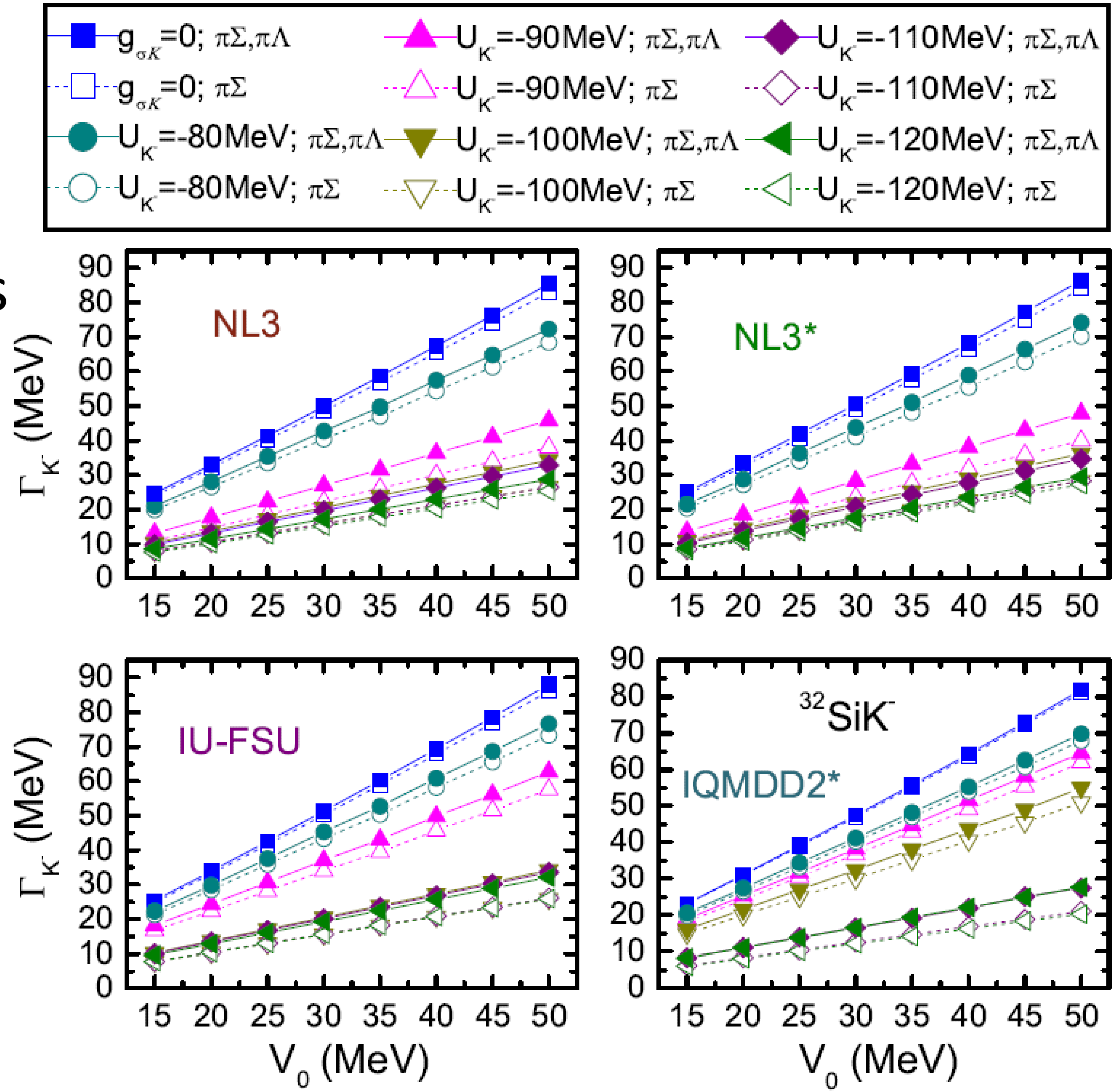
1. K⁻ binding energy



The calculated K^- binding energies of the 1s nuclear state in the $^{32}\mathrm{Si}K^-$ nucleus by using the IQMDD model (IQMDD2*) and RMF models (NL3, NL3* and IUFSU).

2. decay widths

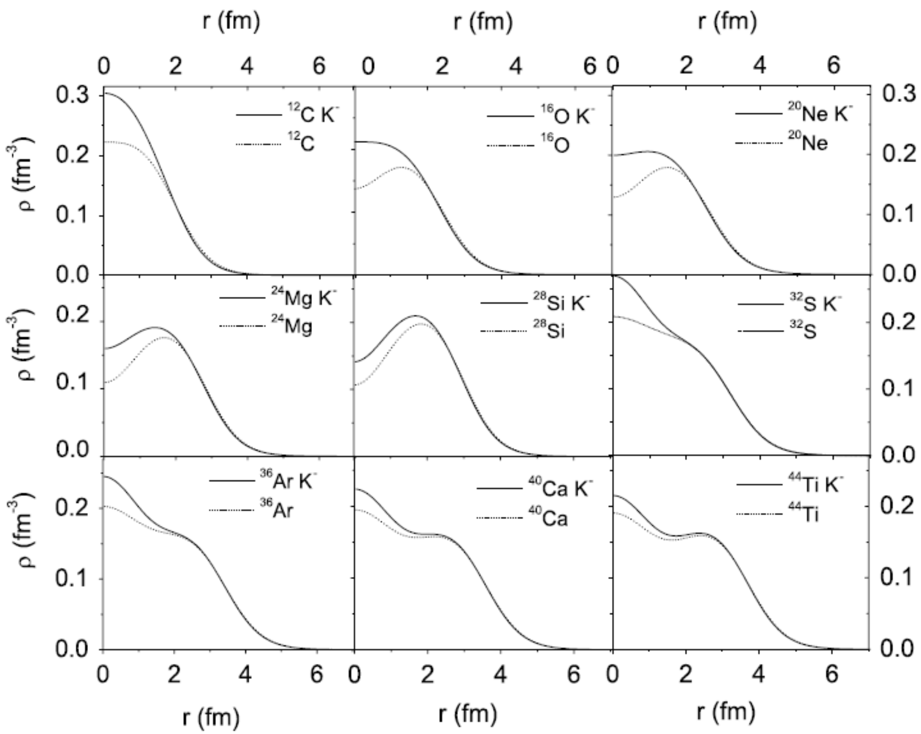
The widths (Γ_{K^-}) of the 1s K^--nuclear state in the $^{32}\mathrm{Si}K^-$ nucleus as a function of the imaginary potential depth by using the IQMDD model (IQMDD2*) and other RMF models (NL3, NL3* and IU-FSU) for different absorption.

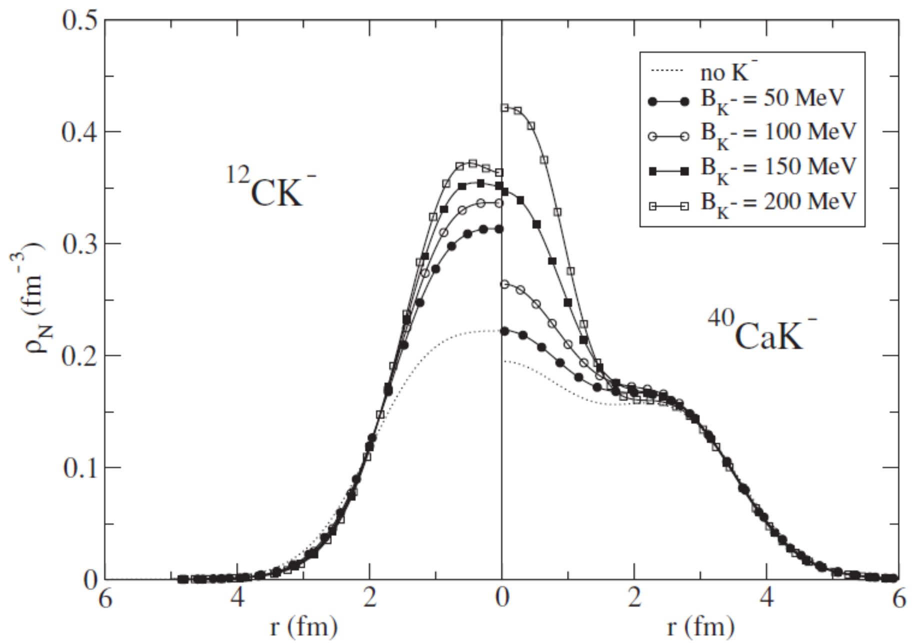


D. Gazda, E. Friedman, A. Gal, J. Mares, Phys. Rev. C 76, 055204 (2007).

3. nuclear density distribution

- The shrinkage effects for the kaonic nuclei

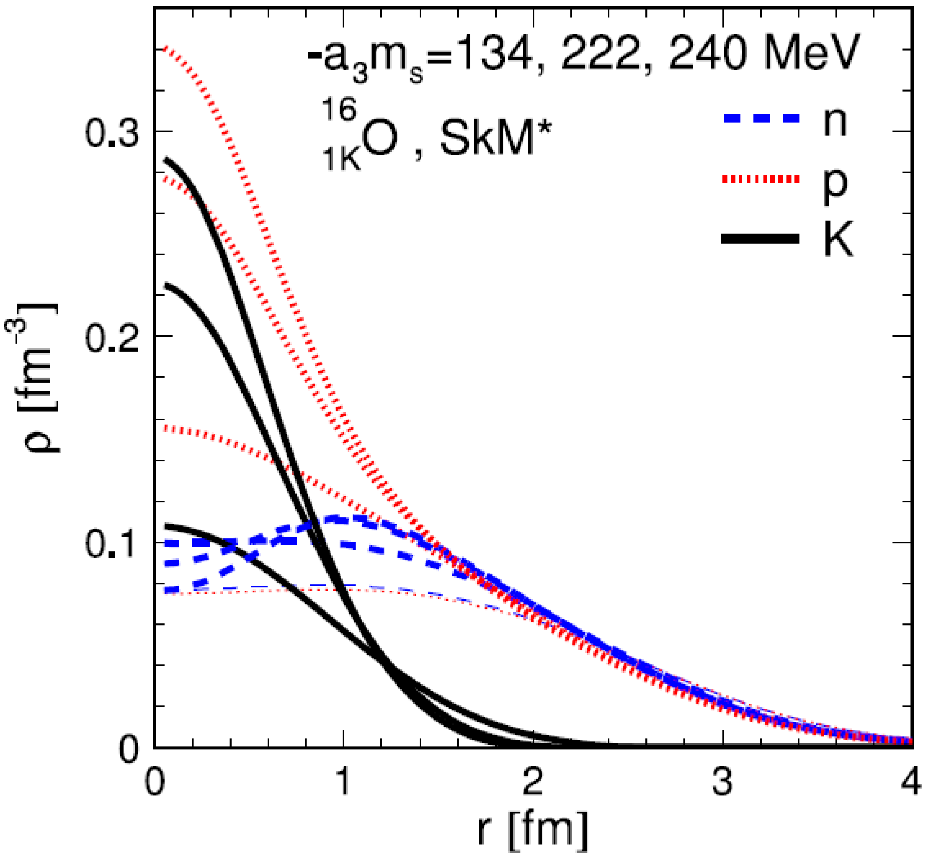




X.H. Zhong, G.X. Peng, L. Li, P.Z. Ning, Phys. Rev. C 74, 034321 (2006).

D. Gazda, E. Friedman, A. Gal, J. Mares, Phys. Rev. C 76, 055204 (2007).

3. nuclear density distribution

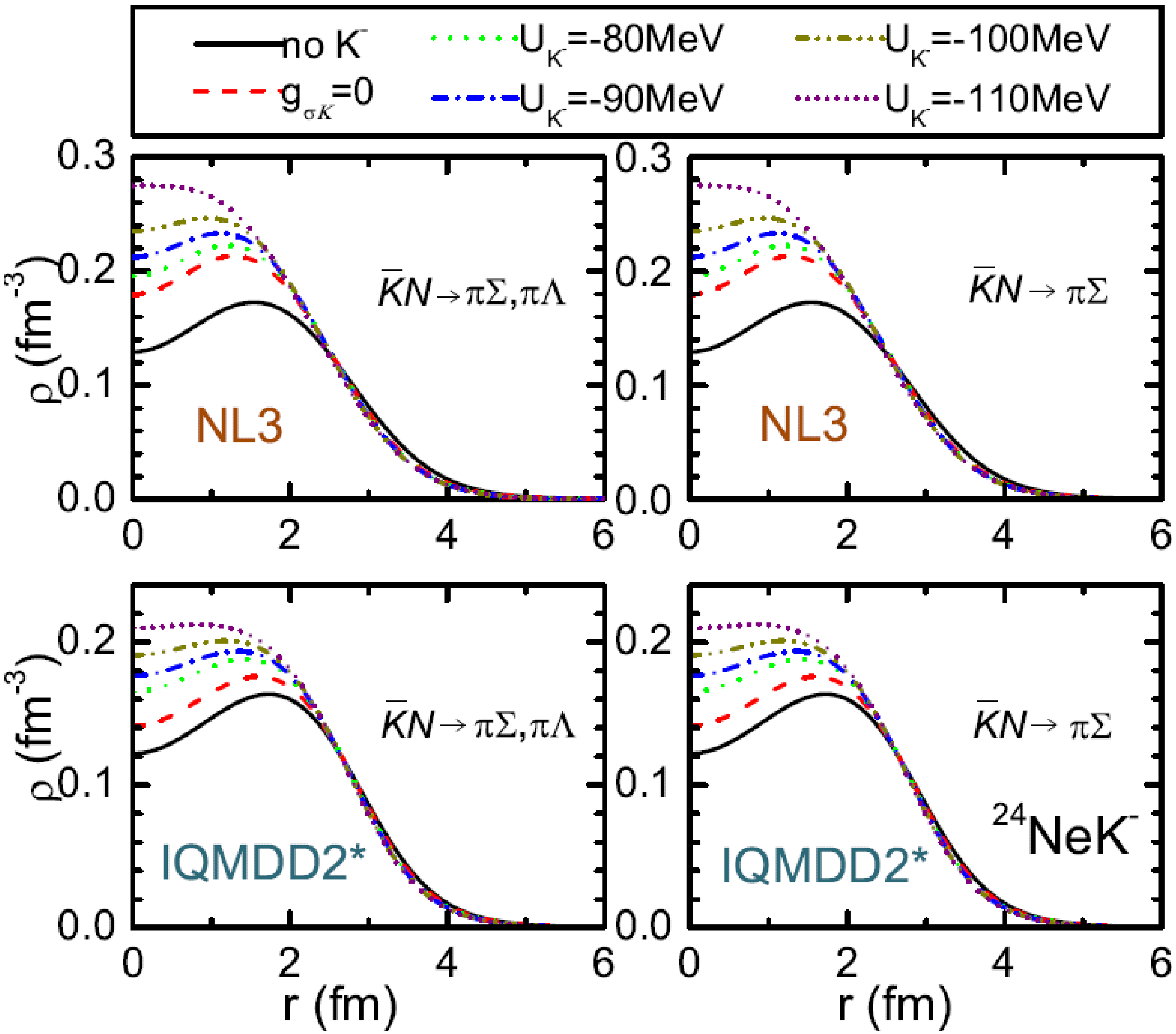


Kaon and nucleon densities of $^{16}OK^{-}$ for various interaction parameters a_3. Increasing absolute a_3 values correspond to increasing curves. The thin curves represent the core nucleus.

X.-R. Zhou, H.-J. Schulze, Nucl. Phys. A 914, 332 (2013).

3. nuclear density distribution

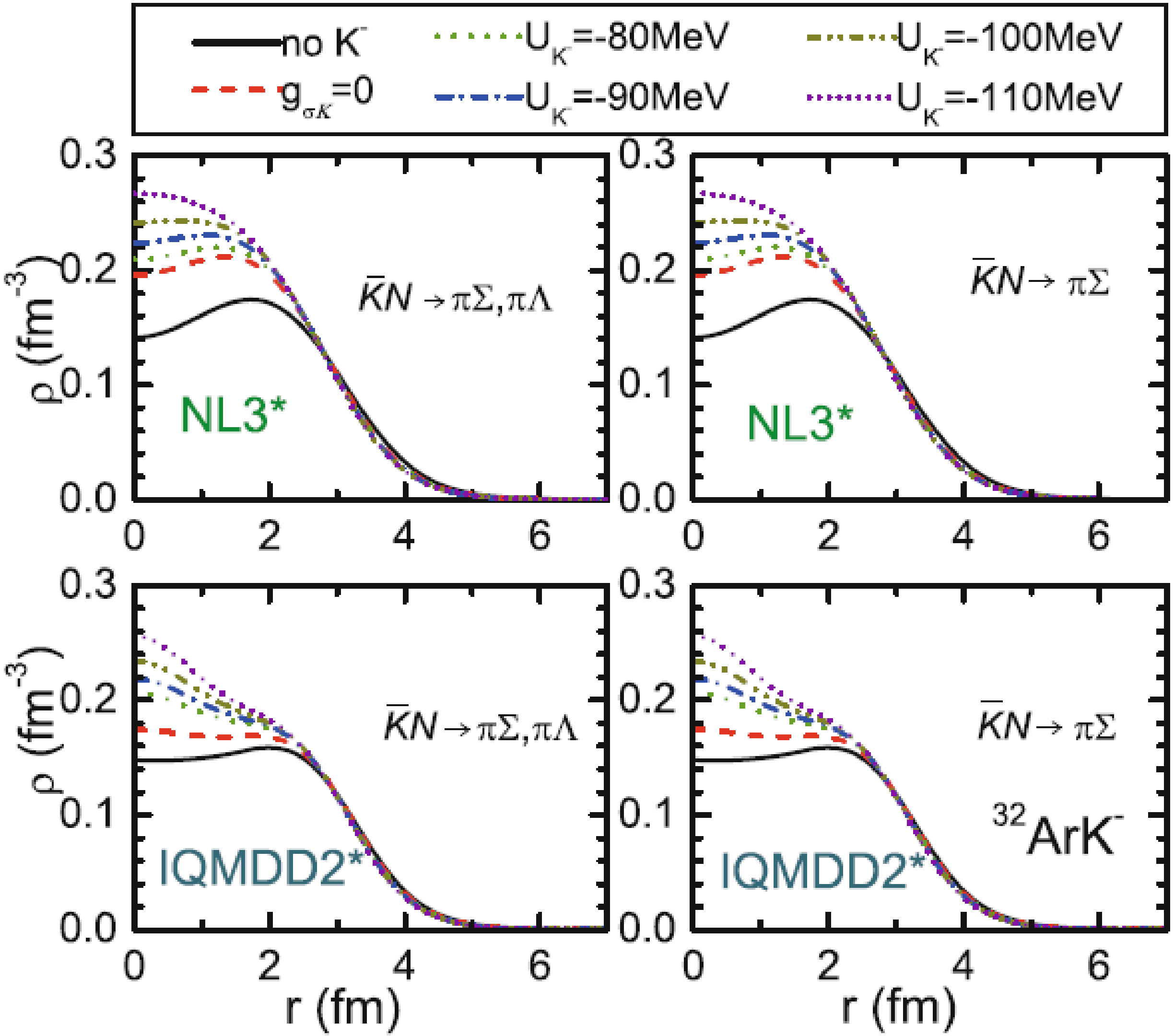
The effects of K^- meson on the properties of bubble nuclei in the light mass region.



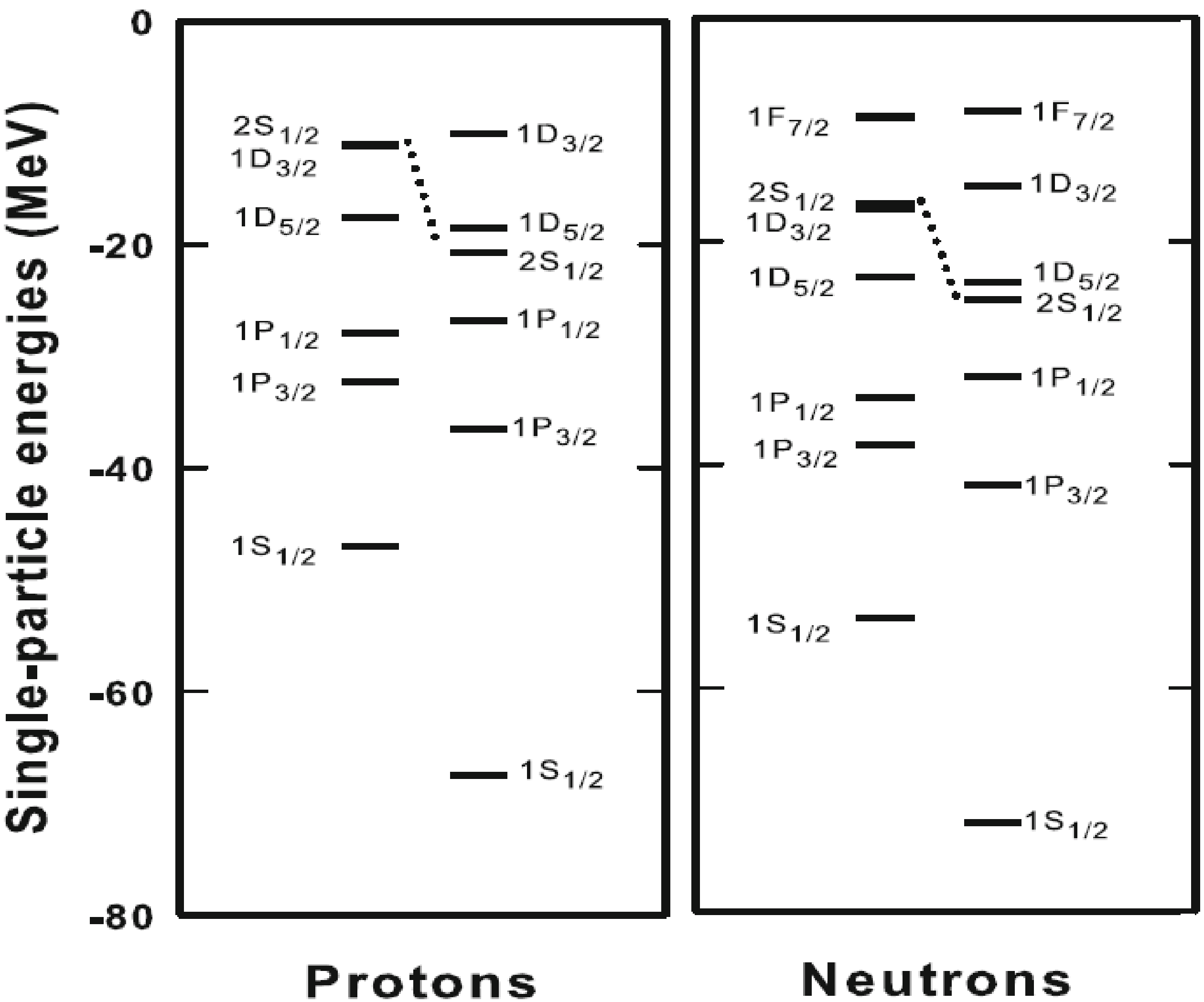
The nuclear density of ^{24}Ne and ^{24}NeK$^-$ nuclei for 1s K$^-$-nuclear state in the NL3 and the IQMDD model.

3. nuclear density distribution

The nuclear density of $^{32}\mathrm{Ar}$ and $^{32}\mathrm{ArK}^-$ nuclei for 1s K^--nuclear state in the NL3* and the IQMDD model , with or without the secondary $\pi\Lambda$ decay mode for absorption through the $\bar{K}N \to \pi\Sigma$.



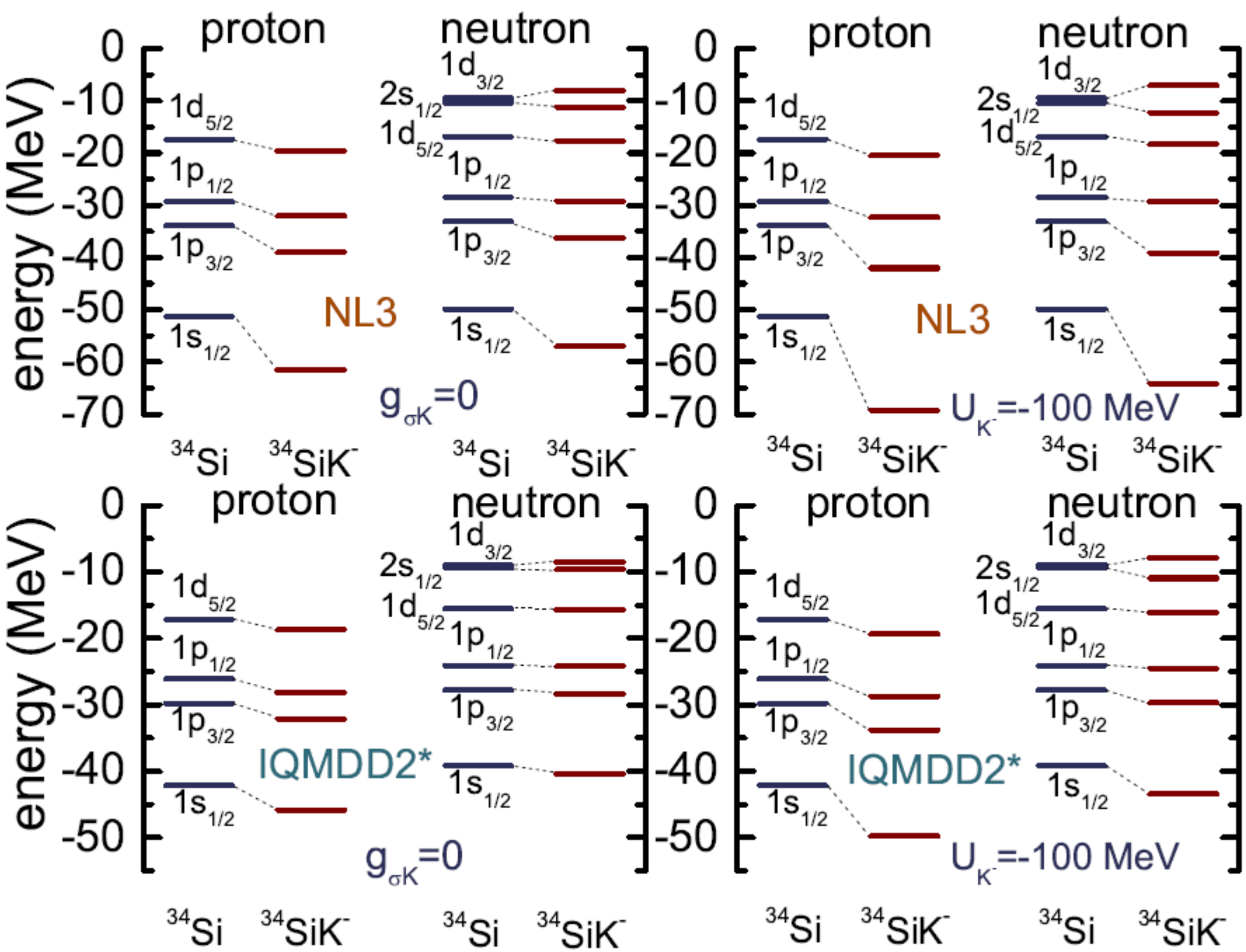
3. pseudospin orbit splitting



Single-particle energies in ^{42}Ca and ^{42}CaK$^-$. The left column in each panel represents energy levels for ^{42}Ca, while the right ones are for ^{42}CaK$^-$.

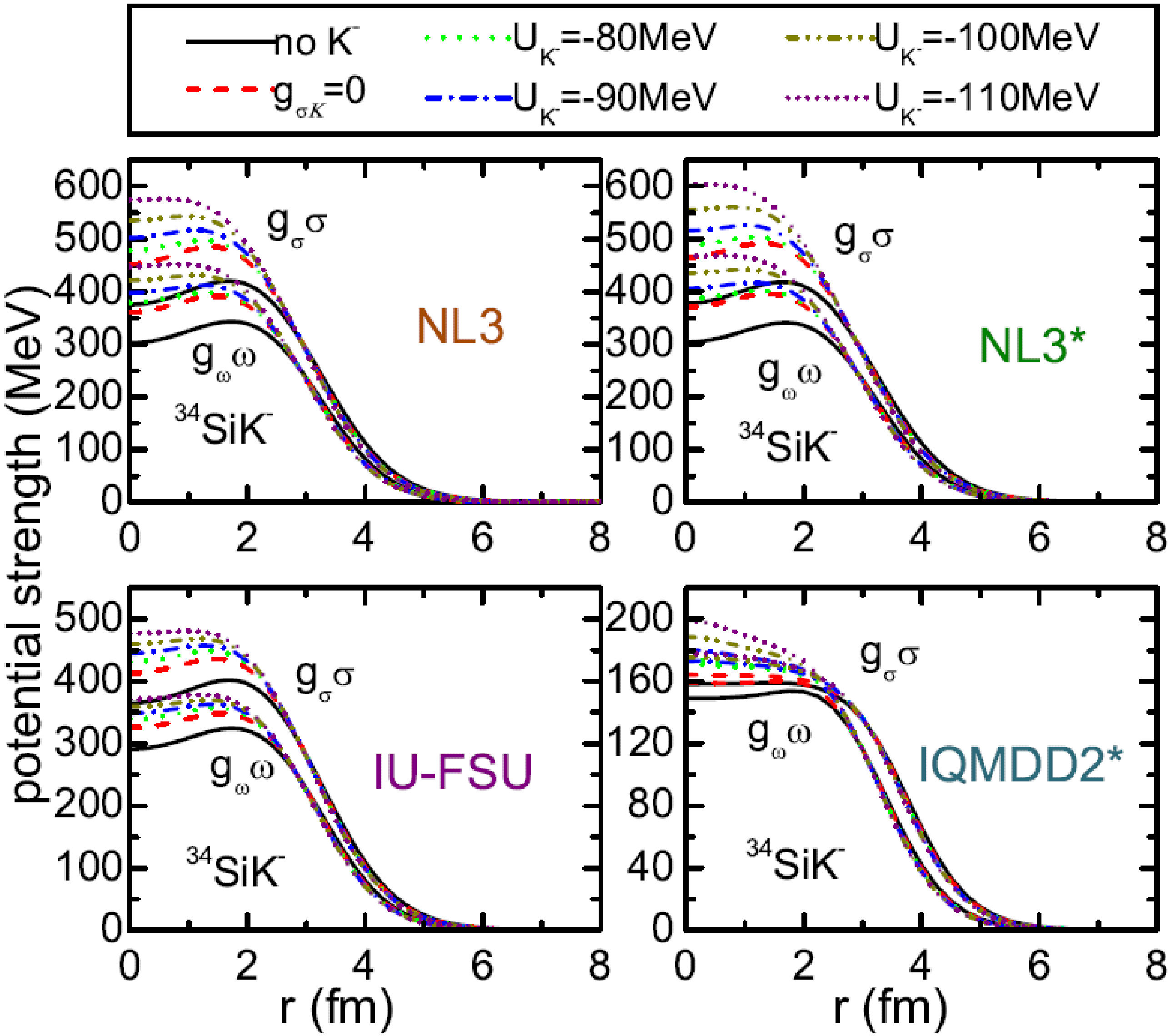
R.-Y. Yang, W.-Z. Jiang, Q.-F. Xiang, D.-R. Zhang, and S.-N. Wei, Eur. Phys. J.A 50, 188 (2014)

3. pseudospin orbit splitting



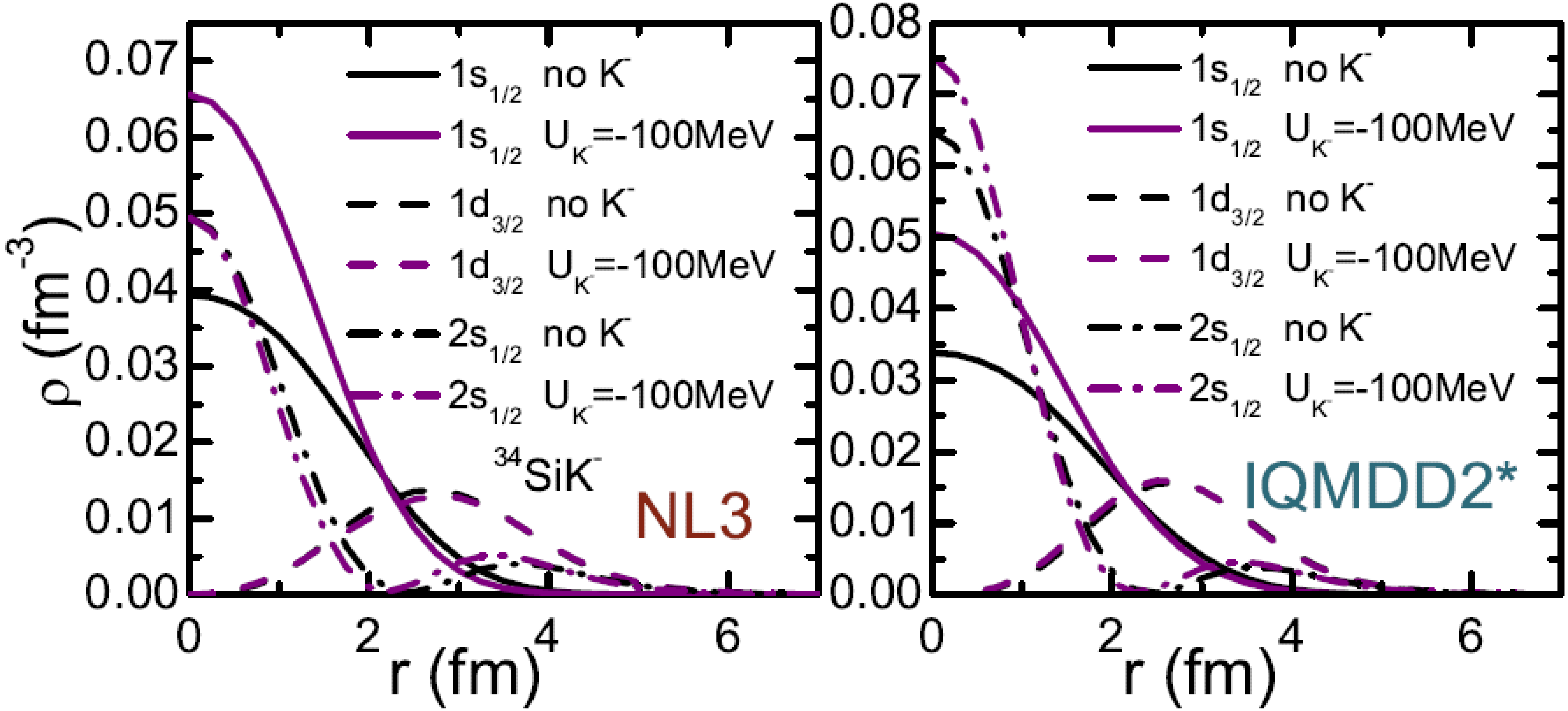
Nucleon single-particle energies of $^{34}\mathrm{Si}$ and $^{34}\mathrm{SiK}^{-}$ nuclei in the NL3 and the IQMDD model by taking $g_{\sigma K}=0$ and $U_{K^-}(\rho_0)$ to be −100MeV.

3. pseudospin orbit splitting



The calculated scalar and vector potentials of nucleon of 1s K^- -nuclear state in ^{34}Si and $^{34}SiK^-$ nuclei by using NL3, NL3*, IU-FSU and IQMDD models.

3. pseudospin orbit splitting



The density distribution of $1s_{1/2}$, 2s1/2 and $1d_{3/2}$ neutron states of $^{34}\mathrm{Si}$ and $^{34}\mathrm{SiK}^{-}$ nuclei in 1s K^{-}-nuclear state by using the NL3 and the IQMDD model, one assumes $U_{K^-}(\rho_0)$ = −100MeV.

Summary

1. The antikaon optical potential $U_{K^-}(\rho_0)$ has a sizable effect on the K^- binding energy. It is found that the K^- binding energy B_{K^-} increases when the antikaon optical potential $U_{K^-}(\rho_0)$ becomes deeper.

2. The antikaon optical potential $U_{K^-}(\rho_0)$ also has a significant effect on the decay width Γ_{K^-}. When the antikaon optical potential becomes deeper, the calculated width Γ_{K^-} decreases.

Summary

3. When the antikaon optical potential $U_{K^-}(\rho_0)$ becomes more negative, the central nuclear density in kaonic nuclei increases. As a result, the nucleon bubble may disappears by embedding the K^- meson in the possible bubble nuclei.

4. the K^- embedment can lead to the pseudospin orbit splitting, and result in the pseudospin symmetry breaking in kaonic nuclei.

Acknowledgement

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Thank you

The phase-space suppression factor corresponding to mesonic decay channel is written as

$$f_{1Y} = \frac{M_{01}^3}{M_1^3}\sqrt{\frac{[M_1^2-(m_\pi+m_Y)^2][M_1^2-(m_\pi-m_Y)^2]}{[M_{01}^2-(m_\pi+m_Y)^2][M_{01}^2-(m_\pi-m_Y)^2]}}$$
$$\times\Theta(M_1-m_\pi-M_Y)$$

Where,

$$M_{01} = m_K + M_N$$

$$M_1 = \mathrm{Re}\,E_{K^-} + M_N$$

The phase-space suppression factor corresponding to nonmesonic decay channel is written as

$$f_{2Y} = \frac{M_{02}^{3}}{M_{2}^{3}} \sqrt{\frac{[M_2^2 - (m_N + m_Y)^2][M_2^2 - (m_N - m_Y)^2]}{[M_{02}^2 - (m_N + m_Y)^2][M_{02}^2 - (m_N - m_Y)^2]}} \times \Theta(M_2 - m_N - M_Y)$$

Where,

$$M_{02} = m_K + 2M_N$$

$$M_2 = \mathrm{Re}\, E_{K^-} + 2M_N$$

assuming UK−(ρ0) = −100MeV in the NL3 model, the strength of the scalar and vector potential of a nucleon at the center of the 34SiK− increase about 160 MeV and 118MeV, respectively, compared to those in the 34Si.