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Effects of the tetraneutron condensation in neutron stars

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Can tetraneutrons exist inside neutron stars and affect their properties?

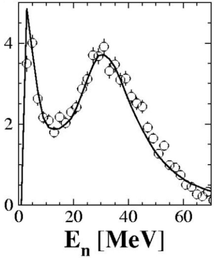
1. Hystory & Motivation

- Unitary symmetry of nuclear interaction $\Rightarrow$

Can ^{4}n exist if α-particle does?

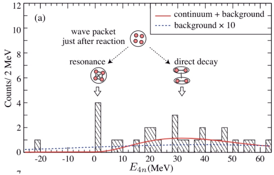
- Formation of ^4n in reaction $^{14}Be \rightarrow {}^{10}Be + {}^4n$?

F. M. Marqués et al., PRC, 65, 044006 (2002)



- Theory excludes bound ^4n with high confidence (negative binding energy, sizable width)

A. M. Shirokov et al., Phys. Rev. Lett. 117, 182502 (2016) and references therein
K. Fossez et al., Phys. Rev. Lett. 119, 032501 (2017) and references therein



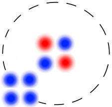
Can ^{4}n exist as a short-living resonance?

- Resonant ^4n in reaction $\alpha + {}^8He \rightarrow {}^8Be + {}^4n$

K. Kisamori et al., Phys. Rev. Lett. 116, 052501 (2016)

- Strong external filed can stabilize ^4n as a subthreshold resonance like in ^8He nucleus

S. A. Sofianos et al., J. Phys. G 23, 1619 (1997) and references therein
K. Fossez et al., Phys. Rev. Lett. 119, 032501 (2017) and references therein



Can ^{4}n-resonance exist inside nuclear medium and affect its properties?

2. Tetraneutrons in medium

- Short lifetime $\Rightarrow$ explicit account of finite width is required
- Self-energy in RMF model with ω and ρ mesons

$$\Sigma_{4n} = g_{4n\omega}\omega_0 + g_{4n\rho} I_{4n}^{(3)} \rho_0^{(3)}$$

Mean mesonic fields are real $\Rightarrow$ no effects of width are accounted explicitly

- Mass averaging of Lagrangian

$$\mathcal{L} = \mathcal{L}_{4n} + other\ species \rightarrow \int_{m_{4n}^{th}}^{\infty} dm\ \rho_{4n}(m)\ \mathcal{L}_{4n}(m) + other\ species, \quad m_{4n}^{th} = 4m_n$$

$$\Downarrow$$

$$p = \int_{m_{4n}^{th}}^{\infty} dm\ \rho_{4n}(m)\ p_{4n}(m) + other\ species$$

V. M. Kuksa, Phys. Part. Atom. Nucl., 45, 3 (2014)

Mass averaging is also applied in the Hadron Resonance Gas Model

A. Andronic, P.Braun-Munzinger and J.Stachel, Nucl. Phys. A 772, 167 (2006) and references therein.

3. Mass distribution of tetraneutrons

- Relativistic Breit-Wigner distribution function (normalized to unity)

$$\rho_{4n}(m) = \frac{N}{(m^2 - m_{4n}^2)^2 + m_{4n}^2 \Gamma_{4n}^2}, \quad m_{4n} = 4m_n + E_{4n}$$

- Excitation energy: the most recent experimental value which coincides with theroretical calculations $\Rightarrow$ $E_{4n} = 0.83$ MeV

K. Kisamori et al., Phys. Rev. Lett. 116, 052501 (2016)
A. M. Shirokov et al., Phys. Rev. Lett. 117, 182502 (2016)

- Vacuum width: the most recent experimental value $\Gamma_{4n} = 2.6$ MeV is within $1.4 - 15$ MeV predicted by theory;

R. Lazauskas and J. Carbonell, Phys. Rev. C 72, 034003 (2005)
E. Hiyama, R. Lazauskas, J. Carbonell, and M. Kamimura, Phys. Rev. C 93, 044004 (2016)

mean theoretical value is close to inverse lifetime $\tau = 10^{-22} s$ measured experimentally $\Rightarrow$ $\Gamma_{4n} = 7$ MeV

- Medium width: estimated as average time between collisions with neutrons

$$\tau_{col}^{-1} \simeq \frac{v_F}{l_{col}} \simeq \frac{(3\pi^2 n_n)^{1/3}}{m_n} \Big/ \left(\frac{3}{4\pi n_n}\right)^{2/3} = \frac{\pi (2n_n)^{1/3}}{m_n}$$

$n_n = 0.15 - 0.24$ fm^{-3} $\Rightarrow$ $\tau_{col}^{-1} = 60 - 80$ MeV
earlier experimental result ~ 100 MeV

$\Rightarrow \quad \Gamma_{4n} = 80$ MeV

F. M. Marqués et al., Phys. Rev. C, 65, 044006 (2002)

4. RMF model with tetraneutrons

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_\Delta + \mathcal{L}_e + \mathcal{L}_d + \mathcal{L}_t + \mathcal{L}_h + \mathcal{L}_\alpha + \mathcal{L}_{4n} + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_\sigma + U_\sigma$$

- Species: nucleons, Δ-isobars, electrons, ^2H, ^3H, ^3He, α-particles, tetraneutrons
  All species expect electrons are coupled to ω, ρ and σ mesons
- Δ-isobars are introduced as spin-$\frac{3}{2}$ Rarita-Schwinger field
  E. E. Kolomeitsev, K. A. Maslov and D.N.Voskresensky, Nucl. Phys. A 961, 106 (2017)
- Minimal coupling scheme for nuclear clusters with $m_j = A_j m_N - B_j$
  S. S. Avancini, M. Ferreira, H. Pais, C. Providencia and G. Röpke, Phys. Rev. C 95, 045804 (2017)
- Tetraneutrons are represented by Lorentz scalar ϕ

$$\mathcal{L}_{4n} = \int\limits_{m_{4n}^{th}}^{\infty} dm\ \rho_{4n}(m) \frac{(D_{4n\mu}\phi)^* D_{4n}^{\mu}\phi - (m - g_{4n\sigma}\sigma)^2 \phi^* \phi}{2}, \quad iD_{4n}^{\mu} = i\partial^\mu - g_{4n\omega}\omega^\mu - g_{4n\rho}\ \vec{I}_{4n} \cdot \vec{\rho}^{\ \mu}$$

- Effective chemical potentials and medium masses

$$\mu_j^* = \mu_B B_j + \mu_Q Q_j - g_{j\omega}\omega_0 - g_{j\rho} I_j^3 \rho_0^3, \quad m_j^{*2} = \begin{cases} (m_j - g_{j\sigma}\sigma)^2, & j \neq 4n \\ \int\limits_{m_{4n}^{th}}^{\infty} dm\ \rho_{4n}(m)(m - g_{4n\sigma}\sigma)^2, & j = 4n \end{cases}$$

- Self-interaction of σ meson: $U_\sigma = -\frac{b}{3} m_n (g_\sigma \sigma)^3 - \frac{c}{4}(g_\sigma \sigma)^4$

5. Coupling constants

- Isoscalar couplings: Δ – lack of empirical information, quark counting

  E. E. Kolomeitsev, K. A. Maslov and D.N.Voskresensky, Nucl. Phys. A 961, 106 (2017)

  nuclear clusters – binding, dissociation energy, Mott density

  S. S. Avancini, M. Ferreira, H. Pais, C. Providencia and G. Röpke, Phys. Rev. C 95, 045804 (2017)

- Isovector couplings: the same for all species since isospin $\vec{I}$ is introduced explicitly

  S. Typel, G. Rpke, T. Klahn, D. Blaschke, and H. H. Wolter, Phys. Rev. C 81, 015803 (2010)

$$\begin{pmatrix} g_{N\omega} \\ g_{\Delta\omega} \\ g_{d\omega} \\ g_{t\omega} \\ g_{h\omega} \\ g_{\alpha\omega} \end{pmatrix} = g_\omega \begin{pmatrix} 1 \\ 1 \\ 3.516 \\ 4.382 \\ 4.624 \\ 5.675 \end{pmatrix}, \quad g_{j\rho} = g_\rho, \quad \begin{pmatrix} g_{N\sigma} \\ g_{\Delta\sigma} \\ g_{d\sigma} \\ g_{t\sigma} \\ g_{h\sigma} \\ g_{\alpha\sigma} \end{pmatrix} = g_\sigma \begin{pmatrix} 1 \\ 1 \\ 4/3 \\ 6/3 \\ 6/3 \\ 8/3 \end{pmatrix}$$

- Tetraneutron is short living resonance $\Rightarrow$ neutrons inside it are weakly correlated

$$g_{4n\omega} \simeq 4g_\omega, \quad g_{4n\sigma} \simeq 4g_\sigma, \quad g_{4n\rho} \simeq g_\rho$$

- g_ω, g_ρ, g_σ, b and c are fitted to properties of nuclear matter ground state ($T = 0$, $n_0 = 0.153$ fm^{-3}, $p = 0$, $\frac{E_b}{A} = 16.3$ MeV, $K_0 = 250$ MeV, $\frac{m_N^*}{m_N} = 0.75$, a_{sym}=32.5 MeV

6. Bose-Einstein condensation of tetraneutrons

$$p = \sum_f \frac{g_f}{6\pi^2} \int_0^{k_f} \frac{dk\ k^4}{\sqrt{m_f^{*2} + k^2}} + \sum_b \zeta_b^2(\mu_b^{*2} - m_b^{*2}) + \frac{m_\omega^2 \omega^2}{2} + \frac{m_\rho^2 \rho^2}{2} - \frac{m_\sigma^2 \sigma^2}{2} + U_\sigma$$

- Mean mesonic fields are defined by the selfconsistency conditions

$$\frac{\partial p}{\partial \omega} = 0, \quad \frac{\partial p}{\partial \rho} = 0, \quad \frac{\partial p}{\partial \sigma} = 0$$

- ζ_b represents amplitude of bosonic zero mode and maximizes pressure

$$\frac{\partial p}{\partial \zeta_b} = 2\zeta_b(\mu_b^{*2} - m_b^{*2}) = 0 \quad \Rightarrow \quad \zeta_b \neq 0 \quad if \quad \mu_b^* = m_b^*$$

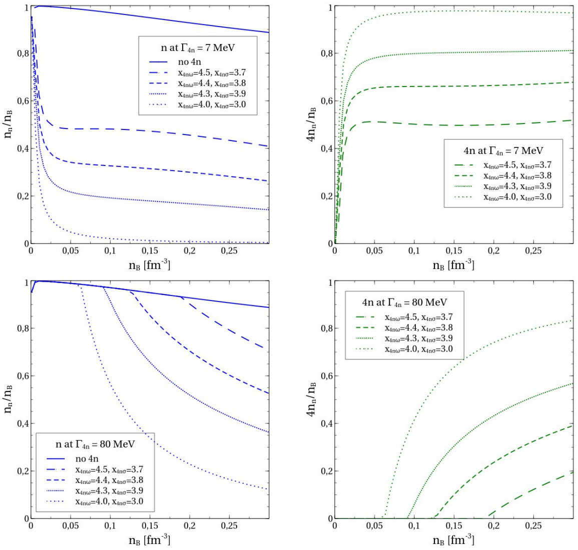
J. Kapusta, Finite temperature field theory, Cambridge University Press, Cambridge (1989)

- Bosonic condensate does not contribute to the pressure but has non-zero density

$$p_b = \zeta_b^2(\mu_b^{*2} - m_b^{*2}) = 0$$

$$n_b = \frac{\partial p}{\partial \mu_b} = 2\zeta_b^2 \mu_b^* \neq 0 \quad if \quad \zeta_b \neq 0$$

7. Chemical composition



$x_{4n\omega}$	$x_{4n\sigma}$	$\Gamma_{4n} = 7$ MeV		$\Gamma_{4n} = 80$ MeV	
		n^{os}_{4n}/n_0	n^{os}_{Δ}/n_0	n^{os}_{4n}/n_0	n^{os}_{Δ}/n_0
–	–	–	2.967	–	2.967
4.5	3.7	0.039	6.190	1.288	6.556
4.4	3.8	0.039	5.784	0.804	7.098
4.3	3.9	0.039	5.667	0.641	6.954
4.0	4.0	0.039	5.529	0.412	6.242

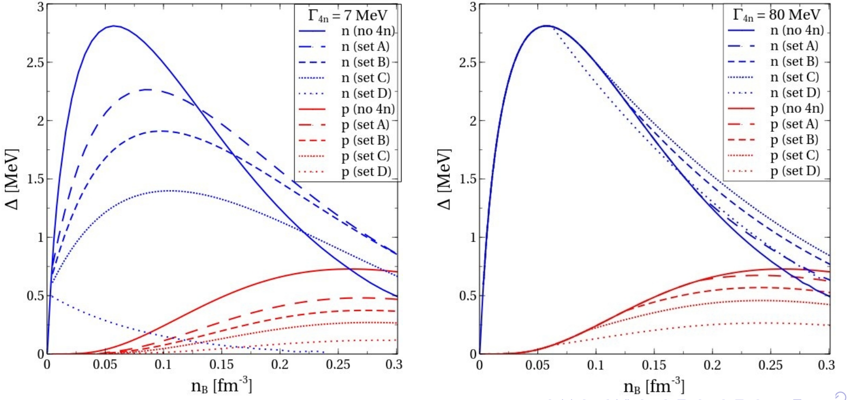
- ^4n dramatically reduce fractions of all species including neutrons
- ^4n significantly increase onset density of Δ-isobars
- Width Γ_{4n} and repulsion controlled by $x_{4n\omega}$ suppress ^4n
- Attraction controlled by $x_{4n\sigma}$ enhances ^4n

8. Pairing of nucleons in $^1S_0$ scattering channel

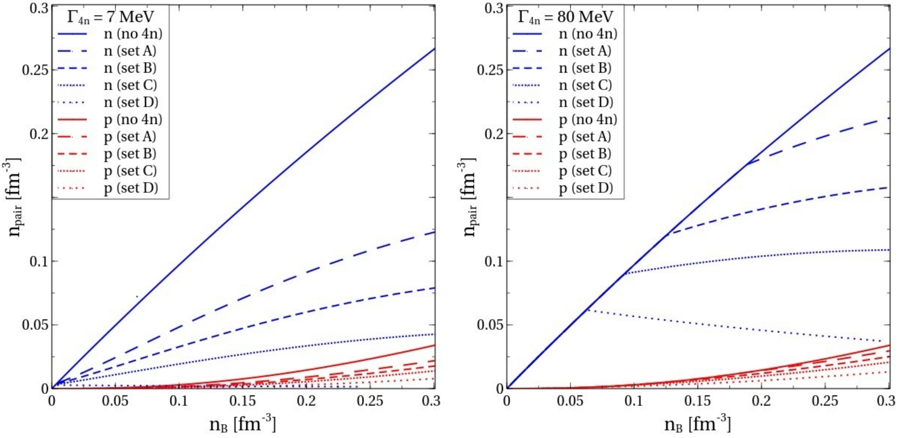
$$\Delta(k) = \frac{1}{\pi}\int_0^\infty \frac{dk' k'^2 V(k,k')\Delta(k')}{\sqrt{(\sqrt{k'^2 + m_N^{*2}} - \mu_N^*)^2 + \Delta(k')^2}}, \quad V(k,k') = \int_0^\infty dr\ r^2 j_0(kr)V(r)j_0(k'r)$$

- One boson exchange potential of the Yukawa type

$$V(r) = \frac{A}{r}\left(g_\omega^2 e^{-m_\omega r} + g_\rho^2 I_N^{3\,2} e^{-m_\rho r} - g_\sigma^2 e^{-m_\sigma r}\right), \quad V_{min} = 83.728\ MeV\ at\ r = 0.481\ fm$$



$$n_{pair} = \frac{1}{2\pi^2}\int_0^\infty dk' k'^2 \left[1 - \frac{(\sqrt{k'^2 + m_N^{*2}} - \mu_N^*)}{\sqrt{(\sqrt{k'^2 + m_N^{*2}} - \mu_N^*)^2 + \Delta(k')^2}}\right]$$



10. Conclusions

- Tetraneutrons can exist in the neutron rich matter inside NS as the Bose-Einstein condensate of resonant states
- Tetraneutrons reduce fractions of individual nucleons and Δ-isobars. In presence of tetraneutrons onset density of Δ-isobars increases at least to 5.5 saturation ones
- Tetraneutrons suppress pairing of nucleons through reduction of their pairing gap and density of paired particles
- Condensation of tetraneutrons can be important for astrophysical applications (superfluidity, formation of superconducting phase, EoS)

Thank you for attention!