Suppression of the Repulsive Force in Nuclear Interactions near the Chiral Phase Transition

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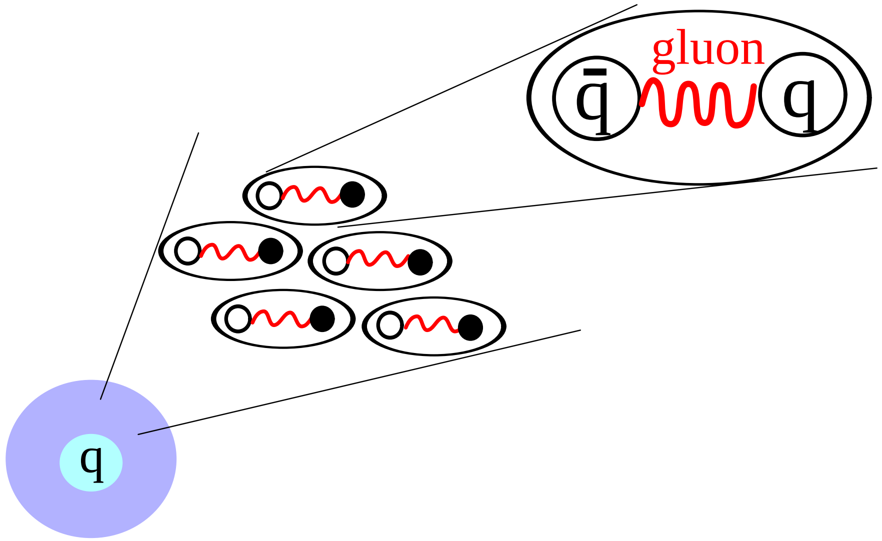
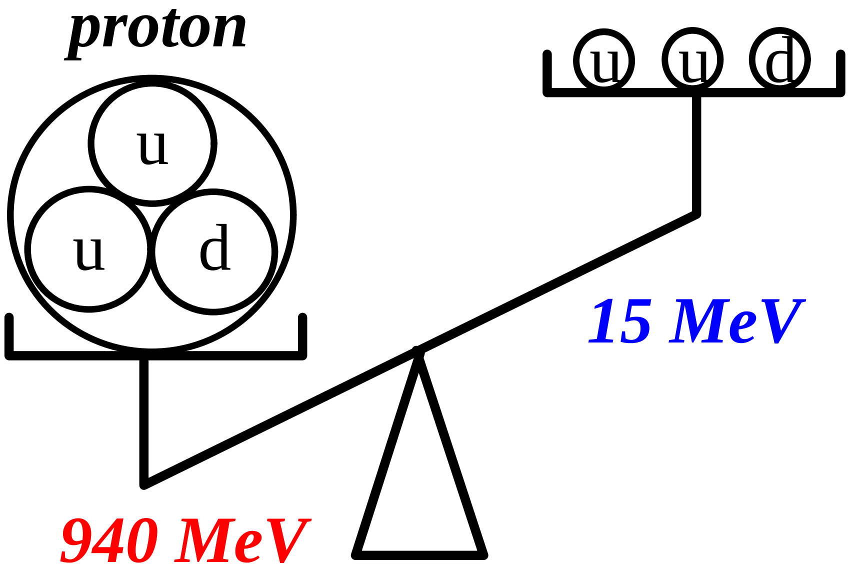
References

- C.S., H.K.Lee, W.-G.Paeng, M.Rho, Phys. Rev. **D84**, 034011 (2011).
- W.-G.Paeng, H.K.Lee, M.Rho, C.S., [arXiv:1109.5431 [hep-ph]].

Origin of hadron masses?

- spontaneous chiral symmetry breaking $\cdots$ dynamics of strong int., $\Lambda_{\rm QCD}$





- scale symmetry breaking $(x^\mu \to e^\tau x^\mu)$ $\cdots$ emergence of a scale in QCD

$$\partial_\mu J^\mu = T^\mu_\mu = -\left(\frac{11}{24}N_c - \frac{1}{12}N_f\right)\frac{\alpha_s}{\pi}G_{\mu\nu}G^{\mu\nu} + \sum_f m_f \bar{q}_f q_f$$

- hadron masses: not only from $\langle \bar{q} q \rangle$ but also other condensates

$$m_H = \mathcal{F}\left(m_{\rm SCSB}\,, m_{\rm non-SCSB}\right)$$

Baryons near chiral symmetry restoration

- m_N at χ-symmetry restoration? $\cdots$ dynamical origin of nucleon mass?
  - standard assignment: DχSB generates entire masses. $\quad m_N \overset{\sigma\to 0}{\to} 0$

$$\psi_L \to L\,\psi_L\,, \quad \psi_R \to R\,\psi_R \quad \Rightarrow \text{no } \bar{\psi}\psi$$

  - mirror assignment: DχSB generates mass difference of parity doublers.

$$m_{N_+} \overset{\sigma\to 0}{\to} m_{N_-} = m_0 \neq 0$$

[Detar-Kunihiro (89)]

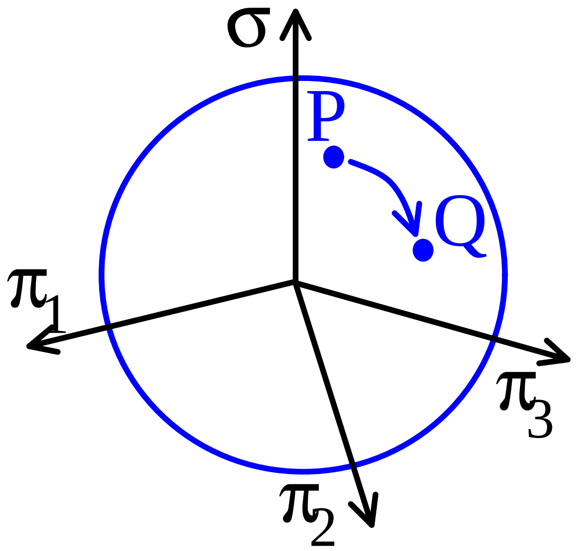
$$\psi_{1L} \to L\,\psi_{1L}\,, \quad \psi_{1R} \to R\,\psi_{1R}\,, \quad \psi_{2L} \to R\,\psi_{2L}\,, \quad \psi_{2R} \to L\,\psi_{2R}$$

$$\mathcal{L}_m = m_0\left(\bar{\psi}_2\gamma_5\psi_1 - \bar{\psi}_1\gamma_5\psi_2\right) \;\Rightarrow\; m_{N_\pm} = \frac{1}{2}\left[\sqrt{c_1\sigma^2 + 4m_0^2} \mp c_2\sigma\right]$$

- how large is m_0?
  - vacuum: 300 MeV from $N^* \to N\pi$ [DeTar-Kunihiro (89), Nemoto et al. (98)]
  - nuclear matter: $800 \overset{\text{4quark}}{\Rightarrow} 450$ MeV [Zschiesche et al. (07), Gallas et al. (09)]
  - finite $T \simeq T_{\rm ch}$: 200 MeV from $\langle G_{\mu\nu}G^{\mu\nu}\rangle_T$ [CS-Lee-Paeng-Rho (11)]

Role of scalar mesons

- stable nuclear matter: a scalar boson in Walecka model, "modified" σmodel
- nonlinear realization of chiral symmetry
  d.o.f.: pions, NO scalar mesons loops: chiral perturbation theory
- near χSR: scalar meson gets lighter $\Rightarrow$ O(4) multiplet with pions $(s, \vec{\pi})$
- **from linear to non-linear basis, or the other way around**



$P \rightarrow Q$: chiral transformation

$$\Phi = \sigma + i\vec{\tau}\cdot\vec{\pi} \qquad f_\pi = \sqrt{\sigma^2 + \vec{\pi}^2}$$

$$= (\sigma_0 + \tilde{\sigma})U\,, \quad U = e^{-i\vec{\tau}\cdot\vec{\pi}/f_\pi}$$

$$\Rightarrow \mathcal{L} = \frac{f_\pi^2}{4}\mathrm{tr}\left[\partial_\mu U^\dagger \partial^\mu U\right]$$

- **two-component gluon condensate** [Miransky-Gsynin (89), Lee-Rho (09)]

  – trace anomaly in QCD

$$\partial_\mu J^\mu = T^\mu_\mu \propto \langle H|G^2|H\rangle\,, \quad H = \text{quarkonium, glueballs, etc.}$$

  – decomposition

$$\langle H|G^2|H\rangle = \underbrace{\langle G^2\rangle_{\rm soft}}_{\chi\text{SB}\,,\,N_c N_f} + \underbrace{\langle G^2\rangle_{\rm hard}}_{\text{CSB}\,,\,N_c^2}$$

  – from Lattice EoS: gluon *decondensation* at finite T [Miller (07)]

$$\langle G^2\rangle_{T_{\rm chiral}} \simeq \frac{1}{2}\langle G^2\rangle_{T=0} \quad \Rightarrow \quad \text{melting } \langle G^2\rangle_{\rm soft}$$

  – soft and hard dilatons

$$V(\chi) = V(\chi_s) + V(\chi_h)\,, \quad V_i = \frac{1}{4}B_i\left(\frac{\chi_i}{F_{\chi_i}}\right)^4\left[\ln\left(\frac{\chi_i}{F_{\chi_i}}\right)^4 - 1\right]$$

  – **role of hard dilaton**
  origin of m_0, bag "function": $B(T_{\rm chiral}) \simeq \frac{1}{2}B(T=0)$

- **transmutation of a scalar from NLSM to LSM** [Beane-van Kolck (94)]

1. soft dilaton (gluonium) in a NLSM: $U = \xi^2 = e^{2i\pi/F_\pi}$, $\sqrt{\kappa} = F_\pi / F_{\chi_s}$

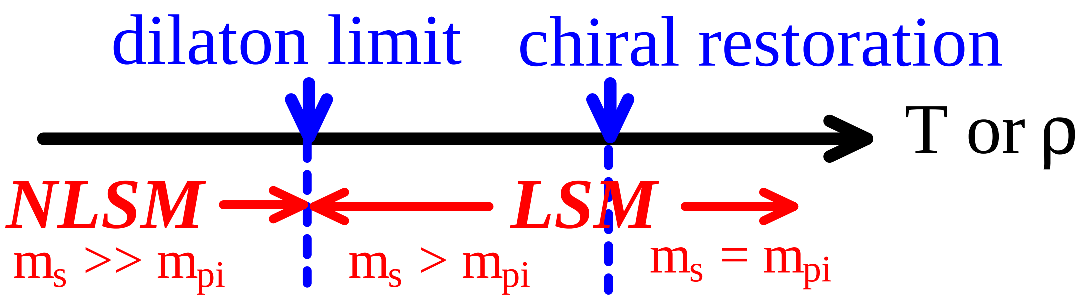
$$\mathcal{L} = \bar\psi i(\partial\!\!\!/ + V\!\!\!/)\psi + g_A \bar\psi A\!\!\!/ \gamma_5 \psi - m\left(\frac{\chi_s}{F_{\chi_s}}\right)\bar\psi\psi + \frac{F_\pi^2}{4}\left(\frac{\chi_s}{F_{\chi_s}}\right)^2 \text{tr}\left[\partial_\mu U^\dagger \partial^\mu U\right] + \mathcal{L}(\chi_s)$$

2. linearization: $\Sigma = \sqrt{\kappa} U \chi = s + i\vec\tau\cdot\vec\pi$ & $B = \frac{1}{2}[(\xi + \xi^\dagger) - \gamma_5(\xi - \xi^\dagger)]\psi$

$$\mathcal{L} = \bar B i\partial\!\!\!/ B - \frac{m_N}{2F_\pi}\bar B\left[\Sigma + \Sigma^\dagger + \gamma_5\left(\Sigma - \Sigma^\dagger\right)\right]B + \frac{1}{4}\text{tr}\left[\partial_\mu\Sigma\cdot\partial^\mu\Sigma^\dagger\right]$$
$$+ \frac{m_s^2}{64F_\pi^2}\left(\text{tr}\left[\Sigma\Sigma^\dagger\right]\right)^2 - \frac{m_s^2}{32F_\pi^2}\left(\text{tr}\left[\Sigma\Sigma^\dagger\right]\right)^2 \ln\left(\frac{\text{tr}\left[\Sigma\Sigma^\dagger\right]}{2F_\pi^2}\right) + \mathcal{L}_{\text{sing}}(1/\text{tr}[\Sigma\Sigma^\dagger]; \kappa, g_A)$$

3. a LSM $\mathcal{L}(s, \vec\pi, B)$ emerges when $\kappa \to 1$ & $g_A \to 1$ (dilaton limit).

$$\mathcal{L}_{\text{sing}} = (1-\kappa)\mathcal{F}(1/\text{tr}[\Sigma\Sigma^\dagger]) + (1 - g_A)\mathcal{G}(1/\text{tr}[\Sigma\Sigma^\dagger]) \to 0$$



- **introduce vector mesons:** $(N\,,\pi\,,\rho\,,\omega\,,\chi)$ [CS-Lee-Paeng-Rho (2011)]

  hidden local symmetry (HLS) [Bando-Kugo-Uehara-Yamawaki-Yanagida (85)]

  – an extension of non-linear chiral Lagrangian: $U = \xi^2 \to \xi_L^\dagger \xi_R$

  – vector mesons $V = \rho, \omega$ introduced as gauge bosons of HLS (redundancy in decomposition of U)

  – chiral perturbation theory: $m_V \sim \mathcal{O}(p)$ [Georgi, Tanabashi, Harada-Yamawaki]

results:

– dilaton limit: $\kappa = 1$ and $g_A = g_V$ (common to "naive" and mirror)

cf. $g_A = 1$ recovers algebraic sum rules [Beane-van Kolck (94)]

– consequence: VN repulsion suppressed $g_{VN} = g\,(1 - g_V) \to 0$

- **softer equation of state at high density**
- **two-body repulsion via vector-meson exchanges suppressed**
- **symmetry energy suppressed:** $E_{\rm sym} \propto g_{\rho N}^2$

– unchanged at quantum level: IR fixed point $(g_A = g_V = 1)$

Implications, remarks and issues

asymmetric nuclear mass EoS

- how does $E_{\rm sym}$ behave above ρ_0? onset of kaon condensation?
- softer EoS w/ quenching $g_{\rho N}$ vs. $1.97 M_\odot$ neutron star? [Demorest et al.,(10)]
  $\Leftrightarrow$ three-layered model (NM, kaon condensed NM, SQM): bag "constant" $B(\rho) < B(\rho = 0)$, consistent with the soft-dilaton picture [Kim-Lee-Rho (11)]

scaler modes and mixing

- 2-quark, 4-quark and glueball states, three-level crossing at T and ρ
- a toy model implementing χ sym. and scale inv. [CS-Mishustin (11)]
  $\Rightarrow$ a large vacuum $m_\sigma \sim 1$ GeV & $T_{\rm chiral} \simeq T_{\rm deconf}$ at $\mu = 0$

what protects dilaton-limit fixed point?

- vector realization? [Georgi (89,90)]: if $g \to 0$ then symmetry enlarged, $SU(2)\times SU(2) \times SU(2) \to [SU(2)]^4$
- mended symmetry? [Weinberg (69,90)]: $(s\,,\pi\,,\rho\,,a_1)$ classified by 4 irr. repr., becomes manifest at dilaton limit when A_1 included

Conclusions

- **an effective chiral Lagrangian with scale invariance**
  - dilaton limit associated with IR fixed point at quantum level
  - consequence: VN repulsive forces suppressed
  - common to standard and mirror assignments of chirality
  - dilaton limit $\simeq$ Georgi's vector limit? or Weinberg's mended symmetry?

- **at which T or ρ does dilaton limit set in?**
- **mixed scaler modes: quarkonium, tetraquarks, glueballs**
- **how to make a reliable estimate of m_0 in dense matter?**
- **what are phenomenological consequences on thermodynamics?**