Partial restoration of chiral symmetry in nuclei

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collaboration with
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Reference

Nuclear bound state of eta'(958) and partial restoration of chiral symmetry in the eta' mass.
Daisuke Jido, Hideko Nagahiro, Satoru Hirenzaki. Sep 2011.
e-Print: **arXiv:1109.0394 [nucl-th]**

S. Goda, D. Jido, **in preparation**

Mesonic nuclei

bound systems of meson and nuclei

experimental tool to observe medium modification of meson

we do not have to remove in-vacuum contributions

modification of mass and width by many-body effects

ex. mass shift

$$mN \to mN$$
$$mN \to B^*$$

width

$$mN \to \pi N$$
$$mNN \to NN$$

interactions between meson and nucleus

usually comparably large width to level spacing

extract **more fundamental and universal quantities**

ex. quark condensate $\langle \bar{q}q \rangle$

quark-hadron duality

hadronic quantities ⇄ quark-gluon description (substantial)

all hadron quantities have their substantial quark-gluon description **in general, not simple**

sometimes we have simple relations, so-called low energy theorem

Partial restoration of chiral symmetry

model-independent theoretical relation

Drukarev, Levin,
Prog. Part. Nucl. Phys. 27, 77 (1991)

$$\langle \bar{q}q \rangle^* = \left(1 - \frac{\sigma_{\pi N}}{m_\pi^2 f_\pi^2}\rho\right)\langle \bar{q}q \rangle + \mathcal{O}(\rho^{n>1})$$

$\sigma_{\pi N}$: πN sigma term, $O(m_q)$, obtained from $T_{\pi N}$ at soft limit

density expansion

$$\langle \bar{q}q \rangle^* = \underbrace{\langle 0|\bar{q}q|0\rangle}_{\text{negative}} + \rho\underbrace{\langle N|\bar{q}q|N\rangle}_{\sigma_{\pi N}\text{ : positive}} + \mathcal{O}(\rho^{n>1})$$

$$2m_q\langle N|\bar{q}q|N\rangle = \sigma_{\pi N}$$

$$m_\pi^2 f_\pi^2 = -2m_q\langle \bar{q}q\rangle$$

quark condensate does decrease at finite density

pheno. proof by exp. and analyses of pionic atom and low ene. pi-A scattering

K. Suzuki et al. PRL92, 072302, (04); Friedman et al., PRL93, 122302 (04); DJ, Hatsuda, Kunihiro, PLB 670, 109 (08).

30-40 % reduction at saturation density, if believe linear extrapolation

(theoretical) issues : density dependence and amount of reduction at ρ_0

Kaiser, Homont, Weise, PRC77, 025204, (08)

one of the proofs that ChS is really spontaneously broken by physical state

quark-hadron duality

reduction of quark condensate is also consequence of nuclear many body dynamics

Master formula for in-medium quark condensate

an in-medium extension of Glashow-Weinberg relation $F_\pi G_\pi^{1/2} = -\langle \bar{q} q \rangle$

DJ, Hatsuda, Kunihiro, PLB 670 (2008), 109.

derived by chiral Ward identity

sum rule in chiral limit

$$\sum_\alpha \mathrm{Re}\left(F_\alpha^t G_\alpha^{*1/2}\right) = -\langle \bar{q} q \rangle^*$$

Matrix elements

pseudoscalar $\langle \Omega_\ell^b(k) | \phi_5^a(x) | \Omega \rangle = \delta^{ab} G_\ell^{*1/2} e^{ik\cdot x},$

axial vector $\langle \Omega | A_0^a(0) | \Omega_\alpha^b(k) \rangle = i\delta^{ab} \varepsilon_\alpha F_\alpha^t$

in-medium pion and **particle-hole excitations**

- not use density expansion
- sum up **all zero modes**
  - pion modes, particle-hole excitations, etc.
- **particle-hole modes also account for in-medium quark condensate**
- need description of dynamics for actual calculations of matrix elements
- available for experimental confirmation of PRChS, once matrix elements are experimentally extracted
- can be extended with finite quark mass perturbatively

S. Goda
poster session

hadronic quantities ⇄ quark-gluon description (substantial)

Partial restoration of chiral symmetry

effective reduction of quark condensate in nuclear medium

$$\langle \bar{q}q \rangle^* / \langle \bar{q}q \rangle < 1$$

hadronic quantities closely connected to dynamical breaking

1) **pion decay constant**

deeply bound pionic atom

W. Weise, NPA690 (01) 98.
K. Suzuki et al., PRL92 (04) 072302.
DJ, Hatsuda, Kunihiro, PLB 670 (08) 109. etc.

2) **spectrum of sigma meson**

ππ production off nuclei

Hatsuda, Kunihiro, PRL55 (1985), 158.
Hatsuda, Kunihiro, Shimizu, PRL82 (99) 2840.
DJ, Hatsuda, Kunihiro, PRD63 (01) 011901. etc.

3) **mass difference of chiral partners**
(spectrum difference)

ρ-a_1 N-N*(1535)

Weinberg, PRL18 (67) 507.
Kapusta, Shuryak, PRD49 (94) 4694.
DeTar, Kunihiro, PRD39 (89) 2805.
H.C. Kim, DJ, Oka, NPA640 (98) 77. etc.

4) **mass of eta' meson**

S.H. Lee, Hatsuda, PRD57 (96) 1871
DJ, Nagahiro, Hirenzaki, arXiv: 1109.0394 etc.

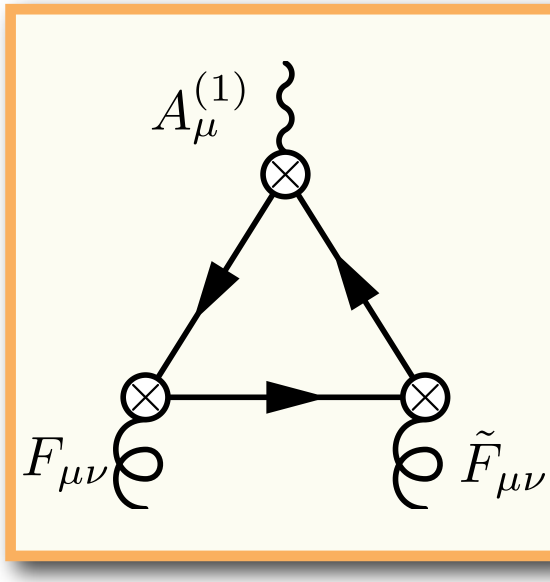
etc.

$\mathrm{U_A}(1)$ anomaly

there is no $\mathrm{U_A}(1)$ symmetry in QuantumChromoDynamics

“classical” chromodynamics (CCD) does have the symmetry

$\mathrm{U_A}(1)$ symmetry is broken by quantum anomaly



$$\tilde{F}_a^{\mu\nu} \equiv \epsilon^{\mu\nu\rho\sigma} F^a_{\rho\sigma}$$

divergence of axial current

flavor octet

$$\partial^\mu A_\mu^{(8)} = \frac{i}{\sqrt{3}}(m_u \bar{u}\gamma_5 u + m_d \bar{d}\gamma_5 d - 2m_s \bar{s}\gamma_5 s)$$

flavor singlet

$$\partial^\mu A_\mu^{(0)} = 2i(m_u \bar{u}\gamma_5 u + m_d \bar{d}\gamma_5 d + m_s \bar{s}\gamma_5 s) + \frac{3\alpha_s}{8\pi} F^a_{\mu\nu}\tilde{F}_a^{\mu\nu}$$

(small) PCAC **anomaly**

the anomaly term always breaks the $\mathrm{U_A}(1)$ symmetry,
no matter how the physical state are.

the $\mathrm{U_A}(1)$ symmetry not to be restored

for simplicity,
we consider SU(3) and chiral limits, and neglect η and η’ mixing

Origin of η′ mass

divergence of axial current

$$\partial^\mu A_\mu^{(8)} = \frac{i}{\sqrt{3}}(m_u \bar{u}\gamma_5 u + m_d \bar{d}\gamma_5 d - 2m_s \bar{s}\gamma_5 s)$$ **convergent**

$$\partial^\mu A_\mu^{(0)} = 2i(m_u \bar{u}\gamma_5 u + m_d \bar{d}\gamma_5 d + m_s \bar{s}\gamma_5 s) + \frac{3\alpha_s}{8\pi} F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$ **not convergent**

(small) PCAC **anomaly**

octet axial currents are conserved

chiral SU(3)xSU(3) symmetry is there

with chiral symmetry breaking

the octet mesons are massless (Nambu-Goldstone bosons)

singlet axial current is NOT conserved due to quantum anomaly

no $U_A(1)$ symmetry

η' is not necessarily massless

$U_A(1)$ anomaly effect keeps η' to be massive

η′ meson in chiral restoration

DJ, Nagahiro, Hirenzaki, arXiv:1109.0394 [nucl-th]

When chiral symmetry is restored...

all the particle belonging to the same multiplet of SU(3)xSU(3) should degenerate

in fact, η and η’ are in the same multiplet of $\mathrm{SU}_L(3) \otimes \mathrm{SU}_R(3)$

Vector and Axial vector mesons

$$(\mathbf{8}, \mathbf{1}) \oplus (\mathbf{1}, \mathbf{8}) \qquad \bar{q}_i^L q_j^L \qquad \bar{q}_i^R q_j^R$$

$3\times\bar{3}=8+1$ flavor single is independent

parity eigenstate

8 vector and 8 axial vector

$$\bar{q}_i \gamma_\mu q_j \,,\, \bar{q}_i \gamma_5 \gamma_\mu q_j$$

Scalar and Pseudoscalar mesons

$$(\bar{\mathbf{3}}, \mathbf{3}) \oplus (\mathbf{3}, \bar{\mathbf{3}}) \qquad \bar{q}_i^L q_j^R \qquad \bar{q}_i^R q_j^L$$

both octet and singlet contain

$$\pi, K, \eta_8, \eta_0 \qquad \sigma, a_0, \kappa, f_0$$

parity eigenstate

9 scalar and 9 pseudoscalar

$$\bar{q}_i \gamma_5 q_j \,,\, \bar{q}_i q_j$$

if chiral symmetry is manifest or restored,

η_8 and η_0 should degenerate even though anomaly is there

dynamical argument is given by Lee and Hatsuda

Lee, Hatsuda, PRD54, 1871 (1996)

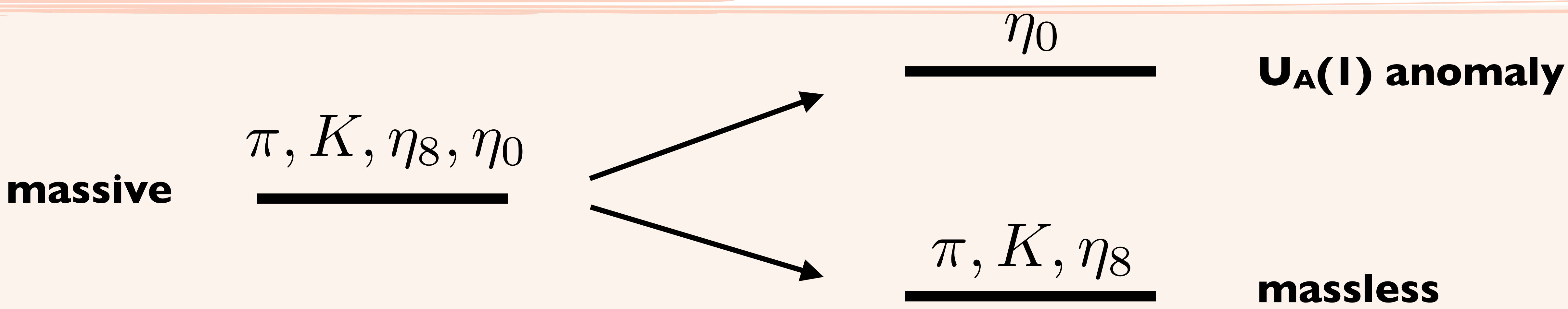
η′ meson in chiral restoration

DJ, Nagahiro, Hirenzaki, arXiv:1109.0394 [nucl-th]

When chiral symmetry is restored... as a consequence of $\mathrm{SU}_L(3) \otimes \mathrm{SU}_R(3)$

9 PS π, K, η_8, η_0 9 S σ, a_0, κ, f_0 get degenerate

even though U$_A$(1) anomaly exists in the singlet axial current



manifest chiral sym. **broken chiral sym.**

$\langle 0|F\tilde{F}|\eta'\rangle = 0$ $\langle 0|F\tilde{F}|\eta'\rangle \neq 0$

in order that U$_A$(1) anomaly affects the η' mass, chiral symmetry is **necessarily** broken spontaneously and/or explicitly.

η-η' mass difference comes from the anomaly effect but through chiral symmetry breaking (or quark condensate at the chiral limit).

note that **U$_A$(1) anomaly is always there** and U$_A$(1) symmetry is broken.

η' meson in nuclear matter

DJ, Nagahiro, Hirenzaki, arXiv:1109.0394 [nucl-th]

a simple estimation

linear dependence of quark condensate on η'-η mass difference (400 MeV)

partial restoration of ChS takes place with 35% at ρ_0

we expect strong η' mass reduction

$$\Delta m_{\eta'} \sim 150 \text{ MeV} @ \rho = \rho_0$$

η′ meson in nuclear matter

DJ, Nagahiro, Hirenzaki, arXiv:1109.0394 [nucl-th]

a simple estimation

linear dependence of quark condensate on η’-η mass difference (400 MeV)

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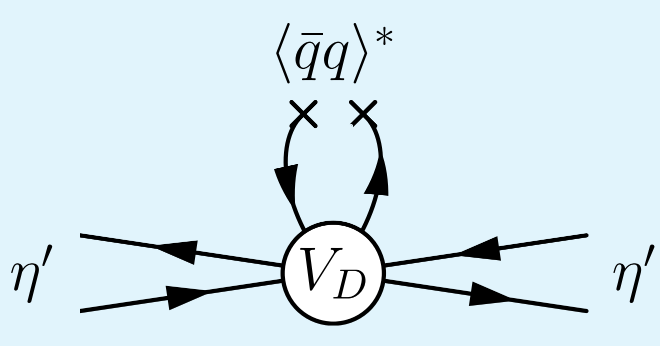
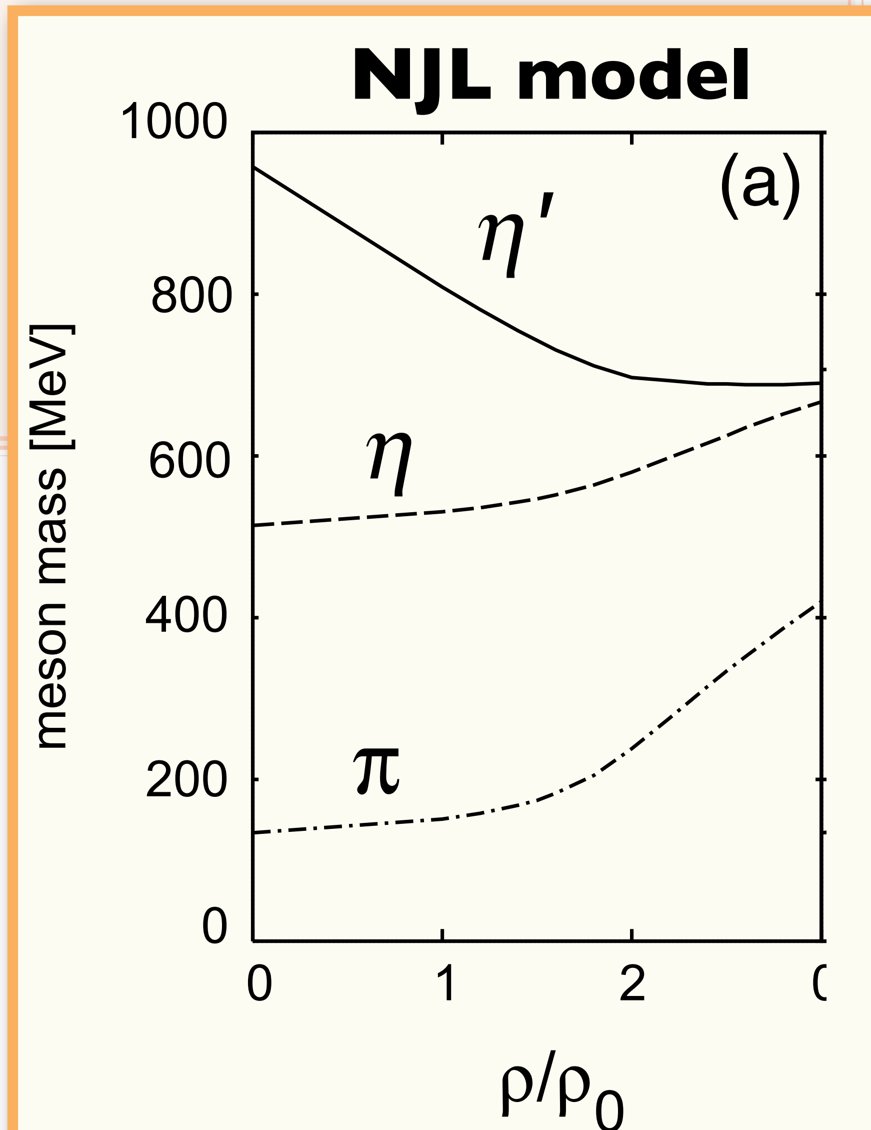
‘t Hooft - Kobayashi - Maskawa interaction

$U_A(1)$ anomaly contributes η’ mass through ChSB





Nagahiro, Takizawa, Hirenzaki PRC74,045203 (2006)

See also, P. Costa, M. C. Ruivo, and Y. L. Kalinovsky, Phys. Lett. B560, 171 (2003).

Narrow width ??

nuclear many body effects

absorption $\eta' N \to \eta N \qquad \eta' N N \to N N$

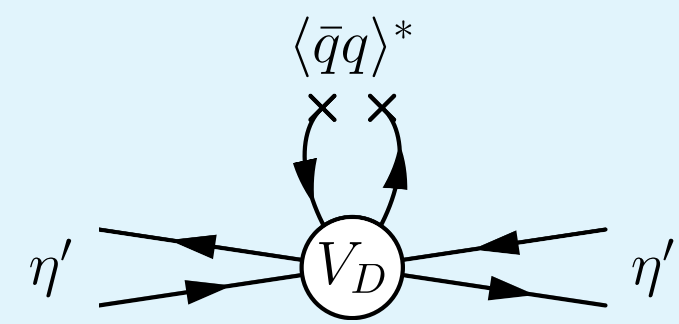
attraction $\eta' N \to N^*$

attraction coming from suppression of anomaly effect

contact interaction
in hadronic level

no hadronic imaginary part

$U_A(1)$ anomaly contributes η' mass through ChSB



suppression of anomaly effect selectively affects η' channel

only **elastic channel** $\eta' N \to \eta' N$

no **inelastic channel** $\eta' N \to \eta N \qquad \eta' N \to \pi N$

The width may be smaller than binding energy.

$$\Delta m \sim 150 \text{ MeV} > \Gamma$$

Current experimental status

RHIC: phenix/star (low energy pion)

indirect measurement : η' mass reduction of at least 200 MeV

Csorgo, Vertesi, Sziklai, PRL 105 (2010) 182301

COSY three-body final state interaction $pp \to \eta' pp$

pη' scatt. length ~ 0.1-0.8 fm (Δm~ a few - tens MeV)

Moskal et al, PLB482(2000) 365

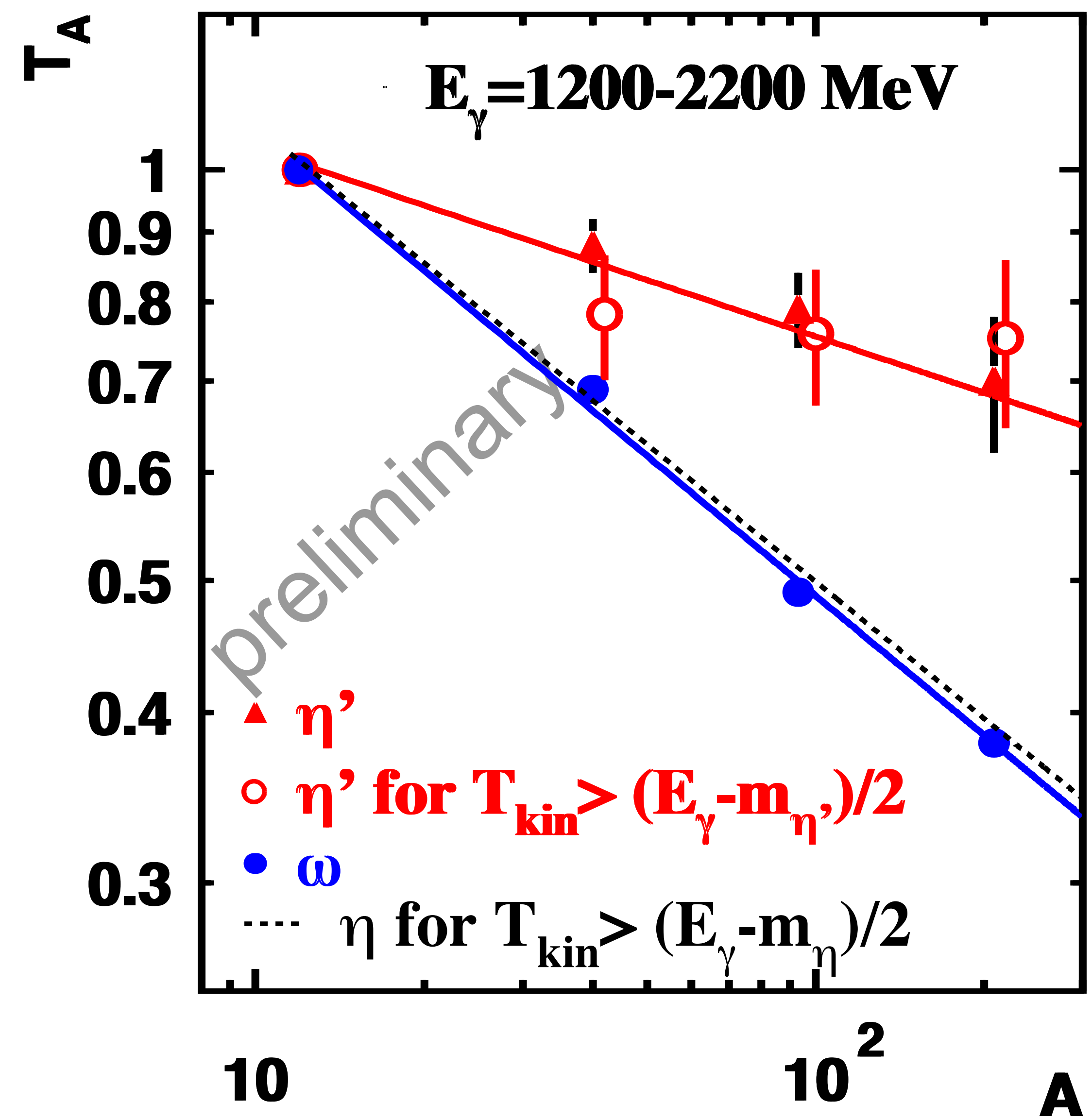
CB-ELSA/TAPS

transparency ratio $T_A = \dfrac{\sigma_{\gamma A \to \eta' X}}{A \cdot \sigma_{\gamma N \to \eta' X}}$

normalized to ^{12}C

$\Gamma(\rho_0, <|\vec{p}_{\eta'}|> \approx 0.9\ \mathrm{GeV/c}) \approx 25\text{-}30\ \mathrm{MeV}$

Nanova, talk at Baryon2010



Possible bound state spectra

a simple η’ optical potential (Woods-Saxon type)

proportional to nuclear density

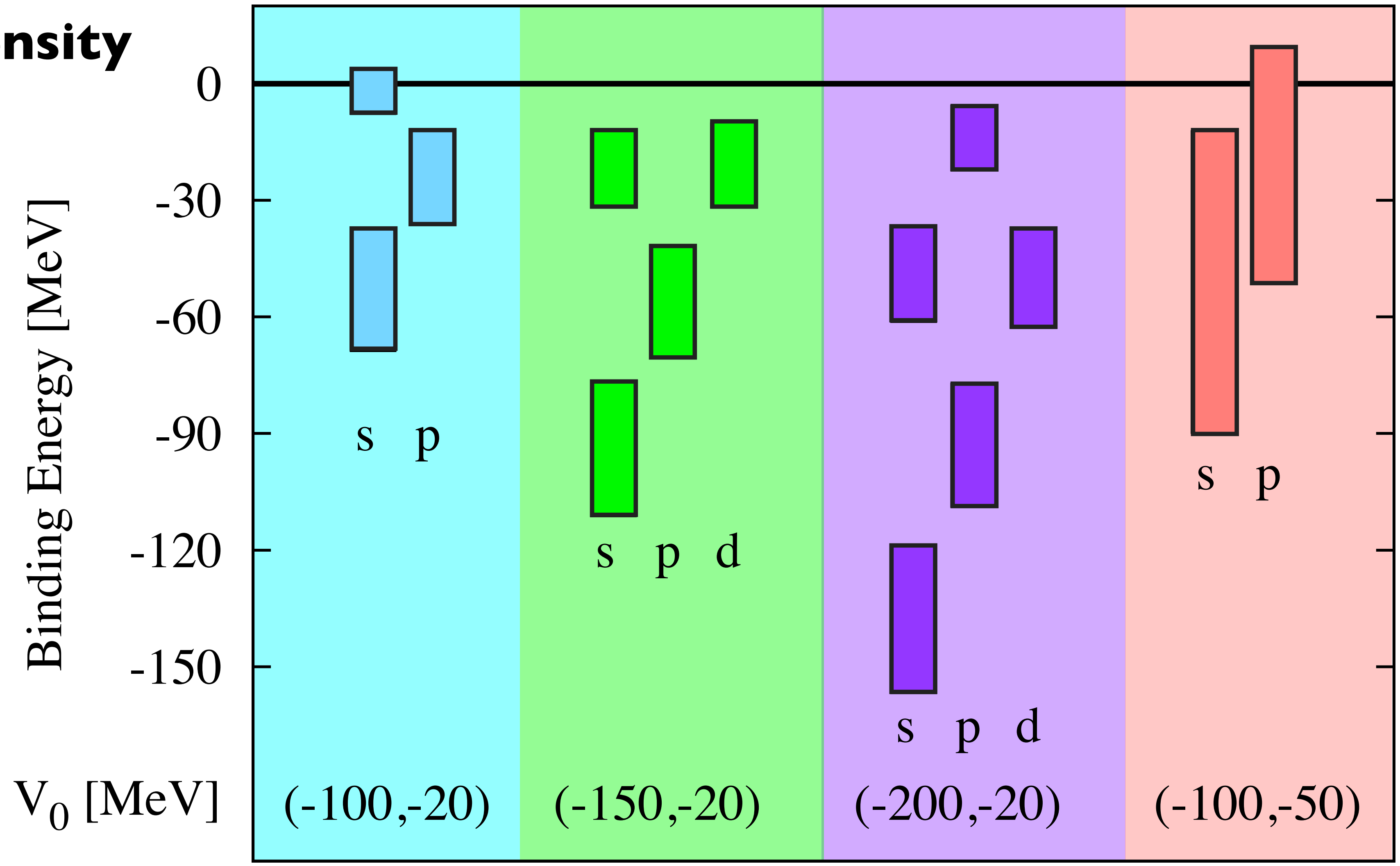
$$V_{\eta'}(r) = V_0 \frac{\rho(r)}{\rho_0}$$

Δm = 150 MeV
Γ/2 = 20 MeV

Re: theoretical expectation

Im: phenomenological observation

^{11}C



well-separated bound states

for realistic calculation

core polarization effect could be important

Re V_0 / Im V_0	−100 MeV	−150 MeV / −20 MeV	−200 MeV	−100 MeV / −50 MeV
s	(53, 31)	(94, 34)	(138, 37)	(51, 77)
	(2, 11)	(22, 19)	(49, 24)	–
p	(24, 23)	(56, 28)	(93, 31)	(21, 60)
	–	–	(14, 16)	–
d	–	(21, 21)	(50, 25)	–

Conclusion

quark condensate decrease at finite density

accordingly hadronic quantities also change

η' mass : interplay of chiral symmetry breaking and $U_A(1)$ anomaly

$U_A(1)$ anomaly can affect η' mass only through chiral symmetry breaking

reduction of η' mass due to partial restoration of chiral symmetry

large mass reduction without large absorption

selective attraction to flavor singlet meson, small inelastic channel

150 MeV order of mass reduction and 30 MeV order of absorption width at ρ_0

theoretical expectation **phenomenological observation**

hopeful observation of η' bound state with narrow width

a good phenomenological sample to investigate $U_A(1)$ anomaly and partial restoration of chiral symmetry

need further qualitative discussion

effective theory for η' based on partial restoration of chiral symmetry