Pseudoscalar mesons in nuclei and partial restoration of chiral symmetry

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Mesons in nuclei

recipe

create mesons in nuclei

observe energy spectrum

compare in-vacuum spectrum

modification of mass and width by many-body effects

ex. mass shift

$$mN \to mN$$

width

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

interaction between meson and nuclei

in-medium self-energy of meson

mode mixing **B*-hole mode** meson in nucleus can excite surrounding nucleons

extract **more fundamental and universal quantities**

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

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**

ρ-a_1 N-N*(1535)

Weinberg, PRL18 (67) 507.
Kapusta, Shuryak, PRD49 (94) 4694.
DeTar, Kunihiro, PRD39 (89) 2805. etc.

4) **mass of eta' meson** → next talk

etc.

Nuclear bound state of meson

complementary methods

scattering

elastic scattering — π-nucleus scattering @ 20 MeV

meson production — vector mesons

(quasi) bound state

advantage for spectroscopy

fixed quantum number

mesons are in nuclei

quasi static

unnecessary dynamical evolution

drawback

formation of one-body potential

well-separated bound states

Nuclear bound state of meson

complementary methods

scattering

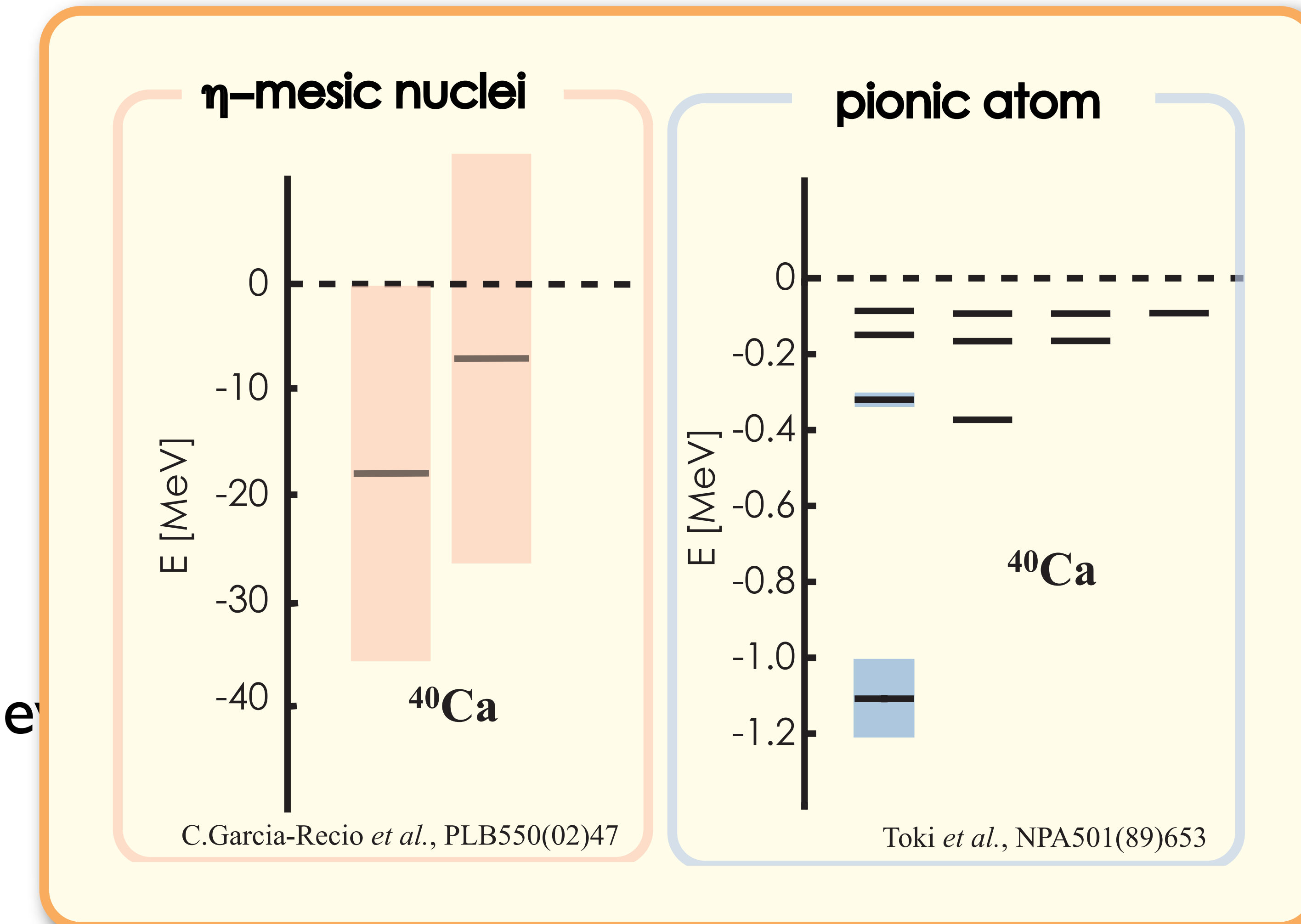
elastic scattering — π-nucleus scattering @ 20 MeV

meson production — vector mesons

(quasi) bound state

advantage for spectroscopy

- fixed quantum number
- mesons are in nuclei
- quasi static
  - unnecessary dynamical e



drawback

- formation of one-body potential
- well-separated bound states

Connection of quark condensate to hadronic quantities

quark condensate is not a direct observable

connect quark condensate to hadronic quantites

in vacuum **Glashow-Weinberg relation** (low energy theorem)

$$F_\pi G_\pi^{1/2} = -\langle \bar{q} q \rangle$$ **chiral limit**

Glashow, Weinberg, PRL 20 (1968) 224

matrix elements of pion

pion decay constant

$$\langle 0 | A_\mu^a(x) | \pi^b(p) \rangle = \delta^{ab} i p_\mu F_\pi e^{-ip\cdot x}$$

wavefunction normalization

$$\langle 0 | \phi_5^a(x) | \pi^b(p) \rangle = \delta^{ab} G_\pi^{1/2} e^{-ip\cdot x}$$

PCAC relation

$$G_\pi^{1/2} = \frac{m_\pi^2 F_\pi}{2 m_q}$$

Gell-Mann Oakes Renner relation

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

correlator of axial vector current and pseudoscalar density

$$\Pi_5^{ab}(q) = \mathrm{F.T.}\ \partial^\mu \langle 0 | \mathrm{T}[A_\mu^a(x) \phi_5^b(0)] | 0 \rangle,$$ **chiral limit**

- calculate it in soft limit, only the pion mode contributes
- low energy theorem obtained by **operator relation**

An exact sum rule in medium

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

extension to finite density is easy

operator relation does not depend on states

for hadronic part, only zero modes contribute to correlator again in soft limit.

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

in chiral limit

summing up pionic zero modes **in-medium pion** and **particle-hole excitations**

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

relate **hadronic quantities** to **in-medium quark condensate**

Exact sum rule at all density

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

sum rule in chiral limit

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

- valid for **all densities**
- 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

In-medium GW relation and scaling law

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

at low density limit, only pion mode contributes

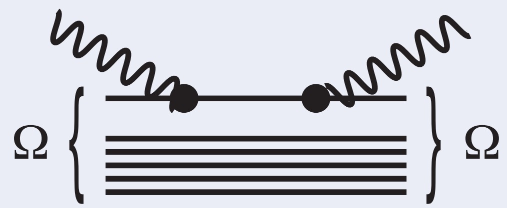
in-medium Glashow-Weinberg relation

$$F_\pi^t G_\pi^{*1/2} = -\langle \bar{q} q \rangle^*$$

valid only for linear density

1p-1h

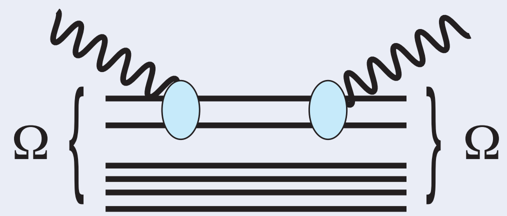
$\mathcal{O}(\rho)$



$$\gamma_5 \not{q} \frac{(\not{p}+\not{q}) + m_N}{(p+q)^2 - m_N^2} \gamma_5 = \not{q} \frac{\not{p}+\not{q} - m_N}{(p+q)^2 - m_N^2} = \frac{q^2}{2p\cdot q} \to 0$$

2p-2h

$\mathcal{O}(\rho^{n>1})$



beyond linear density

In-medium GW relation and scaling law

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

at low density limit, only pion mode contributes

in-medium Glashow-Weinberg relation

$$F_\pi^t G_\pi^{*1/2} = -\langle \bar{q} q \rangle^*$$

valid only for linear density

scaling law

$$\left(\frac{F_\pi^t}{F_\pi} \right) Z_\pi^{*1/2} = \frac{\langle \bar{q} q \rangle^*}{\langle \bar{q} q \rangle}$$

wavefunction renormalization

$$Z_\pi^* \equiv G_\pi^* / G_\pi$$

In-medium modification of quark condensate is given by in-medium change of pion **decay constant** and **wavefunction renormalization**.

In-medium quark condensate

decay constant

$$\frac{b_1}{b_1^*} = \left(\frac{F_\pi^t}{F_\pi}\right)^2$$

enhancement of b1
pionic atom

wavefunction renorm.

$$Z_\pi^{*1/2} = 1 - \gamma\frac{\rho}{\rho_0}$$

linear density
a negative slope
πN scattering

scaling law

$$\left(\frac{F_\pi^t}{F_\pi}\right) Z_\pi^{*1/2} = \frac{\langle\bar{q}q\rangle^*}{\langle\bar{q}q\rangle}$$

$$\frac{\langle\bar{q}q\rangle^*}{\langle\bar{q}q\rangle} \simeq \left(\frac{b_1}{b_1^*}\right)^{1/2}\left(1 - \gamma\frac{\rho}{\rho_0}\right)$$

$$\frac{\langle\bar{q}q\rangle^*}{\langle\bar{q}q\rangle} \simeq 1 - 0.37\frac{\rho}{\rho_0}$$

$b_1/b_1^* = 0.79 \pm 0.05$ at an effective density $\rho \approx 0.6\rho_0$

conclude a qualitative **reduction of quark condensate** in nuclear medium from pion observables in experiments

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

In-medium quark condensate

decay constant

$$\frac{b_1}{b_1^*} = \left(\frac{F_\pi^t}{F_\pi}\right)^2$$

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linear density
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πN scattering

scaling law

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$$\frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle} \simeq \left(\frac{b_1}{b_1^*}\right)^{1/2} \left(1 - \gamma \frac{\rho}{\rho_0}\right)$$

linear density low energy theorem

$$\frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle} = 1 - \frac{8c_1}{f^2}\rho$$

conclude a qualitative **reduction of quark condensate** in nuclear medium from pion observables in experiments

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

What is next ?

Theory

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

leading order of ρ

already known result

in-medium Glashow-Weinberg relation

$$F_\pi^t G_\pi^{*1/2} = -\langle \bar{q}q\rangle^*$$

extend the discussion to next-to-leading order of ρ

$$\frac{\langle \bar{q}q\rangle^*}{\langle \bar{q}q\rangle} \simeq \left(\frac{b_1}{b_1^*}\right)^{1/2}\left(1-\gamma\frac{\rho}{\rho_0}\right)$$

$$\frac{\langle \bar{q}q\rangle^*}{\langle \bar{q}q\rangle} = 1 - \frac{8c_1}{f^2}\rho$$

Experiments

RIKEN-RIBF

more precise data (Ito's talk on Tuesday)

observe 2s state (non-yrast state)

determine widths of 1s and 2s accurately

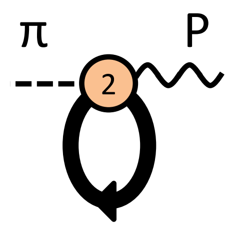
observe pion wavefunction renormalization directly in pionic atom

Higher order corrections

S. Goda, DJ, in progress

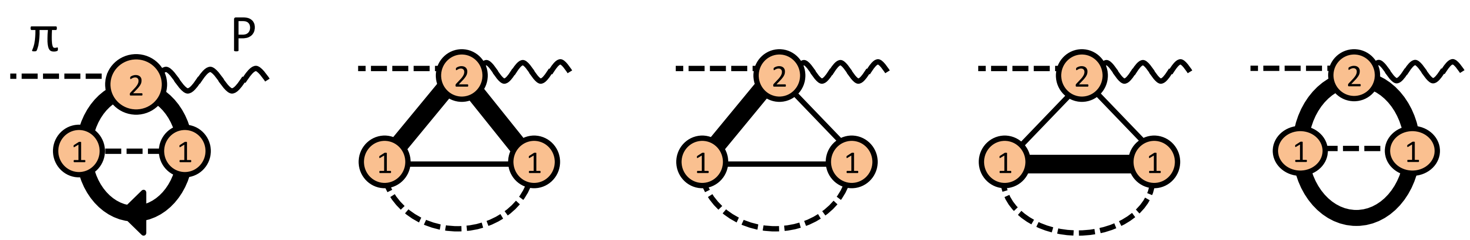
in-medium chiral perturbation theory
(written in terms of in-vacuum quantities)

$O(p^5)$

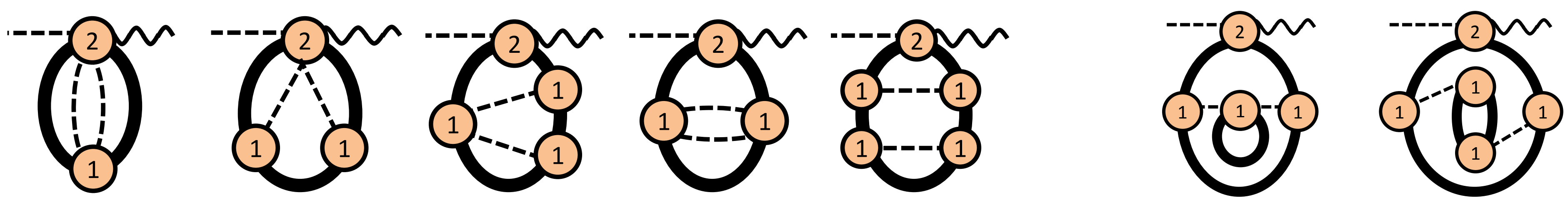


linear density

$O(p^7)$



further higher order corrections



nucleon-nucleon correlations

corrections for nuclear matter description

calculation of in-medium quark condensate can be reduced to conventional nuclear physics

Eta mesonic nuclei

η meson: neutral charge no electromagnetic interaction
purely strong interaction

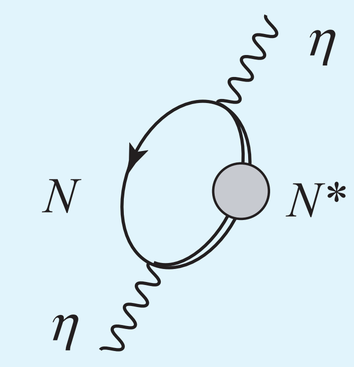
ηN interaction is attractive

expect η bound states in nuclei (Haider, Liu)

experimental attempts, but not yet clearly observed

large width due to strong absorption

ηN → πN, ηNN → NN, etc



ηN strongly couples to N(1535)

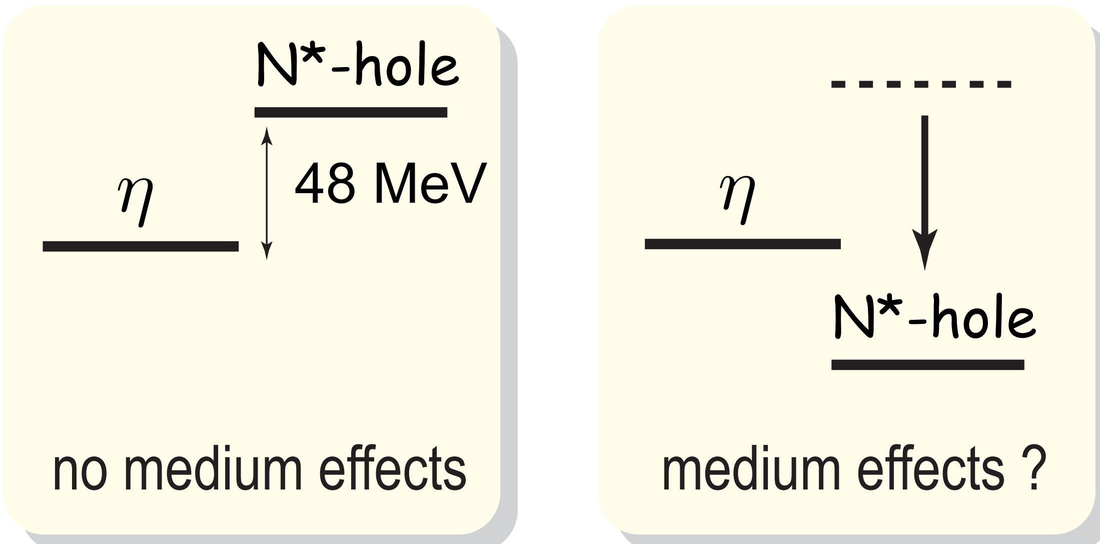
in-medium η meson ⇔ in-medium N(1535)

N(1535) is a candidate of chiral partner of nucleon

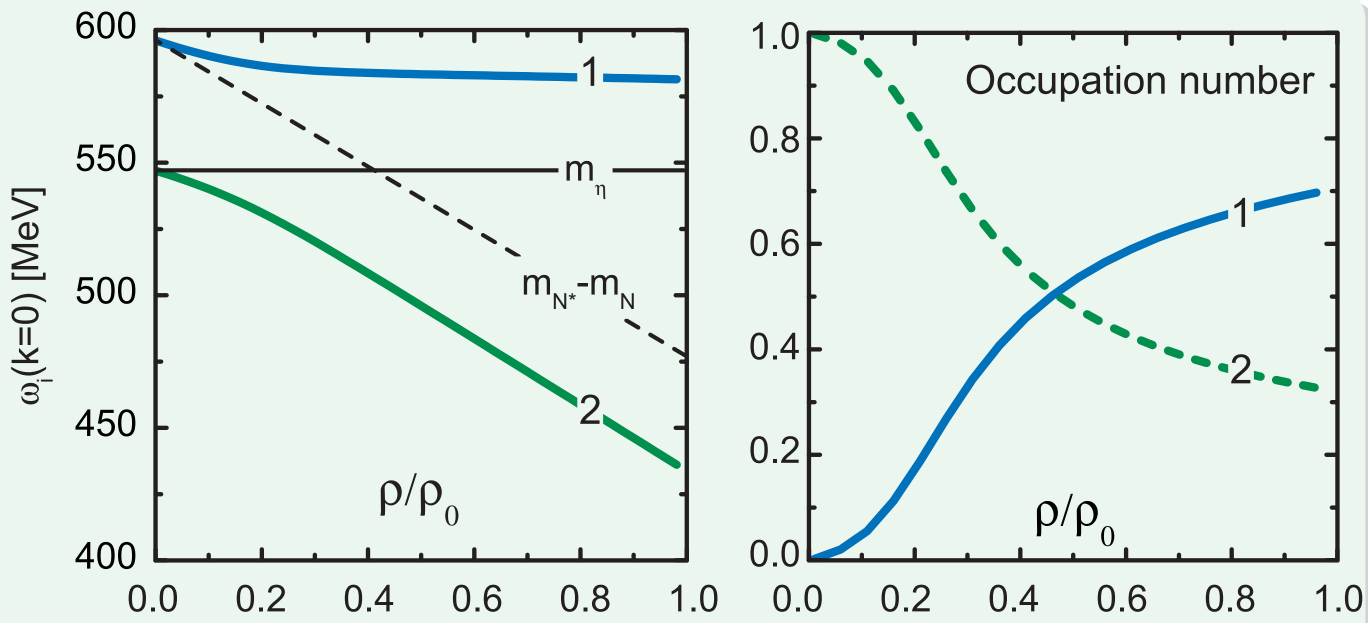
eta mesonic nuclei probe chiral symmetry of baryon

Spectral function of in-medium eta meson

Reduction of the mass difference of N and N* causes level crossing between η and N*-hole



Attractive **Repulsive**

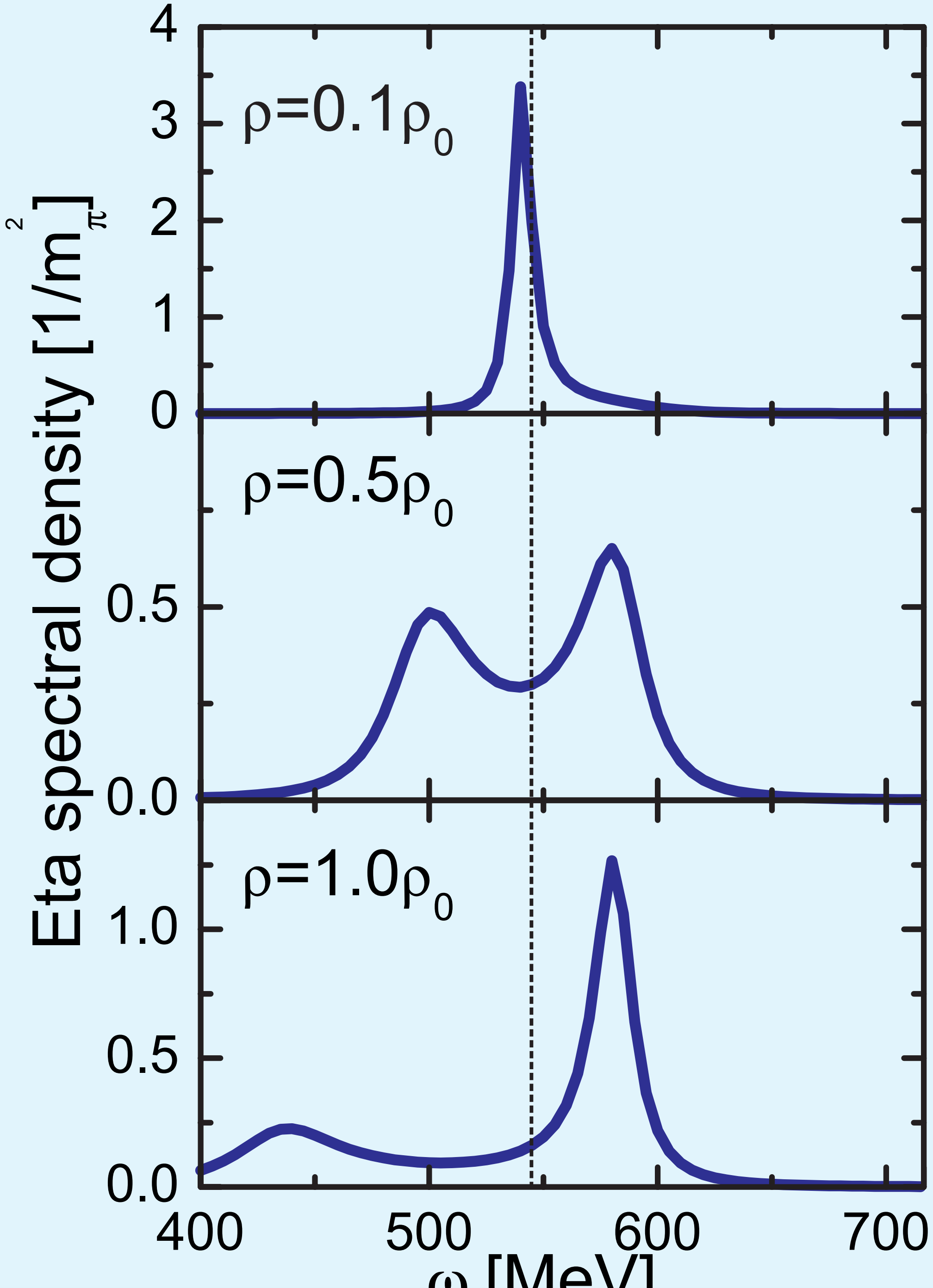


$$G_\eta(\omega) = \sum_i \frac{Z_i}{\omega - \omega_i}$$

$$Z_i = \left(1 - \frac{\partial V_\eta(\omega)}{\partial \omega}\Big|_{\omega=\omega_i}\right)^{-1}$$

Spectral function

$$S(\omega) = -\mathrm{Im}\, G_\eta(\omega)$$



Jido, Nagahiro, Hirenzaki, PRC66, 045202 ('02)
Nagahiro, Jido, Hirenzaki, PRC68, 035205 ('03), NPA761,92 ('05)
Jido, Kolomeitsev, Nagahiro, Hirenzaki, NPA811, 158 ('08)

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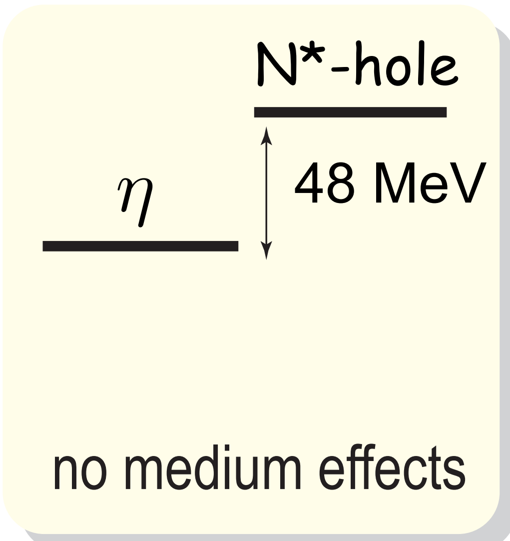
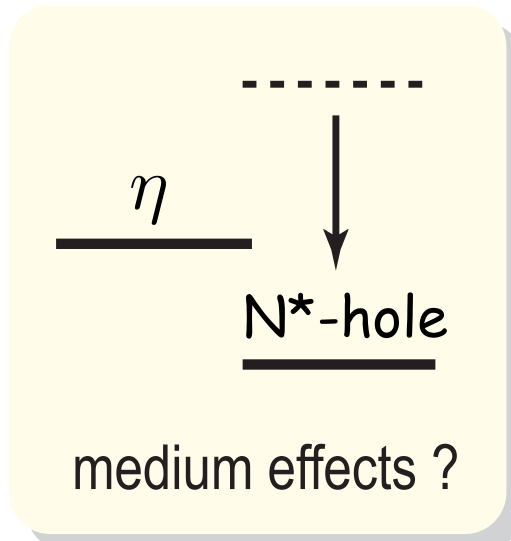
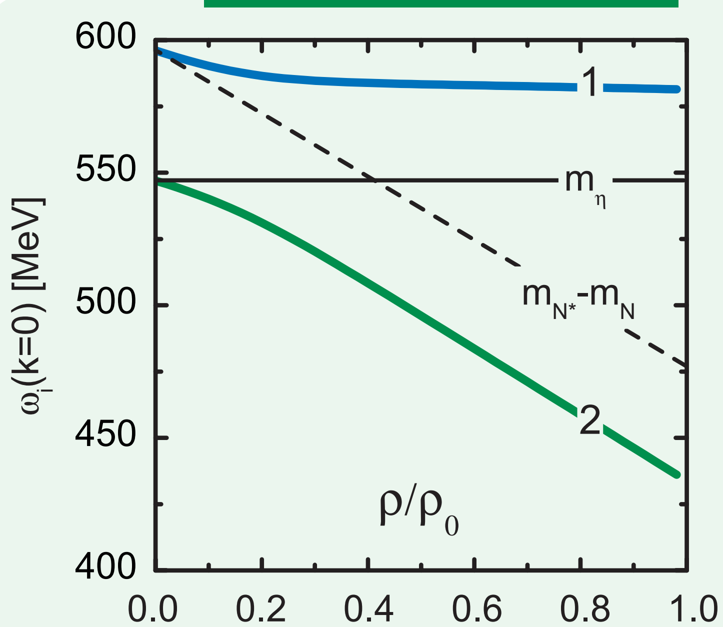
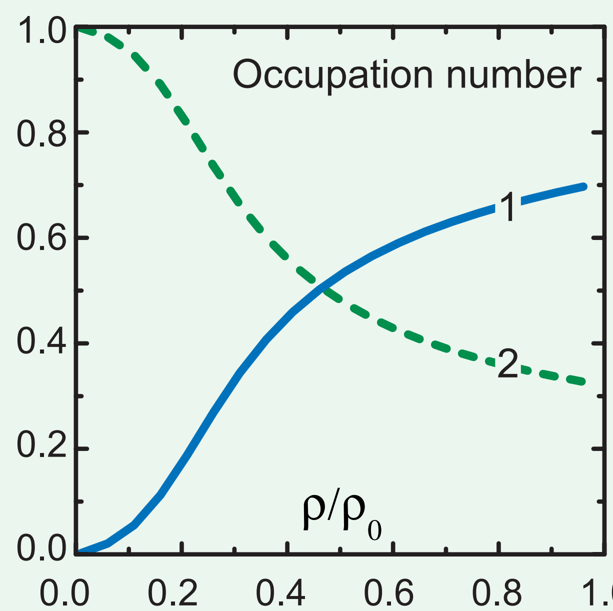




Attractive



Repulsive



$$G_\eta(\omega) = \sum_i \frac{Z_i}{\omega - \omega_i}$$

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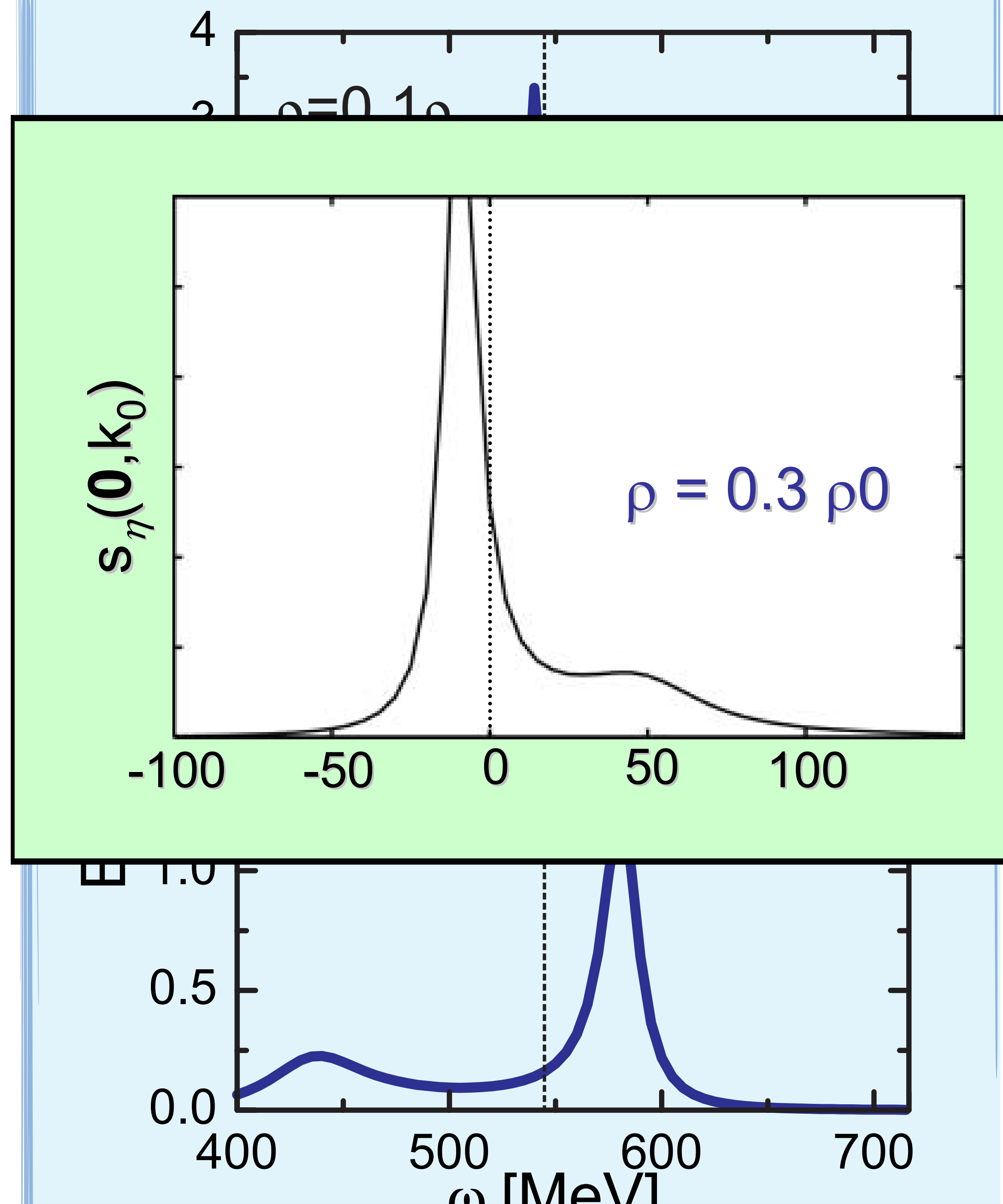

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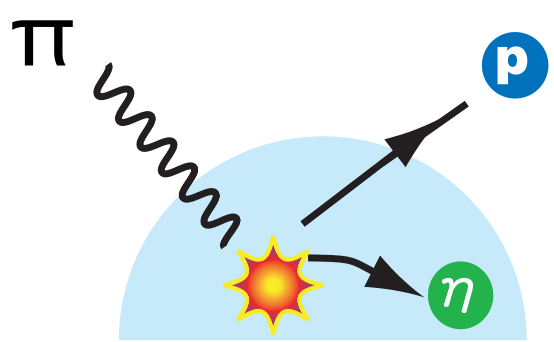
Eta mesonic nuclei @ J-PARC

Nagahiro, Jido, Hirenzaki, PRC80, 025205 (09)



consider (π^+,p) reaction

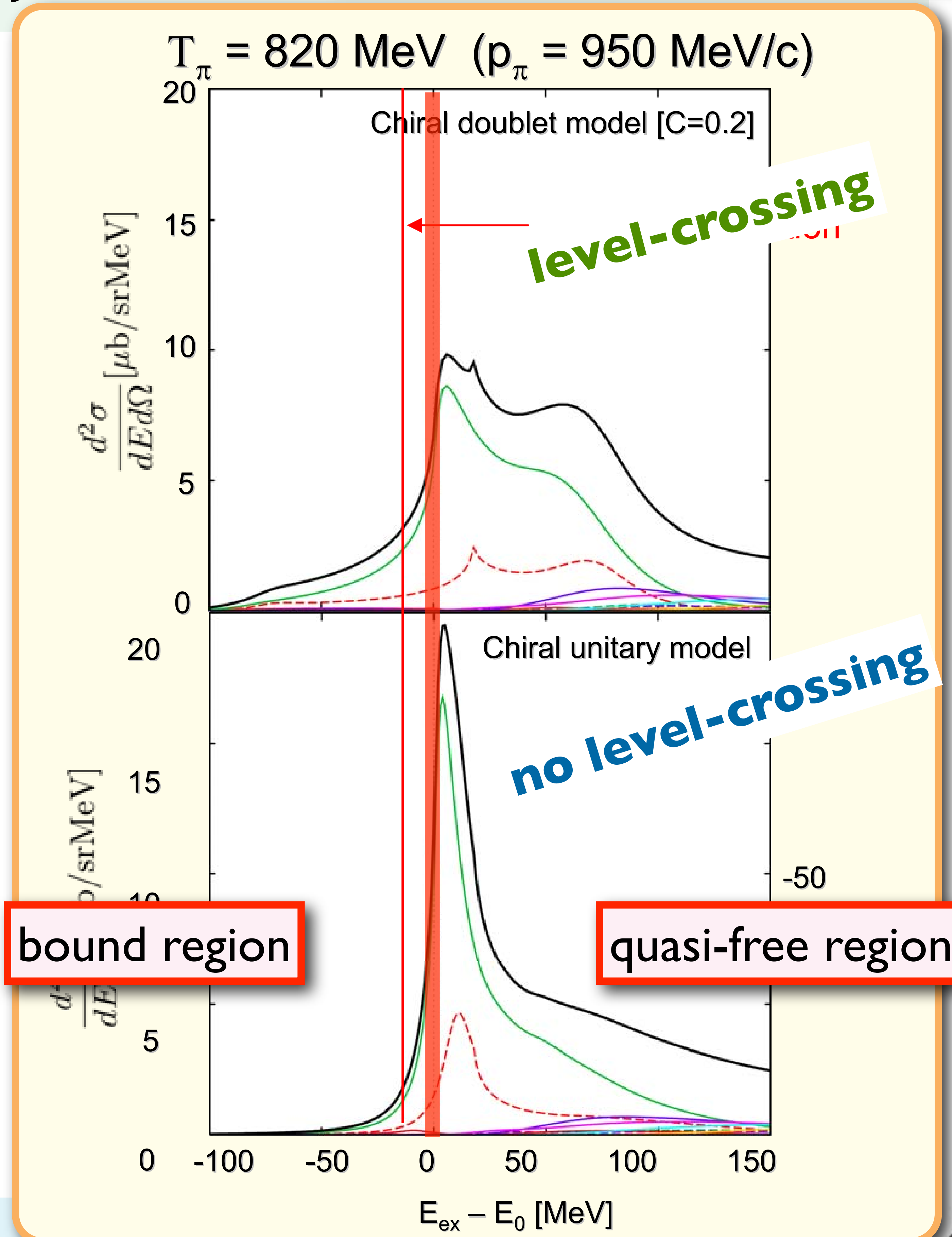
missing mass spectra

of emitted proton

^{12}C target

in recoilless condition
(no momentum transfer)

Green function method
(Morimatsu-Yazaki)



Summary

(deeply bound) pionic atom

- most successful system
- complete story from observation to QCD
- observe partial restoration of chiral symmetry in nucleus

theoretical development

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

$$\left(\frac{F_\pi^t}{F_\pi}\right) Z_\pi^{*1/2} = \frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle}$$

- both pionic mode and p-h excitation contribute to in-medium quark condensate
- calculation of in-medium quark condensate is closely related to description of nuclear matter

mesons in nuclei

η mesonic nuclei in-medium N(1535) probe ChS for baryon

η' mesonic nuclei suppression of $U_A(1)$ effect on η' mass in nuclear matter

K mesonic nuclei few-body nuclear systems with kaons, $K^{bar}NN$, $K^{bar}KN$

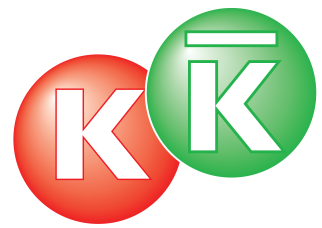
Kaonic few-body systems

K^{bar} should be bound in nucleus but with a large width

Λ(1405)

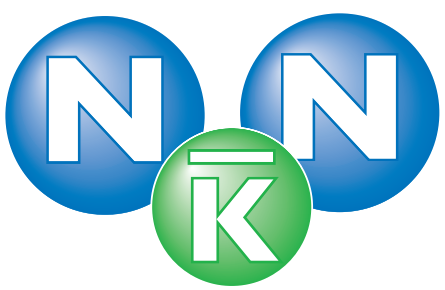
BE ~10 MeV (30 MeV)

f_0(980), a_0(980)



BE ~10 MeV

K^{bar}NN



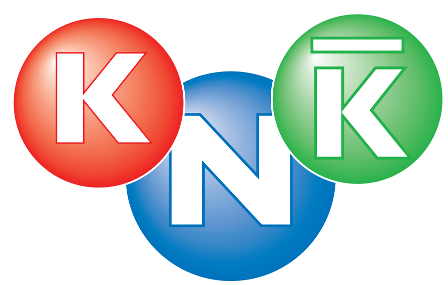
BE ~20 MeV

or more

K^{bar}KN

N*

$J^P=1/2^+$



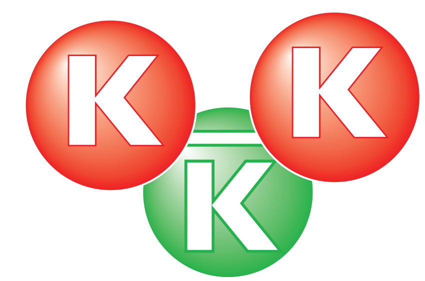
a new N* resonance N(1910)

BE ~20 MeV

K^{bar}KK

K*

$J^P=0^-$



1420 ~ 1465 MeV

BE 20~60 MeV

K^{bar}N and **K^{bar}K** interactions are "similar" in a sense of chiral dynamics

Λ(1405) f_0(980), a_0(980)

pion is too light to be bound in range of strong interaction

Reduction of pion decay constant F_π

enhancement of s-wave repulsive interaction

Deeply bound pionic atom K. Suzuki et al. PRL92, 072302 (04)

systematic study of π^- bound states in Sn isotopes

$$b_1^{\rm free}/b_1 = 0.78 \pm 0.05 \qquad \rho \sim 0.6\ \rho_0$$

Elastic scattering (Friedman et al.)

$$b_1^{\rm free}/b_1 \sim 0.69$$

This is related to in-medium reduction of pion decay constant F_π **at low density**

Weinberg-Tomozawa realtion

in vacuum

$$4\pi\left(1+\frac{m_\pi}{m_N}\right) b_1^{\rm free} = -\frac{m_\pi}{2F^2}$$

in medium at low-density

$$4\pi\left(1+\frac{m_\pi}{m_N}\right) b_1 = -\frac{m_\pi}{2(F_\pi^t)^2}$$

$$\frac{b_1^{\rm free}}{b_1} = \left(\frac{F_\pi^t}{F_\pi}\right)^2$$

Kolomeitsev, Kaiser, Weise, PRL90 (03), 092501.

DJ, Hatsuda, Kunihiro, PLB 670 (08), 109.

The next question is how to conclude partial restoration of chiral symmetry from the reduction of F_π.

In-medium Tomozawa-Weinberg relation

in-medium Tomozawa-Weinberg relation can be obtained at low density

relation between b_1^* and F_π^t

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

axial vector correlator

$$\Pi_\nu^{ab}(q) = \mathrm{F.T.}\, \partial^\mu \langle \Omega' | \mathrm{T}[A_\mu^a(x) A_\nu^b(0)] | \Omega' \rangle$$

in slightly asymmetric nuclear matter

take soft limit and use Ward-Takahashi identity

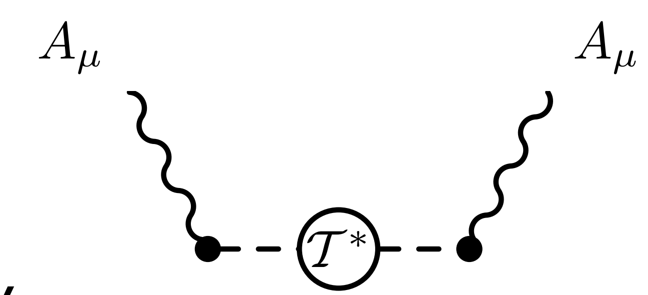
$$\int d^4x\, \partial^\mu \mathrm{T}[A_\mu^a(x) A_\nu^b(0)] = [Q_5^a, A_\nu^b(0)] = i\epsilon^{abc} V_\nu^c(0)$$

$$\Pi_0^{ab}(0) = i\epsilon^{ab3} \langle \Omega' | V_0^3 | \Omega' \rangle \simeq i\epsilon^{ab3} \tfrac{1}{2} \delta\rho$$

count isospin of nuclear matter

hadronic part perturbation of linear δρ

$$\Pi_0^{12}(q) \xrightarrow[\mathbf{q}=0]{} i\omega \sum_{\alpha,\beta} \left[\frac{\omega F_\alpha^t}{\omega^2} \cdot \mathcal{T}_{\alpha\beta}^{(-)*}(\omega;0)\delta\rho \cdot \frac{\omega F_\beta^t}{\omega^2} \right]$$



full order of isoscalar density

in low density expansion of Ft

in-medium TW relation

$$\mathcal{T}^{(-)*}(\omega;0) \simeq \frac{\omega}{2(F_\pi^t)^2}$$

at low density

$$\frac{b_1}{b_1^*} = \left(\frac{F_\pi^t}{F_\pi} \right)^2$$

Kolomeitsev, Kaiser, Weise, PRL 90 (2003) 092501

In-medium wavefunction renormalization

we can estimate wavefunction renormalization by πN scattering amplitude

at low density

$$Z_\pi^{*1/2} = 1 - \frac{\rho}{2} \frac{\partial \mathcal{T}_{\pi N}^{(+)}}{\partial \omega^2}\bigg|_{\omega^2=0}$$

forward isosinglet πN scatt. amp. $\mathcal{T}_{\pi N}^{(+)}(\omega^2)$

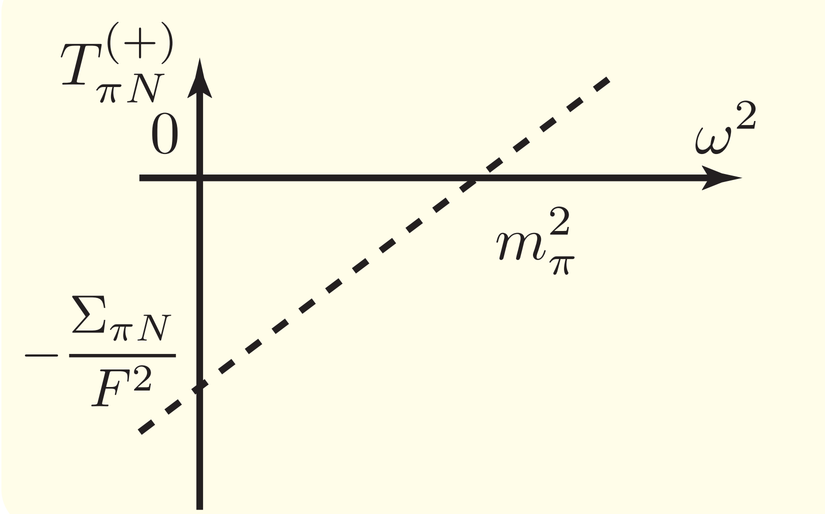
wavefunction renormalization $Z_\pi^{*1/2} = \left(\frac{G_\pi^*}{G_\pi}\right)^{1/2} = \left(1 - \frac{\partial \Sigma}{\partial \omega^2}\bigg|_{\omega=0}\right)^{-1/2}$

self-energy in low density $\Sigma(\omega^2) = -\rho \mathcal{T}_{\pi N}^{(+)}(\omega^2)$

energy slope of scattering amplitude

Weinberg point (soft limit) $\mathcal{T}^{(+)}(0; m_\pi) = \alpha = -\sigma_{\pi N}/F_\pi^2$

threshold $\mathcal{T}^{(+)}(m_\pi; m_\pi) = 4\pi(1 + m_\pi/m_N) a_{\pi N}$



$$Z_\pi^{*1/2} = 1 - \gamma \frac{\rho}{\rho_0}$$

$\gamma = \beta \rho_0 / 2 \simeq 0.184$

positive value

$\sigma_{\pi N} \simeq 45\text{MeV}$

$a_{\pi N} = (0.0016 \pm 0.0013) m_\pi^{-1}$

reduction in nuclear medium

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

$\mathrm{KK^{bar}N}$ system **N* at 1910 MeV**

DJ, Y. Kanada-En'yo, **PRC78, 035203 (2008)**

$K\bar{K}N$ is bound blow thresholds of Λ(1405)+K, $a_0(f_0)$+N

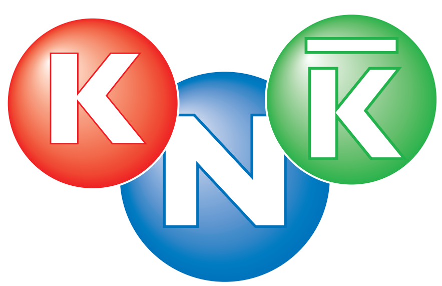
threshold of $\mathrm{KK^{bar}N}$ 1930 MeV

- loosely bound system

B.E. from $\mathrm{KK^{bar}N}$	width
19 MeV (1911 MeV)	**88 MeV**

sum of those of isolated two-particle systems

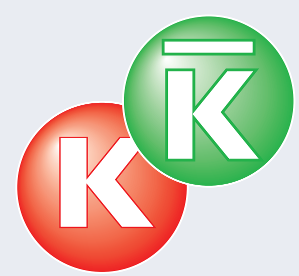
N*



Λ(1405)

binding energy	width
11 MeV	44 MeV

f_0(980), a_0(980)



binding energy	width
11 MeV	60 MeV

Faddeev calculation also obtains this resonance

mass: 1923 MeV, width 20-30 MeV

almost **$\mathrm{KK^{bar}N}$ single channel** for three-body model space

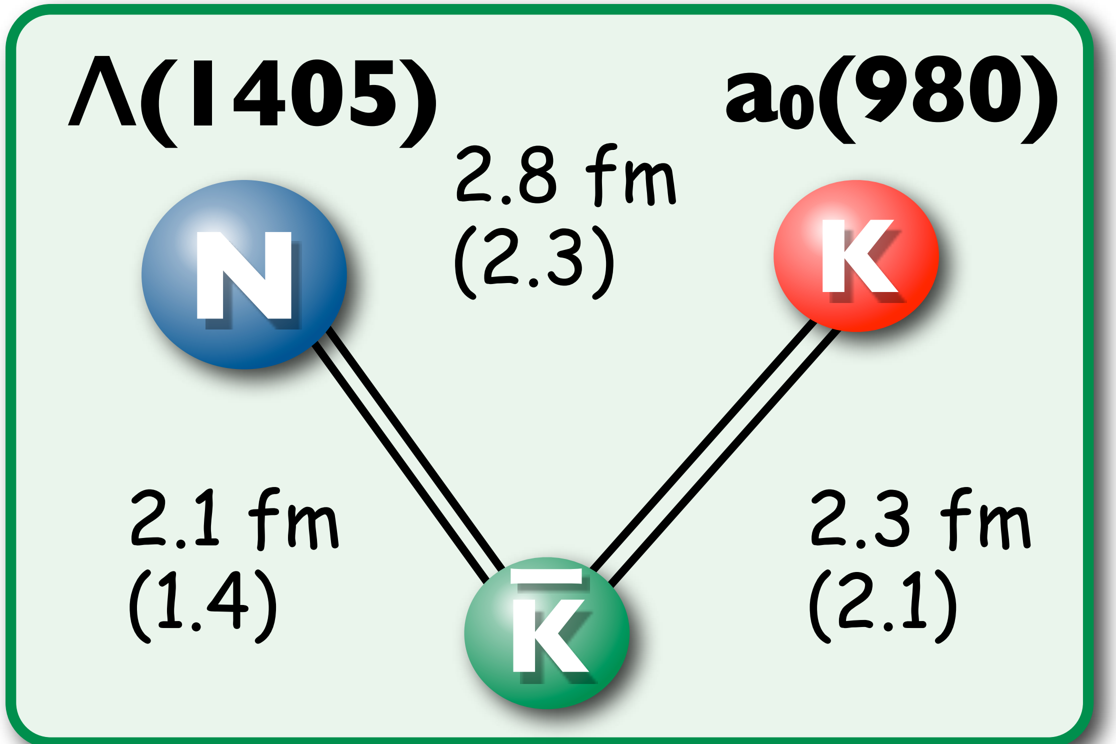
Martinez Torres, Khemchandani, Oset, **PRC79**, 065207 (2009)
Martinez Torres, DJ, **PRC82**, 038202 (2010)

Structure of N*(1910)

1) relativistic potential model

DJ, Y. Kanada-En'yo, **PRC78, 035203 (2008)**

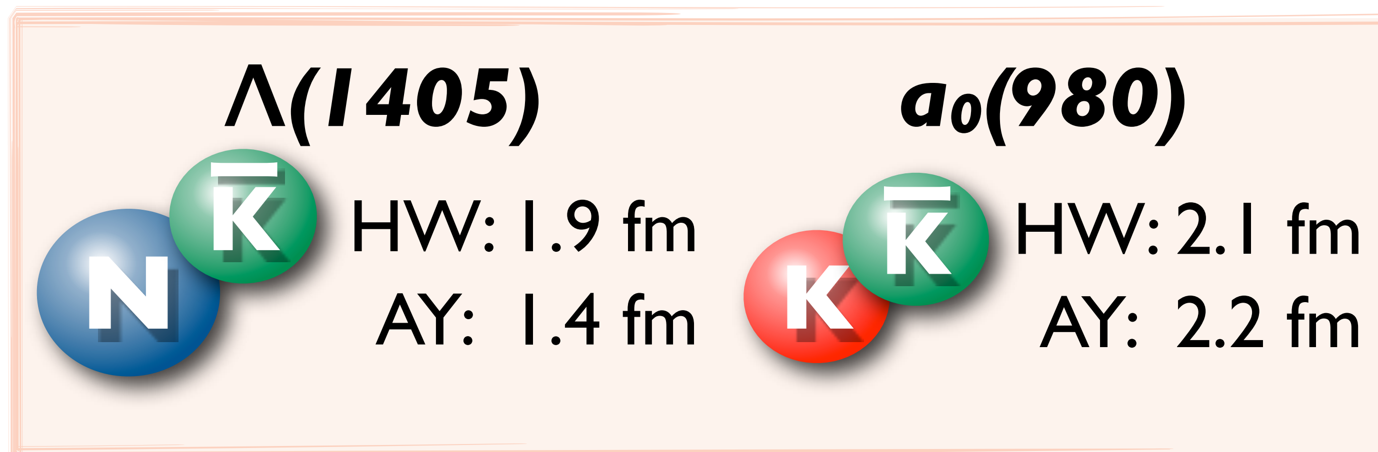
spatial structure



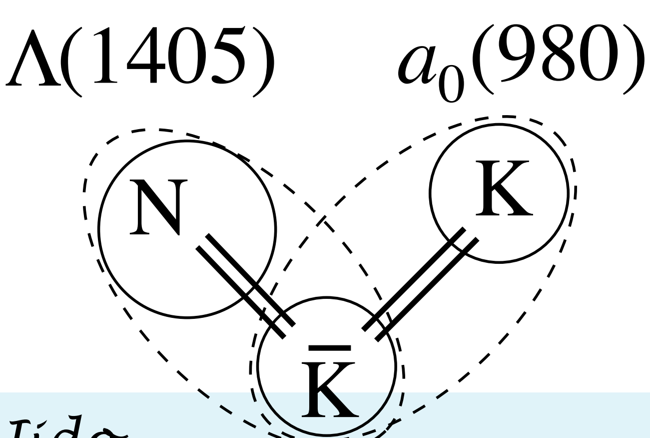
r.m.s radius: **1.7 fm** cf. 1.4 fm for ^{4}He

hadron-hadron distances are comparable with nucleon-nucleon distances in nuclei

mean hadron density: **0.07 hadrons/fm^3**



- coexistence of two quasi-bound states keeping their characters



Λ(1405)+K

a_0(980)+N

- main decay modes

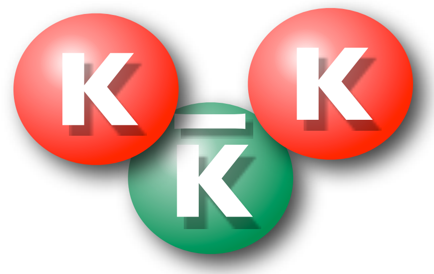
$\pi\Sigma K$ from Λ(1405)

$\pi\eta N$ from a_0(980)

$K^{bar}KK$ system

Kaon Ball K*

$J^P=0^-$



A. Martinez Torres, DJ, Y. Kanada-En'yo, PRC (2011), arXiv:1102.1505 [nucl-th]

threshold: 1488 MeV

potential model **1467 MeV (BE: 21 MeV), width 110 MeV**

Faddeev **1420 MeV, width ~50 MeV**

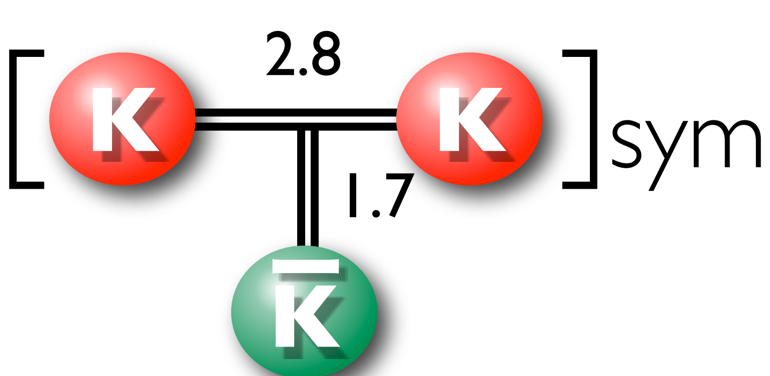
$K^{bar}K$ Inv.Mass : 983 MeV (I=0), 950 MeV (I=1)

spatial structure obtained in potential model

r.m.s radius: **1.6 fm**

K-K distance: **2.8 fm**

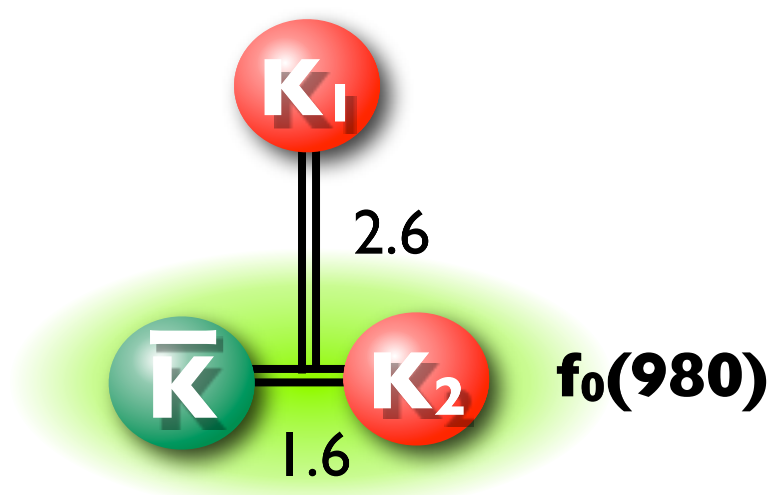
(KK)-K^{bar} distance: **1.7 fm**



before symetrization ...

K_2-K^{bar} distance: **1.6 fm**

K_1-(K_2K^{bar}) distance: **2.6 fm**



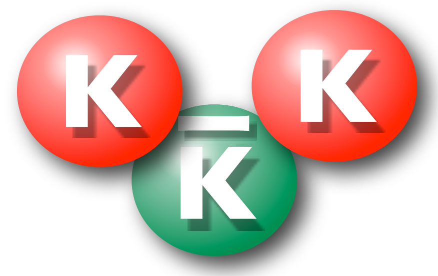
role of repulsive KK interaction

$K^{bar}KK$ system

Kaon Ball

K^*

$J^P=0^-$



A. Martinez Torres, DJ, Y. Kanada-En'yo, PRC (2011), arXiv:1102.1505 [nucl-th]

threshold: 1488 MeV

potential model **1467 MeV (BE: 21 MeV), width 110 MeV**

Faddeev **1420 MeV, width ~50 MeV**

$K^{bar}K$ Inv.Mass : 983 MeV (I=0), 950 MeV (I=1)

- also found in $f_0(980)K$, $a_0(980)K$ two-body systems

Albaladejo, Oller, Roca, PRD82, 094019 (2010)

PDG

K(1460) seen in Kππ partial wave analyses

omitted from summary table

large width

$K(1460)$ $I(J^P) = \frac{1}{2}(0^-)$

OMITTED FROM SUMMARY TABLE

Observed in $K\pi\pi$ partial-wave analysis.

$K(1460)$ MASS

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 1460	DAUM	81C	CNTR	−	63 $K^- p \to K^- 2\pi p$
~ 1400	[1] BRANDENB...	76B	ASPK	±	13 $K^\pm p \to K^+ 2\pi p$

[1] Coupled mainly to $K f_0(1370)$. Decay into $K^*(892)\pi$ seen.

$K(1460)$ WIDTH

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
~ 260	DAUM	81C	CNTR	−	63 $K^- p \to K^- 2\pi p$
~ 250	[2] BRANDENB...	76B	ASPK	±	13 $K^\pm p \to K^+ 2\pi p$

[2] Coupled mainly to $K f_0(1370)$. Decay into $K^*(892)\pi$ seen.