Hadrons in nuclear medium

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- 1. Hadron physics program at J-PARC and Raon?: Hadrons in medium
- 2. Few words on confinement
- 3. Few words on chiral symmetry and UA(1)
- 4. $f_1(1285)$ and ω meson
- 5. Conclusion

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Understanding the mass of a composite object



Mass of an Atom

Nucleon: 99.95 % electron: 0.05 % EM binding< 0.00001 %

Nucleus

Nucleons: 99% Nuclear binding < 1 %

Nucleon

Quark < 5 % The rest ??

QCD

QCD and hadron masses



Few words on Confinement

Confinement

<E²>, <B²> vs confinement potential (Morita, Lee $08 \rightarrow$)

Local vs non local behavior



OPE for Wilson lines: Shifman NPB73 (80)

W(S-T) = 1- $\langle \alpha / \pi E^2 \rangle$ (ST)² +... W(S-S) = 1- $\langle \alpha / \pi B^2 \rangle$ (SS)² +...

• Behavior at T>Tc

E and B Condensates [GeV⁴] 0.004 $< \alpha/\pi |\mathsf{B}^2>$ $W(SS) = exp(-\sigma SS)$ 0.002 0 $< \alpha / \pi E^2 >$ W(ST) = exp(-g(1/S) S)-0.002 $(\alpha_s/\pi)E^2$ $(\alpha_s/\pi)B^2$ -0.004 0.8 0.9 1.1 1 T/T_c Deconfinement \rightarrow comes with $\Delta \left\langle \frac{\alpha}{\pi} E^2 \right\rangle > 0$

1.2

> Dynamical quark will have little effect on gluon condensate (Morita, Lee 09)



Mass shift: QCD 2nd order Stark Effect (Morita, Lee PRD09)

> OPE for bound state: $m \rightarrow$ infinity, Peskin 79

$$\varepsilon_0 = m \left(N_c g^2 / 16\pi \right)^2 \rightarrow O(mg^4), \qquad |\vec{k}| \rightarrow O(mg^2)$$



 $\Delta M_{i} = \sum_{n} \frac{|\langle i|zE|n\rangle|^{2}}{E_{i} - E_{n}}$ $\Delta M_{i} = \sum_{n} \frac{|\langle i|zE|n\rangle|^{2}}{E_{i} - E_{n}}$ $\Delta m_{J/\psi} = -\frac{128}{9\pi^{2}} \left[\frac{a_{0}^{2}}{\varepsilon_{0}} \int dx \frac{x^{3/2}}{(1+x)^{6}} \frac{1}{x + a_{0}^{2} \varepsilon m} \times \left\langle \frac{\alpha}{\pi} E^{2} \right\rangle_{\text{Mediu}}$

Expected Mass shift of heavy quark system in nuclear matter

	Quantum numbers	QCD 2 nd Stark eff.	Potential model	QCD sum rules	Effects of DD loop
η _c	0-+	-8 MeV		–5 MeV (Kiingi, SHL ,Weise, Morita)	No effect
J/ψ	1	–8 MeV (Peskin, Luke)	-10 MeV (Brodsky et al).	–7 MeV (Kiingi, SHL ,Weise, Morita)	<2 MeV (SHL, Ko)
χς	0,1,2++	-20 MeV		-15 MeV (Morita, Lee)	No effect on χ _{c1}
ψ(3686)	1	-100 MeV			< 30 MeV
ψ(3770)	1	-140 MeV			< 30 MeV

Chiral symmetry and $U_A(1)$

1. Correlation function of **chiral partners**

$$\left< \overline{q}(0) q(0) \right> ext{ vs } \left< VV - AA \right>$$

Cohen 96

2. $U_A(1)$ breaking effects in Correlators

 $\langle \eta'\eta' - \sigma\sigma
angle$

Chiral symmetry restoration at finite T and ρ



\rightarrow What will happen to hadron masses : A bridge between QCD and experiment ?

- 1. Soft modes, scalar meson: Hatsuda, Kunihiro (85,87)
- 2. Pseudoscalar mesons: Bernard, Jaffe, Meissner (88), Klimt, Lutz, Vogel, Weise (90)
- 3. Brown-Rho: 91
- 4. Vector mesons: Hatsuda, Lee (92)
- + many more

Chiral symmetry breaking (m->0) : order parameter

• Quark condensate

$$\left\langle \overline{q}(0)q(0)\right\rangle = -\lim_{x\to 0} \left\langle \operatorname{Tr}[S(x,0)]\right\rangle = -\lim_{x\to 0} \left\langle \frac{1}{2} \operatorname{Tr}[S(x,0) - i\gamma^5 S(x,0)i\gamma^5]\right\rangle$$



→ Chiral symmetry breaking order parameter : any operator that checks the existence of this link

$$\langle \overline{q}q \rangle = \langle \overline{q}_L q_R + \overline{q}_R q_L \rangle \neq 0$$
 q_L

 \rightarrow Casher Banks formula: nontrivial zero mode ($\lambda = 0$) contribution

using
$$i D \psi_{\lambda} = \lambda \psi_{\lambda}$$
 where $\psi_{\lambda}(0) = \langle 0 | \lambda \rangle$



$$\frac{1}{V}\int d^{4}x \left[\left\langle \overline{q}(x)\gamma^{\mu}\tau^{a}q(x), \overline{q}(0)\gamma^{\mu}\tau^{a}q(0) \right\rangle - \left\langle \overline{q}(x)\tau^{a}i\gamma^{5}\gamma^{\mu}q(x), \overline{q}(0)\tau^{a}i\gamma^{5}\gamma^{\mu}q(0) \right\rangle \right]$$
$$= -\operatorname{Tr}\left[\gamma^{\mu}S(x,0)\gamma^{\mu} \left(S(0,x) - i\gamma^{5}S(0,x)i\gamma^{5} \right) \right]$$



• Meson with one heavy quark : S-P $D(1864)[0^{-}] - D_0(2400)[0^{+}]$

$$\frac{1}{V}\int d^{4}x \left[\left\langle \overline{H}(x)q(x), \overline{q}(0)H(0) \right\rangle - \left\langle \overline{H}(x)i\gamma^{5}q(x), \overline{q}(0)i\gamma^{5}H(0) \right\rangle \right]$$
$$= -\operatorname{Tr} \left[S_{H}(x,0) \left(S(0,x) - i\gamma^{5}S(0,x)i\gamma^{5} \right) \right]$$



• Baryon sector :
$$\Lambda - \Lambda^* = \Lambda(2286)[1/2^+] - \Lambda(2595)[1/2^-]$$

$$\frac{1}{V}\int d^{4}x \left[\left\langle \left(u^{T}i\gamma^{5}Cd\right)H(x), \left(\overline{u}i\gamma^{5}C\overline{d}^{T}\right)\overline{H}(0) \right\rangle - \left\langle \left(u^{T}Cd\right)H(x), \left(\overline{u}C\overline{d}^{T}\right)\overline{H}(0) \right\rangle \right] \right]$$
$$= -S_{H}(x,0)\mathrm{Tr}\left[S(x,0)\left(S(x,0)-i\gamma^{5}S(x,0)i\gamma^{5}\right) \right]$$



$$U_A(1)$$
 effect1. Correlation function of chiral partners $\langle \overline{q}(0)q(0) \rangle$ vs $\langle VV - AA \rangle$ Cohen 962. $U_A(1)$ breaking effects in Correlators $\langle \eta'\eta' - \sigma\sigma \rangle$ Hatsuda, Lee 96

U_A(1) effect : effective order parameter (Lee, Hatsuda 96)

• Topologically nontrivial contributions

$$Z = \int dA e^{-S_{Glue}} \det[\mathcal{D} + m]$$

$$Z = Z_{\nu=0} + \dots$$

$$Z = \ldots + Z_{\nu=\pm 1} + \ldots$$





$$\langle \overline{q}q \rangle \neq 0$$
 $\qquad \qquad \nu = \frac{\alpha_s}{4\pi} \int d^4 x \left(G\widetilde{G} \right) = n_R - n_L$

• $\eta - \pi$ correlator : v nonzero part

Lee, Hatsuda (96)

$$\frac{1}{V}\int d^{4}x e^{ikx} \Big[\langle \overline{q}(x)i\gamma^{5}q(x), \overline{q}(0)i\gamma^{5}q(0) \rangle - \langle \overline{q}(x)\tau^{a}i\gamma^{5}q(x), \overline{q}(0)\tau^{a}i\gamma^{5}q(0) \rangle \Big]$$

For SU(3) :

$$=\frac{1}{V}\int d^{4}x \left\langle \overline{u}_{0}(x)d_{0}(0)\overline{d}_{0}(0)u_{0}(x)\int d^{4}y\overline{s}_{0}(y)s_{0}(y) + \text{permutations} \right\rangle_{v\neq 0}$$

= [const] x
$$\prod_{q>3} \langle \overline{q}q \rangle$$

For SU(2) : Always non zero



 ι_R

For 2-point function: $U(1)_A$ will be restored when Chiral symmetry is restored for $N_F = 3$ but always broken for $N_F = 2$

But Non trivial to check because

$$Z = \int dA e^{-S_{Glue}} \det[D + m]$$

11.

Also $\langle \overline{q}q \rangle$ is not good to check UA(1) effect when flavor is larger than 2 that is why it is called the chiral order parameter in SU(N)xSU(N) case.

How can we observe restoration of chiral symmetry

- 1. $\langle \overline{q}q \rangle$ can not be directly related to physical observable in a model independent way
- 2. $\langle VV AA \rangle$ could be considered



- → Whole spectrum not necessary
 (Glozeman: Chiral symmetry is restored for excited states+ QCD duality)
- → Ground states that couple to each current can be compared $\langle SS - PP \rangle \rightarrow \sigma$ and π $\langle VV - AA \rangle \rightarrow \rho$ and a_1
- \rightarrow Both states should have small intrinsic width and experimentally observable

How can we observe mass shift – small width hadrons

KEK E325, J-PARC E16



Vacuum values	Mass	Width	
φ	1020 MeV	4.266 MeV	

How can we observe mass shift – small width hadrons

CBELSA/TAPS coll (V. Metag, M. Nanova et al)



Vacuum values	Mass	Width	
ω	782.65 MeV	8.49 MeV	
η΄	957.78 MeV	0.198 MeV	

$f_1(1285)$ and ω meson

1. Chiral partners $\langle VV - AA \rangle$

2. CLAS measurement





MIN2016, Kyoto Japan, Aug. 1, 2016



f1(1285) measurement by CLAS at J-Lab [PRC93,065202 (2016)]

- observation
 - \rightarrow Missing mass analysis for η

 $\gamma p \rightarrow p x \rightarrow p \pi^{+} \pi^{-}(\eta)$



FIG. 1. Missing mass off the proton for the $\eta \pi^+ \pi^- p$ final state summed over the full kinematic range. The $\eta'(958)$ and $f_1(1285)$ mesons are visible. The $f_1(1285)$ is seen atop a substantial multiplon background.

Could be done on nuclear target

Light vector mesons – chiral partners ?

J ^{PC} =1	Mass	Width	J ^{PC} =1 ⁺⁺	Mass	Width
ρ	770	150.	a ₁	1260	250-600
ω	782	8.49	f ₁	1285	24.2
φ	1020	4.266	f ₁	1420	54.9

• ρ and a_1 are chiral partners

$$\rho \to \left(\overline{q}_R \gamma_\mu \tau q_R + \overline{q}_L \gamma_\mu \tau q_L\right) \qquad a_1 \to \left(\overline{q}_R \gamma_\mu \tau q_R - \overline{q}_L \gamma_\mu \tau q_L\right)$$

• The I=0 singlet and octet states are mixed ideally \leftarrow suppression of disconnected diagrams

$$\omega \to \left(\overline{u} \gamma_{\mu} u + \overline{d} \gamma_{\mu} d \right) \qquad \qquad \phi \to \left(\overline{s} \gamma_{\mu} s \right)$$

→ mass degeneracy between ρ and ω : Due to suppression of disconnected diagram $\rho \rightarrow \left(\overline{u}\gamma_{\mu}u - \overline{d}\gamma_{\mu}d\right)$

 \rightarrow What about quark content of f₁(1285) and f₁(1420)

f1(1285) mass shift in QCD sum rules -2

• OPE -q².=Q²
$$\rightarrow$$
 large $J = \overline{u} \gamma^5 \gamma_{\mu} u + \overline{d} \gamma^5 \gamma_{\mu} d$

$$\Pi(q) = \int d^4 x e^{iqx} \langle J(x)J(0) \rangle = q^2 \ln q^2 + \frac{C_n}{q^n} \langle Op \rangle_{n.m.} + ...$$



• Borel transformed Dispersion relation

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f1(1285) and f1(1420) sum rules (Gubler, Kunihiro, Lee, 16)



• Hence,

$$\rho \to \left(\overline{u} \gamma_{\mu} u - \overline{d} \gamma_{\mu} d \right)$$
$$\omega \to \left(\overline{u} \gamma_{\mu} u + \overline{d} \gamma_{\mu} d \right)$$
$$\phi \to \left(\overline{s} \gamma_{\mu} s \right)$$

$$a_{1} \rightarrow \left(\overline{U}\gamma_{\mu}\gamma^{5}U - \overline{d}\gamma_{\mu}\gamma^{5}d\right)$$
$$f_{1}(1285) \rightarrow \left(\overline{U}\gamma_{\mu}\gamma^{5}U + \overline{d}\gamma_{\mu}\gamma^{5}d\right)$$
$$f_{1}(1420) \rightarrow \left(\overline{s}\gamma_{\mu}\gamma^{5}s\right)$$

Independent correlation

L-R representation

$$\left\langle \rho\rho - a_{1}a_{1}\right\rangle \rightarrow \left\langle \left(\overline{U}_{R}\gamma_{\mu}U_{R}\right)\left(\overline{U}_{L}\gamma_{\mu}U_{L}\right) - \left(\overline{U}_{R}\gamma_{\mu}U_{R}\right)\left(\overline{d}_{L}\gamma_{\mu}d_{L}\right)\right\rangle \propto \left\langle \overline{q}q\right\rangle$$

$$\langle \omega \omega - f_1 f_1 \rangle \rightarrow \langle (\overline{u}_R \gamma_\mu u_R) (\overline{u}_L \gamma_\mu u_L) + (\overline{u}_R \gamma_\mu u_R) (\overline{d}_L \gamma_\mu d_L) \rangle$$

= $\langle \rho \rho - a_1 a_1 \rangle + \langle 2 (\overline{u}_R \gamma_\mu u_R) (\overline{d}_L \gamma_\mu d_L) \rangle \propto \langle \overline{q} q \rangle + \text{small}$

Disconnected diagram

• Small width particles can also probe "chiral symmetry restoration" $\omega \eta' \phi$ and very useful to add f1(1285) in the measurement at nuclear matter

 \rightarrow can understand how chiral symmetry restoration is realized in nature

f1(1285) mass shift in QCD sum rules -2

- Borel curve
 - \rightarrow Most important input

$$\left\langle \overline{q}q\right\rangle _{\rho}=\left\langle \overline{q}q\right\rangle _{0}+rac{\sigma_{\pi N}}{m_{q}}
ho$$



Mass shift

 $\sigma_{\pi N} = 45 \text{ MeV} \pm 15 \text{ MeV}$

$$\Delta m_{f_1} = -96 \text{ MeV} \pm 35 \text{ MeV}$$



f1(1285) measurement by CLAS at J-Lab [PRC93,065202 (2016)]

- observation
 - \rightarrow Missing mass analysis for η

 $\gamma p \rightarrow p x \rightarrow p \pi^{+} \pi^{-}(\eta)$



FIG. 1. Missing mass off the proton for the $\eta \pi^+ \pi^- p$ final state summed over the full kinematic range. The $\eta'(958)$ and $f_1(1285)$ mesons are visible. The $f_1(1285)$ is seen atop a substantial multipion background.

Could be done on nuclear target

Summary

- 1. Confinement: $J/\psi \chi \psi'$ in medium
- 2. D-D0, and $\Lambda \Lambda *$ measurement in medium
- 3. Mass shift measurement of small width particles such as

 $f_1(1285)$ together with ω , ϕ , on a nuclear target can link chiral symmetry restoration to mass generation in the light quark system

4. All that could be finalized at Hadron Physics program at J-PARC !!

η' mass? Witten-Veneziano formula - I

$$P(k) = -i \int dx e^{ikx} \left\langle G\widetilde{G}(x), G\widetilde{G}(0) \right\rangle$$

• Gluons only $P_0(k=0) \neq 0$ from low energy theorem

• With quarks
$$P(k=0) = -i \int dx e^{ikx} \left\langle \partial^{\mu} j^{5}_{\mu}(x), \partial^{\mu} j^{5}_{\mu}(0) \right\rangle \propto k^{\mu} k^{\nu} P_{\mu\nu} = 0$$
 using $\partial_{\mu} j^{5}_{\mu} = \frac{\alpha_{s}}{4\pi} G \widetilde{G}$

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11/

• Large Nc argument
$$P(k) = \sum_{glueballs} \frac{\left\langle 0 \mid G\widetilde{G} \mid glueball \right\rangle^2}{k^2 - m_n^2} + \sum_{mesons} \frac{\left\langle 0 \mid G\widetilde{G} \mid meson \right\rangle^2}{k^2 - m_n^2}$$

$$G\widetilde{G} \bigoplus_{\substack{N_c^2 \\ N_c^2}} G\widetilde{G} \bigoplus_{\substack{N_c \\ N_c}} G\widetilde{G} \bigoplus_{\substack{N_c \\ N_c}} G\widetilde{G}$$
• Need η ' meson
$$+ \frac{\left\langle 0 \mid G\widetilde{G} \mid \eta' \right\rangle^2}{k^2 - m_{\eta'}^2} \quad \text{with} \quad m_{\eta'}^2 \approx O\left(\frac{1}{N_c}\right)$$

$$\rightarrow \quad P(k = 0) = \boxed{P_0(0)} + \frac{\left\langle 0 \mid G\widetilde{G} \mid \eta' \right\rangle^2}{m_{\eta'}^2} = 0$$

• W-V formula at finite density: Y. Kwon, SHL, K. Morita, G. Wolf, PRD86,034014 (2012)

$$\left\langle \overline{q}q \right\rangle$$

$$\rightarrow Most model calculations$$

$$\frac{\left\langle 0 \mid G\widetilde{G} \mid \eta' \right\rangle^2}{m_{\eta'}^2} = P_0(0) \longrightarrow \left(\frac{4\pi}{3\alpha}\right)^2 \frac{2d}{11} \left(1 - 0.02 \frac{\rho}{\rho_{nm}}\right) \left\langle \frac{\alpha}{\pi} G^2 \right\rangle_0$$

Very small change

Therefore ,
$$\, m_{\eta^{\,\prime}} - m_{\eta^{\,\prime}} \propto \left\langle \overline{q} \, q \,
ight
angle^{1/2}$$

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