QCD motivated meson models with a chiral imbalance

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SPhGII

Parity Symmetry Breaking (CP-breaking)



- ► CP-odd condensates as regular phase at finite density ⇔ baryonic chemical potential
 - Migdal A B Zh. Eksp. Teor. Fiz. 61 (1971); Lee T D and Wick G C Phys. Rev. D 9 . 2291 (1974)
 - Andrianov A A, Andrianov V A and Espriu D Phys. Lett. B 678, 416 (2009)
- ▶ Topological fluctuation as regular phase at finite density or temperature ⇔ chiral chemical potential
 - Kharzeev D E, Pisarski R D and Tytgat M H G Phys. Rev. Lett. 81, 512 (1998)
 - Buckley K , Fugleberg T and Zhitnitsky A Phys. Rev. Lett. 84, 4814 (2000)
 - Andrianov A A, Andrianov V A, Espriu D and Planells X Phys. Lett. B 710 (2012)
 - Yamamoto A Phys. Rev. D 84 (2011) 114504; Phys. Rev. Lett. 107 (2011) 031601

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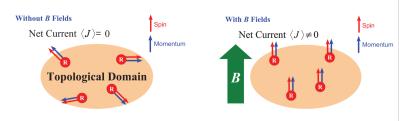




Introduction Detection of CP-breaking



- ► Chiral magnetic effect $j = \frac{e^2}{2\pi^2}\mu_5 \, B$
 - ► Wang G. Experimental Overview of the Search for Chiral Effects at RHIC. Journal of Physics: Conference Series, 779, 1 (2017)
 - Search for the Chiral Magnetic Effect in Relativistic Heavy-Ion Collisions. Jie Zhao, Int. J. Mod. Phys. A, 33, 1830010 (2018)



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► Anomalous escape of dileptons

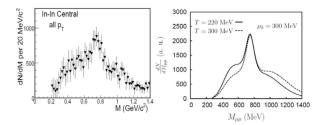
- NA60 Collaboration. Eur. Phys. J. C, 2009, vol 61 (4); STAR Collaboration. Phys. Rev. Lett., 2014, vol 113 (2); PHENIX Collaboration. Phys. Rev. C, 2010, 40, vol 81 (3)
- ► Andrianov A.A., Andrianov V.A., Espriu D., Planells X. Analysis of dilepton angular distributions in a parity breaking medium. Phys. Rev. D, 2014, vol. 90

Massive vector mesons split into three polarizations with masses:

$$m_{V,+}^2 < m_{V,L}^2 < m_{V,-}^2$$

Anomalies in dilepton production in meson decays:

$$\rho,\omega\rightarrow e^+e^-$$
 , $\eta,\eta^\prime\rightarrow\gamma\,e^+e^-$, $\omega\rightarrow\pi^0e^+e^-$



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Processes which violate the party explicitly

► Andrianov A.A., Espriu D., Planells X. An effective QCD Lagrangian in the presence of an axial chemical potential. Eur. Phys. J. C, 2013, vol. 73 (1)

CP-symmetry: $\eta \to \pi^+\pi^-\pi^0$, $\eta \to 3\pi^0$, $\eta' \to \pi^+\pi^-\eta$ CP-breaking: $\eta \to \pi^+\pi^-, \eta' \to \pi^+\pi^-$

Asymmetry of photon polarization

Kawaguchi M., Harada M., Matsuzaki S., Ouvan R. Charged pions tagged with polarized photons probing strong CP violation in a chiral-imbalance medium. Phys. Rev. C, 2017, vol. 95 (6) $\pi^+ \gamma \to \pi^+ \gamma$

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Detection of CP-breaking



Formulation of the problem



Aim of work:

study of the environment with the chiral chemical potential within the framework of Nambu-Jona-Lasinio Model and QCD motivated sigma model

The results of this work were published in:

- ► Andrianov A.A., Andrianov V.A., Espriu D., Putilova A.E., lakubovich A.V. Decays of light mesons triggered by chiral chemical potential. Acta Physica Polonica B, 2017, Vol. 10, No. 4, P. 977-982.
- Andrianov A.A., Andrianov V.A., Espriu D., Putilova A.E., lakubovich A.V. Exotic meson decays in the environment with chiral imbalance. European Physical Journal: Web of Conferences, 2017, Vol. 158, No. 03012, 10 p.
- Andrianov A.A., Andrianov V.A., Espriu D., Putilova A.E., lakubovich A.V. QCD with chiral chemical vector: models versus lattice. Physics of Particles and Nuclei Letters, 2018, Vol. 15, No. 4, P. 357–361.

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Formulation of the problem





Topological fluctuations in the restricted region



$\partial^{\mu} J_{5,\mu} = 2 i \bar{\psi} \,\hat{m}_q \gamma_5 \,\psi + \frac{N_f \,g^2}{8\pi^2} \epsilon_{\mu\nu\alpha\beta} \,tr(G_{\mu\nu} G_{\alpha\beta}) \tag{1}$

$$\mathcal{L}_{\theta} = \theta \frac{g^2}{16\pi^2} \epsilon_{\mu\nu\alpha\beta} \operatorname{tr}(G_{\mu\nu}G_{\alpha\beta}) \tag{2}$$

Hypothesis: $\theta = \theta(x)$ - is pseudoscalar field

$$\mathcal{L}_{\theta} = \frac{-1}{2N_f} J_{5,\mu} \, \partial^{\mu} \theta(x) - \frac{\theta(x)}{N_f} \, i \, \bar{\psi} \, \hat{m}_q \gamma_5 \, \psi \quad . \tag{3}$$

$$\frac{1}{2N_f}\partial^0\theta(t) = \mu_5 = const$$

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Connection between chiral and topological charge



$$\partial^{\mu} J_{5,\mu} = 2 i \,\bar{q} \,\hat{m}_q \gamma_5 \,q + \frac{N_f \,g^2}{8\pi^2} \epsilon_{\mu\nu\alpha\beta} \,tr(G_{\mu\nu} G_{\alpha\beta}) \tag{5}$$

$$Q_5(t_2) - Q_5(t_1) + \int_{\partial V} d^3 \Sigma^i J_{5,i} =$$

$$=2i\int_{t_1}^{t_2} dt \int_V d^3x \ \bar{q} \, \hat{m}_q \gamma_5 \, q + \frac{1}{2N_f} (Q_t(t_2) - Q_t(t_1)) + \frac{1}{2N_f} \int_{\partial V} d^3 \Sigma^i J_{t,i}$$
(6)

 $\triangle Q_5 = \frac{1}{2N_f} \triangle Q_t$ (7)

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Connection between chiral

and topological charge

Model

Left-right oscillations of quarks



Fireball lifetime $\approx 10 \text{ fm}$

Oscillation time for u/d-quark $pprox rac{1}{m_{u/d}} pprox rac{1}{5~{
m MeV}} pprox$ 40 fm

Oscillation time for s-quark $\approx \frac{1}{m_s} \approx \frac{1}{150 \text{ MeV}} \approx 1 \text{ fm}$

$$\partial^{\mu} J_{5,\mu} = 2i\bar{\psi}\hat{m}_{s}\gamma_{5}\psi + \frac{N_{f}g^{2}}{8\pi^{2}}\epsilon_{\mu\nu\alpha\beta}tr(G_{\mu\nu}G_{\alpha\beta}) = 0$$
 (8)

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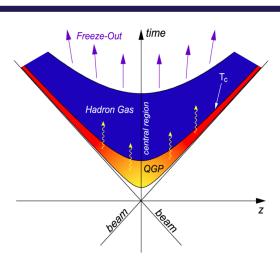
Left-right oscillations

Model



Model Relativistic heavy-ion collisions





Quark-gluon plasma \iff Nambu-Jona-Lasinio model Hadron gas ← Sigma model

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Model

Relativistic heavy-ion collisions



Model

Chiral Nambu-Jona-Lasinio model



$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_V \otimes U(1)_A \otimes \mathcal{T}:$

$$\mathcal{L} = \bar{\psi}(\partial \!\!\!/ + m - \mu_5 \gamma_0 \gamma_5) \psi$$
$$- \frac{G_1}{N_c} \left(\left(\bar{\psi} \, \psi \right)^2 + \left(\bar{\psi} \, i \, \gamma_5 \, \vec{\tau} \, \psi \right)^2 \right) - \frac{G_2}{N_c} \left(\bar{\psi} \, \vec{\tau} \, \psi \right)^2$$

$$\bar{\psi} \psi \iff \sigma \iff (J^P, I) = (0^+, 0)$$

$$\bar{\psi} \gamma_5 \vec{\tau} \psi \iff \pi \iff (J^P, I) = (0^-, 1)$$

$$\bar{\psi} \vec{\tau} \psi \iff a_0 \iff (J^P, I) = (0^+, 1)$$

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Model Chiral sigma model



$\mathcal{L}_{m} = \frac{1}{4} Tr \left(D_{\mu} H \left(D^{\mu} H \right)^{\dagger} \right) + \frac{b}{2} Tr \left[\hat{m} (H + H^{\dagger}) \right] + \frac{M^{2}}{2} Tr \left(H H^{\dagger} \right)$

$$-\frac{\lambda_1}{2}Tr\left[(HH^{\dagger})^2\right] - \frac{\lambda_2}{4}\left[Tr\left(HH^{\dagger}\right)\right]^2 + \frac{c}{2}(\det H + \det H^{\dagger}) \tag{9}$$

$$H = \xi \, \Sigma \, \xi \tag{10}$$

$$\Sigma = \begin{bmatrix} v + \sigma + a_0 & \sqrt{2} a_+ \\ \sqrt{2} a_- & v + \sigma - a_0 \end{bmatrix} \qquad \xi = \exp\left(i\frac{\vec{\pi}\vec{\tau}}{2f_{\pi}}\right)$$
 (11)

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Chiral sigma model

Model Chiral sigma model



$\mathcal{L}_{m} = \frac{1}{4} Tr \left(D_{\mu} H \left(D^{\mu} H \right)^{\dagger} \right) + \frac{b}{2} Tr \left[\hat{m} (H + H^{\dagger}) \right] + \frac{M^{2}}{2} Tr \left(H H^{\dagger} \right)$

$$-\frac{\lambda_1}{2} Tr \left[(HH^{\dagger})^2 \right] - \frac{\lambda_2}{4} [Tr (HH^{\dagger})]^2 + \frac{c}{2} (\det H + \det H^{\dagger})$$
 (9)

$$D_{\mu}H = \partial_{\mu}H - i\mathcal{L}_{\mu}H + iH\mathcal{R}_{\mu} \tag{12}$$

$$\mathcal{L}_{\mu} = e \, Q_{em} \, A_{\mu} - \mu_5 \, \delta_{\mu 0} \, I \quad \mathcal{R}_{\mu} = e \, Q_{em} \, A_{\mu} + \mu_5 \, \delta_{\mu 0} \, I \quad (13)$$

$$Q_{em} = \frac{1}{2}\tau_3 + \frac{1}{6}I\tag{14}$$

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Model

Chiral sigma model

Model

Chiral Wess-Zumino-Witten model



$W_{-} = -\frac{iN_c}{96\pi^2} \int_0^1 dx_5 \int d^4x \epsilon^{\mu\nu\sigma\lambda\rho} Tr \left[-j_{\mu}^- F_{\nu\sigma}^L F_{\lambda\rho}^L - j_{\mu}^+ F_{\nu\sigma}^R F_{\lambda\rho}^R \right]$ $-\,\frac{1}{2}\,\,j_{\mu}^{+}F_{\nu\sigma}^{L}\,U(x_{5})F_{\lambda\rho}^{R}\,U^{\dagger}\!(x_{5}) - \frac{1}{2}\,j_{\mu}^{+}F_{\nu\sigma}^{R}\,U^{\dagger}\!(x_{5})F_{\lambda\rho}^{L}\,U(x_{5})$ $+\,iF^L_{\mu\nu}\,j^-_\sigma j^-_\lambda j^-_\rho + iF^R_{\mu\nu}\,j^+_\sigma j^+_\lambda j^+_\rho + \frac{2}{{\rm g}}j^-_\mu j^-_\nu j^-_\sigma j^-_\lambda j^-_\rho \Big]$ (15)

$$U = \exp\left(i\,\vec{\pi}\vec{\tau}/f_{\pi}\right),\tag{16}$$

$$j_{\mu}^{-} = (D_{\mu}U)U^{\dagger}, \ j_{\mu}^{+} = U^{\dagger}(D_{\mu}U), \ \mathcal{L}_{5} = \mathcal{R}_{5} = 0$$
 (17)

$$F_{\mu\nu}^{L} = \partial_{\mu}\mathcal{L}_{\nu} - \partial_{\nu}\mathcal{L}_{\mu} + [\mathcal{L}_{\mu}, \mathcal{L}_{\nu}]$$

$$F_{\mu\nu}^{R} = \partial_{\mu}\mathcal{R}_{\nu} - \partial_{\nu}\mathcal{R}_{\mu} + [\mathcal{R}_{\mu}, \mathcal{R}_{\nu}]$$

$$(18)$$

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Model

Chiral WZW model



Explicit form of Lagrangian up to second order on a inverse f_{π}



Sigma meson:

$$\frac{1}{2} \, \partial_{\mu} \sigma \, \partial^{\mu} \sigma - \frac{1}{2} \, m_{\sigma}^2 \sigma^2 \tag{19}$$

Uncharged mesonic sector:

$$\frac{1}{2} \partial_{\mu} a_0 \partial^{\mu} a_0 + \frac{1}{2} \partial_{\mu} \pi_0 \partial^{\mu} \pi_0 - \frac{1}{2} m_a^2 (a_0)^2 - \frac{1}{2} m_\pi^2 (\pi_0)^2 - 4\mu_5 \dot{\pi}_0 a_0$$
 (20)

Charged mesonic sector:

$$\partial_{\mu}a_{-}\,\partial^{\mu}a_{+}\,+\,\partial_{\mu}\pi_{-}\partial^{\mu}\pi_{+}\,-\,m_{a}^{2}a_{-}a_{+}\,-\,m_{\pi}^{2}\pi_{-}\pi_{+}\boxed{-4\mu_{5}\,\dot{\pi}_{+}a_{-}\,-\,4\mu_{5}\,\dot{\pi}_{-}a_{+}}\tag{21}$$

Vertices for uncharged mesonic sector:

$$\frac{1}{v}\sigma \,\partial_{\mu}\pi_{0}\partial^{\mu}\pi_{0} + -\frac{4\mu_{5}}{v}\,\sigma \,\dot{\pi}_{0}a_{0} - \frac{b\,m}{v^{2}}\,\sigma \left(\pi_{0}\right)^{2} \tag{22}$$

Vertices for charged mesonic sector with field of σ meson:

$$\frac{2}{v}\,\sigma\,\partial_{\mu}\pi_{-}\partial^{\mu}\pi_{+}\,-\,\frac{4\mu_{5}}{v}\,\sigma\,\dot{\pi}_{+}a_{-}\,-\,\frac{4\mu_{5}}{v}\,\sigma\,\dot{\pi}_{-}a_{+}\,-\,\frac{2b\,m}{v^{2}}\,\,\sigma\,\pi_{-}\pi_{+}\,-\,24\lambda_{1}v\,\sigma a_{-}a_{+}\,-\,8\lambda_{2}\,v\,\sigma\,a_{-}a_{+}$$

Vertices for charged mesonic sector with electromagnetic field:

$$ie \partial_{\mu}\pi_{+}\pi_{-}A^{\mu} - ie \pi_{+}\partial_{\mu}\pi_{-}A^{\mu} + ie \partial_{\mu}a_{+}a_{-}A^{\mu} - ie a_{+}\partial_{\mu}a_{-}A^{\mu}$$
 (24)



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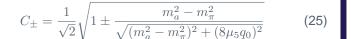
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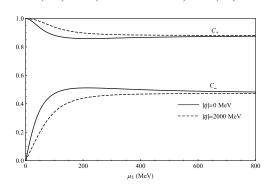
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Coefficients of diagonalization





$$\begin{pmatrix} \tilde{a}_0 \\ \tilde{\pi}_0 \end{pmatrix} = \begin{pmatrix} C_+ & -C_- \\ -i C_- & -i C_+ \end{pmatrix}^{-1} \begin{pmatrix} a_0 \\ \pi_0 \end{pmatrix} \tag{26}$$



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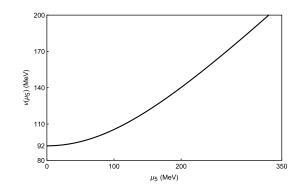
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The equation for the mass gap: quark condensate



$$\langle \bar{\psi}\psi \rangle = -b \cdot v(\mu_5)$$

$$v(\mu_5) \approx v_0 + v_1 m = \sqrt{\frac{M^2 + 2\mu_5^2 + c}{2(\lambda_1 + \lambda_2)}} + \frac{b}{2(M^2 + 2\mu_5^2 + c)} m$$



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The equation for the mass gap: guark condensate



Parameters of lagrangian



From equation:

$$\begin{split} & m_{\sigma}^2 = -2 \left(M^2 - 6 \left(\lambda_1 + \lambda_2 \right) v^2 + c + 2 \mu_5^2 \right) \\ & m_a^2 = -2 \left(M^2 - 2 \left(3 \lambda_1 + \lambda_2 \right) v^2 - c + 2 \mu_5^2 \right) \\ & m_{\pi}^2 = \frac{2 \, b \, m}{v} \\ & v(\mu_5) = \sqrt{\frac{M^2 + 2 \mu_5^2 + c}{2 \left(\lambda_1 + \lambda_2 \right)}} + \frac{b}{2 \left(M^2 + 2 \mu_5^2 + c \right)} \, m \end{split}$$

we can find λ_1 , λ_2 , c μ b. We get two sets of parameters:

- 1) $\lambda_1 = 1.64850 \times 10$, $\lambda_2 = -1.31313 \times 10$, $c = -4.46874 \times 10^4 \, \mathrm{MeB^2}$, $b = 1.61594 \times 10^5 \, \mathrm{MeB^2}$
- 2) $\lambda_1 = 1.79298 \times 10$, $\lambda_2 = -1.52985 \times 10$, $c = -8.13732 \times 10^4 \text{ MeB}^2$, $b = 1.61594 \times 10^5 \text{ MeB}^2$

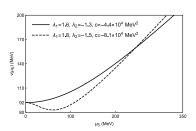


Figure 1: $v(\mu_5)$ from sigma model.

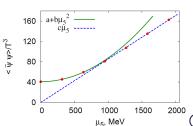


Figure 2: $v(\mu_5)$ from lattice model for nonzero T. (Braguta V.V., Kotov A.Yu. Catalysis of dynamical chiral symmetry breaking by chiral chemical potential, Phys. Rev. D. 2016, vol. 93 (10), pp.)

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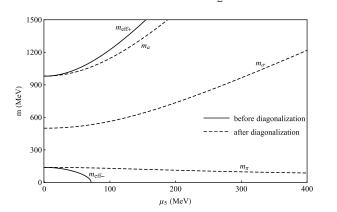
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$$\begin{split} m_{eff\mp}^2 = &\mp \, \frac{1}{2} \sqrt{(16 \mu_5^2 + m_a^2 + m_\pi^2)^2 - 4 m_a^2 \, m_\pi^2 + 64 \mu_5^2 \, |\vec{q}|^2} \,\, + \\ &+ \frac{1}{2} (16 \, \mu_5^2 + m_a^2 + m_\pi^2 \,) \end{split}$$



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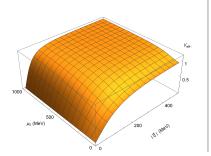
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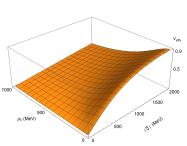
Results Group velocity



$$V_{eff-} = \frac{|\vec{q}\,| + \frac{1}{2} \, \frac{\partial \, m_{eff-}^2}{\partial \, |\vec{q}\,|}}{\sqrt{|\vec{q}\,|^2 + m_{eff-}(|\vec{q}\,|)}}$$



$V_{eff+} = \frac{|\vec{q}\,| + \frac{1}{2} \, \frac{\partial \, m_{eff+}^2}{\partial \, |\vec{q}\,|}}{\sqrt{|\vec{q}\,|^2 + m_{eff+}(|\vec{q}\,|)}}$



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Summary



Topological fluctuations \Rightarrow Axial chemical potential \Rightarrow Hadronic physics

- ► Effective mass of the *a* meson is **more** than the mass of *a* meson in the vacuum
- Effective mass of the π meson is less than the mass of π meson in the vacuum
- ▶ The effective mass of the π meson may become imaginary quantity
- ▶ ↑ chiral chemical potential ⇒ growth of the violation of chiral symmetry
- ↑ baryonic chemical potential ⇒ chiral symmetry partially restores

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Thank you for attention

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Part I

Appendix

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In more detail about quantization of fields



$$\begin{split} \tilde{a}_0(k) &= \delta(k^2 - m_{eff+}^2) F_{a_0}(k) \\ \tilde{a}_-(k) &= \delta(k^2 - m_{eff+}^2) F_{a_-}(k) \\ \tilde{\pi}_-(k) &= \delta(k^2 - m_{eff+}^2) F_{a_-}(k) \\ \tilde{\pi}_-(k) &= \delta(k^2 - m_{eff-}^2) F_{\pi_-}(k) \\ \end{split} \qquad \begin{aligned} \tilde{a}_0(k) &= \delta(k^2 - m_{eff-}^2) F_{\pi_0}(k) \\ \tilde{a}_+(k) &= \delta(k^2 - m_{eff+}^2) F_{a_+}(k) \\ \tilde{\pi}_+(k) &= \delta(k^2 - m_{eff-}^2) F_{\pi_+}(k) \end{aligned}$$

In our case, masses of field depend on momentum, and normalization of wave packets is changed:

$$\int dk_0 e^{ikx} \tilde{a}_0(k) = \frac{2\pi}{\sqrt{f_*}} \left(e^{ikx} a_0^+(\vec{k}) + e^{-ikx} a_0^-(\vec{k}) \right) \Big|_{k_0 = k_0(\vec{k})}$$
(27)

$$\int dk_0 \, e^{ikx} \, \tilde{\pi}_0(k) = \frac{2\pi}{\sqrt{f_-}} \left(e^{ikx} \, \pi_0^+(\vec{k}) + e^{-ikx} \, \pi_0^-(\vec{k}) \right) \Big|_{k_0 = k_0(\vec{k})} \tag{28}$$

$$\int dk_0 \, e^{ikx} \, \tilde{a}_-(k) = \frac{2\pi}{\sqrt{f_+}} \left(e^{ikx} \, \tilde{a}_-^+(\vec{k}) + e^{-ikx} \, a_-^-(\vec{k}) \right) \Big|_{k_0 = k_0(\vec{k})} \tag{29}$$

$$\int dk_0 \, e^{ikx} \, \tilde{\pi}_-(k) = \frac{2\pi}{\sqrt{f_-}} \left(e^{ikx} \, \check{\pi}_-^+(\vec{k}) + e^{-ikx} \, \pi_-^-(\vec{k}) \right) \Big|_{k_0 = k_0(\vec{k})} \tag{30}$$

$$\int dk_0 \, e^{ikx} \, \tilde{a}_+(k) = \frac{2\pi}{\sqrt{f_+}} \left(e^{ikx} \, a_+^+(\vec{k}) + e^{-ikx} \, \check{a}_+^-(\vec{k}) \right) \Big|_{k_0 = k_0(\vec{k})} \tag{31}$$

$$\int dk_0 e^{ikx} \,\tilde{\pi}_+(k) = \frac{2\pi}{\sqrt{f_-}} \left(e^{ikx} \, \pi_+^+(\vec{k}) + e^{-ikx} \, \check{\pi}_+^-(\vec{k}) \right) \Big|_{k_0 = k_0(\vec{k})} \tag{32}$$

QCD motivated meson models with a chiral imbalance

A. lakubovich

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Quark condensate



Nambu and Jona-Lasinio model

$$\begin{split} \left\langle \bar{\psi}\psi \right\rangle &= -(250 \text{ MeV})^3 \\ &= -153 \cdot 10^5 \, \text{MeV}^3 \end{split}$$

(Vogl U., Weise W. The Nambu and Jona-Lasinio model: Its implications for Hadrons and Nuclei. Progress in Particle and Nuclear Physics, 1991, vol. 27, pp. 195-272.)

Investigative model Let's use:

$$\begin{cases} GOR: m_\pi^2 = -\frac{2m}{v^2} \left\langle \bar{\psi}\psi \right\rangle \\ m_\pi^2 = \frac{2\,b\,m}{v} \\ b = 1.61594 \times 10^5\,\mathrm{MeV}^2 \end{cases}$$

If $\mu_5 = 0$ then:

$$\langle \bar{\psi}\psi \rangle = -b \cdot v(\mu_5) =$$

= $-147 \cdot 10^5 \,\text{MeV}^3$

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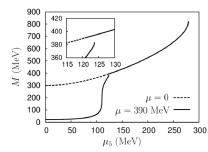
A. lakubovich

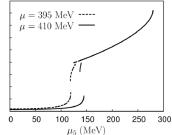
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