Disoriented Isospin Condensates in High Energy Heavy Ion Collisions

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Workshop on Particle Correlations and Femtoscopy 2024

Kapusta, Pratt, Singh, Phys. Rev. C **107**, 014913 (2023) [Editors' Suggestion]
Kapusta, Pratt, Singh, Phys. Rev. C **109**, L031902 (2024)
Chabowski, Kapusta, Singh, arXiv:2409.03711

$\nu_{\rm dyn}(A,B)$

- $\nu_{\rm dyn}(A,B)$ measures how particles of type A and B are correlated.

- $\nu_{\rm dyn}(A,B) = R_{AA} + R_{BB} - 2R_{AB}$ where

$$R_{AB} = \frac{\langle N_A N_B \rangle - \langle N_A \rangle \langle N_B \rangle - \langle N_A \rangle \delta_{AB}}{\langle N_A \rangle \langle N_B \rangle}$$

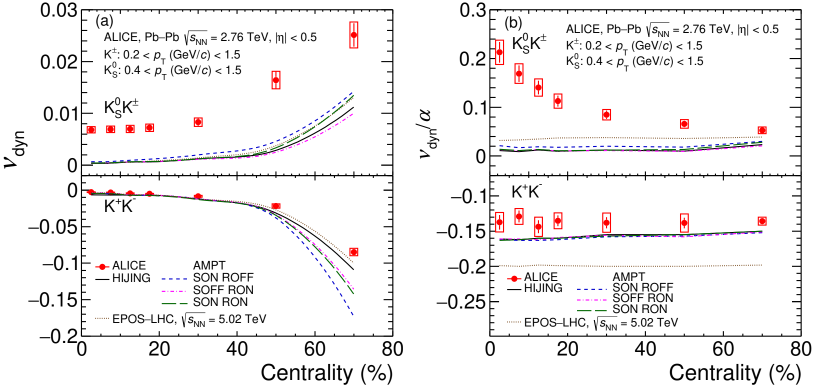
- For uncorrelated particles $R_{AA} = R_{BB} = R_{AB} = 0$ and consequently $\nu_{\rm dyn} = 0$.

- If $\nu_{\rm dyn} > 0$ detection of one particle biases the next particle to be of the same type. It is the opposite for $\nu_{\rm dyn} < 0$.

- It is considered a relatively robust observable.

S. Gavin and J. I. Kapusta, Phys. Rev. C **65**, 054910 (2002)

Models cannot reproduce the measured neutral-charged correlations



$$\alpha \equiv \frac{1}{N_{K^0_S}} + \frac{1}{N_{K^{\pm}}} \approx \frac{6}{N_K^{tot}}$$

ALICE Collaboration, Phys. Lett. B **832**, 137242 (2022)

Isospin fluctuations from condensates

• Suppose we have multiple domains of condensates which give rise to flat neutral kaon fractions $P(f) = 1$. This is the case for DCC with three flavors J. Schaffner-Bielich and J. Randrup, Phys. Rev. C **59**, 3329 (1999) and also for kaons in an electrically neutral degenerate quantum state.

• If the number of domains N_d is greater than 2 or 3 then

$$\nu_{\rm dyn} = 4\beta_K \left(\frac{\beta_K}{3N_d} - \frac{1}{N_K^{tot}} \right)$$

where β_K is the fraction of all kaons that come from condensate domains.

• The relation is derived by folding the distributions of kaons from condensates and thermal/random sources. For multiple condensate sources, $P(f)$ approaches a Gaussian by the Central Limit Theorem.

S. Gavin and J. I. Kapusta, Phys. Rev. C **65**, 054910 (2002)

Isospin fluctuations from condensates

• Arguments can be given for the scaling relations

$$\begin{aligned} N_d &= aN_K^{tot} \\ \beta_K &= b\left(\frac{\tau_{av}}{10\tau_0}\right) \end{aligned}$$

• This results in a two parameter formula for $\nu_{\mathrm{dyn}}/\alpha$

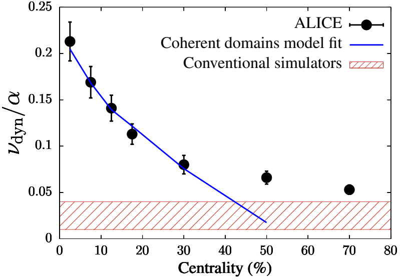
$$\frac{\nu_{\mathrm{dyn}}}{\alpha} = \frac{2}{3}b\left(\frac{\tau_{av}}{10\tau_0}\right)\left[\frac{b}{3a}\left(\frac{\tau_{av}}{10\tau_0}\right) - 1\right]$$

• We obtain the lifetime τ_{av} as a function of centrality from realistic hydrodynamic simulations of heavy-ion collisions using MUSIC with initial time $\tau_0 = 0.4$ fm/c.

Fit to the 5 most central bins

$$b = 0.1044 \pm 0.0380$$
$$\frac{b^2}{a} = 0.2187 \pm 0.0458$$

For reference energy density $\epsilon_\zeta = 25$ MeV/fm^3. Only V_d changes with ϵ_ζ.



Centrality	N_d	$V_d(\text{fm}^3)$	β_K
0-5 %	9.32	1120	0.302
5-10 %	7.29	821	0.283
10-15 %	6.02	640	0.267
15-20 %	4.67	476	0.256
20-40 %	2.88	258	0.225
40-60 %	1.20	82	0.172

Average domain size ranges from 86 fm^3 for 20-40% centrality to 120 fm^3 for 0-5% centrality.

Disoriented Isospin Condensates

• It is always assumed that $\langle \bar{u}u \rangle = \langle \bar{d}d \rangle$. What if their relative magnitudes fluctuated at finite temperature? This means fluctuations between an isosinglet $\langle \bar{u}u \rangle + \langle \bar{d}d \rangle$ and an isotriplet $\langle \bar{u}u \rangle - \langle \bar{d}d \rangle$. The lowest vacuum excitation of the latter is the neutral member of the $a_0(980)$ isotriplet meson.

• If the domain happened to be totally $\langle \bar{u}u \rangle$ then, when it loses energy due to cooling, combination with strange quarks and anti-quarks results in charged kaons. If the domain happened to be totally $\langle \bar{d}d \rangle$ then combination with strange quarks and anti-quarks results in neutral kaons.

• If the distribution in the relative proportion of the two condensates was flat then we essentially recover the previous phenomenology.

• In addition, quarks and anti-quarks are most likely strongly correlated already before chemical freezeout.

2+1 flavor Linear Sigma Model

With $\sigma_u = -\langle \bar{u}u \rangle / \sqrt{2}c'$, $\sigma_d = -\langle \bar{d}d \rangle / \sqrt{2}c'$, and $\zeta = -\langle \bar{s}s \rangle / \sqrt{2}c'$ the field potential can be written as

$$\begin{aligned} U(M) &= -\frac{1}{2}\mu^2(\sigma_u^2 + \sigma_d^2 + \zeta^2) + \lambda'(\sigma_u^2 + \sigma_d^2 + \zeta^2)^2 \\ &+ \lambda(\sigma_u^4 + \sigma_d^4 + \zeta^4) - 2c\sigma_u\sigma_d\zeta \\ &- \sqrt{2}c'(m_u\sigma_u + m_d\sigma_d + m_s\zeta) \end{aligned}$$

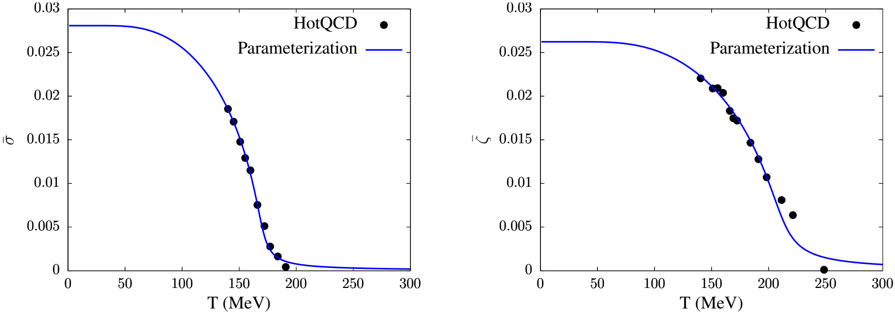
If $\langle \bar{u}u \rangle = \langle \bar{d}d \rangle$ then $\sigma_u = \sigma_d = \sigma/\sqrt{2}$, otherwise write $\sigma_u = \sigma \cos\theta$ and $\sigma_d = \sigma \sin\theta$ with $0 \leq \theta \leq \pi/2$. The departure from the equilibrium potential $(\theta = \pi/4)$ is

$$\begin{aligned} \Delta U(T,\theta) &= \frac{1}{2}\lambda \left[1 - \sin^2(2\theta)\right] \sigma^4 + c(T) \left[1 - \sin(2\theta)\right] \sigma^2 \zeta \\ &+ f_\pi m_\pi^2 \left[1 - \frac{\cos\theta + \sin\theta}{\sqrt{2}}\right] \sigma \end{aligned}$$

Axial U(1) symmetry is approximately restored at high temperature. From instanton calculations[1] we take $c(T) = c(0)/(1 + 1.2\pi^2\bar{\rho}^2T^2)^7$ with $\bar{\rho} = 0.33$ fm and $c(0) = 1.732$ GeV.

[1] J. I. Kapusta, E. Rrapaj and S. Rudaz, Phys. Rev. C **101**, 031901 (2020)

Parameterizing condensates



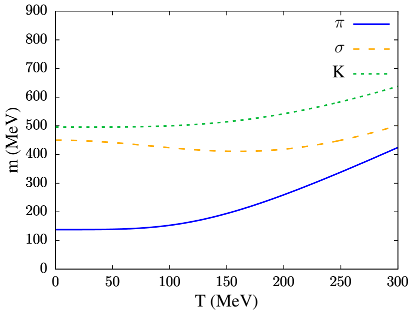
Ising model parameterization. Data is in lattice units.

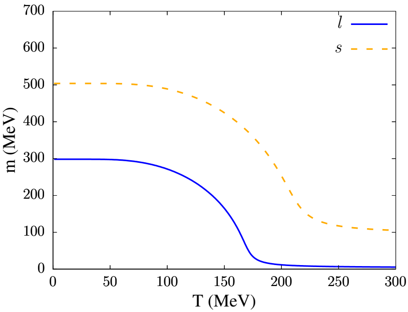
$$m = \tanh\left(\frac{mT_c + h}{T}\right)$$

Light: $T_c = 166.8$ MeV, $h = 0.9216$ MeV

Strange: $T_c = 204.3$ MeV, $h = 2.607$ MeV

Parameterizing masses

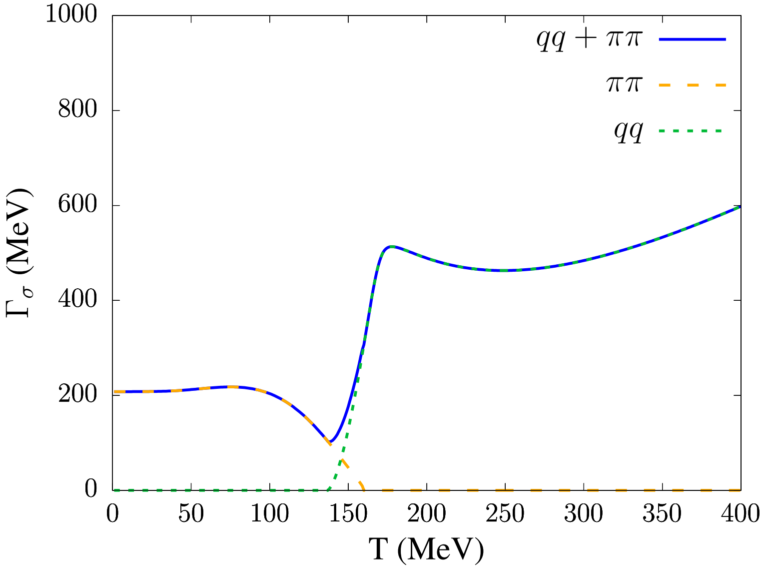




$$
\begin{aligned}
m_\pi^2(T) &= m_\pi^2 + \frac{a_\pi T^4}{T^2 + T_0^2} \\
m_\sigma^2(T) &= m_\sigma^2 + \frac{T^2}{T^2 + T_0^2}\left(a_\pi T^2 - m_\sigma^2 + m_\pi^2\right) \\
m_K^2(T) &= m_K^2 + \frac{a_\pi T^4}{T^2 + T_0^2}
\end{aligned}
$$

$$
\begin{aligned}
M_u &= m_u + g\bar{\sigma} \\
M_d &= m_d + g\bar{\sigma} \\
M_s &= m_s + \sqrt{2} g\bar{\zeta}
\end{aligned}
$$

Decay rate of the σ



A Fokker-Planck equation can be derived for the condensate field $\varphi = \theta - \pi/4$. For temperatures $T \geq 170$ MeV the potential can be well approximated by

$$\Delta U = \tfrac{1}{2} f_\pi m_\pi^2 \bar{\sigma}\, \varphi^2$$

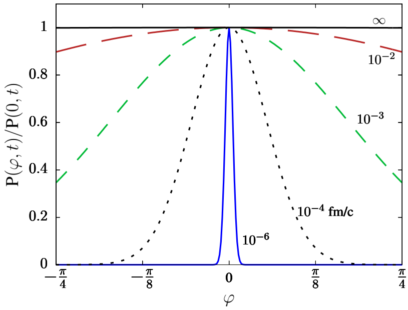
For a field $\varphi(t)$ which is uniform in space in a volume V the problem reduces to a damped stochastic harmonic oscillator whose solution was found by Chandrasekhar in 1943. This results in the distribution

$$P(\varphi, t) = \left[\frac{f_\pi m_\pi^2 \bar{\sigma} V}{2\pi T w(t)}\right]^{1/2} \exp\left[-\frac{f_\pi m_\pi^2 \bar{\sigma}}{2T} \frac{(\varphi - \bar{\varphi}(t))^2}{w(t)} V\right]$$

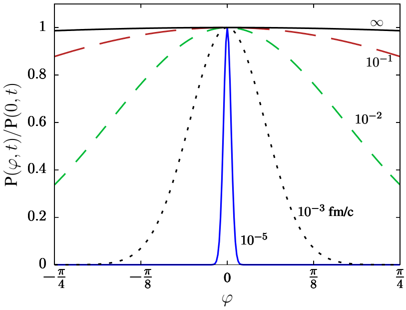
Here $\bar{\varphi}(t)$ is the solution in the absence of noise and $w(t)$ is a width known in terms of the other parameters.

Probability evolution

$$\varphi = \theta - \pi/4$$



$T = 190$ MeV, $V = 10$ fm^3



$T = 190$ MeV, $V = 100$ fm^3

Causal volumes

T_1(MeV)	τ_1(fm/c)	$\bar{\sigma}_l(T_1)/\sigma(0)$	T_2(MeV)	τ_2(fm/c)	$\bar{\sigma}_l(T_2)/\sigma(0)$	V_c(fm^3)
240	5.81	0.01258	180	9.44	0.06818	47.89
220	6.82	0.01730	180	9.44	0.06818	16.61
200	8.01	0.02769	180	9.44	0.06818	2.49
240	5.81	0.01258	170	10.26	0.1802	91.97
220	6.82	0.01730	170	10.26	0.1802	39.21
200	8.01	0.02769	170	10.26	0.1802	10.12
240	5.81	0.01258	160	11.17	0.3932	167.70
220	6.82	0.01730	160	11.17	0.3932	82.74
200	8.01	0.02769	160	11.17	0.3932	29.27

Estimate of causal volumes from P. Castorini and H. Satz, Int. J. Mod. Phys. E **23**, No. 04, 1450019 (2014).

Summary

• ALICE has measured isospin correlations in the kaon sector which are anomalously large.

• These measurements cannot be explained by any known means without invoking kaon condensation (least likely), Disoriented Chiral Condensates (less likely), or Disoriented Isospin Condensates (most likely).

• DCC involve disorientation in the strange quark sector while DIC involve disorientation in the light quark sector.

• It would be illuminating to see similar measurements at $\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb collisions at LHC and at $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at RHIC. More differential measurement in rapidities and azimuthal angles are needed.

• Can lattice QCD contribute?

• Are we seeing the melting and refreezing of the QCD vacuum?

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