Lifetime of the η' meson at low temperature

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Outline

Symmetries of QCD

$$\mathcal{L}_{QCD} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a + \bar{q}[iD_\mu \gamma^\mu - \mathcal{M}]q$$

- gluon field-strength tensor $F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g f_{abc} A^b_\mu A^c_\nu$
- covariant derivative $D_\mu = \partial_\mu - igA^a_\mu \lambda_a/2$
- six dimensional column vector $q_{i,A}$ where $i = 1, .., 6$ and $A = 1, 2, 3$
- quark mass matrix $\mathcal{M} = \mathrm{diag}(m_u, m_d, m_s, m_c, m_b, m_t)$

In the approximation $m_u = m_d = m_s = 0$ the QCD Lagrangian gains the chiral symmetry:

$$U(3)_V \times U(3)_A \simeq SU(3)_V \times SU(3)_A \times U(1)_V \times U(1)_A$$

SSB and anomalous symmetry

The ground state is only symmetric w.r.t. $SU(3)_V \times U(1)_V$

- $U(1)_V$: baryon number conservation
- $SU(3)_V$: flavor multiplets

The spontaneous breaking of the $SU(3)_A$ symmetry gives rise to 8 Goldstone bosons:

$$3\pi_s, 4K_s, \eta$$

- $U(1)_A$ is anomalous *i.e.* is not symmetry of quantized theory

The Noether current corresponding to the $U(1)_A$ symmetry $J_5^\mu = \bar{q}\gamma^\mu\gamma_5 q$ is not conserved:

$$\partial_\mu J_5^\mu = \frac{N_f g^2}{16\pi^2} F^a_{\mu\nu}\tilde{F}_a^{\mu\nu}$$

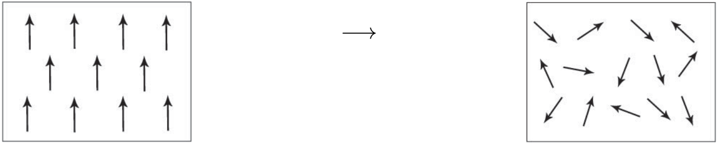
where $\tilde{F}_a^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\lambda\rho}F_{a\lambda\rho}$ is the dual field-strength tensor.

If there was no anomaly, the $U(1)_A$ symmetry would also be spontaneously broken and the η' would be the 9th Goldstone boson

Phase transition → Change in symmetry

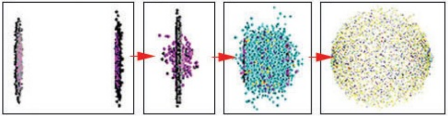
An example: the spin model of a ferromagnet

$T < T_c$ $\longrightarrow$ $T > T_c$



$\langle M \rangle \neq 0$ $\qquad$ $\langle M \rangle = 0$

In heavy-ion collisions → new state of matter: Quark-Gluon Plasma



- production of *fireballs* ($\tau_{fb} \approx 10$ fm/c)
- deconfinement transition around $T_c \approx 160$ MeV

Chiral symmetry restoration

Lattice QCD studies indicate that at $T_c \approx 160$ MeV the order parameter $\langle q\bar{q}\rangle \to 0$

- the chiral symmetry should be restored
- chiral multiplets (L,R) should replace flavor multiplets

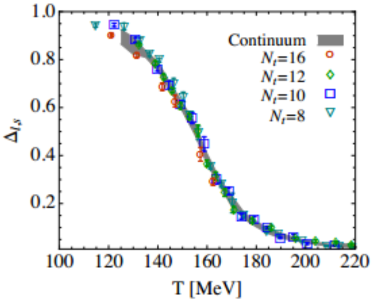


figure from Borsanyi et al.,
Nucl.Phys.A904-905:270c (2013)

What about the $U(1)_A$ anomaly?

$\to$ deduce information from the behaviour of the η'

$\eta' \longleftrightarrow U(1)_A$

Determine temperature dependence of:

- mass of η':

  a light η' might imply effective restoration of $U(1)_A$
- mixing of η' and η

  (Tytgat et al.)
- decay constant of η'
- lifetime of η'

Low-temperature calculations $\rightarrow$ thermal medium $\approx$ gas of pions

-Can we see the effect of the medium on the η'?

$\rightarrow$ Compare: in-medium lifetime of the η' with lifetime of a *fireball* ($\tau_{\eta'}^{vac} \approx 600\ \tau_{fb}$)

Width increase in a thermal medium

The width Γ of a particle with finite lifetime can be derived from its self-energy:

$$m\Gamma = -\mathrm{Im}\,\Pi(m^2)$$

We want to calculate the in-medium width of the η'

- Every medium particle has thermal energy according to the Bose-Einstein distribution $n_B(E_p) = \frac{1}{e^{E_p/T}-1}$

The collisional broadening is the main contribution to the in-medium width:

$$\Gamma_{coll} = \int \frac{\mathrm{d}^3 p}{(2\pi)^3} n_B(E_p) \frac{|\bar{p}|}{E_p} \sum_i \sigma_i(E_p)$$

where we need to sum over all the inelastic cross sections involving an η' and any type of pion in the initial state.

Relevant processes

We consider two types of interactions that contribute to collisional broadening:

$$\eta'\pi \to \eta\pi$$

$$\eta'\pi \to \bar{K}K$$

where

$$\pi = \begin{pmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{pmatrix} \quad K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix} \quad \bar{K} = \begin{pmatrix} \bar{K}^0 \\ K^- \end{pmatrix}$$

Large-N_c limit

In the large-N_c limit, the divergence of the axial current vanishes:

$$\partial_\mu J_5^\mu = \frac{1}{N_c} \frac{N_f \lambda}{16\pi^2} F^a_{\mu\nu} \tilde{F}_a^{\mu\nu}$$

since $\lambda = N_c g^2 = const$ for $N_c \to \infty$.

$\to$ The η' formally becomes the 9th Goldstone boson

In the combined chiral and large-N_c limit there are 9 light pseudoscalars

Why Resonance Chiral Theory?

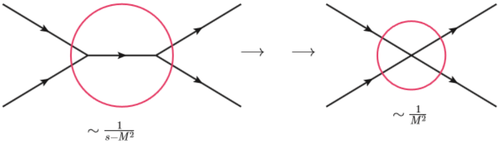
When the energy of the process is of the order of the resonance mass...

- resonance effects must be taken into account

$\rightarrow$ Resonance Chiral Theory (*RChT*)

(Ecker/Gasser/Pich/de Rafael, Nucl.Phys. B321, 311 (1989))

- no systematic effective field theory, but:
  - correct low-energy, large-N_c limit
  - better high-energy behaviour



$$RChT \xrightarrow{low-energy\ lim} ChPT$$

How to include resonances

Ingredients:

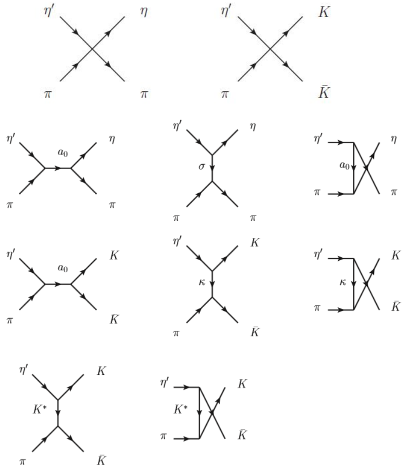
- nonet field S which contains the lowest-lying scalar resonances ($J^{PC} = 0^{++}$)

$$S = \begin{pmatrix} \frac{a_0^0}{\sqrt{2}} + \frac{\sigma}{\sqrt{2}} & a_0^+ & \kappa^+ \\ a_0^- & -\frac{a_0^0}{\sqrt{2}} + \frac{\sigma}{\sqrt{2}} & \kappa^0 \\ \kappa^- & \bar{\kappa}^0 & f_{0s} \end{pmatrix}$$

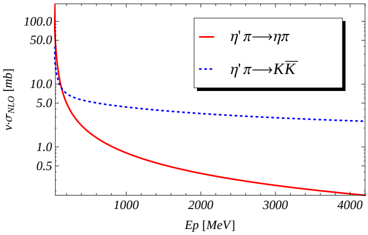
- nonet field V which contains the lowest-lying vector resonances ($J^{PC} = 1^{--}$)

$$V_{\mu\nu} = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_{\mu\nu}$$

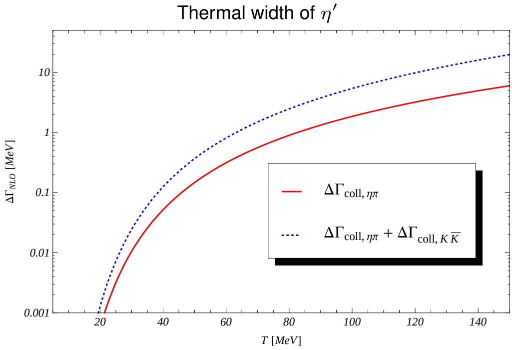
RChT diagrams



→ small cross section for large E_p



RChT results

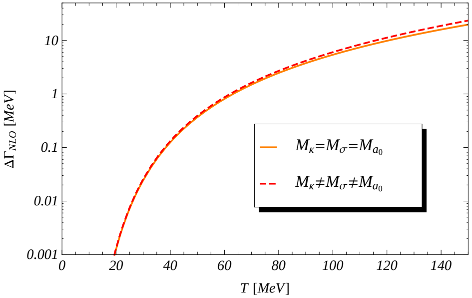


sizeable width increase, $\approx$ 10 MeV at $T \approx$ 120 MeV

(vacuum width $\approx$ 200 keV)

-importance of $K\bar{K}$ final state

Mass modification



- modify propagators

for each resonance use the correspondent mass

$$\frac{1}{t,u - M_{a_0}^2} \to \frac{M_{\kappa,\sigma}^2}{M_{a_0}^2\,(t,u - M_{\kappa,\sigma}^2)}$$

Good agreement between the width increase obtained using:

- the same mass (M_{a_0}) for all scalar resonances
- three different masses for κ, σ, a_0 resonances

Conclusion

Even if approximating the medium by a pion gas does not work close to T_c

- for $T < T_c$ we can trust our results $\rightarrow$ look for the onset of changes at low T

Around $T \approx 120$ MeV we have $\Delta\Gamma \approx 10$ MeV
$\rightarrow$ comparable with $1/\tau_{fb}$

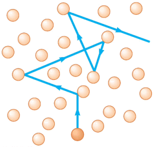
$\rightarrow$ Future studies on the η' in the framework of heavy-ion collisions are possible

Thank you!

Collisional broadening

From classical kinetic theory:

-probe that travels with velocity v in a medium
-mean free path λ
-cross section σ for the probe to interact with a medium particle
-medium made of bosonic gas
$\rightarrow$ density of the medium particles $n = \int \frac{\mathrm{d}^3 p}{(2\pi)^3} n_B(E_p)$



We have:
lifetime of the probe $\tau_p = \frac{\lambda}{v} = \frac{1}{n\sigma v} \longrightarrow$ in-medium width $\Gamma = n\langle\sigma v\rangle$

Average for some observable $\mathcal{O}$:

$$\langle\mathcal{O}\rangle = \frac{\int \frac{\mathrm{d}^3 p}{(2\pi)^3} \mathcal{O} n_B(E_p)}{\int \frac{\mathrm{d}^3 p}{(2\pi)^3} n_B(E_p)} = \frac{1}{n} \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \mathcal{O} n_B(E_p)$$

$\rightarrow$ Average of the probe's in-medium width:

$$\Gamma_{coll} = \int \frac{\mathrm{d}^3 p}{(2\pi)^3} v\sigma(E_p) n_B(E_p)$$

Note: the same result can be obtained using field theory

The phase diagram of strongly interacting matter