Fate of meson states and broken symmetries at high temperature

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Lattice QCD simulations on physical point* show:

- J/ψ and η_c stable beyond phase transition temperature (T_c) RPD91 (2015) 5,054503
- Other mesons with up/down, strange and charmed flavors modified at T_c
- Chiral symmetries restored at T_c, whereas $U_A(1)$ not at T_c

Abstract

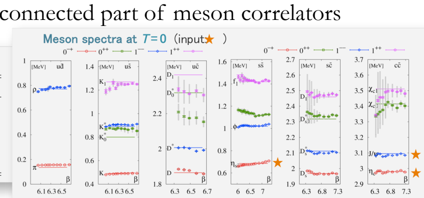
Thermal modifications of meson states and restorations of broken symmetries are studied from spatial correlation functions in (2+1)-flavor lattice QCD. We focus on the meson correlation functions which consist of up/down, strange and charmed flavors and show a direct signal of thermal modifications of meson spectral functions and degeneracies of parity-partner meson states. Results of lattice QCD simulations are shown above. Moreover we find that a modification pattern of π, K and D mesons is very similar below T_c, whereas a clear flavor dependence appears above T_c. The broken $U_A(1)$ symmetry is effectively restored only above $1.6T_c$.

*Lattice setup

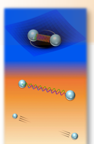
- (2+1)-flavor QCD with Highly Improved Staggered Quarks action
- m_s : physical, $m_l/m_s = 1/20$ ($m_\pi \sim 160$ MeV), charm quenched
- $N_\tau = 8, 10, 12$ keeping $N_s/N_\tau = 4$ → Continuum limit
- Calculating quark-line connected part of meson correlators

Mesons contents

Γ	J^P	$u\bar{d}$	$u\bar{s}$	$u\bar{c}$	$s\bar{s}$	$s\bar{c}$	$c\bar{c}$
γ_5	0^-	π	K	D	$(\eta_{s\bar{s}})$	D_s	η_c
1	0^+	–	K_0^*	D_0^*	–	D_{s0}^*	χ_{c0}
γ_i	1^-	ρ	K^*	D^*	ϕ	D_s^*	J/ψ
$\gamma_i\gamma_5$	1^+	–	K_1	D_1	$f_1(1420)$	D_{s1}	χ_{c1}



Thermal fluctuation in QCD causes:



Modifications of hadrons

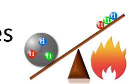
sequential melting of quarkonium and open-flavors

e.g.) J/ψ suppression Matsui and Satz (1986)

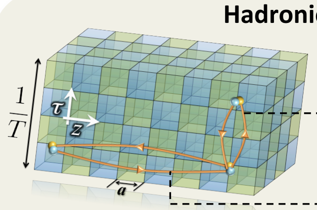
Restorations of broken symmetries

restored pattern of chiral and $U_A(1)$ symmetries

the nature of phase transition Pisarski and Wilczek (1984)



Hadronic excitation on lattice at finite temperature



Temporal correlation function can describe ground state at large τ:

$$G^T(\tau,T) = \int d^3x \langle J_H^\dagger(0,\mathbf{0}) J_H(\tau,\mathbf{x})\rangle \xrightarrow{\tau\to\infty} Ae^{-m_0\tau}$$

...difficult due to the limitation $\tau < T$

Spatial correlation function characterizes *screening mass* $M(T)$ and has no limitation to spatial direction:

$$G^S(z,T) = \int_0^{1/T} d\tau \int dxdy \langle J_H^\dagger(0,\mathbf{0}) J_H(\tau,\mathbf{x})\rangle \xrightarrow{z\to\infty} Ae^{-M(T)z}$$

...more sensitive to in-medium modification

Limiting case: at low T, bound state $M(T) \sim m_0$, whereas at $T \to \infty$, free quark-antiquark pair: $M(T) = \sqrt{m_q^2 + (\pi T)^2}$

Modifications of meson states

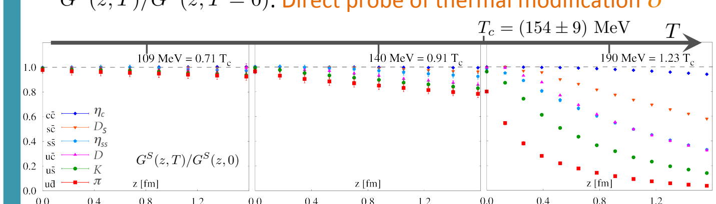
Spectral function σ can describe modification of meson states:

$$G^T(\tau,T) = \int_0^\infty d\omega \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)} \sigma(\omega,T) \quad \text{e.g.) MEM}$$

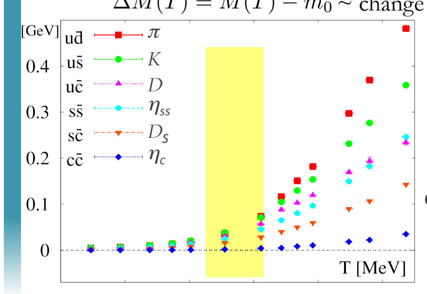
$$G^S(z,T) = \int_0^\infty \frac{2d\omega}{\omega} \int_{-\infty}^\infty dp_z e^{ip_z z} \sigma(\omega,p_z,T)$$

NO T dependence in Kernel:

$G^S(z,T)/G^S(z,T=0)$: Direct probe of thermal modification σ



$\Delta M(T) = M(T) - m_0 \sim$ change of "binding energy"



$c\bar{c}$: stable beyond T_c PRD91 (2015) 5, 054503

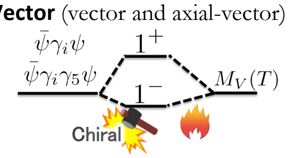
$s\bar{s}$, $s\bar{c}$: slight modified below T_c

$u\bar{d}$, $u\bar{s}$, $u\bar{c}$: explicitly modified below T_c, similar pattern at $T < T_c$, flavor dependence at $T > T_c$

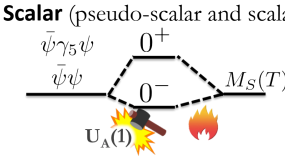
Restorations of broken symmetries

Parity partners of mesons are split due to broken symmetries:

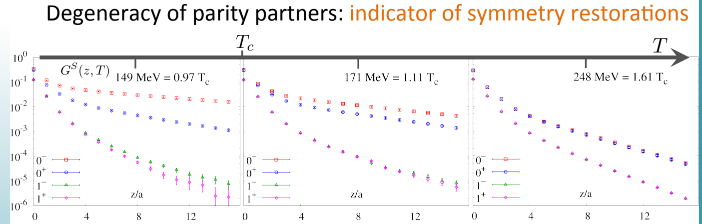
Vector (vector and axial-vector)



Scalar (pseudo-scalar and scalar)



Degeneracy of parity partners: indicator of symmetry restorations



Degeneracies appear: at $T \sim 1.0T_c$--$1.1T_c$ for vector partner, at $T \sim 1.4T_c$--$1.6T_c$ for scalar partner

At T_c, chiral: restored, $U_A(1)$: broken even in continuum limit