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The mass spectroscopy of dark matter in $SU(3)$ hidden color

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We consider the mass spectroscopy of dark matter in the dark hadron model. In the dynamical chiral symmetry breaking in the $SU(3)$ hidden color gauge sector, there exist Nambu-Goldstone bosons which are massive because the hidden sector fermions break explicitly chiral symmetry. Therefore, these bosons are dark matter candidates. We study $SU(3)$ hidden color interaction and $SU(3)$ hidden flavor symmetry, which can be broken into $SU(2)_V \times U(1)$. We present the mass spectroscopy of dark matter by lattice QCD simulations with Wilson fermions and truncated overlap fermions based on domain wall fermions. Truncated overlap fermions satisfy lattice chiral symmetry instead of the chiral symmetry in continuum field theory.

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PoS(TAUP2023)336

1. Introduction

The Higgs boson was the last element predicted in the standard model (SM), and its discovery was essential in confirming parts of the SM. However, the origin of mass is the most critical question still unsolved. Based on the results of recent high-energy experiments, the measured Higgs mass and top quark mass are such that the SM remains perturbative below the Planck scale [1–4]. On the other hand, many physical data support the existence of a substantial amount of dark matter [5]. A model is considered that (pseudo) Nambu-Goldstone bosons are candidates for the dark matter as one of beyond SM models. They aim to introduce a QCD-like hidden sector connected to the SM sector by a real singlet scalar S. This needs to be verified in a non-perturbative manner, as the nature of dynamical chiral symmetry breaking in the hidden sector is essential. In particular, we investigate the production of dark hadrons due to the chiral symmetry breaking in hidden QCD.

In the lattice QCD, the Wilson fermion is a basic action but cannot satisfy the chiral symmetry from the lattice gauge theory. The chiral symmetry is critical for investigating physical phenomena involving light quarks. In such cases, lattice QCD calculations use lattice chiral symmetry-satisfying methods such as domain wall fermions [6, 7]. The lattice chiral symmetry is the chiral symmetry in lattice gauge theory, which is theoretically equivalent to the chiral symmetry if a lattice spacing a, a parameter of the lattice gauge theory, is close to zero.

We test the dark matter model by hidden QCD sectors by predicting the masses of the ρ and a_1 mesons by lattice QCD simulations with Wilson fermions and truncated overlap fermions (TOFs) [8]. TOFs are derived from domain wall fermions.

2. The model

We adopt a scale extension of the SM [4, 9] with a combined breaking of conformal and electroweak symmetry breaking in a hidden color $SU(3)$ interaction with $SU(3)$ flavor hidden fermions (dark quarks) that can explain the origin of mass for dark matter. Ametani's original model treats the hidden color sector from the effective theory. We assume Ametani's model but treat the hidden color sector using lattice QCD. Our model comprises a hidden $SU(3)_{HC}$ gauge sector coupled via a real singlet scalar S to the SM. The interaction part of Lagrangian for the hidden color sector is written as

$$L_{int} = \mathrm{Tr}\, \bar{\psi} \left(g_{HC}\, \gamma^\mu G_\mu \ + g' Q \gamma^\mu B_\mu - yS \right) \psi, \tag{1}$$

where G_μ is the gauge field for the hidden $SU(3)_{HC}$ color, g_{HC} is the gauge coupling for them, B_μ is the $U(1)_Y$ gauge field, g' is the gauge coupling corresponding to them, Q is the hyper charge, y is the Yukawa coupling, and the Dirac fermions ψ_i $(i = 1, 2, 3)$ in the hidden sector belong to the fundamental representation of $SU(3)_{HC}$. The trace in (1) is taken over the flavor and the color indices. We call ψ_i a dark quark. Therefore, the dark matter (dark hadron) consists of dark quarks. While some models consider dark glueballs [5] as the lightest dark hadrons, we consider dark mesons because the σ meson is the lightest composite state rather than glueballs in hadron physics.

Pseudo Nambu-Goldstone bosons that arise due to dynamical chiral symmetry breaking are dark matter candidates. We explore one possibility of Yukawa coupling constants that make the hidden chiral symmetry $SU(3)_L \times SU(3)_R$ dynamically break to its diagonal subgroup $SU(2)_V \times SU(1)$.

In the mesons of QCD, the chiral partner of the π meson is the σ meson (iso scalar-scalar). Also, the chiral partner of the ρ meson is the axial vector meson a_1. As with hadrons for QCD, there are the dark chiral partners of ($\tilde{\pi}$ and $\tilde{\sigma}$) and ($\tilde{\rho}$ and $\tilde{a_1}$) in the case of hidden color. We use lattice QCD results to estimate the masses of the dark chiral partners in a hidden color $SU(3)_{HC}$.

3. Strategy

In previous works by our group, we know that in the case of lattice full QCD using the Wilson fermions, there are the following relationships between the mass of the π meson and the masses of the ρ and σ mesons [10]:

$$m_\rho a = 0.3767(m_\pi a)^2 + 0.8099 , \tag{2}$$
$$m_\sigma a = 1.6818(m_\pi a)^2 + 0.3219 , \tag{3}$$

where a is a lattice spacing. The lattice calculation is employed by a lattice size $8^3 \times 16$ and a lattice coupling $\beta = 4.8$, corresponding to a lattice spacing $a = 0.207(9)$ fm. In addition, we calculated the mass ratio of the π meson to the ρ and a_1 mesons by the quenched lattice QCD simulations using TOFs with the lattice chiral symmetry [11]:

$$m_\rho a = 0.466(m_\pi a)^2 + 0.743 , \tag{4}$$
$$m_{a_1} a = 0.561(m_\pi a)^2 + 1.146 . \tag{5}$$

The lattice calculation is employed by a lattice size $8^3 \times 24$ with plaquette gauge action and a lattice coupling $\beta = 5.7$. The fermion parameters for the TOF were set to $N_5 = 32$, $M_5 = 1.65$. Taking the limit in these expressions where the mass of the π meson is zero, we obtain the following ratios of meson masses:

$$\frac{m_\sigma}{m_\rho} = 0.3975 , \quad \frac{m_{a_1}}{m_\rho} = 1.542 . \tag{6}$$

The π meson has a current quark mass derived from the Higgs boson and a mass derived from the vacuum expectation value due to quark-antiquark condensation. We use the meson mass ratios to obtain mass spectrums of the dark mesons in the hidden color $SU(3)$ case.

4. Result and discussion

Ametani's phenomenological analysis of their model Ref. [4] roughly constrains the range of masses of dark $\tilde{\pi}$ meson. We chose 150 GeV from their analysis. We regard the hidden color energy scale as a scaled-up version of the QCD. Experimental values are used for $m_\pi = 140$ MeV and $m_\rho = 770$ MeV. Assuming,

$$m_{\tilde{\rho}} = \frac{m_\rho}{m_\pi} m_{\tilde{\pi}} = 5.5 \times 150 \text{ GeV} \sim 0.83 \text{ TeV} , \tag{7}$$

we can obtain $m_{\tilde{\sigma}}$ and $m_{\tilde{a}_1}$ using our results of lattice QCD simulations,

$$m_{\tilde{\sigma}} = 0.83 \text{ TeV} \times 0.3975 \sim 0.33 \text{ TeV} , \tag{8}$$
$$m_{\tilde{a}_1} = 0.83 \text{ TeV} \times 1.542 \sim 1.3 \text{ TeV} . \tag{9}$$

We discussed the possibility of dark matter by calculating the mass of mesons from the lattice QCD simulations. We plan to calculate m_π, m_ρ, m_σ and m_{a_1} by a lattice full QCD simulation using the TOF. Since our model considers $SU(2)_V$ symmetry, the dark $\tilde{\pi}$ meson is a candidate for dark matter. Also, assuming that the result of the $1/N$ expansion for QCD is correct, where N is the number of the hidden color, the $\tilde{\sigma}$ in the hidden $SU(2)$ color case can be lighter than the $\tilde{\pi}$ [12]. On the other hand, in the $N > 3$ case, the lightest dark matter would be $\tilde{\pi}$. In the $N = 3$ case, $\tilde{\sigma}$ can decay to $2\tilde{\pi}$ just barely, so $\tilde{\pi}$ would be the lightest dark matter. We will calculate the mass of the σ meson by the full lattice QCD simulations using TOF with the lattice chiral symmetry. We will also perform a phenomenological analysis of dark mesons [12].

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PoS(TAUP2023)336