Turbulent meson condensation in quark deconfinement†

K. Hashimoto,*1,*2 S. Kinoshita,*3 K. Murata,*4 and T. Oka*5

Quark confinement is one of the most fundamental and challenging problems in elementary particle physics, left unsolved. Although quantum chromodynamics (QCD) is the fundamental field theory describing quarks and gluons, their clear understanding is limited to the deconfined phase at high energy or high temperature limits due to the asymptotic freedom. We may benefit from employing a more natural description of the zero temperature hadron vacuum. A dual viewpoint of quark confinement in terms of the "fundamental" degrees of freedom at zero temperature - mesons, is a plausible option.

The mesons appear in families: they are categorized by their spin/flavor quantum numbers, as well as a resonant excitation level n giving a resonance tower such as $\rho(770), \rho(1450), \rho(1700), \rho(1900), \cdots$. In this Letter we find a novel behavior of the higher meson resonances, *i.e.*, mesons with large n. In the confined phase, when the deconfined phase is approached, we observe *condensation of higher mesons*. In this state, macroscopic number of the higher meson resonances, with a characteristic distribution, are excited. The condensed mesons have the same quantum number as the vacuum. The analysis is done via the anti-de Sitter space (AdS)/conformal field theory (CFT) correspondence, one of the most reliable tools to study strongly-coupled gauge theories. By shifting our viewpoint from quark-gluon to meson degrees of freedom, we gain a simple and universal understanding of the confinement/deconfinement transition, with a bonus of solving mysteries in black holes physics through the AdS/CFT.

The system we study is the $\mathcal{N} = 2$ supersymmetric $SU(N_c)$ QCD which allows the simplest AdS/CFT treatment. The deconfinement transition is induced by external electric fields. In static fields, the confined phase becomes unstable in electric fields stronger than the Schwinger limit $E = E_{\mathrm{Sch}}$ beyond which quarks are liberated from the confining force. We find that this instability is accompanied by the condensation of higher mesons. A striking feature is revealed for the case of an electric field quench: The kick from the quench triggers a domino-like energy transfer from low to high resonant meson modes. This leads to a dynamical deconfinement transition$^{1)}$ even below the Schwinger limit. The transfer we find resembles that of turbulence in classical hydrodynamics as higher modes participate; thus we call it a "turbulent meson condensation" and suggest it being responsible for deconfinement. See Fig.1.

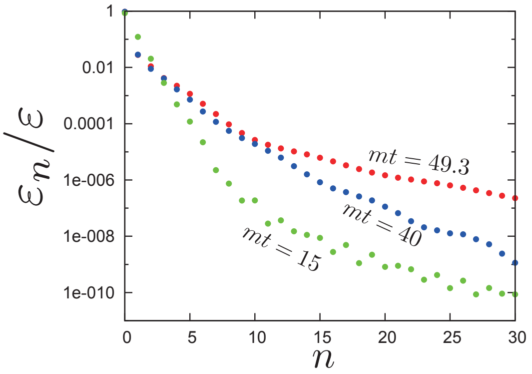

Fig. 1. Turbulent behavior of mesons toward deconfinement. The horizontal axis is the meson resonance level n, and the vertical axis is the meson energy. m is the quark mass, and t is time measured after the electric field quench. It shows a power-law behavior turned from an exponential behavior, which is a turbulence.

We remind that the $\mathcal{N} = 2$ theory is a toy model: The meson sector is confined and has a discrete spectrum while the gluon sector is conformal and is always deconfined. Here, we concentrate on the deconfinement of heavy quarks and not the gluons. Note that the mesons with low spins in this theory are described by a confining potential and an effective QCD string exists, whereby we define our "quark confinement".

The higher meson resonances are naturally interpreted as long QCD strings, therefore our finding is consistent with interpreting deconfinement as condensation of QCD strings$^{2)}$. Under the condensation, a quark can propagate away from its partner antiquark by reconnecting the bond QCD string with the background condensed strings. The gravity dual of the deconfined phase is with a black hole, so given the relation with long fundamental strings, our result may shed light on the issue of quantum black holes; In particular, our time-dependent analysis gives a singularity formation on the flavor D-brane in AdS, a probe-brane version of the Bizon-Rostworowski turbulent instability in AdS geometries$^{3)}$.

References

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*1 RIKEN Nishina Center

*2 Department of Physics, Osaka University

*3 Osaka City University Advanced Mathematical Institute

*4 Keio University

*5 Department of Applied Physics, University of Tokyo