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On chiral symmetry breaking, topology and confinement

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Abstract

We start with the relation between the chiral symmetry breaking and gauge field topology. New lattice results further enhance the notion of Zero Mode Zone, a very narrow strip of states with quasizero Dirac eigenvalues. Then we move to the issue of "origin of mass" and Brown–Rho scaling: a number of empirical facts contradicts to the idea that masses of quarks and such hadrons as ρ, N decrease near T_c. We argue that while at $T = 0$ the main contribution to the effective quark mass is chirally odd $m_{\not\chi}$, near T_c it rotates to chirally-even component m_χ, because "infinite clusters" of topological solitons gets split into finite ones. Recent progress in understanding of topology require introduction of nonzero holonomy $\langle A_0 \rangle \neq 0$, which splits instantons into N_c (anti)selfdual "instanton–dyons". Qualitative progress, as well as first numerical studies of the dyon ensemble are reported. New connections between chiral symmetry breaking and confinement are recently understood, since instanton–dyons generate holonomy potential with a minimum at confining value, if the ensemble is dense enough.

1. Introduction

Like other authors of this volume, I am much indebted to Gerry Brown. His decision to make me his successor, as a leader of Stony Brook Nuclear Theory, was obviously the highest honor of my life. Twenty years of nearly daily discussion with Gerry about physics, life and life in physics have not resulted in many common papers. Yet those thousands of hours were invaluable, especially for me, after another twenty plus years in a relative solitude in Novosibirsk. Layers upon layers of knowledge came from Gerry, on science, scientists and life, with good share of his characteristic jokes.

It was not easy to select the topic for this article. Gerry was seriously excited a decade ago, while – induced by strongly coupled QGP – Ismail Zahed and myself returned to the fate of

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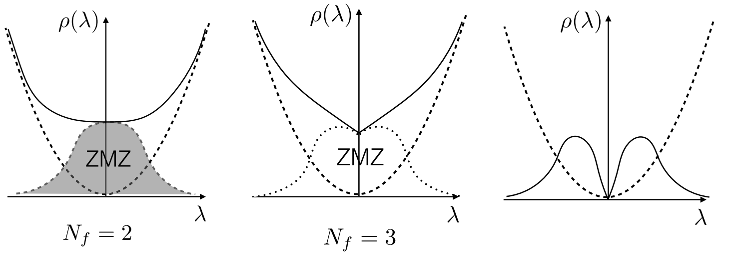

Fig. 1. The density of Dirac eigenvalues for $N_f = 2$ (left), $N_f = 3$ (middle) and in the critical case of restoring chiral symmetry (right).

the Coulomb bound states at the coupling approaching or exceeding the critical value: a subject close to his heart from large-Z atoms and Birmingham days. While progress since then include strongly coupled quarkonia in AdS/CFT and observations of supercritical resonances in graphene, theoretically this problem remains basically unsolved. On the other hand, progress in fields I was mostly involved lately – hydrodynamical description of higher flow harmonics in heavy ion collisions, or of the "explosive" high multiplicity pA and even pp – would not be so exciting to Gerry. So I decided to return to the core issues of our science – chiral symmetry breaking, confinement and gauge topology. Slow but steady progress is there, not much known outside of a narrow circle. It would interest Gerry for sure.

2. The chiral symmetry breaking and the zero mode zone

One way to describe this phenomenon – a "3-d manybody" one – goes back to Nambu–Jona-Lasinio (NJL) paper based on an analogy to the BCS theory of superconductivity. A 4-fermion attraction at soft momenta $|k| < \Lambda$, if strong enough, leads to a nonzero quark condensate and a gap, at the surface of the Dirac sea.

Another approach – a "4-dimensional single body" one – is simpler to explain and to work with, in Euclidean setting. Dirac eigenvalues can be defined for any gauge fields configuration $\not{D}\psi_\lambda = \lambda\psi_\lambda$ and those may have finite or zero density of states $\rho(\lambda)$ at $\lambda \to 0$. The former case breaks the chiral symmetry, and the condensate is just proportional to $\rho(\lambda = 0) \neq 0$ [1]. The alternative case $\rho(0) = 0$ is chirally symmetric. This is reminiscent to the density of states at the Fermi surface: if nonzero it definds a conductivity and many other properties of a *conductor*, if zero it makes it an insulator. In Fig. 1 we sketch the shapes of such density of states,[1] for $N_f = 2$ (left) and $N_f = 3$ (middle). The right picture corresponds to the critical case, when $\rho(0)$ vanishes and the chiral symmetry is being restored. At $T > T_c$ there appears a finite gap around $\lambda = 0$, like in an insulator.

The idea that only a tiny subset of states near the Fermi surface dominates the physics is one of the pillars of 20-th century condense matter theory. Similar fundamental concept is the *zero mode zone* (ZMZ) introduced in the context of the instanton liquid model (ILM) [2]. The topological index theorems demand a connection between the topological charge of the gauge fields and the number of *exactly zero* eigenvalues. Thus a collection of well-separated instantons and anti-instantons produce many $\lambda = 0$ states, if interactions are neglected. If those are included,

[1] Note that for brevity we do not discuss finite-size effects, assuming macroscopic limit $V \to \infty$ is already taken. Note also that for $N_f > 2$ there exists the so called *Stern–Smilga cusp* $(\rho(\lambda) - \rho(0)) \sim (N_f^2 - 4)|\lambda|$ in the middle.