

REVIVAL OF NON-ABELIAN MONOPOLES AND CONFINEMENT IN QCD

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Dedicated to Jan Kwieciński in honour of his 65th birthday

Central role played by certain non-Abelian monopoles (of Goddard–Nuyts–Olive–Weinberg type) in the infrared dynamics in many confining vacua of softly broken $\mathcal{N} = 2$ supersymmetric gauge theories, has recently been clarified. We discuss here the main lessons to be learned from these studies for the confinement mechanism in QCD.

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1. Introduction

Non-Abelian monopoles in spontaneously broken gauge theories have remained a rather obscure object for some time now. Apart from the often discussed applications in conformally invariant $\mathcal{N} = 4$ theories few field theory models were known where such objects play an important role. A class of $\mathcal{N} = 1$ theories exhibit well-known Seiberg's duality; the origin of the "dual quarks" however remains somewhat mysterious.

Recent series of work on softly broken $\mathcal{N} = 2$ gauge theories based on gauge groups $SU(n_c)$, $USp(2n_c)$ and $SO(n_c)$ and with various numbers of flavors, has changed the situation considerably [1]. It turns out that certain "dual quarks" appearing as the low-energy effective degrees of freedom and carrying various non-Abelian charges, have the right properties of the "semi-classical" non-Abelian monopoles studied earlier, most notably by Goddard, Nuyts, Olive and by Weinberg [2].

For example, in softly broken $\mathcal{N} = 2$ $SU(n_c)$ theories with n_f flavors, confining vacua are labeled by an integer r , $r = 0, 1, \dots, [\frac{n_f}{2}]$, which have low-energy effective $SU(r) \times U(1)^{n_c-r}$ gauge theory description. The infrared degrees of freedom contain "dual quarks" carrying charges in the fundamental representation of the effective $SU(r)$ gauge group, as well as in the

fundamental representation of the flavor $SU(n_f)$ group. They carry also a common Abelian charge with respect to one of the $U(1)$ factors.

These are precisely the properties expected for the Goddard–Nuyts–Olive–Weinberg monopoles, becoming light due to quantum effects, as has been shown recently [3]. One crucial lesson is that quantum behavior of non-Abelian monopoles depends on the massless flavors in the original theory, in an essential manner.

2. Confinement as non-Abelian dual superconductor

The importance of the above observation lies in the fact that in *most* of the $\mathcal{N} = 1$ vacua, confinement is caused by the condensation of these non-Abelian monopoles. Exceptionally ($r = 0$ or $r = 1$ vacua of $SU(n_c)$ theory) the low-energy theory is an Abelian magnetic gauge theory and confinement is described as a dual Meissner effect, as proposed by 't Hooft for QCD [4]. However, confinement in generic r -vacua is a dual superconductivity of non-Abelian variety.

The fact that such r -vacua appear only for $r < \frac{n_f}{2}$ can be understood as an effect of renormalization: only for these values of r , the low-energy $SU(r)$ gauge group is infrared free, with the monopoles carrying flavor charges of the fundamental quarks. The beta function of the dual, magnetic theory has an opposite sign with respect to that of the electric $SU(n_c)$ theory,

$$b_0^{(\text{dual})} \propto -2r + n_f > 0, \quad b_0 \propto -2n_c + n_f < 0, \quad (1)$$

and this reflects a particular property of $\mathcal{N} = 2$ gauge theory with a small coefficient (2) in front of the color multiplicity in b_0 .

3. Deformed conformal vacua and confinement

For this reason, it is not surprising that the most typical set of vacua in confinement phase in the class of models studied in [1] turn out to be based, rather, on a nontrivial superconformal theory¹. Examples are the $r = \frac{n_f}{2}$ vacua of $SU(n_c)$ theory and *all* of confining vacua of $USp(2n_c)$ and $SO(n_c)$ theories with vanishing bare quark masses. $\mathcal{N} = 1$ perturbation — nonzero adjoint matter mass which triggers dual Higgs mechanism — gives a deformation of such infrared fixed-point theories. Low-energy effective theory contains relatively non-local set of gauge and matter fields carrying non-Abelian charges, and no simple local field theory description is available. This makes the analysis of these vacua a difficult task. A first step to study these cases more closely was undertaken in [5], by considering a concrete

¹ In contrast, the generic r -vacua are trivial — infrared free — superconformal theories.

example of $r = 2$ vacua of softly broken $SU(3)$ gauge theory with four quark flavors. This study indicates that the confinement is a dual (non-Abelian) superconductor, but that the condensation of the monopoles is a strong interaction phenomenon, rather than a (dual) perturbative mechanism as in the $r < \frac{n_f}{2}$ vacua.

4. QCD

What can one learn from these studies in supersymmetric theories about the confinement mechanism in the real-world QCD? Here we know

- (i) that no dynamical Abelianization occurs;
- (ii) that, on the other hand, in QCD with n_f flavor, the original and dual beta functions have the first coefficients ($n_c = 3$, $\tilde{n}_c = 2, 3$)

$$b_0 = -11 n_c + 2 n_f \quad \text{vs} \quad \tilde{b}_0 = -11 \tilde{n}_c + n_f : \quad (2)$$

they have the same sign because of the large coefficient in front of the color multiplicity (*cf.* Eq.(1)).

Barring that higher loops change the situation, this leaves us with the option of strongly-interacting non-Abelian monopoles, somewhat like in the cases discussed in Section 3. Is it possible that non-Abelian monopoles (perhaps certain composite there-of) carrying nontrivial flavor $SU_L(n_f) \times SU_R(n_f)$ quantum numbers condense yielding the global symmetry breaking such as $G_F = SU_L(n_f) \times SU_R(n_f) \Rightarrow SU_V(3)$, observed in Nature? How are 't Hooft's Abelian monopoles related to these non-Abelian monopoles? These are the questions to be studied further.

A more detailed account of these discussions appeared in [6].

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