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FRACTIONAL TOPOLOGICAL CHARGE AND TORONS IN SUPERSYMMETRIC O(3)σ-MODEL AND IN GAUGE THEORIES

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НОВОСИБИРСК

Fractional Topological Charge and Torons
in Supersymmetric O(3)σ-Model
and in Gauge Theories

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ABSTRACT

The new class of self-dual solutions with a fractional topological number in the 2d O(3) σ-model and 4d SUSY gluodynamics (SYM) are considered. The corresponding contribution to fermion condensate $\langle\bar\psi\psi\rangle$ has finite nonzero value.

1. SOME REMARKS ON FRACTIONAL TOPOLOGICAL CHARGE Q AND WHY IT SHOULD BE CONSIDERED

It is well-known that the action is finite for solutions with integer Q only. But this theorem holds for special boundary condition, which corresponds to consideration of the theory on sphere S'^d (the $|x|=\infty$ are identified). Still another boundary conditions can provide the finite action with fractional topological number. So, the only problem is to analyze stability of classical solution. In other words, we have to analyze the small quantum fluctuation around classical background with fractional Q.

The well-known example of self-dual solution with $Q=1/N$ in SU(N) gauge theory is toron [1]. The solution is defined on a hypertorus $T_1\times T_1\times T_1\times T_1$ and has finite action $S=\frac{8\pi^2}{g^2N}$.

The main properties of this solution are following: the fields are defined in a box of sizes L_μ and are smeared over the box $(G_{\mu\nu}\sim L^{-2})$; the solution exists only if the ratios of the sizes L_μ of box satisfy certain relations; the introducing into the theory of fundamental (not adjoint) representation of fields is rather difficult because of special (twisted) boundary condition; the quasi-classical calculations [2] of $\langle\bar\psi\psi\rangle$ in SYM are incorrect because $g(L\to\infty)\to\infty$. So, 't Hooft's solution can be considered only as an illustrative example with fractional charge.

Still, we believe that solutions with a fractional number may play an important role in the theory, but this solutions should be formulated in another way than 't Hooft's solution.

The reasons to consider fractional Q are more clearly seen for supersymmetric theories than for ordinary ones. Indeed, in supersymmetric $O(3)\sigma$-model there are 4 fermion zero modes [3, 4]. This means that instanton transition is always accompanied by emission of 4 fermion fields and so $\langle\bar\psi\psi(x), \langle\bar\psi\psi(0)\rangle \neq 0$ [3, 4]. However, $\langle\bar\psi\psi\rangle_{instanton}=0$ because we have 4 (but not 2) zero modes.

It is obvious that we get $\langle\bar\psi\psi\rangle\neq 0$ for solution with $Q=1/2$, which has 2 zero modes. Corresponding calculations in SYM, based on 't Hooft's toron solution were carried out earlier [2]. The finite (at $L\to\infty$) value $\langle\bar\psi\psi\rangle\sim\Lambda^3$ was obtained. The quasi-classical approximation which was used in [2] is unreliable because $g(L\to\infty)\to\infty$. However, the nonzero $\langle\bar\psi\psi\rangle$ indicates that localized solution with required properties exists.

Our main goal is to formulate the self-dual solution in R^2 (for $O(3)\sigma$-model) and in R^4 (for YM theory) which is characterized by $Q=1/2$. For this purpose let's remind some facts from instanton calculations. Then we present a solution with fractional topological charge and describe some modifications of calculations connected with fractional topological charge.

2. O(3)σ-MODEL. INSTANTON

The action, being formulated in terms of n^a-fields, is equal to:

$$S=\frac{1}{4f}\int d^2x(\partial_\mu n^a)^2;\quad n^a n^a=1;\quad a=1,2,3;\quad \mu=1,2. \tag{1}$$

The constraint $n^a n^a=1$ can be resolved with the help of stereographic projection (Fig. 1)

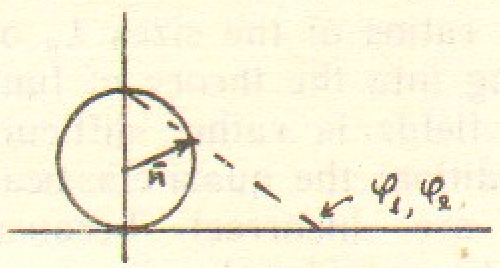


Fig. 1.

$$n_1=\frac{2\varphi_1}{1+\bar\varphi\varphi},\quad n_2=\frac{2\varphi_2}{1+\bar\varphi\varphi}$$
$$n_3=\frac{1-\bar\varphi\varphi}{1+\bar\varphi\varphi},\quad \varphi=\varphi_1+i\varphi_2 \tag{2}$$

Then the action is described by one complex field:

$$S=\frac{1}{f}\int d^2x\,\frac{|\partial_\mu\varphi|^2}{(1+\bar\varphi\varphi)^2}. \tag{3}$$

The self-dual equation and instanton solution in this language takes the form:

$$\frac{\partial}{\partial\bar z}\varphi=0,\qquad \varphi_{inst}=\frac{\rho}{z-a},\qquad z=x_1+ix_2. \tag{4}$$

Here ρ, a are 4 free parameters associated with translational and scale invariance. The instanton in terms of n^a-fields is the hedgehog $n^a\sim r^a$ with the action:

$$S_{inst}=\frac{2}{f}\int d^2x\left|\frac{\partial\varphi}{\partial z}\right|^2\frac{1}{(1+\bar\varphi\varphi)^2}=\frac{2\pi}{f},\qquad Q_{inst}=1. \tag{5}$$

The next step is the calculation of quantum fluctuations in instanton background. It is necessary for this to consider the following form [5, 6]:

$$m^2_{inst}\,q^a=\lambda q^a,$$

$$m^2_{inst}=-(1-\eta^2)\frac{\partial^2}{\partial\eta^2}+2\eta\frac{\partial}{\partial\eta}-\frac{1}{1-\eta^2}\frac{\partial^2}{\partial\alpha^2}-2=L^2-2, \tag{6}$$

$$\eta=\frac{|z|^2-1}{|z|^2+1},\quad \alpha=\mathrm{arctg}\,\frac{x_2}{x_1},\quad -1\leqslant\eta\leqslant 1,\quad 0\leqslant\alpha\leqslant 2\pi.$$

Here $\lambda=l(l+1)-2$, $l=1, 2, 3, \ldots$; $g_l=2(2l+1)$ is multiplicity; η, α are the coordinates of sphere obtained by stereographic projection. The additional condition $q^a n^a_{cl}=0$ must be fulfilled because of constraint $(q^a n^a_{cl})^2=1$. As usually we have to consider the quantum fluctuations in vacuum background as well. In this case we have:

$$m^2_{vac}=L^2,\quad \lambda=l(l+1),\quad g_l=2(2l+1),\quad l=0, 1, \ldots \tag{7}$$

Due to eqs. (6), (7) we have 6 zero modes in instanton field and 2 zero modes in vacuum field. So, there are $4=6-2$ nontrivial zero eigenstates associated with 4 free parameters (4).

Let's note that the contribution of nonzero modes to instanton measure can be easily calculated (with logarithmic accuracy) with the help of ordinary diagram (as it has been made in [7] for gauge theories) and is equal to (Fig. 2):

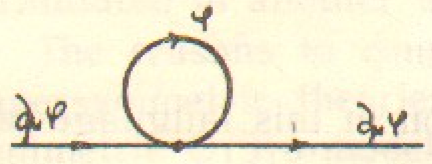


Fig. 2.

$$S_{eff}=\frac{2}{(2\pi)^2}\int\limits_{1}^{M_0^2}\frac{d^2k}{k^2}\,\frac{|\partial_\mu\varphi|^2}{(1+\bar\varphi\varphi)^2}\,d^2x=$$

$$=\frac{\ln M_0^2}{2\pi}\,(S_{cl}\,f)\,. \qquad (8)$$

For instanton $S_{cl}f=2\pi$ so that the contribution of nonzero modes is [5, 6]:

$$e^{-S_{eff}}=e^{-\ln M_0^2}.$$

Therefore, the instanton measure is proportional to [5, 6]:

$$Z_{inst}\sim\underbrace{d^2a\,M_0^2\,d^2\rho\,M_0^2}_{4\ \text{zero modes}}\ \underbrace{e^{-\ln M_0^2\rho^2}}_{\text{nonzero modes}}\ \underbrace{e^{-2\pi/f}}_{\text{classical action}}=\mu^2 d^2a\,\frac{d\rho}{\rho}\,. \qquad (9)$$

The instanton measure for SUSY O(3)σ-model is defined only by zero modes so that [3, 4]

$$Z_{inst}(\mathrm{SUSY})=\underbrace{d^2a\,M_0^2\,d^2\rho\,M_0^2}_{4\ \text{boson z.m}}\ \underbrace{\frac{d^2_{\varepsilon_1}}{M_0}\,\frac{d^2\varepsilon}{M_0}}_{4\ \text{fermion z.m}}\ \underbrace{e^{-2\pi/f}}_{\text{classical action}}\sim\mu^2 d^2a\,d^2\rho\,d^2\varepsilon_1\,d^2\varepsilon_2\,. \qquad (10)$$

Here $\mu^2\sim M_0^2\exp\{-2\pi/f(M_0)\}$ is renorminvariant value. Here ε_1, ε_2 are collective Grassmann coordinates associated with 4 fermion zero modes. The instanton contribution to two-point function does not vanish [3, 4]

$$\langle\bar\psi\psi(x),\bar\psi\psi(0)\rangle\sim\mu^2.$$

In other language (in terms of unconstrained φ-field) the zero modes satisfy equation:

$$\frac{\partial}{\partial\bar z}(\delta\varphi_0)=0\,. \qquad (11)$$

However, the arbitrary analytical function is not yet a zero mode; only the functions also satisfying finitness condition [8]

$$\frac{|\delta\varphi_0|^2}{(1+\bar\varphi\varphi)^2}\bigg|_{z\to a}=\mathrm{const} \qquad (12)$$

are acceptable. There are only two independent analytical functions $\delta\varphi_0\sim(z-a)^{-1}$, $\delta\varphi_0\sim(z-a)^{-2}$, which satisfy these conditions. So, we have 4 real zero modes, as it was expected.

3. THE TORONS IN O(3)σ-MODEL

We admit a more general class of solutions of equation $\frac{\partial}{\partial\bar z}\varphi_{cl}=O(4)$. Namely:

$$\varphi_{toron}=\lim_{\Delta\to 0}\sqrt{\frac{\Delta}{z}}\,,\qquad Q=1/2\,,$$

$$S_{cl}=\frac{2}{f}\int\frac{d^2x}{(1+\bar\varphi\varphi)^2}\left|\frac{\partial\varphi}{\partial z}\right|^2=\frac{\pi\Delta}{f}\int\limits_0^\infty\frac{\rho\,d\rho}{\rho(\Delta+\rho)^2}=\frac{\pi}{f}\,. \qquad (13)$$

Here $\Delta\to 0$ is regulator of fixed points of orbifold (see below). The solution is defined on two Riemann sheets. The physical space is one of them. Note, that the topological charge equal 1/2 is the only stable one under quantum fluctuations; the solutions with another fractional number are unstable.

Let's describe the geometrical features of toron solution. Compactify for this purpose the complex plane z to sphere S_2 (Fig. 3)

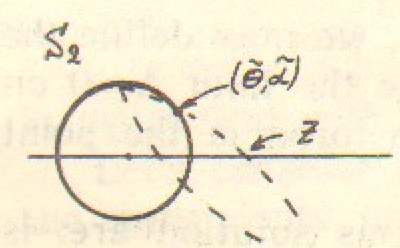
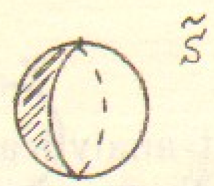


Fig. 3

$$\cos\tilde\theta=\tilde\eta=\frac{1-|z|}{1+|z|}\,,\quad \tilde\alpha=\frac{1}{2}\,\mathrm{arctg}\,\frac{x_2}{x_1}\,. \qquad (14)$$

We make a cut along a line joining O to ∞, open up the sphere, so that it becomes a hemisphere and then glue a copy of itself (the second sheet) to it. The sphere we obtain (Fig. 4) is to be thought of as the compactified complex plane $\tilde z$



$$z=\tilde z^2 \qquad (15)$$

Fig. 4

Let us remind that $\varphi_{inst}\sim 1/z$ is hedgehog on S. The toron $\sqrt{1/z}$ is hedgehog on $\tilde S$.

There is alternative point of view on toron solution*). It is connected with consideration of the manifold with boundary. Let's consider conformal mapping (15). In this case physical space is half-plane with boundary $\mathrm{Im}\,\tilde z=0$ (Fig. 5*a*, 5*b*). In ω—variable

$$\omega=R\frac{\Delta+i\tilde z}{\Delta-i\tilde z} \qquad (16)$$

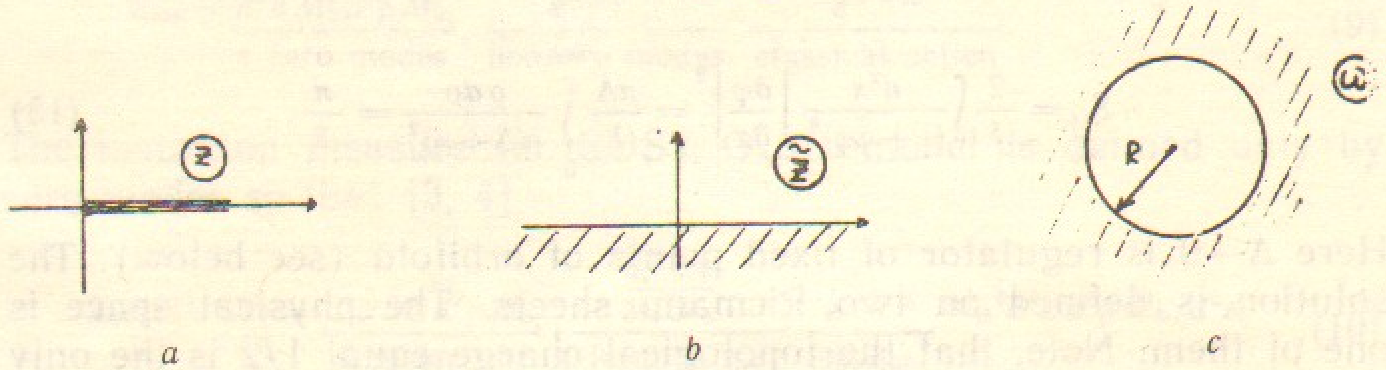


Fig. 5.

physical space corresponds to disk with radius R (Fig. 5*c*). So, we may define the theory on a disk R and take the limit $R\to\infty$ on the final stage of calculation. On the other hand, we may define the theory on the exterior of small circle Δ and take the limit $\Delta\to 0$ on the final stage of calculation. In this language toron is the point defect at $\Delta\to 0$.

The only questions which arise concerning this solution are: is this solution stable?; is the contribution to $\langle\psi\psi\rangle$ of this toron solution finite at $R\to 0$ or $\Delta\to 0$?

To answer this questions we have to calculate the toron measure.

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*) The author is grateful to A. Morosov and A. Rosly (who considered analogous solutions earlier) for explanation of this opinion on solutions with fractional topological number.

4. THE TORON MEASURE

The contribution of nonzero modes can be easily calculated with logarithmic accuracy as before (8) and is equal to:

$$\exp\left(-\ln M_0^2\frac{1}{2\pi}(S_{cl}\; f)\right)=\exp\left(-\frac{1}{2}\ln M_0^2\right). \qquad (17)$$

($e^{-\ln M_0^2}$ for instanton). So, decreasing action two times we have the nonzero modes contribution deminished two times as well. How this phenomenon can be understood from the spectra of eigenstates viewpoint? To answer this question, let's note that in terms of $\tilde\eta$, $\tilde\alpha$ (14) the equation for quantum fluctuations in background toron field coincides with that in the instanton case (6):

$$m^2_{toron}=L^2(\tilde\eta,\tilde\alpha)-2. \qquad (18)$$

However, the multiplicity g_l decreases twice in comparison with the instanton case. It follows from the fact that one-half modes are unacceptable because of the boundary condition. So, due to

$$\Delta S_{nonzero}\sim\frac{1}{2}\sum_l g_l\ln\lambda_l$$

and

$$(g_l)_{toron}=\frac{1}{2}(g_l)_{instanton}$$

we have

$$\Delta S_{\substack{toron\\ n.z.m.}}=\frac{1}{2}\Delta S_{\substack{inst.\\ n.z.m.}} \qquad (19)$$

in agreement with more simple calculation (17).

Let's consider the zero modes in toron background. In this case the multiplicity of zero modes is 2 (not 4 as for instanton). It comes from the fact that the only analytical function

$$\delta\varphi_0\sim 1/z \qquad (20)$$

satisfies to finitness condition (11, 12) [8]. Taking into account this facts we write down the toron measure for SUSY O(3)σ-model in following form:

$$Z_{toron}(\mathrm{SUSY}) \sim \underbrace{d^2 a\, M_0^2}_{\text{2 boson z.m.}} \underbrace{\frac{d^2\varepsilon}{M_0^2}}_{\text{2 fermion z.m}} \underbrace{e^{-\pi/f}}_{\text{classical action}} \sim \mu d^2 a\, d^2\varepsilon\,. \tag{21}$$

Here we have taken into account that supersymmetric measure is defined only by zero modes and the multiplicity of zero modes is equal 2 (20). Toron contribution to $\langle\bar{\psi}\psi\rangle$ does not vanish.

$$\langle\bar{\psi}\psi\rangle \sim \mu \int \varepsilon^2 d^2\varepsilon = \mu \tag{22}$$

and the result is defined exactly by renorminvariant combination: $M_0 \exp\{-\pi/f_0\} = \mu$. This phenomenon can be easily understood if one starts from instanton measure (10). Decreasing action twice we see the multiplicity of zero modes decreased two times as well. That's why the renorminvariant combination $\mu = M_0 \exp\{-\pi/f_0\}$ is conserved.

In conclusion of this section let's describe the geometrical interpretation of acceptable modes. For this purpose we consider the manifold $\tilde{S}$ having a discrete group G. Dividing $\tilde{S}$ by group action G we have $S = \tilde{S}/G$. We may consider the theory on $\tilde{S}$ but we demand the physical states to be invariant with respect to G:

$$G \left| \begin{matrix}\text{physical}\\ \text{states}\end{matrix} \right\rangle = \left| \begin{matrix}\text{physical}\\ \text{states}\end{matrix} \right\rangle .$$

In our case G: $\tilde{z} \to -\tilde{z}$ and, in particular, zero modes (20) $\delta\varphi_0 \sim 1/z \sim 1/\tilde{z}^2$ satisfy this condition. Let's note that G: $\tilde{z} \to -\tilde{z}$ has fixed points (North and South Poles) and so $\tilde{S}/G$ is orbifold (see, for example, [9, 10]). The orbifold has singularities in fixed points. For their regularization one uses usually the dimensional parameter $\Delta \to 0$ (the «blowing up» in literature). At each fixed point, there is a conic singularity with deficit angle π. So, the topological charge

$$Q = \frac{1}{2\pi} \oint d\alpha = \frac{\pi}{2\pi} = \frac{1}{2},$$

as it was expected (13).

5. TORONS IN SU(2) SUPERSYMMETRIC GLUODYNAMICS

Let's formulate the self-dual solution for gauge theories on the language analogous to Cauchy—Riemann condition for O(3)σ-model. For this purpose consider Witten's Anzats [11]:

$$A_0^a = n^a A_0(r, t)\,,$$

$$A_i^a = \varepsilon^{iak} n^k \frac{1+\Phi_2}{r} + (\delta^{ai} - n^a n^i)\frac{\Phi_1}{r} + n^a n^i A_1\,, \tag{23}$$

$$A_\mu = (A_0, A_1)\,, \quad \Phi = \Phi_1 - i\Phi_2\,, \quad z = r + it\,, \quad \mu = 0.1\,.$$

Now the problem is effectively 2-dimensional one. Then $A_\mu(r, t)$ $\mu = 0$, 1 is the gauge field and $\Phi(r, t)$ — complex scalar field of this 2d-theory. The solution of the self-duality equation is described by any analytical function $g(z)$ [11]:

$$f = \frac{dg}{dz}, \quad \Psi = \ln\frac{z+\bar{z}}{1-\bar{g}g}, \quad \Phi = f e^{\Psi}, \quad A = A_1 - iA_0 = -2i\frac{\partial\Psi}{\partial z}. \tag{24}$$

The topological charge in Anzats (23) is determined by change of phase $f = dg/dz$ around the countour which encloses the region $\mathrm{Re}\, z \geqslant 0$ [11].

$$Q = \frac{1}{2\pi}\int dt\, dr \left[\frac{1}{2}\varepsilon_{\mu\nu} F_{\mu\nu} + i\varepsilon_{\mu\nu}\partial_\mu(\bar{\Phi} D_\nu \Phi)\right] = \frac{1}{2\pi i}\oint ds \frac{d}{ds}\ln f; \tag{25}$$

$$F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu\,, \quad D_\mu = \partial_\mu + iA_\mu\,.$$

So, the solution $g(z) = \dfrac{a-z}{\bar{a}+z}$ is a gauge transform of the vacuum and has $Q = 0$; the

$$g(z) = \prod_{i=1}^{2}\left(\frac{a_i - z}{\bar{a}_i + z}\right)$$

is the 1-instanton solution with $Q = 1$. The toron solution with $Q = 1/2$ (by analogy with O(3)σ-model) is described by the function

$$g(z) = \left(\frac{a-z}{\bar{a}+z}\right)^{3/2}. \tag{26}$$

Here $\Delta = a + \bar{a} \to 0$ is the regulator, analogous to dimensional parameter Δ (13) in O(3)σ-model.

We can show that in the toron's background the only two regular fermion zero modes exist (remember that in the instanton background 4 zero modes exist). As we have seen (20) the analogous phenomenon is inherent in O(3)σ-model too.

It is well-known [12] that for each solution of the spinor field equation there exist precisely two linearly independent solutions of vector field equation (in $D_\mu A^a_\mu = 0$ gauge). In particular, the Dirac equation in instanton field has 4 solutions:

$$\psi^a_{1,2} \sim G^a_{\mu\nu}\sigma_{\mu\nu}\varepsilon\,, \qquad \psi^a_{3,4} \sim \sigma^a_{\mu\nu}\hat{x}\, G^a_{\mu\nu}\varepsilon\,. \tag{27}$$

Thus there are 8 gluon's zero modes:

$$A^a_\mu \sim G^a_{\mu\lambda}\,, \qquad \lambda = 0, 1, 2, 3\,;$$
$$A^a_\mu \sim G^a_{\mu\nu}\,\bar{\eta}^d_{\nu\lambda}\,x_\lambda\,, \qquad d = 1, 2, 3\,; \tag{28}$$
$$A^a_\mu \sim G^a_{\mu\nu}\,x_\nu\,.$$

Therefore, the instanton measure is equal to:

$$Z_{inst} \sim \underbrace{M_0^4\, d^4x_0\, M_0^4\, d^4\rho}_{8\ \text{boson z.m}\ (28)}\ \underbrace{\frac{d^2\varepsilon_1}{M_0}\frac{d^2\varepsilon_2}{M_0}}_{4\ \text{fermion z.m}\ (27)}\ e^{-8\pi^2/g^2} \sim$$
$$\sim M_0^6 \exp\left\{-\frac{8\pi^2}{g^2}\right\} d^4x_0\, d^4\rho\, d^2\varepsilon, d^2\varepsilon_2\,, \tag{29}$$
$$\mu^6 \sim M_0^6 \exp\left\{-\frac{8\pi^2}{g^2}\right\}.$$

The instanton contribution to two-point function does not vanish [13, 14]:

$$\langle \bar{\psi}\psi(x), \bar{\psi}\psi(0)\rangle \sim \mu^6.$$

In our case, the Dirac equation in toron field (24), (26) has 2 regular solutions (the gluino zero modes). Thus [12] there are 4 regular gluon's zero modes). So, the toron measure is equal to:

$$Z_{toron} \sim \underbrace{M_0^4\, d^4x_0}_{4\ \text{boson z.m}}\ \underbrace{\frac{d^2\varepsilon}{M_0}}_{2\ \text{fermion z.m.}}\ \underbrace{\exp\left\{-\frac{4\pi^2}{g^2}\right\}}_{\text{classical action}} \sim$$
$$\sim \mu^3 d^4x_0\, d^2\varepsilon\,; \qquad \mu^3 = M_0^3 \exp\left\{-\frac{4\pi^2}{g^2}\right\}. \tag{30}$$

The toron contribution to $\langle\bar{\psi}\psi\rangle$ does not vanish:

$$\langle\bar{\psi}\psi\rangle \sim \mu^3. \tag{31}$$

With decreasing action twice the multiplicity of zero modes de-

creases two times as well. That's why the form of renorminvariant combination $\mu^3 \sim M_0^3 \exp\{-4\pi^2/g^2\}$ conserves.

Details of the toron calculations in $O(3)\,\sigma$-model will be published in [15] and corresponding calculations in SYM will be published in [16].

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Дробный топологический заряд и тороны в суперсимметричной O(3)σ-модели и в калибровочных теориях

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