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## Spontaneous Generation of Angular Momentum in Holographic Theories

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The Schwarzschild black two-brane in four-dimensional anti-de Sitter space is dual to a finite temperature state in three-dimensional conformal field theory. We show that the solution acquires a nonzero angular momentum density when a gravitational Chern-Simons coupling is turned on in the bulk, even though the solution is not modified. A similar phenomenon is found for the Reissner-Nordström black two-brane with axionic coupling to the gauge field. We discuss interpretation of this phenomenon from the point of view of the boundary three-dimensional conformal field theory.

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*Introduction.*—The gauge-gravity correspondence has provided many important insights into strongly coupled gauge theories. In particular, parity violating interactions in the bulk have been shown to generate interesting effects on boundary field theories. One example is the effect of anomalies in four dimensions [1–3] (see also Chap. 20 of [4] and references therein), which had been overlooked in the traditional approach to hydrodynamics. Another is the existence of spatially modulated phase transitions in three and four dimensions [5–8]. In this Letter, we point out yet another striking effect of a parity violating interaction—spontaneous generation of an angular momentum density and an edge current. This question was previously examined by Saremi [9]. Parity violation effects in hydrodynamics have been discussed in [10], which also pointed out angular momentum generation, though its physical mechanism and its connection to the edge current have not been examined.

The spontaneous generation of angular momentum and an edge current are typical phenomena in parity-violating physics. They occur, for example, in the *A* phase of helium-3, where the chiral *p*-wave condensate breaks parity (see, for example, [4,11,12]). There has been a controversy on its value in a given container geometry since different methods give different answers. The holographic mechanism to generate the angular momentum density described here may provide a new perspective on such macroscopic parity-violating effects.

We consider here a (2 + 1)-dimensional boundary field theory with a *U*(1) global symmetry, which is described by classical gravity (together with various matter fields) in a four-dimensional, asymptotically anti-de Sitter spacetime (AdS<sub>4</sub>). The conserved, *U*(1) boundary current  $j^\mu$  is mapped to a bulk gauge field  $A_a$ . We use  $a, b = 0, 1, 2, z$  to denote bulk indices,  $\mu, \nu = 0, 1, 2$  for boundary indices, and  $i, j = 1, 2$  for boundary spatial indices.

We discuss two representative bulk mechanisms for the spontaneous generation of angular momentum, with a

gravitational Chern-Simons interaction  $\int \vartheta R \wedge R$  [13] and with an axionic coupling  $\int \vartheta F \wedge F$  [14,15], where  $\vartheta$  is a dynamical massless pseudoscalar, which is dual to a marginal pseudoscalar operator  $\mathcal{O}$  in the boundary field theory, and  $R$  and  $F$  are the Riemann curvature two-form and the field strength for a gauge field  $A_a$ , respectively. To break the parity symmetry, we turn on a non-normalizable mode for the pseudoscalar field  $\vartheta$ . With the gravitational Chern-Simons interaction, we obtain a nonzero angular momentum density at finite temperature. Similarly, the axionic coupling can generate a nonzero angular momentum density at a finite chemical potential. In both situations, if we put the system in a finite box (i.e.,  $\vartheta$  is nonzero only inside the box), the spontaneous generation of angular momentum is always accompanied by an edge current.

Without going into details of the bulk calculation, both bulk mechanisms can be understood from the boundary perspective as follows. The constant value  $\theta$  of the massless pseudoscalar  $\vartheta$  is a non-normalizable mode, corresponding to turning on a marginal deformation  $\theta \int d^3x \mathcal{O}$  in the boundary theory that breaks parity. The presence of bulk interactions ( $\int \vartheta R \wedge R$  or  $\int \vartheta F \wedge F$ ) generates a mixed two-point function

$$\langle T_{0i}(x) \mathcal{O}(y) \rangle_\theta = -C \epsilon_{ij} \partial_j^{(y)} \delta^{(3)}(x - y) + \dots, \quad (1)$$

at a finite temperature or a finite charge density, where  $\epsilon_{12} = -\epsilon_{21} = 1$ ,  $C$  is a constant depending on the temperature or charge density of the system, and  $\dots$  denotes higher-order derivative terms which are irrelevant here.

Now, consider making  $\theta$  slightly nonhomogeneous; then, from (1) and to leading order in the derivative expansion of  $\theta$ , we have

$$\langle T_{0i} \rangle_\theta = C \epsilon_{ij} \partial_j \theta(x) + \dots, \quad (2)$$

which vanishes for constant  $\theta$ . Let us consider a profile of  $\theta(x)$  which takes constant value  $\theta_0$  inside a spherical box of

size  $L$  but eventually goes to zero outside the box along the radial direction. (We use a spherical box for convenience of illustration. Our conclusions do not depend on the shape of the box, as far as it is sufficiently big.) At the end of the calculation we take  $L$  to infinity. From (2), we then find that the angular momentum  $J$  of the boundary is given by

$$J = \epsilon_{ij} \int d^2x x_i \langle T_{0j} \rangle_\theta = -2C\theta_0 \int d^2x, \quad (3)$$

which remains nonzero for a constant  $\theta$ . For a finite (but large)  $L$ ,  $\langle T_{0i} \rangle_\theta$  is zero both inside and outside the box, but will be nonzero in the transition region where  $\theta(x)$  changes from  $\theta_0$  to zero. In other words, there is an edge momentum flow. In terms of the polar coordinate  $(r, \phi)$ , the nonvanishing component of this edge current is

$$\langle T_{0\phi} \rangle_\theta = Ch_L(r) + \dots, \quad (4)$$

where  $h_L(r)$  is a function with compact support near  $r=L$ , and whose precise form depends on the specific profile of  $\theta(x)$ .

Heuristically,  $\theta$  can be considered as a measure of the strength of parity breaking. A constant nonzero  $\theta$  inside the box thus has two effects: (i) a nonzero angular momentum inside the box and (ii) an edge current at the boundary of the box.

When the system is at a finite charge density, then there is also a parallel story for the  $U(1)$  charge current  $j_i$ , with  $T_{0i}$  in (1) and (2) replaced by  $j_i$  and  $C$  replaced by some other constant  $C_{\text{charge}}$ . We can also define a ‘‘charge angular momentum’’  $J_{\text{charge}} = \int d^2x \epsilon_{ij} x_i j_j$ . A nonzero  $\theta$  inside the box then also leads to a nonzero charge angular momentum  $J_{\text{charge}}$  and an edge  $U(1)$  current  $j_\phi$ , which can be obtained by replacing  $C$  in (3) and (4) by  $C_{\text{charge}}$ .

We now provide an explicit derivation of (1) and the corresponding  $C$  and  $C_{\text{charge}}$  from bulk gravity.

*Gravitational Chern-Simons interaction.*—Consider the following action [16]:

$$S = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g} \left[ R + \frac{6}{\ell^2} - \frac{1}{2} (\partial\vartheta)^2 - \frac{\alpha_{\text{CS}} \ell^2}{4} \vartheta^* RR \right], \quad (5)$$

where  $*RR = *R^{abcd} R_{abcd}$  and  $*R^{abcd} = \frac{1}{2} \epsilon^{cdef} R_{ef}^{ab}$ .  $\epsilon^{abcd}$  is the totally antisymmetric tensor with  $\epsilon^{012z} = 1/\sqrt{-g}$ . The equations of motion are

$$R_{ab} + \frac{3}{\ell^2} g_{ab} = \alpha_{\text{CS}} \ell^2 C_{ab} + \frac{1}{2} \partial_a \vartheta \partial_b \vartheta, \quad (6)$$

$$\frac{1}{\sqrt{-g}} \partial_a (g^{ab} \sqrt{-g} \partial_b \vartheta) = \frac{\alpha_{\text{CS}} \ell^2}{4} *RR, \quad (7)$$

where  $C^{ab} \equiv \nabla_c (\nabla_d \vartheta^* R^{c(ab)d})$  and parenthesis in index lists denote symmetrization. Equations (6) and (7) are solved by the standard Schwarzschild black brane

$$ds_0^2 = \frac{\ell^2}{z^2} \left[ -f(z) dt^2 + \frac{dz^2}{f(z)} + \gamma_{ij} dx^i dx^j \right], \quad (8)$$

if  $\vartheta$  is a constant, where  $\gamma_{ij}$  is the flat metric in  $(x, y)$  space and  $f(z) = 1 - z^3/z_0^3$ . The horizon is located at  $z = z_0$  with a temperature  $T = 3/(4\pi z_0)$ .

Let us now take the boundary value for  $\vartheta$  to be space-time dependent  $\theta(x^\mu)$ . Clearly,  $\vartheta(z, x^\mu) = \theta(x^\mu)$  and (8) no longer solves (6) and (7). Nevertheless, if  $\theta(x^\mu)$  varies slowly over spacetime, we can solve the bulk equations of motion order by order in a derivative expansion of  $\theta(x^\mu)$ . In particular, from the modification of the bulk metric, we could read the response of the boundary stress-energy tensor to a nonuniform  $\theta(x^\mu)$ . The calculation is similar in spirit to that of forced fluid dynamics [17], but at the end of the calculation we will take  $\theta(x)$  to be a constant. For our purpose, it is enough to work out the expansion to first order in  $\partial_i \theta$  with  $\theta$  time independent, in which case only the  $g_{0i}$  components of the metric and  $\vartheta$  are modified. To carry out the derivative expansion, it is convenient to introduce the bookkeeping parameter  $\epsilon$  to count the number of boundary spatial derivatives, with  $\partial_i \vartheta = \mathcal{O}(\epsilon)$ ,  $\partial_i \partial_j \vartheta = \mathcal{O}(\epsilon^2)$ ,  $\partial_i \vartheta \partial_j \vartheta = \mathcal{O}(\epsilon^2)$  and so on.

Writing the metric as

$$ds^2 = ds_0^2 + 2 \frac{\ell^2}{z^2} a_i dx^i dt, \quad (9)$$

with  $(a_1, a_2)$  functions of  $(z, x, y)$ , the nontrivial components of the Einstein equations (6) are the  $(z, t)$  component

$$\partial_t a_i = f(z) G(x^i), \quad (10)$$

with  $G(x^i)$  an arbitrary function of  $x^i$ , and the  $(t, i)$  components

$$\begin{aligned} \epsilon_{ij} \partial_j B - \frac{f}{z} (z \partial_z^2 a_i - 2 \partial_z a_i) \\ = -\epsilon_{ij} \frac{\alpha_{\text{CS}} z f f''}{2} (\partial_j \vartheta + z \partial_z \partial_j \vartheta), \end{aligned} \quad (11)$$

where  $B \equiv \partial_x a_y - \partial_y a_x$  and  $f' = \partial_z f$ , etc. Equation (7) gives (to first order in  $\partial_i \theta$ )

$$z^2 \partial_z (z^{-2} f \partial_z \vartheta) = \frac{\alpha_{\text{CS}}}{2} z^2 f'' \partial_z B. \quad (12)$$

Since we are considering a normalizable solution for the metric,  $G$  must vanish. We thus have  $\partial_t a_i = 0$ , which implies that  $\epsilon_{ij} \partial_j B = -(\partial_x^2 + \partial_y^2) a_i$ . Assuming regularity of  $a_i$  and  $\vartheta$  at the horizon, Eq. (11) then implies that  $(\partial_x^2 + \partial_y^2) a_i(z_0, x^i) = 0$  at the horizon. Imposing the boundary condition  $a_i(z_0, x^i) \rightarrow 0$  at spatial infinity  $r \rightarrow \infty$  [note that this boundary condition is consistent with that for  $\theta(x)$  as discussed in the paragraph following Eq. (2)], we then conclude that

$$a_i(z_0, x^i) = 0 \quad (13)$$

at the horizon. From Eq. (11),  $a_i \sim \mathcal{O}(\epsilon)$  and thus  $\partial_j B \sim \mathcal{O}(\epsilon^2)$ ; i.e., we keep  $\epsilon_{ij}\partial_j B$  above only to impose the boundary condition (13). Applying  $\partial_i$  on both sides of (12), imposing regularity of  $\vartheta$  at the horizon, and keeping terms only to  $\mathcal{O}(\epsilon)$ , we find that

$$\partial_z \partial_i \vartheta = 0 \rightarrow \partial_i \vartheta(z, x^\mu) = \partial_i \theta(x^\mu); \quad (14)$$

i.e.,  $\partial_i \vartheta$  is  $z$  independent. Now Eq. (11) can be immediately integrated at  $\mathcal{O}(\epsilon)$  to give

$$a_i = \epsilon_{ij} \frac{3\alpha_{\text{CS}} z^3 (z_0 - z) \partial_j \theta}{4z_0^3}, \quad (15)$$

fixed uniquely by normalizability at infinity and (13).

We now proceed to compute the boundary stress-energy tensor due to (15). Although there are potential contributions from (i) direct variation of the  ${}^*RR$  term and (ii) additional boundary counterterms required due to the presence  ${}^*RR$ , we have evaluated them explicitly and verified that both vanish separately. Therefore, it suffices to use the standard formulas as in [18–20], which give

$$T_{0i} = \frac{\ell^2}{2\kappa^2} \frac{9\alpha_{\text{CS}} \epsilon_{ij} \partial_j \theta}{4z_0^2}. \quad (16)$$

Equation (16) leads to (1) with

$$C = \frac{\ell^2}{2\kappa^2} \frac{9\alpha_{\text{CS}}}{4z_0^2} = \frac{\alpha_{\text{CS}}}{2} \mathcal{S}_3 T^2 = \frac{9\alpha_{\text{CS}}}{16\pi} s. \quad (17)$$

Here,  $\mathcal{S}_3 = ((2\pi)^2 \ell^2)/(\kappa^2)$  is the central charge of the conformal field theory defined using either entanglement entropy on a disk [21] or equivalently the free energy on an  $S^3$  [22]. Moreover,  $s = (2\pi \ell^2)/(\kappa^2 z_0^2)$  is the entropy density of the finite temperature system.

*Axionic coupling.*—Let us now set  $\alpha_{\text{CS}} = 0$  in (5) and add to this equation the following terms:

$$S_{\text{ax}} = -\frac{\ell^2}{2\kappa^2} d^4 x \sqrt{-g} [F^{ab} F_{ab} + \beta_{\text{CS}} \vartheta^* F^{ab} F_{ab}], \quad (18)$$

with  $\beta_{\text{CS}}$  a dimensionless constant and  ${}^*F^{ab} \equiv \frac{1}{2} \epsilon^{abcd} F_{cd}$ . The equations of motion are now

$$R_{ab} + \frac{3}{\ell^2} g_{ab} - 2\ell^2 \left( F_{ca} F^c{}_b - \frac{g_{ab}}{4} F^2 \right) = \frac{1}{2} \partial_a \vartheta \partial_b \vartheta, \quad (19)$$

$$\frac{1}{\sqrt{-g}} \partial_a (g^{ab} \sqrt{-g} \partial_b \vartheta) = \beta_{\text{CS}} \ell^2 {}^* F F, \quad (20)$$

$$\partial_a [\sqrt{-g} (F^{ab} + \beta_{\text{CS}} \vartheta^* F^{ab})] = 0, \quad (21)$$

which admit as a solution the standard AdS charged brane if  $\vartheta$  is a constant. The metric has the form (8) but with

$$f(z) = 1 - \frac{z^3}{z_M^3} + \frac{z^4}{z_Q^4}, \quad (22)$$

and the gauge potential is

$$A_i^{(0)} = \mu \left( 1 - \frac{z}{z_0} \right), \quad \mu = \frac{z_0}{z_Q^2}, \quad (23)$$

where  $z_0$  is the location of the horizon and  $\mu$  the chemical potential.

As before, we take the boundary source  $\theta(x^i)$  to be spatially inhomogeneous, but slowly varying. In addition to a metric deformation as in (9), such a boundary source will now also excite the bulk gauge field  $A_i$  along the boundary spatial direction. The analysis of the equations is similar to the previous example; in particular, the scalar equation still yields (14), and (13) also applies. To  $\mathcal{O}(\epsilon)$ , the nontrivial equations from (20) and (21) and are

$$\partial_z (f z_Q^2 A'_i - a_i) = \beta_{\text{CS}} \epsilon_{ij} \partial_j \vartheta, \quad (24)$$

$$z a_i'' - 2a_i' - \frac{4z^3}{z_Q^2} A'_i = 0, \quad (25)$$

which can be integrated exactly. Upon imposing the normalizability condition at infinity and the boundary condition (13) at the horizon, we find that  $a_i$  and  $A_i$  have the following leading-order behavior near the boundary:

$$a_i(z) = \frac{2z^3 z_0^2}{3z_Q^4} \beta_{\text{CS}} \epsilon_{ij} \partial_j \theta + \mathcal{O}(z^4), \quad (26)$$

$$A_i = -\frac{z_0 z}{z_Q^2} \beta_{\text{CS}} \epsilon_{ij} \partial_j \theta + \mathcal{O}(z^2). \quad (27)$$

We then find the stress-energy tensor and the charged current

$$T_{0i} = \frac{\ell^2}{2\kappa^2} \frac{2z_0^2}{z_Q^4} \beta_{\text{CS}} \epsilon_{ij} \partial_j \theta, \quad (28)$$

$$j_i = \frac{4\ell^2}{2\kappa^2} \frac{z_0}{z_Q^2} \beta_{\text{CS}} \epsilon_{ij} \partial_j \theta, \quad (29)$$

which lead to

$$C = \frac{\ell^2 \beta_{\text{CS}}}{\kappa^2} \frac{z_0^2}{z_Q^4} = \beta_{\text{CS}} \frac{\pi \rho^2}{2s}, \quad (30)$$

$$C_{\text{charge}} = \frac{2\ell^2 \beta_{\text{CS}}}{\kappa^2} \frac{z_0}{z_Q^2} = \frac{\beta_{\text{CS}}}{2\pi^2} \mathcal{S}_3 \mu, \quad (31)$$

where  $\rho = (2\ell^2)/(\kappa^2 z_Q^2)$  is the charge density,  $s = (2\pi \ell^2)/(\kappa^2 z_0^2)$  is the entropy density, and  $\mathcal{S}_3$  is the central charge as discussed earlier. Note that  $C_{\text{charge}}$  is temperature independent. In the extremal limit,  $s = (\pi/\sqrt{3})\rho$ , and we then find that [in the strict extremal limit, the intermediate steps appropriate for a nonzero temperature no longer apply due to the singular nature of the extremal horizon,

but expression (30) has a well-defined zero temperature limit]

$$C = \frac{\sqrt{3}}{2} \beta_{\text{CS}} \rho, \quad T = 0. \quad (32)$$

Finally, we can turn on a nonzero  $\alpha_{\text{CS}}$  in the charged black brane background (setting  $\beta_{\text{CS}} = 0$ ), and we find that the corresponding  $C$  and  $C_{\text{charge}}$  are

$$C = \frac{3\ell^2}{2\kappa^2} \frac{\alpha_{\text{CS}} z_0^4 (320z_0^2 z_M^6 - 432z_0 z_M^3 z_Q^4 + 135z_Q^8)}{180z_M^6 z_Q^8} \\ = \frac{\alpha_{\text{CS}} s}{240\pi} \left[ 135 - 162 \left( \frac{\pi\rho}{s} \right)^2 + 23 \left( \frac{\pi\rho}{s} \right)^4 \right], \quad (33)$$

$$C_{\text{charge}} = 0. \quad (34)$$

$C$  decreases monotonically with  $(\rho/s)$ , reaching 0 at

$$\frac{\rho}{s} = \frac{1}{\pi} \sqrt{\frac{3}{23} (27 - 8\sqrt{6})} \approx \frac{0.983}{\pi} \approx 0.313, \quad (35)$$

which corresponds to  $T/\mu \approx 0.165$ , and in the extremal limit we find

$$C = -\frac{\sqrt{3}}{5} \alpha_{\text{CS}} \rho, \quad T = 0. \quad (36)$$

With the chemical potential  $\mu$  fixed, as the temperature  $T$  varies from 0 to  $\infty$ , the ratio  $\rho/s$  decreases monotonically from  $\sqrt{3}/\pi$  to 0. It is curious that, in going from the low temperature to the high temperature limit,  $C$  changes sign, increasing monotonically from the negative value of (36) at  $T = 0$  to (17) at infinite temperature.

*Hall viscosity.*—Another interesting parity odd response to gravitational perturbations is Hall viscosity, which occurs in quantum Hall states [23], where it is shown to be proportional to angular momentum density in various examples [24,25]. A holographic model exhibiting Hall viscosity has been proposed [26]: the Einstein-scalar system studied in this Letter plus a potential for the scalar field. There, the Hall viscosity coefficient is shown to be proportional to the normal derivative of the scalar field at the horizon of the black brane. Explicit models with nonzero Hall viscosity have been constructed in [27,28]. We have verified the Saremi-Son formula of [26] in our gravitational Chern-Simons setups, but the Hall viscosity turns out to be zero since the scalar field is constant in our solution. It should be noted, however, that the holographic model used here is dual to a conformal field theory at finite temperature and not to a gapped zero temperature state. We hope to investigate the Hall viscosity phenomenon in a more realistic setup in the future.

To summarize, in this Letter we identified from two classes of holographic models a field theoretical mechanism for spontaneous generation of a nonzero angular momentum density and edge current. Although our

analysis was restricted to a marginal operator, likely it is more general, applicable to relevant operators, or in the absence of an external source. We will leave these issues for future investigation.

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