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Non-extreme black holes from D-branes at angles

Satoshi Nagaoka

High Energy Accelerator Research Organization (KEK)
Tsukuba, Ibaraki 305-0801, Japan
E-mail: nagaoka@post.kek.jp

Abstract: We construct the non-extreme solutions of non-orthogonal intersecting D-branes. The solutions reduce to non-extreme black holes upon the toroidal compactification. We clarify the relation between two configurations with equal mass and charge, one of which is non-orthogonal intersecting D-branes and the other one is orthogonal D-branes, from supergravity and string theory perspective. We also calculate mass and entropies for these black holes.

Keywords: D-branes, Black Holes in String Theory.

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Contents

1. Introduction

A microscopic understanding of the Bekenstein-Hawking entropy of extreme black holes is given in string theory [1]. One of the directions of the extension of this result is to generalize away from extremality. Non-extreme black holes play an important role in the study of the properties of realistic black holes. The non-extremality parameter μ, which is the mass of neutral Schwarzschild black hole by setting all charges to zero, interpolates between extremal and Schwarzschild black holes. Entropies of non-extreme black holes are discussed in [2] in various dimensions. $D = 10$ type-IIA supergravity can be obtained from the dimensional reduction on a circle of $D = 11$ dimensional supergravity. The type-IIA theory has the solitonic objects, Dp-branes, with $p = 0, 2, 4, 6$, which preserve $1/2$ of a supersymmetry. Orthogonal intersecting D-branes preserve part of a supersymmetry and extreme black holes are constructed from these configurations. Non-extreme generalization of orthogonal intersecting D-brane solutions of supergravity, which reduce to non-extreme black holes upon toroidal compactification, is shown in [3, 4]. Non-orthogonal intersecting D-branes, which are widely studied as realistic brane models like Standard Model on intersecting D-branes recently, also preserve part of a supersymmetry [5].[1] Extremal black holes are constructed from branes at angles [7, 8, 9]. But it is not yet known the non-extreme generalization of non-orthogonal intersecting D-branes.[2]

In this paper, we will present the non-extreme solutions of supergravity from 2-angled non-orthogonal intersecting D-branes. The relation between two configurations, one of which is non-orthogonal intersecting D-branes (A) and the other one is orthogonal D-branes (B), is discussed from supergravity and string theory perspective. In section 2, we construct

[1]Configurations of supersymmetric intersecting D-branes are constructed in many other papers, for example [6].

[2]Recently, brane-antibrane systems at finite temperature are analyzed to account for the entropy of the black branes far from extremality [10].

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the non-extreme solutions from intersecting D2-branes. The correspondence between (A) and (B), which is essential for constructing the non-extreme solution, is discussed from supergravity. In section 3, we compare (A) and (B) from string theory. Section 4 is devoted to the conclusion and discussion. In appendix, we calculate mass and entropies of non-extreme black holes which are obtained upon the toroidal compactification.

2. Non-extreme solutions from branes at angles

Part of type-IIA supergravity lagrangian which we need for the analysis is written as

$$L = \sqrt{-g}\left(e^{-2\Phi}(R + 4(\nabla\Phi)^2) - \frac{1}{48}F_4^2\right), \tag{2.1}$$

where the four-form field strength F_4 couples to D2-branes. We adopt the string frame here. Equations of motion for this action are written as

$$\begin{aligned} R &= -4\nabla^2\Phi + 4(\nabla\Phi)^2\,, \\ R_{ij} &= -2\nabla_i\nabla_j\Phi + \frac{1}{12}e^{2\Phi}\left(F_i{}^{klm}F_{jklm} - \frac{1}{8}g_{ij}F_4^2\right), \\ 0 &= \frac{1}{\sqrt{-g}}\partial_i(\sqrt{-g}F^{ijkl})\,. \end{aligned} \tag{2.2}$$

We consider two stacks of D2-branes and both stacks are intersecting each other at angles 2θ to preserve 1/4 of a supersymmetry. The location of the D2-branes is shown in figure 1. For simplicity, we consider these configurations here, but we can generalize the analysis to arbitrary numbers of stacks of intersecting D-branes.

Now, we would like to construct the non-extreme solution of this system. The idea is to achieve understanding of the properties of the Schwarzschild black hole by doing perturbation theory in μ. An algorithm which leads to a non-extreme solution from a given extreme solution is developed in [4]. This procedure is applied for orthogonal intersecting D-branes [4], but not yet for non-orthogonal intersecting D-branes.

Relation to the orthogonal intersecting D-branes. Let us focus on q D2-branes intersecting at two angles (figure 2A). The relation between Q and q is

$$Q \equiv q \cdot (\text{D2 charge per unit area})\,. \tag{2.3}$$

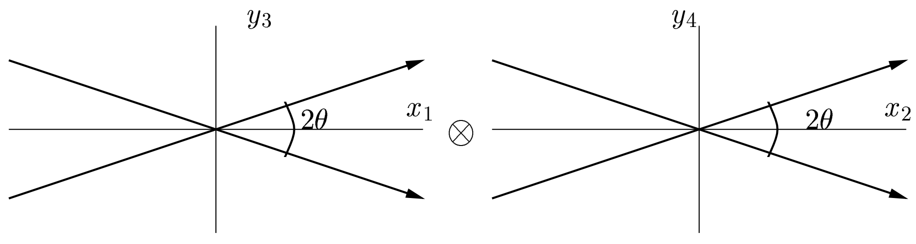

Figure 1: Intersecting D2-branes: the first brane is denoted by upper arrows on the x_1y_3 plane and x_2y_4 plane, and the second brane by lower arrows on the x_1y_3 and x_2y_4 planes. These branes do not extend to other transverse directions. Both of them have the same D2-brane charge Q with different orientations.

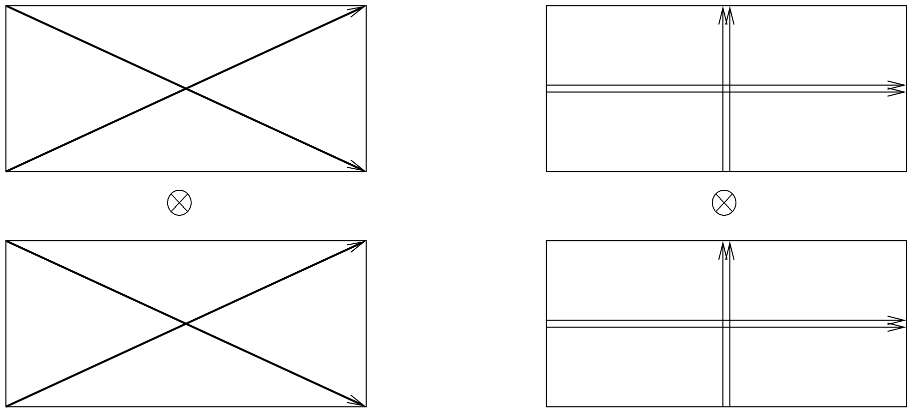

Figure 2: Two cycles are wrapped on T^4. Configuration (A) is non-orthogonal intersecting D-branes, on the other hand, configuration (B) is orthogonal intersecting D-branes. Both systems have 1/4 of a supersymmetry and topological charge $2q(1,0)\otimes(1,0)\oplus 2q(0,1)\otimes(0,1)$.

We compactify x_1, x_2, y_3 and y_4 directions with the periods a_1, a_2, b_1 and b_2. This system has topological charge

$$q(1,1)\otimes(1,1)\oplus q(1,-1)\otimes(1,-1) = 2q(1,0)\otimes(1,0)\oplus 2q(0,1)\otimes(0,1)\,, \tag{2.4}$$

where $(q_1, q_3)\otimes(q_2, q_4)$ denotes that branes wrap q_i times along $x_i(y_i)$ directions.

The system (B) also has topological charge $2q(1,0)\otimes(1,0)\oplus 2q(0,1)\otimes(0,1)$.

Next, we notice energy(tension) of these configurations. Total energy of configuration (A) is

$$E_{\mathrm{A}} = 2c\sqrt{a_1^2+b_1^2}\sqrt{a_2^2+b_2^2}\,, \tag{2.5}$$

where $c \equiv \frac{1}{g(2\pi)^2(\alpha')^{3/2}}$ is D2-brane tension and g is string coupling constant. On the other hand, total energy of configuration (B) is

$$E_{\mathrm{B}} = 2c(a_1a_2 + b_1b_2)\,. \tag{2.6}$$

Using the relation which corresponds to the supersymmetric condition,

$$\frac{b_1}{a_1} = \frac{b_2}{a_2}\,, \tag{2.7}$$

we can easily check $E_{\mathrm{A}} = E_{\mathrm{B}}$.

Therefore, we conclude that there are supersymmetric 2-angled non-orthogonal branes (A) which have the same total charge and tension as the orthogonal intersecting branes (B). An non-extremalization procedure for the orthogonal intersecting branes is already known [4], then, we can construct the non-extreme non-orthogonal intersecting D-brane solutions by applying this procedure to the configuration (B). It is interesting to construct supersymmetric 3-angled D-brane solutions which preserve 1/8 of a supersymmetry.

Now, what is the difference between the configurations (A) and (B)? We can not find the difference between (A) and (B) under the supergravity description because supergravity solution is constructed by the global charge, which (A) and (B) have equally. On the other hand, the mass spacing of the open strings connecting the different D-branes is determined by the intersection angle, therefore, configurations (A) and (B) have different mass spacing of the spectrum.[3] The relations between (A) and (B) will be discussed further in section 3.

Constructing the solutions. We will construct the non-extreme solutions from non-orthogonal intersecting D-branes. Extremal supergravity solutions of orthogonal intersecting D-branes are written as

$$\begin{aligned} ds^2 &= F^{1/2}\Big[F^{-1}(-dt^2+(1+X_1)(dx_1^2+dx_2^2)+(1+X_2)(dy_3^2+dy_4^2))+\sum_{i=5}^{9}dx_i^2\Big]\,,\\ A_3 &= dt\wedge\left(-\frac{X_1}{1+X_1}dx^1\wedge dx^2+\frac{X_2}{1+X_2}dy^3\wedge dy^4\right),\\ e^{2\Phi} &= F^{1/2}\,, \end{aligned} \tag{2.8}$$

where

$$\begin{aligned} F &= \Pi_{i=1,2}F_i\,, \qquad F_i = 1+X_i\,,\\ X_1 &= \frac{Q_1}{r^3}\,, \qquad X_2 = \frac{Q_2}{r^3}\,. \end{aligned} \tag{2.9}$$

Q_1 and Q_2 are D2-brane charges along x_1x_2 plane and y_3y_4 plane respectively. Both configurations (A) and (B) have total charge $2q(1,0)\otimes(1,0)\oplus 2q(0,1)\otimes(0,1)$, which corresponds to

$$\begin{aligned} Q_1 &= \frac{2Qb_1b_2}{\sqrt{(a_1^2+b_1^2)(a_2^2+b_2^2)}} = 2Q\sin^2\theta\,,\\ Q_2 &= \frac{2Qa_1a_2}{\sqrt{(a_1^2+b_1^2)(a_2^2+b_2^2)}} = 2Q\cos^2\theta\,. \end{aligned} \tag{2.10}$$

The solution (2.8) with charge[4] (2.10) is already found in [7]. Non-extreme procedure for orthogonal intersecting D-branes consists of the steps as

$$\begin{aligned} dt^2 &\to f(r)dt^2\,,\\ \sum_{i=5}^{9}dx_i^2 &\to f^{-1}dr^2+r^2d\Omega_4^2\,, \end{aligned}$$

[3]I would like to thank H. Shimada for bringing us this point.

[4]Q_1 and Q_2 might become irrational number for some value θ, but this is no problem because only the ratio of the area becomes irrational and the number of branes remains to be integer.

$$\begin{aligned} Q_1 &= 2q\sin^2\theta\cdot(\text{D2 charge per unit area})\,,\\ Q_2 &= 2q\cos^2\theta\cdot(\text{D2 charge per unit area})\,. \end{aligned} \tag{2.11}$$

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$$F_i \to \tilde{F}_i = 1 + \tilde{X}_i = 1 + \frac{\tilde{Q}_i}{r^3}\,,$$
$$A_3 \to \tilde{A}_3 = dt \wedge \left(-\frac{X_1}{1+\tilde{X}_1} dx^1 \wedge dx^2 + \frac{X_2}{1+\tilde{X}_2} dy^3 \wedge dy^4 \right), \tag{2.12}$$

where

$$f(r) = 1 - \frac{\mu}{r^3}\,, \tag{2.13}$$

and

$$\tilde{Q}_i = \mu \sinh^2 \delta_i\,, \qquad Q_i = \mu \sinh \delta_i \cosh \delta_i\,, \qquad i = 1, 2\,. \tag{2.14}$$

The extremal limit corresponds to $\mu \to 0$ and $\delta_i \to 0$ with Q_i kept fixed. A non-extreme solution of the non-orthogonal intersecting D-branes is obtained as

$$\begin{aligned} ds^2 &= \tilde{F}^{1/2}\Big[\tilde{F}^{-1}(-f dt^2 + (1+\tilde{X}_1)(dx_1^2+dx_2^2) + (1+\tilde{X}_2)(dy_3^2+dy_4^2)) + f^{-1}dr^2 + r^2 d\Omega_4\Big]\,, \\ A_3 &= \tilde{F}^{-1} dt \wedge (-X_1(1+\tilde{X}_2)dx^1 \wedge dx^2 + X_2(1+\tilde{X}_1)dy^3 \wedge dy^4)\,, \\ e^{2\Phi} &= \tilde{F}^{1/2}\,, \end{aligned} \tag{2.15}$$

where

$$\tilde{F} = \tilde{F}_1 \tilde{F}_2 = (1+\tilde{X}_1)(1+\tilde{X}_2)\,, \tag{2.16}$$

and the functions $\tilde{X}_1$ and $\tilde{X}_2$ are harmonic functions in the transverse space,

$$\begin{aligned} \tilde{X}_1 &= \frac{\tilde{Q}_1}{r^3}, \qquad \tilde{Q}_1 = -\frac{\mu}{2} + \sqrt{(2Q\sin^2\theta)^2 + \left(\frac{\mu}{2}\right)^2}\,, \\ \tilde{X}_2 &= \frac{\tilde{Q}_2}{r^3}, \qquad \tilde{Q}_2 = -\frac{\mu}{2} + \sqrt{(2Q\cos^2\theta)^2 + \left(\frac{\mu}{2}\right)^2}\,. \end{aligned} \tag{2.17}$$

This solution satisfies the equations of motion (2.2). In the extremal limit $\mu \to 0$, we obtain the extreme solution (2.8).

3. State counting of D-branes

We consider the number of states of configurations (A) and (B) here. The massless degrees of freedom which contribute to the entropy formula are associated with open strings stretching the intersecting D-branes [11]. Configuration (B) is constructed from $2q$ D2-branes along x_1x_2 plane and $2q$ D2-branes along y_3y_4 plane. Therefore, the configuration (B) has $4q^2$ massless excitation modes which contribute to the entropy.

The number of massless modes of non-orthogonal intersecting D-branes (A) which contribute to the entropy formula is obtained in [9]. We will briefly review the bosonic part of the analysis. Fundamental strings stretching two intersecting D-branes are described by the following boundary condition,

$$\partial_\sigma Z_a + i \tan\theta\, \partial_\tau Z_i|_{\sigma=0} = 0\,,$$

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$$\partial_\sigma Z_a - i\tan\theta\partial_\tau Z_i|_{\sigma=\pi} = 0\,, \tag{3.1}$$

where $Z_a = x_a + iy_{a+2}$ for $a = 1,2$. The classical solutions of the equations of motion for the complex bosons with these boundary conditions have mode expansions which are written as

$$Z_a = z_a + i\left(\sum_{n=1}^{\infty} a^a_{n-\epsilon}\phi_{n-\epsilon}(\tau,\sigma) - \sum_{n=0}^{\infty} a^{a\dagger}_{n-\epsilon}\phi_{-n-\epsilon}(\tau,\sigma)\right), \tag{3.2}$$

where

$$\phi_{n-\epsilon} = \frac{1}{\sqrt{|n-\epsilon|}}\cos((n-\epsilon)\sigma+\theta)\exp(-i(n-\epsilon)\tau)\,, \tag{3.3}$$

with $\epsilon \equiv 2\theta/\pi$. The commutators of zero modes x_a and y_{a+2} are obtained as

$$[x_1, y_3] = [x_2, y_4] = i\frac{\pi}{2\tan\theta}\,. \tag{3.4}$$

Dirac quantization condition restricts the values of x_1 and x_2 as

$$\begin{aligned} x_1 &= \frac{n_1 p_1 p_3 a_1}{N_1}\,, \qquad n_1 : \text{integer}\,, \\ x_2 &= \frac{n_2 p_2 p_4 a_2}{N_2}\,, \qquad n_2 : \text{integer}\,, \\ N_1 &= |p_1 q_3 - p_3 q_1|\,, \qquad N_2 = |p_2 q_4 - p_4 q_2|\,, \end{aligned} \tag{3.5}$$

where p_i and q_i $(i = 1,2,3,4)$ are wrapping numbers on cycles $x_i(y_i)$ of the first and second D2-branes. N_1 and N_2 denote the intersection numbers of x_1y_3 plane and x_2y_4 plane respectively. The degeneracy of the massless mode is N_1N_2. The wrapping number of configuration (A) is

$$\begin{aligned} (p_1,p_3)\otimes(p_2,p_4) &= (1,1)\otimes(1,1)\,, \\ (q_1,q_3)\otimes(q_2,q_4) &= (1,-1)\otimes(1,-1)\,, \end{aligned} \tag{3.6}$$

on each $T^2 \times T^2$, therefore, the total number of massless mode is obtained as

$$q^2 N_1 N_2 = q^2|(-1-1)(-1-1)| = 4q^2\,, \tag{3.7}$$

which is equal to the number of massless modes of (B).

On the other hand, the mass spectrum of open string ending on D-branes is written as [5]

$$m^2 = \frac{2n\theta}{\pi\alpha'}\,, \qquad n = 0,1,\dots\,, \tag{3.8}$$

therefore, configuration (A) and (B) have different mass spectrum.

4. Conclusion and discussion

It is well-known that the orthogonal intersecting branes can be generalized to the non-extreme solutions, on the other hand, it was not yet known the non-extremalization procedure of the non-orthogonal intersecting D-branes. In this paper, we have constructed the non-extreme black holes from non-orthogonal intersecting D-branes. The essential point for the construction is that we can transform the basis of the brane charge from non-orthogonal D-branes to orthogonal D-branes. After the transformation, we non-extremalize the solutions for each orthogonal intersecting brane charges.

The configuration (A) and (B) have the same mass and global charge, therefore, (A) and (B) reduce to the same black hole. They also have the same number of massless states of D-branes. But they are different configurations in string theory, that is, they have different mass spectrum. In other words, this is something like 'hair' of the black hole.

Intersecting D-branes are the fundamental and important objects in string theory, and it has much possibility to bring information from the string theory to the realistic world. In our research directions, first, it is interesting to construct the 3-angled intersecting D-brane solutions, which is the geometrical aspects to interpolate between the string theory and the realistic world. In these configurations, we can consider $D = 4$ black holes, and black holes with more than 3-charges. Another context is to realize Standard Model on intersecting D6-branes, which are constructed as 3-cycles wrapped on $(T^2)^3$ with 3 intersection angles. When we consider M-theory lift of intersecting D6-branes (plus O6-planes), the background is a singular 7-manifold with G_2 holonomy. It might be interesting to analyze it from this direction. Second, to clarify the relation between supergravity approach and the effective field theory (gauge theory) approach is also interesting. In [12], intersecting branes were analyzed by using Yang-Mills theory in the small intersection angles. We have extended the angle parameters to arbitrary value for the non-extreme black brane solutions. It might become some clue to explain the recombination mechanism, which corresponds to Higgs mechanism on Standard Model, on the intersecting D-branes from the supergravity approach. Third, the black hole degrees of freedom should be studied further. It might be interesting to consider the 'hair' conjectured by Mathur [13], which is closely related to the information paradox, in this case.

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A. Mass and entropies of non-extreme solution

The area of the horizon at $r = \mu^{1/3}$ is

$$A_8 = \left[\frac{8\pi^2}{3} a_1 a_2 b_1 b_2 r^4 \tilde{F}^{1/2}\right]_{r=\mu^{1/3}}$$

$$= \frac{8\pi^2}{3} a_1 a_2 b_1 b_2 \mu^{4/3} \cosh\delta_1 \cosh\delta_2 \,, \tag{A.1}$$

where internal coordinates $x^a(y^a)$ have period a_1, a_2, b_1 and b_2. The corresponding 6-dimensional metric is

$$ds_6^2 = -\tilde{F}^{-1/2} f dt^2 + \tilde{F}^{1/2}[f^{-1}dr^2 + r^2 d\Omega_4^2] \,. \tag{A.2}$$

The ADM mass is calculated as

$$\begin{aligned} M &= \frac{4\pi^2 a_1 a_2 b_1 b_2}{3\kappa^2}(4\mu + 3\tilde{Q}_1 + 3\tilde{Q}_2) \\ &= \frac{4\pi^2 a_1 a_2 b_1 b_2}{\kappa^2}\left(\sqrt{(2Q\cos^2\theta)^2 + (\frac{\mu}{2})^2} + \sqrt{(2Q\sin^2\theta)^2 + (\frac{\mu}{2})^2} + \frac{\mu}{3}\right) , \end{aligned} \tag{A.3}$$

where κ is 6-dimensional Planck constant. In the extremal limit, we obtain

$$M = \frac{8\pi^2 a_1 a_2 b_1 b_2 Q}{\kappa^2} \,. \tag{A.4}$$

Bekenstein-Hawking entropy is

$$\begin{aligned} S_{\rm BH} &= \frac{2\pi A_8}{\kappa^2} \\ &= \frac{16\pi^3 a_1 a_2 b_1 b_2}{3\kappa^2}\mu^{4/3}\cosh\delta_1\cosh\delta_2 \\ &= \frac{16\pi^3 a_1 a_2 b_1 b_2}{3\kappa^2}\mu^{1/3}\left(\sqrt{(2Q\sin^2\theta)^2 + \left(\frac{\mu}{2}\right)^2} + \frac{\mu}{2}\right)^{\frac{1}{2}}\left(\sqrt{(2Q\cos^2\theta)^2 + \left(\frac{\mu}{2}\right)^2} + \frac{\mu}{2}\right)^{\frac{1}{2}} , \end{aligned} \tag{A.5}$$

and Hawking temperature is

$$T = \frac{3\mu^{2/3}}{4\pi}\left(\sqrt{(2Q\sin^2\theta)^2 + \left(\frac{\mu}{2}\right)^2} + \frac{\mu}{2}\right)^{-\frac{1}{2}}\left(\sqrt{(2Q\cos^2\theta)^2 + \left(\frac{\mu}{2}\right)^2} + \frac{\mu}{2}\right)^{-\frac{1}{2}} . \tag{A.6}$$

In the near extremal limit, we obtain

$$\begin{aligned} M &= M_0 + \Delta M + \mathcal{O}(\mu^2) \,, \\ M_0 &= \frac{4\pi^2 a_1 a_2 b_1 b_2 Q}{\kappa^2} \,, \qquad \Delta M = \frac{4\pi^2 a_1 a_2 b_1 b_2 \mu}{3\kappa^2} \,, \end{aligned} \tag{A.7}$$

and

$$\begin{aligned} S_{\rm BH} &= \frac{16\pi^3 a_1 a_2 b_1 b_2}{3\kappa^2}\mu^{1/3} Q\sin 2\theta\left(1 + \frac{\mu}{2Q\sin^2 2\theta} + \mathcal{O}(\mu^2)\right) \\ &\sim \left(\frac{4\pi^2 a_1 a_2 b_1 b_2}{3\kappa^2}\right)^{2/3} 4\pi Q\sin 2\theta \,. \end{aligned} \tag{A.8}$$

By using the Hawking temperature, $S_{\rm BH}$ is written as

$$S_{\rm BH} = \frac{4\pi^2 a_1 a_2 b_1 b_2}{\kappa^2}\left(\frac{4\pi}{3}\right)^{3/2}(Q\sin 2\theta)^{3/2} T^{1/2} \,, \tag{A.9}$$

where

$$T = \frac{3\mu^{2/3}}{4\pi}\left(\frac{1}{Q\sin 2\theta}\right) . \tag{A.10}$$

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