The open string pair production and its detection

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The talk is based on the following papers:

- J. X. Lu, B. Ning, R. Wei and S. S. Xu, “Interaction between two non-threshold bound states, ”Phys. Rev. D **79**, 126002 (2009)
- J. X. Lu and S. S. Xu, “The Open string pair-production rate enhancement by a magnetic flux,” JHEP **0909**, 093 (2009)
- J. X. Lu and S. S. Xu, “Remarks on D(p) and D(p-2) with each carrying a flux,” Phys. Lett. B **680**, 387 (2009)
- J. X. Lu,“Magnetically-enhanced open string pair production,” JHEP **1712**, 076 (2017), [arXiv:1710.02660 [hep-th]]
- J. X. Lu, “Some aspects of interaction amplitudes of D branes carrying worldvolume fluxes,” Nucl. Phys. B **934**, 39 (2018)
- J. X. Lu, “A possible signature of extra-dimensions: The enhanced open string pair production,” Phys. Lett. B **788**, 480 (2019)
- Q. Jia and J. X. Lu,“Remark on the open string pair production enhancement,” Phys. Lett. B **789**, 568 (2019)
- Q. Jia, J. X. Lu, Z. Wu and X. Zhu, “On D-brane interaction & its related properties,” arXiv:1904.12480 [hep-th].
- J. X. Lu, “A note on the open string pair production of the D3/D1 system,” JHEP **1910**, 238 (2019), [arXiv:1907.12637 [hep-th]]

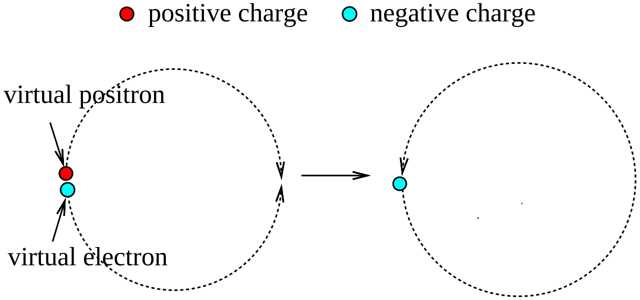
Outline

- A brief introduction/motivation
- The D3/D3 system
- The D3/D1 system
- Discussion & Implication

QED Vacuum Fluctuations

VACUUM FLUCTUATION!

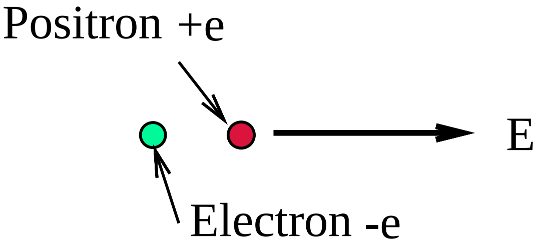
An anti-charge moving forward in time equivalent to a charge moving backward in time



$(\delta t \sim 10^{-21} s)$

QED Vacuum Fluctuations

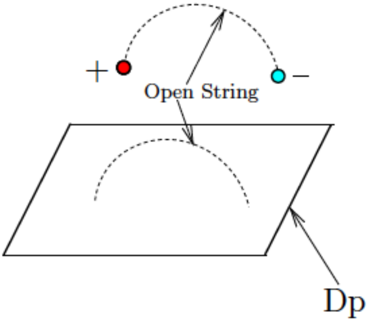
Applying a constant E to QED vacuum, there is certain probability to create real electron and positron pairs from the vacuum fluctuations, called Schwinger pair production (1951).



$$(2eE\frac{1}{m_e} \approx 2m_e \to E = \frac{m_e^2}{e} \sim 10^{18}\ V/m)$$

The current lab E-field limit: $\sim 10^{10}\ V/m$

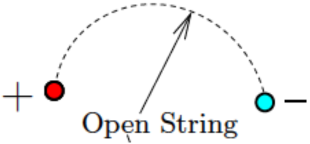
D-branes in Type II



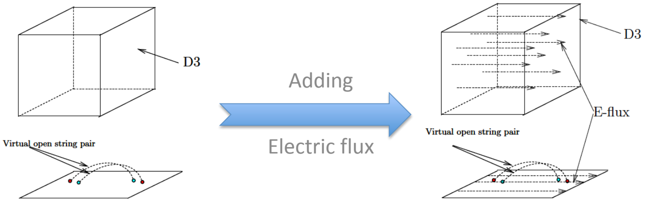
The open string pair production

We know now that an isolated Dp-brane in Type II string theory cannot give rise to the so-called open string pair production when its worldvolume electric fluxes are applied.

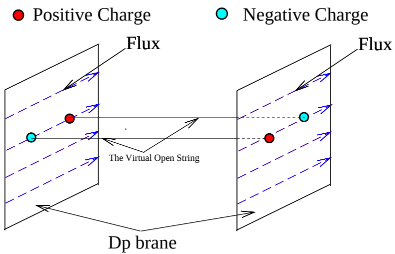
This is due to the theory being oriented, as such the charges at the two ends of the open string are equal in size but opposite in sign.



Take our 4-dim world as a D3 carrying an electric field



The open string pair production



Stringy computations show indeed a non-vanishing pair production rate for this setup. However, this rate is usually vanishing small for any realistic electric fields and so has no any practical use.

This rate can be greatly enhanced if we add in addition a magnetic flux in a particular manner on each Dp.

The pair production rate

For this purpose, consider the electric/magnetic tensor $\hat{F}^1$ on one Dp brane and the $\hat{F}^2$ on the other Dp brane, respectively, as

$$\hat{F}^a = \begin{pmatrix} 0 & -\hat{f}_a & 0 & 0 & 0 & \dots \\ \hat{f}_a & 0 & 0 & 0 & 0 & \dots \\ 0 & 0 & 0 & -\hat{g}_a & 0 & \dots \\ 0 & 0 & \hat{g}_a & 0 & 0 & \dots \\ 0 & 0 & 0 & 0 & 0 & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}_{(p+1)\times(p+1)}, \quad (1.1)$$

where $\hat{f}_a$ denotes the dimensionless electric field ($|\hat{f}_a| < 1$) while g_a the dimensionless magnetic one ($|\hat{g}_a| < \infty$) with $a = 1, 2$, and $6 \geq p \geq 3$. Note $\hat{F} = 2\pi\alpha' F$.

The open string pair production rate

The pair production rate can be computed to be Lu'17

$$\mathcal{W}^{(1)} = \frac{8\,|\hat{f}_1 - \hat{f}_2||\hat{g}_1 - \hat{g}_2|}{(8\pi^2\alpha')^{\frac{p+1}{2}}}\nu_0^{\frac{p-3}{2}}\, e^{-\frac{y^2}{2\pi\nu_0\alpha'}}\,\frac{\left[\cosh\frac{\pi\nu_0'}{\nu_0} + 1\right]^2}{\sinh\frac{\pi\nu_0'}{\nu_0}} Z_1(\nu_0, \nu_0'), \qquad (1.2)$$

where

$$Z_1(\nu_0, \nu_0') = \prod_{n=1}^{\infty}\frac{\left[1 + 2e^{-\frac{2n\pi}{\nu_0}}\cosh\frac{\pi\nu_0'}{\nu_0} + e^{-\frac{4n\pi}{\nu_0}}\right]^4}{\left[1 - e^{-\frac{2n\pi}{\nu_0}}\right]^6\left[1 - e^{-\frac{2\pi}{\nu_0}(n-\nu_0')}\right]\left[1 - e^{-\frac{2\pi}{\nu_0}(n+\nu_0')}\right]}. \qquad (1.3)$$

In the above, the parameters $\nu_0 \in [0, \infty)$ and $\nu_0' \in [0, 1)$ are

$$\tanh\pi\nu_0 = \frac{|\hat{f}_1 - \hat{f}_2|}{1 - \hat{f}_1\hat{f}_2}, \qquad \tan\pi\nu_0' = \frac{|\hat{g}_1 - \hat{g}_2|}{1 + \hat{g}_1\hat{g}_2}. \qquad (1.4)$$

The pair production rate

In practice, $\nu_0 \ll 1$ & $\nu_0' \ll 1$ ($Z_1(\nu_0, \nu_0') \approx 1$). Let us explore the posibility for a large rate (note $p \geq 3$) .

The rate (1.2) becomes

$$(2\pi\alpha')^{\frac{(1+p)}{2}} \mathcal{W}^{(1)} \approx \frac{\nu_0 \nu_0'}{2} \left(\frac{\nu_0}{4\pi}\right)^{\frac{p-3}{2}} \frac{\left[\cosh \frac{\pi \nu_0'}{\nu_0} + 1\right]^2}{\sinh \frac{\pi \nu_0'}{\nu_0}} e^{-\frac{y^2}{2\pi\alpha' \nu_0}}. \tag{1.5}$$

- It is clear the $p = 3$ gives the largest rate (Lu'19) and the rate, say, for $p = 4$, is smaller by a factor of $(\nu_0/4\pi)^{1/2}$ and so on.
- Adding more magnetic flux doesn't help (Jia & Lu'19).

Let us estimate this factor to see how large it is (set $\hat{f}_2 = \hat{g}_2 = 0$ for simplicity).

The pair production rate

Note $M_s = 1/\sqrt{\alpha'} \sim$ a few TeV upto $10^{16} \sim 10^{17}$ GeV (Berenstein'14),

The current lab. limit $eE \sim 10^{-8} m_e^2 = 2.5 \times 10^{-21} \mathrm{TeV}^2$,

$\hat{f}_1 = 2\pi\alpha' eE = 2\pi\, m_e^2/M_s^2 \leq\sim 10^{-21} \ll 1$

$$\nu_0 = \frac{|\hat{f}_1|}{\pi} = 2\frac{m_e^2}{M_s^2} \leq\sim 10^{-21} \to \left(\frac{\nu_0}{4\pi}\right)^{1/2} \sim 10^{-11} \ll 1 \qquad (1.6)$$

In other words, the dimensionless rate for any other $p > 3$ brane is at least smaller than that of the D3-brane by a factor of 10^{-11}!

So the pair production for D3 is the only hope for detection!

The pair production rate

In terms of the lab. field E and B via

$$\hat{f}_1 = 2\pi\alpha' eE \ll 1, \qquad \hat{g}_1 = 2\pi\alpha' eB \ll 1, \tag{2.1}$$

the pair production rate(1.5) for D3 brane is now

$$\mathcal{W}^{(1)} = \frac{2(eE)(eB)}{(2\pi)^2} \frac{\left[\cosh \frac{\pi B}{E} + 1\right]^2}{\sinh \frac{\pi B}{E}} e^{-\frac{\pi m^2}{eE}}, \tag{2.2}$$

where we have introduced a mass scale

$$m = T_f y = \frac{y}{2\pi\alpha'}. \tag{2.3}$$

Keep in mind, we need to have a nearby D3 brane for this rate!

The pair production rate

Let us try to understand (2.2) a bit more.

In the absence of both E and B, the mass spectrum for the open string connecting the two D3 is

$$\alpha' M^2 = -\alpha' p^2 = \begin{cases} \frac{y^2}{4\pi^2\alpha'} + N_{\rm R} & ({\rm R-sector}), \\ \frac{y^2}{4\pi^2\alpha'} + N_{\rm NS} - \frac{1}{2} & ({\rm NS-sector}), \end{cases} \quad (2.4)$$

where $p = (k, 0)$ with k the momentum along the brane worldvolume directions, $N_{\rm R}$ and $N_{\rm NS}$ are the standard number operators in the R-sector and NS-sector, respectively, as

$$\begin{aligned} N_{\rm R} &= \sum_{n=1}^{\infty}(\alpha_{-n}\cdot\alpha_n + n d_{-n}\cdot d_n), \\ N_{\rm NS} &= \sum_{n=1}^{\infty}\alpha_{-n}\cdot\alpha_n + \sum_{r=1/2}^{\infty} r d_{-r}\cdot d_r. \end{aligned} \quad (2.5)$$

The pair production rate

The R-sector gives fermions with $N_{\rm R} \geq 0$ while the NS-sector gives bosons with $N_{\rm NS} \geq 1/2$. The $N_{\rm R} = 0$, $N_{\rm NS} = 1/2$ give the usual massless $4(8_{\rm F} + 8_{\rm B})$ degrees of freedom (The 4D N = 4 U(2) SYM) when $y = 0$.

Among these, $2(8_{\rm F} + 8_{\rm B})$ become massive ones, all with mass $T_f y = y/(2\pi\alpha')$ due to unbroken SUSY, when $y \neq 0$. This just reflects $U(2) \to U(1) \times U(1)$ when $y = 0 \to y \neq 0$. The two broken generators give 16 pairs of charged/anti-charged DOF with respect to the brane observer (5 scalar pairs, 4 spinor pairs and one vector pair).

The pair production rate (2.2) is obtained in the weak field limit and all massive other than the lowest 16 charged/anti-charged pairs of dof are dropped since $Z_1 \approx 1$.

In other words, only these 16 pairs of dof actually contribute to this rate or the one for the N = 4 massive SYM.

The pair production rate

We now compare the open string pair production rate (2.2) with QED charged scalar, spinor and W-boson pair production rate with the same E and B. The present rate is

$$\mathcal{W}^{(1)} = \frac{2(eE)(eB)}{(2\pi)^2} \frac{\left[\cosh \frac{\pi B}{E} + 1\right]^2}{\sinh \frac{\pi B}{E}} e^{-\frac{\pi m^2}{eE}}, \qquad (2.6)$$

while for the QED massive scalar Nikishov'70

$$\mathcal{W}_{\text{scalar}} = \frac{(eE)(eB)}{2(2\pi)^2} \text{csch}\left(\frac{\pi B}{E}\right) e^{-\frac{\pi m_0^2}{eE}}, \qquad (2.7)$$

for massive spinor

$$\mathcal{W}_{\text{spinor}} = \frac{(eE)(eB)}{(2\pi)^2} \coth\left(\frac{\pi B}{E}\right) e^{-\frac{\pi m_{1/2}^2}{eE}}, \qquad (2.8)$$

and for massive vector Kruglov'01,

$$\mathcal{W}_{\text{vector}} = \frac{(eE)(eB)}{2(2\pi)^2} \frac{2\cosh \frac{2\pi B}{E} + 1}{\sinh \frac{\pi B}{E}} e^{-\frac{\pi m_1^2}{eE}}. \qquad (2.9)$$

The pair production rate

Identifying the mass $m_0 = m_{1/2} = m_1 = m$, when $B = 0$, we have

$$\begin{aligned} \mathcal{W}_{\rm vector} &= 3\mathcal{W}_{\rm scalar}, \quad \mathcal{W}_{\rm spinor} = 2\mathcal{W}_{\rm scalar}, \\ \mathcal{W}^{(1)} &= 16\,\mathcal{W}_{\rm scalar} = 8\,\mathcal{W}_{\rm spinor} \\ &= \frac{16}{3}\,\mathcal{W}_{\rm vector} = \frac{8(eE)^2}{(2\pi)^2}\, e^{-\frac{\pi m^2}{eE}}. \end{aligned} \tag{2.10}$$

While for large B/E (or $B \neq 0, E \sim 0$),

$$\mathcal{W}^{(1)} \approx \frac{(eE)(eB)}{(2\pi)^2}\, e^{-\frac{\pi(m^2 - eB)}{eE}}, \quad \mathcal{W}_{\rm vector} \approx \frac{(eE)(eB)}{(2\pi)^2}\, e^{-\frac{\pi(m_1^2 - eB)}{eE}}$$

$$\mathcal{W}_{\rm scalar} \approx \frac{(eE)(eB)}{(2\pi)^2}\, e^{-\frac{\pi(m_0^2 + eB)}{eE}}, \quad \mathcal{W}_{\rm spinor} \approx \frac{(eE)(eB)}{(2\pi)^2}\, e^{-\frac{\pi m_{1/2}^2}{eE}}, \tag{2.11}$$

The pair production rate

The pre-factor for vector, spinor and the present rate is the same as that for the scalar but the exponential suppressing factor is different for different case. How to understand this?

Further if set $m_0 = m_{1/2} = m_1 = m$, we have

$$\frac{\mathcal{W}_{\rm scalar}}{\mathcal{W}_{\rm vector}} = e^{-\frac{2\pi B}{E}} \to 0, \quad \frac{\mathcal{W}_{\rm spinor}}{\mathcal{W}_{\rm vector}} = e^{-\frac{\pi B}{E}} \to 0,$$

$$\mathcal{W}^{(1)} = \mathcal{W}_{\rm vector} = \frac{(eE)(eB)}{(2\pi)^2}\, e^{-\frac{\pi(m^2 - eB)}{eE}} \tag{2.12}$$

The pair production rate

It is well-known that an electrically charged particle with mass m_S and spin S in a weak magnetic field B background has energy

$$E^2_{(S,S_z)} = (2N+1)eB - g_S eB \cdot S + m_S^2, \qquad (2.13)$$

with g_S the gyromagnetic ratio ($g_S = 2$) and N the Landau level. So for the lowest Landau level ($N = 0$), we have the following mass splittings

S	0	1/2	1
$E^2_{(S,S_z)}$	$E^2_{(0,0)} = m_0^2 + eB$	$E^2_{(\frac{1}{2},-\frac{1}{2})} = m^2_{\frac{1}{2}} + 2eB$ $E^2_{(\frac{1}{2},\frac{1}{2})} = m^2_{\frac{1}{2}}$	$E^2_{(1,-1)} = m_1^2 + 3eB$ $E^2_{(1,0)} = m_1^2 + eB$ $E^2_{(1,1)} = m_1^2 - eB$

So for large B/E and from the scalar rate in (2.11), we have for each spin polarization

$$\mathcal{W}_{(S,S_z)} \approx \frac{(eE)(eB)}{(2\pi)^2} e^{-\frac{\pi E^2_{(S,S_z)}}{eE}}. \qquad (2.14)$$

Discussion of the rate

The above explains why only the lowest energy polarization survives when B/E is large. For example,

$$\frac{\mathcal{W}_{(1,0)}}{\mathcal{W}_{(1,1)}} = e^{-\frac{2\pi B}{E}} \to 0. \tag{2.15}$$

For general B/E, we also expect to have,

$$\mathcal{W}^{(1)} = 5\, W_{\text{scalar}} + 4\, W_{\text{spinor}} + W_{\text{vector}}, \tag{2.16}$$

when all the modes with the same mass.

One can check this holds indeed true and it explains the previous results for $B = 0$ and large B/E, respectively.

It is also very satisfied to have this since they are computed completely differently, one in string theory and the other in QFT.

Discussion of the rate

Can the rate (2.6), rewritten below, be useful for actual detection in practice?

$$\mathcal{W}^{(1)} = \frac{2(eE)(eB)}{(2\pi)^2} \frac{\left[\cosh \frac{\pi B}{E} + 1\right]^2}{\sinh \frac{\pi B}{E}} e^{-\frac{\pi m^2}{eE}}. \tag{2.17}$$

Since the modes contributing to the above rate all have the same mass m, due to unbroken SUSY, we expect $m > \mathrm{TeV}$. A detection of the pair production requires either $eE \sim m^2 > \mathrm{TeV}^2$ if $B/E \sim \mathcal{O}(1)$ or $eB \sim m^2$ if $B/E \gg 1$ since now

$$\mathcal{W}^{(1)} \sim \frac{(eE)(eB)}{(2\pi)^2} e^{-\frac{\pi(m^2 - eB)}{eE}}. \tag{2.18}$$

This is impossible in practice since the field required is much too larger than the lab limit $eE \sim eB \sim 10^{-8} m_e^2 \sim 10^{-21}\mathrm{TeV}^2$. (Note also this rate is actually for N $=$ 4 SYM, not necessarily the stringy one).

A possibility of detection

For a potential detection, we need to have

- a non-supersymmetric system of D-branes even in the absence of worldvolume fluxes,
- the corresponding mass scale is comparable to the current lab electric field.

One such system is the D3/D1 (Lu&Xu' 09, Jia et al'19), which has no SUSY and the D1 appears effectively as a stringy scale magnetic such that it can gives a small effective mass scale.

For this, first consider a system of D3/D3 with our own D3 carrying the electric and magnetic fluxes $\hat{f}$ and $\hat{g}$ as before but the other D3 carrying only a large magnetic flux $\hat{g}'$ ($F'_{23} = -F'_{32} = \hat{g}'$). So from (1.4), we have here

$$\tanh \pi\nu_0 = |\hat{f}| = 2\pi\alpha' eE \ll 1, \quad \tan \pi\nu'_0 = \frac{|\hat{g} - \hat{g}'|}{1 + \hat{g}\hat{g}'}. \qquad (3.1)$$

A possibility of detection

and the pair production rate for this D3/D3 is, from (1.2),

$$\mathcal{W}^{(1)}_{D3/D3} = \frac{|\hat{f}||\hat{g} - \hat{g}'|}{(2\pi)^2(2\pi\alpha')^2} e^{-\frac{y^2 - 2\pi^2\alpha'\nu_0'}{2\pi\nu_0\alpha'}}, \qquad (3.2)$$

where $\nu_0 \ll 1$ is used.

The D3/D1 rate

As shown in Jia-Lu-Wu-Zhu'19, so long the interaction and the pair production for D3/D1 are concerned, the D1 along 1-direction can be effectively taken as the other D3 carrying magnetic flux $F'_{23} = -F'_{32} = \hat{g}'$ with $\hat{g}' \to \infty$, for example,

	0	1	2	3
$\hat{F}'_{\alpha\beta}$			$\bullet$	$\bullet$
D3	×	×	×	×

$\equiv$

	0	1	2	3
D1	×	×		
D3	×	×	×	×

$\xrightarrow{\hat{g}' \to \infty}$

	0	1	2	3
D1	×	×		

The D3/D1 rate

The pair production rate for D3/D1 is

$$\begin{aligned} \mathcal{W}^{(1)}_{D3/D1} &= \lim_{\hat g' \to \infty} \frac{(2\pi\sqrt{\alpha'})^2 \mathcal{W}^{(1)}_{D3/D3}}{\hat g'}, \\ &= \frac{eE}{2\pi} e^{-\frac{\pi(m^2 - \nu_0'/(2\alpha'))}{eE}}, \end{aligned} \tag{3.3}$$

where $\mathcal{W}^{(1)}_{D3/D3}$ is the rate (3.2) and $\nu_0 = 2\alpha' eE$ from (3.1) has been used. Here the mass is still given as $m = y/(2\pi\alpha')$.

Now also from (3.1) when $\hat g' \to \infty$ is taken, we have

$$\tan \pi\nu_0' = \frac{1}{\hat g}. \tag{3.4}$$

which gives $\nu_0' = 1/2$ when $\hat g = 0$ and $\nu_0' \sim 1/2$ for small lab $\hat g$.

The D3/D1 rate

As before, we now try to understand which open string mode(s) actually contributes to the rate given in the second line of (3.3), i.e.,

$$\mathcal{W}^{(1)}_{D3/D1} = \frac{eE}{2\pi} e^{-\frac{\pi(m^2 - \nu_0'/(2\alpha'))}{eE}}. \tag{3.5}$$

In the above, we have

$$\frac{\nu_0'}{2\alpha' eE} = \frac{\nu_0'}{\nu_0} \gg 1, \tag{3.6}$$

since $\nu_0' \sim 1/2$ and $\nu_0 \ll 1$, so only the lowest energy mode contributes to this rate. Let us now identify this mode.

The fermionic modes from the R-sector have mass no less than $m = y/(2\pi\alpha')$ when magnetic fluxes are applied, so they are not the ones contributing to the rate.

The lowest energy mode

Then the needed mode must come from the NS-sector. The spectrum in the NS-sector is now,

$$\alpha' E^2_{\rm NS} = (2N+1)\frac{\nu'_0}{2} - \nu'_0\, S + \alpha' M^2_{\rm NS}, \qquad (3.7)$$

where $b^+_0 b_0 = N$ defines the Landau level, the mass $M_{\rm NS}$, the spin operator S in the 23-direction and the number operator $N_{\rm NS}$ are

$$\alpha' M^2_{\rm NS} = \frac{y^2}{4\pi^2\alpha'} + N_{\rm NS} - \frac{1}{2}, \qquad (3.8)$$

$$\begin{aligned} S &= \sum_{n=1}^{\infty}(a^+_n a_n - b^+_n b_n) + \sum_{r=1/2}^{\infty}(d^+_r d_r - \tilde{d}^+_r \tilde{d}_r), \\ N_{\rm NS} &= \sum_{n=1}^{\infty} n(a^+_n a_n + b^+_n b_n) + \sum_{r=1/2}^{\infty} r(d^+_r d_r + \tilde{d}^+_r \tilde{d}_r) + N^{\perp}_{\rm NS}. \end{aligned} \qquad (3.9)$$

The lowest energy mode

It is not difficult to check that the lowest energy is given by the GSO projected state $d^{+}_{1/2}|0\rangle_{\rm NS}$ with now the spin $S = 1$ and the energy is

$$\alpha' E^2_{\rm NS} = -\nu'_0/2 + y^2/(4\pi^2\alpha'), \tag{3.10}$$

with a tachyonic shift $-\nu'_0/2$.

The present rate (3.5) can now be expressed as

$$\mathcal{W}^{(1)}_{D3/D1} = \frac{eE}{2\pi} e^{-\frac{\pi E^2_{\rm NS}}{eE}}. \tag{3.11}$$

A possibility of detection

So it is clear that the same pair of charged/anti-charged vector polarizations, as in the D3/D3 case discussed previously, contribute to the rate (3.3).

However, the present pair production rate for D3/D1 is completely different from the one (2.18) for D3/D3 for the same applied lab. E and B on our own D3.

$$\mathcal{W}^{(1)}_{D3/D1} = \frac{eE}{2\pi} e^{-\frac{\pi\left(m^2 - \frac{\nu_0'}{2\alpha'}\right)}{eE}}, \qquad \mathcal{W}^{(1)}_{D3/D3} \sim \frac{(eE)(eB)}{(2\pi)^2} e^{-\frac{\pi(m^2 - eB)}{eE}}. \tag{3.12}$$

The present D3/D1 rate appears to give a unique stringy signature.

A possibility of detection

Most importantly, unlike the previous rate for D3/D3, the present rate gives a possibility for detection in the following sense:

The lowest energy defines an effective mass $m_{\rm eff}^2 = m^2 - 1/(4\alpha')$ when we take $\hat{g} = 0$. Concretely, if $m \approx 1/(2\sqrt{\alpha'})$, or $y \sim \pi\sqrt{\alpha'}$, giving a small effective $m_{\rm eff}$, we need then only a small $eE \sim m_{\rm eff}^2$ to detect the pair production.

Further, with a small tunable $\hat{g} = 2\pi\alpha' eB \ll 1$, we can check the rate behavior against E and B and this can be used to check the stringy computations.

Implication

Implications: If such a detection, for example as an electric current due to the pair production, is indeed possible,

- it first implies the existence of extra dimensions.
- secondly, it gives a new way to verify the underlying string theory without the need to compactify 10 D to 4D so long the pair production is concerned.

THANK YOU!