What does it imply if the Schwinger pair production in QED cannot be observed?

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2024 全国粒子物理大会, 青岛
2024.8.13-18

August 14, 2024

The talk is based on the following papers:

- J. X. Lu,“Magnetically-enhanced open string pair production,” JHEP **12**, 076 (2017)
- 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)
- J. X. Lu, “A note on the open string pair production of the D3/D1 system,” JHEP **10**, 238 (2019)
- Q. Jia, J. X. Lu, Z. Wu and X. Zhu, “On D-brane interaction & its related properties,”Nucl. Phys. B 953 (2020)114947
- J. X. Lu and Nan Zhang, “More on the open string pair production” , Nucl. Phys. B **977** (2022) 115721
- J. X. Lu, “Understanding the open string pair production of Dp/D0 system”, JHEP **11**, 019(2023).
- J. X. Lu, “The open string pair production, its enhancement and the physics behind,” PLB 848 (2024)138397
- J. X. Lu, “The open string pair production revisited” arXiv 2405.02558

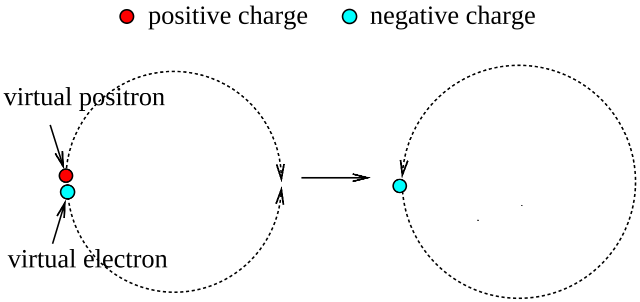
Outline

- Motivation/Introduction
- The open string pair production in Type II string theories
- The detection of the stringy pair vs the QED Schwinger pair
- Conclusion and discussion

QED Vacuum Fluctuation

THE QED VACUUM FLUCTUATION

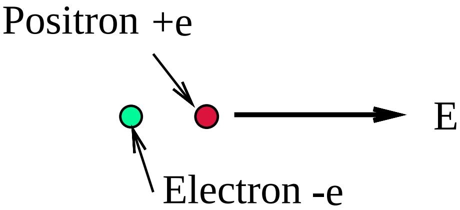
An anti-charge moving forward in time equivalent to a charge moving backward in time



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

QED Vacuum Fluctuations

There are ways to test the QED vacuum picture. One is to apply a constant E to the vacuum and there is certain probability to create real electron and positron pairs from the vacuum fluctuations, called Schwinger pair production (1951).



The rate obtained by Schwinger is actually the decay one of the QED vacuum and is

$$\mathcal{W}^{\text{Schwinger}}_{\text{spinor}} = \frac{2(eE)^2}{(2\pi)^3} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-n\pi \frac{m_e^2}{eE}}, \tag{1.1}$$

where $m_e = 0.51$ MeV is the mass of electron and e is unit charge or the gauge coupling g_{YM}.

QED Vacuum Fluctuations

The pair production rate, in a constant applied electric field E, can be computed Nikishov'70 and happens to be the leading $n = 1$ term of the Schwinger decay rate as

$$\mathcal{W}^{\rm QED}_{\rm spinor} = \frac{2(eE)^2}{(2\pi)^3}\, e^{-\frac{\pi m_e^2}{eE}}\,. \qquad (1.2)$$

The question is: how large E is such that the pair production can actually be detected, say, via an electric current?

This can be estimated to be

$$2eE_T\,\frac{1}{m_e} = 2m_e \to E_T = \frac{m_e^2}{e} \sim 10^{18}\,{\rm Volt/m}. \qquad (1.3)$$

QED Vacuum Fluctuations

- The great success of QED makes nobody doubt the QED vacuum picture.
- However, this pair creation process has so far not been directly detected or observed:
  1. In the case of Schwinger pair production, its null detection is partly due to the current lab limit $E \sim 10^{10}$ V/m.
  2. This pair creation is expected to be seen, for example, in the case of superheavy nuclei ($Z > 173$), though via a different mechanism, but so far the detection is still null.
  3. The Schwinger pair production naively appears to occur within stable atoms, for example, at a radial distance $r \leq 10^{-13}$ m from the proton (its classical radius is 8.8×10^{-16} m) in a hydrogen atom for which $E \geq E_T \sim 10^{18}$ Volt/m but this cannot happen for sure and the underlying physics is unclear (please let me know if you know why).

The Schwinger pair production

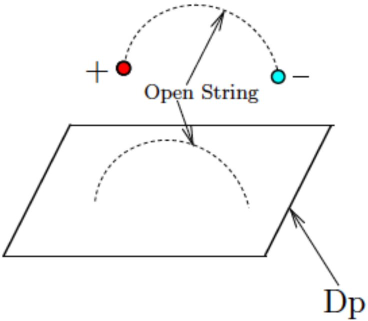
- These null detections could point to a possibility regarding if the QED vacuum picture, an effective one from the modern view, is complete.

In this talk, I will try to address this issue by mimicking the underlying true vacuum of our $(1+3)$ dimensional QED by a D3 brane in the Type IIB superstring theory and to consider the corresponding Schwinger process in this setting.

This will provide an explanation to the null detection even when the applied $E \geq E_T$ at the current stage of our Universe.

The future (positive or negative) detection of this pair production, for example, by the heavy ion collision facilities in Germany (GSI/FAIR), China (HIAF) and Russia (NICA) or the next generation of laser facilities, can decide or falsify this alternative picture.

D-branes in Type II

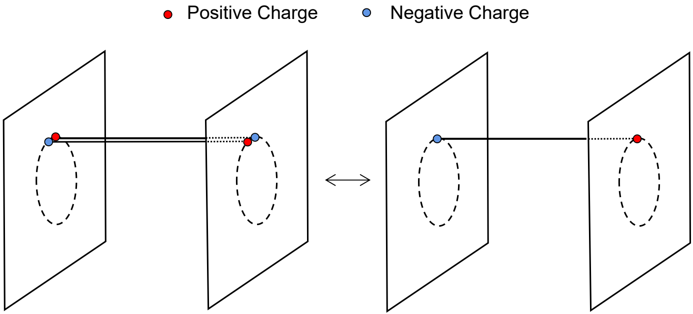


D-branes in Type II

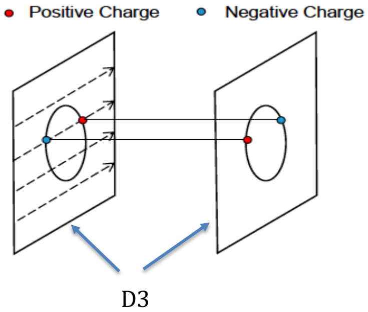
The point is: unlike in QED, an isolated D3 brane cannot give rise to the pair production even if a large but less than the critical electric field is applied.

The open string pair production

A simple setup for this is to consider two D branes in Type II string theory, placed parallel at a separation.



The open string pair production



The D3/D3 rate

Consider the electric/magnetic tensor $\hat{F}^1$ on one D3 brane and the $\hat{F}^2$ on the other D3 brane, respectively, as

$$\hat{F}^a_{\alpha\beta} = \begin{pmatrix} 0 & \hat{f}_a & 0 & 0 \\ -\hat{f}_a & 0 & 0 & 0 \\ 0 & 0 & 0 & \hat{g}_a \\ 0 & 0 & -\hat{g}_a & 0 \end{pmatrix}, \qquad (2.1)$$

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 $a = 1, 2$. Note $\hat{F}_{\mu\nu} = 2\pi\alpha' F_{\mu\nu}$. Note $[\alpha'] = -2$, $[F] = 2 \to [\hat{F}] = 0$.

The D3/D3 rate

In order to compute the pair production rate, we first need to compute the open string one-loop annulus amplitude between the two D3, following Lu'17, 18, 19, as

$$\Gamma_{3,3} = \frac{4\,V_4|\hat{f}_1 - \hat{f}_2||\hat{g}_1 - \hat{g}_2|}{(8\pi^2\alpha')^2}\int_0^\infty \frac{dt}{t}\, e^{-\frac{y^2 t}{2\pi\alpha'}}\,\frac{(\cosh\pi\nu_0' t - \cos\pi\nu_0 t)^2}{\sin\pi\nu_0 t\,\sinh\pi\nu_0' t}\prod_{n=1}^{\infty} Z_n, \tag{2.2}$$

where y is the brane separation and

$$Z_n = \frac{\prod_{j=1}^{2}[1 - 2\,e^{(-)^j\pi\nu_0' t}|z|^{2n}\cos\pi\nu_0 t + e^{(-)^j 2\pi\nu_0' t}|z|^{4n}]^2}{(1-|z|^{2n})^4(1-2\,|z|^{2n}\cos 2\pi\nu_0 t + |z|^{4n})\prod_{j=1}^{2}(1 - e^{(-)^{(j-1)}2\pi\nu_0' t}|z|^{2n})}, \tag{2.3}$$

with $|z| = e^{-\pi t}$. In the above, the parameters $\nu_0 \in [0,\infty)$ and $\nu_0' \in [0,1)$ are determined via

$$\tanh\pi\nu_0 = \frac{|\hat{f}_1 - \hat{f}_2|}{1 - \hat{f}_1\hat{f}_2}, \quad \tan\pi\nu_0' = \frac{|\hat{g}_1 - \hat{g}_2|}{1 + \hat{g}_1\hat{g}_2}. \tag{2.4}$$

The D3/D3 rate

- For large t, the integrand of the above amplitude behaves like $e^{-\frac{t}{2\pi\alpha'}(y^2-2\pi^2\alpha'\nu_0'^2)}/t$ which vanishes when $y \geq \pi\sqrt{2\nu_0'\alpha'}$ but blows up when $y < \pi\sqrt{2\nu_0'\alpha'}$ if $\nu_0' \neq 0$, indicating a tachyonic instability at this separation for which the computations fail.
- The above amplitude has an infinite many simple poles which are determined by $\sin \pi\nu_0 t = 0$, $\nu_0' \neq 0$ and occur at

$$\pi\nu_0 t_k = k\pi \to t_k = \frac{k}{\nu_0}, \quad k = 1, 2, \cdots , \tag{2.5}$$

  along the positive t-axis.
- The system will relax itself or decay to a stable 1/2 BPS one by producing open string pairs at these poles to lower its excess energy due to the presence of electric fluxes or via tachyonic condensation in the presence of pure magnetic fluxes under the attractive interaction.

The D3/D3 rate

- For the pair production case, the presence of an infinite many number of simple poles implies that the amplitude has an imaginary part and this will give the decay rate of the underlying system.
- This decay rate can be computed as the sum of the residues of the integrand in (2.2) at these poles times π per unit worldvolume following Bachas and Porrati' 92 as

$$\begin{aligned}\mathcal{W} &= -\frac{2\,\mathrm{Im}\Gamma}{V_4}\\ &= \frac{8|\hat f_1-\hat f_2||\hat g_1-\hat g_2|}{(8\pi^2\alpha')^2}\sum_{k=1}^{\infty}(-)^{k-1}\frac{\left[\cosh\frac{\pi k\nu_0'}{\nu_0}-(-)^k\right]^2}{k\sinh\frac{\pi k\nu_0'}{\nu_0}}\,e^{-\frac{ky^2}{2\pi\alpha'\nu_0}}\prod_{n=1}^{\infty}Z_n^k\end{aligned} \tag{2.6}$$

where

$$Z_n^k=\frac{\left(1-(-)^k\,e^{-\frac{2nk\pi}{\nu_0}(1-\frac{\nu_0'}{2n})}\right)^4\left(1-(-)^k\,e^{-\frac{2nk\pi}{\nu_0}(1+\frac{\nu_0'}{2n})}\right)^4}{\left(1-e^{-\frac{2nk\pi}{\nu_0}}\right)^6\left(1-\,e^{-\frac{2nk\pi}{\nu_0}(1-\nu_0'/n)}\right)\left(1-\,e^{-\frac{2nk\pi}{\nu_0}(1+\nu_0'/n)}\right)}. \tag{2.7}$$

The D3/D3 rate

The non-perturbative open string pair production rate is however different and happens to be given as the first term $(k = 1)$ of the above decay rate, following Nikishov'70 & Lu'17, 18, 19, 24, as

$$\mathcal{W}^{(\mathrm{String})} = \frac{8\,|\hat{f}_1 - \hat{f}_2||\hat{g}_1 - \hat{g}_2|}{(8\pi^2\alpha')^2}\, e^{-\frac{y^2}{2\pi\nu_0\alpha'}} \frac{\left[\cosh\frac{\pi\nu_0'}{\nu_0} + 1\right]^2}{\sinh\frac{\pi\nu_0'}{\nu_0}} Z_1(\nu_0, \nu_0'), \tag{2.8}$$

where

$$Z_1(\nu_0, \nu_0') = \prod_{n=1}^{\infty} \frac{\left[1 + 2e^{-\frac{2n\pi}{\nu_0}}\cosh\frac{\pi\nu_0'}{\nu_0} + e^{-\frac{4n\pi}{\nu_0}}\right]^4}{\left[1 - e^{-\frac{2n\pi}{\nu_0}}\right]^6 \left[1 - e^{-\frac{2\pi}{\nu_0}(n-\nu_0')}\right] \left[1 - e^{-\frac{2\pi}{\nu_0}(n+\nu_0')}\right]}. \tag{2.9}$$

The D3/D3 rate

In practice, $|\hat{f}_a| \sim |\hat{g}_a| \ll 1$ with $a = 1, 2$, giving

$$\nu_0 \ll 1,\ \nu_0' \ll 1, \tag{2.10}$$

the above $Z_1(\nu_0, \nu_0')$ can be expanded

$$Z_1(\nu_0, \nu_0') = 1 + 4\left[1 + \cosh\frac{\pi\nu_0'}{\nu_0}\right]^2 e^{-\frac{2\pi}{\nu_0}} + \cdots\,, \tag{2.11}$$

which gives

$$Z_1(\nu_0, \nu_0') \approx 1, \tag{2.12}$$

The D3/D3 rate

For simplicity, we consider the case $\hat{f}_2 = \hat{g}_2 = 0$ on the hidden D3 while on our own D3, in terms of the lab. field E and B via

$$\hat{f}_1 = 2\pi\alpha' eE \ll 1, \qquad \hat{g}_1 = 2\pi\alpha' eB \ll 1, \tag{2.13}$$

the pair production rate (2.8) for D3 brane is now

$$\mathcal{W}^{(\mathrm{String})} = \frac{2(eE)(eB)}{(2\pi)^2} \frac{\left[\cosh \frac{\pi B}{E} + 1\right]^2}{\sinh \frac{\pi B}{E}} e^{-\frac{\pi m^2(y)}{eE}}, \tag{2.14}$$

where we have introduced the mass for the lowest modes of the open string connecting the two D3

$$m(y) = T_f y = \frac{y}{2\pi\alpha'}. \tag{2.15}$$

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

The D3/D3 rate

In particular, we find the following remarkable, though expected, relation (Lu'23),

$$\mathcal{W}^{(\mathrm{String})} = 5\, W^{\mathrm{QED}}_{\mathrm{scalar}} + 4\, W^{\mathrm{QED}}_{\mathrm{spinor}} + W^{\mathrm{QED}}_{\mathrm{vector}}, \tag{2.16}$$

where we write again (2.14) explicitly for comparing

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

while the various QED rates are

$$\mathcal{W}^{\mathrm{QED}}_{\mathrm{scalar}} = \frac{(eE)(eB)}{2(2\pi)^2} \mathrm{csch}\left(\frac{\pi B}{E}\right) e^{-\frac{\pi m^2}{eE}}, \quad \mathcal{W}^{\mathrm{QED}}_{\mathrm{spinor}} = \frac{(eE)(eB)}{(2\pi)^2} \coth\left(\frac{\pi B}{E}\right) e^{-\frac{\pi m^2}{eE}}, \tag{2.18}$$

for a massive charged QED scalar pair and a massive charged QED spinor pair, respectively Nikishov'70, and

$$\mathcal{W}^{\mathrm{QED}}_{\mathrm{vector}} = \frac{(eE)(eB)}{2(2\pi)^2} \frac{2\cosh \frac{2\pi B}{E} + 1}{\sinh \frac{\pi B}{E}}\, e^{-\frac{\pi m^2}{eE}}. \tag{2.19}$$

for a massive charged QED vector pair Kruglov'01. In (2.16), we have set $m_0 = m_{1/2} = m_1 = m$ with m given by (2.15).

The D3/D3 rate detection

Unless there exists already a hidden D3 from our own D3 at a separation y giving a mass $m = y/(2\pi\alpha') \sim m_e$ for some specific reason at the current stage of our Universe, we have to wait for such an event to happen so that a non-zero detection is possible when the lab $E \geq E_T \sim 10^{18}$ Volt/m

In other words, even when we can realize the lab $E \sim E_T$, the chance to detect such a pair production is quite unlikely in a short amount of time though there might be a possibility for this if we wait long enough, therefore providing an explanation to the possibility raised at the outset, i.e., a still null detection.

The stringy rate vs the Schwinger rate

Suppose that we can realize $E \sim E_T \sim 10^{18}$ Volt/m in the Lab in the foreseeable future, we expect two possibilities:

- If QED vacuum is indeed correct, we then expect the QED Schwinger pair production to be detected during a reasonable time and this positive detection will rule out the alternative possibility we are taking here.
- If on the other hand, we still have a null detection of the pair production in a reasonable short time, this will point to the alternative picture, for example, the brane picture we are taking here.

This sharp distinction between the two scenarios makes its easier to falsify either.

Conclusion and discussion

- Unlike in QED, we need at least two separate D branes to give rise to the open string pair production in Type II superstring theories (Lu PLB788 (2019) 480, JHEP11 (2023) 019, PLB 848 (2024) 138397);
- If in the near future, the detection of the pair production indeed follows the QED Schwinger one, this will then point to the QED vacuum picture, an effective one;
- If on the other hand, we still have a null detection even for a large enough electric field $E \geq E_T$, this will point to the need of the underlying true vacuum of a fundamental theory such as the stringy picture taken here Lu'24 .

THANK YOU!

Conclusion and discusion

- The open strings so produced can have the following potential applications:
  1. Detection of them by a brane observer, say, as the produced current, will signal the existence of extra dimension(s) (Lu PLB788 (2019) 480, JHEP10 (2019) 238, Lu&Zhang NPB977 (2022) 115721) ;
  2. If this pair production occurs in our early Universe, the so produced open string pairs can then annihilate to give rise to the standard model particles, therefore can provide a new mechanism for the reheating process in cosmology (Lu JHEP12 (2017) 076, Lu&Zhang NPB977 (2022) 115721); if in the late time of our universe, this can give rise to high energy cosmic rays and γ-burst (LuJHEP12 (2017) 076, Lu&Zhang NPB977 (2022) 115721);
  3. Unlike in QED, such a pair production needs the presence of the second D3 and as such, the hidden brane relative to the our world (the visible D3 brane) can be a source of Dark matter (Lu PLB848 (2024) 138397).