Dirac Vacuum as a Transport Medium for Information

Q. Su and R. Grobe

Phys. Rev. Lett. **122**, 023603 — Published 18 January 2019

DOI: 10.1103/PhysRevLett.122.023603

The Dirac vacuum as a transport medium for information

Q. Su and R. Grobe

Intense Laser Physics Theory Unit and Department of Physics
Illinois State University, Normal, IL 61790-4560, USA

Usually the transport of information requires either an electromagnetic field or matter as a carrier. It turns out that the Dirac vacuum state itself can be exploited as a potentially loss-free carrier of information between two distant locations in space. At the first location a spatially localized electric field is placed, whose temporal shape is modulated, for example, as a binary sequence of distinguishable high and low values of the amplitude. The resulting distortion of the vacuum state reflecting this information propagates then to a second location, where this digital signal can be read off sequentially by a static electric field pulse. If this second field is supercritical it can create electron-positron pairs from the manipulated vacuum state. The original information transported by the vacuum is then imprinted on the temporal behavior of created particle yield for a selected energy.

There are typically three distinct modes under which classical (either analog or digital) information can be communicated from a sender to a receiver. These can involve the direct transport of matter (e.g., regular mail), the propagation of a (coded) distortion of a matter-based medium (e.g., sound waves) or, technologically most important, the transport of electromagnetic radiation. In this Letter, we provide a proof of concept, that, at least in principle, there can be a fourth mode, which requires neither a medium nor any propagating radiation. It is based on the numerical finding that the Dirac vacuum state itself can be manipulated in a controlled way by a spatially localized electric field if its amplitude is modulated in time. The resulting coded distortion of the vacuum state evolves to a distant location where the receiver is located, which can read off this signal using, for example, the electron-positron pair creation process.

The very idea that information (about the existence of objects) can be obtained without particles being exchanged has already been suggested by Elitzur and Vaidman [1] and observed experimentally [2]. In contrast to our scheme, here this information is communicated by an interrogating photon based on an "interaction-free" measurement in an interferometer.

Several of the remarkable properties of the vacuum state (leading to the Casimir effect [3] or the vacuum polarization [4]) have already been verified experimentally. Recently, probing the vacuum using very intense external laser fields has also become a subject of wide interest [5]. Numerous experimental labs worldwide [6] aim at exploring the vacuum's non-linear properties with the goal to test spectacular predictions such as light-light scattering [7], photon splitting [8], vacuum birefringence [9], or the intriguing creation of electron-positron pairs [10,11].

Our theoretical approach is based on computational quantum field theory to determine the electron-positron field operator from the Dirac equation [12]. The data show that the original coded distortions due to the temporal modulation of the sender's field modify the pair creation process at the receiver's location. We compare the resulting number of electron-positron pairs as a function of time as a key diagnostic obtained from the Dirac equation with the predictions by a simple but fully analytical model that captures the basic ideas of this scheme.

In the framework provided by the Dirac equation, the vacuum state is described by unoccupied states of positive energy ($>mc^2$) and the full occupation of each state of negative energy ($<-mc^2$). A direct interpretation of the states with a negative energy (called negaton states or Dirac sea) is possible based on the charge-conjugation symmetry and the resulting corresponding hole theory. The complete set of occupied states can be described equivalently by either standing or by (left and right) traveling waves. For our phenomenon, it is more illustrative to view these states as traveling waves with a fixed momentum. As a side issue, we note that due to its negative energy, denoted by e, a state with negative momentum k corresponds to a probability flux to the right, i.e. the velocity is v = ck/e. Due to the fermionic Pauli exclusion principle it is not possible to increase the population of each negaton level, however, by using a spatially localized electric field, it is possible to rearrange the populations by effectively blocking some of the right traveling probability by forcing it to a complete stop and a consequent reflection.

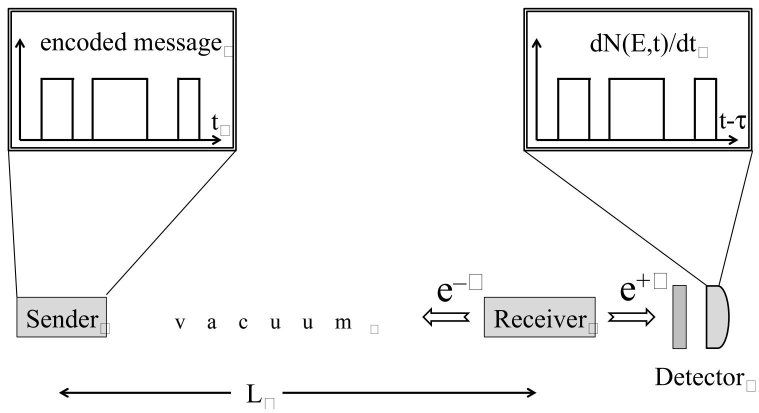

Figure 1 Sketch of the set-up for the vacuum as a carrier of information. In the left inset we show the time-dependence of an electric pulse that is spatially localized at a distant L from the receiver. The receiver contains a spatially localized supercritical field that creates e^{-}- e+ pairs from the (modulated) vacuum.

The geometry of our set-up is sketched in Figure 1. The sender modulates the temporal amplitude F_S of an electric field, which is spatially localized around x = –L and points in the direction opposite of the receiver. In our simplified example, the original sender's message is encoded here by a three-square pulse sequence with characteristic pulse turn-on and -off times. The receiver is is located at x = 0, where a temporally constant narrow electric field F_R is placed. This field is supercritical, i.e. its associated potential energy V_R exceeds twice the positron's rest energy, (V_R>2mc^2), such that it can create fermions based on the Schwinger mechanism [11]. The detector measures the number of positrons N(E,t) within a selected energy range centered at E and outputs the corresponding time-dependence of the creation rate $\Gamma(t) \equiv dN(E,t)/dt$.

In the absence of the sender's action (F_S = 0), the receiver's supercritical electric field F_R at x = 0 would create a constant flux of positrons (electrons) evolving to the right (left). The particles' growth is described by a production rate Γ that depends on the strength V_R (>2mc^2) and the spatial profile of the field $F_R(x)$. If this shape is given by $F_R(x) = V_R\, \mathrm{Sech}(x/w)^2/(2w)$ with a narrow spatial width w, the creation rate per unit energy for positrons with energy E (for $mc^2 < E < V_R - mc^2$) is given by the well-known expression [13,14]

$$\Gamma(E) = c\,[V_R - E)^2 - m^2c^4]^{1/2}/[B(V_R - E)]\; T(E) \quad (1a)$$

$$T(E) \equiv -\sinh[\pi p w]\,\sinh[\pi k w] \,/\, \{\sinh[\pi(V_R/c + p + k)w/2]\,\sinh[\pi(V_R/c - p - k)w/2]\} \quad (1b)$$

where $k \equiv -[(E-V_R)^2 - m^2c^4]^{1/2}/c$, $p \equiv [E^2 - m^2c^4]^{1/2}/c$ and B is the extension of the system. The number density of positrons would grow here linearly in time, i.e., $N(E,t) = \Gamma(E)\, t$. In a prior note, it was shown [14] that the positrons with energy E are converted uniquely from the particular negaton state with (negative) energy $e \equiv E - V_R$, with (negative) momentum k and (positive) velocity $v = -c\,[e^2 - m^2c^4]^{1/2}/e$. This one-to-one match follows from the usual tunneling picture for the thoroughly studied Schwinger pair creation process for a spatially localized force field, where an incoming (negaton) state (with uplifted energy) can tunnel through the supercritical force region. This also means that the fastest negaton states for $x < 0$ [with velocity $v = c\,[(V_R - mc^2)^2 - m^2c^4]^{1/2}/(V_R - mc^2)$] create the slowest positrons [with zero velocity, i.e. $E = mc^2$].

In the presence of the sender's field ($F_S \neq 0$), the probability flux of those negaton states with energy e in the range $-mc^2 < e < -mc^2 - V_S$, [where V_S is the (positive) magnitude of the potential energy associated with the field] is completely reflected at $x = -L$. As $V_S < 2mc^2$, the sender cannot create any particles. The spatially vacated portion in the negaton states originates at $x = -L$, evolves with the speed $v = -c\,[e^2 - m^2c^4]^{1/2}/e$ towards the receiver and finally arrives there after a characteristic delay time $\tau \equiv L/v$, or

$$\tau(E,L) = L\,(V_R - E)\,/\{c\,[(E - V_R)^2 - m^2c^4]^{1/2}\} \quad (2)$$

In other words, if the sender's field was turned on at t=0, then after a delay time τ the creation process for positrons with energies in the range $V_S - mc^2 - V_R < E < V_S - mc^2$ will come to a complete halt. As this delay time increases monotonically with E, the halt of the creation process manifests itself first for the slowest positrons (E close to mc^2). The shortest possible delay time τ decreases naturally with increasing amplitude of the sender's field V_S. If V_S is sufficiently large, then fast negaton states (with a speed close to c) can be blocked, such that the shortest arrival time of the vacant portion of the negaton state would be $L\,(mc^2+V_S)/\{c\,[(mc^2+V_S)^2-m^2c^4]^{1/2}\}$, which approaches consistently the natural limit $\tau \rightarrow L/c$ with increasing V_S.

If we assume now that the sender's field $F_S(x,t)$ can be turned on and off in time in a controlled way, i.e. V_S becomes a function of time, then this modulation (provided in our example by the three-pulse sequence) is directly mapped onto the pair creation rate of the positrons at a given energy. Using the simplistic assumptions discussed above one can define and calculate a time-dependent pair-creation rate $\Gamma(E,t) = \chi(E,t)\,\Gamma(E)$. The resulting number density of all accumulated positrons with energy E is given by $N(E,t) = \int dt\, \Gamma(E,t)$ and the total number of pairs naturally amounts to $N(t) = \int dE\, N(E,t)$. Here $\chi(E,t)$ conveys the information contained by $V_S(t)$. It can be chosen as a smooth threshold function that changes its value continously from $\chi=0$ to $\chi=1$ or by the Heaviside unit step function $\theta(x) \equiv (1+x/|x|)/2$ as its discontinous limit. To reflect the energy dependent time delay due to the finite propagation speed from the sender to the receiver, we could model the threshold function as $\chi(E,t) = \theta\big[V_R-mc^2-V_S(t-\tau(E,L))-E\big]$. We therefore arrive at the prediction

$$N(E,t) = \int dt\, \Gamma(E)\, \theta\big[V_R - mc^2 - V_S\big(t - L(E-V_R)/\{c[(E-V_R)^2 - m^2c^4]^{1/2}\}\big) - E\big] \qquad (3)$$

where the rate $\Gamma(E)$ is calculated from Eq. (1).

In order to examine the validity of this analytical prediction, we have to solve the quantum field theoretical system exactly. We refer the reader here to numerous prior works about the computational details and just state the final results here [12,15]. In short, the method to compute the energy spectra, pair creation rates and spatial distributions of the particles for external fields with arbitrary space-time dependence is based on numerical solutions to the time-dependent Dirac equation, which governs the time evolution of the electron-positron field operator. This operator in its momentum representation is obtained on a numerical space-time grid. The spectra of the created positrons are then determined via the expectation values of the creation and annihilation operators as $N(E,t) \equiv \langle b(E,t)^\dagger b(E,t)\rangle$.

In Figure 2 we display the temporal growth of the positrons N(E,t) with energy $E = 1.2\ mc^2$. The receiver's field of amplitude $V_R = 2.5\ mc^2$ was turned on at time t=0 leading to the early linear growth with slope Γ matching that of Eq. (1). We assume that the sender decodes her message by turning her field on and off three times with various durations as shown by the rectangular pulse train $F_S(t)$ in the Figure. Here the first pulse was turned on at time $T_{S,1}$ (=10^{-3} a.u.) and lasted a duration $T_{D,1}$ (=4×10^{-3} a.u.). After a time $T_{S,1} + \tau$, the blocked (spatially vacant) portion of the negaton states arrives at x=0 and, as a result, N(E,t) stops growing for a period of $T_{D,1}$, after which the pair creation process resumes with its original rate Γ. The sender's second and third pulses (with $T_{S,2} = 10^{-2}$ a.u. and duration 6×10^{-3} a.u. and $T_{S,3} = 2.5\times10^{-2}$ a.u. with duration 3×10^{-3} a.u.) are then equally mapped onto the corresponding following intervals of interruption and resumption of the pair creation process. The open circles for N(E,t) correspond to the numerical solution of the Dirac equation, while the solid line is the analytical prediction of Eq. (3). In view of the extreme simplicity of this model and the fact that there are no free parameters to fit the data, the agreement is superb and therefore describes the basic mechanism of the propagation of the vacuum's distortion remarkably well.

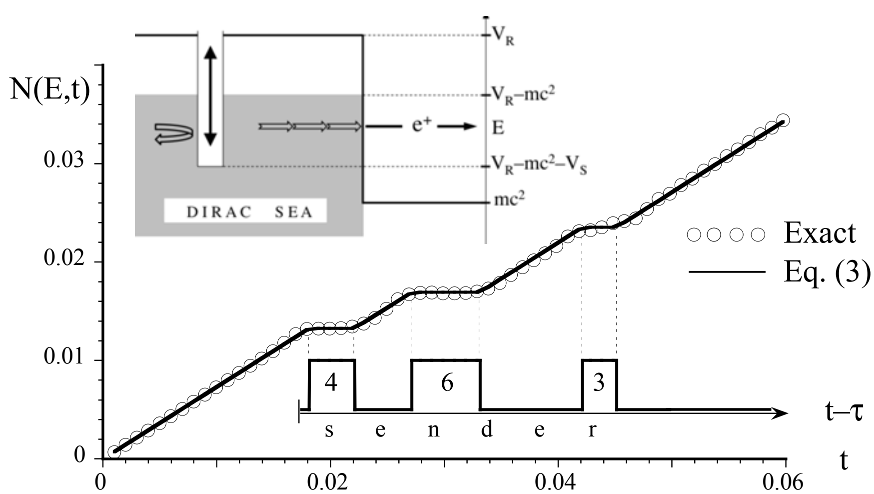

Figure 2 The open circles show the growth of the number density of created positrons N(E,t) as the vacuum is temporally modulated by the sender's electric field of magnitude $F_S(t)$ shown below. For comparison, the solid line is the prediction according to Eq. (3). The displayed pulse durations of the sender's field are in 10^{-3} atomic units [L=1.5 a.u., $V_S=0.35mc^2$, $w_S=2.2\times10^{-2}$ a.u., $V_R=2.5mc^2$, $w_R=2.2\times10^{-3}$ a.u., the electric fields have the spatial shape $-V_S\ \mathrm{sech}[(x+L)/w_S]^2/(2w_S)$ and $V_R\ \mathrm{sech}(x/w_R)^2/(2w_R)$, positron energy $E=1.2mc^2$, the slope of the graph is Γ(E)=0.732 with T(E)=0.268 and delay $\tau=1.71\times10^{-3}$a.u., numerical box B=32 a.u.

with 32,768 spatial and 10,000 temporal grid points to solve the Dirac equation]

There is an interesting secondary side effect of "electron echoes" that is based on the actual transport of matter and can accompany the vacuum distortion effect at later stages. It occurs if the distance between the sender and reader L is too small, or equivalently, if the duration of the sender's message is too long. This most important modification of the vacuum transmission scheme arises from the fact that (starting at time t=0) also electrons are simultaneously created by the receiver's field. These are ejected to the left back towards the sender's field, which can bounce them back to the receiver, where they can re-enter the creation zone at x=0. To avoid the dynamical complication of this bouncing back, we have purposely chosen the timing of the sender's field such that it was zero precisely when the left traveling electron-bunch traversed the region around $x = -L$.

In order to focus now exclusively on the impact of this echo effect, we have chosen a simple sender's signal that was turned on at time T_S ($=10^{-4}$ a.u.) and remained on as displayed on the bottom of Figure 3.

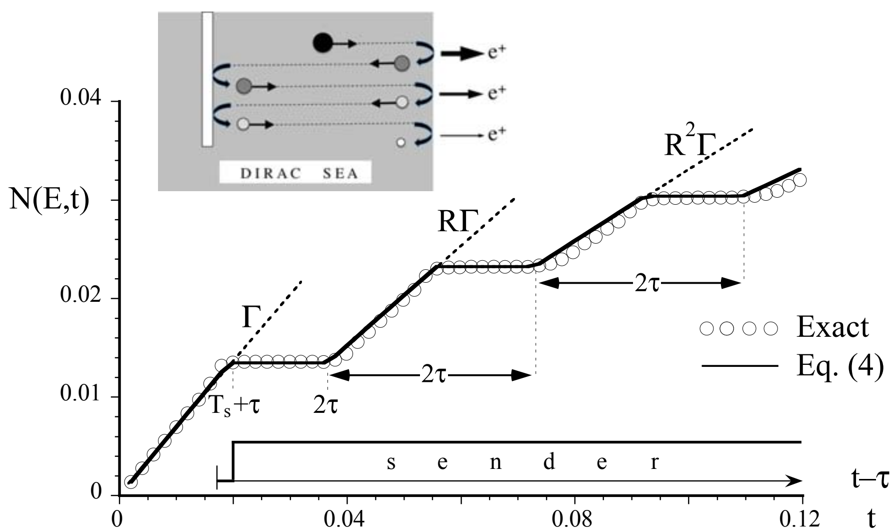

Figure 3 Impact of the electron echoes on the growth of the number density of created positrons N(E,t) as the vacuum is blocked by the sender's electric field $F_S(t)$ shown below. For comparison, the solid line is the prediction according to Eq. (4). [All field and numerical parameters are as in Fig. 2, except the positron energy $E = 1.25mc^2$, leading to $\Gamma(E) = 0.700$ with $T(E) = 0.272$ and delay $\tau = 1.824\times10^{-3}$a.u.,]

The data obtained from the numerical solution of the Dirac equation (open circles) shows that after the time 2τ, the creation of the positrons unexpectedly resumes, despite the fact that E_S is still turned on and the relevant negaton states (for $x < -L$) continue to be blocked in this case. However, in contrast to Figure 2, here the growth resumes at a different time and also with a different rate $R\,\Gamma$, which is *reduced* by a factor of R<1. This is precisely the time when the returning partially occupied negaton states begin to re-open the positrons' creation channel. The corresponding hole picture based on the negaton states (sketched in the inset) suggests how we can compute the rate reduction factor R analytically. Here the original (fully occupied) negaton states are not only partially transmitted to x>0 [with a transmission coefficient T(E) that is given by Eq. (1b)] but also partially reflected to x<0 with reflection coefficient R(E) [= 1–T(E)]. After a time $\max(T_S,\tau)$ this portion is reflected at x = –L and approaches x = 0 at time $\max(T_S,\tau)+\tau$. Due to the prior reduction of its probability current by a factor of R, now only the new fraction of RT can be transmitted (corresponding to the creation of positrons), while the fraction R^2 is reflected. This alternative view suggests the following simple analytical prediction for N(E,t) based on a periodic sequence of linear growth and plateau intervals for $\max(T_S,\tau) = \tau$:

$$N(E,t) = \Gamma \Sigma_{n=1} R^{n-1} \{[t-(2n-2)\tau]\, U[(2n-2)\tau, T_S+(2n-1)\tau; t] + (T_S+\tau)\, U[T_S+(2n-1)\tau, \infty; t]\} \quad (4)$$

Here the generalized unit-step function is defined as $U[t_1,t_2;t] \equiv 1$ if $t_1 < t < t_2$ and $U \equiv 0$ otherwise. Once again, the good agreement with the exact numerical data (open circles) suggests that the above simple picture captures the basic ideas of the electron echoes. We should mention that in an equivalent electronic picture (where the field in the Dirac Hamiltonian is coupled to a negative charge) this step-wise periodic sequence of the complete inhibition and the resumption of the growth (at reduced rate) corresponds to the well-known formation process of electronic bound states in the corresponding attractive (but asymmetric) potential well as studied in [16,17].

The geometry as well as the numerical parameters were chosen with the main focus of presenting this new phenomenon from a most transparent perspective. We certainly made several oversimplifications, none of which, however, should have a qualitative impact. From an experimental perspective, the most serious assumption was that the receiver's supercritical electric field can break down the vacuum and generate electron-positron pairs. Even though this process has not been observed in a laboratory setting yet (due to the enormously large required electric field strength), its observation is consistently predicted by many independent theoretical works [5].

While the main focus of the present work was to point out that the Dirac vacuum is in principle capable of transporting classical information loss-free under idealized conditions, we briefly outline here some dispersion-based mechanisms that could deteriorate the signal's quality for long distances L in a real experiment. First, due to the (unavoidable) finite turn-on duration, the sender's field would not impact (block) the flux of all negaton states simultaneously. In fact, the flux of low-momentum modes would be naturally reduced before faster modes, which could be modelled by a generalized time-dependent delay time τ. Furthermore, realistic particle detectors would measure positrons within a finite energy band. If the delay time τ varies strongly within this band, dispersive effect might deteriorate the recovery of the original sender's signal by the positron current. As one measure of this effect ($\sim |d\tau/dk|$) decreases with large momenta, we would expect it be relevant only for slower negaton states. In addition, if the orientation of the sender's or the reader's electric field varies significantly with the position in three spatial coordinates, this could also act as an (independent) loss-mechanism. In contrast to quantum information theory, where the decoherence induced by the interaction with the environment can be decremental to photonic or ionic signal storage and its transport, it is not fully explored what the leading physical mechanisms for decoherence in negaton states may be.

Finally, we should note some differences of our proposed scheme to the quantum energy teleportation protocols pioneered by Hotta [18], where the entanglement of the vacuum's fluctuations plays a central role. In contrast to our scheme, here the result of the sender's local (energy inducing) measurement needs to be communicated classically to the receiver, who then performs an (energy extracting) measurement that depends on the information announced. Also, recently, Jonsson et al. [19] showed that quantum information can be transmitted using a massless quantum field without the mediation of any energy carrying quanta related to Casimir-like interactions. Here the receiver has to provide the (signal dependent) energy for the detection of the signal.

In summary, we have suggested that the Dirac vacuum state has sufficient structure that it could act -at least in principle- as a carrier of information. For example, this information can be imprinted on the Dirac vacuum via a temporally modulated electric field. We should comment that the required complete reflection of the incoming negaton states at $x = -L$ (into left moving states) is not in contradiction with the fermionic Pauli-exclusion principle, even though all negaton states are initially already fully occupied. The original positive momentum of each (left moving) state is shifted by the sender's field at $x = -L$ to even larger momenta, which automatically vacates these low momentum modes for $x < -L$. Therefore, the required complete transfer of population (reflection) of the right traveling states into left going modes at $x = -L$ is actually allowed, as it does not involve any (unpermitted) double excitation of these particular modes. Lastly, we should mention that while in this work the focus was on the impact of the modified vacuum on the pair creation process, modulated negaton states could also influence photon-photon scattering, birefringes processes, or other fascinating nonlinear phenomena predicted to occur already for the unperturbed vacuum. We certainly hope that this work can motivate further exciting future studies.

Acknowledgements

We are very thankful for helpful discussions with Dr. Q.Z. Lv in the early stage of the project. We also acknowledge illuminating discussions with Profs. N. Christensen and Y.T. Li. This work was supported by the NSF, NSFC (#11529402) and by a SEED award from Research Corporation.

References

[1] A.C. Elitzur and L. Vaidman, Found. Phys. 23, 987 (1993).

[2] For example, see, e.g., P.G. Kwiat, H. Weinfurter, T. Herzog, A. Zeilinger and M. A. Kasevich, Phys. Rev. Lett. 74, 4763 (1995).

[3] For recent works on the Casimir effect, see, E.A. Chan, S.A Aljumid, G. Adamo, A. Lliotis, M. Ducloy and D. Wilkowski, Science Adv. 4, 4223 (2018); P. Rodriguez-Lopez, W.J.M. Kort-Kamp, D.A.R. Dalvit and L.M. Woods, Nature Comm. 8, 14699 (2017).

[4] For an introductory overview, see, e.g., P.W. Miloni, "The quantum vacuum" (Academic Press, Boston, 1994).

[5] For a comprehensive review, see A. Di Piazza, C. Müller, K.Z. Hatsagortsyan and C.H. Keitel, Rev. Mod. Phys. 84, 1177 (2012) or a more recent one, see, B.S. Xie, Z.L. Li, S. Tang, Matter and Radiation at Extremes 2, 225 (2017).

[6] For recent advances in high power laser systems, see, for example, the web sites of the following labs: ELI (Paris), diocles (Lincoln), xfel (Hamburg), sparc (Darmstadt), Vulcan, HiPER and Astra Gemini (Oxfordshire), polaris (Jena) or Shenguang III (Mianyang), LCLS (Stanford), TPL (Austin) or numerous references in https://eli-laser.eu/.

[7] R. Karplus and M. Neuman, Phys. Rev. 83, 776 (1951). For some first evidence of light-by-light scattering at the LHC, see, e.g., M. Aaboud, Nature Physics 13, 852 (2017).

[8] S.L. Adler, Ann. Phys. 67, 599 (1971). For early observations, see, e.g., G. Jarlskog, L. Jönsson, S. Prünster, H.D. Schulz, H.J. Willutzki and G.G. Winter, Phys. Rev. D 8, 3813 (1973).

[9] R. Baier and P. Breitenlohner, Nuov. Cim B 47, 117 (1967). For recent observations in neutron stars, see, e.g., R.P. Mignani, V. Testa, D.G. Caniulef, R. Taverna, R. Turolla, S. Zane and K. Wu, Mon. Not. Roy. Astron. Soc. 465, 492 (2017) or L.M. Capparelli, L. Maiani and A.D. Polosa, Euro. Phys. J. C77, 754 (2017).

[10] W. Heisenberg and H. Euler, Z. Phys. 98, 714 (1936).

[11] J.S. Schwinger, Phys. Rev. 128, 2425 (1952).

[12] T. Cheng, Q. Su and R. Grobe, Cont. Phys. 51, 315 (2010).

[13] F. Sauter, Z. Phys. 69, 742 (1931).

[14] Q.Z. Lv, S. Dong, C. Lisowski, R. Pelphrey, Y.T. Li, Q. Su and R. Grobe, Phys. Rev. A 97, 053416 (2018).

[15] H. Bauke and C.H. Keitel, Comp. Phys. Comm. 182, 2454 (2011).

[16] W. Greiner, B. Müller and J. Rafelski, "Quantum electrodynamics of strong fields" (Springer Verlag, Berlin, 1985).

[17] P. Krekora, K. Cooley, Q. Su and R. Grobe, Phys. Rev. Lett. 95, 070403 (2005).

[18] M. Hotta, Phys. Rev. D 78, 045006 (2008), Phys. Lett. A372, 5671 (2008), Phys. Rev. A 89, 012311 (2014), and many references therein.

[19] R.H. Jonsson, E. Martin-Martinez and A. Kempf, Phys. Rev. Lett. 114, 110505 (2015).