2020-07

Luxe: combining high energy and intensity to spark the vacuum

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http://hdl.handle.net/10026.1/17544

10.1051/epn/2020401
Europhysics News
EDP Sciences

LUXE: Combining high energy and intensity to 'spark' the vacuum

The vacuum of quantum electrodynamics (QED) can be viewed as a medium akin to a dielectric which can be polarised by external fields. If these are sufficiently strong, the response of the vacuum becomes nonlinear and involves phenomena such as light-by-light scattering ('nonlinear optics') and, *in extremis*, 'dielectric breakdown', i.e. real pair production, if a critical field strength is exceeded. The LUXE experiment aims to realise near-critical fields through collisions of photons stemming from an ultra-intense optical laser with high energy electrons or photons provided by the European XFEL linear accelerator. This set-up provides a golden opportunity to enter the uncharted territory of strong-field quantum electrodynamics in the non-perturbative regime.

The quantum vacuum and its breakdown

Faraday, Maxwell and Hertz have told us that the vacuum is filled with electromagnetic fields, but it took an Einstein to realise that this does not require a luminiferous aether: Fields and their wave excitations do not need a medium in which to propagate. Ironically, with the advent of quantum field theory, the idea of the vacuum as a medium was resurrected. It is the quantum fields themselves, through their virtual fluctuations, which lend the vacuum properties akin to a dielectric [1]. The basic phenomenon in this context is vacuum polarisation: Applying a weak external field (e.g. due to an electron), the vacuum dipoles formed by virtual electron positron pairs align and screen the electron charge. A probe particle 'diving' into the polarisation cloud surrounding the electron will thus 'see' the elementary charge, e, increasing with probe energy (charge renormalisation). As a result, 'perturbative QED', based on the coupling being small ($e^2/4\pi \ll 1$) becomes invalid at ultra-high energies.

Alternatively, one may ask what happens if one applies stronger and stronger external fields. The first issue to address is the notion of a 'strong' field in QED. As a relativistic quantum field theory, QED contains two fundamental constants of nature, Planck's constant, $\hbar$, and the speed of light, c. Combining these with the QED parameters, e and m, the electron mass, one can form the QED electric field strength, $E_S = m^2c^3/e\hbar = 1.3 \times 10^{18}$ V/m. This (by everyday standards) enormous field magnitude is typical for *elementary* processes in QED, such as the scattering of electrons and photons. The associated energy balance, $eE_S(\hbar/mc) = mc^2$, corresponds to an electromagnetic energy transfer of mc^2 (the electron rest energy) over the distance of an electron Compton wavelength, $\hbar/mc$. The challenge, though, is to realise the QED field strength E_S over macroscopic distances, say 1µm or larger. Sauter noted in 1931 that even in this *classical* field scenario the anti-particles of the electrons, the positrons, become relevant degrees of freedom [2]. This was further elaborated by Schwinger (1951) who interpreted the appearance of the positrons as an instability of the QED vacuum which starts to 'spark' with electron positron pairs [3]. The vacuum thus becomes 'conducting' similarly to an insulator suffering dielectric breakdown.

Pictorially, the situation is described in Fig.1(a) which displays a vacuum polarisation loop forming a virtual electron positron dipole. This dipole is exposed to the superimposed fields of laser and probe photons, γ_L and γ, respectively. Altogether, this diagram describes the nonlinear interaction of light with light, a subtle quantum effect first analysed in [1]. Schwinger found a way to calculate its imaginary part, which physically amounts to pair production via the *nonlinear Breit-Wheeler process*, $\gamma + n\gamma_L \to e^+e^-$, *see* Fig. 1(b). It thus corresponds to the creation of matter from light.

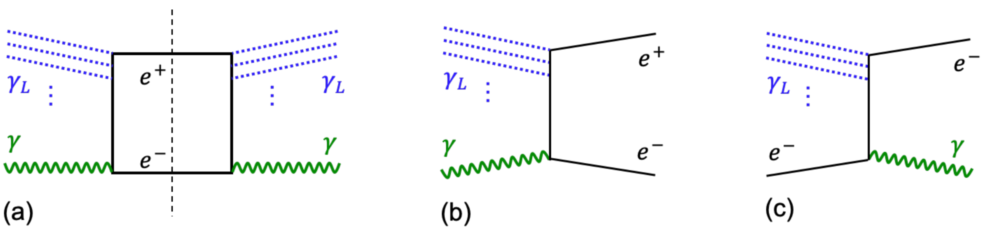

Figure 1: Diagrams representing basic processes of strong-field QED. (a) Light-by-light scattering enabled by nonlinear vacuum polarisation due to a superposition of laser photons (γ_L) and probe photons (γ). The dashed vertical line 'cuts' the diagram such that its imaginary part corresponds to nonlinear pair production (b). 'Crossing' results in the diagram for nonlinear Compton scattering (c).

The regime of electromagnetic field strengths reaching or even exceeding E_S is referred to as *strong-field* QED. It may be realised by approaching highly localised charge distributions, for instance at a distance of 30 fm from an electron. Alternatively, one may probe *bound* Coulomb systems by colliding heavy ions or by analysing the spectroscopy of heavy atoms, hence studying the physics at large atomic number Z [4]. High field strengths are also relevant for the early Universe and several astrophysical phenomena such as the gravitational collapse of Black Holes [5], the propagation of cosmic rays [6], and the surface of magnetars (strongly magnetised neutron stars) [7]. They are also expected to be present in future linear high energy e^+e^-colliders [8,9]. Unfortunately, the different suggestions above suffer either from nuclear background effects (at large Z) or experimental inaccessibility (astrophysics).

The LUXE experiment

To overcome these problems, the LUXE collaboration proposes [10] to approach the critical field, E_S, by exploiting (i) recent advances in high-power laser technology and (ii) the 'magic' of Lorentz invariance. Item (i), the increase in laser intensity due to chirped pulse amplification (Nobel prize 2018 [11]), allows production of optical-laser fields with a lab-measured strength just a few orders of magnitude below the Schwinger field. Employing (ii) by transforming to the rest frame of a relativistic electron, the electric field of the laser, as 'seen' by the electron, increases by the electron gamma factor. When combined with a laser with intensities of $O(10^{20})$ W/cm^2, electrons with energies above 5 GeV will have a gamma factor of 10^4 or larger, and thus will encounter a field strength comparable to or even exceeding E_S.
The basic experimental ideas are the following: one can send the electrons through a tungsten converter foil, in order to generate photons (γ) by bremsstrahlung and then collide these with the photons (γ_L) of the laser beam, see Fig. 1 (b). This corresponds to the nonlinear Breit-Wheeler process, i.e. the imaginary part of Fig. 1 (a). In addition, one may collide the electrons directly with the high-power, tightly focused laser beam, which results in *nonlinear Compton scattering*, $e^- + n\gamma_L \to e^- + \gamma$, see Fig. 1 (c). The two processes are related through 'crossing symmetry': swapping the lower electron and photon lines in process 1 (b) yields process 1 (c) and vice versa.
In the 1990s, experiments of this kind were conducted at SLAC in Stanford (E144 [12,13]) using the SLC accelerator. Although the electron energy was almost 50 GeV, the field achieved in the electron rest frame was a factor four below the Schwinger field as the optical lasers employed then were of low intensity compared to modern standards. Nonetheless, this pioneering experiment was able to explore what is now called *two-step trident pair production.* This is a *succession* of the two nonlinear processes introduced above, using the blue-shifted photons produced in nonlinear Compton scattering by colliding them with the laser photons to produce pairs, recall Fig.1. The observed production rates were proportional to higher-than-linear powers of the laser intensity. As the two-step trident process requires two separate interactions, it is strongly suppressed, i.e. rates are small and difficult to measure. The goal of LUXE is to enter far deeper into the strong-field region by using the much more powerful lasers available today, together with the high energy electrons from the European XFEL linear accelerator.
A key parameter characterising the processes in question is the *dimensionless laser amplitude*, ξ, defined as the ratio of the work done by the laser field E_L when 'pushing' an electron across a reduced laser wavelength, $\bar{\lambda}_L = c/\omega_L$, and the electron rest energy, mc^2, hence, $\xi \equiv eE_L/\omega_L mc^2$. When this is of order unity, an electron probing the laser becomes relativistic. There is more to this parameter, though. It turns out to be the basic 'book-keeping' device for the processes involved. One can show that a process involving n laser photons (see again Fig. 1) contributes with a probability amplitude proportional to ξ^n. When ξ becomes of order unity, all these n-photon amplitudes become equally important, and one has to sum over all of them. As higher order effects thus cease to be 'small perturbations' of lower order ones, the overall process becomes *non-perturbative.* The SLAC E144 experiment had $\xi \sim 0.5$, still in the perturbative regime. For LUXE we expect $\xi > 2$, which takes us well into the uncharted non-perturbative regime.
The second key parameter is the *quantum parameter* χ_e, defined as $\chi_e = \xi \times \hbar\omega_0/mc^2$, where $\omega_0 = 2\gamma_e\omega_L$ is the laser frequency in the rest frame of an electron with energy $\gamma_e m$. Equivalently, one may write this parameter as $\chi_e \equiv 2\gamma_e\, E_L/E_S\,(1 + \cos\theta)$, where θ is the angle between the laser and particle beams. Either way, we manifestly see the enhancing electron γ factor playing its crucial role. For LUXE we have $\gamma_e = 3 \times 10^4$ from the EU.XFEL beam, whence $\chi_e \approx 0.2\,\xi$. Thus, one enters the genuine quantum regime, $\chi_e > 1$, for $\xi > 5$.
LUXE is also in the unique position to test the structure of the vacuum near the Schwinger limit via light-by-light scattering. High-energy probe photons, γ_B, created through bremsstrahlung will be brought into collision with the ultra-intense laser-beam. This will allow to study the nonlinear Breit-Wheeler process *in isolation* for the first time. The relevant parameter in this case is $\chi_\gamma = \xi \times (\hbar\omega_*/mc^2)^2$, where $\omega_* = (\omega_L\omega_B)^{1/2}$ is the common frequency in the laser-probe centre-of-mass system. At low ξ and χ_γ, the rate is

expected to follow the power-law (ξ^{2n}) expectation based on counting the dominant number of photons contributing in perturbation theory. In constrast, when $\xi \gg 1$ and $\chi_\gamma \approx 1$, a non-perturbative QED calculation shows that the rate of e^+e^-pair production is proportional to $\chi_\gamma \exp\,(-8/3\chi_\gamma)$. Measuring this rate will be the first experimental test of non-perturbative QED.

Experimental setup

The European XFEL (EU.XFEL) is designed to run with energies up to $E_e = 17.5$ GeV, and contains trains of 2700 electron bunches, each typically containing 1.5×10^9 electrons, that pass at a rate of 10 Hz. For the beam-laser interaction, one electron bunch per EU.XFEL bunch train is extracted using a fast kicker magnet, and guided to the interaction region hosted in a currently unused annex of the shaft at the end of the linear accelerator of the EU.XFEL [14]. Out of the 10 Hz electron bunch extractions, 1 Hz will collide with the laser and 9 Hz will be used for *in-situ* beam background estimates.

The laser envisaged has a power of 40 TW at an initial stage and up to 400 TW in a 2nd stage. Its light will be focused to achieve intensities of about 10^{20} W/cm^2 in the initial and 10^{21} W/cm^2 during the 2nd stage. The laser will operate with a repetition rate of 1 Hz. An elaborate state-of-the-art diagnostics system for the laser intensity will be designed with the goal of achieving a precision in the absolute laser intensity below 5%. The angle between the beam and the laser will be about 20°; this ensures that the laser can be diagnosed well and reduces the rate only modestly compared to head-on collisions.

A schematic layout of the experiment is shown in Fig. 2 for the $\gamma_B + n\gamma_L$ processes of Fig. 1(b). For this layout, electrons and positrons produced at the interaction point (IP) are deflected by a magnet and detected in a system of silicon pixel detectors and calorimeters. Photons continue towards a photon detection system. For $e + n\gamma_L$ interactions (Fig. 1(c)), the layout is similar, except that the electron rate at the detector planes is now expected to be very high, and Cherenkov counters will likely be used in this region.

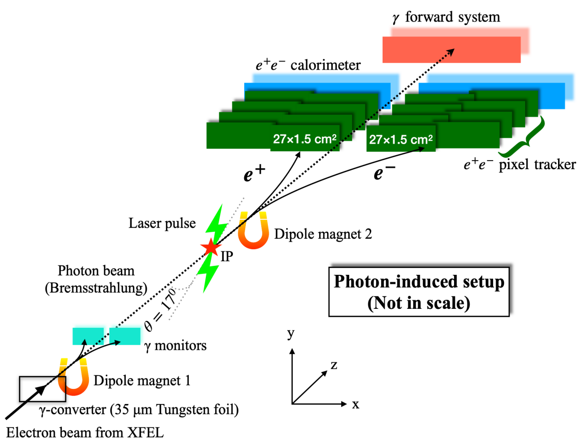

Figure 2: Sketch of the experimental setup for the γ_B–laser setup. A dipole magnet and a set of detectors (pixel tracker, calorimeters) for the e± and γ detection are shown behind the IP. A γ_B–monitoring system after the tungsten foil is also shown.

Expected Scientific Results

Compared to previous, current or planned facilities [15,16], LUXE will achieve higher values of $\chi_e$for the electron-laser collisions. The EU.XFEL operates at energies normally ranging between 8 and 16.5 GeV, and taking data at different energies will allow for a *range* of ξ and χ_e parameters.

For the photon-laser setup the LUXE experiment is unique. The calculated rate [17] of e^+e^-pairs per laser shot for the $\gamma_B + n\gamma_L$ process is shown in Fig. 3. Initially, for all energies it rises like a power-law, however, at $\xi \sim 2$, the rate increase slows down. When considering experimental effects, the event rates per laser shot range from about 10^{-3} to 10,000 in the relevant parameter space. The goal of LUXE is to measure these rates to better than 10% in the accessible phase space.

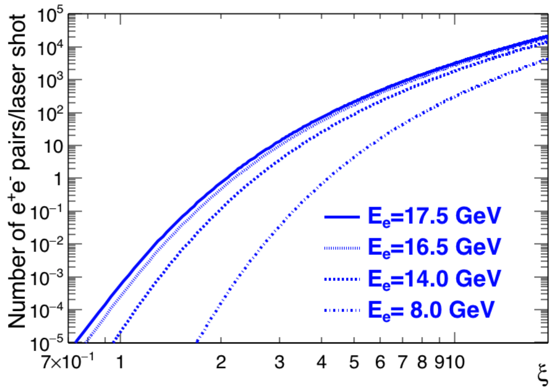

Fig. 3: Theoretical rate of e^+e^- *pairs per laser shot as a function of the laser intensity for several electron beam energies versus* ξ *(adapted from Ref. [17]).*

Conclusions

LUXE will shed new light on the vacuum and reveal new insights into our Universe. It presents a unique opportunity to pioneer a novel regime of quantum physics, the strong-field regime of QED, combining one of the premier European research infrastructures, the European XFEL, with a high-power laser, and employing systems of cutting-edge laser diagnostic and particle detectors. The goals are to observe for the first time directly the $\gamma\gamma \to e^+e^-$ process, and to perform the first studies of the transition from the perturbative to the strong-field (non-perturbative) regime in both e-laser and γ-laser collisions.

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