Title

Light—matter interactions driven by lasers at highest intensities

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Standfirst: [The interaction of electrons and photons lies at the very foundation of quantum electrodynamics. However, if an electron is able to scatter off several hundred photons, provided by a high power laser, new physical phenomena come into play. This might pave a way for future light sources and photon-photon colliders.]

Stepan Bulanov

The interaction of high-energy charged particles and photons with strong electromagnetic fields has long attracted the attention of the scientific community. It is not only because of its practical importance to the future particle accelerator design and astrophysical phenomena studies, but also because of the possibility of creating novel and powerful particle and radiation sources. Strong electromagnetic fields can be encountered in various astrophysical environments, including near pulsars, magnetars, and black holes, as well as around heavy nuclei stripped of most of their electrons. They are generated in the foci of high power lasers and significantly alter the dynamics of high energy particle beams colliding in conventional accelerators, or traveling through a crystal along an axis of symmetry. Out of these environments producing strong electromagnetic fields, lasers offer the most flexible and direct pathway for the fundamental physics research into a parameter space that was not accessible before. Especially, because strong field phenomena can be significantly boosted by colliding high-energy particles and intense laser beams.

The theoretical description of high-energy charged particle and photon interactions with strong electromagnetic fields requires nonperturbative methods in quantum electrodynamics (QED), which is often referred to as strong-field QED [1,2]. The experimental validation of these methods is long overdue. However, until recently the experimental studies of the strong field QED processes were limited to the 'E144' experiment at SLAC, where a 46.4 GeV electron beam collided with a 10^{18} W/cm^2 laser pulse [3]. This was mostly due to the challenges of co-locating a conventional electron-positron accelerator and a high power laser. With the fast progress in laser technology, which made available lasers with intensity exceeding the one used in the E144 experiment by many orders of magnitude, and Laser Plasma Acceleration of electrons, reaching almost 10 GeV energies [4], these studies became possible in the all-optical regime, where two laser pulses provide electron acceleration and strong electromagnetic fields [5]. It was demonstrated by two experiments at the Rutherford Appleton Laboratory, which reported the radiative energy loss of GeV-class electron beams colliding with intense (10^{20} W/cm^2) laser pulses due to the strong-field QED effects [6,7]. Moreover, the study of the strong-field QED phenomena are a part of the scientific program of almost every major high-power laser facility around the world that is either already under operation, being constructed, or being planned.

Now writing in *Nature Photonics,* Mirzaie and colleagues described a new experiment [8] carried out at a 4-petawatt laser facility at the Center for Relativistic Laser Science (CoReLS), Gwangju, South Korea. The work is in the all-optical regime, where a multi-GeV electron beam was collided with a 4×10^{20} W/cm^2 laser pulse, making it possible to investigate the process of nonlinear Compton scattering.

Enabling this involved high-energy photon emission by an electron moving in a strong electromagnetic field and absorbing a large number of laser photons. An all-optical regime required the laser to be split in two parts, one for multi-GeV electron acceleration in plasma, and the other to be focused and provide a strong electromagnetic field during the collision with the electron beam.

The experiment is very challenging since it requires the overlap of a several micron long, tens of micron wide electron beam, moving close to the speed of light with a focus of a laser pulse, which is only 5 micron in diameter. The properties of the high-energy photons detected after the interactions led to the conclusion that on average 400 laser photons needed to be absorbed by an electron to emit one such photon.

The comparison of the experimental results, i.e., the number of photons, their energy and angular distributions, with the theoretical and simulation predictions, showed good agreement, allowing for the validation of strong-field QED theory. As a result of this interaction, a beam of gamma-rays was generated with unprecedented brightness ($\approx1\times10^{23}$ mm^{-2} mrad^{-2} s^{-1} [0.1% BW]), exceeding current laser and accelerator-based inverse Compton sources by several orders of magnitude. This might pave a way for future light sources and compact gamma-gamma colliders.

With increased laser intensity and higher electron beam energies future experiments will be able to probe into unexplored regimes of strong-field QED, where the motion of charged particles is dominated by the recoil due to photon emissions, and the photons are able to transform into electron positron pairs. This will give rise to one of the most fascinating phenomenon of strong-field QED, the QED cascades [1]. This phenomenon is characterized by an almost total transformation of electron beam energy into photons and electron positron pairs during the collision with a high intensity laser pulse. Ultimately, such experiments will add to our understanding of physics processes in extreme environments.

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The author declare no competing interests

Figure 1: The scheme of the all-optical nonlinear Compton scattering experiment. CoReLS laser is split into two parts: (i) main laser beam, which accelerates electrons to multi-GeV energies in the gas cell, and (ii) scattering laser beam, which is tightly focused to provide 4×10^{20} W/cm^2 intensity. The electron beam and scattering laser beam collide at 30^o angle generating high energy gamma photons.