HEAVY ION COLLISIONS

A clash of photons

The ATLAS Collaboration observed photons elastically scattering from other photons — an effect predicted by quantum electrodynamics over 80 years ago.

Spencer R. Klein

Photons are electrically neutral so, classically, light beams pass through each other without any interaction. In more sophisticated terms, Maxwell's equations are linear, with no photon–photon coupling. But, in quantum mechanics, things are different. According to the Heisenberg uncertainty principle, photons may briefly fluctuate to short-lived (virtual) electron–positron pairs (e^+e^-). The electron and positron carry electrical charge, so they can interact with other photons, leading to the appearance of a real (long-lived) electron–positron pair.

By 1934, physicists had realized that photons could also interact and scatter off each other while both remaining intact[1,2]. This interaction is represented by a particular type of Feynman diagram called a box diagram (Fig. 1a). The two incoming photons couple to the two outgoing photons through a virtual charged particle loop. This loop includes contributions from all electrically charged particles, including any that are as yet undiscovered. Hence, this process is sensitive to charged particles predicted by new theories, such as supersymmetry and others that go beyond the standard model.

Because the coupling at each photon–charged particle vertex is small, the overall cross-section is small, so a high flux of photons is required to observe this interaction. Moreover, since the cross-section increases with increasing photon energy, it was not possible to detect such light-by-light scattering even with the strongest laser beams. So far, scientists have only been able to explore processes with related quantum behaviour such as photon scattering from the electromagnetic field of an atomic nucleus (Delbrück scattering)[3] and photon splitting (one photon splitting into two)[4] in a strong magnetic field. In both cases, one of the photons attached to the charged particle loop is virtual.

Writing in *Nature Physics*, the ATLAS Collaboration[5] reports the first direct evidence for light scattering from light. Their study takes advantage of an unusual source of photons: the electromagnetic fields carried by the relativistic lead ion beams circulating in CERN's Large Hadron Collider (LHC). Highly charged relativistic ions generate large electric and magnetic fields. The electric fields extend radially outward from the ions, whereas the magnetic fields encircle the ion trajectory. When the ions move at relativistic velocities, the electric and magnetic fields are flattened (Lorentz contracted) into a pancake-shaped region, oriented perpendicular to the direction of the ion trajectory. The electric and magnetic fields are perpendicular to each other and to the direction of motion. Back in the 1920s, it was shown that the crossed electric and magnetic fields act like a field of photons[6–8]. For large emitters, such as lead nuclei, the photons are very nearly real, allowing for tests of quantum electrodynamical phenomena such as light-by-light scattering. The number of photons scales as the square of the nuclear charge, giving for the bare lead ions a flux enhancement 6,724 times larger than that of proton beams.

Because light-by-light scattering requires two incident photons, the cross-section is 45 million times larger than for proton or electron collisions. Still, the predicted cross-section for light-by-light scattering — 370 nanobarns — is tiny, as one barn equals an area of 10^{-28} m^2 (ref. 9). By comparison, the cross-sections for two lead ions to interact hadronically is about 6 barns, 20 million times higher.

The ATLAS Collaboration looked for lead–lead collisions where the final state was composed of two back-to-back photons, and nothing else. The 'and nothing else' criteria eliminated events where the electromagnetic photon–photon scattering was accompanied by a hadronic collision between the two nuclei. This required the two lead ions to miss each other physically, but pass by at a distance small enough for their photon fields

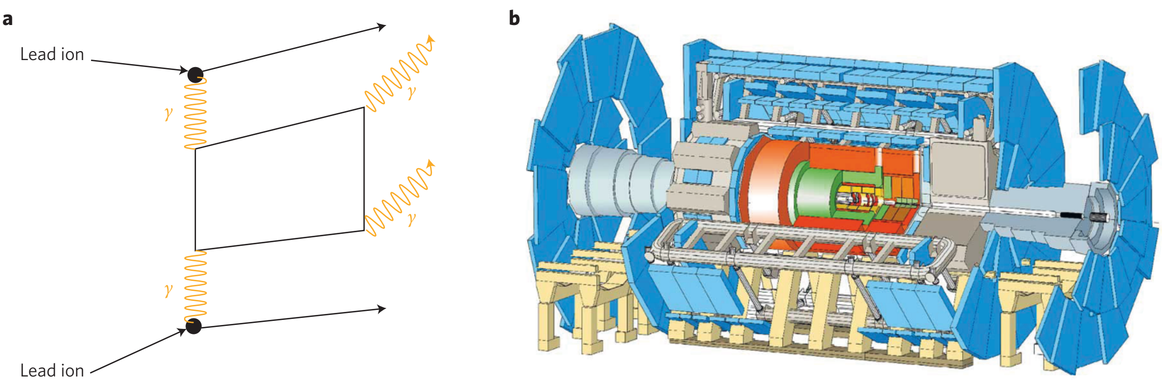

Figure 1 | Light-by-light scattering in the ATLAS detector. **a**, Feynman diagram of light-by-light scattering. Virtual photons emitted by each ion interact with and are absorbed by a charged particle loop, which then emits two real photons. All electrically charged particles contribute to the loop, so the cross-section is sensitive to the presence of as yet undiscovered charged particles. **b**, The ATLAS detector at CERN's Large Hadron Collider. The inner part is sensitive to electrically charged particles, while the electromagnetic calorimeters (red) detect the photons used in the light-by-light analysis. The relativistic lead ions traverse the detector along the thin pipe going through the middle, and collisions take place near the centre of the detector. Image credit: ATLAS Experiment © 2016 CERN (**b**).

to interact — an ultra-peripheral collision[10,11]. Because the lead ions lose only a tiny fraction of their energy, the outgoing lead ions continue their path around the LHC ring, unseen by the ATLAS detector.

Fortunately, the ATLAS detector (Fig. 1b) has active elements that cover almost the entire collision region. The only places where charged particles or photons can escape undetected are the two small regions where the lead beams enter and exit the detector. The Collaboration selected the events with two moderately energetic photons (over 5 GeV) in their electromagnetic calorimeters, with no other particles coming from the collision region. They imposed the requirements that the photons should be well reconstructed (clean) and nearly back-to-back azimuthally, as dictated by momentum conservation.

The Collaboration considered several possible backgrounds that could mimic the light-by-light scattering signature. One possible background is another two-photon process: two photons going into an electron–positron pair ($\gamma\gamma \rightarrow e^+e^-$), where the charged tracks from the electron and positron are missed. Another, more interesting background concerns purely hadronic processes that could lead to the two-photon state. The Collaboration ensured that these backgrounds were under control. ATLAS observed a total of 13 events, compared to a total background of 2.6 ± 0.7 events, giving a significance of 4.4σ. The other characteristics of these events are consistent with the expectations from light-by-light scattering.

Despite the limited accuracy of the current results, they are already sensitive to a few types of beyond-standard-model physics. John Ellis, Nick Mavromatos and Tevong You have already used the current results to set limits on possible nonlinear modifications of conventional quantum electrodynamics[12]. Looking ahead, the relatively high signal-to-noise ratio in the final data set bodes well for future, more accurate analyses. The current analysis used data from 2015, when the LHC ran at substantially lower collision energy and luminosity (collision rate) than it does now. By 2025, the LHC will be upgraded to produce a collision rate ten times higher than the current configuration. With a few years of high-luminosity data, it should be possible to make precise measurements of light-by-light scattering, and thereby observe — or put limits on — new, as yet unseen charged particles. ❒

Spencer R. Klein is at the Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA.
e-mail: srklein@lbl.gov

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