Physics

VIEWPOINT

Intense Laser Sheds Light on Radiation Reaction

Experimentalists have used ultraintense laser light to explore a fundamental problem in quantum electrodynamics: the response of an accelerated electron to the radiation it emits.

by Andrea Macchi*,†

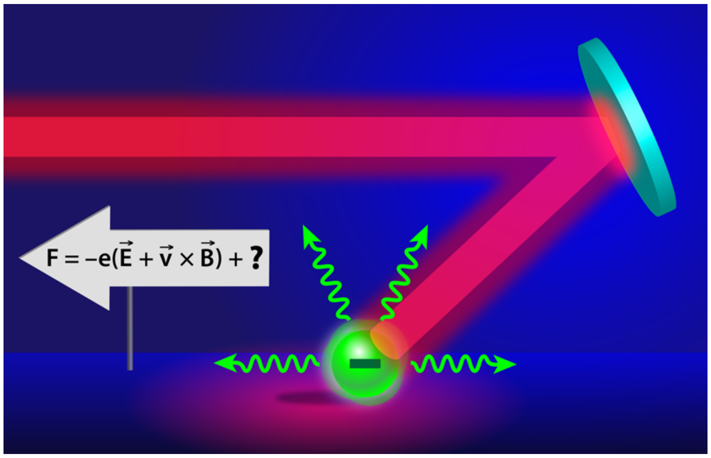

Figure 1: Radiation reaction is the backaction on an accelerated electron from the radiation it emits. Ordinarily the effect is small and can be described classically by adding a term to the equation for the Lorentz force. But a quantum description is required when the electron recoil is significant. Mangles and co-workers [2] and Zepf and co-workers [3] studied this regime of quantum radiation reaction by exposing electrons to super-intense laser fields. The two teams then used their data to try to distinguish between various radiation reaction models. (APS/Alan Stonebraker)

Accelerated electrons emit electromagnetic radiation, an effect we can appreciate every day in the color of the sky or when antennas produce radio waves to send music to our cars. Perhaps a less familiar idea is that the emitted radiation exerts a backaction on the electron itself, which has a dampening effect like that of friction (Fig. 1). Physicists first studied this "radiation reaction" theoretically in the early 1900s. The effect, however, is only sizable when the electron's energy loss is large compared with the work done by the accelerating force, which corresponds to the electron being accelerated in its rest frame within a few yoctoseconds (10^{-24} s) [1]. While this condition can be met in remote astrophysical environments, such as the plasma surrounding a pulsar, it is much harder to come by in the lab. Two papers [2, 3] report preliminary measurements of the energy loss of electrons from radiation reaction that results from "shaking" the electrons with an extremely intense electromagnetic field. Both experiments made use of one of the world's most powerful lasers, but the two papers present differing conclusions about which model best describes the data.

The fact that an accelerating electron radiates means that the familiar Lorentz expression for the force on an electron in an electromagnetic field is incomplete. Take, for example, an electron in a constant and uniform magnetic field. The Lorentz force predicts that the electron will undergo steady circular motion, but that's not technically possible, since the charge is radiating away energy. To describe the true motion of the charge, extra terms must therefore be added to the Lorentz equation to account for the damping effect of the electron's radiation.

Lev Landau's and Evgeny Lifshitz's classic text on the theory of fields [4] provides an expression for the radiation reaction force, which works well when the electron recoil is negligible. However, when the electron emits radiation with a high frequency (large momentum)—a condition that may be met when high-energy electrons encounter strong electromagnetic fields—the electron recoil can be sizable. Sufficiently large recoils correspond to the regime of so-called quantum radiation reaction. Here, radiation reaction is reminiscent of the Compton effect, where one photon is absorbed and another one is re-emitted with a different frequency because of the electron recoil. The difference is that quantum radiation reaction involves both the absorption and the emission of many photons, and the electron dynamics cease to be deterministic because of the probabilistic nature of photon emission [5]. Describing this process requires quantum electrodynamics, but the calculations involved are so complex that one instead relies on simplified quantum models.

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Without experiments that are sensitive to radiation reaction beyond the Landau-Lifshitz description, this theoretical work has, so to speak, gone on in the dark. Enter the two new experiments, which were led by Stuart Mangles from Imperial College London [2] and by Matthew Zepf of Queen's University Belfast [3]. (The same experimentalists but different theorists contributed to the two papers.) Both teams made use of the Astra Gemini laser at the Rutherford Appleton Laboratory in the UK. This laser produces two beams of synchronized pulses, each of which packs about a petawatt of power into a volume the size of a bacterial cell. The researchers directed the first laser beam at a low-density plasma to produce a short bunch of high-energy electrons through a process known as laser-wakefield acceleration. They directed the second laser beam at the electron bunch in a counterpropagating geometry. Because of relativistic effects, this geometry ensures that the electrons "see" the highest possible electromagnetic field strength and frequency in their rest frame. Under these conditions, the electrons will scatter the laser-beam photons, and these scattered photons will be detected as gamma rays in the laboratory frame. The electrons will also lose energy because of radiation reaction.

The two teams' experiments, which were in most respects identical, amounted to measuring the electron and gamma-ray energy spectra in a collision and then comparing the electron spectrum to that measured with the second beam off. The researchers considered a collision event a "successful" demonstration of radiation reaction if they detected a loss of electron energy at the same time as strong gamma-ray emission. Both experiments obtained only a small number of such successful events, mainly because it was difficult to achieve a good spatiotemporal overlap between the laser pulse and the electron bunch, each of which has a duration of only a few tens of femtoseconds and is just a few micrometers in width. A further complication was that the average energy of the laser-wakefield-accelerated electrons fluctuated by an amount comparable to the energy loss from radiation reaction.

The ultimate goal of these measurements was to use the data to discriminate between different radiation reaction models. In their analysis, Mangles and co-workers [2] considered two energy parameters, which characterize the electron and gamma-ray spectra, respectively. The predicted correlation between these parameters is different depending on whether one uses a classical or quantum model for radiation reaction, and the team found that the quantum model provides a better description of the data. But the match between the quantum model and the data is at the "1 sigma" confidence level—in other words, there is only a 68% chance that the data are better described by a quantum model than by a classical model.

The analysis by Zepf and colleagues [3] was slightly different in that they tried to reproduce the detailed shapes of the measured electron spectra using simulations that were based on different radiation reaction models. They concluded that a "semiclassical" model, which introduces a phenomenological correction to the classical Landau-Lifshitz expression for radiation reaction, agrees slightly better with their data than does a quantum model. This may sound surprising, since a quantum description should, in principle, be the most general description possible and therefore inclusive of a classical one. Zepf and colleagues [3], however, say the discrepancy may indicate a failure of some assumptions of the quantum model, an idea that has been put forth in another study of radiation reaction based on the interaction of positrons with crystals [6].

The differing conclusions in these papers serve as a call to improve the quantum theory for radiation reaction. But it must be emphasized that the new data are too statistically weak to claim evidence of quantum radiation reaction, let alone to decide that one existing model is better than the others. Progress on both fronts will come from collecting more collision events and attaining a more stable electron bunch from laser-wakefield acceleration. Additional information could come from pursuing complementary experimental approaches to observing radiation reaction (for example, Ref. [7]), which may be possible with the next generation of high-intensity laser systems [8]. In the meantime, experiments like those from the Mangles and Zepf teams are ushering in a new era in which the interaction between matter and ultraintense laser light is being used to investigate fundamental phenomena, some of which have never before been studied in the lab.

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