

# Minkowski, Abraham and the photon momentum

One might expect that the momentum of a photon, under almost any conditions, would no longer be a matter of dispute. Most textbooks certainly give that impression. Yet, in fact, a fundamental uncertainty, recognized a century ago, still lingers. Suppose that a photon, having momentum  $\hbar k$  in vacuum, enters a transparent medium with index of refraction  $n > 1$ . What is the photon's new momentum? Remarkably, there is still no definitive answer.

In 1908, the German (although Russian-born) physicist Hermann Minkowski derived one possible, yet surprising, answer. In classical terms, Minkowski found the total momentum of the electromagnetic field to be equal to  $\int d^3x \mathbf{D} \times \mathbf{B}$ . In quantum terms, this suggests that the photon momentum should actually increase and take the value  $n\hbar k$ . In effect, Minkowski started from Einstein's earlier suggestion that a photon's energy is given by  $E = h\nu$ . Assuming a velocity  $c/n$  and  $p = h/\lambda$ , one finds that  $p = n\hbar k$ .

One year later, the German physicist Max Abraham proposed a different answer. Abraham's entire career focused on the classical theory of electromagnetism. In 1902,

he proposed an early theory of the electron, and worked hard to find a consistent mathematical description of the reaction force due to radiation emitted by an accelerating charged particle. Abraham argued that the photon inside the medium would have a lower velocity and lower momentum, the medium itself absorbing the difference. In classical terms, Abraham's momentum is  $\int d^3x \mathbf{E} \times \mathbf{H}$ , or in quantum terms  $p = \hbar k/n$ .

Nearly 100 years later there is still no clear answer as to which of these formulae is correct. It's possible, of course, that both could be, yet refer to subtly different situations or interpretations. The past decade has seen renewed interest in this puzzle, stimulated in part by the increasing precision of quantum optics. One recent experiment backs up Minkowski's answer — but still may not prove Abraham wrong.

The idea was to measure the recoil of a Bose–Einstein condensate as photons are reflected from its surface (G. M. Campbell *et al.* *Phys. Rev. Lett.* **94**, 170403; 2005). Such a set-up offers two advantages. First, extreme accuracy can be achieved through atom interferometry. The researchers used



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counter-propagating light beams and detected the interference of the two component recoiling condensates. Second, although the index of refraction for a dilute atomic gas is close to one, larger deviations can be obtained for a condensed gas. The interference fringes measured agreed closely with Minkowski's formula.

Even so, Ulf Leonhardt of the University of St. Andrews points out that Abraham's ideas may still have life (*Nature* **444**, 823–824; 2006). Starting from the perspective of general relativity, other theorists have shown that both Abraham's and Minkowski's formulae can be derived, and may apply under different conditions. Still other work argues that these two formulae correspond to essentially different quantities — one (Abraham) to the momentum of the photon itself, and the other (Minkowski) to that of the photon plus the medium in which it lives. To be certain which momentum an experimental set-up measures is non-trivial.

So despite what seems like conceptual simplicity itself, there is actually very little that is simple. And the debate over this matter shows no sign of ending soon.

Mark Buchanan

## Three steps to fraud

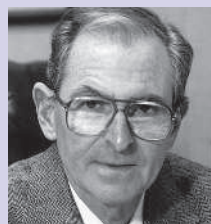
In every case of scientific fraud I knew of, I realized that three factors were present: the scientist was under career pressure; he thought he knew the answer, and didn't need to go to all the trouble of obeying the scientific method; and he was working in a field where reproducibility was not precise. The last of these explained why fraud was almost always in biomedicine, where the truth is generally more statistical and less directly causal.

Then, in 2002, two cases of scientific misconduct by physicists came to light, one involving Jan Hendrick Schön at Bell Laboratories, and the other Victor Ninov at Lawrence Berkeley National Laboratory (LBNL). In both cases, the scientists were

under career pressure (as most scientists almost always are) and both thought they knew the right answer. The test of my hypothesis would be the third factor.

The Schön case fits like a glove. He apparently made a breath-taking series of discoveries in MOSFETs (metal-oxide semiconductor field-effect transistors), a field that is notoriously sample-dependent: the fact that nobody could reproduce his results could just have meant that they had bad samples.

Victor Ninov was a leader of the group at LBNL using the Berkeley Gas-filled Separator (BGS) to sort through the debris of nuclear collisions. In 1999, the group announced the observation of three instances of decay chains characteristic of the element 118.



The scientists were under career pressure, and thought they knew the right answer.

By international agreement, new elements are not official until their discovery has been reproduced, which groups in Germany and Japan immediately undertook to do — but both failed.

In 2001, the BGS group produced a fourth signature decay chain. By now, suspicions had been aroused. A series of investigations ensued, in which it was found that the data for all four decay chains had been fabricated, and that Ninov was the only person in a position to have done it.

Thus he had turned my third factor on its head. Ninov had assumed that his result would be reproduced — and that he would get the credit for discovering it first.

David Goodstein