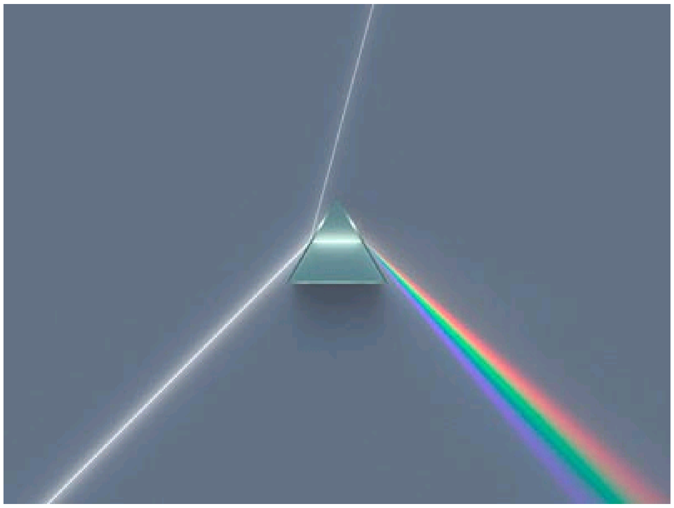
Both answers correct in century-old optics dilemma

Feb 26, 2010 9 comments



Abraham and Minkowski were both right

For 100 years physicists have been struggling to reconcile two different formulations describing the momentum of light travelling through a transparent medium. One, put forward by German mathematician Hermann Minkowski in 1908, stipulates that light's momentum increases when it enters a medium, while the other, advanced a year later by the German physicist Max Abraham, instead says that the momentum of light decreases. Now, Stephen Barnett of the University of Strathclyde in the UK has concluded that both formulations are in fact correct, with the difference essentially boiling down to whether one considers the wave or particle nature of light.

It is well known than when light enters a material medium it slows down in proportion to the refractive index, *n*, of that medium. Minkowski and Abraham wanted to know how light's momentum changes as a result. Abraham calculated that the momentum of a single photon within the light is also reduced by a factor *n*, a result which agrees with our experience of everyday objects – as their speed drops, so too does their momentum. Indeed, a number of powerful arguments have been put forward over the years in support of this position. Prominent among these has been a simple proof based on Newton's first law of motion and Einstein's equivalence of mass and energy, which considers what happens when a single photon travels through a transparent block and transfers some of its momentum to the block, given that the motion of the system's centre of mass-energy must remain constant.

Minkowski's formulation, on the other hand, seems more natural from the point of view of quantum mechanics. As light slows down inside a medium its wavelength also decreases, but quantum mechanics tell us that shorter wavelengths are associated with higher energies, and therefore higher momenta. In fact, Minkowski's approach suggests that the momentum of a single photon of light increases by a factor *n* as it passes through a medium. This result can also be supported by strong theoretical arguments, among them one that considers what happens when an atom moving at some speed through a medium absorbs a photon and experiences an electronic transition.

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Phys. Rev. Lett. **104** 070401

Fundamental physical principles at stake

As Barnett points out, this problem has kept physicists interested for so long because it appears to put one or more fundamental physical principles at stake – on the one side Newton's first law and Einstein's famous $E = mc^2$ and on the other the notion, familiar from de Broglie waves, that momentum is inversely proportional to wavelength.

Both formulations have received experimental support, particularly that of Minkowski. For example, in 2005 Wolfgang Ketterle and colleagues at the Massachusetts Institute of Technology reported evidence in favour of Minkowski by transferring momentum from laser beams to matter waves that had been formed from a few million atoms cooled to just above absolute zero. However, in 2008 a group led by Weilong She of Zhongshan University in China passed a laser beam through a tiny filament of silica and found that the filament recoiled as the light exited, indicating, in accordance with Abraham, that the light gained momentum as it left the material.

These two formulations reflect the fact that in different situations momentum does different things

Stephen Barnett, University of Strathclyde

According to Barnett, however, both formulations are correct. He says that the one put forward by Abraham corresponds to a body's "kinetic momentum" – its mass multiplied by its velocity. Minkowski's momentum, on the other hand, is a body's "canonical momentum" – Planck's constant divided by its de Broglie wavelength. "These two formulations reflect the fact that in different situations momentum does different things," he adds. "In free space they coincide, but not when inside a medium."

Don't mix up the two

Physicists have known for some years that this distinction might explain the dilemma but have been unable to prove it. That is to say, they have been unable to reconcile the two different formulations with electromagnetic theory. Barnett overcame this problem when he realized that the two approaches cannot be treated in the same way mathematically – that of Abraham requires considering momentum as transferred by individual particles whereas that of Minkowski instead involves the commutation relationship between momentum and position, a wave property. "It is when you mix the two up that you get the problem," he says.

This point is underlined by Ulf Leonhardt of the University of St Andrews in the UK, who says that, simply put, Abraham described the momentum of light as a particle whereas Minkowski described the momentum of light as a wave. As such, he agrees that both formulations are correct. However, he does not think that the debate is really over. "The question is: when is the particle momentum relevant and when is the wave momentum relevant? Are there cases when a mixture of wave and particle properties appear?" he asks. "When science answers one question, ten new questions appear."

The question is: when is the particle momentum relevant and when is the wave momentum relevant?

Ulf Leonhardt, University of St Andrews

Barnett is also not entirely satisfied. "We now know that Abraham and Minkowski were both right," he says. "But we don't yet know why nature requires two momenta."

The work is reported in *Phys. Rev. Lett.* **104** 070401.

About the author

Edwin Cartlidge is a science writer based in Rome

9 comments

Add your comments on this article

1 **Ragtime**
Feb 26, 2010 4:06 PM
Prague, Czech Republic

In this experiment result can be interpreted by Abraham's momentum

focus.aps.org…st20

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2 **Ragtime**
Feb 26, 2010 8:38 PM
Prague, Czech Republic

But we don't know why nature requires two momenta

This is because every energy wave spreads in both longitudinal, both transversal waves through dispersive environment. IMO both momenta will be balanced just for microwaves of wavelength, corresponding the wavelength of cosmic microwave radiation. Shorter waves tend to behave like particles, longer waves are of tachyon character.

Edited by Ragtime on Feb 26, 2010 8:43 PM.

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3 **John Duffield**
Feb 27, 2010 5:46 PM
United Kingdom

I've talked about this with people and said I thought Minkowski was correct because I tend to take a wavelike view - but you live and learn. This article is very interesting. I dug up an earlier paper by the same author and was interested to read about the relation to the Aharanov-Casher effect: arxiv.org…0811.2771v1.pdf. This other paper looks interesting too: arxiv.org…0406222. Again lots to read up on.

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4 **John E Royer**
Feb 27, 2010 10:29 PM

Max Abraham is correct because the velocity of light is reduced. Now while one can argue the frequency of light is increased as it travels through the quartz, which it is in a way, but the number of waves does NOT increase. That being the case the momentum of each wave would have to increase which it cannot do at the reduced velocity. So as the velocity of the light decreases it transfers some momentum to the quartz upon entering it and upon exiting each wave is returned to its original velocity and momentum, which kicks back upon the quartz.

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5 **Ragtime**
Feb 28, 2010 5:49 AM
Prague, Czech Republic

Re:I tend to take a wavelike view

Quote:

> *Originally posted by **John Duffield***
> I've talked about this with people and said I thought Minkowski was correct because I tend to take a wavelike view

Phenomenologically speaking, the light could propagate like pure wave in special relativity sense if only its wavelength will be equal to the wavelength of CMB photons in given material. The light of shorter wavelength would autofocus and to propagate through such field in photons, whereas the photons of radiowaves and longer waves would disperse instead.

We can observe similar phenomena in dark Alexander's band between primary and secondary rainbow during heavy rain, which is behaving like CMB noise with respect to sun light.

en.wikipedia.org…Alexander's_band

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6 **shpend**
Mar 2, 2010 2:26 PM
Basel, Switzerland

Abraham-Minkowski Dilemma

the question: what is the momentum of the photon while it is
inside a transparent medium is not correct, because the photon that travels through an optical medium become part of it(i.e. we have a new "photon+medium" particle). One thing is 100% sure the kinetic and the canonic momentum of the photon before, during and after collision of the photon with the transparent medium is conserved. Hence it is matter of taste which form of momentum we choose: we can say the mass of "photon+medium" is increased but the velocity is smaller than ligth (Abraham) or the mass of "photon+medium" is smaller but it travels with the light speed (Minkowski).

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7 **Ragtime**
Mar 4, 2010 1:34 AM
Prague, Czech Republic

Quote:

> *Originally posted by **shpend***
> we can say the mass of "photon+medium" is increased but the velocity is smaller than ligth (Abraham) or the mass of "photon+medium" is smaller but it travels with the light speed (Minkowski).

This is a good point, but it basically says, the result of experiments should be always negative with zero momentum of photons exerted to material.

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8 **hoffmannmillack**
Mar 5, 2010 7:32 AM

But we don't know why nature requires two momenta

Ah, but perhaps this is not nature but merely the mathematical description that requires two momenta.

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9 **Mark Perel'man**
Mar 5, 2010 11:30 AM
Jerusalem, Israel

Existence of such dilemma means necessity of transition for research of the dispersion phenomena onto deeper level, to a kinetics of photons passage in media. So it is necessary to consider photons pass between scatterers on the free path length with the speed c and the durations of their delays at scattering acts and duration of formation (dressing) of particles. Thus the dilemma disappears, both laws of momentum and of movements of the centre of mass of system are carried out simultaneously: for the period of duration of delays and only for it the momentum is transferred to media; so both recent experiments are correct. Such theory was offered for a long time (Sov.Phys.-Doklady, 17, 352 (1972)), it is partially repeated in publications of last years, and is completely described in the "Quantum kinetics" prepared for publication: www.novapublishers.c…product_info.php

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