Particle-Wave Duality Is Subtler Than You Thought

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https://youtu.be/j_t1SakV_gc&lc=UgzAAquhxnFqb0BOJSx4AaABAg

A Comment on the Chris Pattison post:
The BEST Double Slit Experiment (May 8, 2023)
https://youtu.be/j_t1SakV_gc?t=19s

0:19 CP *"The issue for me is that light doesn't really seem to act like a wave most of the time, at least not to my intuition."* Chris, I must confess that my intuition is the opposite: I never assume electromagnetic radiation of any frequency consists of particles unless and until a Feynman-type absorption occurs, most often at an electron. While there is no Schrödinger equation for light, Maxwell's electromagnetic field equations do the equivalent job quite nicely if you do nothing more than translate spacetime volumes containing less than one photon of energy as probabilities rather than absolute energies.

For example, imagine placing a weak green laser so far away from a transparent cube that, according to Maxwell's equations, only the equivalent of half of one green photon of energy passes through the volume of the cube every second. How does this affect the light's behavior when interpreted as a wave?

The answer is that the dilution has no effect. Maxwell's equations still apply, so refraction still applies, reflection still applies, diffraction gratings still work, and, in general, all non-absorbing effects apply as they would for a nearby, full-power beam. The impact of Maxwell's equation on individual photons is no abstraction, either. Human eyes can detect individual photons under careful lab conditions. When they do, the viewer sees light clicks coming from the expected direction since eye corneas and lenses refract individual photons using the save wave functions as bright, coherent light.

Chris, you mentioned you do astronomy. Think about a photon arriving, at long last, at a CCD cell in your telescope after billions of years of travel from the side of a vast Einstein lens. Does the photon "see" the convolutions and distortions of the enormous space (and time) encompassed by that lens? The only possible answer explaining the images is yes: Maxwell's equations determine each photon's path. In fact, there's no fundamental reason why fast-moving neutral particles, such as neutrinos, could not perform the same trick using Schrödinger's equation instead of Maxwell's. Searching… Hah! Wow! Last month, in April 2023, someone published a paper on this topic [1].

Think about that: Just one photon's worth of energy — or much less — passing through millions of cubic light years of mostly empty space still "feels" every gravitational detail of that space just as well as the brilliant light of a supernova would. That's truly remarkable.

However, the persistent waviness of light gets far weirder than that: The waves can deposit energy and momentum *even when no quantum absorption occurs.* Say *what?*

Here's the problem. Long before quantum mechanics, James Clerk Maxwell used his new equations — not the same ones we use; those are Heaviside's — to predict a remarkable effect called radiation pressure. It is a vital concept in astrophysics since it's behind the large-scale movement of dust that creates effects such as the Pillars of Creation. Various tests have proven it effective as a potential propulsion method for solar-sail spacecraft.

However, here's a bit of a shocker: The behavior of photons before and after striking solar sails can *only* be described using Maxwell's equations. Expressing photon momentum transfer purely in terms of quantum field theory absorptions and emissions results not in reflection but in bizarre black-body heating models that bear no resemblance to reflection.

But why should that be surprising? Isn't this the same effect we see every time we look in a mirror? Yes, and as long as you describe the mirror in terms of energy potentials instead of atoms, quantum field theory, and Feynman's QED describe such reflections just fine. (I highly recommend Feynman's QED book [2] for a delightful discussion of how that works, incidentally.)

The problem is that Maxwell's field theory is the only one that correctly describes how *momentum* is deposited on the mirror when light reflects on it. Quantum field theory can model reflection, but it is reflection without the correct momentum transfer. The field theory approach creates a black body mess by insisting on destroying photon coherency. I've not looked lately, but the old Wikipedia article did just that, nominally "explaining" momentum transfer by having an atom absorb and then somehow perfectly re-emit the photon in the reflective direction. That's a mixture of two very different effects: Photon absorption with a delayed, and usually lower-energy, reemission, and purely Maxwellian wave reflection in which it's the reflection of the wave that deposits momentum.

If you want to make your brain hurt, think about that a bit: Quantum waves are *not* just information abstractions since they can deposit momentum even when the particle version of the wave sails off to some other. It's not just photons since accounting for momentum when neutrons reflecting off low-angle neutron mirrors gives the same result.

Textbooks give the information needed to figure out all such cases. However, what they don't give, at least in most cases, is the correct differentiation between non-quantized momentum deposition from electromagnetic *waves* versus quantized energy deposition, in which the radiation becomes quantized and, at least briefly, acts more like a particle.

I do not know immediately if any studies have explicitly searched for deposition of momentum *without* deposition of photon energy packets, but it's certainly a doable experiment. The lack of self-consistent descriptions of photon momentum deposition in most, if not all, textbooks (I haven't checked lately) makes it unlikely for most groups to *imagine* such an experiment, let alone perform it.

On the other hand, there's a powerful argument that this is not an exotic effect since every mirror-like reflection is an example of a non-quantized photon reflection. While the momentum transfer is too tiny to show up in ordinary mirrors, light sails in space probes and other forms of light pressure are explicit examples that electromagnetic waves can deposit momentum without photon absorption and emission. [3]. What is needed instead is clear explanations of how subtle and intransigent the wave behavior of light really is.

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[1] Torben C. Frost, *Gravitational Lensing of Massive Particles in the Charged NUT Spacetime,* arXiv:2304.12563 [gr-qc] (Apr 25, 2023). https://arxiv.org/pdf/2304.12563

[2] R. Feynman, *QED: The Strange Theory of Light and Matter* (Princeton University Press, 1985). https://www.google.com/books/edition/QED/2o2JfTDiA40C?hl=en&gbpv=1

[3] A. Macchi and O. M. Maragò, *Light Pressure Across All Scales: Editorial,* The European Physical Journal Plus (2021). https://link.springer.com/content/pdf/10.1140/epjp/s13360-021-01580-z.pdf