The Path Length of Light in Opaque Media

A seemingly paradoxical prediction in physics has now been confirmed in an experiment: No matter whether an object is opaque or transparent, the average length of the light's paths through the object is always the same.

What happens when light passes through a glass of milk? It enters the liquid, is scattered unpredictably at countless tiny particles and exits the glass again. This effect makes milk appear white. The specific paths that the incident light beam takes depends, however, on the opacity of the liquid: A transparent substance will allow the light to travel through on a straight line, in a turbid substance the light will be scattered numerous times, travelling on more complicated zig-zag trajectories. But astonishingly, the average total distance covered by the light inside the substance is always the same.

Professor Stefan Rotter and his team (TU Wien, Austria) predicted this counter-intuitive result together with French colleagues three years ago. Now he and his collaborators from Paris verified this theory in an experiment. The results have now been published in the journal "Science".

Particles and Waves

"We can get a simplified idea of this phenomenon when we imagine light as a stream of tiny particles", says Stefan Rotter. "The trajectories of the photons in the liquid depend on the number of obstacles they encounter."

In a clear, completely transparent liquid, the particles travel along straight lines, until they leave the liquid on the opposite side. In an opaque liquid, however, the trajectories are more complicated. The beam of light is scattered frequently along its way, it changes its direction many times, and it can only reach the opposite side after covering a long distance inside the opaque substance.

But in a turbid liquid, there are also many photons, which will never reach the opposite side. They do not completely traverse the liquid, but just penetrate a little below the surface and after a few scattering events they exit the liquid again, so their trajectories are rather short. "It can be shown mathematically that, rather surprisingly, these two effects exactly balance", says Stefan Rotter. "The average path length inside the liquid is thus always the same - independent of whether the liquid is transparent or opaque."

At second glance, the situation is a bit more complicated: "We have to take into account that light travels through the liquid as a wave rather than as a particle along a specific trajectory", says Rotter. "This makes it more challenging to come up with a mathematical description, but as it turns out, this does not change the main result. Also if we consider the wave properties of light the mean length associated with light penetrating the liquid always stays the same, irrespective of how strongly the wave is scattered inside the medium."

Experiments in troubled water

The theoretical calculations describing this counterintuitive behaviour have already been published three years ago in a joint publication by Stefan Rotter's team and his colleagues from Paris. Now the same research groups managed to verify the remarkable result in an experiment. Test tubes were filled with water, which was then obfuscated with nanoparticles. As more nanoparticles are added, the light is scattered more strongly and the liquid appears more turbid.

“When light is sent through the liquid, the way it is scattered changes continuously, because the nanoparticles keep moving in the liquid”, says Stefan Rotter. “This leads to a characteristic sparkling effect on the tubes' outer surface. When this effect is measured and analysed carefully, it can be used to deduce the pathlength of the light wave inside the liquid.” And indeed: irrespective of the number of nanoparticles, no matter whether the light was sent through an almost perfectly transparent sample or a milk-like liquid, the average path length of light was observed to be always the same.

This result helps to understand the propagation of waves in disordered media. There are many possible applications for this: “It is a universal law, which in principle holds for any kind of wave”, says Stefan Rotter. “The same rules that apply to light in an opaque liquid also hold for sound waves, scattered at tiny objects in air or even gravity waves, travelling through a galaxy. The basic physics is always the same.”

Original Publication:
Savo et al., Observation of mean path length invariance in light-scattering media, Science, 2017. DOI: 10.1126/science.aan4054. Freely accessible version: https://arxiv.org/abs/1703.07114
The French teams involve Romolo Savo, Ulysse Najar, Sylvain Gigan at the Laboratoire-Kastler-Brossel (experiment) and Romain Pierrat, Rémi Carminati at the Institut Langevin (theory).

Further information:
Prof. Stefan Rotter
Institute for Theoretical Physics
TU Wien
Wiedner Hauptstraße 8-10, 1040 Vienna, Austria
T: +43-680-3063161
stefan.rotter@tuwien.ac.at