The Crookes' Radiometer

Apply Light Pressure

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What did 19th-century scientists know about this fascinating device that many modern physics teachers do not?

I first encountered the Crookes' radiometer as a child, when I saw a storefront display with a couple dozen of them: light-bulb-shaped things with odd little vanes inside. I had no idea what they were or how they worked, but I was impressed.

Years later, in high school, my physics teacher explained how a radiometer operates. In theory, the spinning vanes were sealed into a bulb from which all air had been evacuated, so that nothing could hinder the rotation of the vanes. Photons impinged on the vanes, which were black on one side and white on the other. The white side had reflecting material on it, and the photon rebounded, transferring twice its initial momentum to the vane. Photons hitting the black side were absorbed, and transferred their momentum just a single time. The vanes thus rotated preferentially away from the white side, with the black side being pushed toward the brightest source of light.

But when I watched a radiometer, I saw that it rotated in precisely the opposite fashion, with the black sides receding from the light source, and the white sides approaching the light. Something was clearly wrong with the explanation. In fact, said my teacher, the real reason for the motive power for the vanes didn't come from photons at all.

The vacuum in the bulb was not perfect, so there was a little residual air. When the light fell on the vanes, the white or mirrored side didn't absorb any, while the black side absorbed it all and grew hotter.

When air molecules struck the surface, they picked up extra energy and momentum from the hotter black side, so they rebounded more from that side, which in turn rebounded with more momentum than the white side (action and opposite reaction). Thus, the vanes of the radiometer rotated with the black sides going away from the light source, as observed.

What I didn't know at the time was that this explanation has been known to be incorrect for over a century. Most people don't realize this, even though there have been several excellent articles pointing it out.

A history lesson

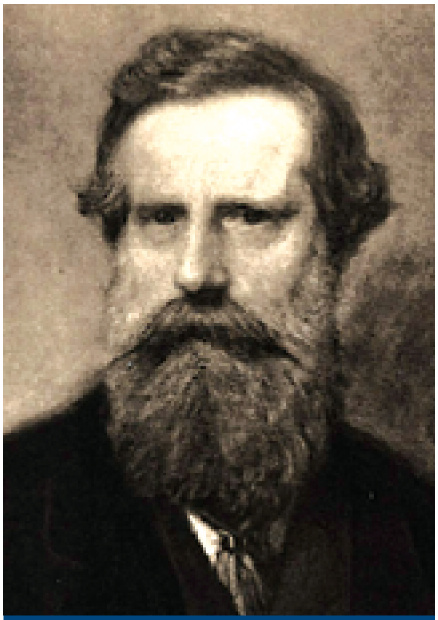
There had been attempts to measure the momentum of light going back well before William Crookes came up with his radiometer in 1873. De Mairan and Du Fay tried to observe it in 1754, and, in 1792, Abraham Bennett constructed a device similar to a Crookes', but without as good of a vacuum. Augustin Fresnel had some success with a device in 1825, but his work drew little attention.

These experiments were intended to demonstrate the corpuscular nature of light. They were not successful, mainly because the quantity to be measured was itself so small. Even James Clerk Maxwell, who propounded the electromagnetic theory of light, knew that light would be capable of generating pressure; he tried to build an apparatus to demonstrate this, but without success.

Crookes was a chemist who was well off enough to fund his own laboratory. In 1873, he attempted to weigh a tiny sample of the element thallium (which he had discovered 12 years earlier), and found that it was difficult to obtain a consistent reading. He used the newly invented Geissler mercury vacuum to evacuate the air from his chamber, but found that the weight depended on the temperature of the sample, and that it made a difference from which direction he heated it. Experimentation showed that blackened surfaces were repelled more than silvered ones.

Crookes demonstrated the effect of repulsion before the Royal Society of London in 1874, and his work was published in the *Journal of the Royal Society of London*. He would ultimately publish five articles on the effect and its variations over the next five years. In 1876, he devised the simple and elegant device with four vanes blackened on one side and silvered on the other. He named it the "radiometer" or "light mill," both terms that are still in use today.

At first, Crookes believed that the observed sense of rotation was correct—that black really should recede from the source of light, since the black side absorbed the photon and its momentum, but the white side clearly did not. Fluid mechanics pioneer Osborne Reynolds saw that the effect was consistent with heating, rather than incident light. His student, Arthur Schuster, performed an experiment in which a radiometer was suspended from fine wires and illuminated. The radiometer vanes and the radiometer casing rotated in opposite directions, following Newton's laws and indicating that something within the case was being impelled in the direction opposite to that of the vanes. This, Reynolds explained, must be due to residual gas. The kinetic gas explanation was the same one that my physics teacher had later passed on to me—but it didn't tell the whole story.



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How it works

The problem is that those gas molecules are not so sparse that they can be assumed to be non-interacting. In fact, gas molecules rebounding from the surface of the vane interfere with incoming molecules, and the hotter the surface, the more effectively the rebounding molecules will block incoming ones. The net effect is that the forces cancel one another out, and the vanes ought not to rotate at all.

The reason that they do turn is that the argument breaks down near the edges of the finite vanes. The outgoing molecules no longer deflect the incoming ones as much on the hotter side than the cooler one, and the imbalance in forces allows the vanes to rotate.

Maxwell and Reynolds wrote papers about the true nature of the impulsive force—largely in mathematical terms—in 1879. (A more accessible explanation was offered by Sutherland in 1896, but it was largely overlooked. Interest was revived in the early 1920s with a series of papers by various physicists, including Albert Einstein.)

Crookes still didn't properly understand the mechanism. He thought that the mean free path of the gas molecule ought to be larger than the size of the bulb, and that the molecule thus managed to "push off" one wall of the bulb and transfer the momentum thus gained to the vanes of the radiometer. Although he hadn't come to grips with the true explanation of the radiometer, his work on long mean free paths of particles in an evacuated bulb led him directly to the creation of the equally famous Crookes' tube, which made cathode rays visible, except where blocked by his Maltese Cross target.

The Crookes' radiometer works for pressures in the range of 10 to 100 μm. Blum and Roller report that true radiation pressure was finally observed in a standard Crookes' radiometer that had been evacuated to very low pressure. However, the effect of radiation pressure was simultaneously observed in different apparatuses by Lebedew and by Nichols and Hull in 1900.

Another twist

In an interesting variation, the effect of radiation pressure using a Crookes-type device was used to demonstrate *acoustic* radiation pressure in an experiment by Bruce Denardo and T.G. Simmons in 2003. Operating at room pressure, the device rotated in the "correct" direction. Even though the edge effect was present, the mean free path was very small, so the effect was negligible. For the first time, an accessible and relatively simple device demonstrated the effect of radiation pressure directly.

One might get the impression from this brief account that Crookes was not a very competent scientist. However, as A.E. Woodruff notes, "Crookes was no mathematical physicist, but [he was] a first-rate experimentalist." It is surely a fitting tribute that his radiometer still enjoys brisk sales at scientific stores and museum gift shops, long after competing devices have been forgotten.

Crookes became a Fellow of the Royal Society in 1863 and was knighted in 1897. He included a depiction of his radiometer on his coat of arms, and chose as his motto *"Ubi crux ibi lux,"* which translates to, "Where the cross is, there is light." With a little imagination, it also could be read as "Where Crookes is, there is light." ◭

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[References and Resources]

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