The Process Driving Crookes Radiometers

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Abstract

The Crookes radiometer, invented in 1879, is a device that rotates when exposed to light. Despite its long history, the mechanism behind its rotation remained a mystery for over a century. Many theories were proposed, but none could account for all observations. Recently, investigations into the mechanism that drives radiometers have led to discovery of a new type of interaction between molecules. When an electron in an atom absorbs energy, the energized electron excites to a higher orbital, increasing the size of the atom or molecule and reducing the distance from adjacent molecules within a few nanoseconds. The sudden decrease in van der Waals distance between molecules creates a repulsion between them, resulting in an explosion at the microscopic level and impacting adjacent particles or objects, namely transimpact. When transimpacts occur between air molecules and the molecules on the vane surface of a radiometer, the air molecules can be pushed away with significant momentum, driving the vane in the opposite direction. The black side of the vane is more efficient at absorbing heat energy, resulting in more electron excitations and transimpacts than the white side. As a result, the uneven impacts push the vanes to rotate. Since electron orbital transitions are an ordinary process in any substance with a temperature above absolute zero, transimpacts are common. Their impacts may be the cause of many physical processes, such as Brownian motion and phase transition of matter.

Introduction

A Crookes radiometer, also known as a light mill, consists of a low pressure glass bulb containing a set of vanes mounted on a low-friction spindle inside, as shown in Figure 1. Each vane is coated black on one side and white on the other. The vanes rotate when exposed to light, with faster rotation for more intense light.[1] It may spin all the time under sunlight. The rotation is such that the black sides of the vanes are retreating from the light source. When the bulb is cooled quickly by putting it into a freezer, it rotates backward slowly and stops in a minute or so.

The mechanism for the rotation has been a scientific debate for over a century. However, there is no convincing explanation. The light mill inventor, Willian Crookes, incorrectly suggested that the force was due to the pressure of photons predicted by James Clerk Maxwell, well known for

Maxwell's equations of electromagnetism.[2] If this were true, a faster rotation would be observed with a better vacuum in the bulb. However, the vanes stay motionless in a hard vacuumed bulb. The best result is observed at a pressure of around one pascal.

Figure 1, Experiment of a flashlight focused a vane of a Crookes radiometer.

There were numerous theories, trying to establish an unbalanced pressure between the black and white sides of the vanes or over the edges.[3-10] One proposal is that air molecules hitting the warmer side of a vane will pick up some of the heat, bouncing off the vane with increased speed. The problem with the idea is that while the faster-moving molecules produce more force, they also do a better job of colliding and preventing incoming air molecules from reaching the vane, so the net force on the vane should be the same as the air pressure.

Albert Einstein demonstrated that the two pressures acting on the vanes of the radiometer do not cancel out exactly at the edges due to a temperature difference. However, the force predicted by Einstein is not significant enough to cause substantial vane movement. A more intricate model known as thermal creep has been proposed, which suggests that air creeps over the edges of the vanes from the white side to the black side. This creates a higher pressure on the black side, which then pushes the vanes forward.

One issue that all air pressure-based theories fail to address is how to generate the driving force at thermal equilibrium. When exposed to an intense light source, such as sunlight, a radiometer will eventually reach thermal equilibrium. At this point, the absorption and radiation on either side of the vanes (regardless of their color) are at the same level. The black side of a vane absorbs light more efficiently and also radiates with the same efficiency, while the white side absorbs less light and reflects more radiation. The total heat energy, including both reflection and emission from each side, is equal to the incoming radiation. As a result, the air is heated by the same amount of energy on both sides of a vane, and the pressure on each side should be equal, providing no pressure difference to drive the vanes.

Experiment Using a Focused Light

To explore this mystery, we conducted an experiment using a small flashlight as the heat source, as illustrated in Figure 1. To initiate the movement of the radiometer, the flashlight was directed and focused on the black side of a vane. The stationary vanes immediately began to rotate, completing the first cycle in under 5 seconds. Within a minute, the rotation stabilized at its maximum speed, which was roughly 2 cycles per second. These outcomes are similar to those obtained from experiments conducted with uniform light sources in sunlight. We then pointed the flashlight on the white side of a vane, ensuring that the light ray was perpendicular to the surface of the vane to prevent reflection on the black side of the adjacent vane. Despite the duration of light exposure, the vanes remained stationary.

The purpose of this experiment is to determine if applying equal amounts of heat to the air on each side of the vanes results in the same air pressure to propel the vanes at the same speed in both directions. If the air pressure-based theories were accurate, the vanes would rotate at a comparable rate in either direction. We used focused light to evaluate if air pressure alone could produce enough driving force to rotate the vanes. To isolate the influence of the black sides, any reflection on them was avoided. By shining the light on the white side, the air close to the white side would receive the same amount of radiation as the black side from direct, reflected, and emitted light from the vane. Given enough time, the air should have been heated, generating the same aerodynamic force that drives the vanes. However, the experiment results showed that the vanes did not rotate with direct light on the white side, indicating that the static friction was not overcome due to insufficient driving force.

At a pressure of one pascal, which is approximately 10^{-5} of sea level pressure, the air becomes as thin as it is at an altitude of 80 km above sea level, on the top of the mesosphere. At this height, aircraft are less effective than rockets, since the air is too thin to provide the necessary lift. Unlike airplanes, rockets rely on the momentum generated by ejecting high-speed molecules to move forward, rather than air pressure. Similarly, in a radiometer operating at such a low pressure, the vanes cannot be propelled by air pressure alone. However, when the light was focused on the black surface, the vanes began to move immediately, without a heating delay. This suggests that the driving force for the radiometer must arise from interactions other than air pressure.

The subsequent experiment was even more intriguing than the previous one, as we employed a more sensitive mill with less static friction. As anticipated, the mill initiated more rapidly and rotated faster in the forward direction. When we directed the flashlight at the white side of a vane, it immediately began to move forward, with the white side of the vane chasing the incident light. The speed was much slower, and the movement ceased within a few seconds. When we switched off the light source, the mill rotated backward and stopped rapidly, much like the observation in the freezer experiment. The fact that the vanes chased the light source raises the question: why did this occur? This phenomenon provides strong evidence against the light pressure theory and poses a new challenge to all air pressure-based theories.

Transimpact

Upon absorption of energy, such as light, an electron in an atom excites to a higher orbital, a process known as an orbital jump, a quantum jump, or atomic electron transition.[11-12] The mechanism behind this process is still an active area of research. Orbital jumps occur spontaneously and typically take place in nanoseconds or less. As a valence electron jumps from a lower energy level to a higher one, the outer electron shell expands and reduces the distance to adjacent particles or objects. Since an orbital jump occurs abruptly, it creates an explosive repulsion on neighboring objects, such as the surface of a vane. Figure 2A illustrates two single-atom molecules located close to each other. Upon absorbing energy, such as photons, one of the atoms goes through an atomic electron transition, which causes the atom to increase in size and decrease the distance between them, as shown in Figure 2B. This process generates repulsion between the atoms, known as **transimpact**.[13] The atoms are pushed apart and move in opposite directions, as depicted in Figure 2C.

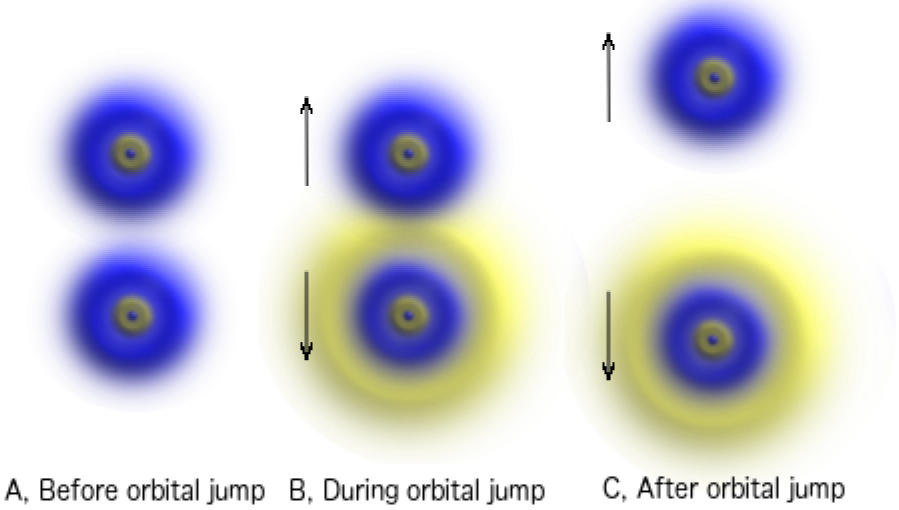

Figure 2, Transimpact resulted from quantum/orbital jump.

To illustrate this process with a concrete example, let us explore the excitation process of a nitrogen atom, which comprises *78%* of the particles in the air. A nitrogen atom has *7* electrons, with a ground state configuration of $1s^2 2s^2 2p^3$. The radius of the atom is determined by the valence orbital and is approximately *56 pm*. The configurations of two typical excited states are $1s^2 2s^2 2p^2 3s^1$ and $1s^2 2s^2 2p^2 3p^1$. Their radii are around *120 pm*. Thus, when a nitrogen atom becomes excited, its radius more than doubles, resulting in a volume increase of over *700%* within a period of a few nanoseconds.

The process of a transimpact can be pictured like the burst of popcorn. Imagine the momentum exerted by the popcorn as it bursts on the heating pane. What would happen if the popcorn is next to a coin? This analogy is similar to the process when an electron of an air molecule becomes excited next to a vane of a radiometer, or a molecule on the vane becomes excited next to an air molecule, which is thought to be the mechanism that drives the radiometer.

Transimpact is as common as an orbital jump that occurs whenever there is an energy exchange between an atom and its surroundings. Transimpact affects many processes in daily life. It may be responsible for kicking and moving particles in Brownian motion.[14-15] The force may also play an important role during phase transition. As temperature increases, this force may eventually overcome the attraction between molecules and free up the molecules, causing melting and vaporization.[14]

Equilibrium at Low Temperatures

Upon absorbing heat energy, the electrons of molecules on the surface of the vanes are excited and jump to higher orbitals, resulting in transimpacts. The impacts kick off air molecules next to the vanes, creating momentum to move the vanes in the opposite direction. When the flashlight was focused on the black side of a vane, the photons were absorbed quickly, resulting in transimpacts to move the vanes immediately. On the white side, the light was mostly reflected.

Here is a simple analysis of the forces in a radiometer. Transimpact takes place on any surface with a temperature above absolute zero. The impact exerts on both the black side F_b and the white side F_w. There is also a resistance F_r, which approximates static friction at low rotation speeds of the vanes. To move the vanes, the force difference between the two sides of a vane must be greater than the resistance:

$$(1) \qquad \left|F_b - F_w\right| > F_r.$$

Otherwise, there will be no motion. When the mill was placed in a freezer, the heat inside the mill was emitted to the environment and the black side was doing the blackbody radiation faster than the white side. The white side was relatively warmer, creating a greater transimpact F_w that pushed the vanes in the backward direction. It stopped quickly as the mill approached the thermal equilibrium in the new environment and the force difference between the two sides of the vanes could not overcome the static friction as required in inequation (1).

When the flashlight was pointed towards the white side in the second experiment, the visible light was mostly reflected and infrared light was bounced around inside of the bulb. The black sides absorbed the infrared radiation faster than the white sides, creating a greater repulsion force F_b that pushed the vanes forward. The mill stopped quickly as the new equilibrium was reached. After the light source was removed, the mill underwent a cooling process similar to the freezer experiment.

Equilibrium at High Temperatures

What is just explained is the situation in which the mill reaches the new equilibrium quickly at a low ambient temperature. The uneven speed of cooling or warming between the two sides creates a short-term temperature difference. The vanes stop quickly after reaching the new equilibrium. Next, let us look into the long-term driving force at the equilibrium of high temperatures, such as in the sunlight. Both are in the equilibrium state. Why the rotation is sustainable at high temperatures, but not at low temperatures?

Recall the blackbody radiation described in Planck's law.[16-18] By integrating Planck's equation over the frequency, then over the solid angle we found that the power P emitted by a blackbody is directly proportional to the fourth power of its absolute temperature T, known as the Stefan-Boltzmann law:

$$(2) \qquad P = pT^4$$

where P is the power emitted per unit area of the surface of a blackbody, T is the absolute temperature, and p is the Stefan-Boltzmann constant.[19-20] Most systems are not a perfect blackbody. Their radiation power P_n can be estimated using the:

$$(3) \qquad P_n = EpT^4$$

where E is the radiation efficiency of a system, which is normally less than 1. For a perfect blackbody, $E_{perfect} = 1$. Let E_b and E_w be the radiation efficiencies of the black and white sides of the vanes. After the mill reaches the equilibrium, such as leaving in the sunlight for enough time, both absorption and radiation power are at the same level that is $E_b pT^4$ and $E_w pT^4$ for black and white sides. The transimpact is a result of the orbital jump proportional to energy absorption. By introducing a transimpact coefficient r, the repulsion forces can be estimated for the black and white sides using:

$$(4) \qquad P_b = E_b rpT^4$$

and

$$(5) \qquad P_w = E_w rpT^4.$$

Now, inequality (1) becomes:

$$(6) \qquad \left|E_b - E_w\right| rpT^4 > F_r.$$

This inequality explains both situations at low and high-temperature equilibriums. The black side is better at absorption and radiation than the white side. In other words, it has a higher radiation efficiency or $E_b > E_w$. For a given Crookes radiometer, $(E_b - E_w)rp$ has a fixed value at equilibrium. If the temperature T is high enough such that inequality (6) is true, the rotation will be sustainable. This explains the situation when the mill is left in sunlight. A higher temperature T provides a stronger force for faster rotation. At low temperatures, such as in the case of the freezer experiment or flashlight focused on the white side of a vane in the second experiment, T is so small that the left side of inequality (6) is too small to overcome resistance F_r. Hence, it cannot create enough force to move the vanes after reaching equilibrium. Note that the initial movement before equilibrium at low temperatures is due to the temperature difference between the two sides of the vanes, as mentioned earlier.

Note that in the high-temperature equilibrium, the resistance term includes two components: static friction and dynamic air drag. The drag is proportional to the square of the rotation speed. The vanes accelerate initially at low speeds when the drag is small. The drag increases as the rotation picks up. The drag eventually reaches a level that prevents the vanes from accelerating further. At this point, the vanes rotate at a steady-state speed, which is the highest speed observed in the experiments under intensive light sources.

The Comprehensive Model

To be comprehensive, there are five interactions on each side of a vane, as shown in Figure 3. The general form for F_b in inequality (1) should be $F_b = F_a + F_{ra} - F_{ca} + F_{rv} - F_{cv}$. F_a is the air pressure due to the incident air molecules onto the vanes. F_{ra} is the repulsion force produced by the air molecules next to the vanes. F_{ra} is the countering effect of the air molecules bouncing off the vanes due to the F_{ca} term that may prevent incoming air molecules from reaching the vanes. This term may cancel part of the air pressure F_a at high densities of air molecules, such as at high pressures. Similar to the repulsion by the air molecules, there are also two terms F_{rv} and F_{cv} due to the transimpact of molecules on the surface of the vanes that kick off air molecules next to the vanes.

Each of the forces is an interaction with air molecules. Their effects are proportional to the density of air molecules inside a mill, which is related to the air pressure. No air molecules mean no interactions. So, all five terms are equal to zero, e.g. $F_a = F_{ra} = F_{ca} = F_{rv} = F_{cv} = 0$ and $F_b = 0$. At very low air pressures, there are not enough air molecules for all five terms, hence not enough interactions to create the driving force F_b to overcome the static friction. Thus, the vanes do not rotate in a highly vacuumed mill.

At low pressures, molecules rarely collide. The two countering terms F_{cv} and F_{ca} are negligible because there are little or no collisions against air molecules to counter the air pressure term. Without the two countering terms F_{cv} and F_{ca}, the air pressure F_a is the same on the two sides of each vane and cancels from the two sides. The F_{ra} term is also the same on both sides of each vane and cancels because the temperature of air molecules is the same on both sides of the vanes. Therefore, all these four terms (F_a, F_{ra}, F_{ca}, and F_{cv}) can be neglected, and $F_b = F_{rv}$. This is the assumption used in the last section. Hence the discussion was simplified.

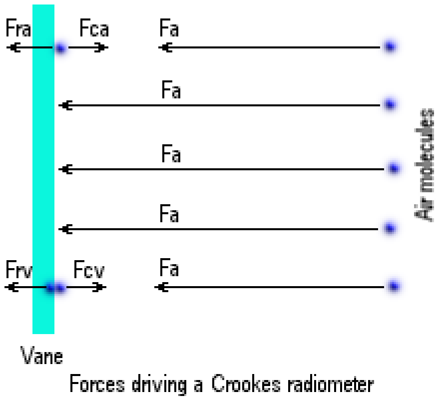

Figure 3, The driving forces on each side of a vane.

At high pressures, there are greater odds that molecules collide with each other. The transimpact of air molecules next to a vane creates a pushing force on the vane F_{ra}. At the same time, the bounced air molecules collide against the incoming air molecules, reducing the air pressure term F_a by F_{ca}. It will eventually cancel the repulsion effect produced on the vane F_{ra}, or $F_{ra} - F_{ca} = 0$. Similarly, $F_{rv} - F_{cv} = 0$. The only term left in the driving force on the black side of the vane is F_a, or $F_b = F_a$. Following the same logic, $F_w = F_a$ on the white side. Both F_b and F_w are equal to the air pressure term F_a which is the same on both sides of each vane, producing a zero net force to each vane. Thus, the vanes do not move at high pressures.

Conclusions

All the existing models based on air pressure fail to explain the rotation of Crookes radiometers at thermal equilibrium. The new phenomena observed in the focused light experiment pose additional challenges to the existing theories. The transimpact theory provides a comprehensive model that can address all the observed phenomena related to Crookes radiometers. Transimpact is a newly identified intermolecular interaction, which is common and affects many physical processes, such as Brownian motion and phase transition.

Revision History

- 06/20/2019: Initial version submitted to arXiv.org
- 06/03/2021: Revision for grammar check.
- 01/08/2023: Revision for transimpact concept.

References

1. Crookes, W. (1874). "*On Attraction and Repulsion Resulting from Radiation*". *Philosophical Transactions of the Royal Society of London*. **164**: 501–527. doi:10.1098/rstl.1874.0015.
2. Maxwell, J.C. (1879). "*On stresses in rarefied gases arising from inequalities of temperature*". Philosophical Transactions of the Royal Society of London. **170**: 231–256. doi:10.1098/rstl.1879.0067.
3. Worrall, J. (1982), "*The pressure of light: The strange case of the vacillating 'crucial experiment*'", Studies in History and Philosophy of Science, **13** (2): 133–171, doi:10.1016/0039-3681(82)90023-1.
4. Gibbs, P. (1996). "*How does a light-mill work?*". math.ucr.edu/home/baez/physics/index.html. Usenet Physics FAQ. Retrieved 8 August 2014.
5. Brush, S.G.; Everitt, C.W.F. (1969). "*Maxwell, Osborne Reynolds, and the Radiometer.*" Historical Studies in the Physical Sciences, vol. 1, 1969, pp. 105–125.
6. Han, L.H.; et al. (2010). "*Light-Powered Micromotor Driven by Geometry-Assisted, Asymmetric Photon-heating and Subsequent Gas Convection*". Applied Physics Letters. **96** (21): 213509(1–3). doi:10.1063/1.3431741.
7. Han, L.H.; et al. (2011). "*Light-Powered Micromotor: Design, Fabrication, and Mathematical Modeling*". Journal of Microelectromechanical Systems. **20** (2): 487–496. doi:10.1109/JMEMS.2011.2105249.
8. Wolfe, D.; et al. (2016). "*A Horizontal Vane Radiometer: Experiment, Theory, and Simulation*". Journal-ref: Phys. Fluids 28, 037103. Department of Physics, Naval Postgraduate School, Monterey CA 93940, USA. **28** – via arXiv.
9. Yarris, L. (2010). "*Nano-sized light mill drives micro-sized disk*". Physorg. Retrieved 6.
10. Osborne, R. (1879). "*On certain dimensional properties of matter in the gaseous state*", Royal Society Phil. Trans., Part 2.
11. Vijay, R; et al. (2011). "*Observation of Quantum Jumps in a Superconducting Artificial Atom*". Physical Review Letters. **106** (11): 110502. arXiv:1009.2969. doi:10.1103/PhysRevLett.106.110502. PMID 21469850.

12. Itano, W.M.; et al. (2015). "*Early observations of macroscopic quantum jumps in single atoms*". International Journal of Mass Spectrometry. **377**: 403. doi:10.1016/j.ijms.2014.07.005.
13. Liu, J.Z. (2022), “*Misconceptions in Thermodynamics*”, Stanford University.
14. Liu, J.Z. (2019), “*Molecular Gravity and Phase Transition*”, Stanford University.
15. Liu, J.Z. (2019), “*The Cause of Brownian Motion*”, Stanford University.
16. Planck, M. (1914). “*The Theory of Heat Radiation”*. Masius, M. (transl.) (2nd ed.). P. Blakiston's Son & Co. OL 7154661M.
17. Planck, M. (1915). “*Eight Lectures on Theoretical Physics”*. Wills, A. P. (transl.). Dover Publications.
18. Draper, J.W. (1847). “*On the production of light by heat*”, London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, series 3, **30**: 345–360.
19. Narimanov, E.E.; Smolyaninov, I.I. (2012). "*Beyond Stefan–Boltzmann Law: Thermal Hyper-Conductivity*". Conference on Lasers and Electro-Optics 2012. OSA Technical Digest. Optical Society of America. pp. QM2E.1. doi:10.1364/QELS.2012.QM2E.1.
20. Knizhnik, K. "*Derivation of the Stefan–Boltzmann Law*". Johns Hopkins University – Department of Physics & Astronomy.