The Force Driving the Crookes Radiometer

Jerry Z. Liu
ZJL@CS.Stanford.EDU
Stanford University, California, USA

Abstract

The Crookes radiometer was invented in 1879. The vanes of a radiometer rotate when exposed to light. However, the force driving the rotation is still a mystery. Numerous models have been proposed to provide solutions. None of them is able to address all the situations. An orbital repulsion force is proposed in this study to provide a comprehensive solution. Upon absorbing energy, an electron jumps to a higher orbital. The process not only increase the size of a molecule, but also reduces the distance to the adjacent molecules. Both processes create repulsions to the adjacent molecules. Because an orbital jump is sudden, the repulsions may exert a significant force to the adjacent molecules. It may be this force produced by molecules on the surface of vanes that pushes the air molecules next to the surface which provides the momentum for the vanes to rotate. This force may also be the cause of Brownian motion and phase transition from solid to fluid.

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, 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 of light.[1] It can spin all day under sunlight. The rotation is such that the black sides of the vanes are retreating from the light. When the bulb is cooled quickly by putting it into a freezer, it turns backwards slowly and stops in a minute or so. The mechanism for the rotation has been a scientific debate over a century. However, a convincing explanation has yet to appear. The light mill inventor, Crookes, incorrectly suggested that the force was due to the pressure of photons predicted by James Clerk Maxwell, well known for his equations of electromagnetism.[2] If this is true, a faster rotation should be observed with better vacuum in the bulb. It turned out the best result is observed at a pressure around 1 pascal. The vanes stay motionless in a hard vacuumed bulb.

There were numerous theories, trying to establish an unbalanced pressure between black and white sides of the vanes or over the edges.[3-10] One proposal is that air molecules hitting the warmer side of the 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 showed that the two pressures do not cancel out exactly at the edges of the vanes because of the temperature difference there. However, the force predicted by Einstein would be barely enough to move the vanes. A more complicated model called thermal creep suggests air creeps cross the edge of vanes from the white side to the black side.[4] This creates a high pressure on the black side that pushes the vanes forwards.

A problem that all the air-pressure-based theories failed to address is how to create the driving force at the thermal equilibrium. Left in an intensive light source, such as sunlight, a mill will reach an equilibrium sooner or later. By that time, the absorption and radiation on each (no matter black or white) side are at the same level. A black side absorbs light more effectively and also radiates at the same efficiency. The total heat flux including both reflection and radiation from each side is the same as the incoming flux. The air is heated by the same amount of energy on either side. For a given body of air, its pressure is a measurement of average kinetic energy level which is determined by the ambient radiation level. The pressure on the two sides of a vane should be the same. Thus, there is no pressure difference to drive the vanes.

Focused Light Experiment

To investigate the problem, we designed an experiment, in which a small torch was used as the light source, Figure 1. To turn the mill forwards, the torch was pointed and focused on the black side of a vane. The motionless vanes started moving immediately. It completed the first cycle in less than 5 seconds. Within a minute, the rotation reached the highest speed, about 2 cycles per second. The results are similar to the experiments with none focused light sources. Next, the torch was focused on the white side of a vane so that the light ray was perpendicular to the surface of the vane to avoid reflecting on to the black side of the adjacent vane. The vanes stayed motionless no matter how long the light was kept on.

Figure 1, Focused light source experiment for the Crookes radiometer.

The purpose for using a focused light was to test if there is enough driving force in the air pressure to move the vanes. Avoiding any reflection onto the black sides isolates the influences of other factors that the black sides might have. As the light focused on the white side, the air near the white side was doubly heated by both the directed and the reflected photons. Giving it enough time, the air should be heated, creating some kind of aerodynamic force to move the vanes. The fact was that the vanes did not move, indicating there was not enough driving force to overcome the static friction. At a pressure of 1 pascal, which is about 10^{-5} of the pressures at the sea level, the air is as thin as that on the top of the mesosphere, an altitude of 80 km above the Earth. This is where an airplane is less efficient than a rocket, where the rocket is not driven by the air pressure but the momentum created through ejecting high speed molecules. In the other direction, the torch was pointed to a single black vane and the push force was so strong that the vane was moved spontaneously without a waiting time for the air to warm up, indicating the driving force may result from interactions other than air pressure.

Not every Crookes radiometer was made equal. Next experiment was more interesting by using a mill with smaller static friction, therefore more sensitive. As expected, in the forward direction, it just started quicker and spun faster. When the torch was pointed to a white vane, it started to move immediately but slowly. More interestingly, the rotation was in the forward direction. The white vane was chasing the light source. It stopped in a few seconds. After removing the light source, it rotated backwards and stopped quickly, which was similar to the situation observed in the freezer experiment. Why did the vanes chase the light source, then stopped instead of moving faster? The discovery of this phenomenon provides sufficient evidence against the light pressure theory and creates a new challenge to all the air-pressure-based theories.

The Driving Force

Upon absorption of energy or photons, an electron in an atom jumps to a higher orbital, known as orbital jump, quantum jump, or atomic electron transition.[11-12] The process of orbital jump is still under active research. It appears spontaneous as an electron jumps from one energy level to another, typically in nanoseconds or less. Because an orbital jump is sudden, it may exert a repulsion force to an object next to the atom. The object being pushed may be anything range from another atom to a dust particle, even the surface of a vane. As shown in Figure 2A, two atoms were next to each other with a small separation. On absorbing energy, one of the atoms went through an orbital jump process, which actually included two sub-processes: the atom size was increased and the distance between them was decreased, Figure 2B. Both processes increased the repulsion between them, called **orbital repulsion**.[13] The atoms were pushed apart and moved in the opposite direction, Figure 2C.

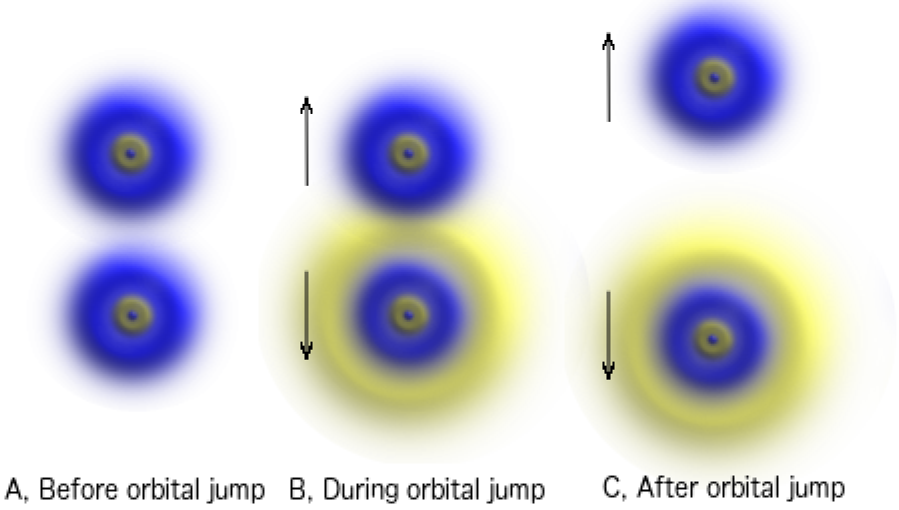

Figure 2, Orbital repulsion resulted from quantum/orbital jump.

The repulsion force is distance sensitive and significant at a close range. Two helium atoms were used to model the force.[14] The repulsion force between the helium atoms at a distance of 140 pm (the radius of a normal helium atom) may be upto 5.4 nano N. To get a sense of the scale of this force, that is equivalent to accelerating a kilogram mass with 8.12×10^{17} N force. This is not a conventional intermolecular force. It occurs only when there is orbital jump. This force may be responsible for kicking molecules to move in Brownian motion.[15] The force may also play an important role during phase transition of matter. As temperature increases, this force may eventually overcome the attraction between molecules in solid, freeing up the molecules for transition to fluid.[14] This force is postulated that drives the Crookes radiometer.

Equilibrium at Low Temperatures

Upon absorbing photons, the electrons of the molecules on the surface of the vanes are excited and jump to higher orbitals, producing orbital repulsion. The process kicks off air molecules next to the vanes, creating a momentum to move the vanes in the opposite direction. When the torch was pointed to the black side of a vane, the photons were absorbed quickly, producing an orbital repulsion to move the vanes immediately. On the white side, the light was mostly reflected. The same repulsion effect applies to the second experiment, however the process is a little more complex.

Orbital repulsion takes place on any surface with a temperature above absolute zero. The repulsion force exerts on both black side F_b and white side F_w. There is also a resistance F_r, which approximates to static friction at a low rotation speed of the vanes. To move the vanes, the force difference between the two sides of a vane must be greater than the resistance:

$$|F_b - F_w| > F_r. \tag{1}$$

Otherwise, there will be no motion. When the mill was placed in a freezer, the heat inside the mill was emitting to the environment and the black side was doing the blackbody radiation that was faster than the white side. The white side was relatively warmer, creating a greater orbital repulsion F_w that pushed the vanes in the backward direction. It stopped quickly as the mill approached the new equilibrium, and the force difference between the two sides could not overcome the static friction as required by inequation (1). When the torch 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 forwards. The mill stopped quickly as the new equilibrium was reached. When the light source was removed, the mill went through a cooling process similar to that occurred in the freezer experiment.

Equilibrium at High Temperatures

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

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:

$$P = pT^4, \tag{2}$$

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 approximated using:

$$P_n = EpT^4, \tag{3}$$

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 with an ambient temperature T, such as left under sunlight for enough time, both absorption and radiation power are at the same level and are $E_b pT^4$ and $E_w pT^4$ for black and white sides, respectively. The orbital repulsion is a result of orbital jump proportional to energy absorption. By introducing an orbital repulsion coefficient r, the repulsion forces can be estimated for the black and white sides using:

$$F_b = E_b rpT^4, \tag{4}$$

and

$$F_w = E_b rpT^4. \tag{5}$$

Now, inequality (1) can be rewritten as:

$$|E_b - E_w| rpT^4 > F_r. \tag{6}$$

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 the equilibrium. This inequality provides an explanation for both situations at low- and high-temperature equilibriums. If the environment temperature T is high enough so that $(E_b - E_w)rpT > F_r$, the rotation will be sustainable. This is the situation when the mill was left under the sunlight. A higher temperature T provides a stronger force for faster rotation. At a low temperature T, such as in the case of the freezer experiment or light pointed towards the white side of a vane in the second experiment, $(E_b - E_w)rpT$ is not large enough to overcome resistance F_r, hence cannot create enough force to move the vanes after the equilibrium. Note, the initial movement before equilibrium in the low temperature experiments is due to the temperature difference between the two sides of the vanes as mentioned earlier.

Keep in mind, in the high temperature equilibrium, the resistance term actually includes two components: the static friction and dynamic air drag. The drag is proportional to the square of the rotation speed of the vanes. When the ambient temperature is high enough, the vanes will start with acceleration. The drag increases with the rotation speed. The resistance including the drag will eventually reach the same level as the driving force produced by the repulsion. By that time, the vanes will rotate at a steady state speed, which is the highest speed observed in the experiments with intensive light sources.

The Comprehensive Solution

To be comprehensive, there are actually five interactions inside a light mill, 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 discussed in most of the existing theories. F_{ra} is the repulsion force produced by the air molecules next to the vanes. F_{ca} is the countering effect of the air molecules bounced off the vanes due to F_{ra} term that may prevent incoming air molecules from reaching the vanes. This term may cancel part of the air pressure F_a if there is a high density of air molecules, e.g. at high pressures. Similar to the repulsion by the air molecules, there are also two terms F_{rv} and F_{cv} due to the repulsion of molecules on the surface of vanes that kicks off air molecules next to the vanes.

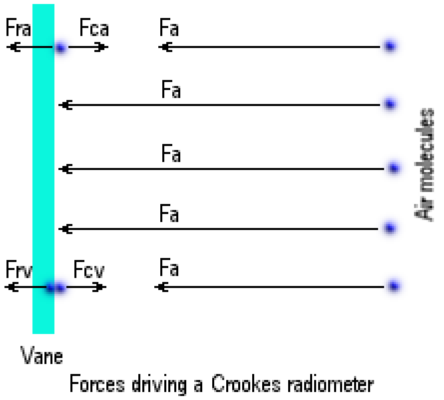

Figure 3, The driving forces on each side of a vane.

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 proportional to the air pressure in the mill. No air molecules means no interactions. So, all the 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 of the vanes. Thus, the mill does not rotation at very low pressures.

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. Therefore, all these four terms (F_a, F_{ra}, F_{ca} and F_{cv}) can be neglected, e.g. $F_b = F_{rv}$. This is the assumption used in the discussion in the last section. Because other terms are neglectable in low pressure situation, the discussion was simplified earlier.

With higher density of air molecules at high pressures, there are greater chances that molecules bump into each other. The orbital repulsion of air molecules next to a vane creates a pushing force to the vane F_{ra}. At the same time, the bounced air molecules colliding against the incoming air molecules, reducing the air pressure term F_a by F_{ca}. The reduced air pressure F_{ca} is the same amount of force that the repulsion produced to the vane F_{ra}. So, the two terms F_{ra} and F_{ca} are cancelled, e.g. $F_{ra} - F_{ca} = 0$, so does $F_{rv} - F_{cv} = 0$. The only term left in the driving force is F_a, e.g. $F_b = F_a$. Similarly, $F_w = F_a$ on the white side of each vane. Both F_b and F_w equals to the pressure term F_a that is the same on both sides of each vane, producing a zero net force to each of the vanes. Thus, the vanes cannot rotate at high pressures.

Conclusions

All the existing models based on the air pressure fail to explain the rotation of the vanes in a Crookes radiometer at the equilibrium with a high temperature. The orbital repulsion theory provides a comprehensive solution that is able to address all the situations. Orbital repulsion force is not a conventional force, but spontaneous and effective only when there is orbital jump of a molecule next to other object. This force may also be responsible for kicking molecules creating Brownian motion in fluid. The magnitude of the force and the frequency of occurrence increases with temperature. As temperature increases, the force will eventually be greater than the intermolecular attraction that holds molecules together in a solid. The molecules of the solid can be knocked apart, which explains the liquefying phase transition.

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. (2019), "*Uncovering the Mystery of Superconductivity*", Stanford University.
14. Liu, J.Z. (2019), "*The Forces Causing Phase Transition of Matter*", Stanford University.
15. Liu, J.Z. (2019), "*Revealing the Mystery 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.