The Mechanism Driving Crookes Radiometers

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Abstract

The vanes of a Crookes radiometer rotate when exposed to light. Despite its long history, the mechanism behind this rotation remained a mystery for over a century. Numerous theories were proposed, but none could fully explain all the observations, particularly the rapid initial acceleration and the backward rotation when cooled. Our investigations into the driving mechanism of radiometers have led to the discovery of a novel type of interaction between molecules, termed *transimpact*. When an electron in an atom absorbs energy, it excites to a higher orbital, expanding the electron cloud of the atom while reducing the distance to adjacent atoms within a few nanoseconds. This sudden reduction in space between atoms disrupts the balance of forces, creating a repulsion between the atom and surrounding particles. When transimpacts occur between air molecules and molecules on the surface of a radiometer vane, the air molecules can be pushed away with significant momentum, similar to the burst of popcorn, propelling the vane in the opposite direction. The black side of a vane, being more efficient at absorbing energy, results in more electron excitations and transimpacts than the white side. This unbalanced impact between the two sides causes the vanes to rotate. Because atomic electron transitions occur instantaneously upon exposure to incident light, the transimpact theory predicts a decreasing acceleration profile marked by an initial peak, resulting from increasing air drag as rotational speed increases. This distinctive feature sets the theory apart from all existing models. To test this prediction, a series of experiments was conducted. The close alignment between theoretical projections and experimental results provides compelling evidence in support of the transimpact theory.

Introduction

Invented in 1879, a Crookes radiometer, also known as a light mill, consists of a set of vanes mounted on a low-friction spindle inside a low-pressure glass bulb, as shown in Figure 1. Each vane is coated black/dark on one side and white/light on the other. When exposed to light, the vanes rotate with the black sides retreating from the light source, and the rotation speed increases with more intense light.[1]

When placed under sunlight, the rotation starts quickly, reaching a steady state within a few seconds, and spinning indefinitely. If the bulb is rapidly cooled by putting it in a freezer, the vanes rotate backward slowly and come to a stop within a few seconds.

For over a century, the mechanism behind this rotation has been a subject of scientific debate. A convincing explanation remains elusive despite numerous theories attempting to elucidate the motion. These theories can be broadly categorized into three groups: light pressure, air pressure, and aerodynamics. The radiometer's inventor, William Crookes, suggested that the force was due to the pressure of light, as predicted by James Clerk Maxwell.[2-5] If this were true, the rotation should occur in the opposite direction because the white side of the vanes would experience higher pressure due to greater reflection.

Figure 1: Crookes radiometer.

Additionally, if light pressure were the driving force, faster rotation would be expected in a better vacuum bulb. However, the vanes remain motionless in a heavily vacuumed bulb. Similarly, if radiometers were driven by the photoelectric effect, faster rotation would also be expected in a highly evacuated bulb. Moreover, the rotation is certainly not driven by the photoelectric effect because there are no high-energy photons to dislodge electrons in cooling experiments. Thus, the photoelectric effect should be ruled out. In reality, the best results are observed at a pressure of around 1 Pa, as shown in Figure 2.

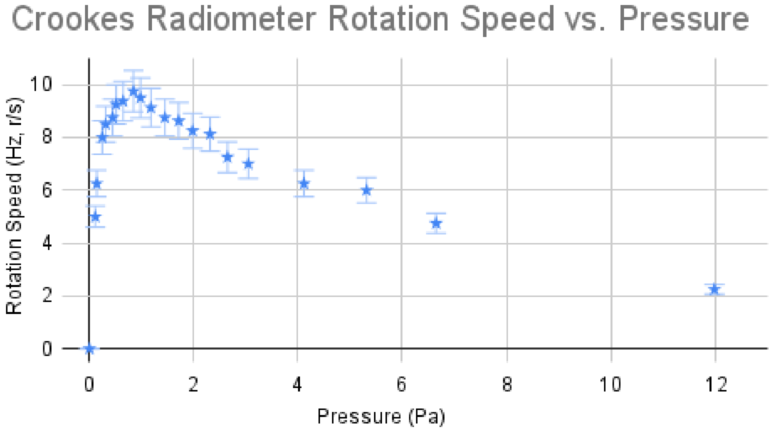


Figure 2: The Maximum rotation speed of Crookes radiometers at around *1 Pa*.

Air pressure-based theories attempt to establish an unbalanced pressure between the two sides of the vanes.[6] One proposal suggests that air molecules hitting the warmer side of a vane will pick up some of the heat, bouncing off the vane at a higher speed. The issue with this idea is that while the faster-moving molecules create more pushing force, they also do a better job of colliding with and preventing incoming air molecules from reaching the vane.

Another challenge for all air pressure-based theories is explaining how the driving force is generated at equilibrium. Given enough time, a radiometer will eventually reach thermal equilibrium. At this point, absorption and emission levels are equal on both sides of the vanes. The black side absorbs light more effectively and also emits energy at the same efficiency. The white side absorbs less light but reflects more photons. Consequently, the total radiation density, including both reflection and emission, matches the incoming light. As a result, the air is heated by the same amount of energy on both sides of a vane, leading to equal pressure on both sides.

In the aerodynamics category, two theories attribute the rotation to edge effects.[7-9] Albert Einstein suggested that the push of air molecules on the vanes does not cancel out exactly at the edges due to a temperature difference. However, calculations have shown that the force predicted by Einstein is insufficient to move the vanes. A more popular theory, known as thermal creep, proposes that air creeps over the edges of the vanes, generating the motion.

However, all air-based theories fail to account for the rapid onset of rotation, particularly the significant initial acceleration. For stationary vanes to begin rotating, the driving force must first overcome friction at the spindle. These theories attribute the movement of vanes to air flow caused by pressure differences, which require time to develop as the air heats up. Consequently, acceleration should start at zero and gradually increase. Yet, this gradual buildup is rarely observed. Instead, this study shows that rotation begins with maximum acceleration, which then decreases as air resistance grows with increasing speed.

Cooling experiments pose additional challenges compared to heating ones. In these setups, radiometers are cooled either by applying a coolant or by transferring them from a high-temperature to a low-temperature environment. Rather than absorbing energy, the devices radiate internal energy, primarily through infrared light. Since air molecules (~0.3 nm in diameter) are much smaller than the wavelength of infrared light (>750 nm), they rarely interact with this radiation. As a result, the air inside should remain largely unaffected by the vanes' radiation during cooling, making it unlikely that enough internal heat exchange occurs to generate the pressure or airflow needed to overcome spindle friction. Yet, rotation still occurs, and notably, it begins rapidly. Even more strikingly, in our microwave-assisted cooling experiments, backward rotation speeds of up to 7 revolutions per second were observed—faster than what is typically seen under direct sunlight.

To minimize the influence of airflow and pressure, an earlier phase of this study employed focused light source experiments. By using direct, collimated light to illuminate the vanes, we reduced interactions between the light and surrounding air molecules, allowing us to isolate the vanes' response to directional illumination. These experiments suggested that airflow and pressure are not the primary drivers of radiometer rotation, indicating the need for alternative explanations. This led to the preliminary formulation of the **transimpact theory**, although no validation method was available at the time. In this revised study, we introduce a new set of experiments specifically designed to test a key prediction of the transimpact theory: a distinctive speed profile characterized by a peak in initial acceleration. The experimental results closely match these predictions, offering strong empirical support for the proposed theory.

Experiments Using a Directional Light

To isolate the effects of airflow and pressure, we conducted directional light source experiments, as illustrated in Figure 3. When a flashlight beam was focused onto the black side of a vane, the stationary vanes began rotating almost immediately, completing a full revolution in under five seconds. After approximately one minute, the rotation stabilized at a steady velocity of about 2 revolutions per second. These results closely resembled those observed in typical experiments using natural sunlight. In a follow-up test, the flashlight was directed at the white side of a vane, with care taken to minimize any reflection onto the adjacent black side. Surprisingly, even under prolonged exposure, the vanes remained stationary.

The design of this experiment aims to determine if applying equal amounts of energy to the air near each side of the vanes produces the same air pressure, propelling the vanes at the same speed in both directions. According to air-based theories, the vanes should rotate at a comparable rate in either direction. Focused light was used to minimize scattering and its side effects. By pointing the light at the white side, the air near the vane would receive the same amount of energy from incoming, reflecting, and emitting photons as the black side. Given enough time, the air should have been heated, generating the same pressure to drive the vanes as on the black side. However, the experiment did not produce the expected result, indicating that the assumption of air-based theories may be incorrect.

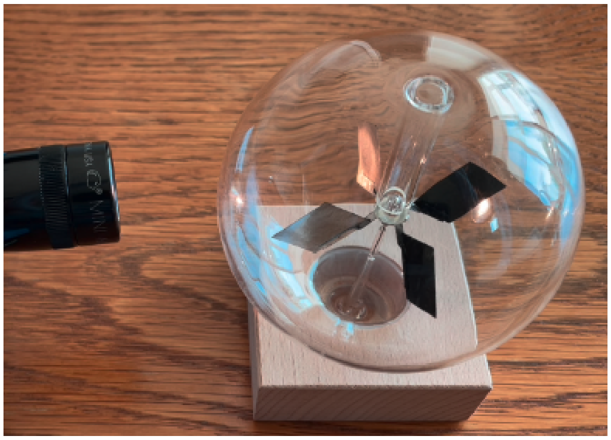


Figure 3: Experiments with light focused on a Crookes radiometer vane.

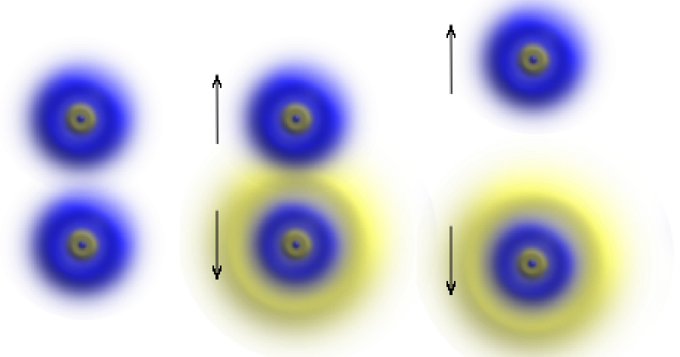
The subsequent experiment was even more intriguing, as we employed a more sensitive radiometer with less static friction. As anticipated, the radiometer initiated more rapidly and rotated faster in the forward direction. When we directed the flashlight at the white side, it began to move forward immediately, with the white side of the vanes chasing the incident light. However, the speed was much slower, and the movement ceased after a few seconds. When we switched off the light, the radiometer rotated backward and stopped before completing the first revolution, much like the observation in freezer cooling experiments. Why do the vanes chase the light when there is no direct light on the other side? As the illuminated side is heated, shouldn't it be pushed away? This phenomenon poses a further challenge to air-based theories.

At an inside pressure of one pascal, equivalent to about 10^{-5} of the pressure at sea level, the air becomes as sparse as it is at an altitude of 80 km above sea level, corresponding to the upper reaches of the mesosphere. At this altitude, the air is too thin to generate sufficient lift for aircraft, rendering it inaccessible to airplanes. Instead, space flight relies on rockets that propel using high-speed streams. Similarly, due to the extremely low pressure, the vanes in the radiometer cannot be propelled by air molecules moving in a conventional manner, such as through aerodynamic lift or air pressure. The distinct reactions observed between the black and white sides, along with the prompt response in most experiments, suggest that the rotation of radiometers is driven by interactions other than airflow or pressure differences.

Transimpact Theory

When an electron in an atom absorbs energy, it excites to a higher orbital, a process known as a quantum jump or atomic electron transition.[10-11] This transition occurs spontaneously and typically within a few nanoseconds. As a valence electron jumps to a higher orbital, the outer electron cloud expands, reducing the distance to neighboring particles. This alteration disrupts the balance established by Van der Waals forces. Since the orbital jump is abrupt, it generates a powerful repulsion on nearby objects, such as the surface of a vane. This phenomenon is similar to the burst of popcorn, where the momentum of a popping kernel exerts force on adjacent kernels or the heating surface. This process is referred to as “transimpact”, coined from "transition impact".

A transimpact can be illustrated using two monatomic molecules placed next to each other, as shown in Figure 4. The distance between the molecules results from a balance of attractive and repulsive forces, known as van der Waals forces, depicted in Figure 4A. When an atom absorbs energy, an electron transition occurs, leading to an increase in molecular size and a reduction in the distance to the next molecule, as indicated in Figure 4B. These changes disrupt the balance of van der Waals forces. Consequently, the repulsive force between the molecules suddenly increases, causing them to be pushed apart, as illustrated in Figure 4C.



A, Before orbital jump B, During orbital jump C, After orbital jump

Figure 4: Transimpact due to an atomic electron transition.

To comprehend the scale of volume changes during an atomic electron transition, we can examine the excitation of nitrogen atoms, which constitute 78% of the molecules in air. A nitrogen atom has 7 electrons with a ground state orbital configuration of $1s^2 2s^2 2p^3$. The atom's radius is approximately 56 pm, primarily determined by the valence orbital. When excited, the nitrogen atom's orbital configuration changes to $1s^2 2s^2 2p^2 3s^1$ or $1s^2 2s^2 2p^2 3p^1$, with a radius of around 120 pm. Thus, the radius of the nitrogen atom more than doubles upon excitation, resulting in a volume increase of over 700% within a few nanoseconds.

When an electron of a molecule on a vane becomes excited next to an air molecule, or an air molecule becomes excited near a vane in a radiometer, there is an explosive impact that pushes them apart in opposite directions. This momentum is much greater than that caused by a simple collision with an air molecule.[12] Therefore, we believe it is this transimpact that drives the rotation of radiometers.

Transimpacts are common phenomena, occurring whenever an electron orbital transition accompanies an energy exchange between an atom and its surroundings. Consequently, transimpacts influence many everyday processes. They may be responsible for moving particles in Brownian motion. Studies indicate that the random motion of water molecules is insufficient to drive pollen in Brownian motion.[12] Transimpacts might also play a crucial role during phase transitions of matter. As the temperature increases, transimpacts can overcome the bonds between molecules, causing them to break apart, leading to melting and vaporization. The intensity of transimpacts is much greater than that of molecular vibrations, with bonds likely to be broken by transimpacts before vibrations reach such high intensity.[13]

Equilibrium at Low Temperatures

By analyzing the interaction forces in this and the following sections, we can apply the transimpact theory to explain the observations related to the rotation of radiometers, covering scenarios from simple to complex. In previous experiments, when a flashlight was directed towards the black side of a vane, the photons were rapidly absorbed, leading to immediate transimpacts that propelled the vanes into motion. Conversely, on the white side, where the light was predominantly reflected, the occurrence of transimpacts was less pronounced compared to the black side.

Here is a simple analysis of the forces in a radiometer. Transimpact occurs on any substance with a temperature above absolute zero. This impact exerts forces on both the black side and the white side, resulting in impact forces F_b and F_w, respectively. Additionally, there is a resistance force F_r, which approximates the static friction at low rotational speeds. To move the vanes, the force difference between the two sides must be greater than the resistance:

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

When a radiometer is placed in a freezer, the overall heat emitted by the radiometer is initially greater than the heat absorbed from the surroundings on both sides of the vanes. The black sides, being better absorbers and emitters, radiate more energy than the white sides and thus cool faster. Consequently, the black sides become relatively cooler, reducing their transimpact level faster and resulting in a smaller F_b compared to F_w. This net force pushes the rotation in the backward direction. The rotation stops once both sides approach equilibrium, as the force difference between the two sides can no longer overcome the friction described in inequality (1). The process is typically short because the small temperature difference can be quickly equilibrated by instantaneous atomic electron transitions.

In the more sensitive radiometer experiment, when the flashlight was directed toward the white side, most of the photons were reflected. The long-wavelength components of the light, such as infrared, had difficulty passing through glass and were reflected within the bulb. The black sides absorbed the reflected light more effectively than the white sides, generating a greater repulsion force F_b , which pushed the vanes forward. The radiometer quickly stopped as the temperature on the white side increased, reducing the temperature difference between the two sides. After switching off the light, the radiometer cooled down like the freezer experiment.

So far, we've examined scenarios where the radiometer rapidly attains a new equilibrium at a low ambient temperature. The uneven rates of warming or cooling on the two sides of the vanes create a short-term imbalance of forces, propelling the vanes to rotate. The vanes come to a stop quickly as the system approaches equilibrium in the new environment.

Equilibrium at High Temperatures

Next, let us explore the long-term driving force at equilibrium under high temperatures, such as in sunlight. In this scenario, a radiometer will rotate at a steady speed when equilibrium is reached. Why is the rotation sustainable at high temperatures but not at low temperatures in both equilibrium states?

Recall the blackbody radiation described by Planck's law.[14-16] By integrating Planck's equation over the frequency and then over the solid angle, we find 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:

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

In this equation, P is the power emitted per unit area of the surface of a blackbody, and p is the Stefan-Boltzmann constant.[17-18] Most systems are not a perfect blackbody. Their radiation power P_e can be estimated using

$$P_{e} = pET^{4} \tag{3}$$

Here, E denotes the emitting efficiency of an imperfect blackbody, typically $E < 1$. Let E_b and E_w be the emitting efficiencies of the black and white sides, respectively. After a radiometer reaches equilibrium, such as after being left in the sunlight for sufficient time, both absorption and emission power are balanced with the surroundings. This means $pE_bT_b^4$ on the black side and $pE_wT_w^4$ on the white side, where T_b and T_w are the temperatures on the black and white sides, respectively. The temperature on the black side is slightly higher than on the white side, even considering heat conduction within the vanes. The transimpact results from the orbital jump proportional to energy absorption. By introducing a transimpact coefficient r, the pushing forces on the two sides can be estimated using:

$$F_{b} = rpE_{b}T_{b}^{4} \tag{4}$$

and

$$F_{w} = rpE_{w}T_{w}^{4} \tag{5}$$

respectively. Now, inequality (1) can be rewritten as

$$rp\left|E_{b}T_{b}^{4} - E_{w}T_{w}^{4}\right| > F_{r} \tag{6}$$

The black side is better at absorption and emission than the white side, i.e., $E_b > E_w$. At high-temperature equilibria, $T_b > T_w$. The left side of inequality (6) can be simplified as

$$rp\left|E_{b}T_{b}^{4} - E_{w}T_{w}^{4}\right| = rp\left(E_{b}T_{b}^{4} - E_{w}T_{w}^{4}\right) > rp\left(E_{b} - E_{w}\right)T_{b}^{4} \tag{7}$$

At a temperature where this inequality

$$(8) \qquad rp\left(E_b - E_w\right)T_b^{\ 4} > F_r$$

is true, inequalities (6) and (1) will also hold, indicating that the net force between the two sides becomes substantial enough to surpass the resistance. This accounts for the indefinite rotation observed when a radiometer is exposed to sunlight or other intense light sources.

The static friction between the radiometer spindle and vane mount is constant for each radiometer. Whenever the condition described by inequality (8) is met, the rotation will accelerate. As soon as the vanes start to move, air resistance increases. The magnitude of air resistance is directly proportional to the square of the rotation speed. Initially, when the rotation speed is low, the vanes experience minimal resistance, allowing for acceleration. However, as the rotation speed increases, the resistance force becomes more significant. Eventually, the resistance force reaches a critical point where it completely cancels out the driving force, preventing further acceleration. At this stage, the vanes reach a steady state and maintain a constant rotation speed.

Indeed, inequality (6) also explains observations at low-temperature equilibrium more accurately. When the ambient temperature decreases, the black side is more efficient at radiating energy, causing it to cool down more rapidly than the white side. As a result, T_b becomes lower than T_w. When there is a significant temperature difference, the impact force on the white side becomes stronger compared to the black side, allowing us to modify inequality (6) as follows:

$$(9) \qquad rp\left|E_b T_b^{\ 4} - E_w T_w^{\ 4}\right| = rp\left(E_w T_w^{\ 4} - E_b T_b^{\ 4}\right) > F_r$$

Because $E_b > E_w$, to ensure inequality (9) holds, the temperature on the black side must be substantially lower than on the white side. This condition typically does not persist for long during a cooling process, explaining the short-term backward rotation observed in cooling experiments. As the temperature on the white side also decreases in the new environment, the force difference diminishes. Eventually, the left side of inequality (9) becomes too small to overcome the resistance term F_r. Therefore, it cannot create a long-lasting driving force at low temperatures. This also explains the situation where a flashlight was focused on the white side of a vane in the second experiment.

Components of Resistance

In the earlier discussion, air resistance was briefly mentioned as a factor contributing to the steady-state rotation of the radiometer. However, for simplicity, it was combined with static friction into a single term, F_r, in inequality (1). Now, let us turn our attention to the components of resistance. The resistance term F_r in inequality (1) comprises both static friction and air resistance:

$$(10) \qquad F_r = F_s + F_a$$

The friction F_s between the vanes and the spindle is a static force that acts as a threshold that the driving force must surpass for rotation to occur. When the vanes remain stationary, it is not due to a lack of transimpacts, but rather because the net driving force they produce is insufficient to overcome this static friction—a condition typically seen with low-energy light sources.

As the vanes start to rotate, the air resistance F_a increases proportionally to the square of the rotational speed. Eventually, the total resistance balances the net driving force, halting further acceleration. At this point, the rotation reaches a stable maximum steady-state speed. This simple resistance model works well at low pressures, where aerodynamic resistance is the dominant factor.

However, at higher pressures, the resistance model becomes significantly more complex. For a more comprehensive analysis, it is necessary to consider all five types of interactions occurring on each side of a vane, as illustrated in Figure 5.

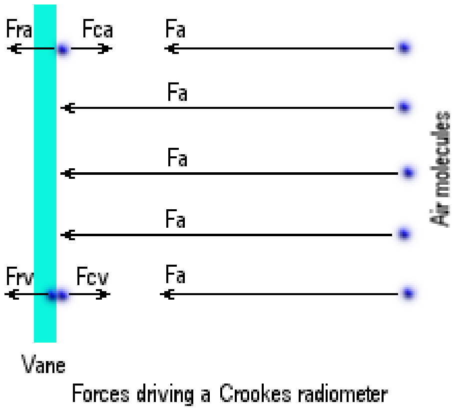


Figure 5: Interactions on each side of a radiometer vane.

In the diagram, F_a denotes the force exerted by air molecules striking the vane, directly contributing to air resistance and increasing with both air pressure and the vane's rotational speed. F_{ra} represents the pushing force generated by transimpacts from nearby air molecules, while F_{ca} is the reactive force that propels air molecules in the opposite direction as a result of the same transimpacts. These expelled molecules may collide with incoming ones, reducing the effective pressure force F_a. At low pressures, such collisions are rare and can be neglected due to the lower air density. However, at high pressures, this effect becomes significant and must be considered.

Similarly, the terms F_{rv} and F_{cv} arise from transimpacts involving the vane's surface molecules, which expel adjacent air molecules. These forces have effects analogous to those of F_{ra} and F_{ca}, and therefore must also be considered when evaluating the total force acting on each side of the vane. Both F_{ra} and F_{rv} contribute to the driving force and are essential components of F_b and F_w in inequality (1).

The vanes' inability to rotate at high pressures can be attributed to two primary factors: increased resistance and a reduced net driving force. Air pressure plays a key role in the air resistance term F_a. At higher pressures, the increased density of air molecules leads to more frequent collisions with the vanes. Since F_a is directly influenced by air pressure, it raises the overall resistance F_r, as shown in formula (10), effectively increasing the threshold the driving force must overcome to initiate rotation. This relationship explains the speed profile as a function of air pressure, illustrated in Figure 2, which shows that the rotational speed decreases as air pressure rises.

Second, at high pressures, rebounded air molecules—associated with the F_{ca} and F_{cv} terms—are much more likely to collide with incoming molecules, partially canceling air pressure. This interaction creates a pressure imbalance between the two sides of the vane, reducing the effective driving force generated by transimpacts. Consequently, high pressure both decreases the net driving force and raises the threshold needed to initiate rotation. This combined effect explains why the vanes fail to rotate under high-pressure conditions.

Predicting Maximum Initial Acceleration

The contrasting predictions of initial rotational acceleration made by the transimpact theory and air-based theories can be readily tested through experiments. Transimpacts occur instantaneously upon exposure to light, while the formation of air pressure differences requires a heating period. Consequently, the transimpact theory predicts a peak initial acceleration at the moment light is applied, whereas air pressure-based theories predict an initial acceleration of zero that gradually increases over time.

Even without exact measurements for the parameters in the equations of transimpact models, qualitative predictions can still be made for experimental validation. For instance, Figure 6 shows the interactions of forces during the heating process, depicting their relative magnitudes and timelines.

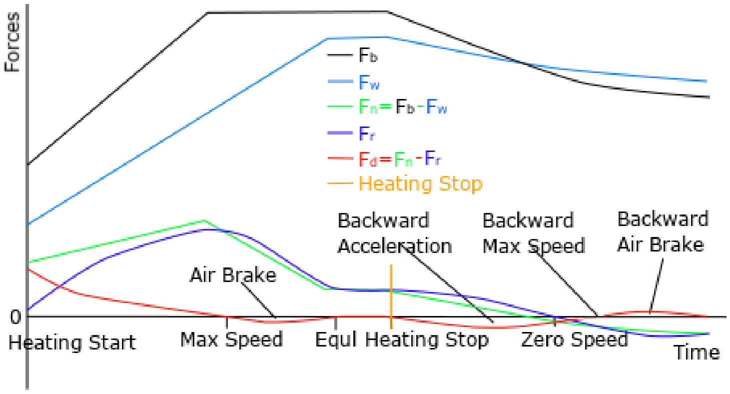


Figure 6: Changes of driving forces in radiometers during a heating process.

In the graph, the black curve illustrates the changes in the transimpact force (F_b) on the black side of a radiometer vane during a heating process. The black side, being a more efficient absorber, experiences a rapid temperature increase in the initial period, and the curve flattens out as it reaches equilibrium. After the light source is removed, the black side cools down quickly.

The temperature on the white side also rises and falls during the same period, but at a slower rate and with a noticeable delay, as indicated by the light blue curve (F_w). The resulting temperature difference between the two sides produces a net pushing force, shown by the green curve (F_n), which drives the vanes to accelerate almost instantaneously.

Once the vanes begin to rotate, air resistance—along with static friction—contributes to the total resistance, as shown by the purple curve (F_r). As the rotational speed rises, air resistance increases sharply, reducing the driving force. This behavior predicts that the maximum net driving force and acceleration occur immediately at the onset of illumination, a prediction confirmed by our experimental results presented in the following section.

A braking effect can occur during high-speed experiments. After reaching peak speed, the accumulated high momentum may cause the resistance to briefly exceed the driving force, resulting in a deceleration even while heating continues. Similarly, a braking effect may also be observed during rapid cooling immediately following intense heating. These braking phenomena are clearly evident in our experimental results.

The driving force generated by transimpacts responds to light sources almost instantaneously, whereas resistance tends to lag due to the slower response of air pressure and airflow. This mismatch in response times can occasionally cause the resistance to overshoot the driving force, resulting in a braking effect. As a result, such braking phenomena are typically observable only in high-energy experiments involving rapid changes.

To facilitate comparison between theoretical predictions and experimental results, the net driving forces predicted by the transimpact theory and air-based theories are represented by the red and blue curves, respectively, in Figure 7. As shown by the blue curve, if the vanes were driven by air pressure or airflow, the initial acceleration would begin at zero and gradually increase as the air warms up. In contrast, the red curve—the net driving force shown in Figure 6—illustrates the prediction of transimpact theory: the initial acceleration reaches its maximum immediately upon illumination.

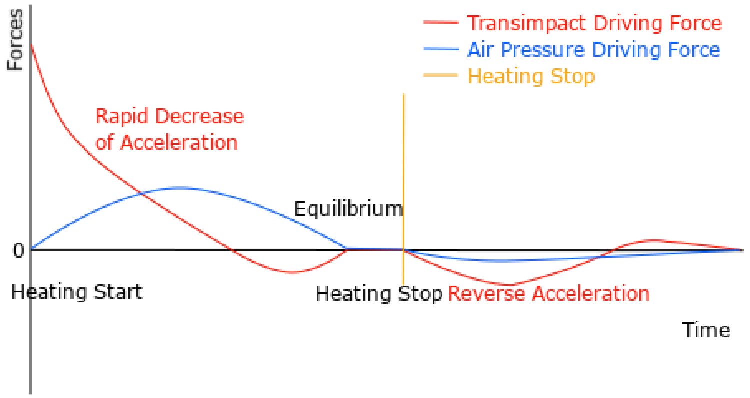


Figure 7: Transimpact driving force vs. air-based driving force

Although these predictions are qualitative, they highlight distinct motion characteristics unique to each theory that should be clearly observable in experiments. The predicted speed profile by the transimpact theory—featuring a pronounced peak in initial acceleration—was confirmed by subsequent experiments, providing strong support for the transimpact theory.

Validation with Rapid Heating

The distinct characteristics predicted by different theories should be observable in experiments by measuring the speed changes of a radiometer during a rapid heating process. One such experiment, using a powerful flashlight, is illustrated in Figure 8. By analyzing the rotation speed and behavior of the vanes during the heating process, we can gain valuable insights into the driving forces behind radiometer motion and differentiate between the various theories.

Figure 8: Radiometer rapid heating experiments using a 120,000-lumen flashlight. The videos of the experiments are available on YouTube: The Process Driving Crookes Radiometers and The Force Driving Crookes Radiometers.

Here are some observations from the experiments: Upon turning on the light, the radiometer exhibited spontaneous rotation. The initial speed increased rapidly, accelerating from 0 to a peak of 25 Hz (rev/s or 2πrad/s) within 30 seconds. Subsequently, the speed gradually decreased and stabilized at around 3 Hz by the 110-second mark, representing the steady-state speed at equilibrium. At 120 seconds, the light was switched off. The rotation speed slowed quickly and came to a complete stop within 8 seconds. The changes in speed over the 128 seconds are compiled in Table 1. Each acceleration value in the table is the average between the two sample points of the rotation speed

Time (s)	0	2	5	17	30	43	64	78	100	110	120	128
Speed (Hz, rev/s)	0	7.5	15	22.5	25	22.5	15	7.5	3.75	3	3	0
Acceleration (Hz/s)		3.75	2.5	0.625	0.192	-0.192	-0.357	-0.536	-0.17	-0.075	0	-0.375

Table 1: Changes in radiometer speed and acceleration during the flashlight experiments.

The experimental data in Table 1 are plotted in Figure 9. By examining the acceleration, which is directly proportional to the driving force, we can better understand the forces behind the radiometer's motion. The red line in Figure 9, representing the observed acceleration, aligns closely with the red curve for the driving force during the Heating Stop period shown in Figures 6 and 7. This strong agreement between observations and predictions provides compelling evidence for the validity of the transimpact theory in explaining the observed phenomena.

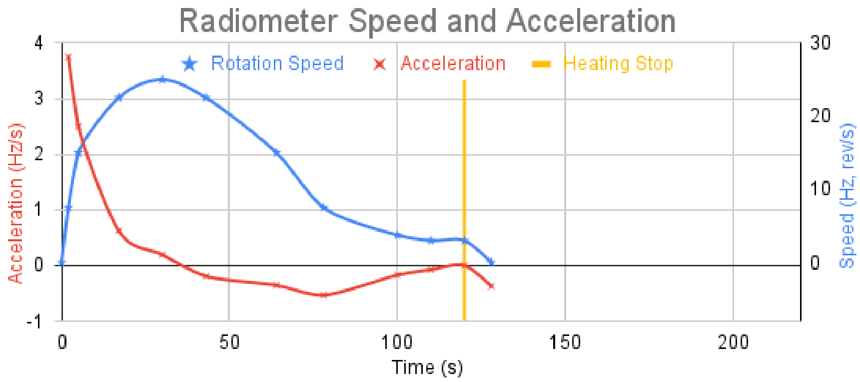


Figure 9: Changes in radiometer speed and acceleration during the flashlight experiments.

The observed characteristics in the speed changes reveal the corresponding changes in transimpact levels and interactions of the forces during the period:

1. The initial acceleration started at its maximum value and rapidly decreased, indicating a high level of transimpacts on the black side of the vanes along with a swift increase in air resistance, as illustrated in Figure 6, confirming the predictions according to the transimpact theory.
2. Around the 30-second mark, the rotation speed peaked, and the acceleration reduced to zero, marking the first intersection point between the pushing force (green curve) and resistance (purple curve) as predicted in Figure 6. This occurs because the transimpacts on the white side increase more slowly after the black side has reached equilibrium.
3. After that point, the acceleration became negative and continued to decrease as the resistance exceeded the overall pushing force due to the high rotational momentum. This led to the emergence of the Air Brake effect on the rotation.
4. As a result, the rotation gradually slowed down, eventually reaching a steady state around 110 seconds. This indicates that the resistance eventually matched and synchronized with the reduced pushing force, typically occurring when both sides of the vanes reached equilibrium.
5. After the light was switched off at 120 seconds, the rotation decelerated quickly and came to a complete stop. This rapid deceleration is primarily due to the swift decrease in transimpact on the black side following the light's shutdown. This process is detailed further below.

Validation with Quick Cooling

Additionally, the braking effect after a Heating Stop shows significant differences between the transimpact theory and air-based theories, as illustrated in Figure 7. According to the transimpact theory, reverse acceleration may be observed during a fast cooling process after intensive heating stops, with the vanes even experiencing a brief backward rotation before coming to a final stop.

In contrast, air-based theories do not predict any backward rotation during the cooling phase. During this process, the radiometers release—rather than absorb—internal energy, primarily in the form of infrared radiation. However, since air molecules (approximately 0.3 nm in diameter) are much smaller than the wavelength of infrared light (typically >750 nm), they interact only minimally with such radiation. Consequently, the internal air remains largely unaffected by the vanes' thermal emission during cooling. This makes it unlikely that sufficient internal heat exchange would occur to generate the pressure differentials or airflow necessary to overcome spindle friction.

In the flashlight experiment examined previously, a quick deceleration was exhibited during the last 8 seconds after turning off the light. However, backward rotation was not observed due to the prolonged heating, which resulted in a minimal temperature difference between the two sides of the vanes. To observe the backward rotation phenomenon, experiments with short, intensive heating should be conducted. These experiments are more likely to create significant temperature differences between the two sides of the vanes in a very short time. To validate this prediction, a radiometer was heated in a microwave for 6 seconds and then allowed to cool rapidly until it came to a complete stop, as depicted in Figure 10.

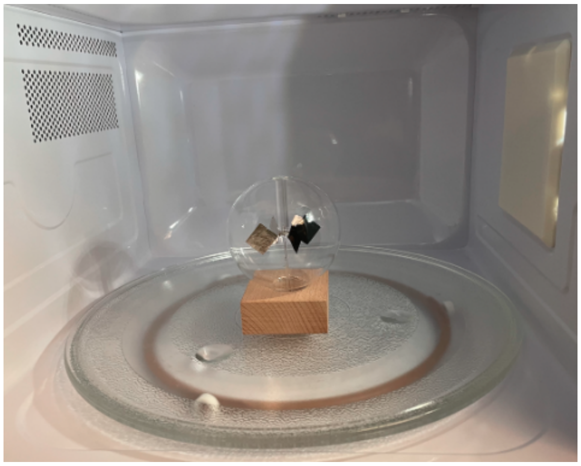


Figure 10: Radiometer quick cooling experiments after being heated in a microwave.

The speed changes are summarized in Table 2. Despite the limited resolution of the data, the reverse acceleration and rapid backward rotation were observed, consistent with the Backward Acceleration and Backward Air Brake phases predicted by the transimpact theory, as illustrated in Figures 6 and 7. In contrast, pressure-based theories do not anticipate any backward rotation, let alone at such high speeds. This further supports the evidence that transimpact is the driving mechanism for the rotation of radiometers.

Time (s)	0	6	15	21	71
Speed (Hz, rev/s)	0	10	0	-7	0
Acceleration (Hz/s)		1.67	-1.11	-1.17	0.14

Table 2: Radiometer speed and acceleration in the microwave experiment.

Since the microwave door had to be closed during the heating period, the speed change inside the microwave was not observable. Nevertheless, the backward rotation was observed after the Heating Stop, which validates our prediction. Here are some major observations from the experiment:

1. After rapid heating for 6 seconds in a microwave, the radiometer's speed reached approximately 10 Hz when the microwave was turned off.

2. Once the microwave was switched off, the radiometer decelerated quickly, with the rotation speed reaching zero at the 9-second mark.
3. Immediately afterward, the rotation reversed. The backward speed accelerated to a peak of around 7 Hz within the next 6 seconds before gradually slowing down.
4. The rotation came to a complete stop over the next 50 seconds.

However, conducting a microwave experiment may pose risks, as the metal piece connecting the vanes in the radiometer caused it to burn out during the second attempt. Therefore, we do not recommend replicating this experiment due to safety concerns. Thankfully, a YouTube video capturing a microwave heating process is available as an alternative reference.[19]

Additional Support from Related Research

Observations from experiments using a horizontal vane radiometer provide additional support for the transimpact theory. Each vane features a two-tone surface, with one half painted black and the other white. The radiometers were positioned on a highly reflective surface, ensuring that both the upper and lower horizontal surfaces were illuminated. The radiometers rotated with the white (cooler) edge leading.[20]

From a topological point of view, a horizontally aligned vane is equivalent to a vertically aligned one via a transformation that compresses the vertical axis and stretches the horizontal. Therefore, the underlying mechanism driving rotation in horizontal vane radiometers is the same as that in vertical ones. However, the driving force is significantly weaker, as transimpact level differences occur only between the black and white edges. Consequently, the rotation speed of the horizontal vane is expected to be much slower—an outcome consistent with transimpact theory and confirmed by the experimental data shown in Figure 11, as compared to the vertical vane results in Figure 2.

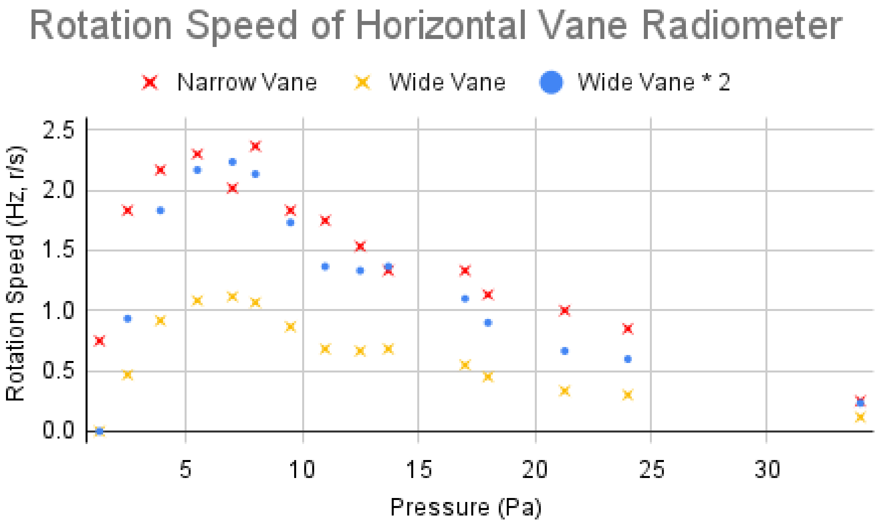


Figure 11: Comparison of rotation speeds of horizontal vane radiometers. Blue dots represent twice the rotation speed of the wide vane radiometer. The rotation speeds for horizontal vane radiometers are compiled from Wolfe, D., Larraza, A., and Garcia, A.'s publication.[20]

Two horizontal vane radiometers were tested in the experiments: one equipped with narrow vanes (8 mm × 16 mm) and the other with wide vanes (16 mm × 16 mm). While the wide vanes exhibited approximately twice the friction and rotational inertia of the narrow vanes, the transimpact-driven forces remained nearly the same in both cases due to their similar edge dimensions. According to the transimpact theory, the narrow vane radiometer was therefore expected to rotate at roughly twice the speed of the wide vane radiometer. This prediction is corroborated by the experimental results presented in Figure 11, providing additional support for the validity of the transimpact theory.

The rotation of a monocolored vane with convex and concave surfaces can also be accounted for by transimpact theory. Instead of relying on color contrast, a radiometer uniformly coated with gold nanocrystals, materials known for their strong light absorption, exhibits rotation with the concave side leading.[8] This rotation direction is anti-aerodynamic. According to transimpact theory, upon illumination, the convex surface receives more incident photons due to its geometry, resulting in a greater rate of transimpacts compared to the concave side. This asymmetry drives the rotation in the observed direction.

Since the force driving the vanes of radiometers originates from the impact of atomic electron transitions according to the transimpact theory, it is expected that high-frequency light, carrying more energy, will cause a radiometer to rotate faster than low-frequency light. This prediction was confirmed in Robert Distinti's YouTube video.[21] In his experiments, the green filter transmits more light than the blue filter. However, the radiometer rotates under blue light but not under green light.

Discussions

Transimpacts are common phenomena, as electron orbital transitions are ordinary processes in any substance at temperatures above absolute zero. This type of impact may also be responsible for various physical processes, such as Brownian motion,[12] phase transitions,[13] and the exchange of different forms of internal energy in a thermal system.[22-23]

With extremely high-frequency light, electrons can be dislodged from the vanes, making these experiments particularly intriguing to observe. Under such conditions, new phenomena may emerge. When electrons are removed from a vane, it becomes positively charged and attracts the freed electrons. It raises the question: Will these electrons move toward the white side of the next vane or return to the original vane? To isolate from transimpacts in these experiments, it is crucial to maintain a high vacuum in the bulbs.

Further study of the average impact momentum of transimpacts should be both fascinating and significant. Estimating the rotational torque of a radiometer is feasible, as the angular momentum of the vanes can be measured relatively easily. This allows for estimating the average momentum of transimpacts under specific conditions. By knowing the density of air molecules and the average mass of these molecules, the average speed of the molecules involved in transimpacts can be estimated. Findings from these experiments may provide valuable insights into the understanding of Brownian motion.

Such a study may open new avenues for scientific exploration and provide opportunities to unravel the complexities of fundamental physical processes, thereby expanding the boundaries of our knowledge. The insights gained from this research could significantly enhance our understanding of the foundational principles governing thermodynamics.

Conclusions

The observations from the specially designed experiments in this study provide compelling evidence that contradicts air-based theories and strongly support the transimpact theory as the explanation for the rotation of radiometers. The transimpact theory presents a comprehensive framework that effectively explains the observed phenomena related to radiometers, enhancing our understanding of the intricate mechanisms governing radiometer operation and similar physical processes. Atomic electron transitions are common interactions and processes at the microscopic scale. Associated with these transitions, transimpacts should significantly influence various physical phenomena, including Brownian motion, phase transitions, and energy exchange at the microscopic scale. Its wide-ranging effects highlight its importance in understanding many fundamental physical processes.

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
- 06/12/2023: Predictions and Verifications of the Transimpact Theory
- 11/01/2025: Published on Zenodo
- 12/17/2025: Adding Links to Summaries of Related Articles

Links to Summaries of Related Articles

- https://cs.stanford.edu/people/zjl/abstract.html, PDF
- https://sites.google.com/view/zjl/abstracts, PDF
- https://xenon.stanford.edu/~zjl/abstract.html, PDF
- https://doi.org/10.5281/zenodo.17967154, PDF

Further Literature

- Misconceptions in Thermodynamics (PDF: DOI) (中文: DOI)
- The Mechanism Driving Crookes Radiometers (PDF: DOI) (中文: DOI)
- The Cause of Brownian Motion (PDF: DOI) (中文: DOI)
- Can Temperature Represent Average Kinetic Energy? (PDF: DOI) (中文: DOI)
- The Nature of Absolute Zero Temperature (PDF: DOI) (中文: DOI)
- The Triangle of Energy Transformation (PDF: DOI) (中文: DOI)
- Is Thermal Expansion Due to Particle Vibration? (PDF: DOI) (中文: DOI)
- Superfluids Are Not Fluids (PDF: DOI) (中文: DOI)
- Why a Phase Transition Temperature Remains Constant (PDF: DOI) (中文: DOI)
- What Causes Friction to Produce Heat? (PDF: DOI) (中文: DOI)
- The Easiest Way to Grasp Entropy (PDF: DOI) (中文: DOI)

- Entropy Can Decrease (PDF: DOI) (中文: DOI)
- The Restoration Principle (PDF: DOI) (中文: DOI)
- Is There a Sea of Free Electrons in Metals? (PDF: DOI) (中文: DOI)
- Electron Tunnel (PDF: DOI) (中文: DOI)
- Unified Theory of Low and High-Temperature Superconductivity (PDF: DOI) (中文: DOI)
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- The Evolution from the Law of Gravitation to General Relativity (PDF: DOI) (中文: DOI)
- The Simplest Derivation of $E = mc^2$ (PDF: DOI) (中文: DOI)
- How to Understand Relativity (PDF: DOI) (中文: DOI)
- Mathematics Is Not Science (PDF: DOI) (中文: DOI)
- Tidal Energy Is Not Renewable (PDF: DOI) (中文: DOI)
- AI Contamination (PDF) (中文)
- DeepSeek pk ChatGPT (PDF) (中文)

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