The Nature of Absolute Zero Temperature

Liu, Jerry Z.
ZJL@CS.Stanford.EDU

Keywords: Absolute Zero, Temperature, Dynamic Energy, Kinetic Energy, Thermal Energy, Internal Energy

Abstract

Absolute zero represents the lowest limit on the thermodynamic temperature scale, theoretically determined by extrapolating the ideal gas law. However, its physical nature remains unclear, largely due to the common misconception that temperature directly reflects the average kinetic energy of particles. A clearer understanding of absolute zero requires distinguishing between dynamic energy and the matter energy inherently stored in matter. Matter energy typically does not influence temperature measurements unless it is released from matter and transformed into dynamic energy. Dynamic energy, comprising potential, kinetic, and radiative components, constantly undergoes transformation and exchange within a system. Absolute zero corresponds to the complete absence of dynamic energy, meaning that all three elements must be simultaneously minimized. Temperature reflects the overall level of dynamic energy in a system, primarily through its radiative output, which originates largely from potential energy transitions and is therefore closely linked to the system's potential energy. Kinetic energy affects temperature only indirectly, through the internal redistribution of energy among different forms as the system approaches equilibrium.

Introduction

The concept of absolute minimum temperature dates back to 1665 in Robert Boyle's work: "New Experiments and Observations Touching Cold".[1] This temperature was initially predicted through Charles's law of volume, which states that the volume of gases tends to expand when heated and is proportional to temperature, as illustrated in Figure 1.[2-3] According to this law, the volume of gases would theoretically reach zero at a temperature of around -273.15 °C, which is commonly regarded as the lowest possible temperature and defined as absolute zero, or 0 K.[4-7]

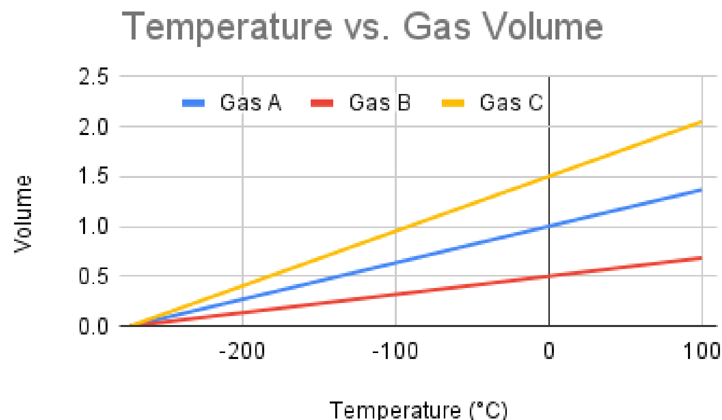

Figure 1: Absolute zero (-273.15 °C or 0 K) as projected based on temperature vs. gas volume.

However, the physical nature of absolute zero remains not fully understood, in part because of long-standing misconceptions about temperature. According to the third law of thermodynamics, the entropy of a closed system in thermodynamic equilibrium approaches a constant value as its temperature approaches absolute zero, as summarized on Wikipedia and shown in Figure 2. At this limit, the system must reside in the state of lowest possible energy.

Third law of thermodynamics

Article Talk

From Wikipedia, the free encyclopedia

The **third law of thermodynamics** states that the entropy of a closed system at thermodynamic equilibrium approaches a constant value when its temperature approaches absolute zero. This constant value cannot depend on any other parameters characterizing the system, such as pressure or applied magnetic field. At absolute zero (zero kelvin) the system must be in a state with the minimum possible energy.

Entropy is related to the number of accessible microstates, and there is typically one unique state (called the ground state) with minimum energy.[1] In such a case, the entropy at absolute zero will be exactly zero. If the system does not have a well-defined order (if its order is glassy, for example), then there may remain some finite entropy as the system is brought to very low temperatures, either because the system becomes locked into a configuration with non-minimal energy or because the minimum energy state is non-unique. The constant value is called the residual entropy of the system.[2]

Figure 2: Screenshot of Wikipedia's definition of the third law as it appeared on November 14, 2025.

There are several issues with the statements above, especially concerning the phrase "minimum possible energy". What type of energy does this refer to—potential, kinetic, radiative, or something else? Commonly used terms such as thermal energy, internal energy, and total energy are often poorly defined or inconsistently applied, which further contributes to the ambiguity. Many textbooks, as well as Wikipedia, describe temperature as reflecting the average kinetic energy of the vibrating and colliding atoms in a substance. If that interpretation is adopted, then the "minimum possible energy" would presumably refer to kinetic energy. However, subatomic particles—such as electrons and nucleons—continue to move even at absolute zero, indicating that the kinetic energy of quantum particles never fully vanishes.

One might argue that the ground state, in the context of the third law and absolute zero, refers to the microstate configuration of atomic particles (atoms and molecules) within a substance, such as a crystal. However, excluding subatomic forms of energy introduces additional challenges. Under this interpretation, an isolated crystal at absolute zero should remain in the ground state of its atomic particles indefinitely. Consider an isolated crystal of radioactive material at absolute zero: before any radioactive decay, it would indeed remain in its atomic ground state. Yet once a decay event occurs, the crystal's temperature rises even though it is isolated. This reveals a fundamental misconception underlying the conventional definition of temperature.[8]

Before delving into the discussion, let us consider an experiment involving a thermometer suspended inside an evacuated glass bulb, as illustrated in Figure 3. The thermometer is thermally insulated from the exterior of the bulb. In the absence of air molecules within the bulb, should we expect the internal temperature to reach absolute zero, given that temperature represents the kinetic energy of particle motion? Furthermore, would the temperature change if the device were moved out of a refrigerator? How would the temperature respond under different frequencies of incident light? This article aims to clarify the physical nature of absolute zero while addressing these questions and related misconceptions.

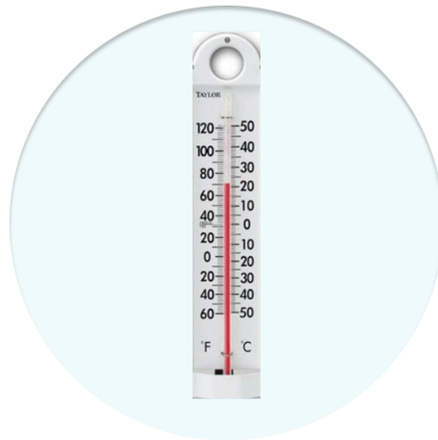

Figure 3: The temperature inside the evacuated glass bulb.

Transformation and Exchange of Dynamic Energy

With a basic understanding of physics, most people can correctly answer questions about the temperature inside the glass bulb. Since it is a closed system with no air molecules present, the temperature inside the bulb is unrelated to particle motion. However, because the system is not isolated, its internal temperature is determined by the radiant energy absorbed by the thermometer from the surroundings. This raises an interesting question: why has the misconception that temperature directly represents particle motion persisted for so long, particularly when describing the temperature of matter?

Many existing terms related to energy are either poorly defined or ambiguous. For instance, thermal energy, often referred to as heat energy, is traditionally defined as the total kinetic energy of a substance's particles, encompassing their translational, rotational, and vibrational motion. To bring clarity, we introduce the term **dynamic energy**, which encompasses potential energy *U*, kinetic energy *K*, and radiative energy *R*:

(1) $$D = U + K + R.$$

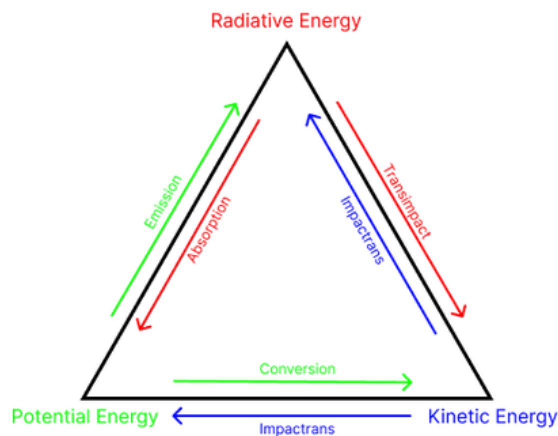

Figure 4: The Triangle of Energy Transformation

These represent the active forms of energy that continuously transform and exchange within a system. Equilibrium—whether within a single system or among multiple systems—arises from these ongoing dynamic interactions. The Triangle of Energy Transformation, illustrated in Figure 4, depicts these relationships. This section examines the underlying mechanisms that drive these energy transformations.

When a body accelerates, variations in its force field give rise to the emission of energy in the form of waves. For example, when an electron undergoes an orbital transition, it emits radiation. This process facilitates the transformation of energy from potential to radiative forms, as indicated by the red arrow in Figure 4.

In the reverse process, electrons can feel incoming waves and absorb the energy, becoming excited to higher orbitals and thereby storing energy. This process enables the conversion of energy from radiative to potential forms, as illustrated by the green arrow in Figure 4. Potential energy is also stored in the bonds between charged particles; as these bonds are stretched, they, like springs, accommodate additional energy. This mechanism also explains thermal expansion because the added energy does work, stretching bonds and increasing the spacing between particles.[9]

Indeed, bonds serve as a more substantial energy reservoir than individual orbital electrons. Conversely, when a bond contracts, the stored potential energy is released as radiation, analogous to the emission that occurs when an electron drops to a lower orbital. The level of radiative energy in a system is positively correlated with its potential energy, which is governed by the strength of the underlying bonds. Because the strength of electric bonds varies significantly across different systems, the energy of emitted waves spans an immense range, from a few kilohertz to beyond 10^{23} hertz.

These electron orbital transitions, along with the stretching and contracting of chemical bonds, enable the continual exchange of energy between potential and radiative forms, representing one of the fundamental processes in energy dynamics, representing one side of the Triangle of Energy Transformation. The next question, then, is how particles initially acquire kinetic energy within a system. As illustrated in Figure 3, consider an experiment beginning at absolute zero: when light shines on the bulb, how does any particle in the thermometer gain its vibrational kinetic energy? The conversion of energy to and from kinetic form occurs through two additional mechanisms: **transimpact** and **impactrans**.[10]

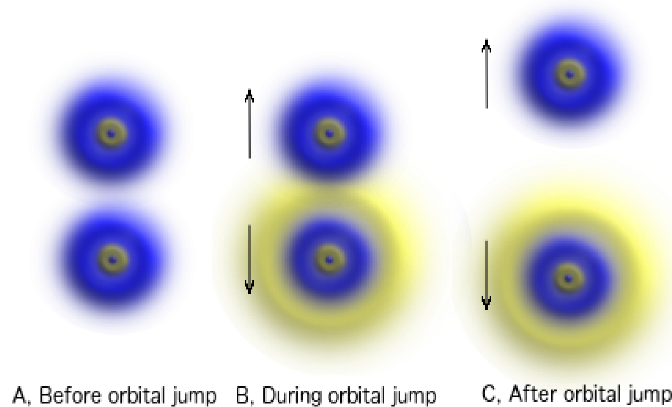

Figure 5: Transimpact due to an atomic electron transition.

Coulomb attraction typically arises between atoms or molecules nearby. However, when the distance between them becomes too close, electron-electron repulsion increases rapidly. A balance between this repulsion and attraction is

reached at a characteristic spacing known as the Van der Waals distance. This equilibrium is often disrupted during atomic electron transitions. When an atom absorbs energy, its electrons may become excited and jump to higher orbitals, usually within a few nanoseconds or less.[11-12] As the electron cloud expands, the volume of the host atom increases, reducing the distance to adjacent atoms. This sudden decrease in spacing disrupts the established balance and usually leads to an increase in repulsive force, pushing the atoms apart. This effect, illustrated in Figure 5, is known as **transimpact**.

Transimpacts are explosive, similar to the sudden burst of popcorn. The resulting momentum delivers significant kinetic energy to adjacent particles, driving them apart and triggering or amplifying their motion. Atomic electron transitions are routine processes at the microscopic scale, continuously occurring in all matter. Consequently, transimpacts are common interactions that influence many aspects of physics, particularly in thermodynamics. They also serve as the underlying mechanism behind phenomena such as Brownian motion,[13-15] phase transitions,[16] and the operation of the Crookes radiometer.[17-20] Therefore, the kinetic energy of microscopic particles originates ultimately from and reflects changes in potential energy.

Through transimpacts, kinetic energy accumulates within a system, but not indefinitely. There must be a mechanism by which kinetic energy is converted back into other forms of energy, a process referred to as **impactrans**. During this process, the motion or vibration of particles, such as molecules, atoms, or subatomic particles, can cause collisions with neighboring particles through electric interactions, effectively “knocking” their electrons into different, even off, orbitals. These impacts accelerate electrons, leading them to emit electric radiation. In this way, the kinetic energy of particle motion is transformed into potential and radiative energy.

The conversion of kinetic energy into radiative or potential energy can be observed in various phenomena. For example, static electricity is built up when electrons are dislodged from atoms by rubbing a plastic rod against fur. Similarly, frictional heat is a result of impactrans: when you rub your palms together, the warmth you feel comes from kinetic energy being converted into radiation. The heating at the bottom of the pump tube is also related to the effect of impactrans.

When an electron transitions between orbitals, represented by the blue Transition arrow in Figure 3, its kinetic energy changes in tandem with its potential energy, meanwhile emitting or absorbing radiative energy. This type of energy conversion is not limited to charged particles at microscopic scales; it also occurs in macroscopic objects governed by gravitational forces, for example, during the conversion between the potential and kinetic energy of a swinging pendulum.

Energy at Absolute Zero

Through the processes discussed above, different forms of dynamic energy can transform within a system and be exchanged between systems. However, these forms do not account for all of a system’s energy. According to Einstein’s mass-energy equivalence principle,[21] the total energy of a system is also tied to its mass, expressed by the equation:

$$E = mc^2 \tag{2}$$

In this equation, c denotes the speed of light, and m represents the effective or equivalent mass of the system. This principle reveals that mass itself is a concentrated form of energy, highlighting that the total energy of a system includes not only dynamic energy but also energy contained in matter. Accordingly, the total energy of a system can be decomposed as the sum of dynamic energy D and matter energy M:

(3) $$E = D + M.$$

Temperature reflects the energy level of a system's total dynamic energy, including kinetic, potential, and radiative energy. However, the energy contained in the matter is generally not captured by temperature measurements unless it is released and converted into dynamic energy. It is now clear that absolute zero corresponds to the complete absence of dynamic energy—that is, when potential, kinetic, and radiant energy are all minimized. Since these forms of energy continuously transform and exchange within a system, true absolute zero cannot be achieved unless all three are simultaneously at their minimum. If anyone remains above its minimum, the system cannot be at absolute zero. For example, for a crystal to reach absolute zero, all radiation must be eliminated, particle vibrations must cease, all electrons must occupy their lowest possible orbitals, and all bonds must be at their shortest possible lengths. Even under these conditions, the crystal may not be at absolute zero if it contains radioactive nuclei. To truly reach absolute zero, the potential energy between nucleons must also be minimized.

Although matter energy is not typically reflected in temperature measurements, it can influence temperature when released from matter. Matter energy can be fully converted into other forms, effectively reducing an object's mass to zero. For example, in positron-electron annihilation, the entire mass of both particles is transformed into radiative energy. Similarly, any fundamental particle can annihilate with its corresponding antiparticle, releasing the total energy of the matter. Conversely, in pair production, high-energy photons interacting near a nucleus can create an electron-positron pair, demonstrating the formation of matter from pure radiative energy R. These processes illustrate the principle of mass-energy equivalence and the interchangeability between matter and energy.

The conversion between mass and energy can occur either spontaneously or under specific conditions. The annihilation mentioned above is spontaneous. However, the pair production occurs with a nucleus nearby. In fusion, the potential energy between nucleons in deuterium and tritium, two isotopes of hydrogen, contributes to their total mass. During nuclear fusion, this potential energy is released, resulting in a corresponding loss of mass. On Jupiter, however, this nuclear potential energy remains stored and is not released spontaneously under normal conditions. In contrast, fusion occurs spontaneously in the Sun, liberating this energy and producing intense heat. This explains why the Sun, despite having a hydrogen abundance like Jupiter, reaches extremely high temperatures, while Jupiter remains comparatively cool.

With this understanding, thermal energy, typically associated with kinetic energy, should be regarded as one component of dynamic energy, as described in Equation 1. As will be shown, thermal energy is not directly proportional to temperature. Instead, temperature should reflect the overall level of dynamic energy within a system. The principle of mass-energy equivalence highlights the fundamental nature of matter, indicating that the majority of a system's internal energy is embedded in its mass. Therefore, internal energy should be defined as the total energy of a system, as outlined in Equations 2 and 3. Most of the energy stored in matter does not ordinarily affect temperature measurements. However, when matter energy (M) is released, it is converted into dynamic energy (D), which can significantly impact temperature, such as during the release of nuclear potential energy in the Sun.

Common Misconceptions about Temperature

With precise definitions of dynamic and internal energy, the concept of absolute zero becomes much clearer. However, a full understanding of temperature remains elusive. The widely accepted notion that temperature directly reflects the kinetic

energy of particle vibrations is problematic. For example, during phase transitions such as melting or boiling, temperature typically remains constant even as energy is continuously added. This appears counterintuitive—molecules breaking free from intermolecular bonds gain increased freedom of motion and higher kinetic energy. One would logically expect the temperature to rise, yet it remains fixed throughout the transition.

Based on the definition of dynamic energy, among the three forms of dynamic energy described in Equation 1, kinetic energy is the least directly correlated with temperature, although all three forms, kinetic, potential, and radiative, contribute to it. Of these, the radiative energy represents one of the most active components. According to the Stefan–Boltzmann law, the radiative power *P* emitted by a blackbody is directly proportional to the fourth power of its absolute temperature *T*:

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

Here, *p* is Stefan-Boltzmann's constant.[22-23] This equation provides the theoretical foundation for designing devices to measure temperature. Infrared thermometers, for instance, determine temperature by detecting the radiation level of electromagnetic waves emitted by a target object, allowing for non-contact measurement.

Stefan-Boltzmann's law can be derived from Planck's law[24-26] by integrating Planck's equation over frequency and then over the solid angle. Another direct consequence of the Planck radiation law is Wien's displacement of the peak wavelength of radiation: the black-body radiation curve for different temperatures peaks at a wavelength (λ) that is inversely proportional to the temperature:

$$(5) \qquad \lambda = \frac{b}{T}$$

In this formula, *b* denotes Wien's displacement constant. Wien's displacement law is evident in everyday experiences. For instance, an experienced baker can tell the temperature of a stove by observing the color of the flame. This relation is often used to estimate the temperature of celestial bodies remotely. For instance, the peak emission of the Sun occurs at a wavelength of approximately 500 nm, and the surface temperature is 5,778 K according to Wien's law.

The temperature measured by a mercury thermometer also reflects radiative energy. When an electron in a mercury atom absorbs this energy, it becomes excited to a higher orbital, leading to atomic expansion and increased spacing between atoms. This results in the thermal expansion of mercury, which causes the mercury column to rise. The column's height is then calibrated to indicate temperature. A similar principle applies to other thermometric substances sensitive to thermal expansion, such as alcohol. This understanding should be applied to address the questions concerning the temperature inside the glass bulb.

As pointed out previously, the radiation emitted by a system originates primarily from its potential energy components and is therefore closely linked to the system's average potential energy. Consequently, the measurement of temperature is more strongly correlated with potential energy than with other forms of dynamic energy. Phase transitions involve the breaking of molecular bonds. As energy is added to a system, these bonds are stretched to store additional potential energy, which in turn increases both radiative output and temperature. However, once the bonds reach their maximum extension, beyond which further input causes them to break, a phase transition occurs. At this point, the potential energy and radiative output remain constant, effectively fixing the temperature. During the transition, the incoming energy is no longer used to increase radiative or potential energy but is instead directed toward bond dissociation and the increase of

kinetic energy associated with molecular motion. Because temperature reflects the radiative energy level, it remains unchanged even as kinetic energy rises. In this sense, temperature becomes decoupled from kinetic energy during a phase transition and remains anchored to the system's radiative and potential energy levels.

This understanding also explains why the kinetic theory of gases fails to accurately predict the specific heat of gases: it neglects the contribution of potential energy stored in molecular bonds. In this theory, the specific heat of ideal gases is typically derived based solely on kinetic energy considerations:[27-28]

$$C_m = \frac{3}{2}R \quad (6)$$

Here, *R* denotes the molar gas constant (8.31 J/mol•K). The kinetic theory predicts a constant specific heat for all gases. These predictions align closely with experimental data for monatomic gases, achieving over 99% accuracy. However, the theory significantly underestimates the specific heat of gases composed of polyatomic molecules. The discrepancy increases with molecular complexity—predicted values fall consistently below measured values. For example, in the case of octane, the predicted specific heat is only about 7% of the experimentally observed value, representing 93% of the prediction error.

This problem has puzzled scientists for hundreds of years. Maxwell proposed an equipartition principle of energy among these three components: transition, rotation, and vibration, suggesting the kinetic theory only predicts ⅓ of kinetic energy.[29] Boltzmann enhanced the concept by introducing the degrees of molecular freedom.[30-33] Planck and Einstein argued for the existence of a zero-point harmonic oscillator.[34-35] Kelvin eventually concluded that the equipartition assumption might be incorrect,[36-37] a view later acknowledged by Einstein.[38-39]

However, when the potential energy of molecular bonds is taken into account, a clear trend emerges between specific heat and the number of bonds within a molecule, as shown in Figure 6.[8] This relationship highlights the strong correlation between temperature and the potential energy components of a system, while also underscoring the disconnect between temperature and kinetic energy alone.

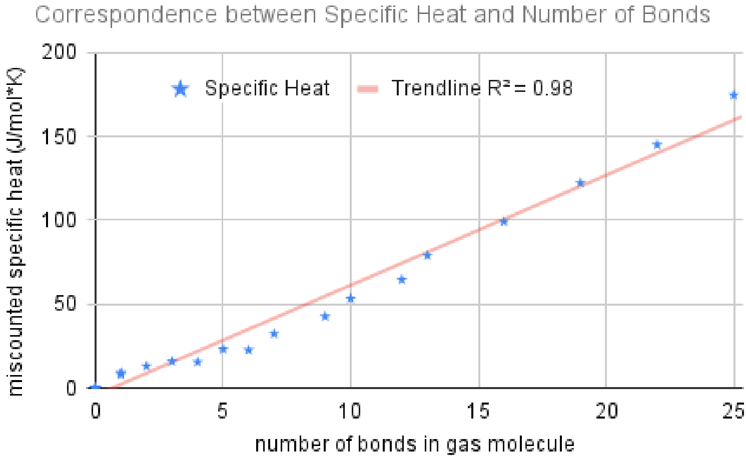

Figure 6: Correspondence between the miscounted molar-specific heat in the kinetic theory and the number of molecular bonds within gas molecules. The miscounted molar-specific heat is a measurement offsetting the

molar-specific heat predicted by the kinetic theory in Equation (6). The slope of the fitted trendline is about 6.56 J/mol•K•bond with an R^2 of 0.98.

Therefore, kinetic energy is only one of the three components of dynamic energy, and it influences temperature indirectly, primarily through its interactions and exchanges with other forms of dynamic energy as the system seeks energy equilibrium. This indirect relationship is a key factor behind common misconceptions regarding phase transitions, thermal expansion, and the predictions of specific heat by the kinetic theory of gases.

Conclusions

Understanding the nature of absolute zero requires distinguishing between **dynamic energy** and the **intrinsic energy stored in matter**, which normally does not participate in continuous transformation or exchange among various forms of dynamic energy. It is important to note, however, that matter energy—such as the potential energy between nucleons—can be released under certain conditions, as in the Sun, thereby increasing dynamic energy and affecting the system's temperature. Dynamic energy, comprising **potential, kinetic, and radiative components**, is in constant interconversion within a system. Achieving absolute zero requires minimizing all three forms simultaneously.

Temperature reflects the level of dynamic energy. Theoretically, any of the three dynamic energy components could serve as a proxy for measuring this level. In practice, temperature is most often inferred from a system's radiative output, which is closely tied to its potential energy. Instruments also exist that measure temperature through potential energy, for example, by detecting the electrical resistivity of matter. Currently, no device can directly measure temperature via the kinetic energy of a system; kinetic energy influences temperature only indirectly, primarily through the redistribution of energy as the system approaches equilibrium.

Revision History

- 11/25/2023: Initial Post on Stanford Site
- 06/08/2024: Clarification of Concepts
- 11/01/2025: Published on Zenodo
- 11/14/2025: Revised Introduction
- 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)
- LK-99 Limitations and Significances (PDF: DOI) (中文: DOI)
- Superconductor Origin of Earth's Magnetic Field (PDF: DOI) (中文: DOI)
- Fundamental Problems about Mass (PDF: DOI) (中文: DOI)
- 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)

References

1. Boyle, R. (1665). “New Experiments and Observations Touching Cold”. *London*: Printed for John Crook.
2. Gourgy, J.B. (1979), “Charles the Obsecure”. *Isis* **70** (254): 576-579.
3. Gay-Lussac, J.L. (1802), “Recherches sur la dilatation des gaz et des vapeurs”. *Annales de Chimie*, **XLIII**: 137. English translation (extract).
4. Dalton, J. (1802), "Essay II. On the force of steam or vapour from water and various other liquids, both in vacuum and in air" and Essay IV. "On the expansion of elastic fluids by heat," *Memoirs of the Literary and Philosophical Society of Manchester*, vol. 8, pt. 2, pp. 550–74, 595–602.
5. William, T. (1848). "On an Absolute Thermometric Scale founded on Carnot's Theory of the Motive Power of Heat, and calculated from Regnault's observations". *Proceedings of the Cambridge Philosophical Society*. **1**: 66–71.
6. William, T. (1852), "On the Dynamical Theory of Heat, with numerical results deduced from Mr. Joule's equivalent of a Thermal Unit, and M. Regnault's Observations on Steam", *Philosophical Magazine*, **4**. Extract.
7. Hugh, C., ed. (1911). "Cold". *Encyclopædia Britannica* (11th ed.). Cambridge University Press.

8. Liu, J.Z. (2023). "Can Temperature Represent Average Kinetic Energy?". Stanford University. Archived (PDF). doi:10.5281/zenodo.17503871
9. Liu, J.Z. (2023). "Is Thermal Expansion Due to Particle Vibrating?". *Stanford University*. Archived (PDF). doi:10.5281/zenodo.17504268.
10. Liu, J.Z. (2019), "The Process Driving Crookes Radiometers". Stanford University. Archived (PDF). doi:10.5281/zenodo.17503377
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). "The Cause of Brownian Motion". *Stanford University*. Archived (PDF). doi:10.5281/zenodo.17503671
14. Feynman, R. (1964). "The Brownian Movement". *The Feynman Lectures of Physics*, Volume I. pp. 41.
15. Einstein, A. (1926). "Investigations on the Theory of the Brownian Movement". *Dover Publications*.
16. Liu, J.Z. (2023). "Why Phase Transition Temperature Remains Constant". *Stanford University*. Archived (PDF). doi:10.5281/zenodo.17504663.
17. Gibbs, P. (1996). "How Does a Light-Mill Work?" *Usenet Physics FAQ*. Retrieved 8 August 2014.
18. 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.
19. 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.
20. Yarris, L. (2010). "Nano-sized Light Mill Drives Micro-sized Disk". *Physorg. Retrieved* 6.
21. Einstein, A. (1905), "Zur Elektrodynamik bewegter Körper", Annalen der Physik (in German), **322** (10): 891–921, Bibcode:1905AnP...322..891E, doi:10.1002/andp.19053221004 (English translation).
22. 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.
23. Knizhnik, K. (2016). "Derivation of the Stefan–Boltzmann Law". *Johns Hopkins University – Department of Physics & Astronomy*.
24. Planck, M. (1914). "The Theory of Heat Radiation". *Masius, M. (transl.)* (2nd ed.). P. Blakiston's Son & Co. OL 7154661M.
25. Planck, M. (1915). "Eight Lectures on Theoretical Physics". *Wills, A. P. (transl.). Dover Publications.*
26. 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.
27. Krönig, A. (1856). "Grundzüge einer Theorie der Gase". *Annalen der Physik und Chemie* (in German). **99** (10): 315–22. Bibcode:1856AnP...175..315K. doi:10.1002/andp.18561751008. Facsimile at the Bibliothèque nationale de France (pp. 315–22).
28. Clausius, R. (1857). "Ueber die Art der Bewegung, welche wir Wärme nennen". *Annalen der Physik und Chemie* (in German). **176** (3): 353–79. Bibcode:1857AnP...176..353C. doi:10.1002/andp.18571760302. Facsimile at the Bibliothèque nationale de France (pp. 353–79).
29. Maxwell, J.C. (1875). "The Question of the Atom". *J. Chem. Soc.* (London), Facsimile published in Mary Jo Nye, **1875** (28): 493-508.
30. Reif, F. (1965). "Fundamentals of Statistical and Thermal Physics". *McGraw-Hill*, New York.
31. Carey, V. (1999). "Statistical Thermodynamics and Microscale Thermophysics". Cambridge University Press.
32. Goldstein, H. (1980). "Classical Mechanics". (2nd edition). Addison-Wesley.

33. Boltzmann, L. (1895). “On Certain Questions of the Theory of Gases”. *Nature*, **51** (1322): 413-415.
34. Planck M. (1901). “On the Law of the Energy Distribution in the Normal Spectrum”. *Ann. Phys.*, **4** (553): 1-11.
35. Einstein, A. and Stern, O. (1913). “*S*ome Arguments for the Assumption of Molecular Agitation at Absolute Zero”. *Ann. Phys.*, **40** (551) 551-560.
36. Thomson, W. (1904). “Historical and Philosophical Perspectives”. *Baltimore Lectures*. Baltimore: Johns Hopkins University Press. Sec. 27.
37. Rayleigh, J.W.S. (1900). “The Law of Partition of Kinetic Energy”. *Phil. Mag.*, **49**: 98–118.
38. Pais, A. (1982). “Subtle is the Lord”. *Oxford University Press.* Oxford UK.
39. Armin, H. (1971). “The Genesis of Quantum Theory (1899–1913*)*”. (translated by Claude W. Nash), Cambridge, MA.