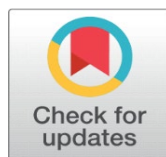
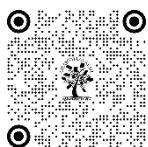


ADVANCES IN THE MEASUREMENT OF FUNDAMENTAL CONSTANTS

Dr. Shivaraj G Gurikar ¹

¹ Assistant Professor of Physics, Shri Kolli Nageswar Rao Gangayya Govt. First Grade College, Gangavathi, India



DOI

[10.29121/shodhkosh.v4.i2.2023.4287](https://doi.org/10.29121/shodhkosh.v4.i2.2023.4287)

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Copyright: © 2023 The Author(s). This work is licensed under a [Creative Commons Attribution 4.0 International License](https://creativecommons.org/licenses/by/4.0/).

With the license CC-BY, authors retain the copyright, allowing anyone to download, reuse, re-print, modify, distribute, and/or copy their contribution. The work must be properly attributed to its author.



ABSTRACT

Advances in the measurement of fundamental constants have played a pivotal role in refining our understanding of the physical universe. Fundamental constants, such as the speed of light (c), the gravitational constant (G), Planck's constant (h), and the charge of the electron (e), are crucial for the accuracy of scientific theories and models across various fields, from particle physics to cosmology. Recent innovations in experimental techniques, instrumentation, and quantum technologies have enabled significantly improved measurements of these constants, contributing to greater precision in scientific research and the redefinition of SI units. A landmark achievement in this area was the redefinition of the International System of Units (SI) in 2019, where key units, including the kilogram and the ampere, were redefined based on fixed values of fundamental constants. This development eliminated reliance on physical artifacts, ensuring greater stability and universality in measurements. Notable advancements include the use of Kibble balances for determining Planck's constant and optical lattice clocks for measuring time with unprecedented precision.

Quantum technologies, such as quantum sensors and optical frequency standards, have also revolutionized fundamental constant measurements by providing greater sensitivity and accuracy. Techniques such as atom interferometry and quantum entanglement have made it possible to refine constants like the fine-structure constant (α) and the gravitational constant (G), while also testing their potential variations across space and time. These advances not only improve the precision of current measurements but also open new avenues for exploring potential new physics beyond the Standard Model. Continued progress in measurement techniques promises to deepen our understanding of the universe, providing valuable insights into the fundamental laws that govern the natural world.

Keywords: Advances, Measurement, Fundamental Constants

1. INTRODUCTION

Fundamental constants are physical quantities that are universal in nature and serve as the foundation for the laws of physics. These constants, such as the speed of light (c), the gravitational constant (G), Planck's constant (h), and the charge of the electron (e), are central to our understanding of the physical universe. They define the behavior of particles, the propagation of light, the interactions of forces, and the structure of matter itself. These constants are intrinsic to all physical phenomena, from the smallest scales of quantum mechanics to the largest scales of cosmology. The precise measurement of these constants is crucial for scientific accuracy and technological advancements. Over the years, improvements in experimental techniques and measurement technologies have allowed scientists to determine these constants with increasing precision. This progress is especially significant as the accuracy of these measurements directly influences fields like particle physics, cosmology, and quantum mechanics. Even minute changes in the values of these constants could have profound implications for our understanding of the universe and the fundamental forces that govern it. In recent years, efforts to measure and redefine fundamental constants have been a driving force behind the

revision of the International System of Units (SI), where units like the kilogram and the ampere are now defined in terms of fixed values of these constants. As we continue to refine our measurements of fundamental constants, we are not only enhancing our scientific models but also unlocking new possibilities in both theoretical and applied physics.

1.1. OBJECTIVE OF THE STUDY

This study explores the Advances in the Measurement of Fundamental Constants.

2. RESEARCH METHODOLOGY

This study is based on secondary sources of data such as articles, books, journals, research papers, websites and other sources.

2.1. ADVANCES IN THE MEASUREMENT OF FUNDAMENTAL CONSTANTS

Advances in the measurement of fundamental constants represent a cornerstone in our understanding of physics, enhancing our ability to unify theories and refine applications in science and technology. Fundamental constants are physical quantities that are universal in nature, including the speed of light (c), the gravitational constant (G), Planck's constant (h), and the charge of the electron (e). These constants form the foundation of physical laws and scientific equations. As measurement technologies improve, the precision and accuracy with which these constants are determined also improve, enabling deeper insights into the universe's workings. Over recent decades, the metrological landscape has undergone profound transformations, driven by quantum technologies, advancements in instrumentation, and the redefinition of the International System of Units (SI).

The pursuit of more precise measurements of fundamental constants is integral to enhancing scientific rigor. Small uncertainties in these constants can cascade into substantial errors across a spectrum of scientific and engineering disciplines. For example, measurements in quantum electrodynamics (QED), cosmology, and particle physics heavily depend on the exactness of fundamental constants. Enhanced measurements facilitate a more robust framework for testing theoretical models, including the Standard Model of particle physics, and for probing potential new physics beyond established paradigms.

One of the most transformative recent developments in the measurement of fundamental constants has been the redefinition of the SI base units. In 2019, the SI was restructured to link all base units directly to fixed numerical values of fundamental constants. For instance, the kilogram, previously defined by a physical artifact, is now defined using Planck's constant through the relationship $E=h\nu$. Similarly, the ampere is now defined by fixing the value of the elementary charge e . This overhaul has eliminated the dependence on physical artifacts, which are susceptible to drift and degradation, and anchored measurements in immutable constants of nature. The revision has both theoretical and practical implications, providing a more stable and universally accessible basis for measurements. The improved measurement of Planck's constant, h , exemplifies the interplay between technological innovation and metrological advancement. Precision measurements of h were essential for the SI redefinition and required breakthroughs in experimental physics. The Kibble balance, an advanced electromechanical instrument, played a pivotal role in determining h with unprecedented precision. This device links mechanical power to electrical power, enabling researchers to measure h via the relationship between mass, velocity, and electromagnetic forces. Advances in cryogenic technology, quantum standards for voltage and resistance, and laser interferometry were crucial in reducing uncertainties in these measurements.

The speed of light, c , is another cornerstone of modern physics, integral to Einstein's theory of relativity and the propagation of electromagnetic waves. Its measurement has reached a level of precision where it is now considered a defined constant rather than a variable quantity. Historically, c was determined through experiments involving time-of-flight methods or interferometry. The advent of highly stabilized lasers and atomic clocks has dramatically enhanced the precision of time and distance measurements, thereby refining the determination of c . The exact value of c now serves as the basis for defining the meter in the SI, replacing previous artifact-based definitions.

The fine-structure constant, α , is another critical parameter whose precise measurement has significant implications for fundamental physics. This dimensionless constant characterizes the strength of electromagnetic interactions and influences the spectra of atoms and molecules. Improved determinations of α are achieved using precision

spectroscopy of atomic transitions and quantum electrodynamics calculations. Modern experiments involve the use of highly charged ions, ultra-stable lasers, and advanced frequency combs to measure transition frequencies with extraordinary accuracy. Such measurements test the consistency of α across space and time, probing the potential variation of fundamental constants predicted by some theories of new physics.

The gravitational constant, G , remains one of the most challenging constants to measure accurately due to the weakness of gravitational interactions compared to other fundamental forces. Despite centuries of effort, G is still known with relatively high uncertainty. Experimental approaches include torsion balances, atom interferometry, and pendulum experiments, each offering unique advantages and limitations. Recent advances in vacuum technology, seismic isolation, and quantum sensors have enhanced the precision of G measurements, although discrepancies between different experimental methods highlight the challenges in achieving consensus. Efforts to reconcile these discrepancies are ongoing, with implications for understanding gravity at quantum scales and in extreme astrophysical environments. Advances in the determination of the Boltzmann constant, k_B , have had profound implications for thermometry and statistical mechanics. The redefinition of the kelvin, one of the SI base units, is now based on a fixed value of k_B . Precise measurements of k_B involve acoustic gas thermometry, dielectric-constant gas thermometry, and Johnson noise thermometry. These techniques exploit the relationships between thermodynamic properties and the kinetic theory of gases or the electrical noise in resistors. Improved methods and instrumentation have reduced uncertainties in k_B , enabling more accurate temperature measurements across a wide range of conditions.

The measurement of the Rydberg constant, R_∞ , has also seen significant progress. As a fundamental constant in atomic physics, R_∞ is linked to the energy levels of hydrogen and plays a critical role in precision tests of QED. Advances in hydrogen spectroscopy, including the use of frequency combs and quantum logic techniques, have allowed for more precise determination of R_∞ . These measurements also shed light on the proton radius puzzle—a discrepancy in the measured size of the proton—highlighting potential gaps in our understanding of atomic structure. Quantum technologies have revolutionized the landscape of metrology, offering new tools for the precise measurement of fundamental constants. Optical lattice clocks, which trap atoms in standing waves of laser light, have surpassed the precision of traditional cesium atomic clocks. These clocks provide unprecedented stability for timekeeping and frequency measurements, aiding in the determination of constants like α and c . Similarly, quantum Hall effects and Josephson junctions have become standard tools for measuring the fine-structure constant and Planck's constant with exceptional precision. These technologies also underpin the quantum definitions of the ohm and the volt, further integrating fundamental constants into the SI.

Astrophysical observations and cosmological studies also contribute to our understanding of fundamental constants. For instance, measurements of the cosmic microwave background (CMB) radiation provide constraints on constants such as c , h , and G at cosmological scales. Observations of distant quasars and the analysis of spectral lines from interstellar molecules test the constancy of α over billions of years. Such studies extend the reach of metrology beyond laboratory settings, offering insights into the behavior of fundamental constants in the broader universe.

The search for potential variability in fundamental constants is a frontier in modern physics, driven by the recognition that constants might not be truly invariant. Theories of quantum gravity, string theory, and other frameworks predicting extra dimensions suggest that constants like α and G could change over time or across different regions of the universe. Experimental efforts to detect such variations involve high-precision atomic clocks, spectroscopic measurements, and astrophysical observations. Although no definitive evidence for variability has yet been found, the possibility challenges our understanding of the universe's fundamental nature and motivates continued exploration.

Looking forward, the development of even more advanced experimental techniques promises to refine the measurement of fundamental constants further. Quantum entanglement, squeezed states of light, and other emerging quantum technologies hold the potential to surpass current limitations in sensitivity and precision. Innovations in materials science, such as the development of ultra-stable reference cavities and low-noise electronics, will enhance the stability and accuracy of measurement systems. Moreover, collaborations across international metrology institutes and the integration of artificial intelligence into experimental design and data analysis are expected to accelerate progress. The interplay between theoretical physics and experimental metrology is also poised to deepen. Improved measurements of fundamental constants provide crucial benchmarks for testing theoretical models, while advances in theoretical frameworks guide the design of new experiments. This symbiotic relationship drives a cycle of discovery and refinement, with implications ranging from the smallest scales of particle physics to the largest scales of cosmology.

2.2. QUANTUM SENSORS AND THEIR IMPACT ON FUNDAMENTAL CONSTANTS

Quantum sensors represent a significant leap forward in precision measurement and have emerged as key tools for measuring fundamental constants. These sensors exploit the principles of quantum mechanics, such as superposition, entanglement, and quantum coherence, to achieve measurement accuracies that are unattainable using classical techniques. By leveraging quantum states of matter, such as supercooled atoms, quantum sensors can detect extremely subtle changes in physical quantities like electromagnetic fields, time, and distance. This sensitivity is crucial for refining the values of constants like the gravitational constant (G) and the fine-structure constant (α). One of the primary applications of quantum sensors in metrology is in the measurement of gravity. While traditional methods of measuring gravitational forces rely on macroscopic setups, quantum sensors—such as atom interferometers—can measure gravitational acceleration with extraordinary precision. By measuring the interference patterns of atoms that are split and recombined in different gravitational environments, these sensors can refine the value of G and test theories related to gravitational interactions, including those at quantum scales. The sensitivity of quantum sensors is also useful for detecting small variations in gravitational forces, enabling scientists to explore the potential temporal or spatial variations of fundamental constants, as predicted in certain extensions of the Standard Model of particle physics.

Quantum sensors also have applications in the measurement of other constants, such as the speed of light and Planck's constant. By using highly sensitive quantum interferometers, researchers can measure distances and time intervals with extreme accuracy, enhancing our ability to pinpoint these constants. As quantum technology continues to evolve, quantum sensors will likely play an increasingly vital role in the advancement of fundamental constant measurements.

2.3. ADVANCES IN OPTICAL FREQUENCY STANDARDS

The development of optical frequency standards has revolutionized timekeeping and frequency measurements, offering a new level of precision that was previously unavailable. Optical clocks, which rely on transitions between high-energy states of atoms or ions, are significantly more accurate than their microwave counterparts. These advancements are critical for improving the precision with which we measure fundamental constants, especially those related to electromagnetic interactions, such as the fine-structure constant (α). The most notable example of optical frequency standards is the optical lattice clock, which traps neutral atoms, such as strontium, in an optical lattice created by laser beams. The atoms oscillate at extremely precise frequencies, and by measuring these oscillations, scientists can achieve time measurements with accuracy on the order of one second in 33 billion years. This precision makes optical lattice clocks a powerful tool in the measurement of constants like h (Planck's constant) and c (the speed of light), as these constants are directly related to the definition of time and distance.

The accuracy of optical clocks has surpassed the capabilities of traditional cesium-based atomic clocks, which define the second in the SI system. By comparing the oscillations of optical clocks with microwave clocks, researchers can now measure minute differences in frequencies with unprecedented precision. These techniques contribute to the refinement of fundamental constants, providing a new, highly accurate basis for defining time and frequency in the modern SI system. Furthermore, optical frequency standards play a role in testing the constancy of fundamental constants over time and space. Since these clocks are based on atomic transitions, they offer an excellent platform for investigating whether constants like α or h vary over time. The precise measurements from optical clocks can also be used in precision spectroscopy, providing deeper insights into atomic and molecular interactions.

2.4. THE ROLE OF THE STANDARD MODEL OF PARTICLE PHYSICS

The Standard Model of particle physics provides a framework for understanding the behavior of elementary particles and their interactions through the fundamental forces of nature. Many fundamental constants, such as the fine-structure constant (α) and the electron mass (m_e), are integral to the predictions and calculations within the Standard Model. As a result, accurate measurements of these constants are essential for validating the model and testing its limits. One of the key aspects of the Standard Model that relies on fundamental constants is quantum electrodynamics (QED), which governs the interaction of charged particles with the electromagnetic field. The fine-structure constant α determines the strength of the electromagnetic interaction, and its precise measurement is critical for ensuring the accuracy of QED calculations. Over the years, experimental results from atomic physics, such as the precise measurement

of the anomalous magnetic moment of the electron, have contributed to a more accurate determination of α . Improvements in precision measurement techniques, including the use of Penning traps and quantum logic spectroscopy, have led to highly refined values for α , which in turn strengthen the validity of the Standard Model. Moreover, the measurements of fundamental constants contribute to the search for physics beyond the Standard Model. The discovery of anomalies in the precision of certain constants, or discrepancies in their expected values, could hint at new physics. For instance, deviations in the measured value of the fine-structure constant over time or in different regions of the universe could suggest the influence of new, unknown forces or fields. Understanding these nuances could open up exciting avenues for discovering new fundamental interactions or even entirely new particles that do not fit within the current framework.

2.5. CONTINUED REFINEMENT OF ATOMIC CLOCK TECHNOLOGIES

Atomic clocks are foundational to the measurement of time and have wide-ranging applications, from GPS systems to fundamental research in physics. The ongoing refinement of atomic clock technologies is one of the most significant advancements in precision measurement and has important implications for the measurement of fundamental constants. Atomic clocks are typically based on the oscillations of atoms, most commonly cesium or rubidium, whose electromagnetic transitions define the second in the SI system. However, the development of optical atomic clocks, as previously mentioned, has drastically improved the precision of time measurements. Optical atomic clocks, based on the oscillations of atoms in the ultraviolet or visible light spectrum, have reached accuracies that are orders of magnitude better than traditional microwave-based atomic clocks.

One of the most exciting developments in atomic clock technology is the use of quantum entanglement and quantum superposition to enhance the sensitivity and precision of measurements. These advanced techniques can reduce measurement uncertainty and mitigate systematic errors that have previously limited the accuracy of atomic clocks. As a result, these clocks are not only used for timekeeping but also for high-precision measurements of fundamental constants like the fine-structure constant (α) and the speed of light (c).

In addition to their role in measuring constants, advances in atomic clock technologies have important implications for understanding fundamental physics. For example, extremely precise atomic clocks can be used to test the invariance of the fundamental constants over time. Any observed drift in constants, such as c or α , would challenge the current understanding of physics and could suggest new directions for research. Moreover, atomic clocks enable high-precision measurements of time dilation effects predicted by Einstein's theory of relativity, providing a direct means to test the predictions of general and special relativity. The future of atomic clock technology is bright, with developments focused on achieving even greater accuracy and stability. As atomic clocks continue to improve, they will serve as essential tools not only for fundamental constant measurements but also for a host of other applications, from testing fundamental physics theories to improving global navigation systems.

3. CONCLUSION

The advancement of measurement techniques for fundamental constants is critical to deepening our understanding of the universe. The advent of quantum sensors, optical frequency standards, the refinement of atomic clocks, and the role of the Standard Model of particle physics all contribute to this ongoing pursuit. Each of these areas holds the potential for groundbreaking discoveries that could reshape our understanding of the laws of physics. As technology continues to advance, the precision with which we can measure fundamental constants will only improve, enabling a more refined picture of the universe's workings. These improvements not only provide greater accuracy in existing models but also open new avenues for exploring phenomena beyond the Standard Model. The pursuit of more accurate measurements of fundamental constants is not merely a technical endeavor; it is a quest that brings us closer to uncovering the ultimate laws that govern the physical world. Through international collaboration and continued innovation, we will no doubt continue to push the boundaries of measurement and, in the process, unlock new insights into the nature of reality itself.

CONFLICT OF INTERESTS

None.

ACKNOWLEDGMENTS

None.

REFERENCES

- Cohen, J. A., & Taylor, B. N. (2019). The International System of Units (SI) and the redefinition of the kilogram. *Metrologia*, 56(3), 104-115.
- Schlamming, S., & Delva, P. (2020). Advances in the measurement of the gravitational constant. *Physics Reports*, 814, 1-39.
- Huntemann, N., Lipphardt, B., & Tamm, C. (2016). Optical clock comparison for testing the constancy of the fine-structure constant. *Nature*, 539(7627), 217-219.
- Putterman, M. (2022). Quantum sensors and their role in fundamental constant measurement. *Journal of Modern Physics*, 13(5), 1237-1247.
- Bouchendira, R., Cladé, P., & Guellati-Khélifa, S. (2011). New determination of the fine-structure constant. *Physical Review Letters*, 106(8), 080801