

Quantum Electrodynamics: Foundations and Modern Perspectives

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Editorial

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ABSTRACT

Quantum Electrodynamics (QED) is one of the most successful and precise theories in modern physics, describing the interaction between light and matter at the quantum level. It integrates the principles of quantum mechanics with special relativity to explain how charged particles interact through the exchange of photons. Developed primarily during the mid-20th century, QED has provided remarkably accurate predictions, including the anomalous magnetic moment of the electron and the Lamb shift. This article presents an overview of the theoretical foundations, mathematical structure, and applications of QED. It also highlights the role of perturbation theory, Feynman diagrams, and renormalization in resolving infinities inherent in early formulations. Furthermore, the article discusses contemporary developments and applications of QED in atomic, molecular, and condensed matter physics. Through its predictive power and experimental verification, QED remains a cornerstone of quantum field theory and a model for understanding fundamental interactions in nature.

Keywords

Quantum Electrodynamics, Photons, Quantum Field Theory, Light-Matter Interaction, Feynman Diagrams, Renormalization

INTRODUCTION

Quantum Electrodynamics (QED) is the relativistic quantum field theory that describes the interaction of charged particles with the electromagnetic field. It provides a unified framework for understanding how light (photons) interacts with matter such as electrons and positrons. The foundations of QED were laid by Paul Dirac in 1928 through his relativistic wave equation, which incorporated both quantum mechanics and special relativity^[1].

In QED, electromagnetic interactions occur through the exchange of photons, which act as force carriers. These photons may be real (observable as light) or virtual (temporary carriers of force). The theory successfully explains a wide range of phenomena, including scattering processes and atomic structure. Its precision is unparalleled, with experimental results matching theoretical predictions to extremely high accuracy.

THEORETICAL FRAMEWORK AND MATHEMATICAL STRUCTURE

The mathematical structure of QED is based on quantum field theory, where particles are treated as excitations of underlying fields. The electromagnetic field is quantized, leading to the concept of photons as discrete energy packets. Charged particles interact by emitting and absorbing these photons^[2].

A key feature of QED is perturbation theory, which allows calculations to be performed as a series expansion in terms of a small parameter known as the fine-structure constant. This approach simplifies complex interactions by considering contributions from successive orders, where higher-order terms become progressively smaller^[3]. Feynman diagrams provide a graphical representation of these interactions, enabling physicists to visualize and compute probabilities of particle processes. Each diagram corresponds to a mathematical expression describing a specific interaction pathway. These diagrams revolutionized the field by making calculations more intuitive and manageable.

EXPERIMENTAL VERIFICATION AND APPLICATIONS

QED has been extensively tested through experiments and is considered one of the most accurate theories in science. One of its most notable successes is the precise prediction of the electron's magnetic moment, which agrees with experimental measurements to many decimal places.

The theory also explains phenomena such as the Lamb shift, which refers to small energy differences in hydrogen atom energy levels that cannot be accounted for by classical theories. Additionally, QED plays a crucial role in understanding scattering processes like Compton scattering and electron-positron annihilation. Beyond fundamental physics, QED has applications in various fields, including condensed matter physics, quantum optics, and chemistry. It serves as a foundation for studying interactions in atoms, molecules, and solids, and it is instrumental in the development of technologies such as lasers and semiconductors ^[4].

MODERN DEVELOPMENTS AND CHALLENGES

While QED is highly successful, it also presents theoretical challenges. Early formulations of the theory encountered infinities in calculations, which were resolved through a process known as renormalization. This technique allows physicists to redefine certain quantities, leading to finite and meaningful results.

Modern research in QED extends into areas such as molecular quantum electrodynamics and quantum information science. Recent studies explore the interaction of light with complex systems, including biological molecules and nanostructures. Advances in experimental techniques have enabled the study of strong light-matter coupling and quantum coherence effects. Furthermore, QED serves as a prototype for other quantum field theories, including those describing the strong and weak nuclear forces. It has also contributed to the development of unified theories that aim to describe all fundamental interactions within a single framework ^[5].

CONCLUSION

Quantum Electrodynamics stands as a cornerstone of modern physics, offering a comprehensive and precise description of electromagnetic interactions at the quantum level. Its integration of quantum mechanics and relativity has enabled profound insights into the nature of light and matter. Through concepts such as photon exchange, perturbation theory, and renormalization, QED has overcome significant theoretical challenges and achieved remarkable agreement with experimental results.

The theory's influence extends beyond fundamental physics, impacting fields such as chemistry, materials science, and quantum technology. Despite its success, ongoing research continues to refine and expand its applications, particularly in complex and strongly interacting systems. As a model for other quantum field theories, QED remains central to the pursuit of a deeper understanding of the universe and the unification of fundamental forces.

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CONFLICT OF INTEREST

None.

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