



Planck's estimate of the elementary charge: a bibliometric study on its limited reception (1901-1921)

Iliaria Cacciari^a

Istituto di Fisica Applicata “Nello Carrara”, Consiglio Nazionale delle Ricerche, Via Madonna del Piano 10, 50019 Sesto Fiorentino (FI), Italy

Received 20 January 2026 / Accepted 13 May 2026
© The Author(s) 2026

Abstract Max Planck is widely recognised for founding quantum theory. In his 1900 seminal work on black-body radiation, he also provided a numerical estimation of the elementary charge. This result, however, was embedded within his broader theoretical development and was not presented as a primary result, so that his contemporaries likely approached it with caution. Planck himself acknowledged that the theoretical basis that led to this estimate was fragile and explicitly noted that further experimental work was needed to confirm it. Remarkably, despite these limitations, his estimate closely matched values later confirmed by precise experiments. In this study, we examine how Planck's contemporaries received and cited this estimate. We first situate his work within the scientific context of black-body radiation, then we analyse primary literature from 1901 to 1921, covering journals from Europe and the USA, to trace patterns of citation and engagement with Planck's elementary charge estimate. Finally, a statistical bibliometric analysis quantifies these trends, revealing the visibility and impact of Planck's work across different journals, national contexts, and scientific communities.

1 Introduction

At the turn of the twentieth-century, physics stood on the brink of a profound transformation, driven in large part by the work of Max Planck. In 1900, his investigation of black-body radiation and the introduction of energy quantisation (Planck 1900a,c) opened a new theoretical landscape, laying the foundations for what would later become quantum mechanics. While Planck is rightly celebrated as a central figure in the emergence of quantum theory, one notable aspect of his early work received comparatively limited attention from contemporaries: his numerical estimation of the elementary charge (e), derived around 1900 (Planck 1900b,d). This result was embedded within his broader study of black-body radiation rather than presented as a stand-alone contribution, and, at a time when the experimental determination of the electron charge was only beginning, it appears to have attracted relatively little interest. In the context of the present study, this limited reception refers not to the later historiography of Planck's work, which has been extensively analysed, but to the modest circulation, citation, and uptake of Planck's determination of e in early twentieth-century scientific literature. Crucially, this limited immediate attention does not imply neglect or irrelevance. Although Planck's derivation rested on a theoretically fragile basis awaiting empirical validation, it yielded a value remarkably close to that later confirmed by precise experimental determinations. Notably, the only scientist who elevated Planck's theoretically obtained value of e to the level of experimental measurements, in order to judge which was most probable, was R.A. Millikan in 1910 (Millikan 1910). However, a systematic experimental verification of Planck's estimate had to wait until 1910.

In this sense, bibliometric analyses of citations to Planck's 1900 estimate must be interpreted with care, reflecting the appropriate scientific reception of a theoretically derived quantity pending verification.

Indeed, Planck's work has long been the subject of extensive historical analysis. Classic and more recent studies have highlighted divergent interpretations, emphasising both continuity and discontinuity between Planck's early works on black-body radiation and the 1900 quantum derivation (Kuhn 1978; Darrigol 1988; Klein 1961). The contrasting views underscore that the origin of the quantum theory remains an unresolved historical problem (Taschetto 2025) and one that is still open to further analysis (Badino 2009).

Although Planck was not primarily an experimentalist and generally remained distant from the domain of high-precision measurement, then regarded as the domain of empirical physicists, he nevertheless ventured into this territory when he proposed a numerical value for e . His effort to anchor abstract thermodynamic and statistical

^a e-mail: i.cacciari@ifac.cnr.it (corresponding author)

considerations in concrete, measurable constants represents a significant moment in the evolving relationship between physical theory and numerical precision. Remarkably, his estimate emerged at a time when neither the electron nor its charge had yet acquired a stable experimental status, which likely contributed to the modest reception among his contemporaries.

Despite its conceptual and methodological significance, Planck's 1900 estimate of the electron charge played only a marginal role in subsequent experimental and theoretical discussions among his contemporaries. This raises a set of closely related historical questions: to what extent was Planck's estimate taken up, cited, or compared with competing determinations? Was its limited visibility already apparent in the scientific literature of the period? Or was it gradually eclipsed by the broader development and later reception of quantum theory as a whole?

Addressing these questions requires attention not only to scientific content but also to the mechanisms through which contributions acquire visibility and authority. While originality and conceptual innovation are often emphasised in retrospective narratives, citation practices provide a concrete indicator of how results circulated and were valued within the scientific community at the time.

The present study does not seek to revisit the well-established interpretations. Instead, it focuses on assessing, quantitatively, how cautious Planck's contemporaries were in receiving his estimate of the electron charge, a value that, although based on theoretically fragile assumptions acknowledged by Planck himself (Planck 1900b), would later prove to be remarkably close to experimentally confirmed results.

The core of the paper consists of a bibliometric analysis covering the years 1901–1921, i.e. the twenty years following Planck's determination, based on citations drawn from 26 scientific journals published in Europe and the USA. This analysis provides a quantitative assessment of how Planck's estimate of the elementary charge was cited, compared, or ignored in relation to other contemporary determinations, thereby providing a statistical measure of its visibility and impact within the international scientific literature. By tracing where, when, and how Planck's contribution appeared in print, we offer a quantitative perspective on its contemporary reception.

The originality of the present work lies in the systematic construction of a dataset of reported values of the electron charge (1901–1921), its normalisation and organisation into a coherent framework, and its use to enable direct comparison and quantitative analysis. This approach allows us to move beyond a purely narrative historical account and to identify trends in the convergence towards the accepted value, as well as to assess the role of Planck's estimate within this process. To the best of our knowledge, no previous study has constructed a year-resolved, multi-country dataset of citations specifically targeting the dissemination of early electron charge measurements over the period 1901–1921.

The structure of the paper is as follows. Section 2 presents the sources and methodology, detailing the primary literature analysed and the quantitative approaches used to trace the reception of Planck's estimate of the elementary charge. Section 3 presents the results; Section 3.1 reviews Planck's 1900 determination of the elementary charge; Sect. 2.2 examines the historical context and values reported by other scientists between 1901 and 1921 in primary journals from Europe and the USA; Sect. 2.3 analyses the footprint of Planck's estimate, including its visibility and influence in contemporary literature. Finally, Sect. 4 presents the conclusions, reflecting on the broader significance of Planck's estimate and the ways in which its reception and recognition illuminate the mechanisms by which scientific memory and historiography shape the legacy of foundational ideas.

2 Sources and methodology

This study was based on a systematic examination of primary scientific literature published in the early twentieth-century, with the aim of analysing both the numerical determination of the electron charge and the contemporary reception of Planck's estimate. Rather than relying on retrospective historical syntheses, we constructed a well-defined corpus of original experimental and theoretical papers, selected according to explicit temporal, geographical, and bibliographical criteria.

The methodological framework adopted here was designed to ensure internal consistency and reproducibility. In particular, we specified a fixed set of scientific journals, a clearly delimited time window, and applied uniform criteria for the inclusion and classification of reported values of the electron charge. This approach allowed us to trace how numerical values of e were produced, communicated, and compared within the scientific literature of the period, while avoiding duplication and retrospective reinterpretation.

This section describes the sources examined and the procedures used to extract, normalise, and organise the data, which are implemented in Sect. 3. By making these methodological choices explicit, we provide a transparent foundation for the historical and statistical analyses that follow. In particular, the resulting dataset provides a coherent and comparable basis for the subsequent sections, enabling temporal and cross-experimental comparisons that are not readily accessible in the existing literature.

2.1 Temporal window (1901–1921)

At the turn of the twentieth-century, the existence of the electron and its fundamental properties, including its charge, were subjects of intense debate. While J.J. Thomson's discovery (1897) and Millikan's oil-drop experiments (from 1910) were often regarded as decisive, establishing a reliable value for e was the result of a prolonged, collective effort. Within this context, Planck's theoretical work on black-body radiation and energy quantisation played a role, providing a link between macroscopic thermodynamics and microscopic constants, and enabling an indirect quantitative estimate of e . To evaluate how cautiously Planck's contribution to determining the electron charge was received by his contemporaries, we surveyed the most relevant literature from 1901 to 1921. This period was chosen as it aligns with the Planck's paper of December 1900, in which he first addressed the value of the elementary charge (Planck 1900b), making it appropriate to begin the analysis in January of the following year. Regarding the end of the period, experimental efforts to measure the electron charge - by researchers such as Thomson, H.A. Wilson, and Millikan - underwent significant development between the first and second decades of the twentieth-century. For this reason, we extended the study to 1921, twenty years after the presentation of Planck's quantum theory. This window captures two decades of intense experimental activity and methodological refinement, during which a wide range of techniques were employed and progressively improved, and this ends when the value of e can be regarded as experimentally stabilised.

2.2 Selection of journals

To broaden the scope beyond the German context in which Planck primarily worked, we included a wide range of journals representative of the contemporary physics community (Dahl 1997), covering major European scientific centres and, to a lesser extent, American contributions, based on their relevance, continuity, and availability over the period considered. The leading journals active in 1901–1921 (Wheaton Rider 1993), accessible in digital or print form, were predominantly published in Germany, the UK, and France. To achieve a more comprehensive perspective, we also included journals from Spain, Italy, Switzerland, and the Netherlands.

Appendix A provides a comprehensive list of the journals included in this study, along with their acronyms and periods of activity. Tables 3, 4, 5 and 6 present key information about the selected journals: the first column lists the full name of each journal and its commonly used abbreviation during the period under consideration; the second column indicates the years of publication; and the third column shows the abbreviation used in this work. Table 7, in Appendix A, also reports the country of publication for each journal.

It is not uncommon for journals to undergo name changes during their publication history, often due to political or editorial reasons. For example, the *Sitzungsberichte der Mathematisch-Physikalischen Klasse der Bayerischen Akademie der Wissenschaften zu München* changed name at the end of the First World War, eliminating the reference to the Bavarian kingdom. Although the journal underwent a name change, it is still regarded as the same publication.

Some journals, despite being officially active during the period under consideration, occasionally missed publications in certain years due to political or economic factors. Additionally, a few journals commenced publication shortly after 1901; for instance, *RRAM* released its inaugural issue in 1904. These instances were minimal and do not warrant the exclusion of such journals from this research.

Examining the evolution of scientific journals in the early twentieth-century, particularly those devoted to physics, reveals several complexities, especially when journals were established through mergers. A notable example is the *Journal de Physique et le Radium* (*JPR*), founded in 1920 through the merger of *Journal de Physique Théorique et Appliquée* (*JPT*, 1901–1919) and *Le Radium* (*Rd*, 1904–1919), with interruptions in publication as detailed in Table 1.

This merger reflects a broader trend towards the consolidation of physics publications, as specialised fields such as radioactivity became increasingly integrated into the wider discipline. Although the founding journals covered partially overlapping themes and were published concurrently over substantial portions of the period 1904–1919, they maintained distinct editorial directions and readerships.

For the purposes of this study, we adopt a non-overlapping attribution convention to ensure consistency in temporal and country-level aggregation. In this framework, the *JP* series is defined as the continuation of *JPT* (1901–1919), extended by *JPR* (1920–1921), thereby preserving a single continuous lineage. Since *JPR* represents the unified post-merger output, its attribution to the *JP* series is a normalisation choice that does not affect aggregated citation counts by year or by country, as each observation is counted exactly once.

The *Rd* series, corresponding to *Le Radium*, is instead treated as a self-contained reference stream and is not extended beyond 1919. As a result, *Rd* is considered only over its years of activity (1904–1919), with interruptions as reported in Table 1, and serves as an independent baseline, while only the *JP* series is reconstructed to ensure longitudinal continuity across the 1920 merger.

Table 1 Temporal coverage of a subset of French journals considered in this study (1901–1921). *JPT* and *Rd* are independent journals prior to 1920, after which they merge into *JPR*. Interruptions in publication are explicitly indicated

Year Range	<i>JPT</i>	<i>Rd</i>	<i>JPR</i>
1901–1903	Active	–	–
1904–1914	Active	Active	–
1915	–	–	–
1916–1917	Active	–	–
1918	–	–	–
1919	Active	Active	–
1920–1921	–	–	Active (merger of <i>JPT</i> and <i>Rd</i>)

2.3 Criteria for inclusion and data extraction

To assess the influence of Planck’s estimate of the elementary charge within the scientific community, we measured the number of citations of the term “Planck” across 26 journals over a specific year in the period under consideration. Planck’s own publications were included in this count, taking into account his limited output outside Germany alongside his broad international recognition. The citation survey also encompassed references specifically to Planck’s estimation of the elementary charge. The initial query, deliberately broad, yielded a number of occurrences not directly related to Planck’s theoretical contributions. These results were therefore refined by excluding references unrelated to his scientific work, such as mentions of his administrative roles, including membership on the advisory board of *AP* (Fuchs 2011), his chairmanship of the *VDPG*, his position as secretary of the *SPAW*, or references to ceremonial events, such as the meeting held by the *VDPG* to mark his 60th birthday.

The set of citations obtained from the query “Planck” was then further filtered to retain only those containing explicit references to Planck’s elementary charge (4.69 esu). Each paper citing this value was assigned a score of one, regardless of the number of times the value appeared within the same paper. Citation counts were subsequently calculated by summing these scores for each journal and year, resulting in the quantity $C_P(j, y)$, where j denotes the journal index and y the year index. This procedure enables a quantitative analysis of the frequency of explicit citations to Planck’s value in articles published between 1901 and 1921. An analogous procedure was applied to citations of the electron charge attributed to other scientists, such as Millikan, E. Regener, and F. Ehrenhaft. Instances in which such values were explicitly referenced were identified and separated from citations to Planck’s estimate. The resulting data were organised into two sets: one comprising explicit references to Planck’s value, and the other including values obtained by other researchers. As in the case of Planck’s citations, each paper citing an estimate by “Other Scientists” was assigned a value of one, regardless of repetition within the same article. The corresponding citation counts were denoted as $C_O(j, y)$. This classification allowed for a direct quantitative comparison between citations attributed to Planck and those attributed to other scientists.

As an illustrative example, applying this methodology to *AP* for the year 1908 allowed us to identify all explicit references to electron charge values in volume 25–27, comprising fifteen issues. Eight such references were retrieved: three cited Planck’s value, while five referred to estimates by other scientists. Specifically, E. Meyer and Regener (Meyer et al. 1908), F. Jentzsch (Jentzsch 1908), and E. Wagner (Wagner 1908) explicitly cited Planck’s value of 4.69 esu. Meyer and Regener also derived a value of 1.3 esu using probability theory applied to radioactive decay (Schweidler 1906), comparing it with earlier determinations of 1.29 esu by R. v. Helmholtz and F. Richarz (1894) and 3.4 esu by Thomson (1903) (Meyer et al. 1908). Additionally, H. Sirk cited Thomson’s value of 3.4 esu, alongside values between 2.0 and 4.0 esu obtained by H.A. Wilson in 1903 (Sirk 1908).

In counting citations of Planck’s value for the elementary charge, we included self-citations authored by Planck himself. This decision was guided by two considerations: Planck’s personal ethos and the scientific milieu of his era. Known for his reserved and upright nature (Heilbron 2000), Planck was unlikely to employ self-citations merely to enhance his academic visibility without substantial scholarly contribution. Moreover, in the early twentieth-century, the ethical concerns surrounding self-citations were far less pronounced than they are today (Costas et al. 2010; Flatt 2017; Kiado 2026), and such practices were not regarded negatively.

3 Results: electron charge determinations and citations (1901–1921)

In this section, we present the results of our analysis. We begin by revisiting Planck’s original 1900 determination of the elementary charge, drawing on his papers (Planck 1900b, d) as well as relevant modern literature. This serves as a well-defined reference baseline, against which subsequent experimental determinations can be systematically compared. We then examine the primary literature from 1901 to 1921 to trace the experimental determinations

of the electron charge over this period. Finally, we explore the visibility and influence of Planck's estimate within the scientific community, highlighting both how frequently and in which venues it was cited in the contemporary literature. This approach enables us to situate Planck's contribution within the broader experimental efforts to measure e , while also allowing us to quantify its impact over time.

Throughout this section, the term “electron charge” refers to experimentally determined values reported in the contemporary literature, whereas “elementary charge” denotes Planck's theoretically derived quantity and its later universal interpretation.

3.1 Planck's 1900 determination of the elementary charge

At the turn of the twentieth-century, the electron had already emerged as a theoretical and experimental entity, yet many of its physical properties, most notably its elementary charge, remained the subject of active investigation. The broader history of the electron and the birth of microphysics have been extensively analysed in the historiography, including authoritative accounts (Buchwald Warwick 2001; Arabatzis 2006; Navarro Thomson 2012) that have reconstructed the experimental, conceptual, and institutional processes through which the electron acquired its modern status. The present work, however, deliberately restricts its scope to experimental and theoretical works on the determination of the electron charge published between 1901 and 1921, that is, to the period immediately following Planck's numerical estimate of the elementary charge. Later historical reconstructions are therefore not discussed here, as our aim is to examine the contemporary scientific reception of Planck's result rather than its subsequent historiographical interpretation.

Between 1894 and 1900, Planck brought together thermodynamics, electromagnetic theory, and statistical mechanics - three major strands of nineteenth-century physics - into a unified framework that would ultimately give rise to quantum theory and profoundly transform classical physics over the following decades (Kuhn 1978). As an expert in thermodynamics, Planck was particularly concerned with absolute quantities such as energy and entropy, a vision he outlined in his 1894 inaugural address before the Prussian Academy of Sciences: *The times are over when the special and the general could comfortably find their place next to each other in a single personality*¹ (Planck 1894).

Investigations in this direction were initiated by G. Kirchhoff in 1859, who established the universal character of thermal radiation (Kirchhoff 1859). In 1879, J. Stefan conjectured on the basis of experimental evidence that the total radiative energy density scales with the fourth power of the temperature (Stefan 1879), and five years later L. Boltzmann provided its theoretical foundation using thermodynamic reasoning (Boltzmann 1884). Further progress came almost a decade later with W. Wien's displacement law, which demonstrated that the wavelength at which the radiation intensity is maximal is inversely proportional to the temperature (Wien 1893).

Planck soon realised that thermodynamics and electromagnetic theory alone could not fully account for the observed radiation distribution (Kuhn 1978). Beginning in 1895, he examined electrodynamic mechanisms responsible for thermalisation of radiation (Planck 1895, 1896a, b, 1897b, a), and incorporated these results into a series of five papers, all presented before the Prussian Academy of Sciences between 1897 and 1899. In these *mémoires*, Planck formulated the electrodynamic basis for the irreversible approach of radiation towards equilibrium (Klein 1961).

In a subsequent paper presented in March 1900 (Planck 1900a), Planck further clarified certain aspects of the entropy definition he had introduced earlier (Planck 1900d). However, this formulation - central to the derivation of Wien's law - was criticised by Wien in August 1900 (Wien 1900). The inconsistencies pointed out by Wien explicitly undermined the theoretical foundation of Planck's new theory.

Experimental developments further challenged his theoretical framework: measurements in 1900 revealed systematic deviations from Wien's law, particularly at high temperatures and long wavelengths (Lummer Pringhsheim 1900; Lummer Jahnke 1900; Thiesen 1900; Rubens Kurlbaum 1900). In particular, H. Rubens and F. Kurlbaum's October 1900 measurements definitively excluded the universal validity of Wien's law (Rubens Kurlbaum 1900; Hettner 1922; Pais 1979), prompting Planck to revise his entropy expression. On October 7, 1900, after discussions with Rubens, Planck proposed a new distribution law that accurately fit the experimental data, a formulation he later described as a “lucky guess” (Mehra 2001).

On October 19th 1900, following the presentation by Kurlbaum and Rubens to the German Physical Society of their measurements at the longest infrared waves then accessible, Planck remarked during the discussion that these results had strongly confirmed that Wien's law lacked general validity, instead possessing the character of a law applicable only within a limited range of frequencies and temperatures (Planck 1900c). In this remark, Planck intended to justify how the electromagnetic theory of radiation he developed on the basis of Wien's law was modified in light of this new experimental evidence. He launched his remark, summarising some of the results of his theory presented so far, and announced that he had built, in a very arbitrary way, a new distribution law which satisfied both thermodynamic and electromagnetic requests.

¹ Translation by the author from the original German: “Die Zeiten sind vorüber, wo in einer einzigen Persönlichkeit das Spezielle und das Allgemeine neben einander bequem Platz finden konnten”.

For a theoretician like Planck, the lucky guess that led to the new distribution law, as presented in October 1900 (as he admitted many years later (Planck 2001)), needed further theoretical justification. Therefore, from the day it was proposed, he was concerned with the problem of providing it with a real physical meaning.

He had already shown his belief that thermodynamic considerations alone were insufficient to define the entropy function (Planck 1900a). It is likely that he perceived his recent use of multiple resonators as closely analogous to Boltzmann's treatment of systems composed of many molecules. In particular, the expression for the entropy he derived closely resembled Boltzmann's logarithmic relationship between entropy and probability (Planck 1958a, 1943). This resemblance ultimately led him to abandon a purely thermodynamic definition of entropy in favour of a combinatorial one (Planck 1958b).

On 14th December 1900 Planck read his work at the Meeting of the German Physical Society (Planck 1900b). On that occasion he outlined the theoretical basis of the new law he had only announced to them two months before (Planck 1900c), and at the beginning of 1901, he published a paper with some more theoretical details (Planck 1901a). However, these two derivations of the radiation law were considered obscure by most of Planck's contemporaries until he published the complete derivation in 1906 (Planck 1906).

Planck closed both his December 1900 and January 1901 papers by working on numerical values of some constants that emerged from his new theory. The January 1901 paper ended with the calculation of h and k constants deduced from his new theory and making use of the experimental data presented by Kurlbaum (Kurlbaum 1898). These values were precisely the basis of some other numerical evaluations offered at the end of the December 1900 work. In particular, he compared the entropy expression provided by Boltzmann for a monoatomic gas in equilibrium, to the one he obtained with his theory. He obtained a value for the elementary charge e of 4.69×10^{-10} in electrostatic units², by combining the known Faraday constant F and his own determination of Avogadro's number N_A , itself derived from the relation $k = R/N_A$, where k was the "radiation constant" appearing in his theoretical treatment of black-body radiation. Crucially, Planck's derivation did not rest on a commitment to atomic theory or statistical mechanics as later understood; rather, it relied on a formalism specific to radiation thermodynamics, in which probabilities were introduced as a theoretical device to account for energy distribution among oscillators.

As emphasised in the literature (Seth Smith 2020), the values Planck obtained for N_A and e were "theory-mediated". In fact, at the time, these numerical determinations could not serve as independent evidence for the existence of atoms or for the quantisation of matter. Planck himself acknowledged this limitation and explicitly called for further experimental verification of k using direct methods, noting that such measurements *should be both an important and a necessary task for further research*³ (Planck 1900d).

Even more important, Planck observed that the numerical values agreed with other experimental results closely. However, less obvious at that time was the fact that the elementary unit of electric charge could be estimated essentially as the ratio of the macroscopic Faraday constant (which was also well-established) to the Avogadro's number. Furthermore, Planck emphasised that these numerical evaluations suggested *important consequences for other fields of physics and also of chemistry*⁴ (Planck 1900b), and in the very last sentence of the paper, he expressed the urgency of having to measure them with more direct means. Planck underlined these consequences also in the following papers published in 1901-1902 (Planck 1901b, 1902).

Remarkably, despite resting on such theoretically fragile foundations, Planck's estimate of e was numerically very close to the value that would become universally accepted a few years later through independent experimental efforts. It was only after J. Perrin's seminal experiments on Brownian motion that Avogadro's number (Perrin 1909, 1911) - and, by extension, the elementary charge - acquired independent empirical grounding. This breakthrough provided a firm foundation for the kinetic theory of heat and, in retrospect, offered a molecular interpretation of Planck's constants within a physically grounded framework.

This historical clarification implied that the relative lack of attention to Planck's early numerical determination of e was not an "oversight" but an expected consequence of the theoretical context. The conceptual importance of Planck's calculation was necessarily limited: without independent confirmation of N_A and the physical reality of atoms, the numerical determination of e could not, at the time, provide decisive empirical support for a fundamental subatomic charge. Subsequent experimental efforts - most notably those by Thomson, Perrin, Millikan, and others - were therefore the natural arena in which the value of e was rigorously established and refined. Planck's calculation should thus be understood as a formal derivation contingent on his theoretical framework, whose significance became fully appreciable only in light of later experimental confirmations. In this sense, bibliometric analyses that highlight citations or attention to Planck's 1900 value of e must be interpreted with care: the historical record reflects not neglect, but the appropriate scientific reception of a theoretically derived quantity still awaiting empirical validation. The fact that Planck's theoretically fragile derivation closely approximated the later

² For simplicity, all charge values mentioned hereafter are expressed in electrostatic units (esu), which are more commonly used at the time than the modern Coulomb. The corresponding power of ten is implied throughout; thus, a value of 4.69 esu should be read as 4.69×10^{-10} esu.

³ Translation by the author from the original German: "ebenso wichtige wie notwendige".

⁴ Translation by the author from the original German: "für weitere Gebiete der Physik und auch der Chemie von erheblicher Tragweite zu sein scheinen".

Mapping researcher affiliations in early electron charge experiments (1901–1921)

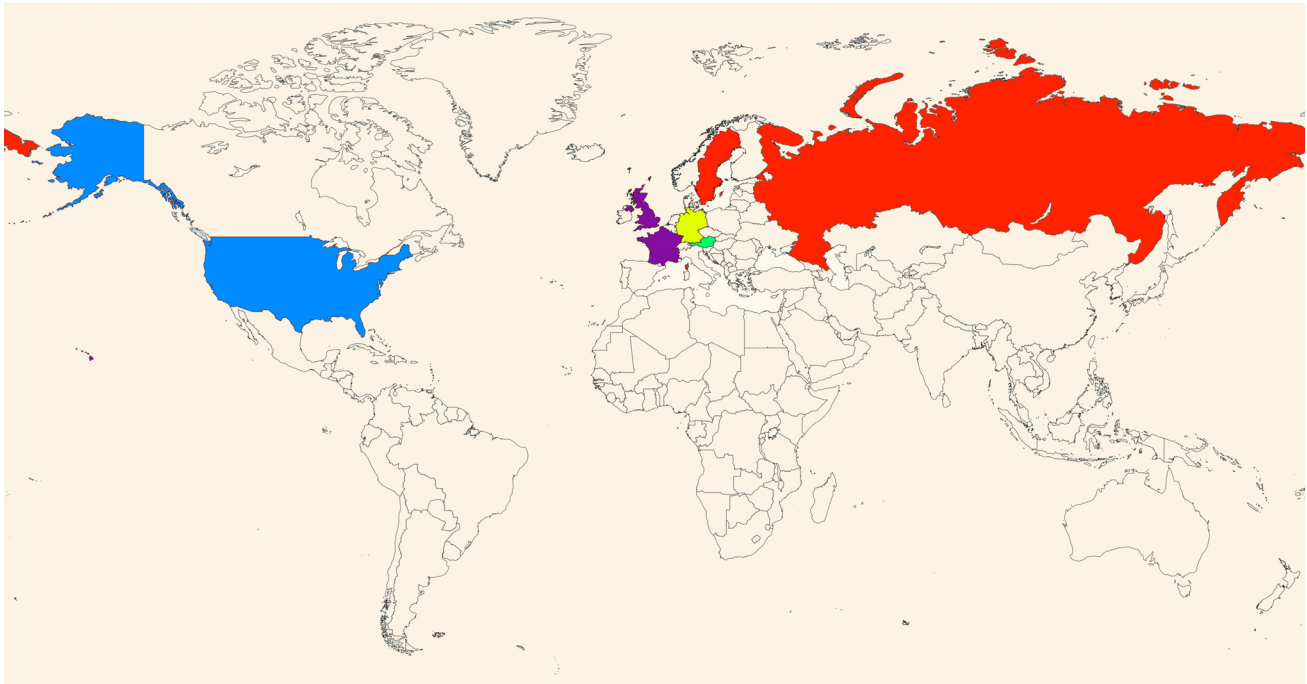


Fig. 1 Geographic distribution of the 31 authors reviewed in this study, who conducted measurements of the elementary electric charge between 1901 and 1921. Countries are colour-coded according to the number of affiliated authors: UK and France (7 each ■), USA (6 ■), Austria (5 ■), Ger-

many (4 ■), and one author each from Russia and Sweden (■). Present-day country boundaries are used for visual clarity. Although national borders have shifted since 1901–1921, the affiliations reflect the modern location of institutions where the electron charge was measured during that period

experimentally confirmed value underscores his remarkable insight, even though it had no immediate influence on experimental research, since such theoretical results at the time tended to function primarily as conceptual guides and reference points rather than as direct drivers of experimental practice.

3.2 Reported values of the electron charge (1901–1921)

To evaluate the position of Planck's numerical estimate of the elementary charge within contemporary physics, it is essential to situate it against the broader experimental landscape of the early twentieth-century. Between 1901 and 1921, numerous determinations of the elementary charge were reported in Europe and the USA, employing a wide range of experimental and theoretical techniques.

Building on the dataset constructed according to the methodological rules set out in Sect. 2, this subsection presents the individual values reported by scientists other than Planck, as they appear in the surveyed primary literature, preserving the diversity of approaches. At this stage, the data are listed in their original form, in the following section these data will be aggregated within a unified framework enabling direct comparison, making it possible to identify trends, quantify dispersion, and assess the degree of convergence.

The geographic distribution of the affiliation of the 31 authors whose work is discussed here is summarised in Fig. 1, highlighting the geographically dispersed nature of early investigations of the electron charge. Although institutional affiliations and national borders evolved during this period, the figure suggests that no single country dominated research on this problem.

Early work on the electron charge emerged from investigations of cathode rays and gaseous ions. Thomson's experiments of 1897 in the UK established the particulate nature of cathode rays and provided the first measurements of the mass-to-charge ratio m/e (Thomson 1897), results that were independently confirmed by E. Wiechert and W. Kaufmann in Germany (Wiechert 1897; Kaufman 1897).

Attention then shifted from m/e to direct or indirect determinations of the charge e itself. In 1898–1899, J.S. Thomson and Townsend employed condensation methods based on C.T.R. Wilson's cloud technique applied to ions produced by X-rays or electrolysis. Thomson obtained values ranging from around 6.5 – 6.8 esu (Thomson 1898; Sutherland 1899; Romer 1942), while Townsend derived values near 3 esu by analysing the motion and charge of droplets formed around ions (Townsend 1900, 1897; Millikan 1917; Townsend 1898). Townsend's primary objective

was to demonstrate that gases released during electrolysis were electrically charged, rather than to establish a fundamental unit of electricity; accordingly, he did not explicitly compare his results with the electrolytic atomic charge (Smith 1997). Nevertheless, these studies established that gaseous ions carried charges of a magnitude comparable to that inferred from electrolysis.

Methodological advances in ion-mobility measurements also contributed to this early phase. In the USA, J. Zeleny and E. Rutherford developed techniques for determining ion drift velocities and mobilities in gases (Zeleny 1898; Rutherford 1897), providing essential experimental input for subsequent charge determinations. Building on this experimental background, Thomson returned in 1899 to the study of cathode rays and photoelectrically emitted electrons, measuring both m/e and e for negative ions and showing that the small value of m/e was due to a very small mass rather than an unusually large charge (Thomson 1899).

Between 1902 and 1904, further refinements of condensation and ionisation methods were introduced. Thomson's combined determination of both the charge and the mass of the negative corpuscle marked the first direct measurement of the electron as a physical entity, a result later recognised as establishing him as the first to measure these fundamental quantities for the electron (Mulligan 2001). At the beginning of 1902, Austrian physicist J. Nabl, who had worked in Thomson's laboratory in 1900, reported values near 2 esu using Wehnelt interrupter (Nabl 1902), in agreement with Townsend's measurements (Nabl 1902; Arrhenius 1912). In April 1902, Thomson and H.A. Wilson published improved measurements based on ionisation by radium and controlled condensation experiments, yielding values in the range 3 – 4 esu (Eve 1939; Wilson 1910; Thomson 1903; Wilson 1903). Although still affected by significant uncertainties, these results provided strong evidence for the atomicity of electric charge. From 1906 onward, Millikan in Chicago began refining H.A. Wilson's condensation method, though his early attempts initially produced no publishable improvements (Millikan 1947).

European efforts between 1902 and 1904, particularly in Germany, focused on theoretical and experimental aspects of electron mass (Kaufman 1901, 1902; Abraham 1902; Bucherer 1904), without providing direct charge measurements. In France, H. Pellat highlighted that the charge of a monovalent ion could be determined from electrolysis alone, yielding values from 2.46 to 6.9 esu and reinforcing confidence in ion theory (Pellat 1907). K. Przibram, from the University of Wien, influenced by C.T.R. Wilson's work, studied condensation of vapour droplets around ions and measured charges between 3.8 esu (July 1907) (Przibram 1907). In early 1907, Millikan, with his student L. Begeman, improved Wilson's method, correcting identified experimental errors, and obtained 4.03 esu in January 1908 (Millikan Begeman 1908).

A better assessment of the validity of the result obtained at Cavendish laboratory by Thomson and coworkers, was not long in coming, furnished by none other than Rutherford, who divided the total charge carried by alpha-particles from a radium source, measured in a separate experiment, by the total number of alpha-particles counted, then gave the charge per alpha-particle namely 9.3 esu, which was close to twice the charge e carried by a hydrogen atom – a value by then nearly universally accepted as the fundamental unit of electricity (Rutherford Geiger 1908).

From 1909, the convergence of measurements accelerated. In 1909, R.T. Lattey measured 4.66 esu using the electrolytic nebula of oxygen (Lattey 1909); Ehrenhaft, studying colloidal particles with and without a horizontal electric field and applying Stokes's law, reported 4.6 esu in April (Ehrenhaft 1909); G. Moreau found 4.3 esu for negative ions in flames in May (Moreau 1909); E. Regener, by counting polonium alpha-particle scintillations and measuring their total charge, obtained 4.79 esu in July (Regener 1909); in the same month, M. De Broglie measured velocities of charged tobacco-smoke particles and derived 4.5 esu (Broglie 1909); Perrin, analysing Brownian motion, reported values around 4.1 esu in September (Perrin 1909); G. Jaffé, from conductivity studies of hexane as a function of temperature and impurities, obtained 3.25 esu, also in September (Jaffé 1909). Finally, A. Alexejew and M. Malikow, applying Wilson's condensation method to superheated water vapour on gas ions, measured droplet fall speeds under gravity and an electric field, yielding 4.5 esu (Alexejew Malikov 1909).

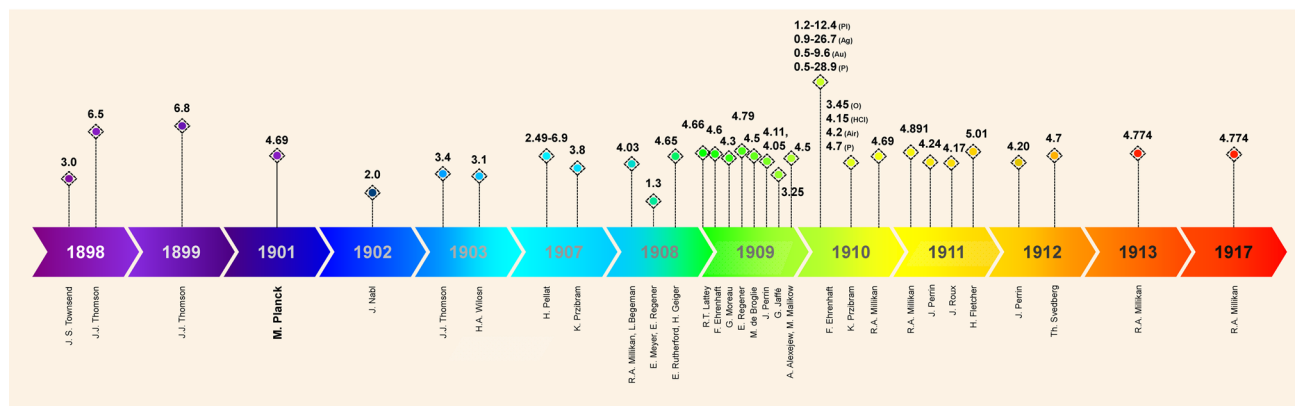
Scientists at the time focused on improving existing methodologies rather than developing new ones. For instance, Ehrenhaft (May 1910) measured a wide range of charges in different materials (Ehrenhaft 1910), while Przibram (June 1910) extended his condensation studies to various mists, obtaining values between 3.45 and 4.7 esu (Przibram 1910).

In October 1910, Millikan's refinement of the oil-drop method, observing individual droplets, produced an average charge of 4.65 esu (Millikan 1910). In this seminal work, Millikan established the most probable value of the electron charge (see Table 2) by averaging five determinations he considered reliable: Planck's value obtained from radiation theory; Rutherford and H. Geiger's, based on counting alpha-particles emitted from a known quantity of radium; Regener's, obtained from scintillations counts of a known amount of polonium; Begeman's, determined using Wilson's method; and his own value, derived from the oil-drop experiment. He argued that the French determinations of de Broglie, Perrin, and Moreau should be disregarded, a position that initiated a controversy with Ehrenhaft (Niaz 2000). By assigning equal weight to these five determinations, Millikan concluded that the most probable value of the electron charge was 4.69 esu (Millikan 1910). This value laid remarkably close to Planck's theoretical estimate and marks the first occasion, namely in 1910, on which Planck's estimate was placed on equal footing with experimental determinations, effectively endorsing it in his attempt to identify the most probable value of the electron's charge.

Table 2 Table showing values of different measurements considered by Millikan for establishing that most probable value of the charge of the electron is the average of five different determinations (Millikan 1910)

Author	Year	Value	Reference
M. Planck	1900	4.69	(Planck 1900b)
E. Rutherford and H. Geiger	1908	4.65	(Rutherford Geiger 1908)
E. Regener	1909	4.79	(Regener 1909)
L. Begeman	1910	4.67	At the time of Millikan's work, these data had not yet been published, as Millikan himself admitted, but they would be in (Begeman 1910).
R.A. Millikan	1910	4.6	(Millikan 1910)

A historical overview of electron charge measurements: key experiments and contributions

**Fig. 2** A chronological representation of published electron charge measurements between 1898 and 1917. Each segment corresponds to a reported experimental value from key studies by researchers such as Planck, Thomson, Perrin, and Millikan, among others. The segment lengths are proportional to the reported values of the elementary charge, allowing a visual comparison of the spread and distribution

of measurements over time. The arrows are meant to guide the reader through the historical progression, whereas the individual markers explicitly encode the years in which measurements were actually performed. Note that this figure reports the chronological distribution of published values of e (years and values only), whereas citation frequencies and their aggregated distributions are presented in Figs. 3-4-5

Millikan's oil-drop experiments were further refined in 1911 by replacing water and alcohol with non-volatile oil droplets, yielding 4.891 esu (Millikan 1911). Parallel work by Perrin (1911, 4.24 esu) (Perrin 1911, 1912), J. Roux (1911, 4.17 esu) (Roux 1911; Millikan 1913), and H. Fletcher (1911, 5.01 esu) (Fletcher 1911) using Brownian motion reinforced the convergence of e values. T. Svedberg (1912) obtained 4.7 esu using colloidal metal solutions (Svedberg 1912). Subsequent oil-drop experiments by Millikan in 1913 and 1917 produced highly precise values: 4.774×0.009 esu and 4.774×0.004 esu, respectively (Millikan 1913, 1917), which remained the standard for over twenty years, later slightly adjusted to 4.770 esu (Dubridge Epstein 1959).

The long-term convergence of reported electron charge values documented in this section is visually synthesised in Fig. 2 through a chronological representation of the principal experimental determinations. This overview covers a period that extends slightly before 1901-1921 range considered in our study to emphasise fundamental experiments, such as Thomson's discovery of the electron, which predated Planck's estimate. The diagram highlights the scientists involved and the values they reported, with each segment corresponding to a specific experimental result. The length of each segment is proportional to the measured value of the elementary charge, visually conveying variations between each determination. Early measurements exhibit a broader range of reported values, reflecting methodological challenges and experimental limitations. As techniques improved, particularly with the introduction of Millikan's oil-drop experiment, the segments become more consistent in length, indicating increasing precision and convergence towards the accepted value of the elementary charge. The figure also includes lesser-known studies, demonstrating the collective effort that contributed to refining this fundamental constant. Furthermore, from 1917 to 1921, no new measurements were reported in surveyed journals, and the electron charge value remained largely stable, despite refinements in experimental techniques and advances in related fields (Dubridge Epstein 1959).

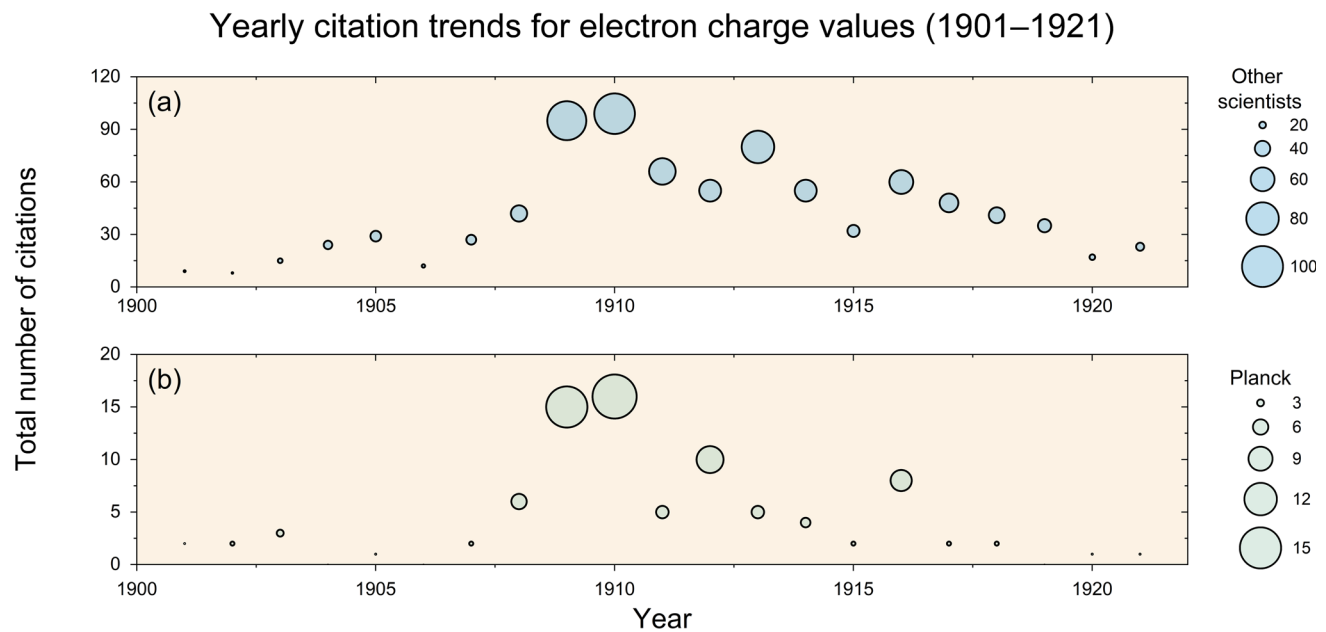


Fig. 3 Bubble plot illustrating annual citation counts from 1901 to 1921 for (a) Planck's electron charge value ($C_P(y)$) and (b) values proposed by other scientists ($C_O(y)$). The horizontal axis indicates the year of publication, while the vertical axis shows the total number of citations. Bubble size is scaled linearly with $C_P(y)$ and $C_O(y)$ to reflect citation

volume, emphasising the relative intensity of scholarly activity over time, whereas the vertical axis reports the exact citation counts. The year 1910 stands out as having the highest number of citations, marking a peak in academic attention

3.3 The Footprint of Planck's elementary charge (1901–1921)

By analysing 26 journals, primarily from Europe (listed in Appendix A), we found that the total number of citations between 1901 and 1921 amounted to 959. Of these, 87 referred to Planck's elementary charge value (4.69 esu), while the remaining 872 cited values proposed by other scientists. Thus, approximately 10% of all citations in the dataset refer to Planck's value.

Our citation data are indexed by journal and year: for each pair (j, y) , we record the number of citations to Planck's value and to values proposed by other scientists. To obtain yearly totals, we aggregate all entries corresponding to the same year by summing their contributions across journals. In this way, citations occurring in a given year, regardless of the journal in which they appeared, are combined into a single yearly value. This procedure yields two annual time series: one tracking the total number of citations to Planck's value $C_P(y) = \sum_j C_P(j, y)$, and the other tracking the total number of citations to the values of other scientists $C_O(y) = \sum_j C_O(j, y)$.

The highest number of citations in a single year occurred in 1910 for both Planck and other contributors, with 16 citations referring to Planck's value and 99 citing alternative values. This peak indicates a period of particularly intense publication and referencing activity related to the determination of the elementary charge. It should be noted that these values are not normalised, as the aim is to capture the overall volume of citation activity over time rather than relative proportions within yearly publication output.

Figure 3 shows the annual citation activity from 1901 to 1921. The horizontal axis represents the year, the vertical axis the total number of citations across all journals, and the bubble size is proportional to citation volume. This representation allows the distribution of citation activity over time to be observed in terms of both absolute counts and relative intensity.

The peak observed in 1910 suggests a delayed but intensified presence of Planck's value in the scientific literature on the electron charge. In this broader context, Planck had indeed become increasingly recognised as a leading figure within the scientific community of Berlin, and later of Germany as a whole (Fuchs Eckern 2010). The concurrent peak in citations to alternative electron charge values can be understood in the context of both ongoing scientific developments and broader publication trends. Before Planck's value gained wider acceptance, experimental determinations of the electron charge were pursued by physicists such as Thomson, H.A. Wilson, and Millikan.

Although Planck's estimate was theoretically well-founded, it had not yet gained broad acceptance by 1910. One reason may have been that it was derived rather than experimentally measured. Consequently, many scientists were sceptical of theoretical approximations, favouring values obtained through direct experimentation. The

Distribution of citations by country for Planck and other scientists in 1910

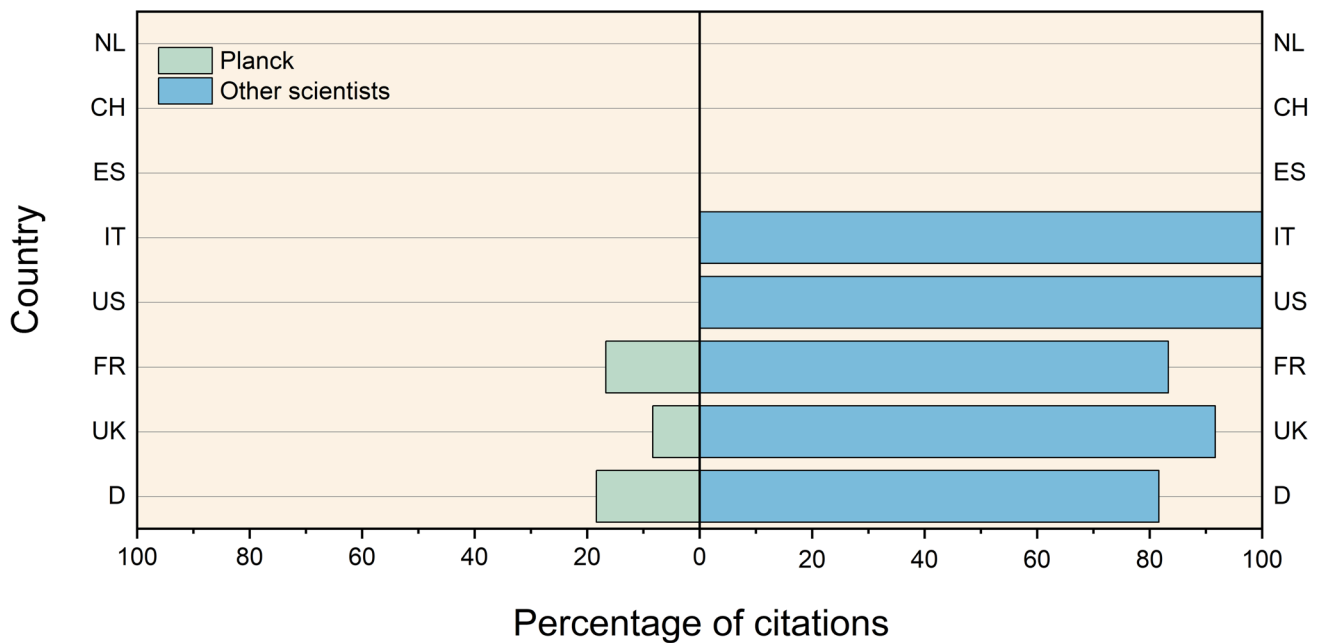


Fig. 4 The bar chart provides a descriptive comparison of citation patterns across countries in the dataset. It illustrates the percentage distribution of citations to Planck (X_P^c) and to other scientists (X_O^c) across various countries

in 1910. The vertical axis lists the countries of publication for the journals considered (e.g. *NL*, *CH*, *ES*, *IT*, *US*, *FR*, *UK*, *D*), while the horizontal axis shows the proportion of citations (ranging from 0% to 100%)

analysis therefore suggests that, by 1910, citations to Planck's value still coexisted with a strong representation of experimentally derived alternatives in the literature.

It should be recalled that by 1910, Millikan effectively treated Planck's value as one of the reliable and plausible determinations of the electron charge alongside experimental results, thereby placing Planck's theoretical estimate on an equal footing with laboratory measurements.

Country-level analysis is restricted to 1910, the year of peak citation activity, in order to ensure sufficient observational density for comparative assessment. To explore citation patterns in 1910 in greater detail and to identify possible country-level differences in the use of Planck's value versus alternative determinations, we aggregated citation counts separately for each country. For a given country c , this procedure involves summing all citations recorded in journals associated with that country in the year 1910, distinguishing between citations to Planck's value and citations to other proposed values. In this way, we obtain two country-specific totals: one corresponding to citations to Planck's value and one corresponding to citations to alternative determinations. This aggregation is performed over all journals attributed to country c , which together form the national subset of the dataset. These country-level citation totals were then normalised in order to account for differences in overall citation volume across countries. Specifically, for each country, we computed the relative share of citations referring to Planck's value and to alternative determinations by dividing each category by the total number of citations recorded for that country in 1910. This procedure yields two complementary proportions: the fraction of citations associated with Planck's value $X_P^c(1910)$ and the fraction associated with other proposed values $X_O^c(1910)$. Normalisation is applied to control for heterogeneity in total citation volume across countries. Together, these measures provide a normalised representation of citation patterns that allows meaningful comparison across countries with different overall levels of citation activity.

The results shown in Fig. 4 provide a descriptive overview of the distribution of citations to Planck's value and to alternative determinations across countries in 1910. The figure highlights variation in the relative proportions of citations across national contexts. However, given the limited number of observations per country, these differences should be interpreted as indicative patterns within the dataset rather than as sharply defined or statistically distinct groups.

From this perspective, Germany stands out as the country in which Planck's value is most frequently cited. This pattern is consistent with historical context, as Planck was German and had high visibility in national scientific publications, notably serving as editor of *Annalen der Physik* for an extended period (Pyenson 2007; Fuchs Eckern 2010).

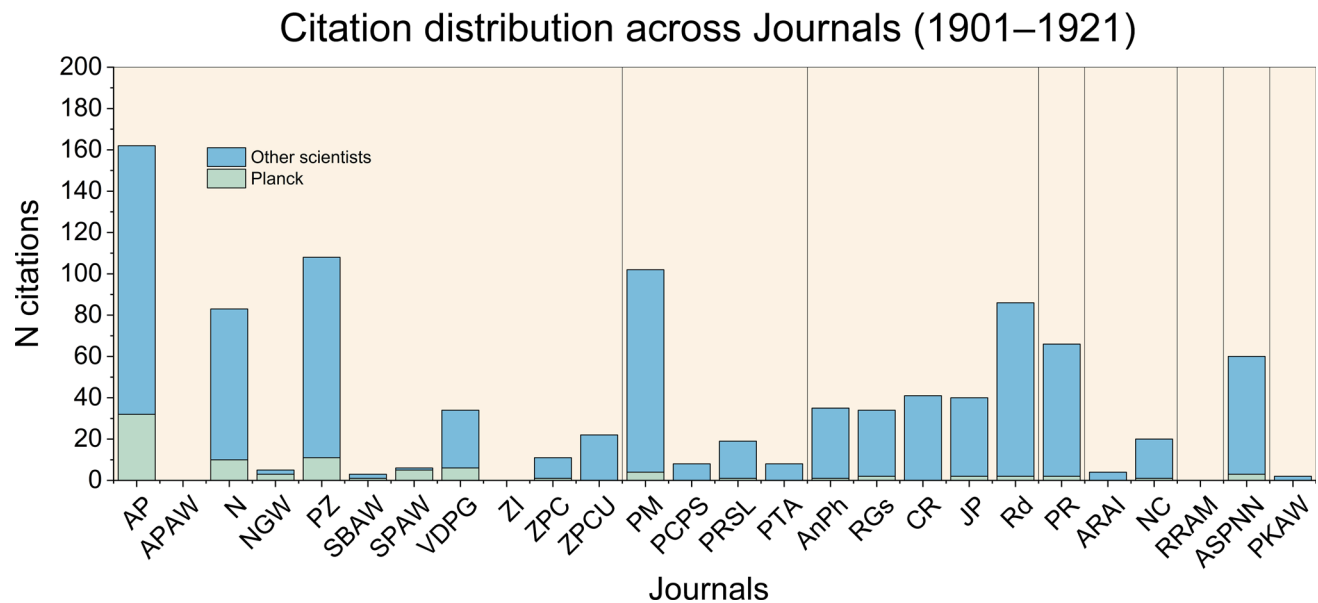


Fig. 5 Citation distribution ($C_P(j)$, $C_O(j)$) across journals grouped by countries (1901–1921). Each box presents citation data for a specific country, arranged from left to right as follows: Germany, UK, France, USA, Italy, Spain, Switzerland, and the Netherlands

The UK and France also show a moderate frequency of citations to Planck's value. In contrast, the USA and Italy form a distinct group characterised by citations of alternative values in the dataset. The absence of citations from Spain, Switzerland, and the Netherlands reflects their representation in the current dataset and may indicate either limited publication activity in the selected journals or lack of engagement with this particular scientific debate.

We now examine the distribution of citations across journals over the period 1901–1921 (Fig. 5). For each journal, we sum all annual citation records to obtain total citation counts, distinguishing between Planck's value and alternative determinations, e.g. $C_P(j) = \sum_y C_P(j, y)$ and $C_O(j) = \sum_y C_O(j, y)$. This yields journal-level totals for each category over the full period analysed.

Consistent with previous analyses, Fig. 5 presents the citation counts for each journal, divided into two categories: citations to Planck's work (green) and citations to other scientists (blue). This representation highlights both the visibility of Planck's contributions and the broader implications of citation inequality in early twentieth-century physics. One of the most striking findings is that Planck's value was cited in a select number of leading journals, reflecting a concentrated pattern of citation distribution across the scientific literature. Planck's contributions show a significant presence in German physics-oriented publications such as *AP*, *N*, and *VDPG*. While his overall citation count is substantial, it is not uniformly distributed across all journals, indicating differences in topical and disciplinary engagement across publication venues. Journals outside Germany, including *PM* and *PR*, also record citations, although the majority refer to other scientists rather than to Planck.

4 Conclusion

The present analysis focuses on a set of countries and journals representative of the principal centres of physics research in the period considered, which together capture the primary channels of dissemination of these results. While other contexts (e.g. Russian publications) may have contributed, their limited accessibility and coverage in the available sources make them difficult to include in a consistent comparative framework. The analysis presented in this study has quantified the contemporary reception of Max Planck's 1900 numerical estimate of the elementary electric charge within the scientific literature of the early twentieth-century. Although emerging from the same theoretical framework that introduced the quantum hypothesis, a framework that rapidly became highly visible in the scientific literature, Planck's determination of e exhibits a relatively low frequency of citations in the period considered.

By examining both the experimental context in which competing values of the electron charge were produced and the citation practices through which scientific results circulated, we show that Planck's estimate was one among several values reported in the literature on the elementary charge, alongside a broader set of experimental determinations. Bibliometric evidence indicates that, between 1901 and 1921, explicit references to Planck's value

account for approximately 10% of all citations related to determinations of the elementary charge, relative to experimental values proposed by Thomson, H.A. Wilson, Millikan, Regener, Ehrenhaft, and others. This distribution reflects the epistemic hierarchy of the period, in which direct experimental measurement retained a privileged status over theoretically derived quantities. While Planck emphasised the importance of the constants emerging from his radiation law, his contemporaries tended to regard the determination of e as an empirical problem best addressed through laboratory techniques rather than theoretical inference.

The temporal evolution of citations further supports this interpretation. While Planck's value remained relatively minor in the early years, a peak in 1910 indicates a gradual increase in visibility, though still coexisting with a dominant presence of experimentally derived alternatives. Notably, in 1910 Millikan treated Planck's value as one of the plausible determinations of the electron charge, placing it on a comparable footing with experimental results and thereby contributing to its limited legitimisation within the experimental community.

More broadly, the findings highlight the role of dissemination, classification, and citation in shaping the reception of scientific contributions. Planck's estimate, though conceptually significant in retrospect, circulated within a scientific environment that had not yet fully integrated quantum considerations into precision measurement. Consequently, his value for the elementary charge did not achieve a high level of citation frequency in the dataset compared to competing experimental determinations.

By combining historical reconstruction with quantitative bibliometric analysis, this study provides a systematic account of how Planck's determination of the elementary charge was received in contemporary citation records. The results underscore that scientific significance cannot be inferred solely from later theoretical prominence; rather, it emerges from a complex interplay between theoretical innovation, experimental practice, and the social mechanisms through which knowledge is communicated and validated. In this sense, the limited contemporary visibility of Planck's estimate offers a revealing case study of how foundational contributions may initially remain peripheral within contemporary discourse before acquiring retrospective importance in the broader narrative of scientific development. By foregrounding this aspect of Planck's work, the study contributes to a more nuanced understanding of his scientific legacy and of early twentieth-century efforts to determine the elementary electric charge.

Acknowledgements The author gratefully acknowledges the assistance and resources provided by the University libraries of Florence ("Polo Scientifico"), Pisa ("Polo 3"), Bologna and Pavia, all of which were essential to the conduct of this research. The author would also like to extend a sincere appreciation to Dr. Ilaria Poggi at the Library of "Museo Galileo - Istituto e Museo di Storia della Scienza" for the helpful suggestions and assistance in navigating the library's resources and gathering information. The author further acknowledges Dr. Aurélie Lemoine, Responsable des fonds patrimoniaux at the Musée Curie, for her kind support and expertise in accessing and interpreting archival materials.

Author contributions

The author conducted all aspects of the research, including literature review, bibliometric data analysis, interpretation of results, and writing of the manuscript.

Funding Information Open access funding provided by Consiglio Nazionale Delle Ricerche (CNR) within the CRUI-CARE Agreement. Not applicable

Data availability The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Material availability Materials are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest Not applicable.

Ethical approval Not applicable.

Consent for publication Not applicable.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated

otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

A Appendix A

In this appendix, we present a comprehensive collection of scientific journals published in different countries during the period under investigation (Tables 3, 4, 5, 6 and 7). Each table is dedicated to a specific country and provides the complete journal names along with their commonly used abbreviations. The period of activity is also included to indicate the years during which each journal was published. These tables serve as a reference for understanding the dissemination of scientific knowledge across different regions and their contribution to the scientific community of the time.

It should be noted that the issue of journal abbreviations for journals published prior to the establishment of the ISO standard is far from solved. In fact, it is common to find multiple abbreviations assigned to the same journal. For instance, the *Sitzungsberichte der Mathematisch-Physikalischen Klasse der Bayerischen Akademie der Wissenschaften zu München* has appeared under more than 200 different abbreviations, as catalogued in the 2nd edition of the Scholarly Societies Project (Parrot yy). To maintain consistency and simplicity, we have considered for the shorter abbreviation commonly found in digital libraries and repositories (Biodiversity Heritage Library yy; Archive yy; Congress yy; Ithaka 2025; Digital Public Library of America yy; Gutenberg 2025; Europeana 2025; Sub G Ttingen Digitalisierungszentrum 2025; Sächsische

Table 3 German journals included in this study with full names, historical abbreviations, activity periods, and the abbreviations used here. The same headings apply to the following tables

Full Journal Name	Years of Activity	Abbreviation
<i>Annalen der Physik (Ann. d. Phys.)</i>	1901–1921	AP
<i>Abhandlungen der Königlich Preussischen Akademie der Wissenschaften. Physikalisch-Mathematische Klasse (Abh. d. K. Preuss. Akad. Wiss. Phys.-Math. Kl.)</i>	1901–1907	APAW
<i>Abhandlungen der Königlich Preussischen Akademie der Wissenschaften aus dem Jahre (Abh. d. K. Preuss. Akad. Wiss.)</i>	1908–1919	
<i>Abhandlungen der Preussischen Akademie der Wissenschaften. Physikalisch-Mathematische Klasse (Abh. d. Preuss. Akad. Wiss. Phys.-Math. Kl.)</i>	1920–1921	
<i>Naturwissenschaftliche Rundschau: wöchentliche Berichte über die Fortschritte auf dem Gesamtgebiete der Naturwissenschaften (Naturwiss. Rundsch.)</i>	1901–1912	N
<i>Naturwissenschaften</i>	1913–1921	
<i>Nachrichten von der Königlich Gesellschaft der Wissenschaften zu Göttingen. Mathematisch-physikalische Klasse (Nachr. Ges. Wiss. Göttingen Math.-Phys. Kl.)</i>	1901–1921	NGW
<i>Physikalische Zeitschrift (Phys. Z.)</i>	1901–1921	PZ
<i>Sitzungsberichte der mathematisch-physikalischen Klasse der Königl. Bayerischen Akademie der Wissenschaften zu München (Sitz. d. Math.-Phys. Klasse d. K. Bayer. Akad. d. Wiss)</i>	1901–1917	SBAW
<i>Sitzungsberichte der Mathematisch-Physikalischen Klasse der Bayerischen Akademie der Wissenschaften zu München (Sitz d. Math.-Phys. Klasse d. Bayer. Akad. d. Wiss)</i>	1918–1921	

Table 3 continued

Full Journal Name	Years of Activity	Abbreviation
<i>Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften zu Berlin (Sitz. d. K. Preuss. Akad. Wiss.)</i>	1901–1918	<i>SPAW</i>
<i>Sitzungsberichte der Preussischen Akademie der Wissenschaft (Sitz. d. Preuss. Akad. Wiss.)</i>	1919–1921	
<i>Verhandlungen Der Deutschen Physikalischen Gesellschaft (Verh. Deutsch. Phys. Ges.)</i>	1901–1921	<i>VDPG</i>
<i>Zeitschrift für Instrumentenkunde (Z. Instr.)</i>	1901–1921	<i>ZI</i>
<i>Zeitschrift für Physikalische Chemie (Z. Physikal. Chem.)</i>	1901–1921	<i>ZPC</i>
<i>Zeitschrift für den Physikalischen und Chemischen Unterricht (Zeit. Phys. Chem. Unter.)</i>	1901–1921	<i>ZPCU</i>

Table 4 This table lists the journals from the UK included in this study

Full Journal Name	Years of Activity	Abbreviation
<i>The London, Edinburgh and Dublin philosophical magazine and journal of science (Phil. Mag.)</i>	1901–1921	<i>PM</i>
<i>Proceedings - Cambridge Philosophical Society (Proc. Camb. Phil. Soc.)</i>	1901–1921	<i>PCPS</i>
<i>Proceedings of the Royal Society of London (Proc. R. Soc. Lond.)</i>	1901–1905	<i>PRSL</i>
<i>Proceedings of the Royal Society of London. Series A, Containing papers of a mathematical and physical character (Proc. R. Soc. Lond. Ser. A.)</i>	1906–1921	
<i>Philosophical Transactions. Series A: Mathematical and physical sciences (Philos. Trans. A)</i>	1901–1921	<i>PTA</i>

Table 5 This table lists the journals from the USA included in this study

Full Journal Name	Years of Activity	Abbreviation
<i>The Physical Review. A journal of experimental and Theoretical Physics (Phys. Rev.)</i>	1901–1921	<i>PR</i>

Landesbibliothek Staats- und Universitätsbibliothek Dresden (SLUB) [2025](#); Hamburger Kulturgut Digital: [2025](#); Deutsche Digitale [2025](#); Biblioteka [2025](#); HAL [2025](#); Bibliothéque Nationale de France [2025](#); Revue Sommaire ISTE [2025](#); LillOnum [2025](#); Landesmuseen [2025](#); Centrale di Roma: Teca Digitale, [2025](#)), online catalogues (Foundation [n.d.](#)), and existing literature (V.A [1937](#); Borisenko Ossicini [2012](#)).

Table 6 This table lists the journals from France included in this study

Full Journal Name	Years of Activity	Abbreviation
<i>Annales de chimie et physique</i> (<i>Ann. Chim. Phys.</i>)	1901–1903	<i>AnPh</i>
<i>Annales de physique</i> (<i>Ann. Physique</i>)	1914–1921	
<i>Revue générale des sciences pures et appliquées</i> (<i>Rev. Gen. Sci. Pures Appl.</i>)	1901–1921	<i>RGS</i>
<i>Comptes rendus hebdomadaires des séances de l'Académie des sciences</i> (<i>C. R. Hebd. Séances Acad. Sci.</i>)	1901–1921	<i>CR</i>
<i>Journal de Physique Théorique et Appliquée</i> (<i>J. Phys. Theor. Appl.</i>)	1901–1919	<i>JP</i>
<i>Journal de Physique et le Radium</i> (<i>J. Phys. Radium</i>)	1920–1921	
<i>Le Radium</i> (<i>Radium</i>)	1904–1919	<i>Rd</i>

Table 7 This table showcases the Italian (IT), Spanish (ES), Swiss (CH), and Dutch (NL) journals examined in this study

Full Journal Name	Years of Activity	Country	Abbreviation
<i>Atti della Reale Accademia d'Italia. Rendiconti</i> (<i>R. Accad. Naz. Lincei</i>)	1901–1921	IT	<i>ARAI</i>
<i>Il Nuovo Cimento</i> (<i>Nuovo Cimento</i>)	1901–1921	IT	<i>NC</i>
<i>Revista de los Progresos de las Ciencias Exactas, Físicas y Naturales</i> (<i>Rev. Prog. Cienc. Exact. Fís. Nat.</i>)	1901–1904	ES	<i>RRAM</i>
<i>Revista de la Real Academia de Ciencias Exactas, Físicas y Naturales de Madrid</i> (<i>Rev. R. Acad. Cienc. Exactas, Fís. Nat. Madr</i>)	1905–1921		
<i>Archives des sciences physiques et naturelles</i> (<i>Arc. Sci. Phys. Nat.</i>)	1901–1921	CH	<i>ASPN</i>
<i>Proceedings of the Section of Sciences. Koninklijke Akademie van Wetenschappen te Amsterdam</i> (<i>Proc. K. Akad. Wet. Amst.</i>)	1901–1921	NL	<i>PKAW</i>

References

- Abraham, M.: Prinzipien der Dynamik des Elektrons. *Annalen der Physik* 315(1), 105–179 (1902)
- Alexejew, A., Malikov, M.: Über die Ladung des Gasions. *Zhurnal Russkago Fiziko-Khimicheskago Obshchestva* 41, 247–257 (1909)
- Arabatzi, T.: Representing Electrons: A Biographical Approach to Theoretical Entities. University of Chicago Press, Chicago and London (2006)
- Archive, I.: Internet Archive. <https://archive.org/>
- Arrhenius, S.: Conférences sur Quelques Thèmes Choisis de la Chimie Physique Pure et Appliquée. A. Hermann et Fils, Paris (1912)
- Badino, M.: The odd couple: Boltzmann, Planck and the application of statistics to physics (1900–1913). *Annalen der Physik* 18(2–3), 81–101 (2009)
- Begeman, L.: An experimental determination of the charge of an electron by the cloud method. *Phys. Rev. (Series I)* 31(1), 41–54 (1910)
- Biblioteca Nazionale Centrale di Roma: Teca Digitale (2025). <http://digitale.bnc.roma.sbn.it/tecadigitale/>

- Bibliothèque nationale de France: Gallica Bibliothèque numérique de la BnF (2025). <https://gallica.bnf.fr/accueil/fr/html/accueil-fr>
- Biodiversity Heritage Library: Biodiversity Heritage Library. <https://www.biodiversitylibrary.org>
- Borisenko, V.E., Ossicini, S.: Abbreviations for the scientific journals which appear as sources in the text. In: What Is What in the Nanoworld: A Handbook on Nanoscience and Nanotechnology, 1st edn., pp. 585–589. Wiley, Weinheim, Germany (2012). <https://doi.org/10.1002/9783527648368.app2>
- Boltzmann, L.: Ableitung des stefan'schen gesetzes betreffend die abhängigkeit der wärmestrahlung von der temperatur aus der elektromagnetischen lichttheorie. Annalen der Physik 22, 291–294 (1884)
- Bucherer, A.H.: Mathematische Einführung in die Elektronentheorie. B. G. Teubner, Leipzig (1904)
- Buchwald, J.Z., Warwick, A. (eds.): Histories of the Electron: The Birth of Microphysics. Dibner Institute Studies in the History of Science and Technology. MIT Press, Cambridge, MA and London, England (2001)
- Costas, R., Van Leeuwen, T.N., Bordons, M.: Self-citations at the meso and individual levels: effects of different calculation methods. Scientometrics 82(3), 517–537 (2010) <https://doi.org/10.1007/s11192-010-0187-7>
- Dahl, P.F.: Flash of the Cathode Rays: A History of J. J. Thomson's Electron. CRC Press, Boca Raton (1997). <https://doi.org/10.1201/9781482268461>
- Darrigol, O.: Statistics and Combinatorics in Early Quantum Theory. Historical Studies in the Physical and Biological Sciences 19(1), 17–80 (1988) <https://doi.org/10.2307/27757616>
- Broglie, M.: Étude sur les suspensions gazeuses. Le Radium 6(7), 203–209 (1909)
- DuBridge, L.A., Epstein, P.S.: Robert Andrews Millikan, 1868–1953: A Biographical Memoir. National Academy of Sciences Biographical Memoirs, vol. XXXIII, pp. 240–282. Columbia University Press, New York (1959)
- Deutsche Digitale Bibliothek: Deutsche Digitale Bibliothek Das Kultur- und Wissenschaftsportal (2025). <https://www.deutsche-digitale-bibliothek.de/>
- Digital Public Library of America: Digital Public Library of America (2025). <https://dp.la/>
- Ehrenhaft, F.: Eine methode zur bestimmung des elektrischen elementarquantums. Physika 10(9), 308–310 (1909)
- Ehrenhaft, F.: Über eine neue Methode zur Messung von Elektrizitätsmengen an Einzelteilchen, deren Ladungen die Ladung des Elektrons erheblich unterschreiten und auch von dessen Vielfachen abzuweichen scheinen. Physikalische Zeitschrift 11(14), 619–630 (1910)
- Europeana: Europeana - Collections of European Cultural Heritage (2025). <https://www.europeana.eu/>
- Eve, A.S.: Rutherford: Being the Life and Letters of the Rt. Hon. Lord Rutherford. The McMillan Company, New York (1939)
- Fuchs, G.W., Eckern, U.: Editorial Note: Ann. Phys. 6/2010. Annalen der Physik 522(6), 371–371 (2010) <https://doi.org/10.1002/andp.201010453>
- Flatt, J.: The case for tracking self-citations. Physics Today 2017(9), 5109 (2017) <https://doi.org/10.1063/pt.6.3.20170919a>
- Fletcher, H.: A verification of the theory of brownian movements and a direct determination of the value of Ne for gaseous ionization. Physical Review 33(2), 107–110 (1911)
- Foundation, W.: Wikispecies. <https://archive.org/>
- Fuchs, G.W.: Eine legende wird neu geboren: Die annalen der physik ein portrait. Physik in unserer Zeit 42(6), 290–295 (2011) <https://doi.org/10.1002/piuz.201101277>
- Gutenberg, P.: Project Gutenberg (2025). <https://www.gutenberg.org/>
- HAL: HAL Open Archive (2025). <https://hal.science>
- Hamburger Kulturgut Digital: Hamburger Kulturgut Digital Digitale Sammlungen der SUB Hamburg (2025). <https://digitalisate.sub.uni-hamburg.de/>
- Heilbron, J.L.: The Dilemmas of an Upright Man: Max Planck and the Fortunes of German Science, With a New Afterword. Harvard University Press, Cumberland (2000)
- Hettner, G.: Die Bedeutung von Rubens Arbeiten für die Plancksche Strahlungsformel. Die Naturwissenschaften 10(48), 1033–1038 (1922) <https://doi.org/10.1007/BF01565205>
- Ithaka: JSTOR (2025). <https://www.jstor.org>
- Jaffé, G.: Die elektrische Leitfähigkeit des reinen Hexans. Annalen der Physik 28(2), 326–370 (1909)
- Jentzsch, F.: Über die Elektronenemission glühender Metalloxyde. Annalen der Physik 27(11), 129–156 (1908)
- Kaufman, W.: Die magnetische Ablenkbarkeit der Kathodenstrahlen und ihre Abhängigkeit vom Entladungspotential. Annalen der Physik 61(3) (1897)
- Kaufman, W.: Die magnetische und elektrische Ablenkbarkeit der Becquerelstrahlen und die Scheinbare Masse der Elektronen. Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse 40, 143–155 (1901)
- Kaufman, W.: Die elektromagnetische Masse des Elektrons. Physikalische Zeitschrift 4, 54–57 (1902)
- Kiada, A.: AKJournals. Accessed: January 13, 2026. <https://akjournals.com/page/244>
- Kirchhoff, G.: Über den Zusammenhang zwischen Emission und Absorption von Licht und Wärme. Monatsberichte der Königlich Preuss. Akademie der Wissenschaften zu Berlin, 783–787 (1859)
- Klein, M.J.: Max Planck and the beginnings of the quantum theory. Archive for History of Exact Sciences 1(5), 459–479 (1961) <https://doi.org/10.1007/BF00327765>
- Kuhn, T.S.: Black-body Theory and the Quantum Discontinuity, 1894–1912. Clarendon Press; Oxford University Press, Oxford : New York (1978)

- Kurlbaum, F.: Über eine Methode zur Bestimmung der Strahlung in absoluten Mass und die Strahlung des schwarzen Körpers zwischen 0 und 100 Grad. *Annalen der Physik* 65(4), 746–760 (1898)
- Landesmuseen, O.: Zoologisch-Botanische Datenbank (ZOBODAT) (2025). <https://www.zobodat.at/>
- Lattey, R.T.: The Ionization of Electrolytic Oxygen. *Philosophical Magazine* 18(4), 26–31 (1909)
- LillOnum: Bibliothèque numérique patrimoniale de l'Université de Lille (2025). <https://lillonum.univ-lille.fr/s/lillonum/page/accueil>
- Lummer, O., Jahnke, E.: Über die Spectralgleichung des schwarzen Körpers und des blanken Platins. *Annalen der Physik* 3(4), 284–297 (1900)
- Lummer, O., Pringsheim, E.: Über die Strahlung des schwarzen Körpers für lange Wellen. *Verhandlungen der Deutschen Physikalischen Gesellschaft* 2(3), 163–180 (1900)
- Millikan, R.A., Begeman, L.: On the charge carried by the negative ion of an ionized gas. *Physical Review* 26(2), 197–198 (1908)
- Mehra, J.: *The Golden Age of Theoretical Physics (Boxed Set of 2 Volumes)*. World Scientific, Singapore (2001). <https://doi.org/10.1142/4454>
- Millikan, R.A.: A New Modification of the Cloud Method of Determining the Elementary Electrical Charge and the most Probable Value of that Charge. *Philosophical Magazine* 19(22), 209–228 (1910)
- Millikan, R.A.: The Isolation of an Ion, a Precision Measurement of its Charge, and the Correction of Stokes's Law. *Physical Review* 2(4), 349–397 (1911)
- Millikan, R.A.: On the Elementary Electrical Charge and the Avogadro Constant. *Physical Review* 2(2), 109–143 (1913)
- Millikan, R.A.: The Electron: Its Isolation and Measurement and the Determination of Some of Its Properties. *The University of Chicago Science Series*, Chicago, Illinois (1917)
- Millikan, R.A.: *Electrons (+ and -), Protons, Photons, Neutrons, Mesotrons And Cosmic Rays*. The University Chicago Press, Chicago, Illinois (1947)
- Moreau, G.: Sur la charge de l'ion négatif d'une flamme. *Comptes Rendus* 148, 1255–1257 (1909)
- Meyer, E., Regener, E., Harling, J.: Über Schwankungen der radioaktiven Strahlung und eine Methods zur Bestimmung des elektrischen Elementarquantums. *Annalen der Physik* 25(4), 757–774 (1908)
- Mulligan, J.F.: Emil Wiechert (1861 1928): Esteemed seismologist, forgotten physicist. *American Journal of Physics* 69(3), 277–287 (2001)
- Nabl, J.: Über die elektrostatischen ladungen der gase, die an der activen elektrode des wehnelt-unterbrechers auftreten. *Anzeiger der Kaiserlichen Akademie der Wissenschaften, Mathematisch-Naturwissenschaftliche Klasse* 39, 23 (1902)
- Navarro, J.: *A History of the Electron: J. J. and G. P. Thomson*. Cambridge University Press, Cambridge, UK (2012). <https://doi.org/10.1017/CBO9780511793745>
- Niaz, M.: The Oil Drop Experiment: A Rational Reconstruction of the Millikan-Ehrenhaft Controversy and Its Implications for Chemistry Textbooks. *Journal of Research in Science Teaching* 37(5), 480–508 (2000) [https://doi.org/10.1002/\(SICI\)1098-2736\(200005\)37:5<480::AID-TEA6>3.0.CO;2-X](https://doi.org/10.1002/(SICI)1098-2736(200005)37:5<480::AID-TEA6>3.0.CO;2-X)
- Congress, L.: Library of Congress Online Catalog. <https://www.loc.gov/collections>
- Pais, A.: Einstein and the quantum theory. *Reviews of Modern Physics* 51(4), 863–914 (1979) <https://doi.org/10.1103/RevModPhys.51.863>
- Parrot, J.: Bayerische Akademie der Wissenschaften. Scholarly Societies Project. <http://www.scholarly-societies.org/history/1759cbaw.html>
- Pellat, H.: Détermination directe de la valeur absolue de la charge électrique d'un ion électrolytique monovalent. *Diamètre d'un atome. Comptes Rendus* 144, 902–904 (1907)
- Perrin, J.: Mouvement Brownien et réalité moléculaire. *Annales de Chimie et de Physique* 18(8), 5–114 (1909)
- Perrin, J.: Les déterminations des grandeurs moléculaires. *Comptes Rendus* 152, 1165–1168 (1911)
- Perrin, J.: Les Preuves de la Réalité Moléculaire (étude spéciale des émulsions. In: *La Theorie du Rayonnement et des Quanta*, pp. 153–250. Gauthier-Villars, Paris (1912)
- Planck, M.: Antrittsrede. *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften zu Berlin* 32, 641–644 (1894)
- Planck, M.: Absorption und emission elektrischer wellen durch resonanz. *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften zu Berlin* 1, 289–302 (1895)
- Planck, M.: Absorption und Emission electrischer Wellen durch Resonanz. *Annalen der Physik* 57(1), 1–14 (1896)
- Planck, M.: Über elektrische Schwingungen, welche durch Resonanz erregt und durch Strahlung gedämpft werden. *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften* 2(10), 81–100 (1896)
- Planck, M.: Notiz zur Theorie der Dämpfung elektrischer Schwingungen. *Annalen der Physik* 63(56), 419–422 (1897)
- Planck, M.: Über elektrische Schwingungen, welche durch Resonators erregt und durch Strahlung gedämpft werden. *Annalen der Physik* 60(4), 577–599 (1897)
- Planck, M.: Entropie und Temperatur strahlender Wärme. *Annalen der Physik* 1(4), 719–737 (1900)
- Planck, M.: Zur Theorie des Gesetzes der Energieverteilung im Normalspectrum. *Verhandlungen der Deutschen Physikalischen Gesellschaft* 2(17), 237–245 (1900)
- Planck, M.: Über eine Verbesserung der Wien'schen Spektralgleichung. *Verhandlungen der Deutschen Physikalischen Gesellschaft* 2(13), 202–204 (1900)
- Planck, M.: Über irreversible Strahlungsvorgänge. *Annalen der Physik* 1(1), 69–122 (1900)
- Planck, M.: Über das Gesetz der Energieverteilung im Normalspectrum. *Annalen der Physik* 4(3), 553–563 (1901)

- Planck, M.: Über die Elementarquanta der Materie und der Elektrizität. *Annalen der Physik* 4(3), 564–566 (1901)
- Planck, M.: Über die Verteilung der Energie zwischen Aether und Materie. *Annalen der Physik* 9(3), 629–641 (1902)
- Planck, M.: Vorlesungen über die Theorie der Wärmestrahlung. J.A. Barth, Leipzig (1906)
- Planck, M.: Zur Geschichte der Auffindung des physikalischen Wirkungsquantums. *Die Naturwissenschaften* 31(14–15), 153–159 (1943) <https://doi.org/10.1007/BF01475738>
- Planck, M.: Die Entstehung und bisherige Entwicklung der Quantentheorie. In: *Entstehung und Bisherige Entwicklung der Quantentheorie*, pp. 1–14. Vieweg+Teubner Verlag, Wiesbaden (1958). https://doi.org/10.1007/978-3-322-98792-1_1
- Planck, M.: *Physikalische Abhandlungen und Vorträge*. F. Vieweg, Braunschweig (1958)
- Planck, M.: *Vorträge Reden Erinnerungen*. Springer, Berlin, Heidelberg (2001). <https://doi.org/10.1007/978-3-642-56594-6>
- Pomorska Biblioteka Cyfrowa: Pomorska Biblioteka Cyfrowa Polish Digital Library (2025). <https://pbc.gda.pl/dlibra>
- Przibram, K.: Über die kondensation von Dämpfen in ionisierten gases. *Physikalische Zeitschrift* 8(17), 561–564 (1907)
- Przibram, K.: Ladungsbestimmungen an Nebelteilchen; Beiträge zur Frage des elektrischen Elementarquantums. *Anzeiger der Kaiserlichen Akademie der Wissenschaften, Mathematisch-Naturwissenschaftliche Classe* 47(17), 262–263 (1910)
- Pyenson, L.: Physical sense in relativity: Max Planck edits the annalen der physik, 1906–1918. *Annals der Physik* 520(2–3), 176–189 (2007) <https://doi.org/10.1002/andp.200852002-312>
- Regener, E.: Über zählung der alpha-teilchen durch die szintillation und über die größe des elektrischen elementarquantums. *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften zu Berlin* 38, 948–965 (1909)
- Revue Sommaire ISTEEX: *Revue Sommaire ISTEEX* (2025). <https://revue-sommaire.istex.fr>
- Rutherford, E., Geiger, H.: The charge and nature of the alpha-particle. *Proceedings of the Royal Society of London A* 81(546), 162–173 (1908)
- Rubens, H., Kurlbaum, F.: Über die Emission langwelliger Wärmestrahlen durch den schwarzen Körper bei verschiedenen Temperaturen. *Sitzungsberichte der Königlich Preussischen Preu ischen Akademie der Wissenschaften zu Berlin* 41, 929–941 (1900)
- Romer, A.: The experimental history of atomic charges, 1895–1903. *ISIS* 34(2), 150–161 (1942)
- Roux, J.: La charge de l'électron. *Comptes Rendus* 152, 1168–1169 (1911)
- Rutherford, E.: The velocity and rate of recombination of the ions of gases exposed to Röntgen radiation. *Philosophical Magazine* 44(54), 422–440 (1897)
- Schweidler, E.v.: Über Schwankungen der radioaktiven Umwandlung. In: *Comptes rendus du Premier Congrès international pour l'étude de la radiologie et de l'ionisation tenu à Liège du 12 Au 14 Septembre 1905.*, pp. 1–3. H. Dunod & E. Pinat, Paris (1906)
- Sirk, H.: Zur Berechnung der molekularen Dimensionen. *Annalen der Physik* 25(5), 894–904 (1908)
- Smith, G.E.: J. J. Thomson and The Electron: 1897–1899 An Introduction. *The Chemical Educator* 2(6), 1–42 (1997) <https://doi.org/10.1007/s00897970149a>
- Seth, R., Smith, G.E.: *Brownian Motion and Molecular Reality*. Oxford University Press, Oxford, UK (2020). <https://doi.org/10.1093/oso/9780190098025.001.0001>
- Stefan, J.: Über die Beziehung zwischen der Wärmestrahlung und der Temperatur. *Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften in Wien, Mathematisch-Naturwissenschaftliche Klasse* 79(8), 391–428 (1879)
- SUB Göttingen Digitalisierungszentrum: SUB Göttingen Digitalisierungszentrum (GDZ) (2025). <https://gdz.sub.uni-goettingen.de/>
- Sutherland, W.: Cathode, Lenard, and Röntgen rays. *Philosophical Magazine* 47(20), 269–284 (1899)
- Svedberg, T.: Die Existenz der Moleküle: experimentelle Studien, p. 136. Akademische Verlagsgesellschaft, Leipzig (1912)
- Sächsische Landesbibliothek Staats- und Universitätsbibliothek Dresden (SLUB): SLUB Dresden (2025). <https://www.slub-dresden.de/>
- Taschetto, D.: Rewriting the “Quantum” Revolution. *Studies in History and Philosophy of Science* 109, 72–88 (2025) <https://doi.org/10.1016/j.shpsa.2024.12.006>
- Thiesen, M.: Über das Gesetz der schwarzen Strahlung. *Verhandlungen der Deutschen Physikalischen Gesellschaft* 2(5), 65–70 (1900)
- Thomson, J.J.: Cathode Rays. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 44(269), 293–316 (1897) <https://doi.org/10.1080/14786449708621070>
- Thomson, J.J.: On the Charge of Electricity carried by the Ions produced by Röntgen Rays. *Philosophical Magazine* 46(57), 528–545 (1898)
- Thomson, J.J.: On the masses of Ions in Gases at low pressures. *Philosophical Magazine* 48(58), 547–567 (1899)
- Thomson, J.J.: On the charge of electricity carried by a gaseous ion. *Philosophical Magazine* 5(27), 346–355 (1903) <https://doi.org/10.1080/14786440309462931>
- Townsend, J.S.: On Electricity in gases and the formation of Clouds in Charged Gases. *Proceedings of the Cambridge Philosophical Society* 9, 244–258 (1897)
- Townsend, J.S.: Electrical Properties of Newly Prepared Gases. *Philosophical Magazine* 45(13), 125–151 (1898)
- Townsend, J.S.: The diffusion of ions into gases. *Proceedings of the Royal Society of London* 65(413–422), 192–196 (1900) <https://doi.org/10.1098/rsp.1899.0024>
- V.A.: Table of abbreviations employed in the references. *Annual Reports on the Progress of Chemistry* 34, 535–540 (1937) <https://doi.org/10.1039/ar9373400535>
- Wagner, E.: Über den Einfluß Des hydrostatischen Druckes auf die Stellung der Metalle in der thermoelektrischen Spannungsreihe. *Annalen der Physik* 27(15), 955–1001 (1908)

- Wien, W.: Eine neue beziehung der strahlung schwarzer Körper zum zweiten Hauptsatz der wärmetheorie. Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften zu Berlin, 55–61 (1893)
- Wiechert, E.: Über das Wesen der Elektrizität. Schriften der Physikalisch- konomischen Gesellschaft zu Königsberg in Pr. 38, 3–16 (1897)
- Wien, W.: Lois Théoriques du rayonnement. In: Rapports Présentés Au Congrès International de Physique Réuni à Paris en 1900, vol. 2, pp. 23–40. Gauthier-Villars, Paris (1900)
- Wilson, H.A.: A determination of the Charge on the Ions produced in Air by Röntgen Rays. Philosophical Magazine 5(57), 429–441 (1903)
- Wilson, C.T.R.: 1899-1902, p. 203. Longmans, Green, and Co., London (1910)
- Wheaton, B.R., Rider, R.E.: Inventory of Sources for History of Twentieth-century Physics: Report and Microfiche Index to 700,000 Letters. Verlag für Geschichte Naturwissenschaften und der Technik, Stuttgart (1993)
- Zeleny, J.: On the ratio of the velocity of the two Ions produced in gases by Röntgen radiation; and on some related phenomena. Philosophical Magazine 46(6), 120–154 (1898)