Experimental Laws and Measurements in Physics: The Legacy of 19th-Century Empiricism

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Abstract

In this study, I concentrate on the notion of experimental laws. As is well known, much of the physics of the late 19th century based its knowledge in experiments, through the use of precision measurements. First, I give a short and streamlined historical narrative of this era of physics and argue that the legacy of 19th- century empiricism is still with us. Second, I interpret and analyse the historical narrative from the point of view of empiricist philosophy of science. Third and finally, I suggest that the picture thus obtained makes the measurements more intelligible for the progress of physics than most of the 20th-century philosophy of science. The conclusion is that in speaking about physics, as well as in teaching physics, we still have all reasons to continue referring to experimental laws, and we have good reasons to believe that precision measurements are valuable in forming new knowledge.

Key words: Experimental laws; precision measurements; empiricism.

Introduction

In physics, in its history and in its contemporary practices, finding and discovering physical laws is apparently considered to be one of its most precious goals. However, looking back to ways in which physicists refer to these laws, it is very difficult to form a concise picture what they actually are. In most cases, what seems to be implied comes close to Richard Feynman's (1918-1988) notions about a certain “rhythm and a pattern between the phenomena of nature”, which is revealed by mathematical analysis, and when revealed these rhythms and patterns are which we call physical laws.[1] Feynman's conception of laws is clarified by his remark that:

> there are a large number of complicated and detailed laws…but across the variety of these detailed laws there sweep great general principles …of conservation, certain qualities of symmetry, the general form of quantum mechanical principles, and…the fact that all the laws are mathematical.[2]

In similar tone, Steven Weinberg characterizes physical laws using such notions as “necessity built in nature itself”, “discovery of explanations built into the logical structure of nature” and “laws that would precisely regulate the all nature”.[3] Surely, discovering these kinds of universal, fundamental laws is the driving motive behind doing physics. However, this dignified view of laws becomes confusing, when one turns to textbooks of physics, which soon reveal the fact that most “laws” they discuss, certainly do not belong to this category of fundamental or universal laws. Instead, physics textbooks display a succession of different, lower level laws; Newton’s laws, Boyle’s law, Ideal Gas Law, Ohm’s law, Kirchhoff’s laws Biot’s law, Ampère’s law, Faraday’s and Henry’s law, Stefan and Boltzmann law and Wien’s law, and many others. Most of them are what can be called idealizations based on empirical regularities. However, even a short glance at contemporary published research reports shows that many formulas or mathematical expressions describing the experimentally found regularities are indeed displayed, but only seldom or hardly ever called "laws". This notion, at least partly, has led some philosophers, paying attention to the practice of science, to the conclusion that physics (and more broadly all science) can do, and actually does, quite well without laws.[4]

Perhaps, then, turning to the more recent philosophers' account of laws can help us to form a better picture of what laws actually are. However, although much is written about "laws" in the philosophical literature, it is discouraging to find, as John Earman has recently noted:

> It is hard to imagine how there could be more disagreement about the fundamentals of the concept of laws of nature – or any other concept so basic to the philosophy of science – than currently exists in philosophy.[5]

As Earman points out, in the philosophical literature there is rather disarray than a disagreement on views. Opinions range from "science without laws" views to the conceptions of laws as universal necessities. Moreover, as Earman notes, the philosophical discussion of laws seems disconnected from the practice and substance of science. Indeed, even the accounts like Marc Lange's claiming to have such connection [6] to "practice of science" seem to be quite far from the conceptions which practising scientists exemplify in their works. In the face of such a murky situation, it would be tempting to put the question of laws aside altogether and to speak perhaps only about models, principles and hypothesis, as e.g. Ronald Giere has suggested. However, Giere is not opposed to laws as generalizations; rather, he objects to laws as universal generalizations, and he challenges the view that science requires laws that have the form of universal generalizations. [7]

It is suggested here that in these muddled waters of laws, a lacuna of clarity can be found in the case of experimental laws. These kinds of laws are first and foremost reliable regularities found in controlled experiments and which can be expressed as mathematical relations. In what follows, the view to be discussed further is the form of laws as generalisation based on experimentally found regularities, but always taken as provisional generalisation. The conception of laws as fundamental principles or universal generalisations, e.g. necessitated by logical structure of nature is set aside here.[8] The restricted conception of law as an empirical regularity is well developed in the empiricist philosophy of the late nineteenth century, in particular by Ernst Mach (1838-1916) and Pierre Duhem (1861-1916). Especially Duhem's views and insights in putting emphasis on methodological aspects of experimentation come close to the themes discussed here. Also more recent philosophical accounts recognize the value of such empirical laws. For example, Nancy Cartwright, who refers to this type of law as "phenomenological laws", notes, that phenomenological laws do not lie, because they are true in their domain by the nature of their construction.[9] These kinds of laws are seen foremost as empirical regularities, and which are common to all true theories. Consequently, as will be argued here, the empiricist conception of experimental laws – although it is old – is not outdated.

Historically, the conception of experimental laws was closely connected to the role of measurements. As is well known, much of the physics of the late 19th century wished to base its knowledge in experiments, through the use of precision measurements. The aim of experimental work was to establish accurate and objective statements in the form of experimental laws, with the counterpart of abstracted and generalized theoretical statements and laws forming the core of the theory. This empiricist ideal is exemplified in works of such experimentalists as Georg Ohm (1787-1854), Victor Regnault (1810-1878), and Rudolf Kohlrausch (1840-1910). An interesting case of the empiricist physics representing this period and its aspirations in subtle form is provided by Hermann von Helmholtz (1821-1894) and his empiricism. To this era of experimental physics, we owe the conception of experimental laws, which connects them to the methodology of doing measurements. From the late 19th century onwards, the methodologically well-defined empiricist approach matured, leading to intricate intertwining of theory and experiment. Within this tradition, such remarkable physicists as Albert Michelson (1852-1931), Heike Kamerlingh Onnes (1853-1926), Philipp Lenard (1862-1947), Robert A. Millikan (1868-1953) and Johannes Stark (1874-1957) demonstrated the power of precision measurements in producing new knowledge. A similar emphasis on precision measurements is found also in works by Owen Richardson (1879-1959), Percy Bridgman (1882-1961), and Polykarp Kusch (1911-1993). The precision experiments as a source of knowledge and in supporting the theorizing was also highly respected by the established physics society, and is exemplified well by the Nobel committee and its decisions the in first half of the 20th century.[10]. The idea of precise measurements and quantitative experiments in producing knowledge – rather than being an outdated view – is a reflection of the continuity of methodology. In physics, there is an ongoing growth of knowledge and a continuous expansion of the region of its applicability. Following Ian Hacking we can note that old methodologies are not always abandoned or changed to new ones, but are quite often incorporated as part of improved new ones.[11] Therefore, we should not expect that old methodologies simply disappear, and in closer scrutiny, we can recognise the legacy of the empiricism of late 19th-century physics in our more modern practices. Owing to this methodological continuity, it is important to understand how the empiricist tradition of experimental physics developed, how it affected the developing methodologies, and how it was itself affected by the developments of new possibilities of instrumentation and improved accuracy of instruments.

In this study I have three goals. First, I give a short (and streamlined) historical narrative of experimental laws and measurements of the century spanning roughly from 1830 up to 1930, and argue on that basis that the legacy of 19th-century empiricism is still with us; physicists still produce knowledge based on experiments, however, they just do not call it "experimental laws". In production of such laws, precision measurements play a central role. Second, I interpret the historical narrative of experimental laws and the role of measurements in producing them from the point of view of empiricist philosophy of science, and thus attempt to demonstrate its relevance in clarifying the relation between experimental laws and measurements. Third and finally, the purpose of the study is to give perspective on speaking about the nature of knowledge in physics and how it is addressed in the teaching of physics. Addressing these matters, we need to make a distinction between several types of knowledge structures (theories, laws and models), and this goal is greatly facilitated if a clear conception of experimental laws as empirically reliable regularities is maintained.

Neglect of measurements in philosophy of science

The question regarding experimental laws is connected to the role of experiments and measurements in physics. However, in most of 20th-century philosophy, experiments and in particular measurements have received very little attention.[12] Not before the last two decades has the philosophy of experiments received renewed interest,[13] and now there are studies addressing the several aspects related to practices of experimentation,[14] instrumentation,[15] experimental reasoning and discovery,[16] and experiments' role in construction of concepts. [17]

The lack of interest in measurements, which is so endemic in 20th-century philosophy, is well exemplified by Thomas Kuhn's account. Kuhn discusses the normal measurement in physics and argues that:

> Only a minuscule fraction of even the best and most creative measurements undertaken by natural scientists are motivated by a desire to discover new quantitative regularities or to confirm old ones. [18]

According to his view, most measurements are carried out to gather "factual information" or to "determine parameters" appearing in scientific theories. Kuhn also mentions that as far as physicists' experimental work is quantitative, its objective is to improve the agreement with theory and set new standards for the good agreement, but that these attempts cannot be described as attempts of discovery or confirmation.[19] For Kuhn, the possibility of starting from measurements and ending up at quantitative regularities in the form of experimental laws is a rarity (the possible exceptions he mentions are Boyle's law, Hooke's law and Joule's law). Instead, he maintains that nearly always some qualitative preconception of the regularity to be established in measurements is needed. In that it is easy to agree with Kuhn, holding a different view seems very difficult, given the historical records of physics. As Kuhn argues:

> *The road from scientific law to scientific measurement can rarely be travelled in the reverse direction.* To discover quantitative regularity one must normally know what regularity one is seeking and one's instruments must be designed accordingly; even then nature may not yield consistent or generalizable results without struggle.[20]

Therefore, the stage of quantitative experiments can come only in a late stage of development of a theory, when a considerable body of knowledge –qualitative as well as quantitative – has already been accumulated. On the basis of these notions, Kuhn asks why the quantitative methods and precision measurements are then so central in physics, and goes on to answer that they are “refined professional criteria for problem selection” and have “increased the effectiveness of professional verification procedures”. [21]

Although we may agree with most of Kuhn’s analysis of measurements and their relation to theory, his conclusions about the uses of precision measurements downplays the epistemological value of such measurements in theory construction. This view not only contradicts the views of the 19th-century physicists, but it also oversimplifies the experiment-to-theory relationship in general. Such conceptions of measurements pay astonishingly little attention to the question of why physics then makes progress mostly in the areas where such “professional verification methods” are successful and can be carried out. What Kuhn seems to miss in his analysis is the way in which the theory constantly becomes both constructed and re-constructed to fit the results of experiments.

More recently, Ian Hacking has discussed the role of measurements along the lines suggested by Kuhn.[22] Also Hacking sees the main virtue of normal measurement as a form of professional verification procedure. The problem with Kuhn’s and Hacking’s views seems to be that they do not make it definite as to what “professional verification procedure” means to them. Taken in Kuhn’s sense as a means of persuasion, or as a means of convincing peers, where an accurate method serves the role of conferring credibility, but not knowledge, it downplays the epistemological role of measurement in physics and is clearly in disagreement with views of most experimental physicists. If, on the other hand, we may understand it as a process of assuring the tentative knowledge, making it gradually more reliable and credible through cycles of more and more precise experiments, the situation is different. This view comes then close to what Hasok Chang has recently discussed as a form of "epistemic iteration" and which he sees as a form of knowledge production.[23] According to Chang, new knowledge becomes moulded in a process of "epistemic iteration", in which successive stages of knowledge build on previous ones and enhance and reinforce the existing knowledge, but which also produces new knowledge, not contained in the previous steps or not deductively derived from it. As he notes, "the whole chain exhibits innovative progress within continuous tradition".[24] Chang has discussed this picture of enriched knowledge formation in the case of the temperature concept, and shows how inventions in measurement techniques and new methodologies have been crucial in advancing the construction of the temperature concept. In this case, the main "epistemic virtue" to be enhanced was precision. In Chang's account, the increasing precision – in clear contrast to Kuhn's view – is of central epistemological importance; precision enables the progress through "enrichment". In enrichment, the initial system of knowledge is refined through self-correction, and in this process, the "system is actually altered in its content as a result of inquiry based on itself".[25] This picture fits in much better to the history of physics in the late 19th century and is quite relevant also in understanding the role of measurements in experimental physics of the 20th century, because it acknowledges the importance of precision measurements in advancing theory construction.

The account given by Chang therefore fits much better in describing the role of measurements in physics and does not deprive it of meaning as Kuhn's account does. When Kuhn's views are applied to such experimental research as reported by, for instance, such well-known Nobel-laureate experimentalist as Millikan, Kamerlingh Onnes, Richardson and Bridgman, where precision measurement have served a central role, it is obvious that they do not easily fit the categories Kuhn disposes. If forced on the categories suggested by Kuhn (or Hacking, as well), it is evident that the resulting interpretation is diametrical to the interpretation of the scientists themselves, indeed, as exemplified in their Nobel-lectures. From the point of view that philosophical interpretations of science should be recognisable to scientist themselves, this is clearly an unsatisfactory situation. On the other hand, the role of such measurements becomes well understood from the point of view Chang has suggested. Consequently, the importance of precision measurements is in their ability to gradually refine and correct existing knowledge, thus making the target knowledge more reliable.

Following these notions, I take as my starting point the notion of law either as empirical regularity or its generalisation. For many this may be an unwarranted restriction, but nevertheless, it has the advantage of being an epistemologically clear notion of "law" and making a methodologically sound contact with measurements. Moreover, as I will argue, it is the conception of experimental laws which is clearly visible in the physics encompassing the late 19th and early 20th centuries.

Experiments for production of knowledge

The idea that empirical laws can be obtained through observations can be ascribed in its mature form to Francis Bacon's (1561-1626) conception of science.[26] According to Bacon, knowledge was obtained directly from experiences, observations and experiments. Through inductive generalizations it became possible to deduce law-like representations, which embraced the regularities and general recurring features thus found; theory was conceived as a copy of relations found in nature. Bacon's method can thus be described as a seminal empiricist programme. Later, Isaac Newton's (1643-1727) inductive method clearly shares much with Bacon's empiricism, but in comparison it is more sophisticated and more mathematically oriented. Newton was probably the first scientist who detailed his method and could ascribe a spectacular scientific success owing to the use of the invented new method.[27] There is a vast literature about the "Newtonian method" and conclusions drawn about its characteristic features differ.[28] What seems to be agreed upon, however, is that Newton separated the mathematical descriptions from the invention of physical explanations. For Newton, the mathematical descriptions were inductive generalisations on the basis of observations, tested against observed facts through "crucial experiments".[29] Even if it can be disputed that this actually was the method Newton himself followed,[30] it was nevertheless the way the following generations understood his method and how they tried to apply it.[31]

Early empiricism and the inductive conception of science

Newton's conception of the scientific method was much transformed in the late 18th century. Ultimately the part relating to experiments and observations received a form of strict experimental approach, where experimental results were not used to hypothesise but instead were taken in a phenomenalistic way. However, the didactic value of experimental proofs in the form of crucial experiments was adopted and much used in late 18th-century research on electricity.[32] In this case, experiments provided connections between different phenomena and demonstrated the similarity of phenomena observed in a laboratory with the phenomena in nature; they served demonstrative and illustrative purposes. This seems to have been the dominant form of experimental physics in Germany even as late as 1830. According to Christa Jungnickel and Russel McCormmach, the German experimental physics in the first half of the 19th century aimed at finding new phenomena and examining the connection between different phenomena, with the purpose to find empirical laws governing those phenomena. It was thought that such knowledge, to be reached through generalizations and inductions, would give a secure basis for physics.[33]

In Germany the inductivistic side of Newton's method was emphasised, while the other part of his method, the manner of theorizing and producing the mathematical formulation of theory, was revived in 18th-century France in the "Neo-Newtonian" school of physics.[34] The best-known representatives of this Neo-Newtonian physics are Pierre-Simon Laplace (1749-1827) and Siméon-Dennis Poisson (1781-1840) and their works on mechanics, hydrodynamics and elasticity theory. However, it appears that not before André Marie Ampère's (1775-1836) work on electrodynamics was there a serious attempt to build theory on the truly inductive use of experiments.[35] Ampère liked to present his results as straightforward inductive generalizations of experimental truths, clearly expressed in his remark:

> I have solely consulted experiment to establish the laws of these phenomena, and I have deduced the only formula that can represent the forces to which they are due.[36]

The later analysis of Ampère's work have shown that for the most part Ampère's experiments were actually planned according to preconceived theoretical ideas and that only the very first experiments which he conducted had the role of a starting point for his theoretical views is mostly Ampère's experiments played little role in the development of his theory.[37]

Nevertheless, the inductive use of experiments as a basis of generalized laws remained an ideal of science in Ampère's time and afterward, and as such it is clearly reflected in many philosophical writings from the 18th century to the 19th century. For example, influential British philosopher William Whewell (1794-1866) gave an account of scientific method, which outlines the inductive generalizations as the main method of producing knowledge – as a method of discovery.[38] In Whewell's picture of physics, the experimental law is the basic element of knowledge, on which all subsequent theory construction is established. The justification of hypothesis produced through induction is seen to take place essentially through confirmation of predictions based on these hypotheses. Therefore, Whewell takes into account the inductive path leading to discovery, as well as the deductive path leading to justification. Nevertheless, the inductive part is similar to Ampère's views, and to views which persisted even in the end of the 19th century. For example, as late as 1904 Gustave Robin notes that physical laws are:

> only a combination of simple inductions suggested by experience. As to these inductions, we shall formulate them always in propositions easy to retain and susceptible to direct verification, never losing sight of the fact that a hypothesis cannot be verified by its consequences.[39]

For Robin, such laws resulting from such inductions are not interpretations but rather just the essential result based on a large number of experiments.

The inductive view of science, outlined by Ampère and later discussed in philosophy of science by Whewell, was in the 18th century and the early 19th century an ideal model of science. This picture of science put stringent demands on the accuracy of experiments and measurements; without accurate experimental data, the whole process of generalizations would rest on unconfirmed foundations. Curiously, however, the completion of this programme imagined already in the late 18th century and the early 19th century was not possible to realize at that time. A major reason for this was the lack of suitable experimental resources. It was only somewhat later, when a change in the methodology of physics itself took place gradually and a methodology of "precision measurements" or quantitatively accurate measurements became gradually available. With the advent of the new methodologies, the old inductive conceptions of physics began to transform more sophisticated empiricist views, in turn deeply rooted in the methodology of measurements itself.

Precision measurements and methodological empiricism

The perfection of the methodology of physical measurements took place rapidly between 1820 and 1840, on the French-speaking continent by researchers like Auguste de la Rive (1801-1873) and Victor Regnault (1810-1878), and in German-speaking research culture by Karl Friedrich Gauss (1777-1855), Johann Christian Poggendorf (1796-1877), Gustav Fechner (1801-1887), Georg Simon Ohm (1789-1854) and Gustav Magnus (1802-1870). In Britain, William Thomson (1824-1907) in his early career followed the same path, having acquired the basic skills and methods of precision measurements from Regnault.[40]

In many respects, Victor Regnault is a good example of the new tradition of precision measurements. The aim of these precision measurements was to produce accurate data as a basis for empirical generalization, thus attempting to solve many problems related with theorizing. The hallmark of this precision science was the complicated and scientifically planned instrumentation and meticulous data collection. The strikingly improved accuracy of this new method of experimentation apparently seemed to provide ways to accomplish the inductivistic ideal of science, freeing it from theorizing.[41] Regnault's goal was not only to make the measurements controllable, correctable and analysable, but to design basic measurements methods which would not need any theoretical interpretation at all. Although this proved to be impossible, it boosted the search for ever more accurate methods and better representations of measurement data.

Regnault's methods were rapidly accepted as superior to any previously existing approaches to experimentation and young researchers around the world gathered to learn his methods, [42] among them William Thomson.[43] In Thomson' s experimental approach one finds the method of quantitative measurements incorporated in a masterful manner with that of Neo-Newtonian theorizing and development of theory. Thomson saw that the goal of experimental physics is the "systematic observations and experiments which have for their object the establishment of laws and formation of theories".[44] The aim of experiments was thus conceived to be that of the discovery and perfection of the laws of nature, inductively. Completion of this ideal successfully required that experiments were thoroughly controllable, amenable to detailed theoretical analysis, which eventually made it possible to "break down the complex systems of nature into controllable and predictable relations".[45] This attitude was also clearly reflected in Thomson's style of teaching and, according to Crosbie Smith and Norton Wise, it was also reflected in the education of physics and in Britain meant a major shift in the educational purposes of experiments from popular illustrations to detailed demonstrations and laboratory works based on precision measurement in a research laboratory.[46]

A similar development took place in Germany as well, where during 1830-1840 a new style of theoretical analysis of instruments and experimental devices gradually emerged. In Germany there existed a strong tradition of experimental research concentrating on phenomena and their relationships, a kind of inductive practice inclined toward phenomenalism. It became customary to design experimental apparatus on a theoretical basis and also to analyse the measurements theoretically. Experimental apparatus and measuring devices also thus became a part of examination of natural phenomena.[47] A good example of this tradition of doing physics is Georg Simon Ohm's work. For Ohm the fundamental value of experimental research derived from its capability to result in empirical laws. He was reserved towards theorizing and noted that the mathematical theory was not always an advantage; he valued more "the discovery of new phenomena and the empirical determination of their laws”.[48] This was a common attitude of most experimental physicists in the middle of the 19th century in Germany, but this does not mean they overlooked the value of theoretical analysis for purposes of experimentation. For example, according to Johann Christian Poggendorf, one of the champions of German empiricism, the advantage lay with the theory that was then developed regarding “measure and number, the true foundation of exact scientific research”.[49] It was this type of theory usage that German physicists were then making their specialty, and Poggendorf may represent here all those German experimentalists, who were involved with tasks to produce through “measure and number” the new foundations they thought physics demanded.

Experimentation in German physics developed therefore in the direction, whereby theory formation and experimentation began to be intertwined in a sophisticated, bi-directional manner. Researchers developed measuring instruments which were novel in their time and which allowed for measurements with unsurpassed accuracy, also allowing for the exploration of already known phenomena in more detail in a methodical way. For this new style of physics research, the name methodological empiricism as suggested by Edward Jurkowitz seems appropriate.[50] On closer inspection it is unmistakable, that when these “methodological empiricists” developed the theory for the interpretation of their measuring devices it, in effect, altered their theoretical views and the manner in which to conceptualise the phenomena they were dealing with.

Experimental laws and theory construction

Methodological empiricism found its most fruitful form in the experimental physics of Hermann von Helmholtz (1821-1894) and Heinrich Hertz (1857-1894), which not only had an empirical character, but also a curious feature of realism blended in with it. This tradition of doing experimental physics and its relation to theory construction is of importance, because clear traces of its views on the experiment-to-theory relationship as well as on the role of precision measurements can be detected in experimental works of the researchers of the many 20th-century physicists. Another reason to pay attention to Helmholtz's and Hertz's work is that many philosophical views on physics are related to the conceptions of knowledge connected to late 19th-century empiricism.

Helmholtz's "methodological empiricism"

Hermann von Helmholtz strove for a coherent, objective picture of natural phenomena based on empiricism and the inductive method. According to Helmholtz's view, the formation of knowledge started by initial steps of fact collecting, subsequent organization of facts into more encompassing ones and construction of restricted laws. It then continued with hierarchical organization of knowledge and inductive inferences towards more general laws and concepts. The existing theory was thus enlarged and extended so that it made possible the making of inferences and predictions in new areas of phenomena, not initially contained in the range of validity of the theory. The inductive inferences forming the core of the theory would always be checked against experience; in that way, induced laws would make up the justified substance of scientific knowledge.[51] However, for Helmholtz, the organization of facts or their mere classification was not enough for the basis of true science, and he made a remark that "individually observed facts and experiments" have no value; "they only attain value, theoretically as well as practically, in that they allow us to recognize a law in a series of similar recurring phenomena".[52] For Helmholtz, conceptual understanding of phenomena meant finding the law of the phenomena, where the law was understood as the general rule summarising the properties and characteristic features of a series of similar recurring phenomena. Helmholtz's ideal of science was a kind of unification of scientific method towards objective knowledge, which was made possible through methodological empiricism. Although Helmholtz's stance was basically empiricist and phenomenological, it also was firmly rooted in realism and had a strong flavour of reductionism built into it. Quite often in his writings, Helmholtz pictured an empirical route to the discovery of microscopic forces through inductive inferences.[53]

The mixture of a phenomenalistic conception of science, methodological empiricism and use of organizing physical principles in theory construction is seen also in the works of Heinrich Hertz. From Helmholtz, Hertz inherited the physics of principles and style of experimentation based on imaginative design and transformation of devices, with purpose to "purify and amplify the effects, analyse their causes, and put them to new service" without letting his theoretical preferences to infect his results.[54] Also Hertz's conception of knowledge greatly resembles that of Helmholtz, but it is characterised more by systematic epistemology, clearly articulated in Hertz's theoretical works on mechanics[55] and electrodynamics.[56] As Olivier Darrigol has discussed, in Hertz's systematic exposition of Maxwell's theory, Hertz does not deduce the system of propositions (Maxwell's equations) forming the basis of theory by *a priori* means, nor does he make any attempt tofound them separately on experiments. Instead, Hertz noted (in complete agreement with Duhem's interpretation and views) that separate equations cannot be justified by experiment, but only the system of equations as a whole.[57] This view is in complete agreement with Pierre Duhem's well-known thesis that only a theoretical system as a whole can be tested, not its parts in isolation.[58] Moreover, the theoretical system of electrodynamics included concepts (charge and current) which were not empirically founded in that form in which they appeared in theory, and Hertz took these concepts as mere expressions or names, whose purpose was only “to permit more concise expressions and partly to permit connections with the older views of electricity”.[59] In his theorizing, Hertz clearly paid most attention to formal and logical completeness and for him the empirical correctness (or empirical adequacy in more recent terms of empiricist philosophy) of theory was enough.

In the case of Hertz, however, the empiricist views are combined with the view that theories represent the world in a way which goes beyond the immediate observation and their descriptions. For Hertz, the instrumental use of theory was essential, and he thought that the purpose of theory is to encompass the phenomenological content of the theoretical laws, but it need not be addressed to the causes behind the phenomena. As Heidelberger has discussed, Hertz thought that physical representations of the theory are necessary, but they can be developed safely only after the descriptive theory was established. The representations thus presuppose a complete mathematical description of experimental results on the phenomenological level.[60]

Pierre Duhem on laws and measurement

Pierre Duhem (1861-1916), a physicists and a philosopher, has given a rich account of the structure of physics and of the role of experiments and measurements in the formation of knowledge in physics, and which in this respect fits well to the picture given by Helmholtz and Hertz. In order to understand Duhem’s views on experimental laws and measurements, one needs to understand his views of the theory and experiments in general. For Duhem, physical theory, rather than an explanation, is:

> a system of mathematical propositions, deduced from a small number of principles, which aim to represent as simply, as completely, and as exactly as possible a set of experimental laws.[61]

He notes that theory is, however, more than just a representation of experimental laws; it is also a "natural classification" of these laws. Accordingly:

> the more complete it becomes, the more we apprehend that the logical order which theory orders experimental laws is the reflection of an ontological order, the more we suspect that the relations it establishes among data of observation corresponds to real relations among things and the more we feel that theory tends to be a natural classification.[62]

Duhem represents the theory as the classification of facts through their "family ties" so that it reflects the ontological order found in nature. Also the order and hierarchy among the classified and ordered experimental laws reflects the order and hierarchy found in regularities in phenomena. When the process of classification and ordering has been accomplished and "a considerable group of experimental laws" has been established, theory condenses the laws into a small number of fundamental principles.

Experimental laws have therefore a central position in Duhem's picture of physics, but the very notion of experimental law is connected in a subtle way to his overall view on theory, as well as his conception of experimental method. First, for Duhem the laws of physics are always symbolic relations and abstractions. Second, laws of physics are neither true nor false but approximate. He notes:

> physical theories are only a means of classifying and bringing together the approximate laws to which experiments are subject; theories, therefore, cannot modify the nature of these experimental laws and cannot confer absolute truth on them.[63]

From this notion it follows that such laws are always provisional and there is always the possibility that further improvements in precision of measurements will improve the accuracy of the laws. This, on the other hand, is connected to the fact that for Duhem laws are symbolic expressions of correlations found in experiments:

> Scientific laws based on the experiments of physics are symbolic relations … Since they are symbolic, they are never true or false; like the experiments on which they rest, they are approximate.[64]

It is interesting to note, that it is just this notion of laws and their specific relation to experiments which is behind Duhem's well known thesis of "underdetermination" which states that it is not possible to test an isolated hypothesis, instead, in testing of hypothesis a whole group of hypotheses is involved.[65]

In Duhem's picture of science the theoretical and empirical are inherently intertwined, even to the extent that the use of instruments itself becomes possible only through the theoretical interpretation of the phenomena upon which their operation is based.[66] For Duhem, the interpretation of experimental results as well as the measurement itself is thus of central importance. For that purpose, Duhem introduces a sequence of "translations" which transforms experimental results in form, which can then be annexed to theory. Karen Merikangas Darling has described Duhem's picture of the experiment-to-theory relationship consisting of the following sequence of translations[67]: (i) the concrete experimental situation into theoretically useful experimental parameters; (ii) the theoretical predictions into expected observations (i.e. practically stated predictions); and (iii) the practically stated results into symbolic constructions which condense the result of the experiment and, lastly, they are used to give meaning to the theoretical terms which were used. The essence of Duhem's viewpoint is that instruments are indispensable to every step outlined above, and that their use requires a number of theoretical propositions. Duhem thus puts much weight on the use of instruments, and their use serves an important role in narrowing the gap between actual measurements and the theoretical predictions; there is a mutual fitting of theoretical models to empirical results as well as models of empirical results to theoretical models. The process outlined by Duhem clearly leads to the generation of new knowledge and is an element (if not the only one) in theory formation. Methodologically, precision measurements are needed to accomplish the task and, therefore, in Duhem's picture of physics they serve an essential and crucial role in knowledge formation.

Experiments as continuation of theory

Many of Duhem's views and also those of the late 19th century of empiricism are reflected in more recent versions of empiricist philosophy, most notably in the constructive empiricism by Bas van Fraassen. Constructive empiricism is seen as an alternative for such realism which assumes that theories of physics (or more generally science) attempts in its theories to give "a literally true story of what the world is like".[68] Consequently, constructive empiricism is committed to resolving the question related to production of knowledge starting from experimentally accessible reality. According to this, measurable properties of phenomena provide the necessary hard core of physics knowledge. It is an approach organized from the "bottom up" instead of from the "top down", and therefore potentially capable of revealing where our knowledge comes from. As van Fraassen outlines:

> To present a theory is to specify a family of structures, its models; and secondly, to specify certain parts of those models (the empirical substructures) as candidates for the direct representation of observable phenomena.[69]

This conception of empirically adequate substructures is closely related to Duhem's "natural classification", which can also be seen as "empirically adequate" structure in its construction.

Bas van Fraassen's conception of the purpose of precision measurements and the design of such measurements parallels Duhem's views in many respects. According to Van Fraassen "the real importance of theory, to the working scientist, is that it is a factor in experimental design".[70] From this it follows that:

> the intimately intertwined development of theory and experimentation is intelligible from an empiricist point of view. For theory construction, experimentation has a twofold significance: testing for empirical adequacy of the theory as developed so far, and filling in the blanks, that is, guiding the continuation of the construction, or the completion, of the theory. [71]

This view matches well with Duhem's conception of the interplay between experiment and theory. Echoing Duhem's "experiment as interpretation of theory" van Fraassen concludes that the relation of experiments to theory is bi-directional, so that "theory is a factor in experimental design" and "experimentation is a factor in theory construction" and in this way, ”experimentation is the continuation of theory construction by other means".[72] The bi-directional view outlined by van Fraassen characterizes well the intertwined role of theory and experiment discernible in the practices of the late 19th century physics. In order to make the intertwining possible, precision measurements are needed, and the purpose of these precision measurements is to produce experimental laws which are closely related to the measurements themselves, but which are also close enough to the theory in order to be useful for theory construction.

The legacy of empiricism in the 20th-century physics

There remains a question as to whether or not empiricist views originating from the practices of the late 19th-century physics – and as they are summarised and condensed in the above outlined philosophical interpretations by Duhem and van Fraassen – can still be recognized in 20th century physics. The answer to this question hinges on the notion that methodologies tend to accumulate, and successful approaches become joined together. As Hacking has noted, there is not only growth and the accumulation of knowledge but also growth and the accumulation of methods.[73] The old methodologies do not vanish, but instead they are incorporated as part of a growing structure of a variety of methodologies.

The form of experimental research, developed in the late 19th century, was influential in structuring the experimental research of the 20th century, simply due to the fact that many of the experimentalists with in the turn-of-the- 20th-century empiricist views, like Philipp Lenard (1862-1947), Heike Kamerlingh Onnes (1853-1926) and Robert A. Millikan (1868-1953), were influential in affecting and outlining the research traditions of the upcoming generation of 20th-century physicists. This happened not only through their personal influence, but also through their laboratories, where many physicists were trained. Of course, all large experimental laboratories shared the emphasis on measurements and precision experiments, but perhaps the most well-known examples of the zeal to reach knowledge through measurements are Millikan's Ryerson Laboratory in Chicago and Kamerlingh Onnes's Laboratory in Leiden. Therefore, in order to understand the legacy of empiricism in 20th-century physics, Kamerlingh Onnes and Millikan are good cases to start with, because their example and their laboratories have provided much of the basic education for leading experimentalists and have taught physicists how and why experiments are done. Later, this experimental style blended with theoretical considerations but is still discernible. Based on that style, Owen Richardson's (1879-1959) work on thermionic emission is a further example and comes close to present day practices.

Heike Kamerlingh Onnes (1853–1926) established his reputation as an experimentalist in quantitative experiments of low temperature properties of matter, and became well known through his achievement of liquefaction of helium as well as his discovery of superconductivity of metallic conductors.[74] Kamerlingh Onnes's guiding philosophy was that through precise quantitative work new knowledge could be produced and new discoveries made. He made his views quite explicit in 1882 in his inaugural lecture (after being appointed Professor) "The Significance of Quantitative Investigations in Physics", where he stated that:

> the quantitative investigations, that is at establishing relations between measurements of phenomena, should take first place in the experimental practice of physics. By measurement to knowledge [door meten tot weten] I should like to write as the motto above the entrance to every physics laboratory.[75]

This emphasis on precision measurements and their purpose of producing quantitative knowledge also came to be the systematic research strategy of Kamerlingh Onnes's Leiden laboratory. As Kostas Gavroglu and Yorgos Goudaroulis have remarked, the "physics culture" in Leiden had a strong positivist flavour, where laws were not only tested but based on precision measurements, new empirical formulas were developed to better describe the recorded data obtained in such measurements.[76] Finally, through theoretical work, explanations could be constructed to explain these patterns.

The importance of precision measurement in providing new empirical formulas is well represented in Kamerlingh Onnes's experiments, where isotherms of helium were determined through precision measurements. On the basis of the quantitative data of low temperature properties of helium, it became possible to extrapolate the properties of helium to even lower temperatures. This, on the other hand, was needed to specify the properties required of the apparatus which ultimately allowed liquefying helium, i.e. producing a new phenomena. The data of thermodynamic properties of helium as well as of other gases and gas-mixtures was accurate enough to be represented in the form of functions, as graphs and also in a form of algebraic relations, i.e. as experimental laws. Such measurements and their products – contrary to Kuhn's view – were certainly more than just "routine fact collection", and neither was their purpose only to point out "deviations in theory" to improve some already existing theory. Rather, their purpose was to produce accurate relationships for the use of further theories and hypothesis, which these theories then should conform to by their construction. For all practical purposes, this can be seen as a production of new knowledge through precision measurements.

Another aspect of Kamerlingh Onnes's philosophy of research which is of interest here is his conception of the complementary role of theory and experiments. For him, as also for Helmholtz, theory and experiments were intertwined. This connection is actually well displayed in a passage from Kamerlingh Onnes's thesis, where he quotes Helmholtz (who, on the other hand, is referring to Gustav Magnus, one of leading experimentalists of 19th-century German physics):

> It seems to me that nowadays the conviction gains ground that in the present advanced stage of scientific investigation only that man can experiment with success that has a wide knowledge of theory and knows how to apply it: on the other hand, only that man can theorize with success who has a great experience in practical laboratory work. [77]

In that passage, the empiricist views which were to guide the work in Leiden in the beginning of the 20th century reach back to Helmholtz's convictions of the inseparability of theory and experiments. Of this stance, Kamerlingh Onnes's experiments with helium liquefaction again provide a good example. In that research, he used van der Waal's theory of gases as a guiding principle, and gradually, by finding new regularities that were related (semi-empirical laws), designed new apparatus to conform to discovered new phenomena, which again were used as a basis for new empirical laws. As Simón Reif-Acherman has discussed, the strength of Kamerlingh Onnes's work was that he conceived theory and experiments as being complementary (i.e. bi-directional) aspects of physical research and the production of knowledge.[78] Kamerlingh Onnes's contemporaries also valued this aspect of his work, as can be seen from the Nobel-committee presentation speech, where in several places the Kamerlingh Onnes's experimental work is not only discussed in the role of testing theory, but also seen as being of direct importance for theoretical developments.[79] These notions bring forward the bi-directional relation of theory to experimentation. Theory supports the design of experiments but, on the other hand, theory construction is based on experiments; experimentation is thus "continuation of theory construction".

Robert A. Millikan (1868-1953) provides us another example with which to examine the role of precision measurements in the production of new knowledge. Millikan is well known for his precision measurements which were taken as the conclusive experimental evidence for the elementary electric charge and also provided a well-defined value for that charge, as well as for his experiments on establishing the law of the photoelectric effect as a valid experimental law. In the case of the photoelectric effect, an interesting aspect of Millikan's work is clearly not refutation nor falsification of any specific theory, but testing the accuracy of quantitative relation suggested by theory, the “Einstein equation” as Millikan calls it.[80] From Millikan’s work, it is quite clear that the aim of the measurements Millikan carried out was to securely establish the form of the Einstein equation for the photoelectric effect, and to determine the natural constant *h* it involved. On the other hand, the theoretical interpretation of the equation was left open and discussed only in the concluding section of Millikan’s paper.[81] Reading Millikan’s discussion, it is quite clear that any role in confirmation, refutation or falsification does not fit into the picture. Rather, according to Millikan’s own interpretation, the results meant that:

> if that equation be of general validity, then it must certainly be regarded as one of the most fundamental and far reaching of the equations of physics; for it must govern the transformation of all short-wave-length electromagnetic energy into heat.[82]

Here the introduction of the “law” also meant a validation of the new principle governing energy exchange in the interaction of heat and radiation. In this case, Millikan’s work as “the continuation of theory by other means” is evident.

Another instance, where Millikan’s conception of “law” can be seen, is again in Millikan’s experiments on the elementary electric charge.[83] This work contains an interesting part, where the resistance of air on moving droplet is studied, and a phenomenological law for this resistance is determined experimentally. The law is meant to replace Stoke’s law for better accuracy, needed in the experiments to determine the value of the elementary electric charge. It is noteworthy, how central that experimental law was for the experiment as whole. Without it, Millikan would have been able to demonstrate the existence of the elementary charge, but unable to determine its value. The “General law of fall of a small spherical body through a gas” was also a topic of a separate research paper he published separately in 1923, and in that study he states as his purpose the "accurate experimental determination of this law", and notes in the end of the paper that he has "obtained the general formula for the complete law of fall of a spherical liquid drop through air".[84]

In both cases for Millikan the quantitative relation or formula based on the experiments, represented by experimental law, is in concordance with Duhem's conception of experimental law as a "symbolic representation and judgment of experimental results". In both cases, we can also see clear indications of "experiments as the continuation of theory". Of course, the role of the photoelectric law and the "law of fall of a small spherical body" have very different significance for theoretical progress, but with respect to method of performing the experiment, in all aspects of the validating of its reliability and also in the manner it produces the new knowledge they are similar. Moreover, both laws can be taken as locally valid "truths" of the correlations contained in experiments. Thus, being an "experimental law" should be understood as a statement concerning the methodology, not concerning the theoretical importance of such laws.

Owen W. Richardson's (1879-1959) work on thermionic emission provides another, and my final, example of the role of precision measurements in forming new knowledge, but now coming closer to present day practices. Richardson received the Nobel Prize in 1928 for his work on the thermionic emission and especially for the discovery of the laws which govern them. The phenomenon itself was known before Richardson's research, but it was unclear whether or not the emission phenomenon was of purely thermal origin. Richardson started his research by developing a theory, which connected the thermionic emission of electrons with the properties of free electrons in a metal. Already in the beginning, the experimental work was thus closely connected to the development of theory. The chairman of the Nobel Committee of 1928 for Physics, C.W. Oseen, summarized Richardson's work, whereby electrons at high temperatures were "emitted according to a fixed law. But a theory alone does not give any knowledge of reality. That can be obtained only by means of experimental research".[85] From Oseen's concluding remark that the "thermion-phenomenon with *fixed laws* was totally confirmed" by Richardson's work, it becomes clear that experiments were conceived in the role of confirming the theory.

Richardson's own account comes close to Oseen's interpretation.[86] Because the theoretical basis of the phenomenon was somewhat insecure, Richardson carried out several experiments which were aimed at settling the question about the correct form of the emission law. Richardson's approach was based on the idea to reduce the effects of surrounding gases and investigate the kind of regularity there was between the number of emitted electrons (maximum current) and temperature of the metallic surface. Based on his theoretical work and controlled precision measurements, Richardson suggested two different relations to describe the emission current, one in 1901 and a second one in 1911.[87] However, on the basis of experimental results it was impossible to distinguish between these two equations. In commenting upon the possibility to confirm his theoretical predictions, Richardson notes that: "It is, of course, very satisfactory to know that either formula will do this. There are not many physical laws which have been tested over so wide a range".[88] This notion in many ways is revealing; first, one can question what then actually was the role of experiments in "confirming the theory"; second, it clearly has a very pragmatic tone, even an instrumentalist attitude towards the "formula" or "law" describing the thermionic emission phenomena.

Richardson’s own account of his research as well as Oseen’s summary of it clearly bring forward the view that: experimental laws are quantitative regularities between measurable quantities; their production is inherently connected to precision measurements; and that such experimental laws are always provisional and correctable in their further development. All this agrees with the case of Kamerlingh Onnes and Millikan. However, now these methodological patterns are mixed with theorizing, and this very same pattern as exemplified in it is quite easily found in many contemporary experimental works in the field of condensed matter physics. The difference is that the regularities reported as products of these more recent researchers are no longer called “experimental laws”, instead, they are stated as being merely quantitative relations or “formulas” based on experiments; they are secularised experimental laws.

Philosophical rejoinders and conclusions

The historical narrative of experimental laws and precision measurements, as it is told here, attempts to show how the methodology of precision measurements accrued, first with a valued purpose of producing knowledge, then for a while with a promise to base all knowledge in experiments. With this history is paralleled the development of the idea of experimental law as an empirical regularity between measurable quantities, expressed as a mathematical relation. Although the contemporary practices of physics no longer attach special importance to its findings by using the term experimental law, nor see it as being possible to obtain such laws directly by the application of precision measurements, it does not necessarily mean that such knowledge structures have vanished altogether, or that the epistemological role of precision measurements have disappeared.

Now, if we see experimental laws as methodologically and correctly validated quantitative relations between measured quantities, we begin to recognize that in physics – even in the contemporary physics – there are plenty of knowledge structures which are well characterized as "experimental laws". It just happens that it is not customary anymore to call them experimental laws, but rather "results" or "formulas" which represent the data and demonstrate the correlation. In searching for traces of precision measurements of 20th-century physics in the role of forming new knowledge, attention must now be paid to the whole set of experiments, and not to single experiments only. In addition to this, the experimental details are of importance, with regard to notions about what has been required, in practice, to produce the reported results. It should not be expected that, if physicists are not using the term "experimental law" to characterize the end product of their experimental investigations, that this should be taken as sign of fundamental changes in the methodological approaches. Precision measurements, generating experimental laws in the way Duhem (and later van Fraassen) has described it, are perhaps no longer found as single, well-isolated projects, and neither are they reported any longer as single papers. Instead, such measurements are now in the background, forming the necessary empirical basis or support of theory construction and modification on the broader scale. Nevertheless, in many contemporary experiments, we can found parts which have the familiar characteristic aspects of precision measurements and their products – experimental laws.

Much of the recent 20th-century philosophy of science, like Kuhn's account, has overlooked the precision measurements and have assumed that they have no significant epistemological value, or value in the progress of science and in producing new knowledge. Consequently, it has also dismissed many important notions about products and processes of science, well captured by the older conceptions contained in the empiricist philosophy. The tendency to neglect the epistemological role of precision measurements has probably been enhanced by the circumstances that, in the practices of physics, the empiricist methodology and its products are now in the background and hardly visible except on the level of practical details for experimental research. Therefore, it is too easy to overlook the role of measurements and see them only in the role of boring and straightforward "measurements of constants" or just "collecting facts" which contribute little to the progress of science. But as I have tried to show here, this would be a mistake. Adopting that view would give a distorted picture of the work of scientists such as Kamerlingh Onnes, Millikan and Richardson, who all pursued new knowledge through precision measurements.

In order to get better views on the epistemological role of measurements in physics we can begin with the notion that the precision measurements provide us results as a kind of touchstone which, from the empirical point of view, are secure, or "empirically adequate" representations of experimentally found regularities which are called here "experimental laws". From the theoretical point of view, they are provisional, and their importance with respect to theory is always under revision. Still, theory must conform to them, and this guides but does not constrain the paths theory construction can take. The experiments and theory construction are thus intertwined, affecting and transforming each other; theory is part of experimental design, and experiments are a continuation of theory. The question concerning experiments' relation to theory construction and the role of measurements in it is first and foremost a methodological question, not only epistemological. For this, Duhem's views of the matchmaking between theory and experiments give valuable viewpoints; what is of importance is the mutual adjustment of the experimental data and the theoretical model or models it is designed to conform with. From a somewhat broader perspective, the emerging picture resembles views advanced by Chang, where progress in measuring methods and instrumentation is essential for theory construction and the progress of physics. Also in Chang's picture, the bi-directionality of experiments and theory, which takes the form of "epistemic iteration", is essential in leading to new knowledge or enhancement of existing knowledge.

The legacy of empiricism in 20th-century physics can best be seen in many contemporary "small scale experiments" in condensed matter physics. In these instances it seems quite possible to distinguish experimental styles intermixing to variable degrees with those aimed at simply confirming existing theoretical prediction, and those supporting the knowledge construction in a more constructive way. There are also other aspects, which need to be remembered in judging the generality of the views discussed here. In an attempt to describe how knowledge is produced, justified and established as socially agreed and shared "scientific knowledge" also social and sociological factors are important. The option that science in general, after all, is not following any specific plan or research program must be taken seriously, which means that in science, coherent epistemologies and methodologies can be distinguished only locally. On a global scale, the picture is much more obscure because the practices and goals and thus, epistemologies, of experimenters and theoreticians differ, and yet, on a global scale their joint effort amounts to science as it is known today. As Thomas Nickles has noted:

> historians, sociologists, and philosophers are becoming aware that experimenters and theoreticians in various mature sciences do not inhabit the same worlds of problems and resources and hence that no single methodological account of a science …can be adequate.[89]

The same general notion is made by Giere, who remarks that although experimentalists are involved in developing experiments that test theories and models proposed by theoreticians, this is often a process guided by the best use of cognitive and material resources for professional advantage rather than well-planned, long-term pursuit of some definite scientific program.[90] Although from the perspective of theory as a completed product of scientific endeavour, there is, on the other hand, agglomeration of different epistemologies, also intertwining experiments and theory as combined methodology, there is, from the other viewpoint, professional separation between experimental activity and theoretical activity. Therefore, it should be kept in mind that also the present views discussed here are necessarily only a detail in a much more complex fabric of physics and its practices.

In this study, I have suggested looking back to ideas and ideals of physics of the 19th century and to be prepared to take a look at current practices and methodologies in physics from this viewpoint. First, based on an analysis of works of such renowned experimentalists with practices not too far removed from present day ones, I have suggested that the legacy of empiricism of the 19th century is still with us; physicists still produce "experimental laws". Second, I have given a philosophical interpretation for that historical narrative. The viewpoint is based on Duhem's conception of experimental laws and measurements, and in parallel with more recent views by van Fraassen, so that the emerging picture emphasises the bi-directionality of this process. Third and finally, it is concluded that such a combined picture makes the measurements more intelligible for the progress of physics than the more well-known views of the 20th-century philosophy of science, which have tended to seriously underestimate the importance of measurements. The conclusion drawn on the basis of these notions is that in speaking about physics, as well as in teaching physics, we still have all reason to keep on referring to experimental laws; we also have good reason to believe that precision measurements are valuable in forming new knowledge.

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[80] Robert A. Millikan, "Einstein's Photoelectric Equation and Contact Electromotive Force", Physical Review 7 (1916), 18–32. For an overview and interpretation, see Robert A. Millikan, "The electron and the light-quant from the experimental point of view" (1924), in: Nobel Lectures, Physics 1922-1941, Elsevier Publishing Company, Amsterdam, 1965, 54-69. A more recent interpretation is given by Gerald Holton, "R. A. Millikan's Struggle with the Meaning of Planck's Constant", Physics in Perspective 1 (1999), 231-237.

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[82] Ibid., p. 383.

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[86] Owen W. Richardson "Thermionic phenomena and the laws which govern them" (1929), in Nobel Lectures, Physics 1922-1941 (Amsterdam: Elsevier Publishing Company, 1965), pp. 224-236.

[87] Owen W. Richardson, O. W.: 1921 Emission of electricity from hot bodies, 2nd ed. (New York, Longman, 1921), pp. 60-65; see also Richardson "Thermionic phenomena and the laws which govern them" (ref. 86), pp. 229-232.

[88] Richardson "Thermionic phenomena and the laws which govern them" (ref. 86), p. 230.

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