Did the great experimentalist doctor his own findings to suit his beliefs? Perhaps not, as a close look at his beliefs reveals.

Millikan's struggle with theory

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In 1916 Millikan published his experimental determination of the value of Planck's constant, with remarkable precision. It was later cited as part of his Nobel Prize award. But as a study of that paper together with Millikan's subsequent comments over the years reveal, he initially refused to accept the interpretation of the theoretical meaning of his work, as seen from the perspective of a present-day physicist. Yet, over time, Millikan adjusted his view retroactively to accept the meaning of what he had done – namely to provide crucial support for Einstein's heuristic point of view on the quantum theory of light (1905). This case also serves as a test whether scientists, as is now often alleged, as a rule arrange to obtain their results in the light of their own beliefs.

Robert A. Millikan's historic paper of 1916 in Physical Review on the measurement of Planck's constant (A Direct Photoelectric Determination of Planck's h; Physical Review [1]) lends itself to two different yet complementary readings—first through the eyes of a physicist of today, second by an historian of science, reconstructing the dramatic meaning the paper had in its own time.

To a physicist Millikan's paper is a patient and eloquent essay on how he came to the conclusion that has been in our physics textbooks ever since: While it had been known for a long time that light falling on metal surfaces may eject electrons from them (the photoelectric effect), Millikan was the first to determine with great accuracy that the maximum kinetic energy of the ejected electrons obeys an equation equivalent to the one Einstein had proposed in 1905, namely $^1/_2mv^2 = hv - P$, where h is Planck's constant, v the frequency of the incident light, and P "the work necessary to get the electron out of the metal" in Millikan's words. Moreover, Millikan determined h to have the value 6.57 x 10^{-27} erg-sec, "with a precision of about 0.5 per cent"—a value far better than had been obtained previously by any other experimenter.

Several factors were responsible for the success of the experiment, performed at the Ryerson Laboratory of the University of Chicago. First of all, Millikan's use of an ingenious device he termed "a machine shop in vacuo," assembled thanks to "the skill and experience of the mechanician, Mr. Julius Pearson". Essentially, the device allowed a rotating sharp knife, controlled from outside the evacuated glass container by electromagnetic means, to clean off the surface of the metal used (sodium, potassium, lithium) before exposing it to the beam of the fairly monochromatic light coming from a quartz-mercury lamp. Second, the frequencies of light Millikan used covered a much larger span, between 2399 Å, and 5461 Å, than had been achieved previously, permitting the relation of the kinetic energy of the electron and the frequency of light to be determined with a "maximum uncertainty" of 0.5%. In addition, the kinetic energies of the photoelectrons were found by measuring the potential energy Ve of the electric field needed to stop the electrons—and there Millikan was in the excellent position of being able to confidently use the value for the charge e of the electron he had published in 1913 with unprecedented accuracy, obtained with his oil drop experiment.

Last but not least, shining through it all were Millikan's typical characteristics as experimenter and person: His penchant for experimenting in an area involving the hottest question of the day – in this case the value of a fundamental constant of nature (as he had done in his 1913 paper) and, as we would now put it, the quantum theory of light; his energetic persistence – this paper was the culmination of work he had begun in 1905; his passion for obtaining results "with very great precision" (Fig. 1) – even at the cost of some practices that are perhaps questionable from our current perspective, for instance, his frank remark that to get the curves derived from his experimental results to intersect correctly at the ordinates, he decided "simply to cut the feet off" where those curves were trailing on too far.

In short, a triumphant work by a superbly confident scientist, of highest importance in its day, and richly deserving to be cited as part of his Nobel Prize award in 1923, "for his work on the elementary charge of electricity and the photoelectric effect". If historically minded scholars look through that 1916 volume of the Physical Review in which Millikan's paper appeared, they will notice that physics in America at that time was still a mixed bag. One finds in the volume a number of contributions by scientists such as A.H. Compton, P.W. Bridgman, Irving Langmuir, E.C. Kemble, among others (with A.A. Michelson listed on the Board of Editors). Their papers show that the main attention was the experimental part of science, in which Americans were regarded as most interested and competent. But the volume as a whole, published in monthly parts of some 200 pages each on average, indicates that a good deal of the work going on in physics in the US in the early years of this century was still narrow and unambitious, even tending to descend to lengthy descriptions of improvements in power supplies, pumps, galvanometers, and the like.

Next, on looking at the early pages in that same volume, and the segment published two months earlier in January 1916, we come upon another article by Millikan, on the same subject, in which the very first sentence announces Millikan's opinion that "Einstein's photoelectric equation... cannot in my judgment be looked upon at present as resting upon any sort of a satisfactory theoretical foundation," even though "it actually represents very accurately the behavior" of photoelectricity (p. 18).

Indeed, knowing this, and rereading Millikan's subsequent (March 1916) paper on Planck's constant, we see more clearly that he is emphatically distancing himself throughout from Einstein's attempt in

1905 of what Millikan calls a "coupling of photo effects ... with any form of quantum theory" (p. 355). What we now refer to as the photon was, in Millikan's view, a "bold, not to say reckless, hypothesis" – reckless both because it was contrary to such classical concepts as light being a wave propagation phenomenon, and because of the "facts of interference" (p. 355). In the background we glimpse the presence of Michelson, the "Artist of Light," who was Millikan's admired patron and colleague at the Ryerson Laboratory, the 1907 Nobelist, famous for his interferometers, the work carried out with their aid – and for his adherence to ether physics until his death in 1931.

So Millikan's paper is not at all, as we might now naturally consider it to be, an experimental proof of the quantum theory of light. Although Millikan admits that the facts seem "to demand some modification of classical theory," (p. 355) that is not what he is willing to attempt here. And in truth, Einstein himself, from the beginning, was not comfortable with the quantum theory of light, calling it, in a letter of May 1905 to his friend Conrad Habicht, "very revolutionary." It was the only time he so characterized any of his work, using the phrase because his was still only a "heuristic" proposal, devoid of sufficient theoretical grounding.

As it happened, Millikan was in Europe in 1912 for six months, primarily to meet the foremost physicists, and particularly to attend in Berlin Planck's lectures on his theory of heat radiation. He also took the opportunity in June 1912 to lecture on the results of his oil drop experiment before the Deutsche Physikalische Gesellschaft. Planck was delighted with this relative newcomer who was bringing the best available value for the charge of the electron at the time, which fitted well with Planck's own deduction of e from his formula for radiation. Two of the most important universal constants, h and e, were finding common ground through this personal encounter.

On returning to the United States, Millikan gave a lecture in December 1912 at the Cleveland joint meeting of the American Association for the Advancement of Science and the American Physical Society, in which he clearly regarded himself as the proper presenter of Planck's theory of radiation. Millikan compared the various forms of quantum theory then being discussed, siding with the "least concentrated," namely that of Planck, as against "the most concentrated," that of Einstein, which he called "radical" because it could not be reconciled with "the facts of diffraction and interference, so completely in harmony in every particular with the old theory of ether waves." Indeed, he confessed a corpuscular theory of light was for him "quite unthinkable". In short, Millikan's classic 1916 paper was purely intended to be the verification of Einstein's equation for the photoelectric effect and the determination of h, without accepting any of the "radical" implications which to us now seem so natural.

Recently opened records of the Nobel Prize Foundation show that from 1916 on, Millikan was nominated constantly. When the award at last came to be in 1923, his Nobel address of May 23, 1924, contained passages that showed his continuing struggle with the meaning of his own achievement: "After ten years of testing and changing and learning and sometimes blundering ... this work resulted, contrary to my own expectation, in the first direct experimental proof ...of the exact validity,

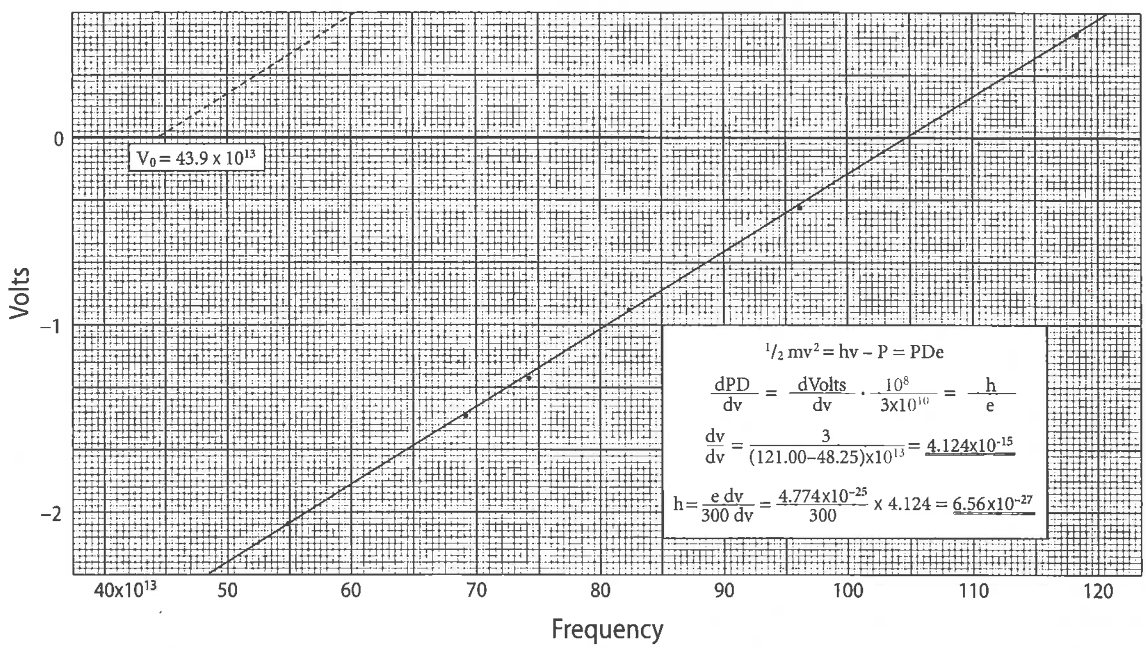

Fig 1 Taken from p. 373 of Millikan's 1916 article, Ref. 1, it is the key figure in that paper. It shows how he calculated h from the slope of the graph plotting the observed stopping potentials versus the light frequencies. As in a similar crucial figure in his 1913 paper on finding the value of e, one notices how small the deviations of the readings are from the straight line – and how casual Millikan was about giving the units of calculated values (then still a practice among many physicists).

within narrow limits of experimental error, of the Einstein equation and the first direct photo-electric determination of Planck's h." In fact it is difficult to find any published basis in Millikan's experimental papers of that struggle with his own expectations. His internal conflict was of a somewhat different sort, as can be read in a later passage of that same speech: "[T]he general validity of Einstein's equation is, I think, now universally conceded, and to that extent the reality of Einstein 's light-quanta may be considered as experimentally established. But the conception of localized light-quanta out of which Einstein got his equation must still be regarded as far from being established." [Emphases in original.] These sentiments would not have shocked his audience in Stockholm, for Einstein had received the Nobel Prize in 1922, "especially for his discovery of the law of the photoelectric effect," excluding both relativity and quanta. Ironically, it had been Millikan's experiment which convinced the experimentalist-inclined committee in Stockholm to admit Einstein to that select circle.

Two final ironies: In 1950, at age 82, Millikan published his Autobiography. Chapter 9 is entitled simply "The Experimental Proof of the Existence of the Photon – Einstein's Photoelectric Equation." By then, Millikan had of course come to terms with the photon. Moreover, he had changed his mind about what he had done around 1916. For now, he wrote (pp. 101–102) that as the experimental data became clear in his lab, they "proved simply and irrefutably, I thought, that the emitted electron that escapes with the energy hv gets that energy by the direct transfer of hv units of energy from the light to the electron [emphasis in original] and hence scarcely permits of any other interpretation than that which Einstein had originally suggested, namely that of the semi-corpuscular or photon theory of light itself." In the end, Millikan re-imagined the complex personal history of his splendid experiment to fit the simple story told in so many of our physics textbooks [2].

The other irony emerging from this story concerns the fact that, as one of my personal correspondents has put it so well, "In the current deconstruction of science by non-scientists, much is made of the tendency of researchers to ask the questions and analyze results in the light of their own beliefs. Millikan's paper is an excellent counter-example, being clearly a case of someone doing superlative work in establishing a result from a theory in which he himself clearly had little faith. In this case at least, the carefully established facts spoke for themselves through a very sceptical scientist". Millikan is only one of countless examples of that sort. Planck himself, from 1900 on, was among the most conservative and hesitant of the interpreters struggling with the quantum theory. His motivation was completely orthogonal to his findings [3]. What did appeal to him about his result that now bears his name, and which Millikan was the first to measure with great precision, was Planck's hope to have found a constant of nature that would be absolute, in the sense that even extraterrestrials, despite all their differences from humans, would agree on the experimental value of h. In the meantime, we can be quite satisfied with the fact, so awkward for the "relativists," that h is found to have the same value, when measured with care or calculated from theory in Millikan's Chicago or anywhere else on this globe, regardless of environmental or social conditions, and even in the face of false initial presuppositions.

References

1. Physical Review 7 (March 1916), 355–388. An abstract of his paper, and early results, had been published by Millikan in Physical Review 4 (1914), 73 and 6 (1915), 55. A much abbreviated version of part of this essay was published (electronically only) in Physical Review Focus 3, Story 23 (April 22, 1999).

2. In his lecture "History as Myth and Muse" (given at the University of Amsterdam, November 11, 1998), Roger H. Stuewer concluded, concerning this change of the historic record, that "even an experimental physicist as great as Millikan could be dead wrong in his theoretical views – and then also was human enough to try to hide his error much later by giving a patently false account in his autobiography" (p. 17).

3. For a brief account of that struggle, see G. Holton, Thematic Origins of Scientific Thought (Harvard University Press, 1988), pp. 156–159.

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Phys. perspect. 1 (1999) 231–237 © Birkhaüser Verlag, Basel, 1999 1422–6944:99:030231–07 $ 1.50_0.20:0

Physics is everywhere, but how much do the citizens of Europe really know about physics?

Physics on stage

Three major European research organisations, the European Centre for Nuclear Science (CERN), the European Space Agency (ESA) and the European Southern Observatory (ESO) are collaborating together to organise a unique European-wide programme to raise the public awareness of physics and related sciences with support from the European Union. Other partners in the project are the European Physical Society and the European Association for Astronomy Education.

In 22 European countries National Steering Committees have been formed with responsibility for their own national programmes to promote national activities and to survey new and exciting educational approaches to physics. The project will culminate in November 2000 with 400 delegates converging on CERN in Geneva for the Physics on Stage festival. During this event, science teachers, science communicators, publishers, top scientists and high-level representatives of the ministries and European organisations will brainstorm future solutions to bolster physics' popularity.

The Physics on Stage festival will be part of the European Science and Technology Week, which was first launched in 1993 on the initiative of the European Commission to raise public awareness of science and technology and to ensure that the public recognises their significance in all our lives.

Luciano Maiani, the Director General of CERN writes : "Science is a critical resource for mankind and among natural sciences, physics will continue to play a crucial role, well into the century. The young people of Europe deserve the best possible physics teaching. An enormous resource of first-class teachers, teaching materials and innovative thinking exists in our countries. The Physics on Stage project will bring them together to generate a new interest in physics education which will be to the long term benefit of children all over Europe".