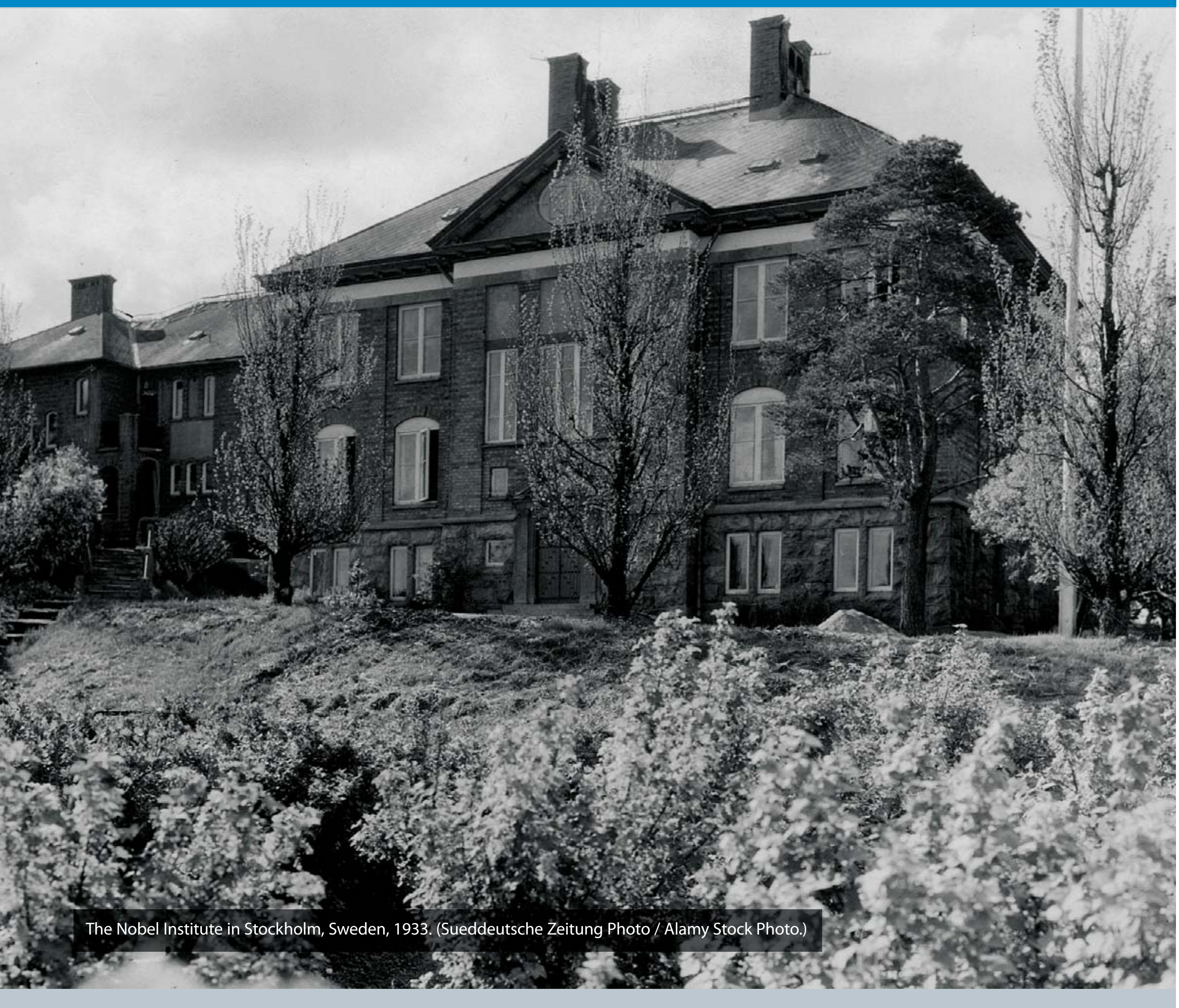
Paul Dirac and the Nobel Prize in Physics



The Nobel Institute in Stockholm, Sweden, 1933. (Sueddeutsche Zeitung Photo / Alamy Stock Photo.)

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Mats Larsson and Alexander Balatsky

Despite the elegance of Paul Dirac's theoretical work, the Nobel Committee nearly passed him over for the prize—until a timely experiment confirmed one of his predictions.

Alfred Nobel's will left only a few criteria for the prizes he created. All five prizes were to be given to "those who, during the preceding year, have conferred the greatest benefit to humankind." For physics, that meant more specifically "the person who made the most important discovery or invention in the field of physics."[1] When the first physics prize was awarded to Wilhelm Röntgen in 1901 for the discovery of x rays, no one could deny that he met the criteria. The nominators overwhelmingly supported Röntgen, and the nomination system has remained essentially unchanged since.

The Nobel Committee for Physics, however, has not always been as unanimous as it was when it chose its first recipient. In the early 20th century, theoretical discoveries in physics were often particularly problematic. Committee members were comfortable awarding the prize to a theorist whose work had clear experimental confirmation; Niels Bohr, whose model of the hydrogen atom matched hydrogen's well-known atomic spectrum and predicted the Rydberg constant, is one example. In contrast, the committee could never unanimously agree that Albert Einstein's special and general theories of relativity had been experimentally and observationally confirmed.[2] Einstein was awarded the 1921 Nobel Prize for his work on the photoelectric effect, but never for one of the most profound theories in the history of physics.

Discoveries in theoretical physics also caused complications for the committee when quantum mechanics (QM) emerged. On 9 November 1933, the Royal Swedish Academy of Sciences announced that the Nobel Prize in Physics for 1932 would go to Werner Heisenberg and the 1933 prize would be shared between Erwin Schrödinger and Paul Dirac (see figure 1). When that announcement was made, three years had elapsed since a physics Nobel had been awarded, the longest peacetime gap in its history. That gap reflects the committee's struggle to come to grips with the new QM. Dirac in particular seemed destined to share Einstein's fate of missing a Nobel Prize for his most important contribution—until experimental confirmation arrived at just the right moment.

The early history of quantum mechanics

Despite the success of the Bohr model and later improvements by Arnold Sommerfeld, it was clear that even the relatively simple spectrum of the helium atom was impenetrable to the

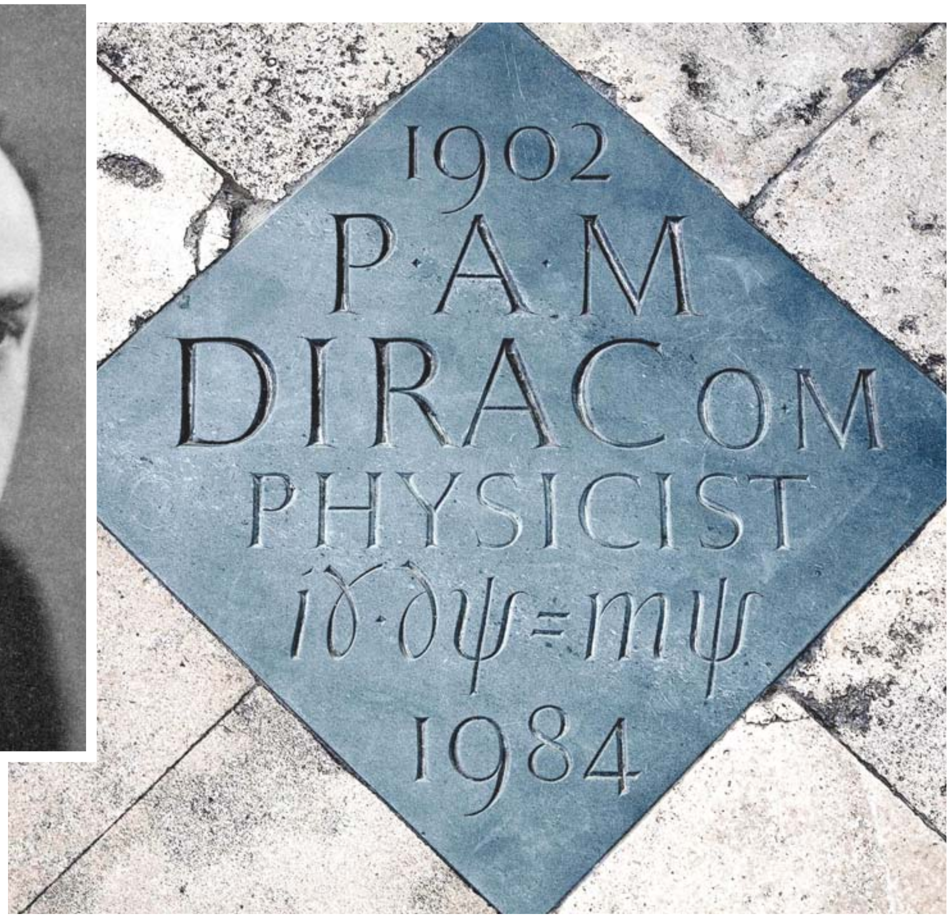


FIGURE 1. PAUL DIRAC (LEFT) AND HIS FAMOUS EQUATION (RIGHT). Dirac's memorial at Westminster Abbey in London includes a version of his Nobel Prize–winning wave equation. "OM" stands for Britain's Order of Merit, which is awarded for distinguished service and is restricted to 24 living members. (Photograph at left by A. Bortzells Tryckeri, courtesy of the AIP Emilio Segrè Visual Archives, E. Scott Barr Collection, Weber Collection; photograph at right published with kind permission of the Dean and Chapter of Westminster Abbey.)

QM developed and applied between 1900 and 1925. Heisenberg was the one who took the first, bold step of formulating a new QM by throwing the nonobservable Bohr atomic orbits overboard. Instead, Heisenberg's QM was based on relationships between observables, such as position and momentum for an oscillator. Heisenberg's groundbreaking paper[3] was received by *Zeitschrift für Physik* on 29 July 1925 and published in December.

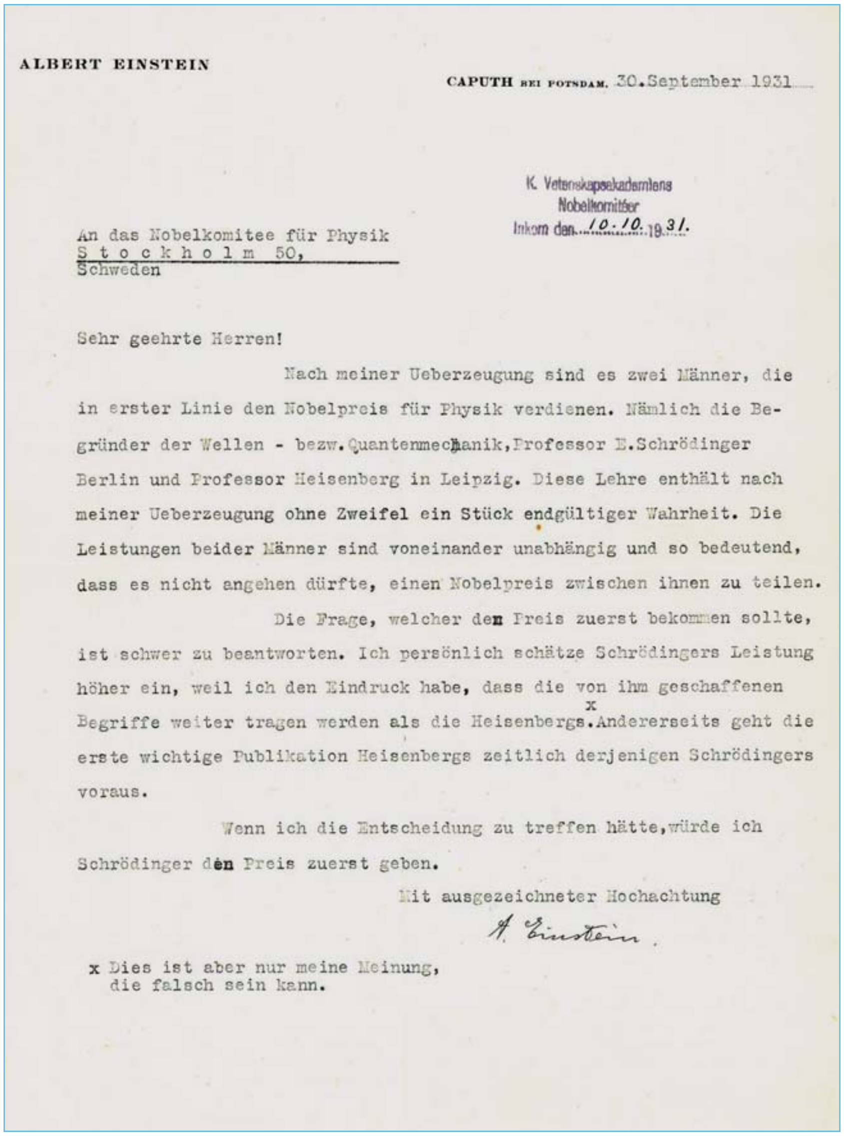
Dirac, then a doctoral student at the University of Cambridge, learned about the paper in advance of publication through his adviser Ralph Fowler, whom Heisenberg visited on his trip to the UK during the summer of 1925. Later that year Dirac came up with his own mathematical formulation of Heisenberg's QM.[4] Meanwhile in Germany, Max Born, Pascual Jordan, and Heisenberg were also working on a mathematical formulation to represent observables with matrices. In Austria, Schrödinger was inspired by Louis de Broglie's concept of the electron's wave nature and formulated his own wave mechanics.[5]

However, neither Heisenberg's matrix mechanics nor Schrödinger's wave mechanics incorporated the special theory of relativity. Another problem was that electron spin had been incorporated into the nonrelativistic quantum equations ad hoc, which resulted in a workable theory that could explain atomic spectra but provided no insight to the origin of spin.[6] It was Dirac who took the decisive step[7] in 1928. His bold idea of writing the wave equation in a relativistic invariant form that was linear in time had a profound impact on physics. That brilliant mathematical insight led to predictions of electron spin and magnetic moment without any ad hoc assumptions. By going from scalar equations to a matrix form, Dirac also introduced the beautiful mathematical formalism that preserves Lorentz invariance:

$$i\partial_t\Psi = (c\boldsymbol{\alpha}\cdot\mathbf{p} + \beta mc^2)\Psi.$$

The introduced matrices $\boldsymbol{\alpha}$ and β, now named after Dirac, act on the wavefunction of the electron. The electron can be written as a four-component spinor: two components for it as particle and antiparticle, and two components for its spin as a fermion. For massless particles, $m = 0$ and the relationship between energy and momentum, the Dirac dispersion, is $E = cp$. Subsequent extensions by Hermann Weyl and Ettore Majorana led to representations that are relevant for modern condensed-matter realizations of Weyl and Majorana fermions.

The seed of the prediction for the antiparticle is apparent from this equation. If the wavefunction of the observed electron required only two components with spin up and spin down, then why are two "unused" components of the spinor needed? Those unused components correspond to negative-energy solutions. At the time, negative-energy solutions were considered undesirable physics, but they predicted an antiparticle, or a positive electron in the terms of Dirac's day. Dirac's


ALBERT EINSTEIN

CAPUTH BEI POTSDAM, 30.September 1931

K. Vetenskapsakademiens
Nobelkomitéer
Inkom den 10.10.1931.

An das Nobelkomitee für Physik
Stockholm 50,
Schweden

Sehr geehrte Herren!

Nach meiner Ueberzeugung sind es zwei Männer, die in erster Linie den Nobelpreis für Physik verdienen. Nämlich die Begründer der Wellen - bezw. Quantenmechanik, Professor E.Schrödinger Berlin und Professor Heisenberg in Leipzig. Diese Lehre enthält nach meiner Ueberzeugung ohne Zweifel ein Stück endgültiger Wahrheit. Die Leistungen beider Männer sind voneinander unabhängig und so bedeutend, dass es nicht angehen dürfte, einen Nobelpreis zwischen ihnen zu teilen.

Die Frage, welcher den Preis zuerst bekommen sollte, ist schwer zu beantworten. Ich persönlich schätze Schrödingers Leistung höher ein, weil ich den Eindruck habe, dass die von ihm geschaffenen Begriffe weiter tragen werden als die Heisenbergs.x Andererseits geht die erste wichtige Publikation Heisenbergs zeitlich derjenigen Schrödingers voraus.

Wenn ich die Entscheidung zu treffen hätte, würde ich Schrödinger den Preis zuerst geben.

Mit ausgezeichneter Hochachtung

A. Einstein.

x Dies ist aber nur meine Meinung, die falsch sein kann.

FIGURE 2. ALBERT EINSTEIN'S NOMINATION LETTER, dated 30 September 1931, in which he nominated Erwin Schrödinger and Werner Heisenberg. Einstein wrote, "In my opinion, this theory [quantum mechanics] contains without doubt a piece of the ultimate truth. The achievements of both men are independent of each other and so significant that it would not be appropriate to divide a Nobel prize between them. The question of who should get the prize first is hard to answer. Personally, I assess Schroedinger's achievement as the greater one, since I have the impression that the concepts created by him will carry further than those of Heisenberg. [Here Einstein adds a footnote: This, however, is only my opinion, which may be wrong.] On the other hand, the first important publication by Heisenberg precedes the one by Schroedinger. If I had to decide, I would give the prize first to Schroedinger." (Translation from ref. 2, p. 515. Image courtesy of the Center for History of Science, Royal Swedish Academy of Sciences, Stockholm.)

equation thus led to a clear prediction of antiparticles and antimatter, one of the great triumphs of physics in the 20th century.

Meanwhile, de Broglie was awarded the 1929 Nobel Prize in Physics for "his discovery of the wave nature of electrons," a theoretical achievement the committee was not entirely sanguine about rewarding. As late as 1928, the committee still hesitated because the members felt the experimental evidence for de Broglie's work was not sufficiently strong and rejected him in favor of experimentalist Owen Willans Richardson. One year later, however, the committee was convinced that the experimental demonstration of the wave nature of electrons was solid enough to award the prize to de Broglie.

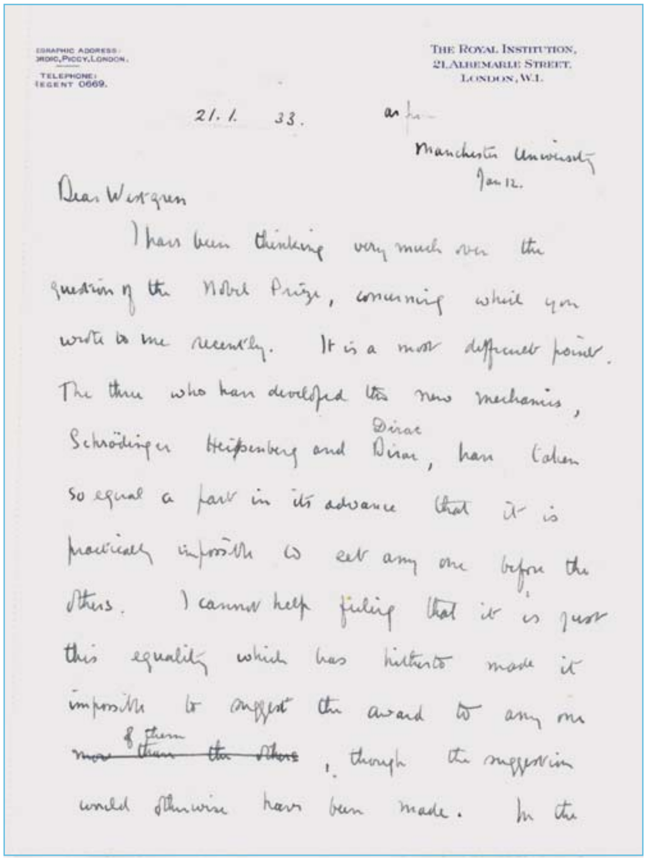
The 1930 physics Nobel went to Chandrasekhara Raman for his work on the scattering of light known as Raman spectroscopy, an experimental achievement that created far less consternation among the committee members. Indeed, they were so confident in the value of Raman's work that they nearly upheld Nobel's wish to reward a discovery from "the preceding year"; Raman made his discovery in early 1928. But as the new decade began, pressure was mounting for the committee to award the prize to work on the new QM.

Nobel nominations 1928–1933

Untangling the reasons behind particular nominations—or their absence—is no easy task. The archives of the Nobel Prize in Stockholm are closely held, and access is granted selectively. Material older than 50 years is open, but only by application and only to historians of science. Newer material is available only to elected members of the Royal Swedish Academy of Sciences.

Furthermore, in contrast to the present-day practice of asking the international physics community to submit confidential expert reports about nominees, in the first six decades of the physics prize, the reports were mainly written by members of the committee and always in Swedish. The reports concerning the Nobel Prize nominees in 1932 and 1933, for example, were mostly written by committee member Carl Wilhelm Oseen, director of the Nobel Institute for Theoretical Physics in Stockholm. The international physics community is visible in the early 1930s only through the nomination letters, which were obviously important but varied in their level of detail.

If we look at nominations from the early 1930s, the following picture emerges. Between 1928 and 1933, the period when the committee was under the most pressure to choose a prize recipient who had worked on the new QM, Schrödinger received 41 nominations; Heisenberg, 29; and Dirac, just 3. The most interesting nominations came from two of the founding fathers of QM, Bohr and Einstein. Writing in Danish, Bohr nominated Heisenberg, arguing that he should be first in line to be recognized for the development of QM. He placed Schrödinger second behind Heisenberg, and never mentioned Dirac at all.[8]



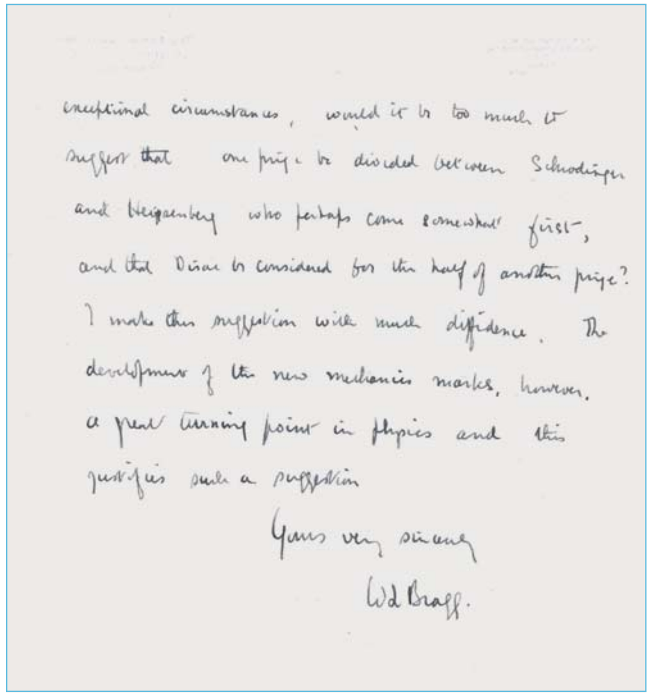
TELEGRAPHIC ADDRESS: ...DIC, PICCY, LONDON.
TELEPHONE: REGENT 0669.

THE ROYAL INSTITUTION,
21, ALBEMARLE STREET,
LONDON, W.1.

21.1.33. as from Manchester University Jan 12.

Dear Westgren

I have been thinking very much over the question of the Nobel Prize, concerning which you wrote to me recently. It is a most difficult point. The three who have developed the new mechanics, Schrödinger Heisenberg and Dirac, have taken so equal a part in its advance that it is practically impossible to set any one before the others. I cannot help feeling that it is just this equality which has hitherto made it impossible to suggest the award to any one of them ~~more than the others~~, though the suggestion would otherwise have been made. In the



exceptional circumstances, would it be too much to suggest that one prize be divided between Schrodinger and Heisenberg who perhaps come somewhat first, and that Dirac be considered for the half of another prize? I make this suggestion with much diffidence. The development of the new mechanics marks, however, a great turning point in physics and this justifies such a suggestion.

Yours very sincerely

W L Bragg.

FIGURE 3. WILLIAM LAWRENCE BRAGG'S NOMINATION LETTER, dated 21 January 1933. It is addressed to "Westgren." Arne Westgren was the secretary of the Nobel Committee for Physics from 1926 to 1943. (Ref. 10; courtesy of the Center for History of Science, Royal Swedish Academy of Sciences, Stockholm.)

Einstein's nomination letter, shown in figure 2, was written from his summer house outside Berlin and is noteworthy in several ways.[9] Einstein was not very active as a nominator, but when he did nominate someone, he had the committee's ear. According to his letter, two men stood at the front of the line for a QM Nobel: Schrödinger and Heisenberg. They had worked independently, and Einstein argued that their work was of such importance that a shared prize should not be considered. Forced to make a recommendation about who should receive the prize first, Einstein put Schrödinger slightly ahead of Heisenberg. Once again, Dirac was not mentioned and, in fact, was never nominated by Einstein.

The date of Einstein's letter, 30 September 1931, is peculiar. It was just barely a month before the Royal Swedish Academy of Sciences was scheduled to announce the 1931 prize. The deadline for nominations, 31 January, had long since passed. Einstein must have known his letter would not count as a nomination for 1931, only for 1932. We can only speculate about his motivation for sending the letter off-cycle, but there seems to have been a growing realization among physicists that the committee ought to acknowledge the new QM.

With such a large number of nominations for Heisenberg and Schrödinger, including from both Bohr and Einstein (albeit a late one), why not award the prize to one or both of them? And why did no one mention Dirac? The committee's problem was how to reconcile a prize for the development of QM with Alfred Nobel's will, which required a "discovery" or "invention" in the field of physics. Oseen, the only theorist on the committee, seems to have particularly struggled with that quandary. True, the new QM had systematized vast swaths of data in atomic physics, but had it led to any new experimental discoveries? In a report to the Nobel Committee dated 16 March 1929, Oseen's conclusion was "no."

Swedish chemist Theodor Svedberg, who had received the 1926 Nobel Prize in Chemistry, tried to help his physics colleagues by nominating Heisenberg in January 1930 for his work on the allotropic forms of hydrogen. In 1927 Heisenberg had predicted that molecular ortho-hydrogen (parallel nuclear spins) should be three times as abundant as para-hydrogen (antiparallel spins), and in 1929 the prediction was experimentally verified. That work was too close to chemistry for the members of the physics prize committee, but the citation for Heisenberg's Nobel Prize mentions the allotropic forms of hydrogen.

Unable to agree on a prize for either Heisenberg or Schrödinger, but also unable to find candidates they preferred, the committee members ultimately decided to postpone awarding the 1931 physics prize. When deliberations for the 1931 and 1932 prizes resumed, they were still ambivalent about their most-nominated candidates, but support was building. Erik Hulthén, an experimentalist whose specialty was molecular spectroscopy, argued that there were now many experimental results, in particular for diatomic molecules, that could only be satisfactorily explained with the new QM. He also emphasized connections between phenomena in nuclear physics, such as radioactivity, and Heisenberg's uncertainty principle.

Oseen, on the other hand, insisted that the new QM was nonrelativistic—an inexcusable omission, in his view. Dirac's theory was relativistic, but Oseen thought it had insurmountable problems—namely, a lack of experimental verification. At the same time, the committee was still unable to identify anyone else who was more worthy of a Nobel Prize than Heisenberg and Schrödinger. Once again, the decision was postponed. The Nobel Prize for 1931 would therefore never be awarded; a prize can only be reserved until the following year.

Experimental confirmation

Before 1933 Dirac received only one Nobel nomination, in 1929 by Hans Thirring at the University of Vienna. In 1933 he received two. One was from Czesław Białobrzeski at the University of Warsaw, who also nominated Heisenberg. The other was from William Lawrence Bragg, recipient of the 1915 Nobel Prize in Physics. Bragg's nomination letter[10] explicitly put Dirac on equal footing with Heisenberg and Schrödinger (see figure 3), and it prompted Oseen to write a long report[11] about Dirac, which he submitted to the committee in March 1933.

Oseen could not accept Dirac as an equal to Schrödinger and especially to Heisenberg. Was Dirac a scientific innovator of the same caliber as Nobel recipients Max Planck, Einstein, and Bohr? For Oseen, the answer was definitely no. He compared Dirac's contributions with those of Born and Jordan in Germany. Their efforts to give a mathematical framework to Heisenberg's QM were never seriously considered worthy of a Nobel Prize. Furthermore, Dirac's 1928 paper had predicted not only the real physical states but also negative energy states in which the electron had positive charge. That charge, though, had never been observed. It is clear from Oseen's report that Dirac was not initially a contender for either the 1932 or 1933 prize. He had done work that was correct but not first, and when he was first, he was not correct—or at least not confirmed.

But a remarkable finding was about to paint Dirac's work in a new light. The same month that Oseen submitted his report about Dirac to the committee, US physicist Carl Anderson published a paper in *Physical Review* about his discovery of the positive electron.[12] Dirac's theory had now made a prediction that had been experimentally verified.

The committee members did not change their stance immediately. At the committee's June meeting, Heisenberg and Schrödinger were shortlisted, but Dirac was not. Anderson's discovery, however, was stirring excitement among physicists. That summer, J. Robert Oppenheimer and Milton Plesset wrote a letter to *Physical Review* in which they suggested that pairs of


SVENSKA DAGBLADET
Fredagen den 10 November 1933
NY AMERIKANSK CIGARETT "MARVELS" 6½ öre
HUGO LUNDGREN, Tobaksimport
KAROTTER
HALLBERG
Luthers släkt lever i Sverige
med över 1200 representanter på spinnsidan.
Två svenska män ättlingar i rakt nedstigande led till reformatorn.
LUTHERS VIGSELRING BEVARAD.
Fyra Nobelpristagare utsedda
Fysikprisen till W. HEISENBERG, Leipzig. E. SCHRÖDINGER, Berlin. P.A.M. DIRAC, Cambridge.
Litteraturpriset till IVAN BUNIN.
Ivan Bunin hämtar själv sitt Nobelpris.
Förbereder utgivandet av "un grand roman".
Telefonintervju.
"Jag tror helt enkelt ej mina öron!"
Vågor eller partiklar: gammal stridsfråga.
Heisenberg varm vän av Skandinavien
"Vistelsen hos professor Bohr mina härligaste år."
Schrödinger återvänder ej till Tyskland.
Fick nyheten om Nobelpriset genom Svenska Dagbladet.
Japan har kallat hem ambassadören i Moskva
Det hålles för troligt att han ej återvänder. Tre divisioner ha beordrats till Korea.
LÄGET YTTERST SPÄNT

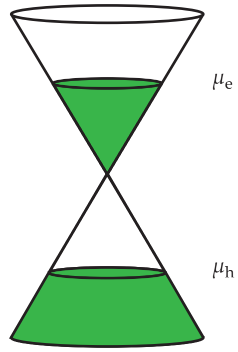
FIGURE 4. THE FRONT PAGE OF *SVENSKA DAGBLADET* ON 10 NOVEMBER 1933, announcing Paul Dirac, Werner Heisenberg, and Erwin Schrödinger as Nobel laureates in physics. (Courtesy of *Svenska Dagbladet*.)

negative and positive electrons could be created in the vicinity of a nucleus.[13] By applying Dirac's relativistic electron theory, they calculated the probability of pair production as a result of the gamma-ray irradiation of matter. The results were in fairly good agreement with experimental results published by Patrick Blackett and Giuseppe Occhialini earlier that year.[14] Now Dirac's theory had both qualitative confirmations and an approximate quantitative confirmation.

A late addition

Those developments prompted Oseen to write an addendum to his March report for the committee's meeting in September, at which it was expected to make its recommendations for the 1932 and 1933 Nobel Prizes in Physics. On 25 September 1933,

INFLUENCE OF DIRAC'S IDEAS



In the modern vernacular, the Dirac equation is a scientific meme: It is a single quantum of knowledge that had no precedence but rapidly gained wide acceptance. It took less than five years from publication of Paul Dirac's 1928 paper to the Nobel Prize decision.

As is often the case with truly insightful ideas, Dirac's equation has a wider range of applicability than even Dirac himself initially realized. That the wavefunction is acted on depending on which direction particles move by matrices α_x, α_y, *and* α_z for the directions *x*, *y*, and *z* turns out to be a simple yet very powerful idea. Physicists have found that a similar mathematical structure governs the behavior of many materials. Researchers have discovered a rapidly expanding list of materials and systems that can be effectively described using Dirac's elegant equation.

Condensed-matter physics in particular has recently seen a resurgence of research on topological nodal materials, including graphene, topological insulators, and the unconventional superconductors that are now called Dirac materials. DMs are those in which the properties of the excitations are physically identical to Dirac fermions. The crossing, or pinch point, also known as the Dirac node, is what makes both DMs and Weyl materials (the simplest irreducible three-dimensional version of a DM) respond to external fields and defects in a universal way.

The left-hand figure is an illustration of the Dirac dispersion and node for electron–hole excitations in a DM, where μ_e is the chemical potential for the electron and μ_h is the chemical potential for the hole. The pinch point creates an inverted particle distribution in driven DMs similar to the inverted mass distribution in an hourglass, as shown in the right-hand figure. The pinch point makes the DM qualitatively different from a conventional metal.

The range of those new nodal materials goes far beyond graphene. There are entire classes of 2D and 3D materials, Weyl and Dirac semimetals, and even unconventional superconductors. We also see the extensions of the concept to bosons like magnon and phonon DMs, something not seen in high-energy physics since the Dirac equation was originally proposed for fermions. Books and reviews published on DMs illustrate their new importance for physicists.[17] If the past is any predictor, we are sure the list of applications will grow.

the committee recommended that Heisenberg should receive the 1932 reserved prize and that Schrödinger and Dirac should be jointly awarded the 1933 prize "for the discovery of new productive forms of atomic theory." In Oseen's undated amendment, Dirac's name was inserted by hand into the typewritten recommendation.[15]

The Royal Swedish Academy of Sciences followed the committee's recommendation when it made the final decision on 9 November 1933 (see figure 4). In committee member Henning Pleijel's presentation speech on 10 December, he said to Dirac, "The experimental discovery of the existence of the positron has in a brilliant way confirmed your theory."[16] The Swedish newspaper *Dagens Nyheter* reported the next day, "Then followed [after Heisenberg], one after the other, professor Schrödinger and young professor Dirac, who staggered down [the stairs] in a real old-fashioned professor's white tie. But this didn't prevent mama Dirac from being somewhat proud where she was sitting and stretching herself on the third row behind the high-sounding foreign ministers."

We now know that Dirac's elegant equation has applications in a wide range of fields, including materials science (see the box). Bragg was the first to suggest that Heisenberg, Schrödinger, and Dirac were equals as physicists. Posterity has confirmed his claim—and for some of us, Dirac is perhaps first among those equals.

We are thankful to the Royal Swedish Academy of Sciences for access to its Nobel archives and to Karl Grandin, head of the archives, for valuable comments. We are grateful to Konrad Kleinknecht for comments. Alexander Balatsky's work was supported by the Villum Centre of Excellence for Dirac Materials, grant 11744, and Knut and Alice Wallenberg Foundation grant 2013.0096.

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