On the history of the Einstein–de Haas effect

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This article contains information on Einstein's experimental work. It pays main attention to three of his studies (1915–1916) aimed at experimental demonstration of Ampère molecular currents. It treats the content of these studies, their prehistory, and the peculiar reevaluation of their results after the discovery of the spin of the electron. It traces the effect of these studies on Einstein's attitude toward the Stern-Gerlach experiments and the studies of Uhlenbeck and Goudsmit, and also points out their genetic tie with the well-known work of Einstein and Ehrenfest.

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1. INTRODUCTION

The studies to demonstrate the existence of Ampère molecular currents, which this article takes as its topic, are the major but far from sole evidence of Einstein's concern with experimental studies. The opinion current among many physicists that Einstein himself never "worked with his hands" but delegated performance of the appropriate experiments to his coauthors or assistants is erroneous and lacking in any real basis—we shall confirm this assessment by direct citation of his studies. Along this line, the appendix to his early (1902) article is noteworthy. It was concerned with the thermodynamic theory of the potential difference between metals and solutions of their salts, and an electrical method of studying molecular forces was developed on its basis. Einstein writes, "I wish to excuse myself in closing for proposing here only an overall plan for the laborious experiments while personally not involved in experimentation. Yet this paper will still reach its aim if someone involves himself with experimental study of molecular forces upon becoming acquainted with it."[1]

Further it is worth recalling that, upon proposing in 1908 a new principle for measuring small amounts of electricity,[2] Einstein took part in studies to design the appropriate instrument, which was described in an article by the brothers P. and C. Habicht, his Swiss friends. They especially recall in their paper[3] Einstein's participation in the studies to build and test this instrument. In 1921 Einstein spent much time on experiment with canal rays; he performed the corresponding experiments jointly with H. Geiger.[4] Three years later, Einstein together with Ehrenfest "daily [became absorbed] for many hours in one experimental study" (as Ehrenfest wrote to A. F. Ioffe[5]) in trying to establish the existence of an effect that Einstein had predicted.

There is an article of the experimentalist Einstein that he wrote jointly with his friend, the physician H. Mühsam. This was a short and elegant study on a method of determing dimensions of channels in filters.[6] It describes an idea for an instrument for measuring the largest dimension of particles that can pass through a given filter and an experimental test of this idea.

2. EINSTEIN'S FIRST PUBLICATIONS ON MOLECULAR CURRENTS

Having confined ourselves to these cursory remarks, we shall now proceed to treat a series of papers of Einstein of 1915–1916 on Ampère currents. These papers, which were written in part with W. de Haas (1878–1960) as coauthor, are concerned with theoretical study and experimental demonstration of the now well-known phenomenon that has become called the Einstein-de Haas effect. As we see it, they deserve a special treatment for a whole set of reasons. First, they played a large role in studies of the magnetic properties of substances and atoms, practically up to the discovery of the methods of EPR and ferromagnetic resonance. Second, these are precisely the studies in which Einstein appears for the first time as the author of experimental investigations. Third, a study of them

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helps in understanding the lively interest with which Einstein reacted to the discovery of the spin of the electron and participated in the discussions about the paper of Unlenbeck and Goudsmit. Finally and fourth, they have an interesting and rather long prehistory. The fact is paradoxial (in the face of the mentioned significance of these studies) that their result involved an experimental error, and in several years after their publication, their treatment had undergone a substantial change. We shall pay special attention to this problem below.

Einstein and de Haas presented the discussed set of papers on Feb. 19, 1915 in Berlin at a meeting of the German Physical Society chaired by H. Rubens. The first publication of this set was signed by Einstein alone. It was printed in the May issue of the journal *Naturwissenschaften* in 1915 with the title "Experimental demonstration of Ampère molecular currents".[7] Its main content amounts to an unusually graphic and simple *theoretical* treatment of the problem; a description of the fundamental scheme for its experimental study is a small appendix to the main part of the article. Starting with the studies on magnetism of P. Curie, Langevin, and Weiss, Einstein recalls the hypothesis of Ampère that the French scientist had formulated in 1820, immediately after Oersted had shown that a magnetic field arises around a conductor bearing a current. It became clear after Oersted had shown that a magnetic field appears not only as a certain inner property of a certain class of solids when permanently magnetized, but it also arises under the influence of an electric current. "This state of affairs," Einstein wrote, "must seem unsatisfactory to physicists striving for a unitary understanding of nature."[1] This is precisely why Ampère had proposed that the magnetic field surrounding a magnetic object is caused by currents flowing in the molecules, or molecular currents.

Another remark of general nature that Einstein made in his article[7] cannot help but arouse attention. He points out in a footnote to the text of his paper, "Ampère's theory in its modern, electronic form also faces the difficulty that, according to Maxwell's electromagnetic equations, the electrons should lose energy by radiation while performing their circular motion, so that the molecules or atoms should lose their magnetic moment in time or have already lost it, which of course does not actually happen." Amazingly, here Einstein does not recall Bohr: the classical paper "On the structure of atoms and molecules" directly begins with general arguments about the "inadequacy of classical electrodynamics" and contains a postulate on the absence of radiation loses in the revolution of an electron in a stationary orbit about the nucleus to resolve this "inadequacy."

The joint paper of Einstein and de Haas[9] also contained a rather extensive theoretical part, partially repeating material of Ref. 7. We note some new, curious arguments expressed in it "against" Ampère's hypothesis. The authors stress that the concept of currents flowing without resistance has aroused doubts as to the validity of the hypothesis of molecular currents even in the pre-Maxwell period. Maxwell's theory added a new difficulty to this: an electron moving in a circular orbit should continuously emit. Finally, a complication has arisen in the *20th* century: the existence of a magnetic moment of the molecule as $T \to 0$ means that the "energy of circular motion must be the so-called zero-point energy—a concept that arouses a quite understandable resistance in many physicists."[9] This is the fundamental importance of Eq. (1) (see below) and the concepts associated with it. The authors also point out that the experiment that they proposed enables an accurate determination of the ratio of the charge of an electron to its mass.[2]

In closing the theoretical part he points out that also the rotation of a magnetic object alters its magnetic state, and this can in principle also be employed to test Ampère's hypothesis (though, as he points out, this test is more complex experimentally). And yet another remark, now of a "geomagnetic" character: a corresponding effect can be employed to explain the phenomenon of terrestrial magnetism: it is not fortuitous that the axis of rotation of the Earth and its magnetic axis approximately coincide.

Before proceeding to present the essence of the study, Einstein writes, "In the past three months *I have performed* (my italics—V.F.) experiments jointly with de Haas—Lorentz in the Imperial Physicotechnical Institute that have firmly established the existence of Ampère molecular currents."

The design of the experiments is based on the following simple "argument," as the author called it. An electron moves uniformly in a circle of radius r at the velocity $v = 2\pi r n$, where n is the number of revolutions per second. This means that the angular momentum here is $M_{\text{mech}} = mvr = 2m\pi r^2 n$ (m is the electron mass). On the other hand, according to Ampère, the magnetic moment M_{magn} of a loop having the current $i = en$, where e is the charge of the electron, is $M_{\text{magn}} = en\pi r^2$. Hence, upon converting to vector notation we get

$$\mathbf{M}_{\text{mech}} = \frac{2m}{e}\mathbf{M}_{\text{magn}} = \lambda\mathbf{M}_{\text{magn}} = -1.13 \cdot 10^{-7}\mathbf{M}_{\text{magn}}. \tag{1}$$

Einstein considered it obvious that the magnetic moment is determined by the rotation of the electron, so that the vectors $\mathbf{M}_{\text{mech}}$ and $\mathbf{M}_{\text{magn}}$ lie in opposite directions. Equation (1) is generalized to the case of an

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[1] As we know, Einstein presented an analogous argument with especial force in connection with the equality of gravitational and inertial mass that Eötvös had discovered.

[2] The stated remark is very characteristic of Einstein: in two papers in 1905 [on the quantum theory of radiation and on methods of determining the dimensions of molecules (Brownian movement)] he stresses the importance of the fact that the theory that he had developed offers a new method of determining Avogadro's number.

ensemble of "loops" bearing a current. Here the left-hand side will contain the total angular momentum of the object, and the right-hand side the total magnetic moment. Einstein makes the simple remark that the total angular momentum of the object should remain constant in the absence of external rotational moments. Hence a change in the magnetization of the object, which entails a change in the corresponding "electronic" component of its angular momentum, must be compensated. This compensation is carried out by transfer of angular momentum of the electrons to the solid (rod) as a whole: when its magnetization is changed it must begin to rotate.

Figure 1 reproduces the diagram of the experiment that Einstein proposed. The iron rod S is suspended by a thin filament coaxially inside a solenoid supplied with current. A change in the direction of the current alters the magnetization of the rod, and consequently causes it to rotate. By fastening a small mirror to the rod, one can register the studied rotation by observing a light beam reflected from it onto a scale.

The article closes by describing an important experimental detail: the winding of the solenoid was supplied with alternating current whose frequency coincided with the intrinsic frequency of torsional oscillations of the rod, and also it was stated that application of this resonance method made it possible to overcome experimental difficulties and to confirm quantitatively Eq. (1) given above.

The article,[9] which contained a detailed description of the experiment, and which was submitted to *Verhandlungen* on Apr. 19, 1915, was signed by Einstein and de Haas. Hence we see that the first article was intended to emphasize that the idea of the entire study as a whole and the corresponding experiments belonged to Einstein, while both authors took part in developing the apparatus for carrying out the experiments themselves. This circumstance, in addition to the reference cited above from Ref. 7, is confirmed by two facts. First, Ref. 10, which de Haas published alone on the same topic as Ref. 9, called the corresponding effect the "Einstein effect"—it kept this name for some time in the German literature (before it received its present name of the "Einstein–de Haas effect"). Second, in 1916 Einstein published an independent article that dealt only with the experimental side of the topic under discussion (see below).

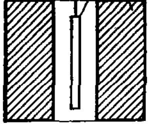

FIG. 1.

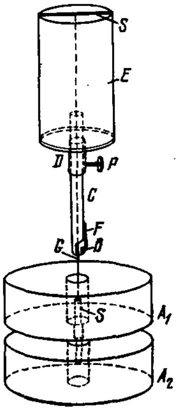

FIG. 2.

The paper of Einstein and de Haas describes and discusses the features of their experimental setup (Fig. 2), which was a realization of the model of Fig. 1 that was proposed in Ref. 7, and they also analyze the sources of possible errors and ways to overcome them.

The authors write down and solve the equation for the torsional oscillations of the soft-iron rod S, undergoing the test, and interrelate the measurable quantities via the constant $\lambda = 2m/e$, which they propose as the quantity being sought, or more exactly, the one to be verified, since the specific charge of the electron had been measured by that time with sufficient accuracy. When the rod is remagnetized, it begins to undergo torsional oscillations. The experiments measured the amplitude α of the angular oscillations (determined by the deflection of a light ray directed onto the mirror attached to the rod S and reflected by this mirror onto a scale 145 cm away) as a function of the frequency ω of the current supplying the winding of the coil inside which the rod was placed. The amplitude reaches its maximum α at the point of resonance when ω coincides with the intrinsic frequency ω_{res} of the torsional oscillations. It turns out as a result that

$$\lambda = \frac{2m}{e} = \pi^2 \frac{Q}{J} \alpha_{\max} \Delta\omega \sqrt{\frac{b^2}{1-b^2}}. \tag{2}$$

Here we have $b = \alpha/\alpha_{\max}$, $\Delta\omega = \omega_{\text{res}} - \omega$, Q is the moment of inertia of the rod, and J is its total magnetization. Thus, we see that if we take the resonance curve and measure Q and J, we can then determine λ. It proved from Einstein and de Haas's measurements to be 1.11×10^{-7}, "in good agreement with the theoretical values of 1.13×10^{-7}. Indeed, add the authors, "this agreement might be fortuitous, since we must ascribe an accuracy of about 10% to our measurements; nevertheless we have shown that the result of circular motion of the electrons described at the beginning of our article is quantitatively confirmed by experiment, at least approximately."[9]

3. EINSTEIN'S SECOND PAPER

Almost exactly a year after the first report on experiments involving Ampère currents, on Feb. 25, 1916, Einstein gave a paper at a session of the same German Physical Society (this time only in his own name) with the title: "*A simple experiment to demonstrate Ampère molecular currents.*" As Einstein saw it, the stated experiment might serve as a lecture demonstration of the treated phenomenon: a visible demonstration of the microscopic properties of matter always impresses!

The difficulty of the prior experiments consisted in isolating the relatively weak gyromagnetic effect against the background of the purely magnetic forces acting on the studied rod (cf. Figs. 1 and 2). In order to avoid this difficulty, in the variant of the experiment proposed by Einstein, the magnetic field of the coil acts on the iron rod (10 cm long and 0.14 cm in diameter) for a very short time of the order of a millisecond. This is achieved by using a simple discharge circuit in which a capacitor and a quenching resistance are connected to the coils. As usual, an essential part of the apparatus is a device to compensate the magnetic field of the Earth. As investigations showed, for a successful lecture demonstration one must carefully center the studied rod. Remarkable in the words of the great theoretician of modern time are the following comments on the point of suspension of the quartz filament to which this rod was attached: "A sufficiently exact suspension of the rod by its center (the point of suspension must lie on its principal axis of inertia.—V.F.) faced great difficulties. The aid of Mr. Eger kindly helped me in overcoming them. Ultimately the following amusing method led to the goal. The rod is clamped vertically (not firmly!) on a stand so that the end from which it is to be suspended is inverted downward. Vertically below it, also in an inverted position, one attaches to the stand respectively a cork with a copper pin and the quartz filament. Here the height is carefully chosen so that the quartz filament when raised upward (with a wet finger) in a straight line doesn't quite touch the flat end of the rod (see Fig. 3—V.F.). Using a gas burner made of a drawn-out glass tube, one heats the end of S with a small flame until a piece of rosin raised from below on the finger will stick to it. The rosin melts and forms a completely symmetrical drop under the action of capillary forces. If now one brings the quartz filament into it from below, it is wetted by the rosin and drawn by capillary forces as far as possible into the interior of the drop. This means that it is automatically centered. Now one needs only to cool the rod and the suspension is ready."[11]

It is worth pointing out in conclusion that Einstein notes at the end of his article the coincidence of the *order* of magnitude of the effect with the theoretical prediction, as well as its correct sign [see Eq. (1)].

4. EINSTEIN'S VIEWS ON HIS STUDIES ON AMPERE CURRENTS

Before we proceed it is appropriate to trace out how Einstein evaluated the discussed studies on molecular currents. It is quite remarkable that he performed these studies simultaneously with intensive investigations on the general theory of relativity. Perhaps in dicussing and performing these "mundane" experiments, Einstein was resting from the tense thinking involved with the theory of gravitation. In telling his friend Michele Besso of the studies under way, in a letter of Feb. 12, 1915, i.e., a week before the paper at the German Physical Society in Berlin, Einstein singles out, along with the general theory of relativity, "an experimental confirmation of the hypothesis of molecular currents .... If the suspended rod is remagnetized, then it will experience an axial rotational moment, whose existence I have proved experimentally jointly with Mr. de Haas (and Lorentz's son-in-law) in the Imperial Institute. The experiments will soon be finished. Thus the existence of a "zero-point energy" is proved in one case. A most marvelous experiment, and a pity that you can't see it. And how zealously nature hides its secrets when one wants to find them out by experiment! In my old age a new passion for experimentation appears."[12] In a certain contradiction to these lines (but one highly characteristic of this sort of general statements of Einstein) is an excerpt from a letter of Einstein (of May 31, 1915) quoted by K. Selig that was addressed to a young student, Einstein writes to his correspondent[3] that "any boy could do the work on magnetism. But the general theory of relativity is quite a different matter."[13]

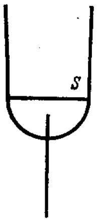

FIG. 3.

The incorrectness of the latter evaluation is evident from the prehistory of the studies on molecular currents and from their subsequent development. The point is that the "boys" that couldn't perform this work (i.e., carry it through to an experimental result) included both Maxwell and Richardson. And the following publications reveal its importance.

The first response to the articles[7,9] was a letter from the American physicist S. J. Barnett, who reported to the editor of *Naturwissenschaften,* Dr. Berliner, that he had already published articles rather long ago on magnetomechanical effects. Berliner informed Einstein and de Haas of this, and they submitted a short note to his journal.[14] While informing the readers that, as they had learned from Barnett's letter, the beginning of studies on gyromagnetism goes back to Maxwell, Einstein and de Haas also pointed out that Barnett had begun his experiments along this line (on magnetization by rotation) "already six years ago, and he now reports that they led to a positive result."

Reference to Barnett's articles in *Science*[15] (published in the issues of July 30 and Oct. 1, 1915, i.e., after Refs. 7 and 9 had been published) and also to his other studies,[16,17] including the one published in 1948, i.e., more than 30 years after the described events,[18] allows us to reconstruct the chronological sequence of the studies in the field of physics under discussion.

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[3] For some reason K. Selig doesn't give his name.

5. PREHISTORY OF EINSTEIN'S STUDIES

The starting link in this chain of studies, as Barnett *et al.* have stressed in a series of papers, is Maxwell's *A Treatise on Electricity and Magnetism*, Vol. 2, Chap. 6: *Dynamical Theory of Magnetism*.[19] In ten very short sections of this chapter, the reader first finds a description of the idea of the famous experiment of Stewart and Tolman (1916). Maxwell writes that if one suddenly causes a coil with a wire wound on it to rotate (Fig. 4), then an emf will arise in the wire and a current will flow. The emf vanishes when the rotation becomes uniform and changes sign upon sudden stopping of the rotating coil (Secs. 574 and 577 of Maxwell's treatise). In the same place he speaks of the inverse effect. Maxwell's theoretical prediction of the Einstein-de Haas effect (Sec. 575) is even more impressive. Here Maxwell even gives a drawing of the appropriate instrument that he had built in 1861 that was designed to prove the existence of the stated effect (P. L. Kapitsa[20] found this instrument in the twenties in the cabinets of the Cavendish Laboratory;[20] Fig. 5). Owing to the great subtlety of the predicted effects, Maxwell's attempts to detect them were not successful.

Yet we must stress that Maxwell predicted the effects described above and related ones (the inverse effects) on the basis of arguments that had nothing to do with Ampère currents. As was characteristic of all of his famous book, Maxwell here also turns to the studies of Faraday, in relating the following statement of his brilliant precursor on the nature of the electric current: "the first thought that arises in the mind is that the electricity circulates with something like momentum or inertia in the wire," in full parallel with the motion of water in pipes when pumped (Ref. 19, Sec. 547). Naturally, without making specific the nature of the carriers of electric charge, Maxwell states that all phenomena involving passage of a current are governed by "some moving system" that can be characterized by a kinetic energy, and to which he deems it possible to apply the general principles of Lagrangian mechanics (Chap. 5 of Vol. 2 of the *Treatise* is specifically concerned with a condensed presentation of the *Analytical Mechanics* of the French scientist and with deriving Hamilton's equations of motion).

It is highly symbolic that the precursor of the discussed studies of Einstein was Maxwell, a scientist whose genius Einstein rated higher than his own. In the above-cited autobiographical remarks Einstein writes, "The most fascinating topic during my student days was Maxwell's theory." There are direct indications that Einstein had studied the *Treatise*.[21] Yet he hardly paid attention to the above-discussed part of Maxwell's book, not being interested in the applications but in the more general and fundamental problems.

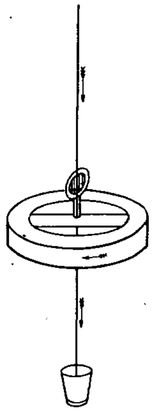

FIG. 4.

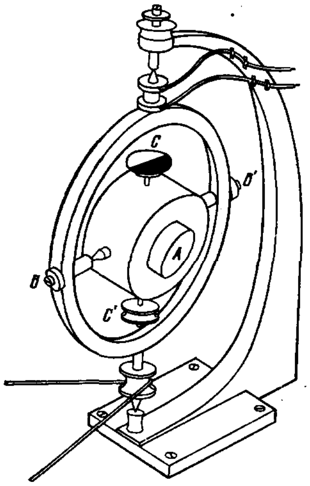

FIG. 5.

Some words on the "intermediary" studies between Maxwell and Einstein-de Haas. Undoubtedly the most substantial in the series were Barnett's studies on the effect inverse to the Einstein-de Haas effect, which has been named after the American physicist. In the first short note on this topic[22] published in *Science*, Barnett discussed the sources of the magnetic field of the Earth, and operates with concepts of "negative (or positive) particles rotating about positive (or negative) centers." He says that the rotation of a cylinder whose substance contains such particles is accompanied by the appearance of a magnetic field around it. The experiments of Barnett in July 1909 established the appearance of such a field (but without measuring its size) in a cylinder whose initial resultant magnetic moment was zero.

The English physicist O. Richardson undertook an attempt to establish the fact of rotation of an iron cylinder upon remagnetization (with the corresponding calculation and theory) in 1907 during his stay at the Palmerston laboratory in the USA.[23] Among other persons who pointed out the existence of and undertook studies of magnetomechanical effects, we should mention J. Perry (1890), P. N. Lebedev (1911) and A. Schuster (1912), whose studies involved searches for the source of the magnetism of the Earth and of other cosmic objects.

We should stress that in 1915 Einstein already possessed worldwide fame. Each of his articles was met with great interest; correspondingly its topic acquired an especial ring, even if it didn't deal with problems of the theory of relativity.[4] Einstein's fame could—of course, with no intent on his part—eclipse the names of other physicists concerned with the same problems. Precisely this explains the fact that Barnett devoted so much attention to questions of priority in all his articles (1915–1952). We can infer how deeply he felt this from the following quotation from his article of 1925: "In 1918 I found that John Perry had published the same fundamental idea as I did (on the source of the magnetic field of the Sun and the Earth—V.F.) as early as October 1890 in a footnote on p. 112 of his book. Perhaps I read this footnote of Perry's but had long since forgotten it"[17] (long ago as compared with 1909, when Barnett's first report was published[22]).

The book that Barnett mentioned (an edited version of a popular lecture given by J. Perry in September 1890) was printed several times in the USA, including 1901 and 1910, and was widely known at the beginning of the century. Page 65 of its Russian edition contains the remark of which Barnett speaks. It reads as follows: "If one makes a large piece of iron rotate rapidly first in one direction, and then in the other, near a freely suspended magnetic needle that is well shielded from the action of air currents, then I believe that a phenomenon must occur that is of greatest interest for the theory of magnetism. As yet I have not succeeded in these studies in detecting any trace of magnetic action, but I ascribe this failure to the relative slowness of the rotation that I applied, and also to the insufficient sensitivity of the magnetometer."[25]

One would think that Einstein, on his part, correctly assumed that he had fully defined in the note of Ref. 14 his attitude to problems of priority: as we know, he was more than indifferent to this type of dispute. As for Barnett, he remained devoted throughout his life to magnetomechanical studies, which he conducted in the latter years of his life at the University of California. In a paper published in 1952 jointly with L. A. Giambomi[26] ("A new gyromagnetic effect in Permalloy and iron") Barnett again speaks of fruitful discussions with Einstein, in the course of which Einstein called attention to the following specific effect. A rod is fixed in a strong magnetic field parallel to its axis. A weak ac field is superimposed on this field. The ac field oscillates in a direction perpendicular to the axis of the rod. Consequently a transverse magnetization arises in the stationary rod (owing to perturbation of the precessional motion of the elementary magnets around its axis) (in the unperturbed case its mean in the direction of axes perpendicular to the axis of the rod was zero). This effect was experimentally detected and studied.[26] In his monograph,[27] Ya. G. Dorfman suggests calling it the "Barnett-Einstein effect." Measurements of transverse magnetization have opened up yet another possibility for determining the g-factor, which was realized in Ref. 26.

6. FURTHER STUDIES

The subsequent studies of European[28,29] and American[30] physicists (we cite here the chronologically first article of Stewart,[30] not to speak of Barnett's studies, only a fraction of which were mentioned above), most of which employed the resonance method proposed by Einstein and de Haas for measuring the torsional oscillations of the studied specimens, have unambiguously shown the value of λ to be 0.57×10^{-7}. This is half the value found by Einstein and de Haas (1.11×10^{-7}), which corresponded to their simple theory that seemed unconditionally correct. This might imply an experimental error in the original study[9] as well as in the study of de Haas[10] published later.

Here we should note that Einstein and de Haas paid special attention to analyzing the source of possible errors and methods of eliminating them. Evidently, when the value of λ that they had calculated from the experimental data approached that expected from Eq. (1), they considered their work complete.[5] And Sommerfeld[32] points out that the repeated experiments of de Haas and other investigators "subsequently yielded with ever greater reliability one-half the value" of the quantity $2m/e$, which he calls the "classical value." Here Sommerfeld is referring to de Haas's article, which amounted to a translation of Ref. 10 into English. In both these studies, the discrepancy between the calculated and measured values amounted to 14%. That is, the subsequent studies of de Haas contained no substantially new results.

Let us summarize. There were cogent grounds for thinking that the experimental results of Refs. 16 and

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[4] In the Russian literature the first response to the discussed studies on magnetomechanical phenomena was the review published by P. L. Kapitsa in *Voprosy Fiziki* (Problems of Physics), a supplement to *Zhurnal Russkogo Fiziko-Khimicheskogo Obshchestva*. Kapitsa's article had the title *Inertia of electrons in Ampère molecular currents*[29] and it contained a detailed, clear analysis of the studies of Einstein and de Haas[7,9] and of Barnett.[15] In evaluating the numerical data from measuring λ obtained in Refs. 7, 9 and 15, P. L. Kapitsa expresses preference for the results of Einstein and de Haas. The same evaluation (favoring Einstein and de Haas) is to be found in O. Richardson's book *The Electronic Theory of Matter*, which was published in 1916.

We should point out that in 1919–1920 P. L. Kapitsa was conceiving and beginning to prepare an experiment whose idea consisted in demagnetizing a ferromagnetic rod by heating it to a temperature above its Curie point. The loss of orientation of the elementary magnets, or "molecular Ampère currents" must be compensated by rotation of the rod as a whole. It was proposed to detect this rotation. However, under the difficult conditions of that period, the experiment could not be finished before P. L. Kapitsa's departure to Cambridge.

[5] Lorentz showed a lively interest in this work. In a letter to Einstein he noted an inaccuracy in the text of Ref. 9. Thereupon a correction was introduced into the English-language version of Ref. 9 published in Holland, and the needed explanation was published in a German journal.[31]

28–30 were correct.[6] At the same time, Eq. (1) occasioned no doubt. This implied that the specific charge of the electron exceeds by a factor of two its well known value from firmly established data. In that pre-quantum-mechanical period rich in "anomalies," "paradoxes," and "catastrophes," the contradiction that arose became termed among physicists the "gyromagnetic anomaly."[7]

We note that the articles of Beck[28] and Barnett[17,26] show that they had (at different times) discussed with Einstein the results of their studies. However, Einstein did not analyze in print the reason for the revealed discrepancies. We can suppose that the essential fact for him was the experimental confirmation of a connection between the magnetic and mechanical properties of atoms, i.e., the existence of real Ampère currents.

The gyromagnetic anomaly, and to an even greater degree the anomalous Zeeman effect, stimulated the corresponding theoretical studies. In 1922 they led A. Landé to the formula for the g-factor (the Landé coefficient) that enters into the modern expression for the ratio of the magnetic moment to the mechanical moment, $g(e/2m)$. The value of the g-factor is determined by a combination of quantum numbers. Quantum mechanics made possible a complete interpretation of Landé's classification, with the expression for the atomic g-factor being derived in a purely theoretical manner. It was established that $g = 1$ whenever the magnetic moment of the atom is determined solely by orbital motion of the electrons. And the value of $ge/2m$ that agreed with the results of measuring the Einstein-de Haas and Barnett effects proved understandable in terms of the electron spin. The case $g = 2$ is realized just when the magnetic moment of the atom is determined by spin. It was precisely with the introduction into physics of the concept of spin that the gyromagnetic anomaly was resolved.

Thus the paradoxical situation consists in the fact that the experiments of the Einstein-de Haas effect have demonstrated the absence of a contribution to this effect from the orbital motion of the electrons. Hence, formally these experiments cannot be considered as a "proof of the existence of molecular Ampère currents!"

7. ELECTRON SPIN. CLOSING REMARKS

As we see from the material presented above, Einstein had special reasons for viewing with particular interest the work of Uhlenbeck and Goudsmit (students of his friend P. Ehrenfest) in which they proposed the concept of the spin of the electron. Ehrenfest told Einstein of the ideas of the young Dutch physicists in December 1925 in Leyden. As Uhlenbeck notes in his reminiscences of this period, in the course of a discussion with him and Goudsmit, Einstein gave an unusually simple and graphic explanation of the appearance of doublet splitting of spectral lines. On this topic Niels Bohr wrote in March 1926 to R. Kronig, "When I came to Leyden to the celebration in honor of Lorentz (December 1925), Einstein immediately asked me as soon as I saw him what I though of the rotating electron. He answered my question on the source of the interaction of the spin direction with the orbital motion that this interaction is a *direct consequence of the theory of relativity*.[8] This remark was a complete revelation to me, and from that time I have never doubted that our difficulties had come to an end."[34]

The classical experiment confirming the spin of the electron is considered to be the Stern-Gerlach experiment. Actually, as we see from the presented material, one can draw this conclusion—of course, also *a posteriori*—on the basis of the earlier experiments of Einstein and de Haas (and Barnett). The brilliant experiment of Stern and Gerlach demonstrated the fact that struck the imagination of their contemporaries that angular momentum (magnetic moment) is quantized.

This does not exhaust the definite connection between the studies of Einstein, on the one hand, and of Stern and Gerlach, on the other. Thus the first publication that implied the possible observation of splitting of an atomic beam in an inhomogeneous magnetic field, and which contained a description of the experimental scheme, was that of Stern (1921), while the results of the experiments that he performed jointly with Gerlach were presented in two subsequent articles by both authors (1922), in full parallel with the sequence of publication of Refs. 7 and 9. Moreover, we may recall that, as was noted in Ref. 35, an error was made in the process of theoretical substantiation of the Stern-Gerlach experiment. As sometimes happens, indeed it only facilitated the successful conduct of the experiment.

Einstein valued Stern and Gerlach's work highly. He wrote on May 24, 1924 to M. Besso, "Only the experi-

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[6] Immediately after the publication of Refs. 9 and 16, preference was accorded to Einstein's results (see, e.g., the cited study, Ref. 24). Interestingly, certain current textbooks affirm that Einstein and de Haas obtained the *anomalous* value (from the standpoint of the views existing in the middle 1910's) of $\lambda = 2m/e = 0.57 \times 10^{-7}$, although actually the value of λ that they determined corresponded to the expected ("normal") results.

[7] Here we shall not dwell on the circumstance that one must take into account in the studied effects the influence of the crystal lattice on the orbital motion of the electrons, and thereby on the magnetic properties of the atoms. The effect can partially or completely "freeze" the orbital angular momentum, so that the g-factor can differ from 2. However, the spin component of the magnetic moment plays the dominant role in ferromagnetic materials on which the experiments of Refs. 9 and 16 and other studies were performed (see, e.g., Ref. 33).

[8] For treating the spin-orbit interaction, Einstein proposed transforming to a system of coordinates in which the "magnetic" electron is at rest, and applying the Lorentz transformation to determine how the Coulomb field of the nucleus is transformed thereby. *(Author's remark.)*

ments of Stern and Gerlach are significant among the recent experimental results."[36] However, in essence, a more direct evidence might be an examination of the article of Einstein and Ehrenfest bearing the title "Quantum-theoretical remarks on the Stern-Gerlach experiment."[37] The article analyzes the behavior of a beam of atomic "magnets" in the field of an electromagnet and discusses the problem of how they become oriented in this field. Here the authors showed that this type of process must be accompanied by emission and absorption of radiofrequency radiation. The genetic link between this idea and modern research methods (ferromagnetic resonance, EPR) is obvious, and this is especially remarkable in view of the fact that precisely these methods can be considered to be the successors of the magnetomechanical methods.

Just as prominent associates of a great man involuntarily find themselves in the shadow cast by his monumental figure (or shine in its reflected light), the studies of Einstein discussed in this article are somewhat lost against the background of his epoch-making works. However, we should recall that, being just an episode (although an important one!) in his scientific biography, they have left a deep imprint on the physics of the first quarter of our century, and have exerted a substantial influence on the formation of our concepts of the structure of matter and on the development of methods to study it.

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