Magnetism in matter before the discovery of quantum spin:

Bohr's less well-known contribution to the transition from classical to quantum physics

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Abstract

How does one explain magnetic effects in matter when one views matter as a collection of classical charges in motion? The answer is: not at all! This is one of the points that Niels Bohr made in his doctoral dissertation in 1911, two years before addressing the issue of the stability of the hydrogen atom. The result, later rediscovered by H.J. van Leeuwen was amplified and formalized in Van Vleck's 1932 text on electric and magnetic susceptibilities and it is currently known as the Bohr-van Leeuwen theorem. We will review Bohr's two derivations, one statistical and one based on the motion of individual electrons. We will then propose reasons why this result, unlike that on the stability of hydrogen, did not lead to a major development in quantum theory but, instead, had to wait until after the introduction of spin and exchange forces in quantum mechanics to become generally known.

The classical-quantum discontinuity

- Classical Theory
  (mechanics, field theory, thermal, …)

1. Critical discoveries: x, α, β, γ, e (e/m), nucleus
2. h-bar effects: Planck, Einstein, Compton, …
3. Atomic models and stability of matter
   (Old quantum theory: Bohr & Sommerfeld)

- Quantum Mechanics
  (Schrödinger, Heisenberg, Dirac, …)

Did we miss something?

Classical Magnetism (1)

- B fields in vacuum: Maxwell's equation
- Lorentz' force: $F = q (E + v \times B)$
- Magnetism in matter

susceptibilities (~T)	Curie	1895	OK
Zeeman effect	Lorentz	1896	OK
diamagnetism	Langevin	1905	OK
paramagnetism	Langevin	1905	?
& permanent magnets	Weiss	1907	?

Classical Magnetism (2)

Failures…

Anomalous Zeeman effect

Anomalously large molecular fields

… and demise!

Bohr-Van Leeuwen theorem:

Lack of relevance of classical theory

& **Need for quantum theory!**

The PhD thesis

STUDIER OVER

METALLERNES ELEKTRONTHEORI

AFHANDLING FOR DEN FILOSOFISKE
DOKTORGRAD

AF

NIELS BOHR

KØBENHAVN
I KOMMISSION HOS V. THANING & APPEL
TRYKT HOS J. JØRGENSEN & CO. (M. A. HANNOVER)
1911

Niels Bohrs Disputats.

1. Dr. Bohr. 2. Prof. Chrisiansen. 3. Prof. Heegaard.

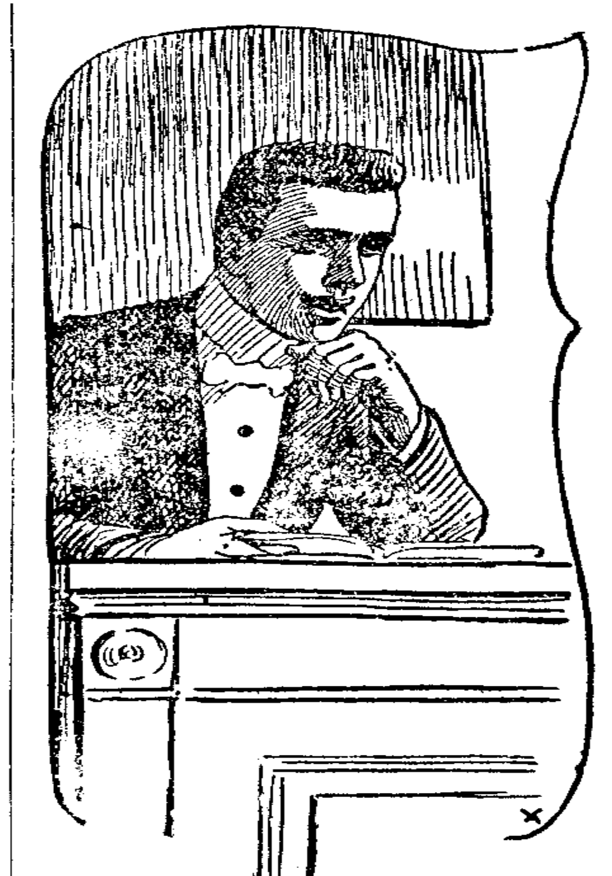
Det er kun et Aars Tid siden afdøde Professor Bohrs ene Søn, Harald, erhvervede sig den filosofiske Doktorgrad. I Gaar er den lidt yngre Broder, Magister Niels Bohr, fulgt i hans lærde Fodspor.

Meningen havde været, at Disputatsen skulde være foregaaet i Annexet; men paa Grund af det amerikanske Professerbesøg var Handlingen i Stedet for Kirken henlagt til et beskedent Auditorium paa selve Universitetet. Dette havde til Følge, at Tilhørerne maatte staa langt ud paa Gangen, og det var for saa vidt af det gode, at Opponenterne temmelig hurtig fik sagt, hvad de havde paa Hjerte.

Metallernes Elektrontheori, der er Emnet for Niels Bohrs Afhandling, er jo ogsaa et rent specielt Emne, og den første af Opponenterne, Professor Heegaard, dvælede i en Kritik af den sproglige Fremstilling væsentlig ved Udenværkerne. Mere ind paa det reelle kom den anden Opponent, Professor Christiansen, der havde megen Anerkendelse tilovers for Doktorandens Arbejde.

Prof. Christiansen mindede om, at efter H. C. Ørsted var Lorentz den Dansker, der havde været bedst hjemme paa det videnskabelige Omraade. Talen var om, og Professoren havde altid plejet at tage ud til Lorentz, naar han i herhen hørende Spørgsmaal vilde have Besked. Siden Lorentz' Tid havde vi ikke havt nogen Fagmand paa det omhandlede Felt, og Opponenten sluttede derfor med at udtale sin Glæde over, at dette Savn nu med Niels Bohr var afhjulpet.

Report of the defense of Niels Bohr's thesis published in the Copenhagen newspaper *Dagbladet*.



Dr. Bohr.

Niels Bohr defending his thesis

(*Politiken*, 14 May 1911)

“The late Prof. Bohr’s other son”

	Niels	Harald
	Physics	Mathematics
	1885-1962	1887-1951
M Sc	Nov 1909	April 1909
PhD	May 1911	June(?)1910

HARALD AND NIELS BOHR AS STUDENTS


NIELS BOHR
HARALD BOHR

The choice of topic

MS: 6 weeks for paper in a field to which the student has shown special interest and dedicated special attention (May ‘09) & exam (Nov ’09)

“Give an account of the application of the electron theory to explain the physical properties of metals”

PhD (May ‘11), continuation of MS topic, defense, 2 opponents

Christian Christiansen, mentor, opponent

A Danish Topic?

- **Oersted, Hans Christian** 1777-1851
  Magnetism related to electric current
- **Lorenz, Ludvig Valentin** 1829-1891
  Lorenz-(Lorentz) gauge (E&M)
  Wiedemann-Franz-Lorenz (thermal, electrical)
  Lorentz-Lorenz equation (dielectrics)
  Lorenz-Mie (light scattering)
- **Christian Christiansen** 1843-1917

Studies on the electron theory of metals

- Chap 1 equations of motion
- Chap 2 stationary systems
- Chap 3 non stationary systems
- Chap 4 influence of magnetic fields

  I states of statistical equilibrium

  II galvano and thermomagnetic effects

1. Statistical: (NR, thermal & electric equilibrium)

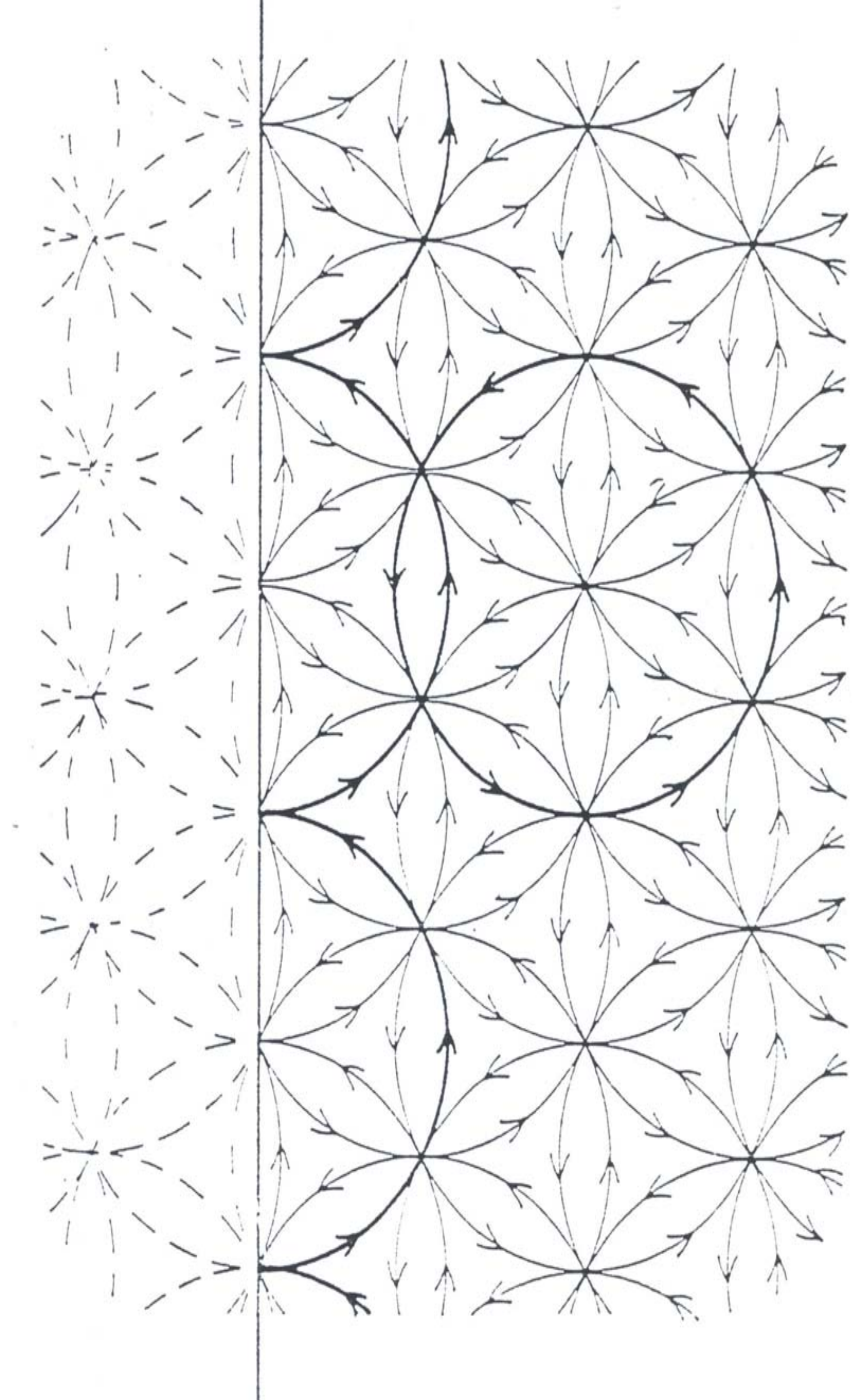
   $B \rightarrow \Delta v \rightarrow \Delta B?$ $f(x,y,z,v_x,v_y,v_z) \rightarrow \Delta f(B)?$

2. Trajectories:

   effect of boundaries

Consider:

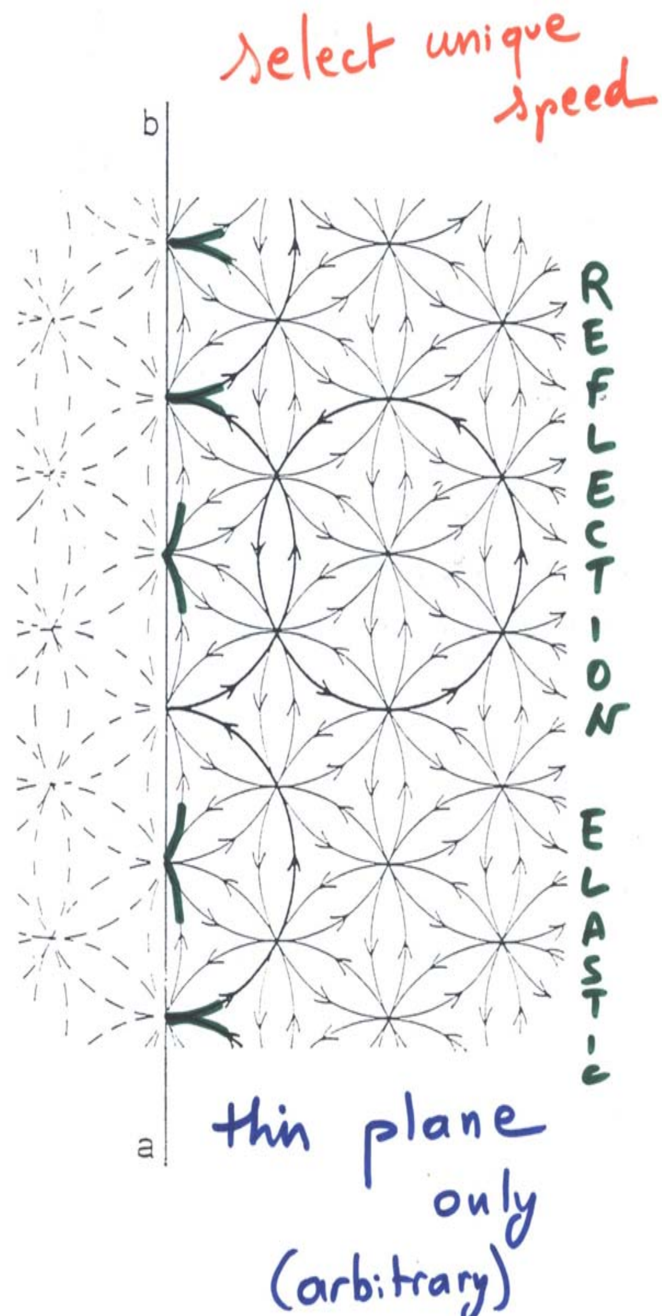
- slice of matter
- e in plane
- B $\perp$ plane
- boundary
- same v



elastic reflection

at

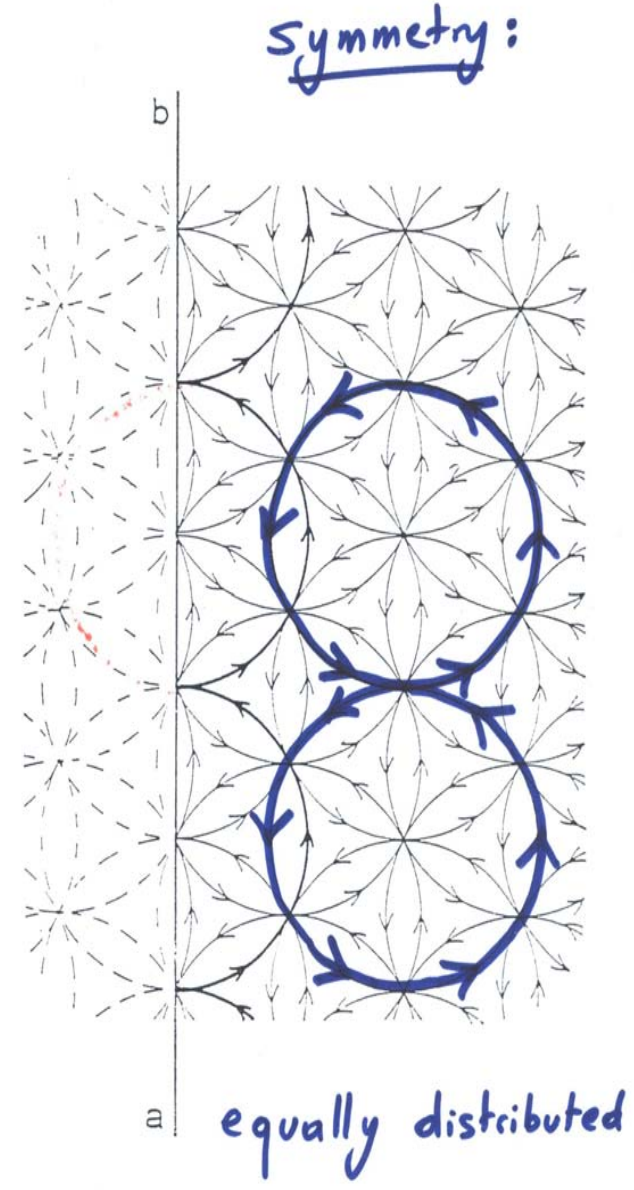
the boundary



- Statistical argument

  Far from wall:
  Still in statistical equilibrium,

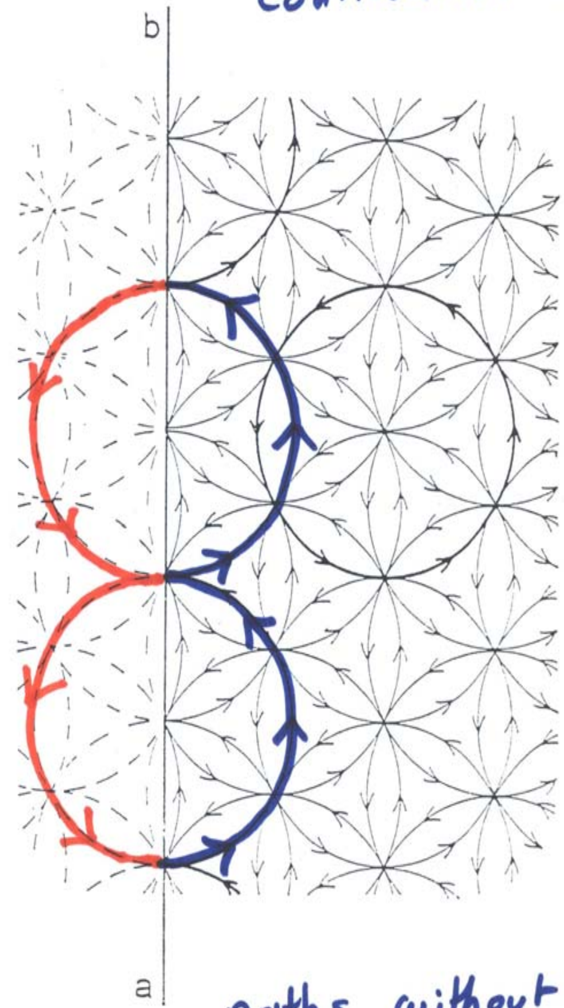
  Equally distributed in all directions



- Statistical argument

  Close to wall:
  Still in statistical
  equilibrium,

  Same distribution
  as if no wall

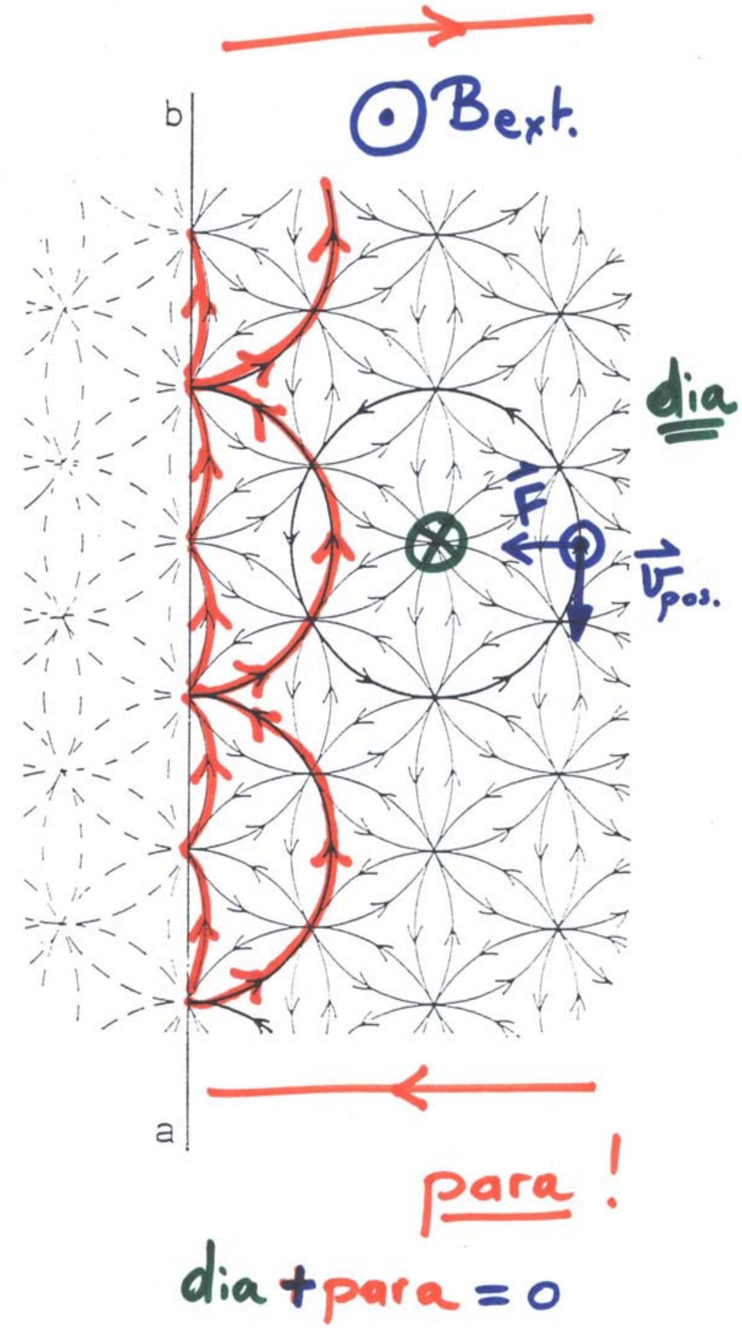


paths : direct
continuation of

paths without
boundary
⟹ equilibrium

Paths of individual Electrons

Closed orbit
Counteracting
Lenz' law!



Bohr's Summary & 6th thesis

It is shown that the presence of free electrons in a metal will give rise neither to diamagnetic nor to paramagnetic properties

It does not seem possible at the present stage of development of the electron theory to explain the magnetic properties of bodies from this theory

What happens to Bohr?

- Carlsberg offers one year post doc in UK
- Cambridge: Thomson is unreceptive

(“It was a disappointment that Thomson was not interested to learn that his calculations were not correct”)

- Manchester: Rutherford offers a new challenge

Upon his return to Denmark, Niels Bohr:

- gets married
- teaches in Copenhagen
- creates Bohr Institute

Miss H.J. Van Leeuwen

- Thesis in Leiden (Lorentz and Ehrenfest)
- Le Journal de Physique et Le Radium (no calculations) VI, 11, 361-377 (1921)
- Considers specific “molecules” and specific “collisions”, statistical argument
- Finds zero susceptibility (in Bohr’s case)
- Comprehensive comparative bibliography

(Lorentz, Langevin, Schrödinger 1908)

LE JOURNAL DE PHYSIQUE

ET

LE RADIUM

PROBLÈMES DE LA THÉORIE ÉLECTRONIQUE DU MAGNÉTISME

Par Mlle H.-J. VAN LEEUWEN.

I. — Introduction.

Dans cet article (¹) la théorie électronique du magnétisme sera étudiée sur les cas les plus simples. Il y a encore de grandes divergences d'opinion sur les points principaux de cette théorie; il suffit, pour s'en rendre compte, de comparer les résultats de *Langevin* [13] (²) et *Kroo* [12]. Le premier conclut, qu'on peut expliquer aussi bien le dia- que le paramagnétisme; le dernier, que la théorie électronique ne peut expliquer que le diamagnétisme. Il semble donc justifié de tirer jusqu'au bout les conséquences d'une méthode généralement admise, en l'appliquant aux hypothèses les plus simples qu'on puisse faire sur la constitution des molécules, afin d'obtenir des résultats auxquels on comparera ceux des auteurs précédents. C'est la méthode du théorème H de *Boltzmann* [2] que nous emploierons. Cette méthode est seulement applicable au cas des gaz, où les molécules ne s'influencent mutuellement dans leurs mouvements qu'aux moments des chocs et aux températures assez élevées pour que les lois de la mécanique classique soient encore valables, et que les quanta ne jouent aucun rôle. Nous négligerons aussi toute radiation due aux mouvements des charges électriques, sans quoi aucun état stationnaire n'est possible. Les mouvements doivent donc être quasi-stationnaires. L'application de la méthode ne réussit tout à fait que pour des hypothèses spéciales faites sur la constitution de la molécule et sur le caractère des chocs. Ces hypothèses sont choisies en accord avec les travaux antérieurs. Quelques remarques sur le problème général suivront le traitement des cas spéciaux. La littérature relative à ce sujet sera discutée très brièvement.

(¹) Extrait d'une thèse soutenue à l'Université de Leyde, où se trouvent les démonstrations et les calculs supprimés ici. Elle est citée comme « thèse de Leyde ».

(²) Les nombres entre crochets se rapportent à la liste de référence placée à la fin de l'article.

What happens to the PhD work?

- 1911-1913 Bohr tries to publish in English
- Translation (with Lautrup) “rather poor”
- Royal Society: does not publish “criticism”
- Cambridge Philosophical Society: too long
- 1915 & 1920 : publication attempts in USA
- 1920: Bohr “only method useful”
- 1928: Bohr : ”no physical interest”

Letter to Hume-Rothery (1928)

"Nowadays the old theories based on the classical mechanics can hardly make claim of actual physical interest. Indeed they are left quite behind by the recent fundamental work of Sommerfeld which has just been published in Zeits.f.Phys. Although not yet complete, Sommerfeld's work surely means a decisive step as regards the adequate quantum theoretical treatment of the metallic problem…"

What happens to magnetism?

- Quantum mechanics 1925, new theory
- Spin 1925, permanent magnets
- Quantum theory of solids, 1928
- Dirac equation, 1928, solidifies spin
- Slater: many-electron wavefunctions
- Heisenberg, … exchange forces
- Van Vleck 1932 “The theory of electric and magnetic susceptibilities”
- Pauli, 1932 “Le Magnétisme” (Solvay, sixth)

Conclusion (1)

- The inability to explain magnetic properties of matter is a major failure of classical theory, comparable to the instability of matter.
- It was Bohr who rigorously demonstrated this inability in his PhD thesis (1911).
- Unlike his solution for the atomic stability problem (the 1913 Bohr model) this contribution has not been retained as a major development in the transition from classical to quantum

Conclusion (2)

- Several reasons can be found to explain this: the language and cultural barrier, Bohr's uncompromising personality, his personal circumstances, the difficulty of the problem, the apparent lack of complete solution until the advent of quantum mechanics and spin, …

- Whether seen as a rich web of coincidences or explained as the coherent story of one scientist's professional development, the facts are compelling and deserve to be better known.

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