Magnetic field effects and dualistic theory of metallic conduction in Italy (1911 - 1926): cultural heritage, creativity, epistemological beliefs, and national scientific community.[1]

Silvana Galdabini[a] and Giuseppe Giuliani[a,b]
[a] Gruppo Nazionale di Storia della Fisica del CNR, Unità di Pavia.
[b] Dipartimento di Fisica 'Volta' dell'Università, Pavia

Summary
The development of researches on thermo and galvanomagnetic effects in Italy between 1911 and 1926 has been studied taking into account several factors: the partial isolation of Italian physics community; its delay in adopting the microscopic and statistical approach to the conduction properties of metals; the choice of a dualistic theory of conduction (based on two charge carries) in a context of predominance of theories in which the only mobile carrier was the electron; an epistemological stand that privileged the theory-experiment relation with respect to the theory compatibility with the background knowledge.

Contents

1 Corbino and the disc

The interest of Italian physicists for magnetic field effects on conduction properties of metals dates back to 1850, when Maggi sought for a magnetic

[1] A preliminary account of this study has appeared in: Galdabini G., Giuliani G. 'Early lines of research in Italy: 1900-1940', in *The Origins of Solid State Physics in Italy: 1945-1960*, edited by G. Giuliani (Bologna, 1988), 1-14, (pp. 3-6).

effect on thermal conductivity of iron.[2]

Maggi's pioneering work has been followed by many experimental contributions, particularly after the discovery of the Hall effect. [3] These contributions seldom dealt with the theoretical explanation of the phenomena, reflecting a main feature of Italian physics of those times. This scarce theoretical commitment stresses the novelty represented by Corbino papers appeared in 1911. [4] , [5] These papers contained the theory and the experimental results of what later will be referred to as the 'Corbino effect' or the 'Corbino disc'. Breaking with a long-lasting tradition, Corbino not only dealt with the theoretical treatement of magnetic effects but he presented first the theory and then the experimental results for three of the four new effects that he claimed to have found. [6] Corbino used Drude's theory of metallic conduction based on two types of charge carriers, defined 'second kind' electrodinamic phenomena and predicted phenomena, distinct from the Hall effect, dependent on the existence of two types of carriers.

Corbino's choice and use of dualistic theory of conduction is interesting for several reasons:
a) it was made and held in a context of increasingly predominance of the electron theory of metallic conduction. In fact, though Lorentz's stand had been characterized, at least at the beginning, by a cautious choice in favour

[2]Quoted by Campbell L.L., *Galvanomagnetic and thermomagnetic effects*, (London, 1923), p. 253.

[3]See, for instance, the bibliography in Campbell's book (footnote 2), 273-308.

[4]Corbino O. M. 'Azioni elettromagnetiche dovute agli ioni dei metalli deviati dalla traiettoria normale per effetto di un campo', *Il Nuovo Cimento*, 1 (1911), 397 - 419; a translation of this paper was published in *Physicalische Zeitschrifts*, 12 (1911), 561 - 568; reports of this work have been also published in *Rendiconti della Reale Accademia dei Lincei*, 20, I (1911), 342-344, 416-423, 424-428, 569-574, 746-749.

[5]Corbino, then thirtyfive, was an already successfull physicist; winner of a chair of experimental physics in 1905, he was called to Rome in 1908, after a three years stay in Messina. President of the Italian Physical Society from 1914 to 1919, he became progressively engaged in political and economical activities. Appointed as senator on october 1920, he held the Ministry of Public Instruction from July 1921 to February 1922 and the Ministry of National Economy from August 1923 to June 1924. In late 1920's and in the 1930's, he used his power for supporting the birth and the growth of Fermi's group. He has certainly been the most distinguished Italian physicist of his generation. For more detailed biographical notes, see for instance: *Dizionario Biografico degli Italiani* vol. 28, (Roma, 1983), pp. 760-766.

[6]We shall discuss at length only the first effect found by Corbino: the generation of a circular current in the disc. We shall touch upon a second effect later.

of the monistic approach, in the 1910's, the physics community was clearly on the monistic side. L.L. Campbell in his beautiful review book discussed twelve theories of the Hall effect appeared between 1900 and 1919: only one, beside Drude's, was dualistic.[7,8]

b) Corbino did not justify his choice, and did not worry about what was meant by mobile positive charges. He usually spoke of 'negative and positive ions' or of 'positive and negative electrons', using both expressions as synonymous of 'charge carriers'. He never presented a model for his dualistic conduction.

c) Corbino constantly underevaluated the problems faced by the 'electronic theory of metallic conduction'. [9]

d) Corbino eventually tried to justify his dualistic choice; but he did it only in 1920, after having being criticized by another Italian physicist, Michele La Rosa.

Second kind electrodinamic phenomena were defined as those which depend on concentrations and properties (charge, mobility) of the two carriers: given the current, they depend on the partition of the current between the two carriers.

As for the expectation of new phenomena, it is important to keep in mind Corbino's view of the Hall effect. Corbino, described the Hall effect as a deformation of the equipotential lines induced by the magnetic field. [10] Consequently, the Hall effect was viewed as a violation of the Ohm law in tridimensional conductors. Therefore:

> It was natural to conceive the idea of passing from the Ohm law's chapter to other chapters of electricity: the electromagnetism, the electrodinamic forces, the electromagnetic induction; and to examine which new effects of the second kind can be predicted and experi-

[7] Campbell L. L., (footnote 2), pp. 69 - 94.

[8] We list as dualistic only those theories that assume two mobile carriers; a theory which bring into play, through some mechanism, the fixed positive ions is considered as monistic.

[9] In particular Corbino underevaluated the fact that the theory was not able to explain: i) the temperature dependence of conductivity without introducing an 'ad hoc' hypothesis on the temperature dependence of carriers' concentration; ii) the observed negligible contribution of electrons to the specific heat of metals.

[10] The description of the Hall effect in terms of the distorsion of the equipotential lines dates back to the discovery of the effect. However, in the 1910's, this kind of description must be considered as typical of a conceptual approach centered on macroscopic quantities (voltages and currents) instead of the microscopic ones (properties of charge carriers).

mentally confirmed. [11]

Corbino used a disc, instead of the more usual rectangular plate. The internal electrode was a wire connected to the center of the disc; the external one was a circular ring placed on the circumference; the magnetic field was perpendicular to the disc. The use of a disc was by no means a novelty. Maggi used a disc for his studies. Hall too, during his first attempts to find a magnetic field effect on the electrical resistance of metals used a disc with electrodes placed at the center and at the periphery: Hall failed to detect the expected increase in resistance and did not publish the results. [12] Boltzmann developed a theory for the magnetic field effect on a radial current in a circular plate. [13] He found that the magnetic field transforms the current lines into logarithmic spirals; as a consequence the radial resistance is increased by a factor $1+(\sigma RB)^2$ where σ is the conductivity, R the Hall coefficient and B the magnetic field. According to Boltzmann, 'Prof. Ettingshausen found for a bismuth disc corresponding to these conditions ... [results] which agree tolerably with the formula ...'. [14]

Apparently Corbino was not aware of Boltzmann's work. But he was not alone. None of Corbino's contemporaries who worked on and discussed about Corbino effect, recalled that the main features of the theoretical treatment of the disc had already been given by Boltzmann and that a preliminary experimental check of Boltzmann's theory had already been made by Ettingshausen. Nor did it L.L. Campbell in his review book. The silence of Campbell is particularly puzzling, since he quoted (and discussed to some extent) Boltzmann's papers together with Ettingshausen and Nernst's. [15]

Corbino developed the theory of the disc by writing down the equations of motion of positive and negative charges under the combined action of a radial electric field and of a magnetic field perpendicular to the disc. He showed that the paths of the charges are logarithmic spirals and that the total current due, for instance, to positive charges, may be espressed as the sum of a radial and a circular component.

Corbino's treatement gave the same general results obtained by Boltzmann 25 years before. However, there were two basic differences. Since

[11] Corbino, O.M., (footnote 4), 398.

[12] Buchwald, J.Z. *From Maxwell to Microphysics*, (Chicago, 1985), p. 89.

[13] Boltzmann L., *Anzeiger der Kaiserlichen Akademie der Wissenschaften in Wien*, (1886), 77 - 80; *Philosophical Magazine*, 22 (1886), 226 - 228.

[14] Boltzmann L. (footnote 13), 227.

[15] Campbell L.L. (footnote 2), 20-21, 77-78.

Corbino supposed two charge carriers, the total current appeared as the sum of two components and the predicted effetcs depended on the properties of the two charge carriers (with the possibility that the combined effects of the two components cancelled). Boltzmann viewed the deviations of current lines from the radial path as the cause of an 'apparent' increase of the radial resistance (this effect will be later called magnetoresistance). Following Boltzmann, Ettingshausen and Nernst looked for an increase of the radial resistance. Corbino viewed instead the current due to a charge carrier as the sum of a radial and a circular component and, consequently, looked for the experimental detection of the circular current, neglecting any magnetoresistance effect. Corbino's view of the effect stressed the peculiarity and the importance of the circular geometry and allowed him to discover the macroscopic effects connected with the induced circular current. [16]

According to Corbino, the observed effect

> ...is not a simple variation of the Hall effect, but it yields another *independent* relation for the characteristic constants of a metal. [17,18]

Corbino's arguments were: the observed effect depends on conductivities and mobilities of charge carriers, while the Hall effect depends also on the temperature dependence of carriers' concentration; [19] the order of magnitude of the two effects is quite different.

The former argument is wrong: also Corbino effect depends, through the conductivities, on carriers' concentration and, therefore, on their supposed temperature dependence. The other argument as well did not escape criticism. Corbino, on the assumption of equal numbers of positive and negative

[16] The detection of the effect, i.e. of the circular current, was performed by looking for the current induced in a plane coil wound around the disc, by switching on and off the radial current in the presence of the magnetic field. (Switching on and off the radial current without the magnetic field does not induce any current in the measuring coil, as one should expect from simmetry considerations). However, the current induced in the measuring coil was a transient one and, in any case, it did not yield quantitative information on the circular current. Therefore, Corbino placed a wire around the disc and measured the current in the wire 'equivalent' to the circular current (i.e. the current in the wire with the same inductive action on the measuring coil as that of the circular current in the disc).

[17] Corbino's italics.

[18] Corbino O.M. (footnote 4) 405.

[19] The temperature dependence of carriers' concentration was assumed by Drude's theory of electrical conduction in metals and was common also to some monistic versions of the theory.

carriers and of the same temperature dependence of their concentrations, obtained the following relation between the circular current C and the Hall coefficient R:

$$C = \sigma R(2KIH) \tag{1}$$

where σ is the electrical conductivity, R the Hall coefficient I the radial current, H the magnetic field and K a factor depending on the circuitry. Since Corbino was interested in the relative magnitude of the two effects, he dropped the term $2KIH$ on the right side of equation (1) and observed that while $\frac{R_{Te}}{R_{Ag}}$ is about 6.5×10^5, the ratio of the 'electromagnetic effect' for the two materials (measured by C) was only 5; for bismuth and silver the ratio between the Hall coefficients is about 11×10^3 while that between the C's is only about 150.

Equation (1) should have induced Corbino to be careful in drawing conclusions about the distinction of the two effects. In fact, equation (1) correlates them and suggests that the quantities to be compared are C and $R\sigma$. [20]

The question if Corbino effect is a 'true' Hall effect, was discussed at some length. E.P. Adams in the first foreign paper on Corbino effect wrote:

> Professor Corbino regards this effect ... as something distinct from the Hall effect. It is certainly true that if the Hall effect is defined as a bending of the equipotential lines by the magnetic field, then this effect is different. For in this case the equipotential lines are concentric circles both in and out the magnetic field. It seems to me, however, that the effect described by professor Corbino is, essentially, the Hall effect, but measured in a different way from that usually employed. In fact, his method seems to be the ideally simplest way to measure the Hall effect. [21]

And, in a following paper:

> The Corbino effect would seem to be the fundamental galvanomagnetic effect, rather than the Hall effect, in that the free transverse boundaries necessary in the latter effect are wholly absent in the Corbino effect. And it is known that these free boundaries introduce very considerable complications into the interpretation of the

[20] This remark has been firstly made by Chapman. However Chapman did not comment on equation (1). See: Chapman K.A., 'The Hall and Corbino Effects', *Philosophical Magazine*, 32, (1916), 303 - 326.

[21] Adams E.P., 'Some Electromagntic Effects related to the Hall effect', *Philosophical Magazine*, 27 (1914), 244 - 252, p. 249.

> Hall effect. The fundamental explanation of one effect will, however, explain the other effect. [22]

Campbell, in his book, essentially followed Adams' arguments and titled the corresponding paraghaph 'The Corbino Effect a True Hall Effect'. [23] Corbino did not enter this debate. In his following papers he went on looking at the Hall effect as a bending of the equipotential lines, thereby maintaining a clear distinction between Hall and Corbino effect. He changed his mind only in 1926.

As said above, Corbino made the dualistic choice without a comment, as though the assumption of the existence of two types of carriers were unproblematic. Nor did Corbino stress that the dualistic approach could easily explain the positive value of the Hall coefficient found in some materials. But there was more: the already quoted paper by Adams [24] was simply a description of Corbino's experimental results in terms of the monistic theory of electrical conduction. As far as we know, all foreign works on Corbino effect were based on a monistic interpretation of the experimental results. However, Corbino simply ignored what was going on abroad and kept on the dualistic way. This attitude was shared by the Italians physicists who, on Corbino's wake, worked on galvanomagnetic effects in the following years. This attitude was associated with a tendency of not quoting papers (particularly, but not only, foreign) on the same or related arguments: the only exception was a paper by Elena Freda appeared in 1916. [25] However, in spite of several quotations of foreign papers, in this case too, the dualistic theory was followed without discussion. This attitude can be understood only in terms of a partial isolation of the Italian physics community. Corbino was, among Italian physicists of his generation, the most attentive observer of new trends in physics; he was an expert in galvanomagnetic effects and he knew wery well the contemporary literature on the argument. Therefore, his ignorance of the monistic approach to the conduction properties of metals must be considered as intentional. The fact that Corbino and the other Italians could escape from discussing their dualistic choice in a context of a widespread diffusion of the monistic approach can be understood only in

[22] Adams P.E., Chapman A.K., 'The Corbino Effect', *Philosophical Magazine*, 28 (1914), 692 - 702, p. 693.

[23] Campbell L. L., (footnote 2), pp. 127-129.

[24] Adams E.P. (footnote 21).

[25] Freda E., 'Sulla variazione di resistenza elettrica di un conduttore sottoposto all'azione di un campo elettromagnetico', *Il Nuovo Cimento*, 12 (1916), 177 - 193.

terms of a basic hypothesis about Italian physics community: the evaluation of research activity of Italian physicists was mainly based on national scientific production and largely ignored foreign contributions. The fact that Corbino was forced to defend his dualistic choice only when criticized in 1920 by another Italian physicist, Michele La Rosa, must be considered as a strong support for this view.

2 The birth of a line of research

Corbino's 1911 paper prompted the birth of a line of research on galvanomagnetic effects in Italy characterized by the use of the dualistic theory. Corbino was explicitly recognized as the founder of this line. The lengthy article by Vito Volterra appeared in 1915 began with: 'Prof. Corbino has shown that the laws describing the flow of electric currents in a homogeneous metallic plate under the action of a uniform magnetic field ...'; and: 'In this memoir, starting from the laws [Corbino's] above, I will develop the mathematical theory of electric current flow in a plate under the action of a magnetic field'. [26] In the same volume a paper by Miss A. Alimenti began with: 'Prof. Volterra, bearing on the laws established by Prof. Corbino, ...' . [27]

For Volterra, as for Corbino, the fundamental entities were currents and voltages. Moreover, his results were independent from the expression of the parameters which appear in the formulas giving the components of the current as a linear combination of the components of the electric field. Therefore, they could be used in combination with any microscopic theory of electrical conduction (monistic or dualistic). As a matter of fact, at the beginning of his paper, Volterra wrote down the expressions for these parameters found by Corbino ; but he never used them. Volterra claimed to have founded his work on the equations found by Corbino. However, what he really needed, were the basic equations relating currents and potentials: he found these equations in Corbino's paper and attributed their discovery to Corbino. However, these equations can be found as early as 1880 in a paper by Lorentz. [28] Furthermore, their dualistic interpretation, though not in the form given by Corbino,

[26] Volterra V., 'Sulle correnti elettriche in una lamina metallica sotto l'azione di un campo magnetico', *Il Nuovo Cimento*, 9 (1915), 23-79, pp. 23-24.

[27] Alimenti A., 'Il fenomeno di Hall in una lamina circolare' *Il Nuovo Cimento*, 9 (1915), 109-117, p. 109.

[28] Quoted by Campbell (footnote 2), 76-77.

dates back to the work by Drude. Corbino's contribution to the conduction theory appears then largely overestimated; on the other hand the relevance of Corbino's disc has been underevaluated by the Italian group and, to a lesser extent, by Corbino himself. As we have seen, abroad the situation was just the opposite. This different evaluation of Corbino's work appears as another manifestation of the partial isolation of the Italian physical community.

The year 1915 has a particular relevance for our story. The first 122 pages of the ninth volume of Il Nuovo Cimento contained nine papers (out of a total of 28) on galvanomagnetic effects. The first was by Hall (then in Italy); the second by Corbino; the third was the already quoted article by Volterra. Likely, the sequence of these three papers reflected a kind of 'galvanomagnetic hierarchy'.

Corbino's 1915 paper presents some interesting features. [29] As in 1911, his fundamental entities were currents and potentials: carriers' mobilities entered his equations, but they were not in the focus of Corbino's concern. Corbino showed that, in general, under the action of a magnetic field, the current does not have the same direction of the electric field: two limiting cases are that of a rectangular plate (with the electrodes carrying the primary current having high resistivity) and that of the disc. In the former case the current lines are unaffected by the magnetic field while the equipotential lines are rotated with respect to them. In the latter the situation is reversed. Corbino wrote down also the equation of the current density along a current line as a function of the corresponding component of the electric field: the proportionality coefficient, i.e. the conductivity, appeared to depend on the magnetic field. Corbino did not comment on this point; as we shall see, he used this equation only in 1918.

Volterra's work on distribution of currents and voltages was further developed by Miss A. Alimenti [30] and partially tested experimentally by Alimenti [31] and Tasca Bordonaro. [32] Three of the remaining five papers dealt with

[29] Corbino O.M., 'Il movimento della elettricità in una lamina metallica sottoposta all'azione di un campo magnetico', *Il Nuovo Cimento*, 9 (1915), 13-22.

[30] Alimenti A. (footnote 27).

[31] Alimenti A. 'Il fenomeno di Hall in una lamina circolare', *Il Nuovo Cimento*, 11 (1916), 217-220.

[32] Tasca Bordonaro G., 'Su alcune conseguenze della teoria generale del fenomeno di Hall', *Rendiconti della Reale Accademia dei Lincei*, 24, I (1915) 336-341. Tasca Bordonaro G., 'La verifica del principio di reciprocità di Volterra, nel caso generale', *Rendiconti della Reale Accademia dei Lincei*, 24, I (1915), 709-711.

applications of the macroscopic properties of the disc found by Corbino in 1911. [33]

In 1916 appeared the already mentioned paper by Elena Freda. [34] Miss Freda showed that, starting from the equations used by Corbino in 1915, it is possible to describe magnetoresistive effects within the dualistic approach. As Corbino put it in his 1918 paper:

> In a theoretical study on the electrical current flow in a [metallic] plate at a constant temperature under the action of the [magnetic] field, it has been pointed out that the proportionality coefficent between the potential drop along a flux line and the current density varies with the field. Since that coefficient is a measure of the specific resistivity of the conductor, Miss Freda, in a valuable paper, claimed, against Drude's opinion, that the dualistic theory can account for the observed resistance variations. [35]

As already observed above, Corbino, in his 1915 paper, did not stress this point and, very likely, did not grasp the relevance of his results for magnetoresistive effects. It was the second time that, during his studies, Corbino encountered magnetoresistance effects without recognizing or adequately appreciating them.[36] Corbino overlooked these hints because he was quite sure that Drude's theory could not explain magnetoresistance effects. [37] In 1918,

[33] Corbino and Trabacchi set up a device behaving as a dc motor or dc generator based respectively on the magnetic properties of the circular currents and on the radial electromotive forces induced in the disc. The device was not suitable for technical exploitation; however, it confirms that Corbino was deeply interested in the macroscopic behaviour of his disc. Tieri dealt instead with a 'thermal motor' based on the magnetic properties of the circular currents induced in the disc under the action of a perpendicular magnetic field when a radial thermal current flows. Corbino O.M., Trabacchi G.C., 'Un generatore invertibile per correnti continue senza collettore né contatti striscianti, fondato sulle azioni elettromagnetiche di seconda specie', *Il Nuovo Cimento*, 9 (1915), 80-94; Tieri L., 'Motore termico fondato sulla rotazione che subisce un disco di bismuto riscaldato al centro e alla periferia, nel campo magnetico', *Il Nuovo Cimento*, 9 (1915), 99-101; Tieri L., 'Rotazione, nel campo magnetico, di un cilindro di grafite e deduzione, per questa sostanza, del prodotto delle costanti caratteristiche di Drude', *Il Nuovo Cimento*, 9 (1915), 102-108.

[34] Freda E. (footnote 25).

[35] Corbino O.M., 'Variazioni magnetiche di resistenza e diminuzione del coefficiente di Hall al crescere del campo', *Il Nuovo Cimento*, 16 (1918), 185-196.

[36] The first one had been in 1911 when he dealt with the theory of the disc.

[37] As a matter of fact, Drude tried to explain magnetoresistance as a kind of feedback of the Hall effect. However, this mechanism can not account for magnetoresistive effects if the plate is kept at a uniform temperature. See, for instance, Corbino (footnote 35), 185.

spurred by Freda's paper, he came back to his 1915 equation and dealt, among other things, with magnetoresistance effects. Corbino showed that magnetoresistance effects depend, in general, on sample's geometry and electrodes' shape; however, they are independent from these factors in the two limiting cases of current or equipotential lines invariance. One case of current lines invariance is given by the usual rectangular plate with point electrodes; an example of equipotential lines invariance is given by Corbino's disc. In both cases Corbino found that magnetoresistance effects depend quadratically on the magnetic field;[38] that they are more pronounced in the case of the disc; that, in a rectangular plate, magnetoresistance effects disappear if only one type of carrier is present. Finally, Corbino wrote down the equation for the Hall coefficient dependence on the magnetic field: in this case too, this dependence disappears if only one type of carrier is present. Corbino's results were soon experimentally 'fully confirmed' by his assistant, Trabacchi. [39] Unfortunately Corbino's relations, though qualitatively correct, were quantitatively wrong. But neither Corbino nor his contemporaries could know that. Therefore Corbino results should have been regarded with interest. As a matter of fact they have been reported, together with Trabacchi's data, in Campbell's book. [40] However, Campbell did not comment upon these results. In particular he did not stress that, according to Corbino, the presence of two types of carriers is necessary for explaining important features of magnetoresistance and Hall effects. Campbell's stand can be understood on the basis of his skepticism about dualistic approach. In fact, though Campbell did not take an explicit position on the monistic-dualistic debate, his implicit choice was clearly in favour of monistic theories.

3 The debate on positive electrons

In the same year La Rosa entered the scene. In a paper published in il Nuovo Cimento he wrote:

> To-day's electronic theory which so successfully deals with many relevant metallic properties, gives only a rough description of the

[38] The quadratic dependence on magnetic field was theoretically known since a long time. See the above discussion of Boltzmann's contributions.

[39] Trabacchi G.C., 'Determinazione delle costanti elettroniche del bismuto', *Il Nuovo Cimento*, 16 (1918), 197-212.

[40] Campbell L.L., (footnote 2), 208.

> Hall effect and only for those metals that present a negative effect ... For metals ... that present a positive effect, every explanation effort, even of the raw experimental fact, has completely failed.

And in a footnote:

> Drude's hypothesis about the existence of a double current of electrons of opposite sign may explain the positive Hall effect, but, as it is known, this hypothesis had shown untenable for various theoretical and experimental reasons during the following development of the entire electronic theory.[41]

In an another paper appeared one year later, La Rosa, in a footnote added in proofs, wrote:

> ... Prof. Corbino has published a work on this argument in which the presence of two kind of electrons is supposed. As it is known, this hypothesis is not supported by experimental facts, and leads to very great difficulties in the development of other branches of the electrons' theory ... so that every effort towards an explanation of the facts in the framework of the generally accepted theory (which admits of negative electrons only) maintains all its value. [42]

And in another footnote, already present in the original paper:

> The expedient of ascribing the electrical phenomena in metals to two kinds of electrons does not avoid the necessity of thinking that n [the electron concentration] must be a function of H. This fact is sufficient for preferring the common electron theory to the *dualistic* attempts that sometime are made. The dualistic hypothesis, after all, simply exploits the arbitrariness introduced in the theory by the new entities (number and velocity of positive particles) in order to account for some relations that the usual theory (the *unitary*), in its present form, does not satisfy. However, when in this [theory] we admit - as we have seen that *it must be done* - that n is a function of H, we get a much greater freedom. And it is clear that the natural logical process forces us to exploit entirely the new possibility before deciding to complicate further the theoretical frame by introducing

[41] La Rosa M., 'Sopra l'influenza che la natura degli elettrodi secondari può avere nelle misure di effetto Hall', *Il Nuovo Cimento*, 15 (1918) 89-99, p. 89

[42] La Rosa M., 'Un confronto fra la teoria elettronica dei metalli e l'esperienza. La relazione fra il potere termoelettrico e resistenza del bismuto, come funzioni del campo', *Il Nuovo Cimento*, 18, (1919) 39-55, p.40.

> a second kind of particles, up to now inaccessible to experience. [43], [44]

La Rosa criticism, though appeared in footnotes, constituted an open attack on the dualistic approach. However, it was not harder or better argumented than others appeared before in the international literature. [45] Another Italian physicist, Collodi, wrote in 1920:

> However, the results obtained by developing this hypothesis [the dualistic one], though outstanding from the mathematical point of view, are less important from the physical one. In fact, the hypothesis is used for explaning the observed phenomenon and it can not be related to other experimental facts in order to strengthen its plausibility. [46]

The criticism of Corbino's dualistic approach coming from his Italian colleagues was many-sided: the hypothesis of two kinds of electrons is not supported by experimental facts (La Rosa); it is in contrast with 'other branches of electrons' theory' (La Rosa); it is an 'expedient' (La Rosa); it is based on a ad hoc hypothesis (Collodi). The criticism was then methodological in character and aimed at the heart of Corbino's approach.

Corbino's answer was quick and intense: during thirteen months (June 1910, July 1921) he presented four memoirs on the argument to the Accademia dei Lincei. These papers amount to two thirds of Corbino's entire scientific production in the two years period 1920-21. Corbino's reaction was somewhat hurried and uneasy: he probably felt to be attacked on a bare side and his response was not sufficiently meditated. His first memoir, presented on June, 6, 1920 was announced in I Rendiconti with the title: 'The existence of positive ions and the electronic theory of metal conduction'. [47] However, this memoir was published together with those of the session held on November, 7, 1920 with the changed title: 'The electronic theory

[43] All italics by La Rosa.

[44] La Rosa M. (footnote 42) p. 41.

[45] See for instance: Campbell N.R., *La théorie électrique moderne*, (Paris, 1919), pp. 89-91 (French version of the second english edition of 1913). The views expressed by Campbell are particularly significant because of the open-mind approach of the author to open problems and because they can be taken as representative of the kinds of objections that were raised against the hypothesis of positive electrons.

[46] Collodi T. , 'L'effetto Corbino nel bismuto fuso', *Il Nuovo Cimento*, 19 (1920) 163-172, p. 163.

[47] *Rendiconti della Reale Accademia dei Lincei*, 29, I (1920) 415.

of metal conduction in a magnetic field'. [48] This change in title together with, perhaps, the delay in publication, well represents Corbino's mood, oscillating between the temptation of a harsh response and the call for a more argumented answer.

The original title of the first memoir is a clear indication of Corbino's ontological committment: he believed in the existence of free positive electrons. Corbino apparently dealt with the interpretation of La Rosa's experimental results on the relation between thermoelectric power and electrical resistance of Bismuth in a magnetic field. [49] But the discussion about the possible interpretations of these results was just a battle field for monistic and dualistic theories. La Rosa tried to interpret his data on the basis of a monistic theory of condunction. The strange thing La Rosa did was to believe that the bending of the electron's path by a magnetic field perpendicular to the current would have increased the conductivity of the metal. [50] The conductivity of a metal was correctly considered as proportional to the electron concentration and to the electron mean free path. Since a transverse magnetic field bends the electron path, La Rosa concluded that the mean free path was increased. Therefore, he made an approximate calculation of the 'increased' mean free path and used this expression for deriving the supposed magnetic field dependence of the electrons' concentration from the observed variations of resistance as a function of magnetic field intensity. The magnetic field dependence of electrons' concentration obtained in this way was then compared with that obtained from the observed magnetic field dependence of thermoelectric power. La Rosa's comment about the agreement between prediction and experiment was somewhat overstated:

> ...I do not hesitate to say that this verification can be considered among the best that the electronic theory of metals can claim up to day. [51]

Corbino's start was smooth. After having asserted that the fundamental data about the transport properties of metals can be qualitatively explained by anyone of the many versions of the 'electronic theory of metals', Corbino acknowledged that:

[48] Corbino O.M., 'La teoria elettronica della conducibilità dei metalli nel campo magnetico', *Rendiconti della Reale Accademia dei Lincei*, 29, II (1920) 282-285.

[49] La Rosa M., 'Potere termoelettrico e resistenza del bismuto nel campo magnetico', *Il Nuovo Cimento*, 18, (1919), 26-38.

[50] Corbino did not comment on this point.

[51] La Rosa M., (footnote 42), 53.

> A further formulation [of the theory] must ideally lead ... to the dismissal of those hypothesis that do not fit well into the general frame of physical phenomenology. In this sense, we must consider as a true progress every effort to explain on the basis of only one type of carriers, the negative ones, those facts which seem to call for the existence, postulated by Drude, of two kinds of carriers: the positive and the negative. A relevant step in this direction has been recently tried by Prof. La Rosa ... [52]

But, after this acknowledgement, his attitude changed dramatically. Corbino claimed that La Rosa's attempt to check his monistic theory in an indirect way 'has concealed the truth' and that the 'simpler direct way' would have shown that the purported agreement between theory and experiment does not exist:

> ... between prediction and experience [there is] a contradiction that can be considered more qualitative than quantitative. Therefore, it does not appear justified La Rosa's claim that his indirect check can be considered among the best that the electronic theory can vindicate up to day. [53]

The final part of the paper was entirely dedicated to a confrontation of monistic and dualistic theories. Corbino stressed some difficulties of monistic theories: they do not explain the magnetic field dependence of Hall coefficient; they do not account for the high value of Hall coefficient in Bismuth. [54] Therefore:

> It is in fact in the explanation of phenomena originated by the transport of heat and electricity in a magnetic field that the theory using electrons of only one kind fails. In all this field of phenomena the dualistic theory not only makes closer the correspondence between

[52] Corbino O.M., (footnote 48), 282.

[53] The 'direct way' suggested by Corbino was the following: take the known value of the thermoelectric power for the Copper-Bismuth pair without magnetic field; put it into the formula giving the thermoelectric power and derive the ratio $\frac{n(0)}{n(H)}$ for Bismuth (on the assumption - made by La Rosa too - that the electron concentration in Copper does not depend from the magnetic field); then compare this ratio with the experimental value $\frac{\sigma(0)}{\sigma(H)}$ of the conductivity ratio.

[54] Bismuth was usually employed because it presented very big galvanomagnetic signals. Bismuth, like Antimony, is a semimetal: its conduction is due to both electrons and holes whose concentration is about two order of magnitude smaller than the electron concentration in a typical metal like Copper. Of course, Corbino and his contemporanies considered Bismuth and Antimony as metals.

> prediction and reality (this would be, in some cases, only an apparent merit, since a greater number of constants is available [to the dualistic theory]); but it eliminates all the categorical contradictions originated by monistic theory. Therefore, it must be concluded that, though it has not been possible to demonstrate the existence of *free* positive electrons, they temporarily constitute an indispensable element to account for the phenomena of metallic conduction and magnetic field effects [55].

As we have seen, Corbino started with the acknowledgement that dualistic hypothesis 'does not fit well into the general frame of physical phenomenology' and that a satisfactory monistic theory would have represented a 'true progress'. Coherently, one would have had to try to achieve a 'true progress' by modifying monistic theory. In fact, after that statement, Corbino affirmed that ' a relevant step in this direction has been recently tried by Prof. La Rosa'. However, as Corbino tried to show just a few lines ahead, this step was by no means 'relevant'. Nor did Corbino try to modify monistic theory in order to contribute to a 'true progress'. So, Corbino partially recognized the correctness of some of La Rosa's remarks; but this acknoledgement played essentially two roles: that of preparing a possible retreat in the case the dualistic approach would have shown untenable; and that of saying that La Rosa did a good job, just before demolishing it. In fact, Corbino avoided a real discussion of La Rosa's methodological criticisms (Corbino never quoted Collodi's paper). This does not mean that Corbino did not have a methodological position. It appears clearly in the paper we are discussing: a theory must explain the experimental facts, or as Corbino put it (see the quotation above), the reality; if necessary, we can introduce some hypothesis 'that do not fit well into the general frame of physical phenomenology' and, if the agreement with the facts is good, the hypothesis has a good chance to be true. In a paper appeared in 1907 Corbino stated explicity that

> ...it would be opportune to abandon every metaphysical prejudice and to evaluate the value of the postulates on the basis of the agreement with the facts". [56]

Corbino did apply this methodological rule rather coherently. In discussing the ideas connected with Planck's formula of black-body radiation, Corbino

[55] Corbino's italics.

[56] Corbino O.M., 'Le recenti teorie elettro-magnetiche e il moto assoluto', *Rivista di Scienza*, 1 (1907) 160-167, p. 165.

wrote:

> ... the most typical consequences of quantum theory: Planck's radiation law and Einstein-Nernst law for specific heats belong to those physical laws whose perfect quantitative agreement with facts is most safely ascertained ... Undoubtely, the hypothesis of sharp variations of molecular energy, in terms of multiples of the quantum $\varepsilon = h\nu$, contrasts deeply with all our mechanical views, even in the case of vibrations, since the energy is a quantity that one can hardly conceive as discontinous ... It is now clear how serious is the trouble that nowdays affects theoretical physics; in fact, we face a hypothesis born in a fortuitous way, as a consequence of a particular calculation procedure used by Planck; it leads to very important and unexpected results; it is tied to these successes so firmly that it can resist to all well founded objections about its thruth. However, no one dares to defend the new theory on its own; but, unfortunately, no one is able to find a way out, or, at least, to show that this will be found in the future and that it will be possible to free the wonderful edifice of theoretical physics from this new guest, so troublesome but so necessary. [57]

In this case too the agreement with the facts entails the thruth of the hypothesis; but the existence of a 'wonderful theoretical edifice' incompatible with the 'true' hypothesis creates 'serious troubles' which it is difficult to see how to get rid of. In the conduction case, according to Corbino, there is not a such a 'wonderful theoretical edifice' to take care of. One can agree; but Corbino's critics were right in holding that the hypothesis of free positive electrons was incompatible with the general picture of the structure of matter.

If Corbino did not answer his critics, what did he do? He maintained his beliefs and tried to show that the monistic theory advocated by his critics was false.

La Rosa replied to Corbino in a paper presented to the Accademia dei Lincei eight months later. La Rosa pointed out that the 'direct method' suggested by Corbino is not so reliable because of the uncertainty in the observed value of the thermoelectric power used in the calculations. [58] Ac-

[57] Corbino O.M., 'La teoria dei quanti e le sue applicazioni all'ottica ed alla termodinamica', *Il Nuovo Cimento*, 3 (1912), 368-387, pp. 381, 386-387.

[58] La Rosa claimed that by using a different value for the thermoelectric power, the agreement between theory and experiment was satisfacory.

cording to La Rosa, his 'indirect way', independent from the absolute value of the thermoelectric power, was justified by this uncertainty. The final part of La Rosa's reply was dedicated to the discussion of monistic and dualistic theories. La Rosa wrote:

> ... it has not been my purpose to deny the merit of researches carried on from the dualistic viewpoint ... Prof. Corbino's researches have gradually brought about an impressive amount of facts and considerations in favour of dualistic theory of metals; this certainly creates new difficulties for the monistic theory and makes it more lively and interesting the struggle between the two theories. However, it seems to me that the set of phenomena grouped around the Hall effect is not a good field for this struggle, owing to the complexity of these phenomena, that higly depend on the crystalline structure of materials ... For this reason I could not ascribe an excessive importance to the new discrepancies concerning the variability of the Hall coefficient [with the magnetic field] or to its absolute value; these discrepancies must be viewed within the more general question of the sign of the Hall effect; they will probably be justified within monistic theory when this theory will be able to account for this question [the sign of the Hall effct]. [59]

La Rosa's reply was clever: he ignored the polemical mood of Corbino; he recognized the relevance of Corbino contributions and their impact on monistic theory; he suggested that galvanomagnetic effects were not a reliable test for the two theories; he concluded by reaffirming that monistic theory would have eventually overcome the difficulties it was facing. The debate between Corbino and La Rosa pratically ended with La Rosa replay. [60,61] Corbino's

[59] La Rosa M., 'Conducibilità e potere termoelettrico nel campo magnetico, secondo la teoria elettronica', *Rendiconti della Reale Accademia dei Lincei*, 30, II (1921), 57-60, pp. 59-60.

[60] We have had the opportunity of seeing the letters Corbino wrote to La Rosa between March 1903 and June 1929. There are no letters during the period of the public debate with La Rosa. The letter closest to this period is dated January, 23rd 1922 (about one year after La Rosa's reply). We thank Mrs. Lucia La Rosa for having sent us, through Prof. Arturo Russo, a copy of these letters.

[61] As a matter of fact, Corbino touched again on this problem in 1925. Corbino defended his choice for the experimental value of thermoelectric power; and concluded: 'Therefore I think that I have nothing to change in the conclusions of my previous work'. Corbino O.M., 'Potere termoelettrico e coefficiente di Hall', *Rendiconti della Reale Accademia dei Lincei*, 2, II (1925), 526-530, p. 530.

attempt to demonstrate that monistic theories were untenable continued, however.

4 Corbino on monistic theories

On November 7th and December 5th of the same year (1920) Corbino presented two memoires entitled 'The thermal analogue of the Oersted - Ampère effect' [62] and 'The thermal analogue of the Oersted - Ampère effect and the electronic theory of metals'. [63,64] These two were followed by another memoir presented on June, 3rd 1921. [65] In the first memoir, Corbino came back to one of the experimental results presented in his first paper on galvanomagnetic effects: a Bismuth disc was placed in a magnetic field and oriented at 45^o with respect to it. When a radial heat current was sent trough the disc, it tended to orient perpendicularly to the magnetic field. [66] The effect was explained as due to the fact that the charge carriers (which for Corbino were two, positive and negative) responsible for the heat transport were deflected by the magnetic field in such a way as to create a circular current: then the disc, being equivalent to a magnetic plate, tended to orient its associated magnetic moment parallel to the magnetic field. [67]

Corbino's idea was the following: consider a metal disc suspended perpendicularly in a magnetic field; if a radial electric current is sent trough the disc, the magnetic field deviates the charge carriers perpendicularly to the radii and they will partially transmit the acquired momentum to the disc that will begin to rotate about its axis. This is the well known Barlow wheel. Now, what will it happen if the radial electric current is replaced by a heat current? Corbino claimed that monistic and dualistic theories answer differ-

[62]Corbino O.M., 'L'analogo termico dell'effetto Oersted - Ampère', *Rendiconti della Reale Accademia dei Lincei*, 30 (1921), 301-305.

[63]Corbino O.M., 'L'analogo termico dell'effetto Oersted - Ampère e la teoria elettronica dei metalli', *Rendiconti della Reale Accademia dei Lincei*, 29 (1920), 335-339.

[64]The first memoir is that presented on December 5th. We do not know the reason for the reversal of what would have been the natural sequence of the two papers.

[65]Corbino O.M., 'Azione di un campo magnetico sul flusso di calore', *Rendiconti della Reale Accademia dei Lincei*, 30, II (1921), 7-.10

[66]Corbino O.M. (footnote 4), 413.

[67]As Corbino effect may be seen as the transposition of the Hall effect in a circular geometry, this may be viewed as the transposition in a circular geometry of the Nerst effect. As in the case of the radial electric current, a circular current will be created.

ently this question. For dualistic theories there will be no effect, that is, there will be no thermal analogous of the Barlow wheel (Corbino claimed that the mechanical effect of the two circular currents induced by the magnetic field will always cancel each other). On the other hand Corbino claimed that monistic theories could not explain even the appearence of circular currents; however, if some modification of monistic theories would ever have accounted for circular currents, they would anyway predict the existence of the 'thermal' Barlow wheel. Corbino was therefore convinced to have found another case of possible disagreement between monistic theory and experiment. In the November memoir (the second in the logical order) Corbino reported that '... *the experimental result can be considered as negative*', [68, 69] i.e. that there is no thermal Barlow wheel. However, the sought disagreement between monistic theory and experiment, has, in the meantime, disappeared. In fact, Corbino wrote:

> The experimental negative result should therefore appear as inconsistent with any theory of electrical and thermal conductivity based on the mobility of the negative carriers only. This has induced me to deepen the investigation ... The result of this new study, whose details will be published in a next memoir, is the following: we can account for the thermomagnetic circular currents observed by myself, with Drude's theory as well as with Lorentz - Gans theory. [70]

But there was more, because, according to Corbino, also within Lorentz - Gans theory:

> *The overall mechanical action on the disc comes out to be nul,* [71] as the experiment has confirmed. Therefore ... this does not imply, as it appeared at a first sight, the necessity of the existence of mobile positive ions. [72]

Corbino was searching for a 'crucial' experiment: monistic and dualistic theories gave contradictory predictions about the existence of the thermal Barlow wheel. Corbino claimed to have found that the thermal Barlow wheel does not exist. However, in the meantime, he became confident that also monistic theories predict that the thermal Barlow wheel does not exist. The sought crucial experiment had disappeared.

[68] Corbino's italics.
[69] Corbino O.M. (footnote 62) 303.
[70] Corbino O.M., (footnote 62), 305.
[71] Corbino's italics
[72] Corbino O.M., (footnote 63), 305.

Corbino did not give up. In a paper on the Thomson effect, [73] Corbino tried to stress the difficulties connected with the assumption that the electron scattering is supposed to be due only to atoms and not also to the other electrons. However, Corbino's criticisms, were not so stringent; Corbino himself was aware of that, as it can be seen from his conclusions:

> Anyhow, we wanted to stress that Lorentz's approach forces us to assimilate the electrons in a metal to a gas in a porous body, with all the consequent anomalous effects, that we must take into account. [74]

In 1925 Corbino dealt again with the dependence of thermoelectric power on magnetic field. [75] As we have seen above, this has been the argument of his first memoir of 1920. Then, it was a 'monistic' paper by La Rosa that attracted Corbino's criticism; five years later the same role was played by a paper by Heaps. [76] Starting with the relations that were usually employed for describing thermoelectric and Hall effect within monistic theories, Heaps deduced that the thermoelectric power of the Bismuth - Copper pair is given by:

$$E(H) - E(0) = \frac{2}{3}\frac{k}{e}\ln\frac{n(H)}{n(0)} \tag{2}$$

where E is the thermoelectric power, H the magnetic field, k the Boltzmann constant, e the absolute value of the electron charge, n the electron concentration. The electron concentration n is supposed to be a function of the magnetic field for Bismuth but not for Copper. Since, on the other hand, the Hall coefficient is given by

$$|R| = \frac{1}{ne} \tag{3}$$

eq. (2) can be written as

$$E(H) - E(0) = \frac{2}{3}\frac{k}{e}\ln\frac{|R(0)|}{|R(H)|} \tag{4}$$

Heaps acknowledged that

[73] Corbino O.M., 'Sulla teoria dell'effetto Thomson', *Rendiconti della Reale Accademia dei Lincei*, 30, II (1921), 33-37.

[74] Corbino O.M. (footnote 73) 37.

[75] Corbino O.M., (footnote 61)

[76] Heaps C.W.,*Philosophical Magazine*, 50 (1925), 1001-1009

> It does not appear likely, however, that the equation [equation (4) above] should be capable of exact experimental verification. The free electron theory of metals upon which it is based has proved insufficient for the explanation of various thermoelectric phenomena, nor does this theory account for the positive Hall coefficient. At best, the free electron gas theory as applied to metals must be considered only as a very rough approximation to the real conditions. Nevertheless, it was thought worth while to make an experimental test of the above relation ....

Heaps' stand was cautious and somewhat ambigous. He considered the theory not so reliable; nevertheless he tried to check it. Corbino correctly pointed out that in eq. (2) a minus sign should appear on the right side. So, Corbino claimed that monistic theory was in contradiction with experimental results for Bismuth and Graphite and that

> ...only Antimony escapes the contradiction [with the experiment]; [77] but just for this metal we have the more serious difficulty: the positive sign of the Hall coefficient that is incompatible with the formula [formula (3) above] of the electronic theory in its simplest form. [78]

In the last two memoirs [79,80] Corbino dealt again with the thermomagnetic effect he had discovered in 1911 and strove to demonstrate that monistic theories ended up in contradiction with experiment. The target of Corbino's criticism was Gans'[81] and Livens' [82] version of Lorentz's monistic theory. Corbino compared with the experiment the theoretical predictions about the direction of the circular current induced in a disc by a radial electrical or thermal current in the presence of a perpendicular magnetic field. According to Corbino, Gans theory predicted the correct direction only for Copper, Gold and Silver '...among the many metals that present thermo and galvanomagnetic effects in a measurable way ...'; in particular it was at odd

[77] Heaps held that his experimental results were all in agreement with formula (4).

[78] Corbino O.M. (footnote 61), 529.

[79] Corbino O.M., 'Sulla teoria elettronica dei fenomeni termamagnetici', *Rendiconti della Reale Accademia dei Lincei*, 3 I (1926), 3-8.

[80] Corbino O.M., 'Ancora sulla teoria elettronica dei fenomeni termomagnetici', *Rendiconti della Reale Accademia dei Lincei*, 3 I (1926), 250-256.

[81] Gans R., 'Zur Elektronenbewegung in Metallen', *Annalen der Physik*, 20 (1906), 293-326.

[82] Livens G.H., 'The Electron Theory of the Hall Effect and Allied Phenomena', *Philosophical Magazine*, 30 (1915), 526-548.

with experiment in the case of Antimony and Bismuth. On the other hand, in Livens' theory (in which the scattering of electrons by atoms is considered anelastic) the direction of the circular current depends on the value of the interaction parameter between electrons and atoms. It is then possible, in general, to obtain the correct direction by a suitable choice of this parameter. However, according to Corbino, Livens theory predicts the thermal Barlow wheel and is, therefore, in contradiction with experiment.

Before leaving the discussion of these two memoirs, we must add that, in the first one, Corbino gave up the idea that his effect was something distinct from the Hall effect. Corbino wrote:

> This experiment [he is referring to his disc with a radial thermal current] is a direct consequence of the Nernst effect, as the other with a radial electric current ... is a consequence of the Hall effect. But those experiments are more easily and directly comparable with the theory; as a matter of fact, with the circular simmetry, there are no transverse electrical and temperature gradients: this eliminates spurious effects, makes the calculations more easy, gives the final formulas a simpler form and makes their interpretation easier and more certain ... [83]

This view is, essentially, that proposeed by Adams in 1914 (see above). With one important difference: according to Adams, Corbino's, and not Hall's, is the fundamental effect.[84]

Viewed as a whole, Corbino's reaction to La Rosa's criticism appears as a kind of monologue. In fact, apart from La Rosa, nobody else entered the debate. It remained circumscribed in the Rendiconti, without any contribution by foreign scientists.

After 1926, Corbino never dealt again with galvanomagnetic effects. However, Edoardo Amaldi recalled that in late 1930's physics students in Rome were asked, during laboratory activity, to measure Hall effect, considered as a very instructive experiment; and Corbino was reported to say: 'See, I was right in holding that there were two charge carriers!'. [85] Corbino was obviously referring to the explanation of the Hall effect and of the related phenomena based on the new - born band theory of solids.

[83] Corbino O.M. (footnote 79), 3.

[84] Modern textbooks do not, usually, stress the advantages of circular simmetry in dealing with magnetic effects. However, after the discovery of the quantized Hall effect, circular simmetries and Corbino's contribution seem to have been revaluated.

[85] Private communication, Erice, November 1989.

5 Right or wrong?

We believe that this story is a good example of a scientific achievement in which individual, cultural and institutional factors strictly combined together. Corbino's ingenuity led to his first paper on the disc. His scientific and cultural background, characterized by a macroscopic approach to the description of phenomena, marked his galvanomagnetic studies. This approach reflected the delay of Italian physics in adopting the microscopic viewpoint and in combining it with the statistical description. [86] Corbino's methodological beliefs helped him in maintaining the dualistic theory, in spite of the trend in the international community. However, the partial isolation of Italian physical community acted as a shelter for the survival of dualistic theory in Italy. Without that shelter, its life would have been, at least, much more troubled. The combined effect of these factors ended up in a peculiar piece of physics: its basic ontological assumptions were inconsistent with the background knowledge about the structure of matter; its epistemological foundations stressed exceedingly the role of experiment in the evaluation of the plausibility of a hypothesis and underevaluated the requirement of the consistency with the background knowledge. These features can be found in many historical cases of innovations. However, Corbino's case can not be considered one of them: it stood midway. Corbino has been right in maintaining that galvanomagnetic effects can be explained only in terms of two charge carriers; but, in the end, the 'free positive carriers' turned out to be just the effect of the collective behaviour of many electrons. The supporters of monistic theory have been right in holding that the anomalies encountered by monistic theories would have been eliminated by modifying the theory without any change in the ontology. However, the modification of the theory has been profound to the extent of including some basic aspects of the dualistic approach.

[86] Corbino began to use the statistical machinery in dealing with transport phenomena only in 1920: but in that case he was forced to use the statistical approach because he was applying Lorentz theory.