What physicists are talking about?

The case of electrons and holes

Giuseppe Giuliani

Dipartimento di Fisica 'Volta', Pavia

Abstract. The problems posed by the basic realistic foundation of science are briefly reviewed and a *tempered* realistic position is advocated. This approach is applied to the case of electrons and holes in solids, as a working and illustrative example. A little moral follows.

1 Realism and Instrumentalism

Science has grown up on the basis of a fundamental postulate: *an external world exists; the observer belongs to this world*. However, once this postulate has been accepted, a problem arises immediately: what are the relations between our descriptions of observed phenomena and the external world? What is, from this point of view, the status of our theories? Do they describe exactly how things go in the world or are they merely instruments for making predictions? And what about our theoretical entities and the associated physical quantities? Do they exist in the world or, again, are they simply conceptual devices invented for describing observed phenomena?[1] The answers given to these questions cover a wide range. At one extreme, we find a hard realistic stance holding that an accepted and consolidated theory describes exactly how things go in the world: this stand implies that all theoretical entities and physical quantities used by the theory exist in the world and that they behave in the world exactly in the way described by the theory. At the other extreme, we find the position according to which the aim of science is simply that of making predictions; the questions posed above are considered as meaningless or without answers. It can be shown that the hard realistic stance is untenable; on the other hand, the opposite strumentalist position in its pure form is a 'paper position', i.e. one that can be sustained only in papers [1]. As a matter of fact, every scientist or physicist holds an *image of the world*: this is a description of the world based on the acquired knowledge (theoretical and experimental)

[1]Here, we denote by the term *theoretical entity* concepts like those of electron, photon, wave, particle, etc... Physical quantities describe instead properties of theoretical entities or interactions or relations between theoretical entities. Their basic property is that they can be measured. For instance, the concepts of *mass, charge, spin* and *magnetic moment* describe properties of the theoretical entity *electron*; the concept of *force* allows the description of the interaction, say, of two electrons; that of *velocity* describes a relation between two theoretical entities. Of course, the distinction between theoretical entities and physical quantities is not a sharp one. However, it may be used as a first level criterion for the classification of physical concepts.

but containing *also* ontological assertions about the existence of theoretical entities and physical quantities. Here, the basic point is that these ontological assertions cannot be logically deduced from the acquired knowledge. We can only require that they are compatible with the acquired knowledge. However, this limit does not imply that an image of the world rationally constructed (coherent with the acquired knowledge) is a useless or unreliable tool: simply, this limit reminds us that an image of the world *rationally constructed* can only be probable and that its main role is of guiding our daily behaviour as scientists or common men. To make an example: according to a *tempered* realistic position, the question 'does the electron exists?' is meaningfull. The answer we should give on the basis of the acquired knowledge is 'yes'. We can go further and maintain that an image of the world (or better of part of it) can be more stable than the acquired knowledge on which it is based. For instance, the theories and experimental knowledge about the electron have changed and may change again; but we are reasonably confident that the electron will enter the images of the world to come. This last point suggests one more comment. The stability of an image of the world is a relevant criterion for its reliability: hence a historical point of view is fundamental for the evaluation of the reliability of the images of the world.

The 'average scientist' can be described as a 'realistic philosopher' leaning towards the 'hard' extreme, who – nevertheless – behaves frequently as a strumentalist. This must not be considered as a 'forbidden blend'. The scientist cannot refrain from bringing water to the mill of the prediction power of science; on the other hand he – firstly as a common man and secondly as a scientist – cannot stand without building an image of the world that he uses daily in crossing streets, creating theories, planning and performing experiments.

2 Electrons and holes

This section is intended to be an application of the ideas presented above to the case of electrons and holes. The exercise will be developed only in a sketchy way. The great experimental discoveries or achievements of the last years of nineteenth century – X - rays (1895), radioactivity (1896), electron (1897), first reliable measures of black - body radiation (1895) – have forced a change in the image of the world of an unprecedented and unsurpassed upshot. The nineteenth century image of the world, symbolised by the pervading ether, has been harshly and progressively challenged not only by the experimental discoveries just recalled, but also by ensuing (light quanta, 1905) or independent theoretical ideas (special relativity, 1905). We shall follow this change through the particular viewpoint of the electrical conduction in solids. The starting point will be the basic work by Drude, published in 1900 [2]. There, the electrical conduction is handled on the basis of two charge carriers, negative and positive (in those times theories of this type were called 'dualistic'). I am not able to say to which extent Drude was committed to a realistic interpretation of his theory. The period was a tumultuous one, full of uncertainties, also from our particular point of view. Significantly, Lorentz made, in those years, only a cautious choice in favour of the monistic theory. However, the horizon was rapidly changing. In a book appeared in 1923, L. L. Campbell discussed twelve theories of the Hall effect: only one, beside Drude's, was dualistic [3]. The ontological question has been dealt explicitly by N. R. Campbell. A paragraph of a book of him is entitled: 'Do positive electrons exist?' [4]. Campbell rules out the possibility of the existence of positive electrons in conductors on the basis of well balanced experimental and theoretical considerations: I would say, on the basis of a rational image of the world concerning electrical conduction phenomena. On the contrary, Corbino, as shown in a detailed analysis [5], held the opposite view on the basic account that the *existence* of two charge carriers is necessary for the explanation of the positive Hall effect. Corbino ontological statement was methodologically unsound: ontological statement are allowed only within an image of the world and *must* be compatible with the entire acquired knowledge. Two charge carriers are necessary to a theory of the Hall effect; but this theoretical need has nothing to do with the possible existence of the theoretical entities used by the theory. Corbino was right in maintaining that a sound theory of the Hall effect needs two charge carriers; he was wrong in asserting that the *existence* of two charge carriers is necessary for the explanation of the positive Hall effect.

The next step I want to consider is the introduction of the 'hole' concept. This breakthrough was made by R. E. Peierls in 1929 on the basis on the band theory of solids [6]. Further developments of this idea led to the now standard treatment of electrical conduction in semiconductors and semimetals in terms of electrons and holes. The theory makes it clear that the hole concept is a mean of describing the collective behaviour of many electrons. Therefore, the case of the hole constitutes a clear example of a more general methodological principle: we can measure the physical quantities associated with a theoretical entity without having any reasonable basis for attributing a real existence to that entity. The case of the hole is obvious. However, it is easy to see, for instance, that electromagnetic waves meet the same fate: it is sufficient to try to interpret a standard interference experiment in a realistic way for seeing that such a realistic interpretation entails causal anomalies [7].

3 A little moral

My short account stresses, among other things, the epistemological and practical relevance of the image of the world that physicists contribute to build up. However, the physics community seems to be very little sensible to this matter. As Corbino put it in 1909:

> And when physicists, already oppressed by the complication of the invented mechanism, are asked if the new entities – that they manage as living things – have an objective existence or are just an economic and tentative means of investigation, they are dismayed by the immensity of the problem and are refrained from the scientific elaboration of an answer whatever. And abdicating the quality of men of science – but following only their own sentimental ten-

> dencies – give out their opinion as if they were judging about a problem of religion, politics or aesthetics [8].

But there is more. Today it is acknowledged that science – and physics within it – is the major, if not the unique, source of knowledge for human species. Nevertheless, irrational intellectual moods are far from being reduced to insignificant levels. Men of science are, therefore, charged with another burden: the image of the world that science is contributing to build up must be freed from irrational components. Furthermore, men of science should care more about how this image and, in general, science achievements are diffused into society. The story I have told about Corbino shows that it is not easy to coherently adhere to his methodological principle. I believe it is worth trying.

References

[1] For a more detailed discussion, see, for instance: Casella A. and Giuliani G., ‘Il realismo dal punto di vista metodologico - Per un realismo empirico, in *Ancora sul realismo - Aspetti di una controversia della fisica contemporanea*, edited by G. Giuliani, (Pavia) 1996, pp. 13 - 30.

[2] Drude P. ‘Zur Elektronentheorie der Metalle’, *Annalen der Physik*, **1**, (1900) 566; Drude P. ‘Zur Elektronentheorie der Metalle’, *Annalen der Physik*, **3**, (1900) 369.

[3] Campbell L. L. *Galvanomagnetic and Thermomagnetic Effects* (London) 1923, pp. 69 - 94.

[4] Campbell N. R., *La theorie lectrique moderne* (Paris, 1919), p. 89; French translation of the second English edition of 1913.

[5] Galdabini S. and Giuliani G., ‘Magnetic field effects and dualistic theory of metallic conduction in Italy (1911 - 1926): cultural heritage, creativity, epistemological beliefs and national scientific community’, *Annals of Science*, **48** (1991), 21.

[6] Peierls R. E., ‘Zur Theorie der Galvanomagnetischen Effekte’, *Zeitschrift für Physik*, **53** (1929), 255.

[7] Antoniazzi A. and Giuliani G., ‘Campi, onde e particelle nei manuali di elettromagnetismo: un esempio di stratificazione concettuale e ontologica’, *Giornale di Fisica*, **38** (1997), 87.

[8] Corbino O. M., ‘I fondamenti sperimentali delle nuove teorie fisiche’, in *Conferenze e discorsi di O. M. Corbino* (Roma) 1938, p. 21 - 22.