The Particle Concept and Solid State Physics

By G. H. WANNIER*

The early decades of this century have witnessed the rise of a new concept in physics, the elementary particle. Elementary particles and their properties are today quite naturally assumed the basis of all physical understanding, in the sense that all properties of matter are thought, at least in principle, reducible to them. This picture of the science of physics did not always exist. As late as 1880 many physical properties were not thought of as reducible to such simple concepts. This was particularly true in the physics of solids. Many properties of solids were measured in those days: electrical and thermal conductivity, elastic constants, index of refraction, etc.; yet reduction of these properties to properties of the atoms composing them was rarely attempted. There is even the case of the physicist OSTWALD who felt that this *de facto* situation had a philosophical basis. To him, atoms were constructs which could never be directly observed, and he was rather annoyed by the flourishing kinetic theory of gases in which these constructs came so close to being real. OSTWALD's form of positivism is now dead. The fate of his philosophy ought, perhaps, make us a little suspicious of similar arguments of a philosophical vein which have been used in more recent scientific discussions.

The era of particles was inaugurated by J. J. THOMSON when he discovered the electron in 1896. It seems that realism in science comes more easily to Englishmen that to others. It is, therefore, not surprising that the search for conceptually simple experiments (which is, of course, not the same as experiments made with simple apparatus) was particularly intense in that country. THOMSON found his simple experiment among the phenomena incident to the electric discharge in gases; this field contains many very complicated effects which even today are only poorly explained. However, as the pressure of the discharge is lowered, these effects give rise to a splendid simplicity which has been vulgarized in the modern television tube. The properties of cathode rays are explained by assuming them to be negatively charged point particles of fixed charge and mass. THOMSON named these particles *electrons*. Thus, the electron is the first in the modern family of particles. In weighing the significance of this concept we must, of course, remember its theoretical convenience: mechanics deals with relative ease with the kinetics of point particles. This ease permitted NEWTON to write down the laws of motion of the planets, yet it does not prevent these planets from being very complicated things whose structure will probably never be fully unravelled. It is, therefore, natural that the point electron was originally thought of as a model, and that atoms and molecules were still thought of for some time after as a continuum filling all voids when in the liquid or solid state.

The next step in the emergence of the particle concept was the discovery by RUTHERFORD of the atomic nucleus in 1911. Not only were electrons like point particles, but the positively charged remainder of the atom also acted like one. This picture had to be modified in the light of later evidence. Only the nucleus of the atom of hydrogen, the atom of lightest weight, is an elementary particle to us today. This particle is called the *proton*. All the other nuclei are, while very compact on an atomic scale, fundamentally composite, consisting of protons and neutrons. Thus, even though the idea of the atomic nucleus as a particle proved to be false, the elucidation of the true situation has enhanced further the idea that matter generally is made up of elementary point particles.

For the purpose of this article, namely the discussion of the particle concept in solid state physics, there is no need to go any further into the development of particle physics. However, if we did break off at this point, then the reader would be unable to appreciate the intellectual situation in which we find ourselves. The particle concept has acquired a tremendous grip over physics in general in the last thirty years. Rather unexpectedly, the advent of quantum mechanics in 1925 to 1930 has strengthened this grip. Before this event there was a competing elementary concept in physics, that of a wave traversing a medium. Quantum mechanics showed that this wave picture is in fact an alternative aspect of the particle concept. So, this competitor is now eliminated through fusion, and the particle picture has spread into wave phenomena. In the case of light we now speak of photons, in the case of sound of phonons, etc. There is a second way in which quantum mechanics has reinforced the particle concept. It is a harder form of mechanics. It is difficult to conceive a quantum mechanics of an extended body, to say nothing of computing its properties. So, we find now that the simplicity of the particle concept is even more forcing for the modern theorist than it was for his predecessor in 1900. The advent of the theory of relativity has acted in the same direction. A further extension of the particle concept has arisen from the probing of the atomic nucleus with projectiles of higher and higher energy. Many of the phenomena observed in this probing are explained by the appearance of elementary particles which are not stable, but finally decay into the stable particles discussed above. The number of elementary particles now known is about thirty.

* Bell Telephone Laboratories, Murray Hill (New Jersey).

This background may be sufficient to indicate how thoroughly we are now wedded to the concept of a universe composed of point-like particles. In other words, a model which was considered crude when proposed fifty years ago has acquired a weight which nobody would have then expected. Is this concept of absolute validity?

In the assessment of this question solid state physics may, perhaps, play an important role. It is a field of physics extremely rich in structure in which precise measurements are relatively easy. Yet, at the same time, it is felt at this time that the fundamental basis of the subject has been laid. Only the existence of electrons and atomic nuclei as particles must probably be assumed together with the uncomplicated quantum mechanics of the 1920's in order to explain the entire range of solid state phenomena. Such a situation enforces 'tight' reasoning: a theory with limited choice faces experimental results of great variety and precision. Successes of the theory under such conditions are worthy of a great deal of credence. Many of these successes are connected with the idea of a *quasiparticle*, that is a particle-like entity which exists only thanks to the medium in which it is embedded, and which ceases to exist as soon as the nature of the particle is probed through methods which tend to disrupt the solid as a medium. It is fairly certain that the complexity acquired by the particle concept in such a situation cannot be blamed on a mistaken theoretical approach.

Let us start with the least radical modification of the particle concept. It is well known that a certain fraction of the electrons in many solids act as if they were free. They move about in the material and can be drawn off as electric current. These electrons move in the solid as in a medium; hence, we must expect modifications of their properties as compared to a situation where they are really independent particles in the vacuum. The simplest change is in their mutual interaction. Their mutual coulomb repulsion must certainly be modified by the dielectric constant of the medium. In addition, the floating mobile charge itself reduces the range of the force between any given pair, thus leading to a force falling off more rapidly with distance than $1/r^2$. These modification would still leave the electron recognizable through its charge and mass. However, a more profound effect arises through the presence of atomic cores with strong positive charge. Even electrons which act as free are in some kind of electronic shell with respect to such atoms. Their free motion is thus not in a simple straight line, but a line with loops around the atoms as shown in Figure 1. Thus, the motion is not rectilinear when considered in the small. It becomes so again, however, when displacements large compared to the atomic spacings are considered. As a consequence, NEWTON's first and second law are finally validated for these electrons in a coarse sense. But, there is obviously no reason to expect the response to an applied force to be exactly like that of a truly free electron. Indeed, one finds that the inertial mass has to be replaced by a different constant in some solids; in others the mass becomes a tensor depending on the crystalline direction, and in others still the kinetic energy must be taken as a more general function of the momentum. Thus, we have finally a quite seriously modified 'electron' arising from these features.

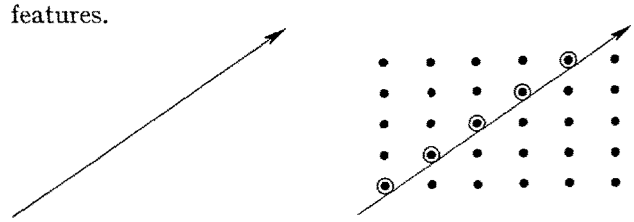

Fig. 1: Simple rectilinear motion as compared to the motion of an electron through the crystalline lattice of a solid. The motion on the right is complicated in detail, but is rectilinear in the mean when averaged over long distances

The next modification of the particle concept arises in the sign of the charge. It should be said here in passing that this type of modification is not original with solid state physics, but is borrowed from the theory of the positron. But here again, the reasoning is particularly tight when applied to electrons in solids, and leaves therefore essentially no freedom either in the technique or the interpretation. Since each electron belongs to a definite electronic shell, we can conceive of an electron missing in such a shell. Such a defect can propagate itself through a crystal in essentially the way indicated in Figure 1, thereby acting as a quasiparticle. This *defect electron* is usually called a *hole*. One can show that it also obeys NEWTON's first two laws of motion and has inertial properties which are very similar to the ones just discussed for conduction electrons. The charge of the defect electron is, of course, positive. It is a fullfledged quasiparticle which can be observed as such in many experiments on semiconductors.

Is there a distinction between particles and quasiparticles? In the context of solid state theory with its conventional quantum mechanical basis there is such a distinction. For an electron we can construct a wave packet as small as we please by using De Broglie waves of small wave lengths in its construction. In this way localization can be pushed well beyond the atomic scale, and is in fact realized for β-particles traversing matter. Of course, such a packet no longer belongs to a given atomic shell, but is composed of waves belonging to many shells, and perhaps even of waves too short to form part of any shell. Obviously, the localization of a defect electron cannot be pushed that far even in principle. A missing electron must be missing from a place where the usual constituent electrons of a solid are. If it is missing from a definite shell, then a wave packet smaller than the size of an electron orbit in that shell cannot be constructed. Thus, the defect electron as a particle will slip us through the fingers if we use more and more powerful apparatus to find its position.

Several other quasiparticles have arisen in solid state physics. The oldest, in a sense, is the *phonon*, a quantum of sound. Its existence was essentially clear as soon as the quantization of light had been proved. The quasiparticle nature of the phonon is particularly obvious. Sound is a wave-like disturbance among the atomic positions in a solid. Its wave length cannot be less than an interatomic distance, and therefore the energy of a phonon:

$$\text{energy} = \frac{h \times (\text{velocity of sound})}{\text{wave length}}$$

is strictly limited, usually to less than one electron volt. Only for such low energy phenomena can we expect the phonon to 'exist'. As soon as a sizeably larger amount of energy is pumped into an atomic displacement, the atom must be considered individually and the solid matrix will be disrupted. Thus, we deal with a different type of particle according to circumstances. A similarly ephemeral existence is lead by the *quantum of spin waves* (a wave-like disturbance in the magnetization of ferromagnets) and the *Bogoljubov particle*, an electron-like particle whose charge depends on its energy and which acquires stability only in the superconducting state of a metal.

In the present-day context of solid state physics the distinction of particles and quasiparticles is fairly obvious and quite useful. However, the distinction is almost certainly not fundamental. We may see this particularly well if we compare the electron-hole concept with the electron-positron theory of Dirac. According to the Dirac theory of the electron the energy of an electron equals:

$$E = \pm \frac{m\,c^2}{\sqrt{1-\frac{v^2}{c^2}}}$$

where m is the electron mass, c the velocity of light and v the electron velocity. Abundant analysis has shown the double sign to be unavoidable. The spectrum of possible states is thus as shown in Figure 2(a): two continua, separated by a gap of 2 mc^2. Vacuum must be thought of as a condition in which the negative energy states are filled and the positive ones empty. Transfer of an electron from a negative to a positive energy state produces then two particles, as explained earlier, an electron and a defect in the negative energy spectrum. This defect is called a *positron* because of its effective positive charge. The positron as a particle is very well known and electron-positron pair production agrees in every way with the Dirac theory as outlined. The analogy with the band properties of solids, as sketched in Figure 2(b) reaches very far. In a semiconductor or insulator, all bands up to a certain level are filled. In some cases electrons from the highest filled band can be induced to transfer to the lowest empty band. This produces also a pair, namely an excess electron and a defect electron or hole. There are essentially two differences between the two cases. First, the energy scale in the two cases differs by a factor 10^6, and second, the excess-defect pair is reducible to a more fundamental structure consisting of real electrons and atomic nuclei. The first distinction is a numerical one only and cannot be thought of as qualitative. The second one appears to make the electron-positron pair real and the excess-defect pair two quasiparticles.

Upon closer inspection these distinctions between particles and quasiparticles lose much of their sharpness and the second appears simply as the first expressed in a different form. In modern field theory all elementary particles are looked upon as wave-like modifications of the vacuum state similar to light waves. We could then comment upon the above distinction by saying that the excess and defect electrons are easily recognized as quasiparticles because their production is a low energy phenomenon. For an electron-positron pair this is not so easy, but it is not unreasonable to suppose a similar situation. The electron-positron pair is unstable, and all the more recently discovered particles are likewise. Therefore, we must think of vacuum as a medium in which particles can be produced under certain conditions. The stability of certain particles is then a historical accident, arising from the fact that they are more abundant than the antiparticles which could annihilate them. All particles become thereby quasiparticles and it becomes the business of physics to elucidate the structure of the medium called 'vacuum' or 'ether' in which these particles appear as transitory phenomena.

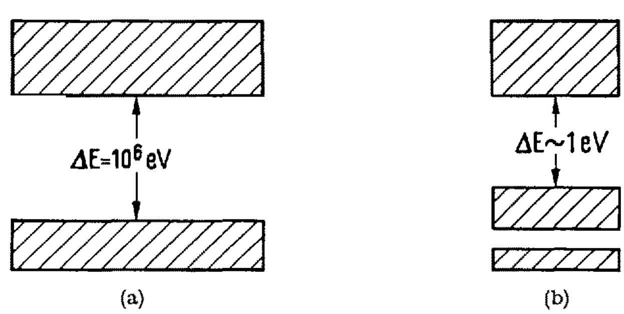

Fig. 2: Comparison of the bands of possible energy states for an electron (a) in vacuum, (b) in a typical solid. The band gap on the left differs only in scale from the gaps on the right

Zusammenfassung

Der Begriff des Elementarteilchens ist zentral in der Struktur der modernen Physik. Sein Ursprung und seine historische Entwicklung werden erläutert. Die Festkörperphysik hat zu dieser Entwicklung einen speziellen Beitrag geleistet; der Beitrag ist das Quasiteilchen, das heisst eine Anregung im Festkörper, die sich wie ein Elementarteilchen verhält. Es ist endlich gezeigt, dass die Unterscheidung zwischen Teilchen und Quasiteilchen nicht gründsätzlich ist.