ELECTRON IS A WAVE?
(article published in the "Engineer" magazine # 6, 2005)

Now, few people doubt that electrons have wave properties in addition to corpuscular ones. In addition to the laws of conduction and the tunneling effect, which indirectly confirm the dual nature of the electron, there is also direct evidence of its wave properties. These are experiments that have revealed interference and diffraction in electron beams and in individual electrons. Among such experiments, the so-called Ramsauer-Townsend experiment is known as the most convincing and simple one.

Briefly, its essence is as follows. Between the source *I* of electrons and the receiver *P* installed opposite it (Fig. 1) there is a scattering medium of inert gas. A narrow beam of electrons of known energy, fired by the source to the receiver, is scattered by gas atoms. Part of the electrons, from those that have not been scattered or scattered at small angles, reaches the receiver, creating an electric current, the measurement of which gives the percentage of particles that have flown in (this percentage and the current is greater, the smaller the scattering).

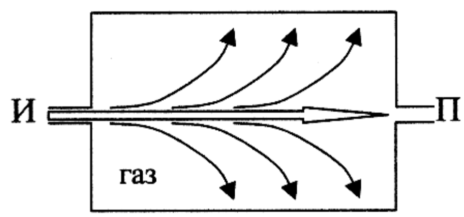

рис. 1

Fig. 1.

Theoretically, with a decrease in the speed (and hence the energy) of particles, the degree of their scattering by atoms, defined as the effective scattering cross section σ, should increase monotonically. In the same way, a fast-moving car, entering an obstacle course, deviates from a straight path, “dissipates” the earlier and more, the lower its initial speed.

But in the experiment, such a picture - an increase in scattering with a decrease in velocity - is observed only up to a certain value E_1 of the electron energy (Fig. 2). When it is reached, a further decrease in speed leads not to an increase, but to a decrease in the scattering. Only after the electron energy passes over the next characteristic value E_0, the degree of scattering starts to grow again. If Rutherford, in his famous experiment, compared α-particles thrown back by a thin gold foil with rifle bullets bouncing off a sheet of paper, then slow electrons piercing a gas layer in Ramsauer's experiment should, on the contrary, be likened to light straws piercing a thick sheet of armor. Indeed, the classical theory of anomalously high gas permeability for very slow electrons could not explain.

But it was enough to assume the wave properties of the electron, how everything fell into place. According to quantum mechanical concepts, the scattering of an electron as a particle can be considered only as long as its momentum is higher than a certain value, as long as the de Broglie wavelength of the electron is small - much smaller than the dimensions of the scattering atom. (In exactly the same way, geometric optics, which essentially considers light as a stream of rectilinearly flying particles - photons, is applicable only for optical systems that are much larger than the wavelengths of light.) But at some sufficiently low velocity, the de Broglie wavelength of the electron ($\lambda = h/p$, where h is Planck's constant and p is the electron momentum) is compared with the dimensions of the atoms scattering electrons.

In this case, the electrons are scattered by the atoms not as particles, but as waves: diffraction of electron waves by atoms will occur. In diffraction, as is known at least from optical experiments, the waves bend around the screen, creating, during addition, interference maxima behind it, in the region of the geometric shadow. So, for example, when a round screen is illuminated in the center of its shadow, under certain conditions, a light spot appears (Poisson spot). Roughly the same thing happens with electrons: at a sufficiently low speed, they begin, as it were, to pass through the atoms, bend around them, which is manifested in a decrease in scattering and the creation of a kind of electronic Poisson spot on the receiver. (Likewise, a car that slowly enters the obstacle course will no longer crash into them, but will go around them, and therefore, despite the low speed, it will be able to move in the right direction for a long time).

That is why it turns out that the scattering of electrons with a decrease in their speed increases only up to a certain value of their momentum, energy. As soon as the speed of the electrons is sufficiently reduced - so that their wavelength becomes comparable to the size of the atoms - their scattering begins to sharply decrease. This explains the unusual character of the graph (Fig. 2), which has an anomalous dip, a minimum in the region of low electron energies.

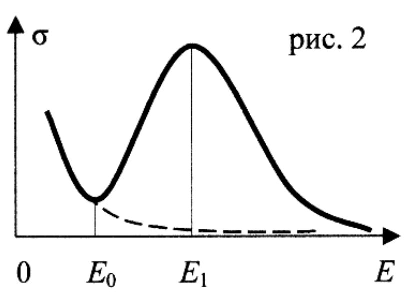

Fig. 2.

It is remarkable that the heavier the used inert gas, the lower the electron velocities it is possible to observe the effect of anomalous decrease in scattering. So, in the General course of physics by D. V. Sivukhin ("Atomic and Nuclear Physics", Part 1, - Moscow: Nauka, 1986, p. 110) for a relatively light argon, the critical value of the energy E_1 = 13 eV is given, for more heavy krypton E_1 = 11 eV, and for heavy xenon E_1 = 6 eV. The decrease in E_1 is explained by the fact that the size of the atoms of inert gases gradually increases with an increase in their atomic number, in the transition from He to Xe (see table: radii under the article "Inert gases" from the BSE). Therefore, the heavier the gas, the larger its atoms, and the larger must be the de Broglie wavelength λ of the electron for diffraction on them. The more, therefore, it is required to reduce the electron velocity for the appearance of anomalously low scattering. It turns out that the dependence of the scattering of electrons by atoms can even estimate the values of atomic radii.

Элемент	Атомные радиусы, Å		Энергия, эВ		
	по А. Бонди	по В. И. Лебедеву	максимума рассеяния	возбуждения	ионизации
He	1,40	0,291	-	20,60	24,58
Ne	1,54	0,350	-	16,77	21,56
Ar	1,88	0,690	13	11,77	15,76
Kr	2,02	0,795	11	10,59	13,94
Xe	2,16	0,986	9	9,52	12,08

This is the quantum-mechanical interpretation of the Ramsauer-Townsend experiment, seemingly extremely clear and convincing. But in reality, not everything is so smooth.

The fact is that the considered law of scattering amplification with decreasing velocity is justified only for the case of elastic scattering, that is, for scattering in which the sum of the kinetic energies of the electron and the scattering atom before and after the collision is the same - the impact energy does not pass into the internal energy of the atom. Therefore, in the textbooks it is specially stipulated that only the case of elastic collision is considered. But the fact of the matter is that at the energies in question, the collision is already close to inelastic.

Indeed, for each of the gases, the energy E_1, starting from which a discrepancy with the classical scattering law arises, is only slightly less than the corresponding ionization energies (see table). And according to other data, these energies for argon coincide at all. So, for example, according to the textbook Matveev A.N. ("Atomic Physics", Moscow: Vysshaya Shkola, 1989, p. 55) for argon the energy of maximum scattering is about 16 eV, which almost coincides with the ionization energy of its atoms (15.7 eV). But with the ionization energy, the collision is already inelastic: individual electrons colliding with an atom with such an energy will no longer bounce off it elastically, but will lose speed, having given part of the energy to ionize the atom - to tear off an electron from it.

But the collision becomes inelastic long before the collision energy exceeds the ionization energy. The excitation energy of the atom is noticeably less than the latter (see table) - the minimum portion of energy that the atom can absorb. Only such, but in no way a smaller portion of energy is capable of transferring an atom into an excited state. Only such energy E (and the corresponding frequency $\nu=E/h$) is able to enter into resonance with the self-energy (and frequency) of vibrations of the electron shell of the atom and therefore is easily absorbed by it, and then emitted in the form of the so-called first resonance spectral line of the atom. The existence of such a threshold value (quantum) of energy was discovered in the Frank-Hertz experiment, an experiment no less simple and convincing than the Ramsauer-Townsend experiment. And in many other ways, these experiments are similar.

Both there and there there is a source and a receiver of electrons with a scattering medium (metal vapor or inert gas) between them. In both experiments, the percentage of electrons reaching the receiver is measured by the current generated in it. As in the Ramsauer experiment, in the Frank-Hertz experiment, some of the electrons do not reach the receiver due to scattering, which changes the direction of particle motion. Only in Hertz's experiment, scattered particles do not reach the receiver (anode) not because of flying past it, but because, having turned, they no longer move along, but mainly across a small blocking electric field created near the receiver itself (anode), and therefore cannot overcome it. Consequently, even here, as the speed and energy of the electrons increase, an increasing part of them, due to a decrease in scattering, must overcome the decelerating field and reach the receiver: the current I of the receiver must increase monotonically as the electron energy increases (see Fig. 3, dashed curve).

But, just as in Ramsauer's experiment, the experimental curve (Fig. 3, solid line) shows minima and maxima: when the electrons reach a certain velocity corresponding to a certain energy E_0, the number of particles that have reached the receiver stops increasing with a further increase in velocity and begins to decrease. Only after the electrons reach the next characteristic value of velocity (and energy E_1), the fraction of particles absorbed by the receiver will begin to grow again. The experiment is explained simply: as long as the velocities of the electrons are small, the atoms scatter them elastically, almost without decreasing their velocity in collisions, since the atom is much more massive than the electrons flying away from it, like from a pea wall.

But the barely increased energy of the electron will exceed the excitation energy of the atom (and its first resonance line), as the latter will take energy away from the particle - the energy of the electrons burns out, as in a bust in the game “point”. Electrons with such an energy lose speed and can no longer overcome the blocking field. If the electron has a noticeably high energy, then, depending on the conditions of the experiment, it either loses only a part of it (equal to the resonance potential), or does not lose it at all (the improved Hertz experiment). Therefore, as the electron energy continues to grow, the percentage of particles reaching the receiver will begin to increase again (Fig. 3).

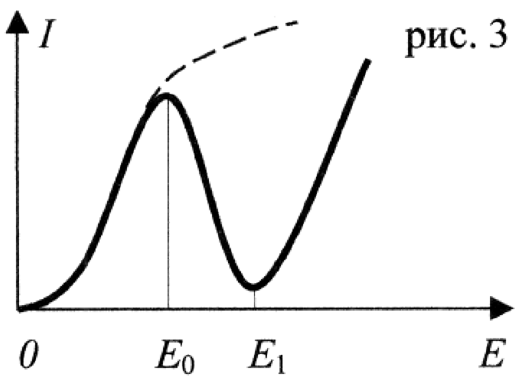

Fig. 3.

The similarity of the experiments is too obvious to pass by without paying attention. In both experiments, contrary to the predicted dependence (shown by a dotted line in Figs. 2 and 3), a sharp drop in the number of electrons reaching the receiver is observed, which is minimized when they reach the energy E_1. No wonder the dependencies in Fig. 2 and 3 are qualitatively mirror images of each other (recall that σ changes in the direction opposite to the change in current I). Therefore, it can be assumed that in the Ramsauer-Townsend experiment such a drop can be explained in the same way as in the Frank-Hertz experiment: having gained a certain energy, electrons cease to dissipate elastically in collisions, and at once give up the accumulated energy to the atoms (equal to the excitation energy). In this case, their speed decreases, which leads to an increase in scattering, which reduces the percentage of particles reaching the receiver: a kind of resonance maximum, a burst, appears on a monotonically decreasing scattering curve. No wonder the graph (Fig. 2) is so reminiscent of the resonance curve familiar to everyone from school.

Thus, the resonance maximum and the accompanying scattering minimum should be observed in any case, regardless of the nature of the electron. The resonance peak of the scattering cross section per excitation energy is also mentioned in the literature on the theory of collisions and scattering of electrons by atoms. And since there are no other extrema on the graph (Fig. 2), apart from the extrema associated with the excitation of the atom, then it turns out there is no use here to attract diffraction and wave properties of the electron. So the result of the Ramsauer-Townsend experiment cannot serve as proof of the wave nature of the electron: this experiment is nothing more than a modified Frank-Hertz experiment.

This is confirmed by the values of the energy of the scattering maxima in the Ramsauer experiment, which are close to the excitation energies of the indicated gases (see table: the excitation energies of atoms according to “Spectral Analysis” by EG Oreshenkova - Moscow: Vysshaya Shkola, 1982, p. 44). Due to the fact that the resonance peak of the scattering curve for various reasons is very blurred, as in a simple resonance curve, the scattering minimum can be quite far from the maximum, and the maximum energy does not exactly coincide with the excitation energy.

In Ramsauer's experiment, the decrease in the energy E_1 of the scattering maximum is not at all explained by the increase in atomic sizes, but by the fact that the excitation (and ionization) energy gradually decreases with a gradual transition from helium to xenon. If the sizes of atoms are indeed sometimes estimated from the scattering and diffraction of electrons on them, then, perhaps, it is precisely the error of this measurement technique that causes the large discrepancies (sometimes 5 times) in the values of atomic radii found by different methods.

So, the Ramsauer-Townsend experiment does not confirm the wave properties of the electron and should be excluded from the corresponding sections of textbooks. So what of that? - the Reader will ask, - Just in this experiment, as in many others, not the wave, but only the corpuscular side of the two-faced electron is manifested, but in other diffraction experiments the wave properties of these and other particles are evident. But not everything is so simple ...

In the Ramsauer experiment, as in the Frank-Hertz experiment, the wave properties of the electron, leading to a decrease in scattering, should nevertheless manifest themselves, if not at the indicated, then at slightly lower energies. But the fact of the matter is that in the dependences (Figs. 2 and 3), apart from the obligatory scattering oscillations associated with the excitation of spectral lines and ionization of atoms, there are no others. It turns out that Ramsauer's experiment not only does not confirm the wave nature of the electron, but even denies it.

But this is not the only point: the erroneous wave interpretation of Ramsauer's experiment, included in textbooks, undermines the credibility of the wave explanation and all other experiments on the interference of electrons or other particles. Perhaps they will eventually be explained more rationally, without involving the wave properties of particles? Perhaps, in fact, there is no wave-particle duality, and we take the expected for reality? It's just that the results of experiments on the interference of electrons, like the results of the Ramsauer experiment, were so unusual, so strongly contradicted the classical concepts that the wave nature of the electron was unconditionally recognized in them, and there were no attempts to give the experiments an alternative explanation.

And yet, as has been shown, such an explanation can sometimes be found, it should be looked for. No wonder Einstein and Planck, whom no one would reproach for inertness of thinking and adherence to dogmas, whose works, in fact, laid the foundation for quantum mechanics and the hypothesis of particle-wave dualism, until their deaths could not accept quantum mechanics, argued that it is impossible for a particle to be simultaneously a wave, and for a wave - a particle, it was believed that over time, in each of the cases, only one model would survive, which would explain both the wave and corpuscular properties of particles or waves.

Sergey Semikov

installed: 27.08.2006

Russian to English translation using Google Translate by Thomas E Miles. Original Russian language files located at: http://www.ritz-btr.narod.ru/. Other Ritz related files located at the Robert Fritzius web site: http://shadetreephysics.com/