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# *Refraction of Single Photons vs Wave Theory*

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*For almost 400 years, the wave theory has been explaining the refraction of light by changing the speed of wave fronts at the interface between media, and no other theory offers another explanation. Light pressure, the photoelectric effect, the laws of thermal radiation and the Compton effect, discovered in the late 19th and early 20th centuries, contradicted the wave theory, and wave-particle duality was invented to save it. And yet, until now, neither wave theory nor quantum mechanics can explain why on the interface of media, not only a wide wave front, but also a single photon changes the direction of motion. And a single photon changes the direction of motion exactly like the wave fronts of a light beam .*

*In this work, it is shown that the direction of light movement changes not due to the fact that the velocity changes at the interface between media, as was assumed in the 17th century by Huygens and Snell, but because of the interaction of each photon with first re-emitting atom of the interface between media.*

In science, such situations often arise when scientists, not understanding the essence of a new discovery, agree with an erroneous and sometimes obviously strange explanation only because it allows predicting some new effects, which are subsequently confirmed by practice. The geocentric system developed by Ptolemy could quite accurately predict the movements of the planets and was considered universally recognized for more than one and a half thousand years. For the same reason, the special theory of relativity, which is based on the erroneous, unconfirmed postulate of the independence of the speed of light from the movement of the observer, is still considered generally accepted. And the same thing happened with the wave theory of light: for several centuries this theory erroneously explains the refraction of a beam by a change in its speed at the interface between two media, but even now, when experiments with single photons are already being carried out, it cannot in principle explain why a single photon changes the direction of movement is the same way as the wave front

The first attempt to determine the law of refraction of light was made by Ptolemy, who measured the dependence of the angles of refraction on the angles of incidence and compiled tables for the refraction of a beam in water and glass. And the currently accepted law of refraction was established by Snell back in 1621.

This law states that the angle of incidence $\alpha$ is connected to the angle of refraction $\beta$ by the expression

$$n_1 Sin\alpha = n_2 Sin\beta ,$$

where $n_1$ - refractive index of the medium from which light enters the second medium,
$n_2$ - refractive index of the second medium,

and *the refractive index of a medium* is understood as the ratio of the speed of light in vacuum to the speed of light in a medium, that is, that Snell's law states that the expression $\frac{n_1}{n_2} = \frac{V_1}{V_2}$ is valid,

where $V_1$ - beam speed before refraction,
$V_2$ - refracted beam speed.

The expression $n_1 Sin\alpha = n_2 Sin\beta$ makes it possible to determine the angle of refraction $\beta$ from known refractive indices $n_1$ and $n_2$ and is confirmed in practice with high accuracy. But the very definition of the refractive index through the speed of light in a medium, as shown below, is erroneous and has no physical meaning.

To understand why light is refracted at the interface between different media, you need to remember how atoms and molecules interact with each other in a solid and what changes when atoms are located directly at the interface between media.

## Interaction of atoms and displacement of electron orbits in the surface layer of matter.

It is known that electrically neutral molecules in a solid are mutually attracted, attractive forces act between their electron cloud and the atomic nuclei of neighboring molecules since. But at the same time, both the electrons and the nuclei of each molecule are repelled, respectively, from the electrons and nuclei of neighboring molecules, and only because of this, the molecules in the substance are stably held in a state of equilibrium at distances of the order of one their diameter.

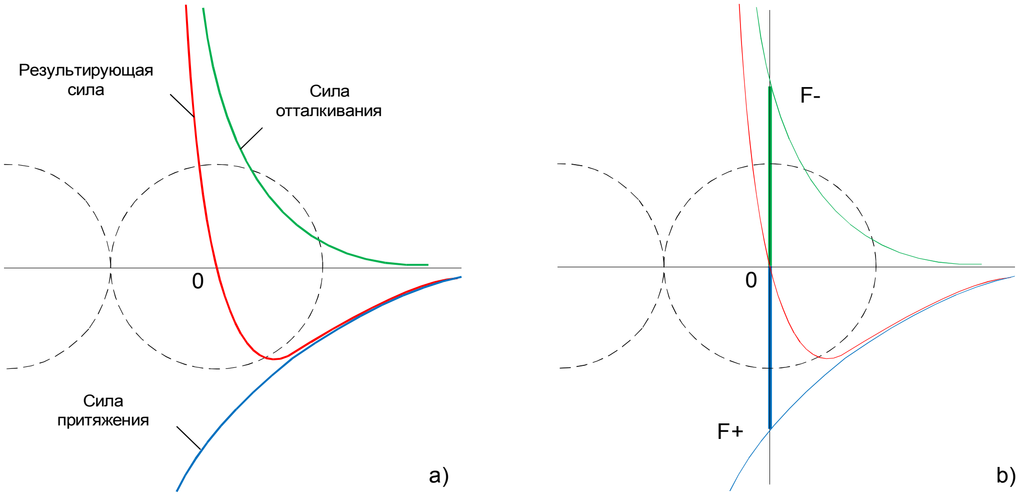


Fig.1

Fig.1, which is given even in school textbooks, shows that at distances of the order of 2-3 molecular diameters, the repulsive force is negligible and only the attractive force is noticeable (Fig.1, a). As the distance decreases, both forces increase, but the repulsive force increases faster , and at a distance equal to the diameter of the molecules becomes equal to the force of attraction (point 0 in Fig.1). The significant electric force of attraction F+ is compensated by the equal force of repulsion F- and the resulting force becomes equal to zero (Fig.1,b).

If for some reason (for example, when a body is stretched) the distance between the molecules becomes larger, the repulsive force decreases faster and the attractive force prevents the distance from increasing. If you try to reduce the distance between the molecules (for example, when compressing the body), the electron shells begin to overlap, the repulsive force increases sharply and becomes much greater than the attractive force and prevents further convergence of the molecules.

It is generally accepted that the curve of change of the resulting force shows only that at large distances the molecules are attracted, at small distances they are repelled, and therefore at point 0 a system of two molecules, like the entire system of molecules of  solid, turns to be stable.

But if we consider not the abstract resulting force, but separately the attractive and repulsive forces, we can see that these forces act differently on different parts of the molecules and therefore a new effect appears, which manifests itself only in the surface layer of the molecules: due to the different influence of these forces on different parts of the molecules, *the electron orbits of the molecules located on the interface turn out to be* ***displaced*** *deep into the body*, and, as shown below, it is this displacement that makes it possible to understand the mechanism of light refraction.

## Interaction of photons with electrons of displaced orbits

If an atom is not affected by other atoms (for example, in the air), its electron cloud, before meeting with a photon. is symmetrical with respect to the nucleus  (Fig. 2, a)

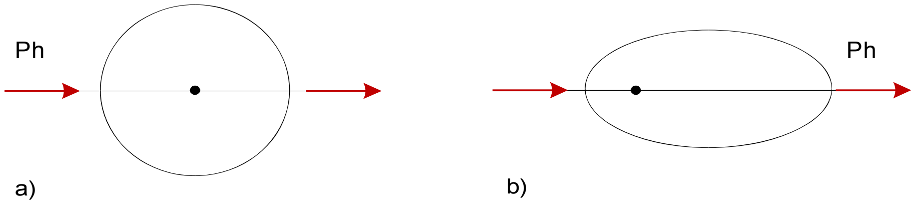


Рис. 2

Meeting with this atom, the photon is absorbed by the electron and transfers its momentum to it, as a result of which the electron orbit shifts in the direction of the photon and, after some delay, the electron emits a photon with a speed C in the same direction (Fig. 2,b).  Since the process of photon re-emission is associated with the transfer of its energy to an electron at the moment of absorption and then with the return of energy to a new photon emitted in the same direction, the re-emission process does not proceed instantly, but over a certain period of time. These delays during multiple re-emissions of a photon by the atoms of the medium lead to a decrease in the speed of light in the medium.

In water or glass, where an atom is evenly surrounded by other atoms, a photon, just like in a gas, does not change the direction of motion after reradiation.

In **the surface layer**, the situation is different. Since the molecules on the surface of water or glass experience attraction only from the side of water or glass and practically do not experience attraction from the side of air molecules, the force of attraction turns out to be directed deep into the body. To simplify the analysis, we further neglect the attraction from the side of air and assume that the light enters the water or glass from the vacuum.

Since a molecule is not a point object, but a spatially complex structure, the attractive force F + and the repulsive force F- affect its different parts in different ways - the electron cloud and the atomic nucleus. Therefore, when in a state of equilibrium the equal forces F+ and F- are mutually compensated, the configuration of the molecule changes simultaneously: the electron cloud of the surface molecule is attracted by the positive nucleus of the medium molecule, the front part of the cloud is obviously attracted more strongly than the back, and the electron cloud of the molecule turns out to be displaced relative to the nucleus.

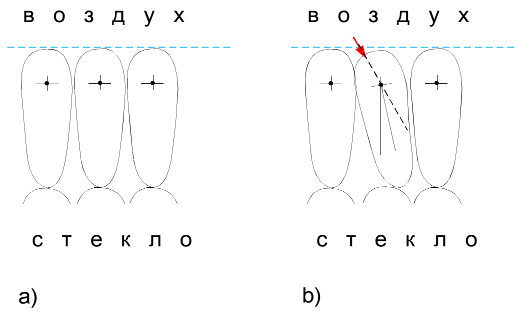
Assuming that, *due to the force of attraction, the electron cloud of the interface molecule is always displaced inward,* we **came to the conclusion** that during re-emission, a photon cannot shift the orbit in the direction of its motion, since, except its momentum, an attractive force also acts on the orbit. The deviation of the orbit and, consequently, the direction of motion of the re-emitted photon are determined by the vector sum of two forces: the force imparted during the transfer of the photon's momentum to the electron, and the force of attraction from the medium. Due to the additional force that shifts the orbit deep into the glass or water, the photon, being re-emitted by the interface atom, changes direction and, both before re-emission and after re-emission, moves - until the next re-emission by an atom of the medium - with a speed C.

That is, *both a single photon and a light beam change the direction of movement* not because of a change in the speed of movement, as the wave theory suggests, but *because of the interaction with the electron of the first re-emitting atom of the surface.*

## Analysis of changes in the trajectories of a single photon at the interface

To test the assumption about the influence of the displacement of the electron cloud in the molecule of the surface layer on the direction of photon movement, we analyzed situations with different angles of incidence of single photons from air into media with different refractive indices - into water (n=1.333), into glass (n=1 .7) and into diamond (n=2.42), and the obtained refraction angles were compared with the known values of the angles.

Before the photon arrives, the surface molecules are in a position where the attractive force is balanced by the repulsive force (Fig. 3a). Since the repulsion force increases very sharply even with a small displacement inward, the orbits are in the most displaced position and cannot move further inward under the influence of the photon momentum. Therefore, regardless of the angle of incidence, the photon momentum can shift the orbit only along the surface, turning it relative to the atomic nucleus, just as the force applied to the pendulum, regardless of its direction, can only deflect the pendulum from the vertical position, but cannot change its length ( Fig. 3b).



a) b)

Рис. 3

To imagine how the orbit changes direction under the simultaneous action of the force of attraction and the force with which the photon acts on the electron, it is necessary to know not only the directions of these forces, but also their magnitudes

The force with which the photon acts on the orbit obviously does not depend on the direction of the photon's motion and in Fig. 4 we take it constant and in arbitrary units equal to 20 (the radius of the circle).

However, we only know about the force of intermolecular attraction so far that it is created by attraction from neighboring atoms and the resultant of these forces is perpendicular to the surface, but the magnitude of this force is not known to us. In addition, the force acting on the orbit must obviously somehow change when, under the action of a photon, the orbit turns through a certain angle.

But the fact that with high accuracy confirmed Snell's law $n_1 Sin\alpha = n_2 Sin\beta$ and numerous tables used in practice allow us to know exactly the angle of refraction $\beta$ for any angle of incidence $\alpha$, gives us the opportunity to very accurately estimate the magnitude of the attractive force

## The dependence of the force of attraction on the angle of refraction

Fig. 4 shows the angles of refraction of 46.5 and 32.5 degrees for the cases when light enters the water at angles of incidence of 75 and 45 degrees.

Vector OB depicts the force with which a photon tends to shift its orbit in the direction of its motion during absorption by an electron (on a conditional scale OB=20 ). But the photon cannot turn the orbit in the direction OB, since the rotation of the orbit is prevented by the force of attraction. At what angle will the orbit turn under the action of two forces - the horizontal component of the photon momentum DC and the attractive force OD ?

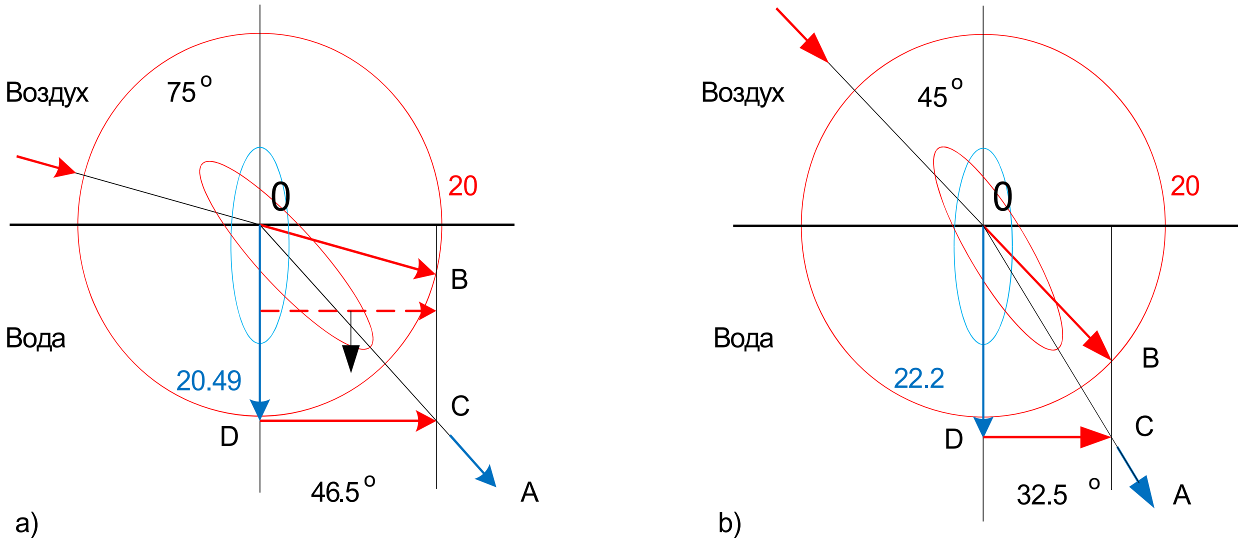


Рис. 4

This question can be answered by the fact that we know at what angle the orbit turns - it turns by the angle of refraction known to us and the re-emitted photon moves in this direction, that is, in the direction of OA.

Since we know that at an angle of incidence of 75 degrees, the angle of refraction should turn out to be exactly 46.5 degrees (Fig. 4, a), we move the horizontal component of the momentum (DC - shown by a dotted line) until its end coincides with the direction of OA in point C and then by point C we find the position of point D. That is, in this way we determine the force OD with which the orbit is attracted when it is rotated through an angle of 46.5 degrees, equal to the angle of refraction. In this case, the force of attraction OD is equal to 20.49.

If the angle of incidence is, for example, 45 degrees and we know that at this angle of incidence the light is refracted at an angle of 32.5 degrees (Fig. 4, b), we can in the same way find the attractive force corresponding to the angle of refraction of 32.5 degrees - it turns out to be greater and is equal to 22.2.

On closer examination of Fig. 4, one can see that *at different angles of refraction* $\beta$, the *vector sum* of the horizontal component of the photon momentum DC and the attractive force OD *turns out to be the same*: the vector sum $\bar{OD} + \bar{DC} = \bar{F}$ turns out to be constant in magnitude and the resulting force $OC = F$ is equal to OD / cos $\beta$.

Using the method described above, we determined the magnitude of the attractive forces OD at different angles of incidence of the beam from air into water (Fig. 5).

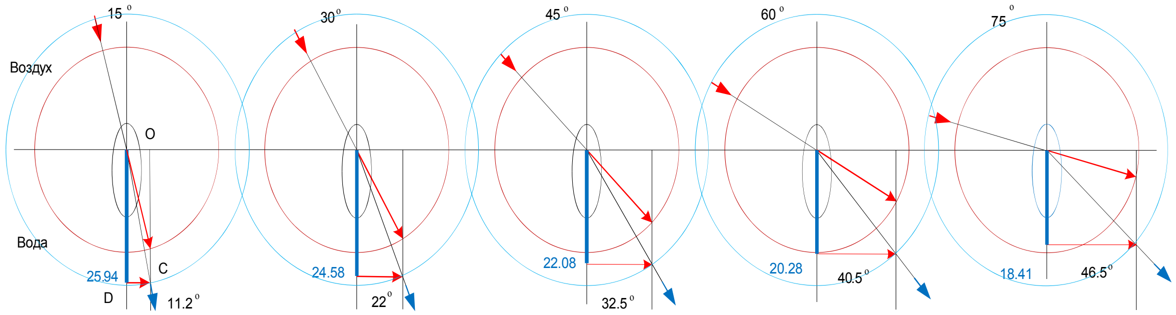


Рис. 5

From these constructions, it can be seen that with an increase in the angle of incidence, the attractive force OD decreases, and the resulting vector $\bar{OC} = \bar{DC} + \bar{OD}$ only rotates through the angle of refraction, but remains constant in magnitude and equal to OD / Cos $\beta$. That OD / Cos $\beta$ = const and point C at any angles it turns out to be on a circle of radius OD / Cos $\beta$, confirms Table.1

**Table 1**

| $\alpha$ | $\beta$ | OD | OD / Cos $\beta$ | ( OD / Cos $\beta$ ) / **1.333** |
|---|---|---|---|---|
| 15 | 11.2 | 25.94 | 26.443614530743877565826012174234 | 20.063718940584162137424140612092 |
| 30 | 22 | 24.58 | 26.424101195600794364887820636576 | 19.823031654614249335999865443793 |
| 45 | 32.5 | 22.08 | 26.180014167346268047861693150038 | 19.639920605661116314975013615932 |
| 60 | 40.5 | 20.28 | 26.669964357785115829956967602994 | 20.007475137123117651880695876215 |
| 75 | 46.5 | 18.41 | 26.744937347798688129186379435918 | 20.063718940584162137424140612092 |

The constancy of the OD / Cos $\beta$ value means that, regardless of the angle of incidence, the re-emission of a photon occurs at the moment when the resulting effect of the photon momentum and the force of attraction becomes equal to a certain value of OD / Cos $\beta$.

**The physical meaning of the expression OD / Cos** becomes clear if OD / Cos $\beta$ is divided by the refractive index of water m = 1.333 and the accepted construction scale is taken into account: OD / Cos is equivalent to the refractive index and characterizes the optical density of the substance.

Thus, without knowing the refractive index n, from the relative value of the expression OD / Cos, for any angle of incidence, the corresponding angle of refraction can be calculated as follows.

$OB = F_{Ph}$ is the force with which the photon deflects the orbit during absorption, and
$DC = F_{Ph} Sin\alpha$ is the projection of this force on the horizontal axis.

The attractive force OD corresponding to the angle of refraction $\beta$ is given by $OD = FCos\beta$ .

Since the resulting force $OC = F$ is equal to the vector sum $\bar{OD} + \bar{DC} = \bar{F}$ ,

$$OD^2 + DC^2 = F^2 \ , \qquad F^2 Cos^2\beta + F_{Ph}^2 Sin^2\alpha = F^2 \qquad \text{и} \qquad F_{Ph}^2 Sin^2\alpha = F^2\left(1 - Cos^2\beta\right),$$

where we get
$$F = F_{Ph}\frac{Sin\alpha}{Sin\beta} \quad \text{or} \quad Sin\beta = \frac{F}{F_{Ph}} Sin\alpha$$

Thus, the angle of refraction, just as in the wave theory, is determined by the sines of the angle of incidence and the angle of refraction, but *instead of the ratio of refractive indices* $\frac{n_1}{n_2} = \frac{V_1}{V_2}$ , where the refractive index in the Huygens-Snell theory is the ratio of the speeds of light in the medium and vacuum, *the ratio* $\frac{F}{F_{Ph}}$ characterizing the interaction each photon with atoms of the surface of the refracting substance *is used*.

**We also checked the dependency** $Sin\beta = \frac{F}{F_{Ph}} Sin\alpha$ **for the cases**
when a photon enters glass from air (Fig. 6) and
when a photon enters diamond from air (Fig.7 ).

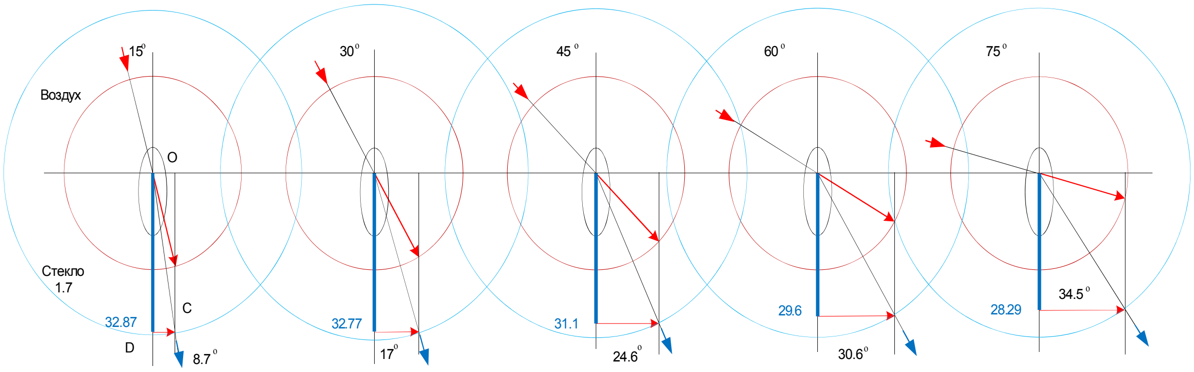


Рис. 6

According to **Fig. 6** for different angles of incidence, the attractive forces for glass are determined (refractive index n = 1.7 ) . The forces of attraction in glass turn out to be greater than in water, and also decrease with increasing angle of incidence.

The resulting vector $\bar{O}C = \bar{D}C + \bar{O}D$ also rotates by the angle of refraction and remains constant in magnitude, but for glass, OD / Cos $\beta$ turns out to be not 26.5, as for water, but 34.3, that is, it is also proportional to the refractive index of glass.

The attraction force OD for glass varies from 32.87 at $\alpha$ = 15 degrees to 28.29 at $\alpha$ =75 degrees. The constancy of the OD / Cos $\beta$ value and its proportionality to the refractive index for glass is confirmed by Table 2.

**Table 2**

| $\alpha$ | $\beta$ | OD | OD / Cos $\beta$ | ( OD / Cos $\beta$ ) / **1.7** |
|---|---|---|---|---|
| 15 | 8.7 | 32.87 | 33.252608274715381997456891445633 | 19.5603578086561070573275832033314 |
| 30 | 17 | 32.77 | 34.2673188600838402057240965322242 | 20.1572463882846118857200567836722 |
| 45 | 24.6 | 31.1 | 34.204536853023335323305534596617 | 20.120315795896079601944432115657 |
| 60 | 30.6 | 29.6 | 34.388933119753873160533851018634 | 20.228784188090513623843441775667 |
| 75 | 34.5 | 28.29 | 34.327267341549279937667049516951 | 20.192510200911341139804146774677 |

According to **Fig. 7,** the value of OD / Cos $\beta$ is similarly determined for the case when a photon enters diamond from air (refractive index n = 2.42) and the obtained numerical values are given in Table 3.

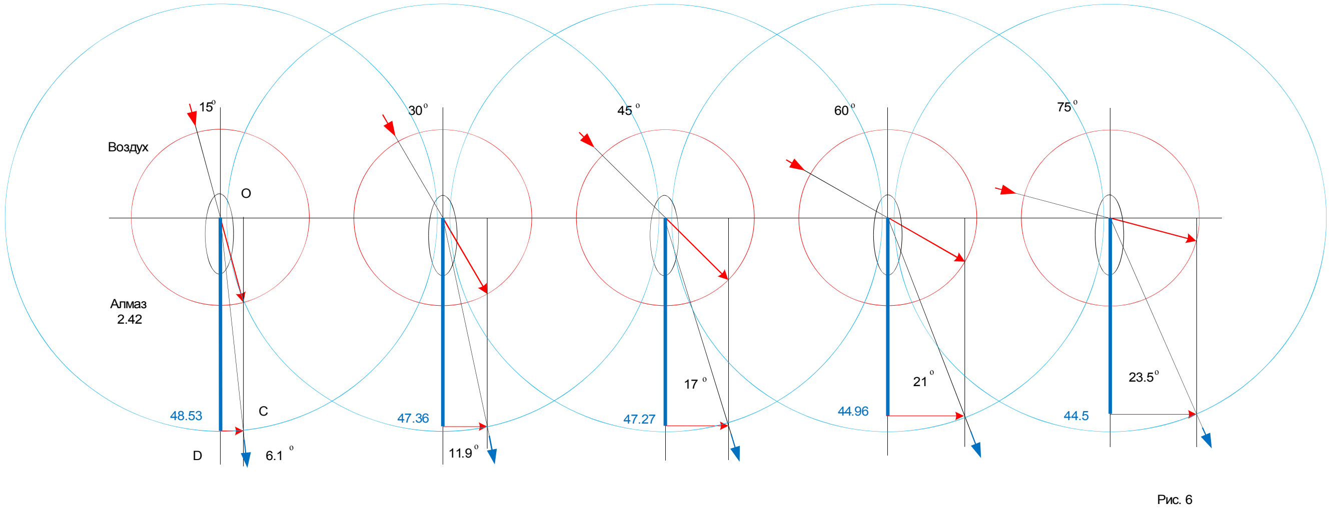


Рис. 7

For diamond, the attractive force OD varies from 48.53 at an angle of incidence of 15 degrees to 44.5 at an angle of 75 degrees and OD / Cos $\beta$ is about 48.5.

**Table 3**

| $\alpha$ | $\beta$ | OD | OD / Cos $\beta$ | ( OD / Cos $\beta$ ) / **2.42** |
|---|---|---|---|---|
| 15 | 6.1 | 48.53 | 48.806344247785006341869729982368 | 20.167910846192151380937904951392 |
| 30 | 11.9 | 47.36 | 48.400168747631794110403856151761 | 20.000069730426361202646221550314 |
| 45 | 17 | 47.27 | 49.429849329147486314451572873942 | 20.425557574027886906798170609067 |
| 60 | 21 | 44.96 | 48.158678913920824444265564072588 | 19.900280542942489439779158707681 |
| 75 | 23.5 | 44.5 | 48.524629130579725195080971559985 | 20.051499640735423634330979983465 |

The constructions shown in Fig. 5-7, not only allow us to determine the magnitude of the displacement forces, but also prove that point C at any angle of incidence lies on a circle radius OD / Cos $\beta$ . Therefore, having once determined OD / Cos $\beta$ value at a certain angle of incidence, it is possible to find from point B and the radius of the circle OD / Cos $\beta$ , as shown in Fig.8, the point C, that is, for any angle of incidence, it is very easy to determine the angle of refraction $\beta$ .

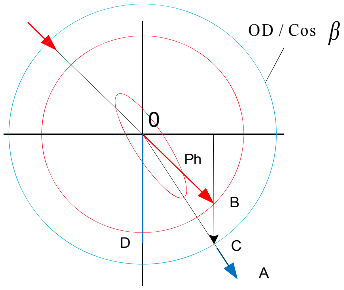


Рис. 8

## Determination of the angle of refraction in the case when a photon leaves the medium into the air

If a photon does not go from air to the medium, but exits, for example, from glass to air, its momentum turns out to be directed from the surface and tends not to increase, but to decrease the orbital shift, as shown in Fig. 9.

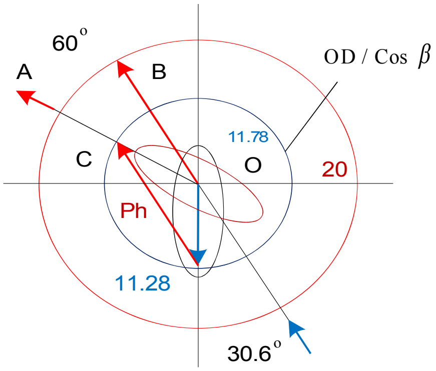


Рис. 9

The displacement of the orbit depends not only on the horizontal component, but on the entire photon momentum, and the position of point C in the direction of motion of the refracted photon is determined by the vector sum of the attractive force (in Fig. 9 it is equal to 11.28) and the photon momentum Ph (taken equal to 20).

Therefore, the displacement of the orbit depends not only on the horizontal component, but on the entire photon momentum, and the position of point C in the direction of motion of the refracted photon is determined by the vector sum of the attractive force (in Fig. 9 it is equal to 11.28) and the photon momentum Ph (taken equal to 20).

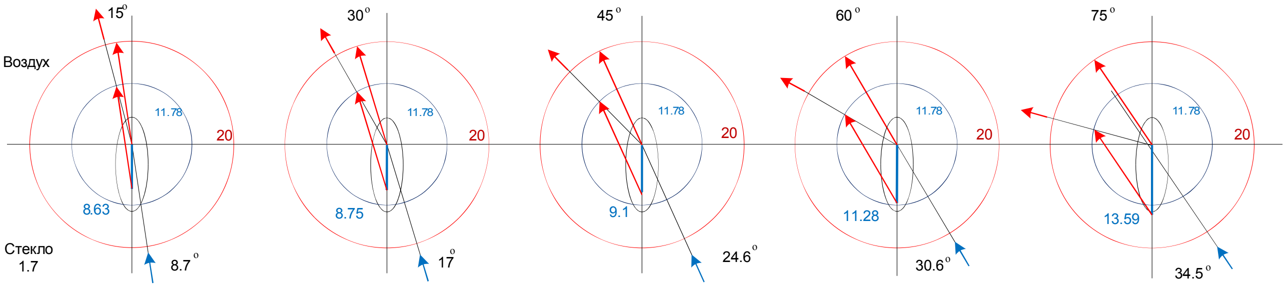


Рис. 10

On Fig. 10 for the case when the photon leaves the glass into the air, for the same angles of incidence as in Fig. 5-7, the forces of attraction are determined and circles of radius OD / Cos $\beta$ are plotted. It can be seen that the forces OD and OD / Cos $\beta$ are much smaller than in the case when a photon enters the medium from air, and at small angles of incidence, the attractive forces turn out to be smaller than at large angles.

The angle of refraction can also be determined by finding the position of point C by point B (the end of the Ph vector) and a circle of radius OD / Cos $\beta$ .

## Conclusion

The *wave theory* explains the refraction of light by the fact that at the interface between media, wave fronts change the speed of movement, and therefore it *cannot* explain the *refraction of a single photon* in principle.

The above analysis shows that such an explanation of refraction is erroneous and *photons change their direction of motion* not due to a change in the speed of motion in the medium, but *due to interaction with displaced orbits of surface layer atoms*

Under the influence of interatomic forces of attraction, the *electron cloud* of an atom on the surface of glass or water *is displaced deep into the body*. Meeting with the first atom of the surface, the photon is re-emitted by it, during the time of re-emission it transfers its momentum to the electron and deflects its orbit from the initial shifted position by the angle of refraction. A new photon is emitted in the direction of the angle of refraction and moves relative to the atom at a speed C until the next re-emission by the atom of the medium. Relative to the re-emitting atoms of the medium, a photon travels at a speed C and relative to medium with an average speed C/n, less than C.

Reemitted by a surface atom, a photon changes direction and moves at a refraction angle $\beta$ , the value of which is determined not by the expression $n_1 Sin\alpha = n_2 Sin\beta$, where the ratio of the refractive indices $n_2 / n_1$ according to Huygens and Snell is the ratio of the speeds of light before and after refraction, but by the expression $Sin\beta = \frac{F}{F_{Ph}} Sin\alpha$, where instead of the ratio of the refractive indices $n_2 / n_1$, the relative values are used attractive force a OD / Cos $\beta$, which characterizes the optical density of the medium.

The interaction of a photon with a displaced orbit of an interface atom allows us to give a new physical meaning to the *concept of refractive index* and explain why a **single photon** is refracted in the same way as Huygens' "wave fronts" and also to explain phenomena such as *reflection, diffraction and total internal reflection* in a new way, and to understand *why and how a photon slows down the speed of movement in a medium.*