(This is a part of the book The Concept of Reality.pdf)

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The Photoelectric Effect

The experimental facts of the photoelectric effect:

If a metal plate gets irradiated by UV-light with a frequency ν above a certain limit ν_{min}, electrons are set free without any delay. The kinetic energy of these electrons depends only on the frequency ν of the radiation.

This is in blatant conflict with the wave model of the light, according to which the displacement of electrons should take place at any light frequency and their energy should depend on the intensity of the light. Furthermore, an enormous delay (under realistic conditions thousands of hours) until the displacement of the first electron would have to be expected, if one assumes that the energy radiated onto an area of the extent of an electron cross section should have to mount up to the required value.

As is well known, Einstein’s solution was to assume an interaction between light and matter in the form of an *impact process* of particles, i.e. of a light-quant with the energy hν and an electron bound with the energy A. Then from the energy balance the following equation results:

$$h\nu = A + mv^2/2 \qquad \text{(A … displacement work)} \qquad (1)$$

This equation describes the process in accordance with the experiment. Insofar it is justified to call this a correct and successful description.

However one would surely prefer to know *how* this magic metamorphosis of a wave into a particle occurred – at least it is decisively proven that light is a wave.

For comparison, imagine the following scene: a magician places an empty top hat on a table, puts a trumpet into it and speaks his magic formula – and out of the hat jumps a pig! – And now all you know is the velocity of the pig. In spite of the undeniable benefit – you would probably be able to sidestep the next pig – you would hardly be content with this knowledge!

What really matters is that, in this case, indeed nobody would assume that the trumpet has *actually* been transformed into a pig. Why not? Plain and simple: there is no magic.

So why do we accept the transformation of the wave into a particle as a fact?

The usual commentary – which pretends to be an explanation – reads as follows:

Our thinking applies only to the medium-sized world. It is not suitable for understanding anything very small.

Let us simply replace this untenable assertion, which, as a standalone assumption, is out of thin air, by the general

No-Nonsense Hypothesis: There is no witchery. There is altogether no nonsense within nature.

Armed with this hypothesis, we turn again to the Photoelectric Effect.

It is completely ascertained that light is a wave. Therefore *it is* a wave. And as there is no witchery, it does *not* turn into a particle – thus it must enter the interaction as a wave.

On the other hand, we know that it is not possible to describe the Photoelectric Effect as interaction between wave and particle.

This means there is only one way out: the electron must be a wave, too.

But the electron is a particle! So, with the assumption that now it is a wave, aren't we also guilty of believing in witchery?

Not at all. As follows:

A particle is not *logically* associated with its attributes (interactions) but *only by definition.* Accordingly its definition changes, if the description of the interaction changes. This means: if we succeed in describing the interaction under the assumption that the electron is a wave, then its definition has changed – in other words: then it has already before been a wave.

In contrast, a wave is *logically* associated with its attributes (interactions): its attributes *ensue* from its dynamics. Thus with a wave, there is no possibility for another definition. A description of the interaction, where the wave appears as a particle – as is the case in Einstein's model – can therefore not change the definition of the wave; in this case the assumption of a transformation – i.e. of duality – is unavoidable.

Thus the No-Nonsense Hypothesis has led us to the assumption that both light and electron are waves.

How can waves interact *as waves?*

The easiest way is by superposition. Thus we will describe the interaction as superposition of the two waves.

At first a preliminary consideration. Let us assume, in an electron exists an oscillation with frequency ν. What follows with respect to this oscillation, if the electron is at rest? It follows that the oscillation is in-phase, because if the oscillation has everywhere the same phase, then there is no motion. Therefore, for an electron at rest, we must set:

$$y = \cos 2\pi \, t \, \nu$$

(This is de Broglie's well-known train of thought.) Then for an electron with velocity v the Lorentz-Transformation leads to

$$y = \cos 2\pi \left(t \, \nu \frac{1}{k} - x \, \nu \frac{v}{c^2} \frac{1}{k} \right) \qquad \left(k = \sqrt{1 - \frac{v^2}{c^2}} \right)$$

Thus the frequency ν_e of an electron moving with velocity v relates to the frequency ν_{e_0} of an electron at rest as follows:

$$\frac{\nu_e}{\nu_{e_0}} = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{k} \qquad (2)$$

In the case of non-relativistic electrons, v is small against c, and therefore

$$\frac{1}{k} = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \approx \frac{1}{1-\frac{v^2}{2c^2}} \approx 1 + \frac{v^2}{2c^2} \tag{3}$$

Now we proceed to the description of the interaction. At first, we look at the interaction between light and a free electron.

Let ν_{e_0} be the frequency of a free electron at rest before the interaction, ν_e the frequency of the electron moving with velocity v after the interaction.

We form a superposition of the in-phase oscillation which represents the electron[1]

$$y = \cos 2\pi\, t\, \nu_{e_0}$$

and a plane wave that represents the light

$$y = \cos 2\pi \left(t\, \nu_L - x \frac{1}{\lambda_L} \right)$$

From the identity:

$$2 \cos a \cos b = \cos(a + b) + \cos(a - b) \tag{4}$$

follows that, as a consequence of the superposition, we obtain two waves with the frequencies

$$\nu_{e_0} \pm \nu_L$$

(where ν_L is the frequency of the light).

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[1] Of course it cannot be claimed that the electron *is* this oscillation. However from the occurrence of this oscillation conclusions can be drawn.

The higher frequency must be the frequency of the electron *accelerated* by the interaction; thus, according to (2), it follows that

$$\nu_e = \nu_{e_0} + \nu_L = \nu_{e_0} \frac{1}{k} \tag{5}$$

(The second wave will be discussed subsequently)

Then $\nu_L = \nu_{e_0} (\frac{1}{k} - 1)$ and according to (3)

$$\nu_L = \nu_{e_0} \frac{v^2}{2c^2} \tag{6}$$

Thus also here, the square of the speed of the electron is proportional to the frequency of the light.

(For the second wave we would have to set

$$\nu_e = \nu_{e_0} - \nu_L = \nu_{e_0} k \tag{5'}$$

However according to (3) $k \approx 1 - \frac{v^2}{2c^2}$

and we obtain again $\nu_L = \nu_{e_0} \frac{v^2}{2c^2}$

The frequency of the second wave would therefore correspond to the frequency of an electron, whose velocity is *reduced* by v as a consequence of the interaction. Since we assumed a stationary electron – so that ν_{e_0} cannot be reduced any more – this part can be omitted.)

Up to now, we have only used simple wave-mathematics. In order to return into the world of physical modeling, we multiply (6) by h:

(It should be emphasized, however, that this multiplication is only necessary due to "dimensional" reasons, i.e. for crossing over to the “mechanical” description. The fact that h is a fundamental *unit* has nothing to do with our considerations. We will discuss this point later.)

$$h\nu_L = h\nu_{e_0} \frac{v^2}{2c^2} = m_e c^2 \frac{v^2}{2c^2} \tag{6'}$$

Eventually we obtain

$$h\nu_L = \frac{m_e v^2}{2} \tag{7}$$

In order to transfer our idea to the interaction between light and a bound electron, now we only have to insert the frequency difference δ_ν between a bound and a free electron into (5)

$$\nu_e = \nu_{e_0} + \nu_L - \delta_\nu = \nu_{e_0} \frac{1}{k} \tag{8}$$

and to carry along this δ_ν, therefore

$$h\nu_L - h\delta_\nu = h\nu_{e_0} \frac{v^2}{2c^2} = m_e c^2 \frac{v^2}{2c^2} \tag{8'}$$

So we get to

$$h\nu_L = \frac{m_e v^2}{2} + h\delta_\nu \tag{9}$$

which is identical with (1).

Let us now compare the two models – the usual one, which is analogue to a mechanical impact, and the one proposed here, which is conceptualized as wave-superposition.

In the mechanical impact model, the fact that the velocities and, accordingly, the energies of the electrons after the interaction are always identical and depend only on the light frequency necessitates the well known interpretation, i.e. light particles, which are defined by frequency and are always identical and indivisible, interact with electrons. (If the light particles were divisible or different from each other we should see also electrons with different velocities after the impacts.)

In the wave model, on the contrary, this fact is self-evident: here, the "electrons" leave the metal plate in a continuous process, *as waves,* whose frequency follows from the superposition of light waves and electron waves. Thus, according to equation (4), after the interaction no other frequencies (i.e. no other energies and velocities) are possible – wave superpositions do not permit other results.

This means: in the wave model it is obvious why the amplitude of the light and its intensity don't matter, and also why no delay occurs until the first measurement takes place: the superposition process starts immediately.

The assumption of indivisible light particles can be dispensed with.

However the most important point is the following one, because here for the first time the core of the new interpretation becomes visible:

The equation

$$\nu_L = \nu_{e_0} \frac{v^2}{2c^2} \qquad (6)$$

contains already the essential result: the square of the velocity of a free electron after the interaction depends only on the frequency of the light (in the case of a bound electron, on the left side the term $-\delta_\nu$ has to be inserted).

For the deduction of this equation, only two presuppositions are required:

1. Both light and electron are waves.
2. The Lorentz-Transformation applies.

Besides these two, *no other physical prerequisites* are needed.

Only after the multiplication by h, that is: at the step from (6') to (7):

$$h\nu_L = h\nu_{e0} \frac{v^2}{2c^2} = m_e c^2 \frac{v^2}{2c^2} \qquad (6')$$

$$h\nu_L = \frac{m_e v^2}{2} \tag{7}$$

and for the physical interpretation of (7), the concepts *energy* and *mass* are required, as well as the relation between those concepts and the frequency

$$h\nu = mc^2 = E$$

In other words: For the description of the interaction between light and electron in the Photoelectric Effect the assumption is sufficient that both partners are waves. Not only the assumption of light quanta is superfluous, indeed *all* physical concepts and relations can be dispensed with. Only at the transition to a mechanical description of the usual kind, the concepts appear, which otherwise are the indispensable basis of the description: mass, kinetic energy, total energy.

Therefore, here the descriptions by waves and by particles are not at the same level. Instead they have a hierarchical relationship: The wave description comes first – it is *fundamental*, the particle description is subordinated – it is *derivative*.

Thus in this case the equations $E = h\nu$ and $p = h/\lambda$ do not prove the wave-particle dualism; they are **definition equations** of the quantities energy and momentum.

The concept *energy* is **reduced** to the concept *frequency*, and the concept *momentum* to the concept *wave-length*.[2]

It is obvious that, if this interpretation, which arises quite naturally at the Photoelectric Effect, is sustainable, then *formally* nothing changes, but conceptually *everything* changes.

Let us summarize. It has been demonstrated that the Photoelectric Effect can be described in two ways:

1. According to the mechanical impact model. Both interaction partners are understood as particles.

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[2] However this reduction is only complete, if mass is eliminated as an independent concept, so that h loses its role as link between the wave- and the particle-realm. This will be carried out in the Second Part. (In 6. A Universe without Mass.)

Then either a *dualistic* position has to be taken (quanta which carry the whole energy are embedded in the waves – this was the point of view of Einstein, de Broglie and later of David Bohm), or *complementarity* has to be assumed (this is the so-called Copenhagen interpretation).

The dualistic position leads to explicit non-locality, the Copenhagen interpretation leads to the relinquishment of any kind of understanding.

2. By superposition of waves. Both interaction partners are understood as waves.

Concerning radiation, the interpretation difficulties connected with the positions mentioned in Point 1 disappear. Neither dualism nor complementarity need to be resorted to.

For the moment, all of that applies only to the Photoelectric Effect. The next step we must take at our branching off from the historical path of physics is testing our model assumptions at the scattering of high frequency light (X-rays) on electrons.