*Speculations in Science and Technology* **21**, 329–344 (1999)

# Planck's constant and necessarily time-extended phenomena

INGVAR JOHANSSON

*Department of Philosophy and Philosophy of Science, Umeå University, S-901 87 Umeå, Sweden*

This paper is an attempt to make a wholly new interpretation of the uncertainty principle in quantum mechanics. It is conjectured that where there is supposed to be uncertainty of energy, there is instead a specific form of energy – non-classical energy – which is necessarily extended in time. The conjecture gives rise to a realist interpretation of quantum mechanics which does not rest on any really new mathematical theorem. Instead, the reinterpretation is based on an insight belonging to the philosophy of science. It says that dimensional identities may hide spatiotemporal differences. Non-classical energy has exactly the same physical dimension as action and Planck's constant, but it does nonetheless not correspond to action.

*Keywords:* Planck's constant, energy, action, uncertainty principle, virtual particle, realism.

## Introduction

This paper is an attempt to do to some concepts of quantum mechanics what Ernst Mach once tried to do with the Newtonian concept of mass, supply a new ontological interpretation. In several respects, however, my reinterpretation moves in a direction opposite to that of Mach's proposals. He tried to turn a *property* into a *relation*, whereas I am trying to turn a curious kind of property or relation, that of uncertainty, into another kind of property. According to Mach, the inertial mass of a particle $x$ is not an intrinsic property of $x$ , but a relation between $x$ and all other particles in the universe with which $x$ interacts. I will argue that there are no uncertainties of energy and temporal position, no uncertainties of momentum and spatial position, and consequently no physically meaningful product in either case. However, there are instead necessarily time-extended energy, *non-classical energy*, and necessarily space-extended momentum, *non-classical momentum*. My discussion is primarily centred around the concept of energy, but the concept of momentum cannot be dispensed with in the discussion.

Mach did not want to reject the functional relationships of Newtonian mechanics. He wanted to free the theory from a realist interpretation of forces and to get rid of absolute space. And in order to achieve this aim, he argued that mass is not a measure of the quantity of matter *in* a particle, but a measure of a coupling *between* the particle and all other particles. (For a brief exposition of Mach's fundamental idea see [1, pp. 13–18]; a more detailed account can be found in [2, pp. 91–102]; for Mach's own words see [3, Ch. II].)

Similarly, I will not propose any new functional relationships. No attempt will be made to deduce any new but hitherto undiscovered mathematical theorem. But in contradistinction to Mach, I have no positivist aims. On the contrary, my conjecture of non-classical energy amounts to a new kind of realist interpretation of quantum mechanics. (Mach's principle can, by the way, be used within a realist frame too; see [4].)

The proposed non-classical energy is necessarily extended in time. Therefore, the time dependence of such energy has to be represented by functions of the form $f(\Delta t)$. Non-classical energy can be measured by a magnitude called its *temporal bulk*. The physical dimension of this magnitude is the same as the dimension of Planck's constant and of action (i.e. energy multiplied by time, or joules times seconds). However, non-classical energy bulks correspond to differences of action ($\Delta A$), not to actions ($A$) in the classical sense. Dimensional identities can hide ontological differences (see 'Work as an aspect of a temporal energy transfer bulk'). This is one of the crucial insights behind my conjecture of non-classical energy. Phenomena which have to be represented by functions of the form $f(\Delta x)$ can nonetheless have the same physical dimension as phenomena which can be represented by $f(x)$.

Before I can put forward my idea of non-classical energy, I have to make the reader familiar both with the concept of temporal bulk in itself and with the difference between the concept as a mere mathematical construct and as a magnitude with real physical significance. This is done by means of a short trip through parts of the history of physics. I start in Newtonian mechanics ('Physics and extension in time', 'The concept of temporal bulk', 'Work as an aspect of a temporal energy transfer bulk'). Then I move via Hamilton's concept of action ('Action as temporal energy state bulk') and Einstein's analysis of the photoelectric effect ('Action versus difference of action – the photoelectric effect') to quantum mechanics. Here, there is first a discussion of the uncertainty principle in general ('Planck's constant and the uncertainty principle'), and after that a discussion of the uncertainties within which virtual particles are assumed to exist ('Virtual particles and non-classical energy'). Some concluding remarks end the paper.

## Physics and extension in time

Pre-Newtonian physics worked only with properties extended in time. Both property states and property changes were taken to be extended for at least a very short period of time. Before the invention of the infinitesimal calculus one simply could not make real sense of what is temporally punctual. In Newtonian and post-Newtonian physics it is the other way round. All magnitudes which are regarded as fundamental represent properties which in principle can exist at a momentary point of time, i.e. they can be described by a function $f(t)$ where $t$ represents continuous time. Mass, force, velocity, field strength and many other magnitudes are defined in such a way that their numerical values primarily relate to points in time. Of course, if the magnitude does not change, the corresponding value represents a property state which, as a matter of fact, is extended in time in the sense that all time points in an interval has the same non-zero value. I shall call such magnitudes momentary magnitudes. The kind of phenomena they represent I will call possibly momentary phenomena.

However, there are also in classical physics magnitudes which cannot, not even in principle, be regarded as representing something temporally punctual. This is true of continuous changes in general. Let me take continuous change of place as an example. Such a change can be described by the integral $\int v(t)\,dt$ between $t_1$ and $t_2$. Here $v(t)$ is the function which tells how the velocity varies with time, $t_1$ is the time the movement begins and $t_2$ the time it ends. These three magnitudes represent momentary phenomena.

But a continuous change of place cannot possibly be momentary. If the integral which measures the distance of the change of place shall yield non-zero results, $t_2$ must differ from $t_1$. There has to be a time interval in order for a continuous change of place to exist. A continuous change is necessarily extended in time. All phenomena which are similar to continuous changes in this respect, I will call necessarily time-extended phenomena. When the corresponding magnitudes are described by functions of time, the functions must have the form $f(\Delta t)$. States, in contradistinction to continuous changes, can be momentary as well as temporally extended.

In order to discuss, from a realist point of view, the distinction between momentary and necessarily time-extended magnitudes, we have to remember that magnitudes can be mathematically definable but lack direct physical significance, and also that only some of the magnitudes which are physically significant need to be regarded as fundamental.

In classical physics, there are physically significant magnitudes which represent possibly momentary phenomena as well as physically significant magnitudes which represent necessarily time-extended phenomena; the magnitudes are physically significant in the sense that they are taken to represent something real in nature. But there has among physicists been a strong tendency to regard only momentary magnitudes as fundamental. And for good reasons. Magnitudes which are derivatives with regard to time must, if they are representing something real at all, represent possibly momentary phenomena, and most fundamental laws of physics contain such magnitudes.

## The concept of temporal bulk

Consider a change of place, e.g. the movement of a classical particle. It is usually characterised by three magnitudes: the distance of the movement $\Delta x$, the time of the movement $\Delta t$, and the mean velocity of the movement, $v = \Delta x/\Delta t$. There is, though, a fourth mathematically possible magnitude. We can also multiply the distance of the change of place by the time of the movement. This magnitude I shall call the temporal bulk of the particle movement, and symbolise it by $\#M$:

$$\#M = \Delta x \cdot \Delta t \qquad (1)$$

The physical dimension of this magnitude is distance times time interval, and if it represents something real at all, it represents something which is necessarily extended in time. But it is hard to give the magnitude a real physical significance, much less regard it as fundamental. It looks like a mere mathematical possibility and plaything.

The definition of the temporal bulk of a change of place (1) fits the following general definition: *A temporal bulk is a magnitude which has been obtained by multiplying a magnitude representing something extended in time by the numerical value of the corresponding temporal extension.*

In what follows I shall use this concept of temporal bulk in order to discuss the general idea of necessarily time-extended phenomena. However, as will be clear later on, many such temporally extended phenomena are connected with phenomena which are necessarily extended in space. Therefore, I will make use of a concept of spatial bulk too. Its definition is obtained by merely substituting 'spatial' for 'temporal' (and 'space' for 'time') in the definition above.

Particle movement is merely one example of something which is necessarily extended in both time and space. Ordinary wave movement is another. A wave at sea may be looked upon as a change of place of a spatially extended wave shape. The temporal movement bulk of a wave pulse (which equals the corresponding spatial bulk) may be defined as:

$$\#M_w = \lambda \cdot T \tag{2}$$

It is equally easy to define a temporal bulk for velocity changes, $\Delta v$. Velocity changes are, like all changes, necessarily extended in time:

$$\#\Delta v = \Delta v \cdot \Delta t = (v_2 - v_1) \cdot \Delta t \tag{3}$$

A movement may undergo a change of velocity, but it may also be in a certain state of velocity during a time interval. Even in this case, i.e. when a state as a matter of fact is temporally extended, a temporal bulk can be defined. We get the temporal bulk for velocity states, $v$:

$$\#v = v \cdot \Delta t \tag{4}$$

The velocity state temporal bulk represents something real. It equals the distance of the movement. The velocity change temporal bulk, however, seems to be a mere mathematical construct.

## Work as an aspect of a temporal energy transfer bulk

Let us now look at the kinetic energy of a classical particle in an inertial system. Since both mass and velocity may be ascribed a momentary existence, i.e. there are functions $m(t)$ and $v(t)$, the same goes for kinetic energy. But as remarked in the section 'Physics and extension in time', continuous changes (here, changes of energy) do not have a momentary existence. Assume that work is either being done on the particle by something or by the particle on something else. In both cases there is a transfer of kinetic energy. Where there is work, there is energy transfer; where there is energy transfer, there are energy changes in at least two entities.

It should be noted that energy states, work, and energy changes have the same physical dimension, joule. This is due to the fact that we represent an energy state by naming its place on a scale. A certain energy state is represented by a point on the scale, whereas an energy change is represented by a distance between two points on the scale. Nonetheless the state and the change have the same dimension because the points on the scale are *named* by their *distance from* other points on the same scale. In particular, of course, from the zero point. Trivially, an energy state of 5 J is 3 units away from an energy state of 2 J, and 5 J away from the zero point. The energy amount of this state equals a change of 5 J.

Independently of whether a scale has an absolute zero or not, it is true of the corresponding quantified magnitude that there is no dimensional difference between having a certain value of the magnitude on the one hand and undergoing a change of the magnitude on the other. Both are represented by a distance on the scale. The ontological difference between energy states and energy changes cannot possibly be found by pure dimensional analysis since the corresponding magnitudes have the same dimension.

In the former section I introduced the concept of temporal bulk and defined some bulk magnitudes. I shall now define yet another temporal bulk, the kinetic energy transfer bulk, $\#\Delta E_k$. This time we multiply the work $\Delta E_k$ by the time interval $\Delta t$ during which the work is done. We get:

$$\#\Delta E_k = \Delta E_k \cdot \Delta t \tag{5}$$

Since $\Delta E_k$ represents a transfer of kinetic energy to or from a particle, $\Delta E_k$ is identical with $(F \cdot \Delta x)$, where $F$ is a constant Newtonian force which does the work, and $\Delta x$ is the distance needed for the work to be done. (If $F$ varies, $\Delta E_k$ is identical with $\int F(x)\,dx$.) Therefore, formula 5 is equivalent to the following formula:

$$\#\Delta E_k = (F \cdot \Delta x) \cdot \Delta t = (F \cdot \Delta t) \cdot \Delta x \tag{6}$$

The expression $(F \cdot \Delta t)$ represents of course the impulse of the particle, i.e. the particle's change of momentum during $\Delta t$. Momentum and impulse have the same physical dimension but different relations to time; momentum, like kinetic energy, may be punctual in time and be represented by functions $f(t)$, whereas continuous impulse (change of momentum), like change and transfer of kinetic energy, is necessarily extended in time and must be represented by functions $f(\Delta t)$.

According to my definitions, the whole expression $((F \cdot \Delta t) \cdot \Delta x)$ represents the spatial impulse bulk. Formula 6 can be read as saying that the temporal bulk of the kinetic energy transfer equals the corresponding spatial bulk of the impulse. It is another way of saying that the work done multiplied by the time for the work equals the impulse multiplied by the distance needed for the work to be done.

The remarks made in relation to formula 6 imply a very simple geometrical representation of the connection between change of momentum (impulse) and change of kinetic energy (work) of a classical particle. We can construct a three-dimensional space where the $x$-axis represents distance along the line the particle is moving, the $y$-axis represents time, and the $z$-axis the force acting along the $x$-axis. When the force is constant the temporal energy transfer bulk, $\#\Delta E_k$, is represented by a parallelepiped where one of the side surfaces represents the work, $\Delta E_k$, and where one of the other sides represents the impulse, $\Delta p$, and where the bottom surface represents the temporal bulk of the movement, $\#M$; see Fig. 1.

The mathematical relationships are easily read off, but I have nevertheless written some of them down.

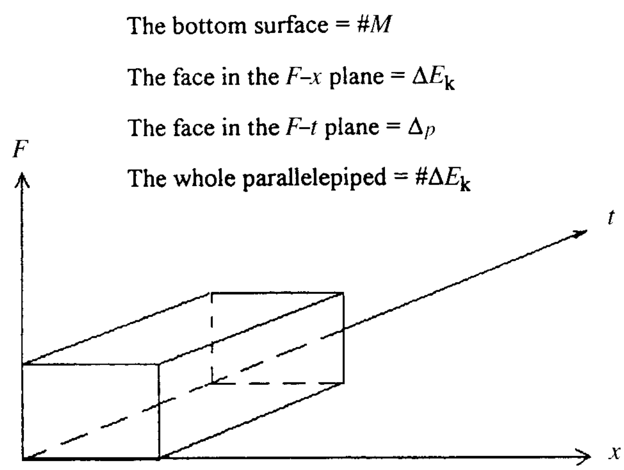


**Fig. 1.**

$$\#\Delta E_k/\Delta t = \Delta E_k \quad \text{or} \quad \#\Delta E_k = \Delta E_k \cdot \Delta t \tag{7}$$

$$\#\Delta E_k/\Delta x = \Delta p \quad \text{or} \quad \#\Delta E_k = \Delta p \cdot \Delta x \tag{8}$$

$$\#\Delta E_k = F \cdot \#M \tag{9}$$

According to formulas 7 and 8 and Fig. 1, we can at least from a mathematical point of view look upon work (energy change) and impulse (momentum change) as two aspects (surfaces) of a transfer bulk (the volume) which is necessarily both spatially and temporally extended. Force may also be seen as a property (the height) of the parallelepiped. This way of speaking turns the original Newtonian mechanics upside down. In Newton's own presentation, force is logically prior to energy and momentum. Newton's laws of motion speak about forces, but not of energies and momenta. In each momentary instant there is a force which in a time interval and over a distance produces impulse and work. Having recourse to the concept of temporal bulk, one can try to imagine the temporal energy transfer bulk as being logically prior to work, impulse, and force; the bulk should then be regarded as the fundamental thing without which the properties of work, impulse, and force would have no existence at all.

All the remarks now made in relation to classical particles, their possibly momentary energy, and their necessarily time-extended energy transfers, can with only minor modifications be made also in relation to classical fields. The particle whose movement is represented in Fig. 1 can be regarded as moving in some kind of constant force field. However, the same quantitative changes of energy and momentum can occur if it is the field instead of the particle that is moving. The field can be ascribed a state of possibly momentary energy which it during $\Delta t$ transfers to the particle. (This momentary field energy, however, cannot, like that of a particle, be localised in one point; it is stretched out along the $x$-axis.) Such a field, of course, need not be constant. It can vary in all sorts of ways, both wave-like and others. Formulas 7–9 can easily be transformed in order to take care of varying forces, momenta, and energies. If $F$ is not constant, but varies according to some continuous function of $x$ and $t$, then the formula 9 has to be substituted by formula 9′:

$$\#\Delta E_k = \int\int F(x,t)\,\delta x \delta t \tag{9'}$$

$F$ takes instantaneous forces as values, i.e. $F$ represents a momentary magnitude. Work (energy transfer) and impulse (momentum change) are, in classical physics, generally regarded as effects of forces. The energy transfer temporal bulk is such an effect, and it appears to be a mere mathematical construct like the temporal movement bulk and the temporal velocity change bulk.

In relativistic dynamics the definitions of energy and momentum of electromagnetic field waves easily lend themselves to a definition of temporal energy transfer bulk similar to the one just put forward in relation to classical particles. The energy of a wave equals the kinetic energy which one completed oscillation can maximally transfer to a particle, and the momentum of a wave equals the linear momentum which one completed oscillation can maximally transfer to a particle. This means that neither the energy nor the momentum of a wave can inhere in something which is point-like in space and time; a wave is necessarily extended in both space and time. Electromagnetic wave energy and wave momentum are in that sense special. In formula 2 the temporal movement bulk of a wave was defined. Since, in relativistic dynamics $p = E/c$, $\Delta p = \Delta E/c$ and $c = \lambda/T$, we can define the temporal energy transfer bulk of an electromagnetic wave pulse as in formula 10.

$$\#\Delta E_w = \Delta E \cdot T = \Delta p \cdot \lambda \tag{10}$$

In passing, we can note that it is here possible to define a mean force $F_w$ of a wave pulse as the quotient between two bulks:

$$F_w = \#\Delta E_w / \#M_w \quad (\text{where } \#M_w = T \cdot \lambda; \text{ compare formulas 1, 2 and 9}) \tag{11}$$

I have introduced the concept of temporal bulk in order to get a wholly new general concept. The magnitude $\#\Delta E$ has, as far as I know, not been used anywhere in physics. It is, however, very closely related to the concept of action put forward by William Hamilton in the nineteenth century. Some words are needed about this connection.

## Action as temporal energy state bulk

When there is a transfer of kinetic energy, we can define its temporal bulk as the whole energy change multiplied by the time it takes for the transfer to take place. Assume now a classical particle moving with constant velocity in the time interval $\Delta t$, i.e. there is no change in kinetic energy during $\Delta t$; the particle is in a certain energy state. Even in such a case, however, we can construct a mathematical magnitude connected with extension in time. We can multiply the constant kinetic energy $E_k$ by $\Delta t$ and get the temporal energy state bulk. For reasons that will soon emerge, I will call this magnitude $A$. We get formula 12:

$$A = E_k \cdot \Delta t \quad (\text{cf. formula 7: } \#\Delta E_k = \Delta E_k \cdot \Delta t) \tag{12}$$

The Hamiltonian action of a particle moving a certain distance is the integral over time for this movement of the infinitesimals $((E_k - E_p)\mathrm{d}t)$, where $E_k$ is the particle's kinetic energy and $E_p$ its potential energy. We can write:

$$A_H = \int (E_k - E_p)\, \mathrm{d}t \tag{13}$$

When the kinetic energy and the potential energy are constant, then the Hamiltonian action of the particle follows from formula 13′

$$A_H = (E_k - E_p)\, \Delta t \tag{13′}$$

When the potential energy is zero (or is disregarded), then formula 13′ becomes equivalent to formula 12. The Hamiltonian action $A_H$ reduces to $A = E_k \cdot \Delta t$, i.e. this Hamiltonian action is identical with an energy state temporal bulk.

In order clearly to see the difference between the Hamiltonian action and the concept of temporal energy transfer bulk introduced in this paper, one should note that a temporal energy transfer bulk does not correspond to an action but to a difference of action.

$$\#\Delta E = \Delta E \cdot \Delta t = (E_2 - E_1) \cdot \Delta t = E_2 \cdot \Delta t - E_1 \cdot \Delta t = A_2 - A_1 = \Delta A \tag{14}$$

The magnitude $\Delta A$ cannot possibly be called a change of action since $A_1$ and $A_2$ refer to exactly the same time interval. It has to be called a difference.

The relationship between action difference and action is analogous to the relationship earlier pointed out both between energy change and energy state and between impulse

(= momentum change) and momentum (=momentum state). Action difference relates to *changes* of energy ($\Delta A = \Delta E \cdot \Delta t$) whereas action relates to time-extended states of energy ($A = E \cdot \Delta t$). And just like energy changes and energy states have the same physical dimension (joule), action differences and actions have the same dimension (joules times seconds). Difference of action corresponds to temporal energy change (transfer) bulk and action corresponds to temporal energy state bulk.

In today's quantum mechanics there is hardly any talk at all about the magnitude of action. But both Planck and Bohr talked a lot about it. Quantum theory, it should be remembered, was born with Planck's hypothesis that action is atomic instead of continuous. And Bohr's original hypothesis was that the electron orbits of the hydrogen atom had actions which were integer multiples of Planck's constant.

**Action versus difference of action – the photoelectric effect**

From the dimensional identity of action and difference of action, it follows that it is mathematically possible to reinterpret Planck's constant as representing temporal energy transfer bulks (or action differences) instead of actions. Let us look at this possibility in relation to Einstein's analysis of the photoelectric effect.

According to Einstein, electromagnetic radiation consists of energy quanta, photons, which in the photoelectric effect are transferred to electrons. The quantized energy can be calculated by means of the formula $E = h \cdot f$, where $f$ is the frequency of the radiation. Both the energy transport by photons and the energy transfer from photons to electrons are in the ordinary interpretation quantized. However, these two kinds of energy phenomena are not necessarily similar. By energy transport I mean a change of place of energy where the energy, during the movement, inheres in one and the same entity. An energy transfer, on the other hand, consists necessarily in at least two simultaenous energy changes. Energy is lost in one entity and gained in another. The discussion below is only about the energy transfers in the photoelectric effect.

Every energy transfer which is not momentary can be associated with a temporal energy transfer bulk, $\#\Delta E$. If, in the usual formulas describing the photoelectric effect, we substitute energy transfer ($\Delta E$) for energy ($E$) and substitute $1/T$ for $f$, where $f$ is the frequency and $T$ the time for one corresponding oscillation, then instead of the usual formula 15 we can deduce Equation 17 below.

$$E = h \cdot f \quad \text{(substitution gives Equation 16)} \tag{15}$$

$$\Delta E = h \cdot 1/T \quad \text{(which is mathematically equivalent to Equation 17)} \tag{16}$$

$$h = \Delta E \cdot T \tag{17}$$

The variable $T$ represents a time interval, and that interval may here very well be interpreted as the time it takes to transfer $\Delta E$ from a photon to an electron, i.e. $T$ corresponds to $\Delta t$ in formula 5. This, in turn, means that $h$ should be interpreted as a temporal energy transfer bulk, $\#\Delta E$. As remarked earlier, $h$ and $\#\Delta E$ have the same dimension (joules times seconds). Formula 17 then implies that in the photoelectric effect all energy transfers must have a temporal bulk which is an integer multiple of Planck's constant:

$$\#\Delta E = n \cdot h \tag{18}$$

In formula 18, Planck's constant represents temporal energy transfer bulks (or differences of action), not actions. Einstein's analysis of the photoelectric effect can be reinterpreted as saying that there is a least atomic temporal energy transfer bulk between photons and electrons. If, now, we regard the parallelepiped of Fig. 1 as measuring the temporal bulk of energy transfers in the photoelectric effect, then that volume has to be an integer multiple of $h$.

Since, in the reinterpretation above, $T$ can represent both the frequency of the impinging radiation and the time needed for a least atomic energy transfer, each frequency has its own specific least time which it needs in order to transfer energy to a particle. But if $h$ is a temporal energy transfer *bulk* in the sense defined, then, beside the energy transfer, there should also be a corresponding change of momentum or *momentum transfer*, $\Delta p$, which satisfies formula 19:

$$\#\Delta E = h = \Delta p \cdot \Delta x = \Delta E \cdot \Delta t \qquad \text{(cf. formulas 7 and 8)} \tag{19}$$

Formula 19 can be read as saying that a spatial impulse bulk ($\Delta p \cdot \Delta x$) equals the temporal energy transfer bulk ($\Delta E \cdot \Delta t$). This kind of impulse transfer can be found in the Compton effect if that effect is reinterpreted along the lines of my reinterpretation of the photoelectric effect. The usual conclusion of the Compton scatter is that photons have a momentum, $p$, which corresponds to its wavelength, $\lambda$, according to formula 20:

$$p = h/\lambda \tag{20}$$

I would like to reinterpret Equation 20 by using the concept of temporal wave energy transfer bulk which was introduced in formula 10, i.e. $\#\Delta E_w = \Delta E \cdot T = \Delta p \cdot \lambda$. In formula 20 we should substitute $\Delta p$ for $p$. This means that, in photon electron interactions, there are not only quanta of energy transfer (work), but quanta of momentum transfer (impulse) as well. The capability of the photon to produce these two kinds of transfers is captured in formula 21. Here we find a temporal energy transfer bulk and a spatial momentum transfer bulk which are determined by Planck's constant:

$$\#\Delta E = h = \Delta p \cdot \lambda = \Delta E \cdot T \tag{21}$$

*Such an interpretation may turn temporal bulk from a mere mathematical construct into something with physical significance.* We can regard this temporal bulk magnitude as representing a really existing necessarily time-extended and mind-independent capability in nature. This interpretation also means that temporal energy transfer bulk is here a fundamental magnitude; we cannot derive its amount ($h$) from any natural laws which are more fundamental.

Now, since the old quantum theory is gone, we shall at last turn to the quantum mechanics of Schrödinger and Heisenberg. The problem is to find out whether the ideas of bulks and necessarily time-extended phenomena can be fitted into these theories and be given physical significance there, too.

## Planck's constant and the uncertainty principle

Let us look at the uncertainty principle, or, rather, principles. One of them (22) says that the product of the uncertainties of energy and time equals or exceeds $h$ divided by $2\pi$, and the other one (23) says that the product of the uncertainties of momentum and position is subject to the same relation.

$$\Delta E \cdot \Delta t \geq h/2\pi \tag{22}$$

$$\Delta p \cdot \Delta x \geq h/2\pi \tag{23}$$

The similarities between the equalities of formula 19 and the inequalities of formulas 22 and 23 are obvious. We have to ask whether in these formulas, too, it is possible to reinterpret $h$ as representing a temporal energy transfer bulk and a spatial momentum transfer bulk, respectively. First of all we should note that $h$ cannot represent a temporal energy state bulk or a Hamiltonian action, since in that case formula 22 should have contained the symbol $E$ instead of $\Delta E$. The concept of action ($= E \cdot \Delta t$), dear to Planck and Bohr, cannot be used here. Quite consistently, the concept of action has got no significant place in modern quantum mechanics. But this does not imply that the concept of difference of action ($= \Delta E \cdot \Delta t$) cannot have such a place.

To repeat, the deltas of formulas 22 and 23 indicate that $\Delta E$ cannot represent an energy eigenstate and that $\Delta p$ cannot represent a momentary momentum. An energy state, $E$, is localised in a point on the energy scale, but $\Delta E$ takes up a distance on the same scale. According to the ordinary interpretation of the uncertainty principle, $\Delta E$ represents an energy interval and $\Delta t$ a time interval; similarly, $\Delta p$ represents a momentum interval and $\Delta x$ a distance. An entity is said to be in a certain state of energy and momentum with a certain uncertainty. In this interpretation, $\Delta E$ is not the magnitude of an energy change, it represents an interval on the constructed energy scale; and $\Delta t$ does not represent something which is extended in time but an interval of time itself. Therefore, the product $\Delta E \cdot \Delta t$ does not represent a temporal state bulk or action.

If we try to regard $h$ in the uncertainty principle as representing a temporal energy transfer bulk (instead of a temporal energy state bulk), we stumble on another difficulty. Since $\Delta E$ is often associated with stable non-changing particles in well defined energy states, $h$ cannot be taken as representing a temporal energy transfer (or change) bulk either. My attempt at a reinterpretation seems to have reached an impasse. Are there other interpretations of $\Delta E$? Yes, there is still another interpretative possibility; although a curious one. $\Delta E$ may be interpreted as representing a (non-classical) form of energy which in itself is necessarily stretched out in time. Such an energy would be to classical energy states what a cylinder is to a circle. A cylinder is stretched out in one spatio-temporal dimension more than the circle is.

If, in the uncertainty principle, $\Delta E$ really represents a form of energy which is necessarily time-extended, then Planck's constant would represent the temporal bulk of this energy. In what follows I will call such a form of energy non-classical energy, and I will symbolize it by $E_N$ instead of $\Delta E$. The inequality 22 is then no longer about uncertainty of classical energy states. Instead it says that there is a temporal bulk of non-classical energy, $E_N$, which is larger than $h/2\pi$. Of course a temporal bulk of non-classical energy ($E_N$), just like an energy transfer temporal bulk ($\Delta E$), corresponds to an action difference ($\Delta A$).

The fact that there can exist very essential differences between properties which relate to different numbers of spatio-temporal dimensions, is most easily seen in the case of two-dimensional shapes. If we go down from two to one dimension, all shapes are projected on a line and turned into distances. Shapes are necessarily extended in at least two dimensions.

*My ontological hypothesis is that energy can exist in a form which is necessarily extended in time.* The physical dimension of this energy is of course joule, but it is not joule in a (time) point. It is joule along a (temporal) line.

If this conjecture is true, then there are two different basic forms of energy, classical (possibly momentary) energy and non-classical (necessarily time-extended) energy. On the one hand there are all the classical kinds of energy which can be defined for momentary time points and be represented by functions of the form $f(t)$. On the other hand there are non-classical energies which, just like energy transfers, have to be represented by functions of the form $f(\Delta t)$. Classical states of energy have their physical dimension of energy (joule) defined for momentary time points ($t$), but non-classical energy has this dimension (joule) defined only for time intervals ($\Delta t$).

Where there is extension along a mathematical line, there are of course mathematical points contained in the line. Where there is non-classical energy, there must be some magnitude which is defined for the contained momentary time points, too. This latter magnitude has the dimension $E_N/\Delta t$, joules per second. Obviously, this magnitude does not represent classical momentary energy, it represents the temporal intensity of the conjectured non-classical energy.

The temporal bulk of kinetic energy change of a classical particle measures a process which is extended not only in time but also in space. When a change of kinetic energy takes place, the particle also necessarily changes its momentum. The temporal energy change bulk ($\Delta E \cdot \Delta t$) of the particle equals its spatial momentum change bulk ($\Delta p \cdot \Delta x$); see formulas 7 and 8. A corresponding connection between temporal energy change bulk and spatial momentum change bulk is to be found in the photoelectric effect; see formula 19. And such a connection remains in quantum mechanics, and even in my reinterpretation of $\Delta E$. If $\Delta E$ in formula 22 is reinterpreted as representing non-classical (necessarily time-extended) energy, $E_N$, then $\Delta p$ in formula 23 should be reinterpreted too. I will symbolize the new interpretation of $\Delta p$ by $p_N$ and say that $p_N$ represents non-classical momentum. Classical momentum can be a property of a point particle in a spatial point, but non-classical momentum is necessarily space-extended. Instead of formulas 22 and 23 we then get:

$$E_N \cdot \Delta t \geq h/2\pi \tag{24}$$

$$p_N \cdot \Delta x \geq h/2\pi \tag{25}$$

If we assume:

$$p_N \cdot \Delta x = E_N \cdot \Delta t \tag{26}$$

we get:

$$\#_T E_N = \#_S\, p_N \geq h/2\pi \tag{27}$$

(Note the subscripts of the bulk symbols; all the earlier uses of # means $\#_T$, i.e. temporal bulk in contradistinction to spatial bulk.)

In this way the uncertainty principle can be reinterpreted as a principle of least temporal bulk of non-classical energy and as a principle of least spatial bulk of non-classical momentum.

My ontological hypothesis is, to put it simply, that what has appeared as two connected uncertainties, the uncertainty of energy and the uncertainty of momentum, may in fact be two properties of an entity which is extended in both time and space. One of these properties, non-classical energy ($E_N$), exists along this entity's temporal extension. However, since changes of spatial extension do not affect the value of $E_N$, it should be assumed to exist in every point of the entity's spatial extension. The other property, non-classical momentum ($p_N$), exists along the entity's spatial extension but in every point of the temporal extension. $E_N$ should be represented by functions of the form $f(x, \Delta t)$ and $p_N$ by functions of the form $f(\Delta x, t)$. This conjecture affords us a non-classical momentum–energy unit in about the sense in which a rectangular surface is a length-breadth unit. The length of a rectangle exists along one side but in every point of the other side.

It is important to note that the question whether a specific quanta of non-classical energy is at rest or is in motion is a meaningless question. Non-classical energy can neither exist at rest in a momentary point of time, nor can it exist as a movement. It simply but necessarily is extended along time's arrow.

Formula 27 says that the temporal bulk of non-classical energy (and the spatial bulk of non-classical momentum) can never be smaller than Planck's (original) constant (divided by $2\pi$). If, now, we regard the parallelepiped of Fig. 1 as representing, not a temporal energy transfer bulk, but a temporal bulk of non-classical energy which equals $h/2\pi$, then the volume of this parallelopiped is the smallest one possible. This means that if we make $\Delta t$ smaller $E_N$ must be made larger, and vice versa. Similarly, if we make $\Delta x$ smaller, then $p_N$ must be made larger, and vice versa. Formula 27 says nothing about the shape or internal structure of the volume. It puts constraints only on the size. These constraints, however, are sufficient to turn $\Delta t$ and $E_N$ on the one hand, and $\Delta x$ and $p_N$ on the other hand, into complementary variables. $E_N$ behaves in relation to time (and $p_N$ in relation to space) as the pressure of a gas behaves in relation to its volume when the temperature is constant.

## Virtual particles and non-classical energy

I have so far tried to apply some different concepts of energy bulks to classical physics, to early quantum theory, and to the uncertainty principle of quantum mechanics. A last attempt of application will be made in relation to relativistic quantum field theory. My conjecture here is that virtual particles can be reinterpreted as being entities with *non-classical energies whose quanta of temporal bulk equals Planck's constant*; and with *non-classical momenta whose quanta of spatial bulk equals Planck's constant*, too. Instead of saying that a photon carries with it a cloud of virtual particles, and that a free electron carries with it a cloud of virtual photons, we should say that all real entities are connected with non-classical energy and non-classical momentum.

Virtual particles are particles which evade or violate the conservation laws of energy and momentum. In relation to both these laws, the 'law-breaking' is regarded as restricted by the uncertainty principle. Let us look at an ordinary space–time diagram (Fig. 2) of an interaction between an electron and a proton which takes place by means of a virtual photon. Both the electron and the proton are at rest when the interaction starts.

The traditional description looks as follows. At time $t_1$ the electron emits a virtual photon which, with the speed of light, travels towards the proton. Then, at $t_2$, the proton absorbs the virtual photon. During $\Delta t = t_2 - t_1$, and in the distance $\Delta x = x_2 - x_1$, the virtual photon has energy and momentum which, together with the energies and momenta of the electron and the proton, break the conservation laws. The energy and momentum of the virtual photon, however, can only exist in a time interval and a space interval which are so small that they are confined within the limits given by the uncertainty principle applied to the energy and the momentum of the electron. The virtual photon 'borrows' its energy and momentum from the uncertainty of the electron. In this story the uncertainty

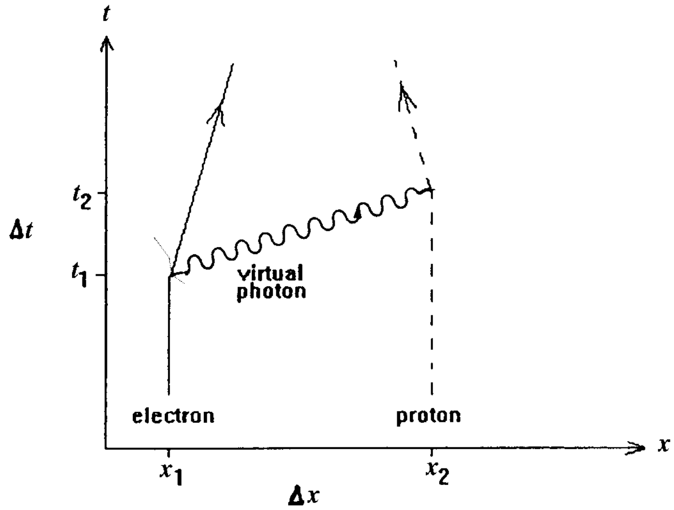


**Fig. 2.**

principle is used in a new way. The products of energy and time (and of momentum and distance), shall now be smaller than or equal to $h/2\pi$, not larger than or equal to $h/2\pi$.

$$\Delta E \cdot \Delta t = \Delta p \cdot \Delta x \leq h/2\pi \tag{28}$$

Let us now assume that, in fact, we here have non-classical energy and momentum instead of uncertainties, and that in these interactions the temporal bulk of this form of energy is always equal to Planck's constant. These assumptions transform Equation 28 into the following formula:

$$\#E_{\mathrm{N}} = E_{\mathrm{N}} \cdot \Delta t = p_{\mathrm{N}} \cdot \Delta x = h/2\pi \tag{29}$$

Formula 29 corresponds to formula 19 which was discussed in 'Action versus difference of action – the photoelectric effect'. That equality was in the pre-Heisenberg/Schrödinger period to be found in the analyses of the photoelectric effect and the Compton effect. With respect to the space–time diagram now at hand (Fig. 2), my proposal is that there is in the represented interaction no moving virtual photon. There is instead a spatiotemporally extended momentum–energy unit which has the property of non-classical energy ($E_{\mathrm{N}}$) along its temporal extension and the property of non-classical momentum ($p_{\mathrm{N}}$) along its spatial extension. The temporal bulk of its non-classical energy (as well as the spatial bulk of its non-classical momentum) is given by formula 29 and it equals Planck's constant. Such quanta of non-classical energy cannot move, since like movements they are extended in time; nor can they be at rest in the ordinary sense of rest. If the amounts of $E_{\mathrm{N}}$ and $p_{\mathrm{N}}$ are given, both the temporal extension ($\Delta t$) and the spatial extension ($\Delta x$) of their common property bearer can be calculated; and vice versa. If the existence of non-classical energy and momentum is assumed, the space–time diagram of the interaction ought to look like Fig. 3.

The non-classical energy which effects the interaction between the electron and the proton does not move at all. It just comes into being, with its temporal extension, and then passes out of being again.

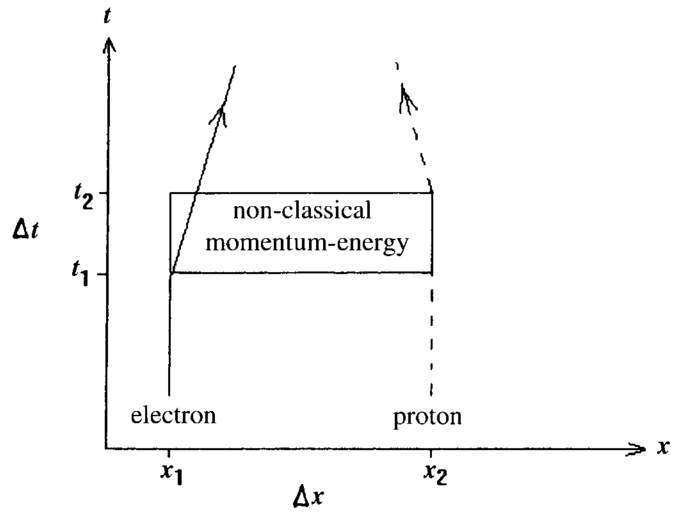


**Fig. 3.**

Instead of assuming virtual momentary particles which move and which 'borrow' energy and momentum from real momentary particles with uncertainties of energy and momentum, we may assume the existence of real but non-moving spatiotemporally extended entities with the properties of non-classical energy and of non-classical momentum. Such entities come into being and pass out of being at the same time as they transfer energy changes, momentum changes and charges among real momentary particles. During the time $0$–$t_1$, and the time after $t_2$, there is in each instant one electron with its energy state and momentum and one proton with its energy state and momentum. In the time interval $t_1$–$t_2$ there is similarly in each *momentary instant* the electron, the proton and their energy *states*, but there is also in each instant the *temporal intensity* of the non-classical energy. It has the dimension $E_N/\Delta t$ , joules per seconds. The momentary energy states of the electron and the proton have of course the dimension joule.

Most conservation laws rely on some principle of addition. If we add the relevant magnitudes, then the sum for the system shall be conserved. Now, a necessary requirement for a physically significant addition is that all the added magnitudes have the same physical dimension. In the law of the conservation of energy, all the different kinds of energies that are meant to be added have to have the dimension joule. Some other requirements, however, relate to time.

When different energy states are added, for instance potential and kinetic energy in Newtonian mechanics, these states must belong to one and the same time point. When an energy change ($\Delta E$) is added to a certain energy state ($E$), two time points have to be reckoned with. First the instant when the change starts and then the instant when it ends. Since a change is necessarily extended in time, when an energy change is added one must take two time points into account. An energy change cannot possibly be added to an energy state in one temporal point. This, of course, means that non-classical energies cannot possibly be added to a classical energy state *in* a time point. Non-classical energies are, just like energy changes, necessarily extended in time.

Classical energy states can have the physical dimension joule in a momentary point of time, but non-classical energies can only have this dimension in a temporal interval. Therefore, non-classical energy cannot possibly be included in the classical law of the conservation of energy states. However, non-classical energy can be added and subtracted to energy processes. Analogous remarks, but in relation to space instead of time, can be worked out for non-classical momentum in relation to the classical law of the conservation of momentum.

## Concluding remarks

I have argued ('Planck's constant and the uncertainty principle') that the uncertainty principle of energy may be reinterpreted as representing an hitherto unnoticed form of energy which is necessarily temporally extended. I named it non-classical energy. This reinterpretation affects the so-called uncertainty principle, and makes its name a misnomer. I have tried to reinterpret the principle as saying that, independently of measurements, there is a least temporal bulk of non-classical energy in the world. Instead of disclosing the curious property of uncertainty, quantum mechanics has uncovered non-classical energy (and non-classical momentum).

I have also argued ('Virtual particles and non-classical energy') that the so-called virtual particles can be regarded as real but necessarily time-extended entities which have non-classical energy as a fundamental property. Their temporal bulk of non-classical energy equals Planck's constant. Such a reinterpretation makes it possible to retain the conservation laws of classical energy (and momentum) without any talk of systems which 'borrow' classical energy.

I am fully aware that the idea of necessarily time-extended phenomena which I have put forward, leads to conceptual and metaphysical difficulties of its own which I have not dealt with. In particular, there is the problem of how to interpret the concept of the present ('now') in physics if temporally extended magnitudes, which are both physically significant and fundamental, are allowed. Should each 'now' embrace the whole temporal extension of a quantum of non-classical energy, or can a quantum of non-classical energy be extended both into the past and into the future? However, in view of all the philosophical riddles and fanciful interpretations connected with quantum mechanics today, I think the notions of necessarily time-extended phenomena, temporal bulks, difference of action, and non-classical energy, are as worthy of consideration as any other ideas which are used in attempts to transcend the Copenhagen interpretation. Perhaps these notions can shed some new light on the measurement problem and the collapse of the wave function, too.

In science, mostly, conceptual construction precedes measurement. For instance, before the theories of electricity were developed no measurement of any electrical magnitude was possible. If we assume that nature contains non-classical energy, then (a) some old theorems of quantum mechanics may take on a new significance, and (b) measurements may be possible to discuss in ways which are closed if the idea of necessarily time-extended energy is not taken into account.

## Acknowledgments

For helpful comments I want to thank Mendel Sachs, Buffalo, USA, Lars-Göran Johansson, Linköping, Sweden, and Kaj Børge Hansen, Uppsala, Sweden.

**References**

1. Sachs, M. (1988) *Einstein versus Bohr*. La Salle, Illinois: Open Court.
2. Jammer, M. (1961) *Concepts of Mass*. Cambridge, Mass: Harvard Univ. Press.
3. Mach, E. (1960) *The Science of Mechanics*. La Salle, Illinois: Open Court.
4. Sachs, M. (1972) *The British Journal for the Philosophy of Science* **23**, 117.