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The entity and modern physics: the creation-discovery-view of reality[1]

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Abstract: The classical concept of 'physical entity', be it particle, wave, field or system, has become a problematic concept since the advent of relativity theory and quantum mechanics. The recent developments in modern quantum mechanics, with the performance of delicate and precise experiments involving single quantum entities, manifesting explicit non-local behavior for these entities, brings essential new information about the nature of the concept of entity. Such fundamental categories as space and time are put into question, and only a recourse to more axiomatic descriptions seems possible. In this contribution we want to put forward a 'picture' of what an 'entity' might be, taking into account these recent experimental and theoretical results, and using fundamental results of the axiomatic physical theories (describing classical as well as quantum entities) such as they have been developed during the last decade. We call our approach the 'creation-discovery view' because it considers measurements as physical interactions that in general entail two aspects: (1) a discovery of an already existing reality and (2) a creation of new aspects of reality during the act of measurement. We analyze the paradoxes of orthodox quantum mechanics in this creation-discovery view and point out the pre-scientific preconceptions that are contained in the well-known orthodox interpretations of quantum mechanics. Finally we identify orthodox quantum mechanics as a first order non classical theory, and explain in this way why it is so successful in its numerical predictions

1. Introduction.

If one takes into consideration the general approach to relativity theory (e.g. W. Misner, K. Thorne and J. A. Wheeler, 1973), it seems to be all inclusive. It starts by stating that *"reality is the collection of all events"*, and this is indeed a starting point that should incorporate all possible physical descriptions. It does not seem to be possible to imagine a more general setting, and yet it is well known that quantum mechanics cannot be incorporated in relativity theory. All attempts to describe a quantum entity by means of a collection of events in the relativity framework have failed till now, and in our opinion are bound to fail. We should of course add that after this very general opening of most approaches to general relativity theory (shortly stated here by the phrase: *"reality is the collection of all events"*), the theory proceeds by taking a second step, that reduces it to a much more specific and limited framework. This second step consists in stating that *"each event is identified with a point of space-time"*. This second step takes for granted that *an event can always be characterized by the place and the time at which it happens*. It puts forward the space-time structure as the setting in which all of reality exists. One of the consequences of the analysis that we put forward in this paper is that this second step is at the

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origin of the incompatibility between the relativity approach and quantum mechanics. Indeed, we shall be led to conclude that a quantum entity cannot be squeezed into the space-time frame introduced by relativity theory, because of its profound quantum nature itself. This impossibility for a quantum entity to be described within a space-time framework has during the last decades been exhibited in a dramatical way by delicate experiments on single quantum entities. The most spectacular effect connected with this impossibility is the property of *non-locality* entailed by quantum entities. This non-locality effect is well-known, in the sense that quantum theory incorporates states for a quantum entity that entail non-local effects; but the effect has now also been demonstrated in various experimental settings, which shows that it really exists and is not just due to a theoretical interpretation of the quantum formalism.

We shall also indicate in which way the concept of *entity* (which we must define, as we shall do later) is brought into difficulties by the nature of these typical quantum effects and their experimental identification. Then we shall argue that in relation with this problem we are on the verge of an important paradigmatical choice: do we save the primitive notion of *quantum entity*, existing within a reality independent of the observer, or, do we opt for a much more subjective worldview, where the concept of entity, existing independently of the observer, looses its meaning and sense. We propose a solution that is very specific, and that we shall call the *creation-discovery view*, where the concept of quantum entity, existing independently of the observer, remains a primary concept (and hence we make the paradigmatical choice to save the primary concept of *entity*). We analyze in detail the pre-scientific preconceptions that we have to drop in order to fit the recent experimental results into this creation-discovery view.

Before we proceed, we want to stress that the creation-discovery view proposed here has not grown out of philosophical speculations. On the contrary, it is the result of an attempt to consolidate the most recent experimental and theoretical findings into a consistent view on reality.

2. Ptolomaeus and Copernicus, waves, particles and quantum entities.

The Ptolomean system for our universe was not abandoned by reason of experimental errors, for it fitted very well with all existing experimental results. To incorporate the descriptions of the known phenomena it only had to introduce additional constructions, called epicycles, which gave rise to many complications but gave a good fit to the experimental observations. But since the primary hypotheses (a) *the earth is the center of the universe*, and (b) *all celestial bodies move in circles around the earth*, were felt to be absolutely essential, the complications could be interpreted as being due to specific properties of the planets. Copernicus (and Greek scientists long before him) dropped hypothesis (a), substituting it by a new one (c) *the sun is the center of the universe.* Clearly this new hypothesis gave rise to a model that is much simpler than the original Ptolomaeus model. Till the theoretical findings of Kepler, using the refined experimental results of Brahe, hypothesis (b), the circle as the basic motion for the celestial objects, remained unaltered, and Kepler was very unhappy when it became clear to him that it was a wrong hypothesis. Now that we know the motion of the planets around the sun as a general solution of Newton's mechanics, the fact that these motions proceed along ellipses does not bother us anymore. On the contrary, the elliptic orbits become a part of a much greater whole, Newtonian mechanics, which incorporate more beauty and symmetry than the original two axioms that were of primary importance to Ptolomaeus.

The change from Ptolomaeus to Copernicus is typical in the evolution of scientific theories. Usually one is not conscious of the concepts that prevent scientific theories from evolving in a fruitful direction. We claim that we have now a similar situation for quantum mechanics, and that the concept of quantum entity, and its meaning, is at the heart of it. We believe that the pre-scientific preconception that has to be abandoned can be compared to that of the earth being the center of the universe. It is a preconception that is due to the specific nature of our human interaction with the rest of reality, and of the subjective perspective following from this human interaction. We can only observe the universe from the earth, and this gave us the perspective that the earth plays a central role. In an analogous way we can only observe the micro-world from our position in the macro-world; this forces us to extend the concepts of the worldview constructed for this macro-world into the worldview that we try to construct for the micro-world. That space-time is the global setting for reality is such a concept.

The two successful pictures that have been put forward to describe quantum entities make use of two basic prototypes: particles and waves. The particle is identified by the fact that upon detection it leaves a spot on the detection screen, while waves are to be recognized by their characteristic interference patterns. Certain experiments with quantum entities give results which are characteristic for particles, other experiments reveal the presence of waves. This is the reason why we use in physics the concepts of particles and waves to represent quantum entities.

2.1 De Broglie and Bohm: an attempt to fit quantum entities into the space-time setting.

There exists a representation using waves and particles together, introduced by Louis de Broglie (de Broglie, 1926) in the early years of quantum mechanics, and which after a long period of neglect, was rediscovered by David Bohm and Jean Pierre Vigier (Bohm and Vigier, 1954) and which is still now the object of active study in different research centers. In this representation, it is assumed that a quantum entity is at the same time always both a particle and a wave. The particle has the properties of a small projectile, but is accompanied by a wave which is responsible for the interference patterns. This representation of de Broglie and Bohm incorporates the observed quantum phenomena and attempts to change as little as possible at the level of the underlying reality where these quantum entities exist and interact. This reality is the ordinary three-dimensional Euclidean space; the quantum entity is considered to be a wave and a particle, existing, moving and changing in this three-dimensional Euclidean space. The specific quantum effects are accounted for by a quantum potential that is effective in this three dimensional Euclidean space, and brings about the quantum non-local effects. The quantum potential is the entity that carries most of the strange quantum behavior. The quantum probabilities appear in the de Broglie-Bohm picture as ordinary classical probabilities, resulting from a lack of knowledge about where the point particle associated with the quantum entity is, exactly as the probabilities of a classical statistical theory, due to a lack of knowledge about the micro-states of the atoms and molecules of the substance considered. The de Broglie-Bohm picture is thus a hidden variable theory. The variables describing the state of the point particle are the hidden variables, and the lack of knowledge about these hidden variables is the origin of the probability.

There is however a serious problem with the de Broglie-Bohm theory when one attempts to describe more than one quantum entity. Indeed, for the example of two quantum entities, the wave corresponding to the entity consisting of the two quantum entities is a wave in the six dimensional configuration space, and not a wave in the three-dimensional Euclidean space, and the quantum potential acts in this six-dimensional configuration space and not in the three-dimensional Euclidean space. Moreover, when the entity consisting of the two quantum entities is in a so called *"non-product state"*, this wave in the six-dimensional configuration space cannot be written as the product of two waves in the three-dimensional space (hence the reason for naming these states "non-product states"). It are these non-product states that give rise to the typical quantum mechanical Einstein-Podolsky-Rosen-like correlations between the two sub-entities. The existence of these correlations has meanwhile been experimentally verified by different experiments, so that the reality of the non-product states, and consequently the impossibility to define the de Broglie-Bohm theory in three-dimensional space, is firmly established. This important conceptual failure of the de Broglie-Bohm theory is certainly also one of the main reasons that Bohm himself considered the theory as being a preliminary version of yet another theory to come (see Bohm 1983, chapter 4.6 and 4.7).

2.2 Bohr: vanishing reality, and a definite movement towards subjectivism.

There exists also the representation using either a wave or a particle, associated with the Copenhagen school, but which was also present in quantum mechanics from the very start. In this picture it is considered that the quantum entity can behave in two ways, either like a particle or like a wave, and that the choice between the two types of behavior is determined by the nature of the observation being made. If the measurement one is making consists in detecting the quantum entity, then it will behave like a particle and leave a spot on the detection screen, just as a small projectile would. But if one chooses an interferometric experiment, then the quantum entity will behave like a wave, and give rise to the typical interference pattern characteristic for waves. When referring to this picture one usually speaks of Bohr's complementarity principle, thereby stressing the dual structure assumed for the quantum entity. This aspect of the Copenhagen interpretation has profound consequences for the general nature of reality. The complementarity principle introduces the necessity of a far reaching subjective interpretation for quantum theory. If the nature of the behavior of a quantum entity (wave or particle) depends on the choice of the experiment that one decides to perform, then the nature of reality as a whole depends explicitly on the act of observation of this reality. As a consequence it makes no sense to speak about a reality existing independent of the observer.

This dramatic aspect of the Copenhagen interpretation is best illustrated by the delayed-choice experiments proposed by John Archibald Wheeler, where the experimental choice made at one moment can modify the past. Wheeler's reasoning is based on an experimental apparatus as shown in Figure 1, where a source emits extremely low intensity photons, one at a time, with a long time interval between one photon and the next.

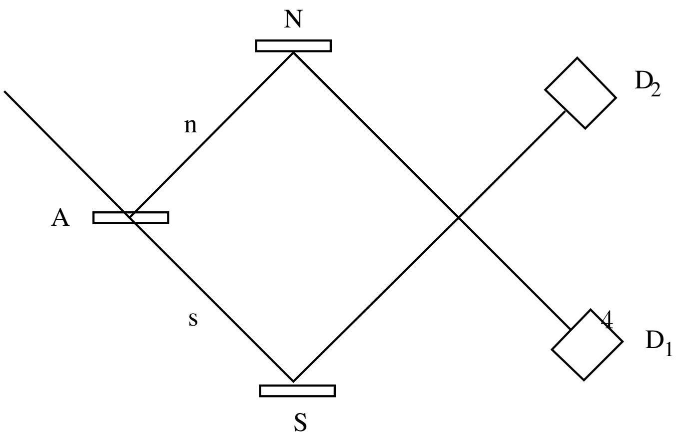

Fig. 1 : The delayed-choice experimental setup as proposed by John Archibald Wheeler. A source emits extremely low intensity photons that are incident on a semitransparant mirror A. The beam divides into two, a northern beam n, which is again reflected by the totally reflecting mirror N and sent towards the photomultiplier D_1, and a southern beam s, which is reflected by the totally reflecting mirror S, and sent towards the photomultiplier D_2.

The light beam is incident on a semitransparant mirror A and divides into two beams, a northern beam n, which is again reflected by the totally reflecting mirror N and sent towards the photomultiplier D_1, and a southern beam s, which is reflected by the totally reflecting mirror S, and sent towards the photomultiplier D_2. We know that the outcome of the experiment will be that every photon will be detected either by D_1 or by D_2. Following the Copenhagen complementarity interpretation, this experimental situation pushes the photons to behave like a particle, that will either be detected in the northern detector D_2 or in the southern detector D_1. It is rather easy to introduce an additional element in the experimental setup, that following the Copenhagen interpretation pushes the photons to behave like a wave. Wheeler proposes the following: we introduce a second semitransparent mirror B as shown on Figure 2, and the thickness of B is calculated as a function of the wavelength of the light, such that the superposition of the northern beam and the southern beam generates a wave of zero intensity.

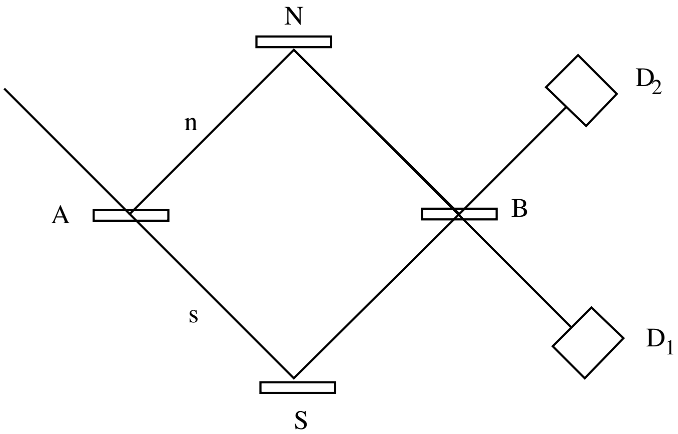

Fig. 2 : The delayed-choice experimental setup as proposed by John Archibald Wheeler, where a second semitransparent mirror is introduced. Following the Copenhagen interpretation, in this experimental situation the photons shall behave like a wave.

This means that nothing shall be detected in D_2 and all the light goes to D_1. This experimental setup pushes the photons of the beam into a total wave behavior: indeed, each photon interferes with itself in region B such that it is detected with certainty in D_1. So, we have two experimental setups, the one shown in Figure 1 and the one shown in Figure 2, that only differ by the insertion of a semitransparent mirror B. Wheeler proposes the semitransparent mirror B to be inserted or excluded at the last moment, when the photon has already left the source and interacted with the mirror N. Following the Copenhagen interpretation and this experimental proposal of Wheeler, the wave behavior or particle behavior of a quantum entity in the past, could be decided upon by an experimental choice that is made in the present. We are dealing here with an inversion of the cause-effect relationship, that gives rise to a total upset of the temporal order of phenomena.

To indicate more drastically the profound subjective nature of the worldview that follows from a consistent application of the Copenhagen interpretation, Wheeler proposes an astronomical version of his delayed-choice experiment. He considers the observation on earth of the light coming from a distant star. The light reaches the earth by two paths due to the presence of a gravitational lens, formed by a very massive galaxy between the earth and the distant star. Wheeler observes that one may apply the scheme of Figure 1 and 2, where instead of the semitransparent mirror A there is now the gravitational lens. The distant star may be billions of light years away, and by insertion or not of the semitransparent mirror, we can force the next photon that arrives to have traveled towards the earth under a wave nature or under a particle nature. This means according to Wheeler that we can influence the past even on time scales comparable to the age of the universe.

Not all physicist believing in the correctness of the Copenhagen interpretation will go as far as Wheeler proposes. The general conclusion of Wheeler's example remains however valid. The Copenhagen interpretation makes it quite impossible to avoid the introduction of an essential effect on the nature and behavior of the quantum entity due to the choice of the type of measurement that one wants to perform on it. The determination of the nature and the behavior of a quantum entity independently of the specification of the measurement that one is going to execute is considered to be impossible in the Copenhagen interpretation.

2.3 The creation-discovery view: neither de Broglie nor Bohr.

The creation-discovery-view that we want to bring forward is different from both of the above mentioned interpretations, the de Broglie-Bohm-interpretation and the Copenhagen interpretation. It is a realistic interpretation of quantum theory, in the sense that it considers the quantum entity as existing in the outside world, independent of us observing it, and with an existence and behavior that is also independent of the kind of observation to be made. In this sense it is strictly different from the Copenhagen interpretation, where the mere concept of quantum entity existing independently of a measurement process is declared to be meaningless. The creation-discovery view is however not like the de Broglie-Bohm theory, where it is attempted to picture quantum entities as point particles moving and changing in our three-dimensional Euclidean space, and where detection is considered just to be an observation that does not change the state of the quantum entity. In the creation-discovery view it is taken for granted that measurements, in general, *do change the state of the entity* under consideration. In this way the view incorporates two aspects, an aspect of 'discovery' referring to the properties that the entity already had before the measurement started (this aspect is independent of the measurement being made), and an aspect of 'creation', referring to the new properties that are created during the act of measurement (this aspect depends on the measurement being made).

The fact that there is a real effect of change during the act of a measurement is a rather plausible hypothesis. It is actually quite amazing, and probably due to the enormous prestige of the Copenhagen interpretation, that such a theory has never yet been tried out. In Brussels we are developing this kind of theory (Aerts 1981, Aerts 1983 a and b, Aerts 1986, 1987, 1990, 1991 b,1993,1994, 1995, D. Aerts and S. Aerts 1995 a and b, Aerts, Coecke and Valckenborgh 1995, Aerts and Durt 1994 a and b, Aerts, Durt and Van Bogaert 1992, 1993, Aerts, Durt, Grib, Van Bogaert and Zapatrin 1993, Aerts and Reignier 1990, 1991, Aerts and Van Bogaert 1992, Coecke 1995 a, b and c, Valckenborgh 1995). I must state immediately however that to be able to explain quantum theory by a *classical theory* with *explicit effect of change of state* during the act of measurement, we are obliged to drop some old and deep pre-scientific preconceptions about the nature of reality.

3. The new methodology, the new 'physical' formalism and the quantum machine.

The fact that it took so long to come to the kind of view that we propose, is largely due to the way in which quantum mechanics was born as a physical theory. Indeed, the development of quantum mechanics proceeded in a rather haphazard manner, with the introduction of many ill-defined and poorly understood new concepts.

3.1 Von Neumann and the mathematical quantum generalizations.

During its first years (1890-1925, Max Planck, Albert Einstein, Louis de Broglie, Hendrik Lorentz, Niels Bohr, Arnold Sommerfeld, and Hendrik Kramers), quantum mechanics (commonly referred to as the *"old quantum theory"*), did not even possess a coherent mathematical basis. In 1925 Werner Heisenberg (Heisenberg 1925) and Erwin Schrödinger (Schrödinger 1926) produced the first two versions of the new quantum mechanics, which then were unified by Paul Dirac (Dirac 1930) and John Von Neumann (Von Neumann 1932) to form what is now known as the orthodox version of quantum mechanics. The mathematical formalism was elaborate and sophisticated, but the significance of the basic concepts remained quite vague and unclear. The predictive success of the theory was however so remarkable that it immediately was accepted as constituting a fundamental contribution to physics. However, the problems surrounding its conceptual basis led to a broad and prolonged debate in which all the leading physicists of the time participated (Einstein, Bohr, Heisenberg, Schrödinger, Pauli, Dirac, Von Neumann, etc.)

The orthodox quantum mechanics of Von Neumann [4] is still dominant in the classroom, although a number of variant formalisms have since been developed with the aim of clarifying the basic conceptual shortcomings of the orthodox theory. In the sixties and seventies, new formalisms were being investigated by many research groups. In Geneva, the school of Josef Maria Jauch was developing an axiomatic formulation of quantum mechanics (Jauch 1968), and Constantin Piron gave the proof of a fundamental representation theorem for the axiomatic structure (Piron 1976). Gunther Ludwig's group in Marburg developed the convex ensemble theory, and in Massachusetts the group of Charles Randall and David Foulis was elaborating an operational approach (Randall and Foulis 1979, 1983). Peter Mittelstaedt and his group in Cologne studied the logical aspects of the quantum formalism, while other workers (Jordan, Segal, Mackey, Varadarajan, Emch) (Segall 1947, Emch 1984) focused their attention on the algebraic structures, and Richard Feynman developed the path integral formulation. There appeared also theories of phase-space quantization, of geometrical quantization and quantization by transformation of algebras.

These different formalisms all contained attempts to clarify the conceptual labyrinth of the orthodox theory, but none succeeded in resolving the fundamental difficulties. This was because they all followed the same methodology: first develop a mathematical structure, then pass to its physical interpretation. This is still the procedure followed in the most recent and authoritative theoretical developments in particle physics and unification theory, such as quantumchromodynamics and string theory. But from 1980 on, within the group of physicists involved in the study of quantum structures, there arose a growing feeling that a change of methodology was indispensable, that one should start from the physics of the problem, and only proceed to the construction of a theory after having clearly identified all basic concepts. Very fortunately, this change in attitude to theory coïncided with the appearance of an abundance of new experimental results concerning many subtle aspects of microphysics, which previously could only have been conjectured upon. We here have in mind the experiments in neutron interferometry, in quantum

[4] The Von Neumann theory constitutes the orthodox mathematical model of quantum mechanics (Von Neumann 1932). The state of a quantum entity is described by a unit vector in a separable complex Hilbert space; an experiment is described by a self-adjoint operator on this Hilbert space, with as eigenvalues the possible results of the experiment. As the result of an experiment, a state will be transformed into the eigenstate of the self-adjoint operator corresponding to a certain experimental result, with a probability given by the square of the scalar product of the state vector and of the eigenstate unit vector. It follows that, if the state of the quantum entity is not an eigenstate of an operator associated with a given experiment, then the experiment can yield any possible result, with a probability determined by the scalar product of the state and eigenstate vectors as indicated above. The dynamical evolution of the state of a quantum entity is determined by the Schrödinger equation.

optics, on isolated atoms, etc. The new insights as to the nature of physical reality, resulting in part from the new experimental data and in part from the new methodological approach, have made it possible to clarify some of the old quantum paradoxes and thereby to open the way to a reformulation of quantum mechanics on an adequate physical basis.

3.2 The quantum machine: a macroscopic spin 1/2 model.

In Brussels we have now decided to work explicitly along this new methodological approach, starting from the physics of the problem, and only proceeding to the construction of a theory after having clearly identified all basic concepts (Aerts 1981, 1994), at the same time introduce a very simple example of a *quantum machine* that we shall use in the next section to put forward our explanation of quantum mechanics.

An entity S is in all generality described by the collection Σ of its possible states. A state p, at the instant t, describes the physical reality of the entity S at the time t.

The quantum machine (denoted qm in the following) that we want to introduce consists of a physical entity S_{qm} that is a point particle P that can move on the surface of a sphere, denoted $surf$, with center O and radius 1. The unit-vector v giving the location of the particle on $surf$ represents the state p_v of the particle (see Fig. 3,a). Hence the collection of all possible states of the entity S_{qm} that we consider is given by $\Sigma_{qm} = \{p_v \mid v \in surf\}$. No mathematical structure is a priori assigned to this collection of states, contrary to what is done in quantum mechanics (a Hilbert space structure) or in classical mechanics (a phase space structure).

One considers further that experiments e are carried out on the entity S, and let $\mathcal{E}$ denote the collection of relevant experiments. For our quantum machine we introduce the following experiments.

For each point $u \in surf$, we introduce the experiment e_u. We consider the diametrically opposite point $-u$, and install an elastic band of length 2, such that it is fixed with one of its end-points in u and the other end-point in $-u$. Once the elastic is installed, the particle P falls from its original place v orthogonally onto the elastic, and sticks on it (Fig 3,b).

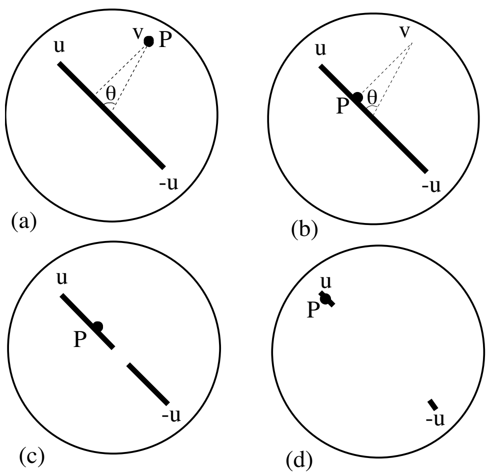

Fig. 3 : A representation of the quantum machine. In (a) the physical entity P is in state p_v in the point v, and the elastic corresponding to the experiment e_u is installed between the two diametrically opposed points u and $-u$. In (b) the particle P falls orthogonally onto the elastic and sticks to it. In (c) the elastic breaks and the particle P is pulled towards the point u, such that (d) it arrives at the point u, and the experiment e_u gets the outcome o_1^u.

Then the elastic breaks and the particle P, attached to one of the two pieces of the elastic (Fig 3,c), moves to one of the two end-points u or $-u$ (Fig 3,d). Depending on whether the particle P arrives in u (as in Fig 3) or in $-u$, we give the outcome o_1^u or o_2^u to e_u. Hence for the quantum machine we have $\mathcal{E}_{qm} = \{e_u \mid u \in surf\}$. Again, no a priori mathematical structure is imposed upon $\mathcal{E}$. The only assumption made is that when the entity S is in a state p and when an experiment e is carried out, a result x is obtained with some probability. Consequently, the state p will have changed into a new state q. We make the hypothesis that the elastic band breaks uniformly, which means that the probability that the particle, being in state p_v, arrives in u, is given by the length of L_1 (which is $1+cos\theta$) divided by the total length of the elastic (which is 2). The probability that the particle in state p_v arrives in $-u$ is the length of L_2 (which is $1-cos\theta$) divided by the total length of the elastic. If we denote these probabilities respectively by $P(o_1^u, p_v)$ and $P(o_2^u, p_v)$ we have:

$$P(o_1^u, p_v) = \frac{1+cos\theta}{2} = cos^2\frac{\theta}{2} \tag{1}$$

$$P(o_2^u, p_v) = \frac{1-cos\theta}{2} = sin^2\frac{\theta}{2} \tag{2}$$

In Figure 4 we represent the experimental process connected to e_u in the plane where it takes place, and we can easily calculate the probabilities corresponding to the two possible outcomes. In order to do so we remark that the particle P arrives in u when the elastic breaks in a point of the interval L_1, and arrives in $-u$ when it breaks in a point of the interval L_2 (see Fig. 4). The probabilities that we find in this way are exactly the quantum probabilities for measuring the spin of a spin 1/2 quantum entity; this means that we can describe this macroscopic machine using the ordinary quantum formalism with a two-dimensional complex Hilbert space as the carrier for the set of states of the entity.

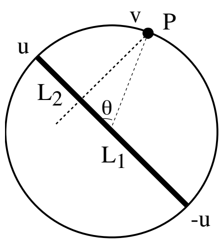

Fig. 4 : A representation of the experimental process in the plane where it takes place. The elastic of length 2, corresponding to the experiment e_u, is installed between u and $-u$. The probability, $P(o_1^u, p_v)$, that the particle P ends up in point u is given by the length of the piece of elastic L_1 divided by the total length of the elastic. The probability, $P(o_2^u, p_v)$, that the particle P ends up in point $-u$ is given by the length of the piece of elastic L_2 divided by the total length of the elastic.

Such an approach provides us with a very general description of the measuring process. If no measurement is made, an entity S is at all times in a well defined state $p(t)$, and this state changes in function of time. Its dynamical evolution is, in the case of quantum mechanics, described by the Schrödinger equation, and in the case of classical mechanics, it is described by Newton's law. This 'physical' formalism has already led to a number of concrete and far reaching results, of which we shall explain some in the following. The most important achievement however, in my opinion, consists in an explanation of the structure of quantum mechanics, and in identifying the reason why it appears in nature.

4. Explaining the structure of quantum and getting out of space-time

Already from the advent of quantum mechanics it was known that the structure of quantum theory is very different from the structure of the existing classical theories. This structural difference has been expressed and studied in different mathematical categories, and we mention here some of the most important ones: (1) if one considers the collection of properties (experimental propositions) of a physical entity, then it has the structure of a Boolean lattice for the case of a classical entity, while it is non-Boolean for the case of a quantum entity (Birkhoff and Von Neumann 1936, Jauch 1968, Piron 1976), (2) for the probability model, it can be shown that for a classical entity it is Kolmogorovian [5], while for a quantum entity it is not (Foulis and Randall 1972, Randall and Foulis 1979, 1983 , Gudder 1988, Accardi 1982, Pitovski 1989), (3) if the collection of observables is considered, a classical entity gives rise to a commutative algebra, while a quantum entity does not (Segal 1947, Emch 1984).

The presence of these deep structural differences between classical theories and quantum theory has contributed strongly to the earlier existing belief that classical theories describe the ordinary 'understandable' part of reality, while quantum theory confronts us with a part of reality (the micro-world) that is impossible to understand. Therefore there still now exists the strong paradigm that *quantum mechanics cannot be understood*. The example of our macroscopic machine with a quantum structure challenges this paradigm, because obviously the functioning of this machine can be understood. We want to show now that the main aspects of the quantum structures can indeed be explained in this way and identify the reason why they appear in nature. We shall focus here on the explanation in the category of the probability models, and refer to (Aerts and Van Bogaert 1992, Aerts, Durt and Van Bogaert 1993, Aerts, Durt, Grib, Van Bogaert and Zapatrin 1993, Aerts 1994, Aerts and Durt 1994) for an analysis of this explanation in other categories.

4.1 What is quantum probability?

The original development of probability theory aimed at a formalization of the description of a probability that appears as the consequence of *a lack of knowledge*. The probability structure appearing in situations of lack of knowledge was axiomatized by Kolmogorov and such a probability model is now called Kolmogorovian. Since the quantum probability model is not Kolmogorovian, it has now generally been accepted that the quantum probabilities are *not* associated with a *lack of knowledge*. Sometimes this conclusion is formulated by stating that the quantum probabilities are *ontological* probabilities, as if they were present in reality itself. In the approach that we follow in Brussels, and that we have named the *hidden measurement approach*, we show that the quantum probabilities can be explained as being due to a *lack of knowledge*, and we prove that what distinguishes quantum probabilities from classical Kolmogorovian probabilities is the *nature of this lack of knowledge*. Let us go back to the quantum machine to illustrate what we mean.

If we consider again our quantum machine (Fig. 3 and Fig. 4), and look for the origin of the probabilities as they appear in this example, we can remark that the probability is entirely due to a *lack of knowledge* about the measurement process. Namely the lack of knowledge of where exactly the elastic breaks during a measurement. More specifically, we can identify two main aspects of the experiment e_u as it appears in the quantum machine.

- The experiment e_u effects a real change on the state p_v of the entity S. Indeed, the state p_v changes into one of the states p_u or p_{-u} by the experiment e_u.
- The probabilities appearing are due to a *lack of knowledge* about a deeper reality of the individual measurement process itself, namely where the elastic breaks.

[5] The axioms formulated by Kolmogorov in 1933 relate to the classical probability calculus as introduced for the first time by Simon Laplace. Quantum probabilities do not satisfy these axioms. John Von Neumann was the first to prove a "no go" theorem for hidden variable theories (Von Neumann 1932). Many further developments were however required before it was definitively proved that it is impossible to reproduce quantum probabilities from a hidden variable theory (Pitovsky 1989).

These two effects give rise to quantum-like structures, and the lack of knowledge about the deeper reality of the individual measurement process come from 'hidden measurements' that operate deterministically in this deeper reality (Aerts 1986, 1987, 1991); and that is the origin of the name that we gave to this approach.

One might think that our 'hidden-measurement' approach is in fact a 'hidden-variable' theory. In a certain sense this is true. If our explanation for the quantum structures is the correct one, quantum mechanics is compatible with a deterministic universe on the deepest level. There is no need to introduce the idea of an ontological probability. Why then there exists the generally held conviction that hidden variable theories cannot substitute quantum mechanics? The reason is that those physicists who are interested in trying out hidden variable theories, are not at all interested in the kind of theory that we propose here. They want the hidden variables to be hidden variables of the state of the entity under study, so that the probability is associated to a lack of knowledge about the deeper reality of this entity; as we have mentioned already this gives rise to a Kolmogorovian probability theory. This kind of 'state' hidden-variables is indeed impossible for quantum mechanics for structural reasons, with exception of course of the de Broglie Bohm theory: there in addition to the state hidden variables a new spooky entity of 'quantum potential' is introduced to express the action of the measurement as a change in these state hidden variables.

If one wants to interpret our hidden-measurements as hidden-variables, then they are hidden-variables of the measurement apparatus and not of the entity under study. In this sense they are highly contextual, since each experiment introduces a different set of hidden-variables. They differ from the variables of a classical hidden variable theory, because they do not provide an 'additional deeper' description of the reality of the physical entity. Their presence, as variables of the experimental apparatus, has a well defined philosophical meaning, and expresses the fact that we, human beings, want to construct a model of reality independent of our experience of this reality. The reason is that we look for 'properties' or 'relations between properties', and these are defined by our ability to make predictions independent of our experience. We want to model the structure of the world, independent of us observing and experimenting with this world. Since we do not control these variables in the experimental apparatus, we do not allow them in our model of reality, and the probability introduced by them cannot be eliminated from a predictive theoretical model. In the macroscopic world, because of the availability of many experiments with negligible fluctuations, we find an 'almost' deterministic model.

We must now try to understand what is the consequence of our explanation for the quantum structure for the nature of reality. Since some of the less mathematically oriented readers may have had some difficulties in understanding our explanation of quantum mechanics by means of the quantum machine we want to give another more methaphorical and less technical example of the creation-discovery view.

4.2 Is cracking walnuts a quantum action?

Consider the following experiment: "we take a walnut out of a basket, and break it open in order to eat it". Let us look closely at the way we crack the nut. We don't use a nutcracker, but simply take the nut between the palms of our two hands, press as hard as we can, and see what happens. Everyone who has tried this knows that different things can happen. A first possibility to envisage is that the nut is mildewed. If after cracking the shell the walnut turns out to be mildewed, then we don't eat it.

Assume for a moment that the only property of the nut that plays a role in our eating it or not is the property of being mildewed or not. Assume now that there are N walnuts in the basket. Then, for a given nut k (we have $1 \leq k \leq N$), there are always two possible results for our experiment: E_1, we crack the nut and eat it (and then following our hypothesis it was not mildewed); E_2, we crack the nut and don't eat it (and then it was mildewed). Suppose that M of the N nuts in the basket are mildewed. Then the probability that our experiment for a nut k yields the result E_1 is given by the ratio $\frac{(N-M)}{N}$, and that it yields the result E_2, by $\frac{N}{M}$. These probabilities are introduced by our lack of knowledge of the complete physical reality for the nut. Indeed, the nut k is either mildewed or not before we proceed to break it open. Had we known about the mildew without having to crack the nut, then we could have eliminated the probability statement, which is simply the expression of our lack of knowledge about the deeper unknown reality of the nut. We could have selected the nuts for eating by removing from the basket all the mildewed ones The classical probability calculus is based, as above, upon a priori assumptions as to the nature of existing probabilities.

Everyone who has had any experience in cracking walnuts knows that other things can happen. Sometimes, we crush the nut upon cracking the shell. We then have to make an assessment of the damage incurred, and decide whether or not it is worth while to try and separate out the nut from the fragments of the shell. If not, we don't eat the nut. Taking into account this more realistic situation, we have to drop our hypothesis that the only factor determining our eating the nut is the mildew, existing before the cracking. Now there are two factors: the mildew, and the state of the nut 'after' the act of cracking. Again we have two possible results for our experiment: E_1, we don't eat the nut (then it was mildewed or is crushed upon cracking); and E_2, we eat it (then it was not mildewed and cleanly cracked). For a given nut k these two possible results will occur with a certain probability. We perceive immediately that this sort of probability depends on the way we crack the nut, and is thus of a different nature from the one only related to the presence of mildewed nuts. Before cracking the nuts, there is no way of separating out those which will be cleanly cracked and those which will be crushed. This distinction cannot be made because it is partly created by the cracking experiment itself. This is a nice example of how aspects of physical reality can be created by the measurement itself, namely, the cracking open of the walnuts.

We can state now easily our general creation-discovery view for the case of the nuts. The mildewed nature of the nut is a property that the nut has before and independent of the fact that we break it. When we break the nut and find out that it is mildewed, then this finding is a 'discovery'. These discoveries, related to outcomes of experiments, obey a classical probability calculus, expressing our lack of knowledge about something that was already there before we made the experiment. The crushed or cleanly cracked nature of the nut is not a discovery of the experiment of cracking. It is a creation. Indeed, depending on how we perform the experiment, and on all other circumstantial factors during the experiment, some nuts will come out crushed, while others will be cleanly cracked.

The mathematical structure of the probability model necessary to describe the probabilities for cleanly cracked or crushed nuts is quite different from that needed for mildewed or non-mildewed ones. More specifically:

- The probability structure corresponding to the indeterminism resulting from a lack of knowledge of an existing physical reality is a classical Kolmogorov probability model.

- The probability structure corresponding to the indeterminism resulting from the fact that during a measurement new elements of physical reality, which thus did not exist before the measurement, are created is a quantum-like probability model [6]. Quantum probabilities can thus be taken as resulting from a lack of knowledge of the interaction between the measuring apparatus and the quantum entity during the measuring experiment. This interaction creates new elements of physical reality which did not exist before the measurement. This is the explanation which we propose to account for quantum probabilities.

4.3 Space and walnuts.

Let us now assume that we have removed all the mildewed walnuts from the basket. We thus have the situation where none of the nuts are mildewed. In the physicist's jargon we say that the individual nuts are in a pure state, relative to the property of being mildewed or not. In the original situation when there were still mildewed nuts present, an individual nut was in a mixed state, mildewed and not mildewed, with weighting factors $\frac{M}{N}$ and $\frac{(N-M)}{N}$. In the new situation with the basket containing only non-mildewed nuts, we consider an event m: we take a non-mildewed walnut, and carry out the measurement consisting in cracking the nut. We have here the two possible results: E_1, the nut is cleanly cracked and we eat it; E_2, the nut is crushed and we don't eat it. The result depends on what takes place during the cracking experiment. We therefore here introduce the concept of potentiality. For the case of mildewed or non-mildewed nuts we could assert for each nut that, previously to the experiment, the nut was mildewed or not. For the case of cleanly cracked or crushed nuts, we cannot relate the outcome of the cracking to any anterior property of the walnut. What we can assert however is that each walnut is potentially cleanly cracked (and will then be eaten), or potentially crushed (and then will not be eaten).

Nobody will have any difficulty in understanding the walnut example. What we propose is that one should try to understand quantum reality in a similar manner. The only difference is that for the measurements in quantum mechanics which introduce a probability of the second type (i.e. with the creation of a new element of physical reality during the measurement), we find it difficult to visualize just what this creation is. This is the case for instance for detection experiments of a quantum entity. Intuitively, we associate the detection process with the determination of a spatial position which already exists. But now, we must learn to accept that the detection of a quantum entity involves, at least partially, the creation of the position of the particle during the detection process. Walnuts are potentially cleanly cracked or crushed, and likewise quantum entities are potentially within a given region of space or potentially outside it. The experiment consisting in finding or not finding a quantum entity in a given region takes place only after setting up in the laboratory the measuring apparatus used for the detection, and it requires the interaction of the quantum entity with that measuring apparatus. Consequently, the quantum entity is potentially present and potentially not present in the region of space considered.

It will be observed that this description of quantum measurements makes it necessary to reconsider

[6] We should point out that the non-Kolmogorovian nature of the probability model corresponding to situations of creation cannot be shown for the case of a single experiment, as considered. At least three different experiments with two outcomes of the creation type are necessary to prove in a formal way that a description within a Kolmogorovian model is not possible. We refer to Aerts 1986 for the details of such a proof for the quantum spin 1/2 model. The fact that we need at least three experiments does not however suppress the fact that the physical origin of the non-Kolmogorovian behavior is clearly due to the presence of explicit creation aspects (see e.g. Aerts D and Aerts S 1994)

our concept of space. If a quantum entity in a superposition state between two separated regions of space is only potentially present in both of these region of space, then space is no longer the setting for the whole of physical reality. Space, as we intuitively understand it, is in fact a structure within which classical relations between macroscopic physical entities are established. These macroscopic entities are always present in space, because space is essentially the structure in which we situate these entities. This need not be, and is not the case for quantum entities. In its normal state, a quantum entity does not exist in space, it is only by means of a detection experiment that it is, as it were, pulled into space. The action of being pulled into space introduces a probability of the second type (the type associated with cracking the walnuts open), since the position of the quantum entity is partially created during the detection process.

4.4 Quantum entities, neither particles nor waves.

Let us consider one photon in Wheeler's delayed-choice experiment. In the creation-discovery-view we accept that the photon while it travels between the source and the detector is not inside space. It remains one entity traveling through reality and the two paths n and s are regions of space where the photon can be detected more easily than in other regions of space when a detection experiment is carried out. The detection experiment is considered to contain explicitly a creation element and pulls the photon inside space. If no detection experiment is carried out, and no physical apparatuses related to this detection experiment are put into place, the photon is not traveling on one of the two paths n or s. We can understand now how the 'subjectif' part of the Copenhagen interpretation, disappears. In the creation-discovery view the choice of the measurement, whether we choose to detect or to make an interference experiment (in the case of Wheeler's experiment this amounts to whether we choose the setting of Figure 1 or the setting of Figure 2), does not influence the intrinsic nature of the photon. In both choices the photon is traveling outside space, and the effect of an experiment appears only when the measurement related to the experiment starts. If a detection measurement is chosen the photon starts to get pulled into a place in space where it localizes. If an interference experiment is chosen the photon remains outside space, not localized, and interacts from there with the macroscopic material apparatuses and the fields, and this interaction gives rise to the interference pattern.

5. What about the quantum paradoxes in the creation-discovery-view?

We have analyzed in foregoing sections in which way the creation-discovery view resolves the problems that are connected to the de Broglie theory and the Copenhagen interpretation. We would like to say now some words about the quantum paradoxes. Our main conclusion in relation with the quantum paradoxes is the following: some are due to intrinsic structural shortcomings of the orthodox theory and others find their origin in the nature of reality, and are due to the pre-scientific preconception about space that we come to explain. In this way we can state that the generalized quantum theories together with the creation-discovery view resolve all quantum paradoxes. We have no time to go into all the delicate aspects of the paradoxes, and refer therefore to the literature. We shall however present a sufficiently detailed analyses, such that it becomes clear in which way the paradoxes are solved in the generalized quantum theories and the creation-discovery view.

5.1 The measurement problem: is Schrödinger's cat dead or alive or neither?

If one tries to apply orthodox quantum mechanics to describe a system containing both a quantum entity and the macroscopic measuring apparatus, one is led to very strange predictions. It was Schrödinger who discussed this problem in detail, so let us consider the matter from the point of view of his cat (Schrödinger 1935). Schrödinger imagined the following thought experiment. He considered a room containing a radioactive source and a detector to detect the radioactive particles emitted. In the room there is also a flask of poison and a living cat. The detector is switched on for a length of time such there is exactly a probability 1/2 of detecting a radioactive particle emitted by the source. Upon detecting a particle, the detector triggers a mechanism which breaks the flask, liberating the poison and killing the cat. If no particle is detected, nothing happens, and the cat stays alive. We can know the result of the experiment only when we go into the room to see what has happened. If we apply the orthodox quantum formalism to describe the experiment (cat included), then, until the moment that we open the door, the state of the cat, which we denote by p_{cat}, is a superposition of the two states "the cat is dead", written p_{dead}, and "the cat is alive", written p_{live}. Thus, $p_{cat} = (p_{dead} + p_{live})/\sqrt{2}$.

The superposition is suppressed, giving a change in the quantum mechanical state, only at the instant when we go into the room to see what has taken place. We first want to remark that if we interpret the state as described by the orthodox quantum mechanical wave function as a mathematical object giving exclusively *our knowledge* of the system, then there would be no problem with Schrödinger's cat. Indeed, from the point of view of our knowledge of the state, we can assume that before opening the door of the room the cat was already dead or was still alive, and that the quantum mechanical change of state simply corresponds to the change in our knowledge of the state. This *knowledge picture* would also resolve another problem. According to the orthodox quantum formalism, the superposition state $p_{cat} = (p_{dead} + p_{live})/\sqrt{2}$ is instantaneously transformed, at the instant when one opens the door, into one of the two component states p_{dead} or p_{live}. This sudden change of the state, which in the quantum mechanical jargon is called *the collapse of the wave function*, thus has a very natural explanation in the *knowledge picture*. Indeed, if the wave function describes our knowledge of the situation, then the acquisition of new information, as for instance by opening a door, can give rise to an arbitrarily sudden change of our knowledge and hence also of the wave function.

The *knowledge picture* cannot however be correct, because it is a hidden variable theory. Indeed, the quantum mechanical wave function does not describe the physical reality itself, which exists independently of our knowledge of it, but describes only our knowledge of the physical reality. It would then follow, if the *knowledge picture* is correct, that there must exist an underlying level of reality which is not described by a quantum mechanical wave function. For the cat experiment, this underlying level describes the condition of the cat, dead or alive, independently of the knowledge of this condition we acquire by entering the room. The *knowledge picture* therefore leads directly to a *hidden variable theory*, where hidden variables describe the underlying level of reality. As we mentioned already, it can be shown that a probabilistic theory, in which a lack of knowledge of an underlying level of reality is the origin of the probabilistic description (a hidden variable theory), always satisfies Kolmogorov's axioms. Now, the quantum mechanical theory does not satisfy these axioms, so that the *knowledge picture* is necessarily erroneous. One also has direct experimental evidence, in connection with the Bell inequalities, which confirms that any state-type hidden variable hypothesis is wrong.

Hence, the quantum mechanical wave function represents not our knowledge of the system, but its real physical state, independently of whether the latter is known or not. In that case, however, Schrödinger's cat presents us with a problem. Is it really possible that, before the door of the room is opened, the cat could be in a superposition state, neither living nor dead, and that this state, as a result of opening of the door, is transformed into a dead or live state? It does seem quite impossible that the real world could react in this manner to our observation of it. A physical reality such that its states can come into being simply because we observe it, is so greatly in contradiction with all our real experience that we can hardly take this idea seriously. Yet it does seem to be an unescapable consequence of orthodox quantum mechanics as applied to a global physical situation, with macroscopic components.

5.2 Classical and quantum components of a general description: the resolution of Schrödinger's cat paradox

In the new physical general description, that we have proposed already earlier (Aerts 1994) it is perfectly possible and even very natural to make a distinction between different types of experiments. One will thus introduce the concept of a *classical experiment*: this is an experiment such that, for each state p of the entity S, there is a well-determined result x. For a classical experiment, the result is fully predictable even before the experiment is carried out. A collection $\mathcal{E}$ of relevant experiments will generally comprise both classical and non-classical ones. It is possible to prove a theorem stating that the classical part of the description of an entity can always be separated out (Aerts 1981, Aerts 1983 a and Valckenborgh 1995). The collection of all possible states for an entity can then be expressed as the union of a collection of classical mixtures, such that each classical mixture is determined by a set of non-classical micro-states. When we formulate within this general framework the axioms of quantum mechanics, it can be shown that the set of states in a classical mixture can be represented by a Hilbert space. The collection of all the states of the entity is then described by an infinite collection of Hilbert spaces, one for each classical mixture. Orthodox quantum mechanics is in this formulation the limiting case for which no classical measurement appears, corresponding effectively to the existence of a single Hilbert space. Classical mechanics is the other limiting case, which is such that only classical measurements are present, and for which the formulation corresponds to a phase space description. The general case for an arbitrary entity is neither purely quantum nor purely classical, and can only be described by a collection of different Hilbert spaces. When one considers the measuring process within this general formulation, there is no Schrödinger cat paradox. Opening the door is a classical operation which does not change the state of the cat, and the state can thus also be described within the general formulation, and the quantum collapse occurs when the radioactive particle is detected by the detector, which is a non-classical process, also within the general description.

The general formalism provides more than the resolution of the Schrödinger cat paradox. It makes it possible to consider quantum mechanics and classical mechanics as two particular cases of a more general theory. This general theory is quantum-like, but introduces no paradoxes for the measuring process because one can treat, within the same formalism, the measuring apparatus as a classical entity, and the entity to be measured as a quantum entity. The paradoxes associated with measurements result from the structural limitations of the orthodox quantum formalism [7].

[7] This decomposition theorem of a general description into an direct product of irreducible descriptions, where each irreducible

5.3 The Einstein-Podolsky-Rosen paradox: further limitations of the orthodox formalism.

The general existence of superposition states which lies at the root of the Schrödinger cat paradox, was exploited by Einstein, Podolsky, and Rosen to construct a far subtler paradoxical situation. EPR consider the case of two disjoint entities S_1 and S_2, and the composite entity S which these two entities constitute. They show that it is always possible to bring the composite entity S in a state in such a manner that a measurement on one of the component entities determines the state of the other component entity. For separated entities, this is a quantum mechanical prediction which contradicts the very concept of separateness. Indeed, for separated entities the state of one of the entities can a priori not be affected by how one acts upon the other entity, and this is confirmed by all experiments which one can carry out on separated entities.

Here again, we can resolve the paradox by considering the situation in the framework of the new general formalism. There, one can show that a composite entity S, made up of two separated entities S_1 and S_2, never satisfies the axioms of orthodox quantum mechanics, even if allowance is made for classical experiments as was done in the case of the measurement paradox (Aerts 1981, Aerts 1982, Aerts 1994). Two of the axioms of orthodox quantum mechanics (*weak modularity*, and the *covering law*) are never satisfied for the case of an entity S made up of two separated quantum entities S_1 and S_2. This failure of orthodox quantum mechanics is structurally much more far-reaching than that relating to the measuring problem. There one could propose a solution in which the unique Hilbert space of orthodox quantum mechanics is replaced by a collection of Hilbert spaces, and one remains more or less within the framework of the Hilbert space formalism (this is the way that super selection rules were described even within one Hilbert space). The impossibility of describing separated entities in orthodox quantum mechanics is rooted in the vector structure of the Hilbert space itself. The two unsatisfied axioms are those associated with the vector structure of the Hilbert space, and to dispense with these axioms, as is required if we wish to describe separated entities, we must therefore construct a totally new mathematical structure for the space of states (Aerts 1984, Aerts 1985 a, Aerts 1985 b).

5.4 Classical, quantum and intermediate.

To abandon the vector space structure for the collection Σ of all possible states for an entity is a radical mathematical operation, but recent developments have confirmed its necessity. The possibility of accommodating within one general formalism both quantum and classical entities resolved the measurement paradox. If the quantum structure can be explained by the presence of a lack of knowledge on the measurement process, as it is the case in our 'hidden-measurement' approach, we can go a step further, and wonder what types of structure arise when we consider the original models, with a lack of knowledge on the measurement process, and introduce a variation of the magnitude of this lack of knowledge. We have studied the quantum machine under varying 'lack of knowledge', parameterizing this variation by a number $\epsilon \in [0, 1]$, such that $\epsilon = 1$ corresponds to the situation of maximal lack of knowledge, giving rise to a quantum structure, and $\epsilon = 0$ corresponds to the situation of zero lack of knowledge, generating a

description corresponds with one Hilbert space, had been shown already within the mathematical generalizations to quantum mechanics (Jauch 1968, Piron 1976). The aim was then to give an explanation for the existence of super selection rules. The decomposition was later generalized for the physical formalisms (Aerts 1981, Aerts 1983 a, Aerts 1994, Valckenborgh 1995).

classical structure, and other values of ϵ correspond to intermediate situations, giving rise to a structure that is neither quantum nor classical (Aerts, Durt and Van Bogaert 1992, 1993, Aerts and Durt 1994 a, b, and Aerts 1995). We have called this model the ϵ-model, and we want to expose it shortly here.

We start from the quantum machine, but introduce now different types of elastic. An ϵ, d-elastic consists of three different parts: one lower part where it is unbreakable, a middle part where it breaks uniformly, and an upper part where it is again unbreakable. By means of the two parameters $\epsilon \in [0, 1]$ and $d \in [-1 + \epsilon, 1 - \epsilon]$, we fix the sizes of the three parts in the following way. Suppose that we have installed the ϵ, d-elastic between the points $-u$ and u of the sphere. Then the elastic is unbreakable in the lower part from $-u$ to $(d - \epsilon) \cdot u$, it breaks uniformly in the part from $(d - \epsilon) \cdot u$ to $(d + \epsilon) \cdot u$, and it is again unbreakable in the upper part from $(d + \epsilon) \cdot u$ to u (see Figure 5).

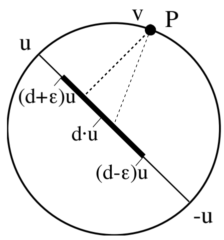

Fig. 5 : A representation of the experiment $e^{\epsilon}_{u,d}$. The elastic breaks uniformly between the points $(d-\epsilon)u$ and $(d+\epsilon)u$, and is unbreakable in other points.

An e_u experiment performed by means of an ϵ, d-elastic shall be denoted by $e^{\epsilon}_{u,d}$. We have the following cases:

(1) $v \cdot u \leq d - \epsilon$. The particle sticks to the lower part of the ϵ, d-elastic, and any breaking of the elastic pulls it down to the point $-u$. We have $P^{\epsilon}(o^u_1, p_v) = 0$ and $P^{\epsilon}(o^u_2, p_v) = 1$.

(2) $d - \epsilon < v \cdot u < d + \epsilon$. The particle falls onto the breakable part of the ϵ, d-elastic. We can easily calculate the transition probabilities and find:

$$P^{\epsilon}(o^u_1, p_v) = \frac{1}{2\epsilon}(v \cdot u - d + \epsilon) \tag{3}$$

$$P^{\epsilon}(o^u_2, p_v) = \frac{1}{2\epsilon}(d + \epsilon - v \cdot u) \tag{4}$$

(3) $d + \epsilon \leq v \cdot u$. The particle falls onto the upper part of the ϵ, d-elastic, and any breaking of the elastic pulls it upwards, such that it arrives in u. We have $P^{\epsilon}(o^u_1, p_v) = 1$ and $P^{\epsilon}(o^u_2, p_v) = 0$.

Recent investigations of intermediate systems, neither quantum nor classical (hence for example the ϵ-example for the case $0 < \epsilon < 1$), has revealed that here again the same two axioms, weak modularity and the covering law, cannot be satisfied (Aerts, Durt and Van Bogaert, 1992, 1993, Aerts and Durt 1994 a, b, and Aerts 1995). A new theory dispensing with these two axioms would allow for the description not only of structures which are quantum, classical, mixed quantum-classical, but also of intermediate structures, which are neither quantum nor classical. This is then a theory for the mesoscopic region of reality, and we can now understand why such a theory could not be built within the orthodox theories, quantum or classical.

5.5 Why orthodox quantum mechanics is so successful.

As our ϵ version of the quantum machine shows, there are different quantum-like theories possible, all giving rise to quantum-like probabilities, that however differ numerically from the probabilities of orthodox quantum mechanics. These intermediate theories may allow us to generate models for the mesoscopic entities, and our group in Brussels is now investigating this possibility. The current state of affairs is the following: quantum mechanics and classical mechanics are both extremal theories, corresponding relatively to a situation with maximum lack of knowledge and a situation with zero lack of knowledge on the interaction between measuring apparatus and the physical entity under study. Most real physical situations will however correspond to a situation with lack of knowledge on the interaction between the measuring apparatus that is neither maximal nor zero, and as a consequence the theory describing this situation shall have a structure that is neither quantum and nor classical. It shall be quantum-like, in the sense that the states are changed by the measurements, and there is a probability involved as in quantum mechanics, but the numerical value of this probability shall be different from the numerical value of the orthodox quantum mechanical probabilities. If this is the case, *why does orthodox quantum mechanics have so much success, also in its numerical predictions?* In this section we want to give a possible answer to this question.

We first want to consider again the quantum machine, and more specifically the ϵ-version of this quantum machine. Suppose that we consider a fixed angle α, such that $u \cdot v = cos\alpha$. We know that for a given ϵ and d, the probability for the point particle P to arrive in u, and hence the probability for the state p_v to be transformed into the state p_u, is given by $P^\epsilon(o_1^u, p_v) = \frac{1}{2\epsilon}(cos\alpha - d + \epsilon)$ (see (3)). We can remark that for some values of ϵ and d, this probability is smaller than the quantum probability $P_q(o_1^u, p_v) = \frac{1}{2}(1 + cos\alpha)$, and for some values of ϵ and d this probability is larger than the quantum probability. More specifically we have, when

$$\frac{d}{1-\epsilon} < cos\alpha \tag{5}$$

then $P^\epsilon(o_1^u, p_v) < P_q(o_1^u, p_v)$, and we are in a 'super-quantum situation' (the situation is stronger than quantum, and with stronger than quantum we mean that $|\frac{dP_q}{d\alpha}| \leq |\frac{dP_\epsilon}{d\alpha}|$), while when

$$\frac{d}{1-\epsilon} > cos\alpha \tag{6}$$

then $P_q(o_1^u, p_v) > P_q(o_1^u, p_v)$, and we are in a 'sub-quantum situation' (the situation is weaker than quantum, hence more close to classical). In Figure 6 we give the example of two possible situations, one 'super-quantum' and the second 'sub-quantum'.

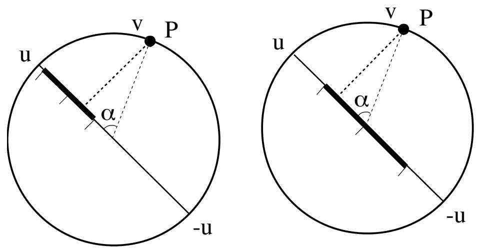

Fig. 6 : A example of two possible ϵ,d situations. The first is a 'super-quantum' situation, the probability for the point P to arrive in u is bigger than the quantum probability, while the second is a 'sub-quantum' situation, the probability for the point P to arrive in u is smaller than the quantum probability.

Suppose now for a moment that we perform $e_{u,d}^\epsilon$ experiments, and we choose 'at random' one of the $e_{u,d}^\epsilon$ experiments, without knowing the values of ϵ and d. The experiment that we have chosen can then be classical, sub-quantum, quantum or super-quantum. We can ask ourselves then what would in this case be the probability for the point P to arrive in u. Let is call this probability $P_\Delta(p_u, p_v)$. Taking into account the well-known Bertrand-paradox from probability theory, we know that there is no unique answer to this question. Indeed, the probability for the point P to arrive at u when an at random choice is made for ϵ and d, depends on the way in which this choice is defined. What we do know however, is that this probability $P_{\Delta}(p_u, p_v)$ is independent of ϵ and d, and shall, in our case of the quantum machine, only depend on v and u, the states before and after the measurement. We have made such a calculation for the case of the ϵ, d quantum machine, choosing the couple ϵ, d at random in the triangle defined by the lines $\epsilon = -d + 1$, $\epsilon = d + 1$ and $\epsilon = 0$, as shown in Figure 7. We find in this case:

$$P_{\Delta}(p_u, p_v) = \frac{1}{2}(1 + cos\alpha) - \frac{1}{2}(1 + cos\alpha)^2 logcos\frac{\alpha}{2} + \frac{1}{2}(1 - cos\alpha)^2 logsin\frac{\alpha}{2} \qquad (7)$$

This probability $P_{\Delta}(p_u, p_v)$ resembles the orthodox quantum probability, but has some additional terms, which makes it numerically different. As we mentioned already, because of the Bertrand paradox, we can certainly invent a way of choosing ϵ and d at random in such a manner that $P_{\Delta}(p_u, p_v)$ equals the orthodox quantum probability. If we do this, is this then not just a way of cheating? Not really, because there is an element of the dimension of the example (we shall come back to this in the next section) that plays a role in this possibility of finding many different answers for P_{Δ}. The idea that we want to bring forward is however very fascinating.

Since, for two given states p_v and p_u, the hidden measurement models of our general theories can lead to situations where the 'lack of knowledge' on the interaction between the measurement apparatus and the entity (let us characterize the nature of this lack of knowledge by ϵ) is such that the resulting 'transition probability' $P^{\epsilon}(p_u, p_v)$ is 'super-quantum' or 'sub-quantum', could it not be so, that an at random choice between all these possible lack of knowledge situations (hence an at random choice between all possible ϵ), gives rise to the orthodox quantum transition probability $P_q(p_u, p_v)$ between the states p_v and p_u?

If the answer would be 'yes' to the foregoing question, this would main that the probabilities of orthodox quantum mechanics can be interpreted as the probabilities corresponding to a first order non-classical theory. A non classical theory where we don't know anything about the amount of lack of knowledge on the interaction between the measuring apparatus and the entity. We shall see in the next section that we have reason to believe that we have found here a completely new explanation for quantum mechanics, and why its numerical values give that good results in all regions of micro-physics.

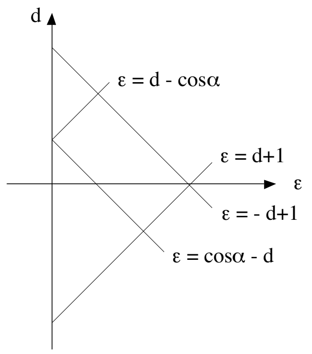

Fig. 7 : The domain that we use for the random choice of ϵ and d.

5.6 Orthodox quantum mechanics as a first order non-classical quantum-like theory

Suppose that we consider the situation of an entity S, and two possible states p_u and p_v corresponding to this entity. We also consider now all possible measurements that can be performed on this entity S, with the only restriction that for each measurement considered it must be possible that when the entity is in state p_v, it can be changed by the measurement into state p_u. Among these measurements there shall be deterministic classical measurements, there shall be quantum measurements, but there also shall be super-quantum measurements and sub-quantum measurements. All these different measurements are considered. We suppose now that we cannot distinguish between these measurements, and hence the actual 'huge' measurement that we perform, and that we denote $\Delta(u,v)$, is an at random choice between all these possible measurements. We shall call this measurement the 'universal' measurement connecting p_v and p_u. We remark that if we believe that there is 'one' reality then there is also only 'one' universal measurement $\Delta(u,v)$ connecting p_v and p_u. We wonder now what is the probability $P_\Delta(p_u,p_v)$ that by performing the universal measurement $\Delta(u,v)$, the state p_v is changed into the state p_u.

There is a famous theorem in quantum mechanics that makes it possible for us to show that the universal transition probability $P_\Delta(p_u,p_v)$ corresponding to a universal measurement $\Delta(u,v)$ connecting states p_u and p_v is the quantum transition probability $P_q(p_u,p_v)$ connecting these two states p_v and p_u. This theorem is Gleason's theorem.

Gleason's theorem proves that for a given vector u of a Hilbert space $\mathcal{H}$, of dimension at least 3, there exists only one probability measure μ_u on the set of closed subspaces of this Hilbert space, with value 1 on the ray generated by u, and this is exactly the probability measure used to calculate the quantum transition probability from any state to this ray generated by u. To understand more clearly in which way Gleason's theorem can be used to determine the universal transition probability between states, let us consider the situation of a three dimensional real Hilbert space [8].

The only positive function $w(p_v)$ that is defined on the rays p_v of a three dimensional real Hilbert space R^3, and that has value 1 for a given ray p_u, and that is such that

$$w(p_x) + w(p_y) + w(p_z) = 1 \tag{8}$$

if the three rays p_x, p_y, p_z are mutually orthogonal, is given by

$$w(p_v) = |<u,v>|^2 \tag{9}$$

Let us consider now two states p_u and p_v, and a measurement e (which is not apriori taken to be a quantum measurement) that has three eigenstates p_u, p_y and p_z, which means that it transforms any state into one of these three states after the measurement. The probability $P_e(p_u,p_v)$, that the measurement e transforms the state p_v into the state p_u is given by a positive function $f(v,u,x,y)$ that can depend on the four vectors v,u,x and y. In the same way we have $P_e(p_x,p_v) = f(v,x,y,u)$, $P_e(p_y,p_v) = f(v,y,u,x)$, and $f(v,u,x,y)+f(v,x,y,u)+f(v,y,u,x) = 1$. This is true, independent of the nature of the measurement e. If e is a quantum measurement, then $f(v,u,x,y) = |<v,u>|^2$, and the dependence on x and y disappears, because the quantum transition probability only depends on the state before the measurement and the eigen state of the measurement that is actualized, but not on the other eigenstates of the measurement. Gleason's theorem states that 'if the transition probability depends only

[8] Gleason's theorem is only valid for a Hilbert space of dimension at least three. The essential part of the demonstration consists of proving the result for a three dimensional real Hilbert space. Indeed, the three dimensional real Hilbert space case contains already all the aspects that make Gleason's theorem such a powerful result. This is also the reason that we want to illustrate our 'interpretation' of Gleason's result for the case of a three dimensional real Hilbert space.

on the state before the measurement and on the eigenstate of the measurement that is actualized after the measurement, then this transition probability is equal to the quantum transition probability'. But this Gleason property (dependence of the transition probability only on the state before the measurement and the eigenstate that is actualized after the measurement) is exactly a property that is satisfied by what we have called the 'universal' measurements. Indeed, the transition probability of a universal measurement, par definition of this measurement, only depends on the state before the measurement and the actualized state after the measurement. Hence Gleason's theorem shows that the transition probabilities connected with universal measurements are quantum mechanical transition probabilities. We go a step further and want to interpret now the quantum measurements as if they are universal measurements. This means that quantum mechanics is the theory that describes the probabilistics of possible outcomes for measurements which are mixtures of all imaginable types of measurements. Quantum mechanics is then the first order non-classical theory. It describes the statistics that goes along with an at random choice between any arbitrary type of manipulation that changes the state p_v of the system under study into the state p_u, in such a way that we don't know anything of the mechanism of this change of state. The only information we have is that 'possibly' the state before the measurement, namely p_v, is changed into a state after the measurement, namely p_u. If this is a correct explanation for quantum statistics, it explains its success in so many regions of reality, also concerning its numerical statistical predictions.

7. Entities, to be or not to be?

Let us now finally come to the basic question of this paper: what about the concept of entity? As we mentioned already in the introduction, the creation-discovery-view chooses in a certain sense for the conservation of the notion of entity. But we should now also finally say what we mean by the concept of entity in general. An entity is a collection of properties that have a certain state of permanence to be clustered together, and a property is a state of prediction towards a certain experiment. A property, as elements of the collection of properties that defines an entity, can be actual, which means that the corresponding outcome can be predicted with certainty, or potential, which means that the outcome cannot be predicted with certainty, but that the actuality of this property is available. This seems at first sight to be a very abstract notion, but it is not. Let us give some examples. Suppose that we consider an entity that is a point particle with a certain mass in space, moving with a certain velocity. Then the cluster of properties that defines the particle is made up of position properties and momentum properties. In a certain state, some of the position and momentum properties shall be actual (those where the particle is, and those that correspond to the particles momentum) ad others potential (those where the particle is not, but where it can come, and those that do not correspond to the particles momentum, but could do so). Clusters of properties that have enough permanence are entities. With this definition for an entity, quantum objects are entities in the creation-discovery view. Indeed, careful experiments have meanwhile shown that even a quantum object that is in a pure superposition state, for example of two states corresponding to localization in spatially separated regions of space (e.g. a photon in the delayed-choice experiment of Wheeler), behaves as an entity. This is most obviously demonstrated by Helmut Rauch in his famous neutron interferrometer experiments. There Rauch manages to manipulate the neutron in the superposition state, and the result is that it still behaves as a neutron (Aerts and Reignier 1990, 1991). So we can conclude by stating that in our creation-discovery view we retain the concept of entity as a cluster of properties that are more or less permanently joined, and we drop the preconception that such clusters of properties are in space and carry a definite impact.

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