

Annales de la Fondation Louis de Broglie,
Vol. 7, n° 1, 1982

CAN AN ACTUAL EXISTENCE
BE GRANTED TO QUANTUM WAVES ?*

by F. SELLERI

Istituto di Fisica
Università di Bari
INFN - Sezione di Bari
(Italie)

(Manuscrit reçu le 15 Octobre 1981)

Abstract : Existence of quantum waves in space and time devoid of energy-momentum seems to be indicated by neutron interferometric experiments. A similar point of view has been discussed in famous papers by Einstein, de Broglie and Bohr. An experiment is proposed which could test this idea using a low intensity photon beam.

Résumé : Des expériences interférométriques faites sur des neutrons semblent indiquer l'existence d'ondes qui se propagent dans l'espace et dans le temps mais dépourvues d'énergie et d'impulsion. Un point de vue analogue a été discuté dans des publications célèbres

* Paper written for Louis de Broglie's 90-th anniversary

d'Einstein, de de Broglie et de Bohr. On propose ici une expérience qui pourrait tester cette idée en utilisant un faisceau de photons à basse intensité.

1 - EXPERIMENTS WITH THE NEUTRON INTERFEROMETER

When a photon and a neutron enter in a crystal as wave packets having dimensions larger than interatomic distance one could think that their behaviour should be very different since photons interact with electric charges and therefore find a medium literally full of dispersing elements while neutrons interact only with nuclei and therefore "see" a medium in which only one part in 10^{15} of the volume is occupied. This difference is however unimportant and a neutron beam behaves in a crystal very similarly to a photon beam with the same de Broglie wavelength. All the laws of classical optics relating to reflection, transmission, diffraction and dispersion are valid for neutrons as well.

The geometrical ordering of the elementary spherical waves, outgoing from single atoms, produces the general macroscopic (diffracted, transmitted, etc.) wave. Thus neutron waves interact only with nuclei, but since these have the same geometrical ordering of the atoms the resulting diffracted or transmitted wave behaves geometrically like a photon wave.

The first neutron interferometer was operated in 1974 by Rauch, Treimer and Bonse at the Austrian Nuclear Institute in Vienna. The interferometer is built starting from a single silicon crystal completely free of dislocations and other defects in the regular atomic structure. For example one can start from a cylindrical crystal about eight centimeters long and five centimeters in diameter and cut away part of it leaving three semicircular "ears" connected by the remainder of the cylinder. The cutting is an operation which must be done

with great care ; in a typical interferometer the distances between the crystal plates and the thicknesses of the ears are exact within 10^{-4} cm.

When a beam of neutrons strikes the first ear in the interferometer at an angle θ from the normal to the surface (Bragg angle) of $20-30^\circ$ it is scattered by planes of atoms *perpendicular* to the face of the crystal. This kind of scattering, gives rise to two beams : a transmitted one at the Bragg angle θ and a diffracted one at the same angle but on the opposite side of the scattering planes. In other words the emerging beams form a V whose vertex lies in the first ear. At the second ear each of these beams is again Laue-scattered, the four emerging beams forming a W whose vertexes lie in the second ear. The geometry of the apparatus is such that the two external beams of this W do not have any further interaction with the interferometer (Fig. 1). The important facts happen when the two internal beams of the W converge in the same point on the face of the third ear : each of them is again Laue scattered and gives rise to a V coming out of the third ear. The two V's are however spatially superimposed in such a way that each of the two beams which emerge from the third ear results from the sum of the transmitted component of one beam and the diffracted component of the other beam.

Let ψ_R and ψ_L be the two wave functions describing the beams which arrive on the *third* ear from right and from left respectively. If we concentrate on the cases in which neutrons do actually arrive on the third ear we can assume that there is an overall normalization

$$|\psi_R|^2 + |\psi_L|^2 = 1.$$

At the third ear each wave is split in a transmitted (T) and a diffracted (D) wave : ψ_R gives rise to ψ_R^T and ψ_R^D ,

while ψ_L gives rise to ψ_L^T and ψ_L^D . The coherence of this phenomenon guarantees that ψ_R , ψ_R^T and ψ_R^D have the same phase and that the same holds for ψ_L , ψ_L^T and ψ_L^D .

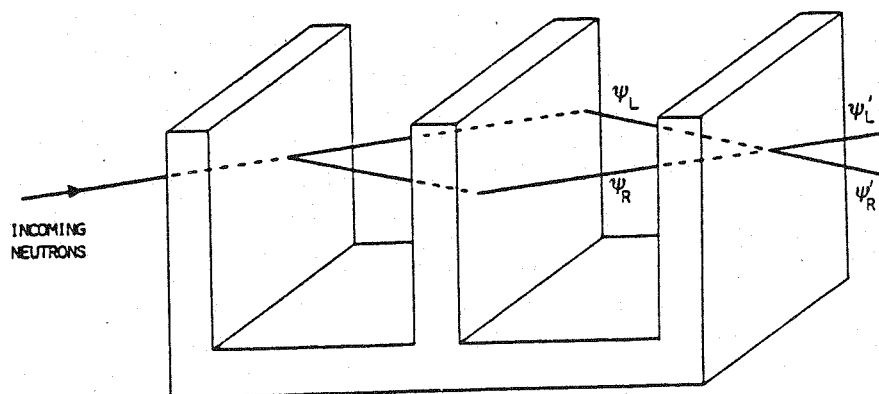


FIG. 1 Neutron paths within a neutron interferometer. Not shown are the paths emerging from the second ear and leading outside the interferometer.

Now in the V which emerges from the third ear one has two waves which we call ψ_R' and ψ_L' and which result from the physical spacial superposition (and therefore the algebraic sum) of two different waves

$$\begin{aligned}\psi_R' &= \psi_L^T + \psi_R^D \\ \psi_L' &= \psi_R^T + \psi_L^D\end{aligned}$$

With some simplifying assumptions it is possible to show that

$$|\psi_R'|^2 = \frac{1}{2} [|\psi_R|^2 + |\psi_L|^2 + 2|\psi_R| \cdot |\psi_L| \cdot \cos \alpha]$$

$$|\psi_L'|^2 = \frac{1}{2} [|\psi_R|^2 + |\psi_L|^2 - 2|\psi_R| \cdot |\psi_L| \cdot \cos \alpha]$$

where α is the phase difference between an R and an L wave. From the previous result one sees first of all that

$$|\psi_R'|^2 + |\psi_L'|^2 = 1$$

so that probability is conserved, and furthermore that the squared modulus of each beam emerging from the neutron interferometer depends on the relative phase of the right and left components. If this phase is known one can check if the famous probability law of Born is really valid : in fact ψ_R' and ψ_L' are spacially divided and the probability of a single neutron to choose the left or the right path could be equal to $|\psi_L'|^2$ and $|\psi_R'|^2$ respectively. Repeating the experiment many times one should have emerging neutron *fluxes* proportional to $|\psi_L'|^2$ and $|\psi_R'|^2$.

Practical experiments have been done with monochromatic neutron beams emerging from a nuclear reactor. Typically these have a flux of about 100 neutrons per second which corresponds to an average time spacing $\Delta t = 10^{-2}$ sec. However the α -dependence of Eq.(1) has sometimes been checked with an average time spacing as high as a fifth of a second.

From a reactor emerge normally thermal neutrons with velocity of $2 \cdot 10^5$ cm/s. Using de Broglie's formula one obtains then a wavelength $\lambda \approx 2 \cdot 10^{-8}$ cm. Every neutron crosses the whole interferometer in a time

$$\tau = 8 \text{ cm} / 2 \cdot 10^5 \text{ cm/s} = 4 \cdot 10^{-5} \text{ s.}$$

The probability of having *two* neutrons at the same time in the apparatus is given by $\tau/\Delta t$ and is therefore of the order of 10^{-3} - 10^{-4} .

One can conclude that in the large majority of the cases only one neutron is present in the apparatus. The experiments performed by using the most diverse physical means for varying the relative phase α (phase-shifting materials, magnetic fields, gravitational field of earth, earth rotation, ...) have shown a very good consistency with eq.(1)(¹). Thus Born's statistical postulate (particle distribution given by $|\psi|^2$) is confirmed. Moreover every neutron interferes with itself (just as in the double slit experiment exposed in textbooks). Thus we conclude that in the case of every single neutron something propagates over both the possible paths within the interferometer.

This conclusion is apparently contradicted by a second experiment which one could do by putting neutron counters immediately behind the first ear : as it well known, since such experiments have been performed many times with photons and electrons, every neutron would be revealed only by a single counter. Neutron counters are in last analysis sensitive to incoming energy-momentum : we can conclude that energy-momentum (and therefore mass) take always only one of the two paths which are possible when crossing an interferometer ear. On the other path one concludes so that a wave propagates which does not carry energy and momentum.

This idea is not necessarily excluded as a solution of the wave-particle puzzle, as one could think at first sight. It will be shown in the following sections that the dualistic proposals put forward in famous papers by Einstein, de Broglie, Bohr and Born seem, in

fact, consistent with the point of view that a physical entity propagates in space and time without carrying with itself any appreciable energy and momentum.

2 - EINSTEIN AND THE OBJECTIVE DUALISM

Difficulties for the classical theory of radiation were found in 1902 by Lenard and in 1903 by Ladenburg in the photo-electric effect. As a consequence the idea began to be accepted that the energy was not uniformly distributed on the wave-front. In a lecture at Yale University in 1903 J.J. Thomson made reference to "bright specks on a dark background" for a correct representation of the wave-front.

Also Einstein started to work on the same idea. He thought that one could not exclude the appearance of new phenomena for instantaneous values of the fields, like those entering in the absorption and emission processes. His basic idea was that the energy of an electromagnetic wave with frequency ν was concentrated in very small regions (quanta or particles of radiation) each with energy $h\nu$, where h is Planck's constant. This was the birth of the wave-particle dualism. The particles carried the energy and other physical attributes. The waves constituted an extended entity which surrounded the particles. The presence of the particles was essential for understanding the photo-electric effect while the presence of the waves allowed one to understand interference and diffraction.

Einstein's dualistic idea had at first very little success among other physicists. He kept working on it, however. In 1909 he showed that Planck's formula for the black-body radiation implied that particle and wave aspects of light gave *additive* contributions to the mean square fluctuation of energy in any small volume. In the same year he proposed to treat light-quanta as

singularities surrounded and guided in their motion by a continuous wave-phenomenon.

Einstein wrote a new paper on dualism in 1917⁽²⁾. In it he considered a gas of molecules interacting through the emission and the absorption of electromagnetic radiation ; assumed for the molecules the existence of discrete energy states capable of transforming into each other by emission or absorption of electromagnetic radiation ; assumed that the possible processes were those of stimulated emission under the influence of the radiation field and of absorption of the same nature and also of emission "without excitation from external causes" ; finally assumed that the different energy states were found in the molecular gas with a frequency deduced from the canonical distribution of states of statistical mechanics. Among the results obtained was a very simple derivation of Planck's formula which is still repeated today in many textbooks. But Einstein considered more important another result which is instead practically forgotten.

When radiation is emitted or absorbed by a molecule it imparts to the latter a momentum (except if one is dealing with a spherically symmetric wave). The maximum momentum is obtained when all of the energy E is emitted in one direction and in this case it equals E/c . Einstein could prove that the experimentally established Maxwell distribution was obtained only under the hypothesis that all energy was emitted in (or absorbed from) a unique direction in every individual radiation-matter interaction process.

In the final paragraph he stressed that the following points could be considered as "fairly certainly proved" : "If a radiation bundle has the effect that a molecule struck by it absorbs or emits a quantity of energy $h\nu$ in the form of radiation (ingoing radiation), then

a momentum $h\nu/c$ is always transferred to the molecule. For an absorption of energy, this takes place in the direction of propagation of the radiation bundle, for an emission in the opposite direction." Einstein considered the previous result as the *most important conclusion of his paper*, obviously because it threw light on the nature of the electromagnetic radiation.

A more spectacular proof of the directional character of quanta was given by Compton in 1923⁽³⁾. He found that in the scattering of x-rays from matter a change of frequency was observed and could obtain a theoretical formula in complete agreement with his experimental data. Compton wrote : "The present theory depends essentially upon the assumption that each electron which is effective in the scattering, scatters a complete quantum. It involves also the hypothesis that the quanta of radiation are received from definite directions and are scattered in definite directions. The experimental support of the theory indicates very convincingly that a radiation quantum carries with it directed momentum as well as energy".

Compton's experiment *suggested* that corpuscles were indeed present in the electromagnetic radiation. Much stronger evidence was obtained in 1925 by Compton and Simon⁽⁴⁾ who observed recoil electrons from x-ray scattering in a cloud chamber. If an unobserved corpuscle was scattered one could calculate from energy and momentum conservation the direction along which it had to move. This corpuscle could make a second scattering on an electron and the resulting electron track should have its starting point on the calculated trajectory of the unseen corpuscle. Compton and Simon observed 18 such double scatterings which was, within statistical errors, what they expected.

Discussing this experiment Compton wrote⁽⁵⁾

two years later : "... we can find no interpretation of the scattering except in terms of the deflection of corpuscles or photons of radiation".

Einstein's objective dualism associated wave and corpuscles in such a way that the particle properties energy and momentum (E and p) and the wave properties frequency and wave number vector (ν and \vec{k}) were related by

$$E = h \nu \quad ; \quad \vec{p} = h \vec{k}$$

As it is well known de Broglie extended these relations to material particles (electrons, neutrons, ...) so that they appear as a very fundamental property of nature.

A problem coming immediately to one's mind within Einstein's philosophy is the following : if the localized particle carries all the energy and momentum in which sense can the wave be considered real ? This problem was felt so acutely by Einstein that he referred to these waves as *Gespensterfelder* (ghost fields) : an object without energy and momentum is in fact unable to exert a pressure when hitting other bodies, which means that it does not have that quality which makes us call real a normal object. Still the equations of quantum mechanics describe this wave as propagating in space and time : this happens for instance in the neutron interferometric experiments. In the last section we will propose an experiment which could conceivably give empirical meaning to waves of this nature.

3 - DE BROGLIE'S DUALISM

Louis de Broglie extended duality to electrons and other particles⁽⁶⁾. His very interesting reasoning was as follows. Consider a particle with rest mass m_0 and rest energy $m_0 c^2$. All forms of energy are reducible to motion. Relativity teaches us that a rest mass is also some form of energy. Therefore there should be some form of motion

associated with mass. Since a particle is a localizable structure which can be put at rest, the motion related to the mass must take place within a very small region. It should then be some kind of rotation or vibration, anyway a periodic motion with some associated frequency ν_0 . How can we determine ν_0 ? Physically one expects ν_0 to increase with energy. Furthermore Planck's relation for photons, $E = h\nu$, has the nice feature that E and ν transform in the same way so that $E = h\nu$ can be true in all frames of reference. Therefore de Broglie assumed very naturally that $E = h\nu$ holds for electrons as well, where E is the total energy. In the particle rest system the previous relation becomes $\nu_0 = m_0 c^2 / h$.

The trouble with this description is that in a moving system one finds not one but two different frequencies associated with the particle. One is obtained by noticing that the moving observer, because of time dilation, sees the internal periodic motion slowed down and measures the frequency $\nu_1 < \nu_0$. The second frequency is obtained by writing $\nu_2 = E/h$ whence obviously $\nu_2 > \nu_0$. Which is the physical interpretation of ν_2 ? de Broglie proposed to introduce a wave associated with the particle having ν_2 as frequency. But in the rest system $\nu_1^0 = \nu_0 = \nu_2^0$: the wave and the internal periodic motion have the same frequency. This is a very physical conclusion : it looks as if the internal motion generated the wave and gave it, of course, its own frequency. If this conclusion is valid every observer in every frame should see *the internal motion and the wave always in phase*. (A cork pushed up and down in the water is a good example. In any moving frame one will see a crest generated when the cork is up and a valley when it is down). Since $\nu_1 \neq \nu_2$, it is not obvious that this condition can be satisfied. de Broglie showed, however, that if the wave velocity is c^2/v the two periodic motions will always be found in phase in the points occupied by the moving particle in various instants of time. From this exciting reasoning, de Broglie was able

to deduce some very important consequences :

- (1) The *group* velocity of the waves could be shown to be just v , the particle velocity. Therefore if the waves were not perfectly monochromatic a region containing the ondulatory disturbance would necessarily move together with the particle.
- (2) A relation between wavelength λ and particle momentum p could be deduced : $p = h/\lambda$.
- (3) Light quanta could be considered a special case of this theory. In the limit $m_0 \rightarrow 0$, Einstein's relations $E = h\nu$, $p = h\nu/c$ could be obtained. Therefore a great unification between particles and electromagnetic radiation was established. Both were now represented as a corpuscle immersed in a wave phenomenon.
- (4) Consideration of a bound electron led to the conclusion that the only stable states are those for which the wave is stationary (orbits whose length ℓ is an integer n times the wavelength λ : $\ell = n\lambda$).

Waves and particles were for de Broglie both objectively existing in space and time : in his Nobel lecture he stated : "The electron ... must be associated with a wave and this wave is no myth ; its wavelength can be measured and its interferences predicted"(').

It is interesting to notice that de Broglie considers his waves as endowed of a very small fraction of the energy whose largest part should certainly be concentrated in the particles. Partial absorption of the wave, which takes place in such optical phenomena as apodization, should then result in a loss of energy on the part of the dual system. This, according to de Broglie, could explain the redshift of the light arriving from distant galaxies without recourse to the expansion of the Universe.

The great virtue of this hypothesis is that it can be checked experimentally : for instance, the Mössbauer effect should take place differently for γ -rays which have or have not crossed a partial absorber.

Perhaps this idea is already excluded by existing evidence and one can add that it looks a little conservative in that it attributes a very small amount of the most fundamental quality of science-energy-just to keep the wave ... real. An alternative way to observe the reality of the wave will be discussed in the last section and it does not need to assume that energy and momentum are associated to quantum waves.

4 - BOHR'S VIRTUAL WAVE

Niels Bohr treated the electromagnetic field in purely ondulatory terms until 1926 : for example the 1918 paper on the Correspondence Principle used classical electrodynamics not only in the region of high quantum numbers but also for low and intermediate quantum numbers⁽⁹⁾. In this way intensities, polarizations and selection rules for the emitted radiation could be calculated.

The success of these calculations helps in understanding why Bohr was not willing to accept Einstein's picture of the electromagnetic field (with the energy carried by small particles). Also the famous 1924 paper by Bohr, Kramers and Slater⁽⁹⁾ treated the electromagnetic field as continuous everywhere but "virtual". This field is introduced in the theory by means of the correspondence principle and is considered coupled to the "virtual harmonic oscillators" which one used then for calculating atomic transitions. The problem of the actual existence in space and time of this virtual field is not discussed explicitly in this work, even though its reality is somewhat implied by the

very fact that one introduces it in the theoretical frame. What is certain, however, is that the BKS field does not carry energy and momentum : "... we abandon on the other hand any attempt at a causal connection between the transitions in distant atoms, and especially a direct application of the principles of conservation of energy and momentum, so characteristic of the classical theories⁽¹⁰⁾.

In this theory an atom in its fourth stationary state, for instance, emits continuously three "virtual" spherical waves with frequencies $\nu_i = (E_4 - E_i)/h$ where $i = 3, 2, 1$. These waves, together with other eventual waves which might come from other nearby atoms, determine an electromagnetic field which through its overall intensity determines a transition probability (in Einstein's 1917 sense) of our atom to different stationary states. The jump of the atom from the given stationary state to higher state takes place violating energy (and momentum) conservation : in fact the atomic energy changes, but no energy is taken from the radiation field which is virtual and carries no energy with itself. Similar conclusions hold for transitions to lower energy states.

Bohr, Kramers and Slater claimed that energy conservation would still be valid as a *statistical* concept.

A consequence of this theory is that no time correlation between atomic events is predicted : consider a gas of identical atoms half of them in the state E_1 and half in the state E_2 . Einstein's description would say that if an atom A goes from E_2 to E_1 it emits a photon which travels in space and eventually makes a second atom B go from E_1 to E_2 : there is clearly a time relation between the events A and B calculable from the AB distance and the speed of light. In the B.K.S. theory, however, no such relation can exist : no energy-quanta

are propagated in space, there is only a continuous field that determines only a *transition probability* for individual atoms.

It was precisely this point which led Bothe and Geiger⁽¹¹⁾, and Compton and Simon⁽¹²⁾ to make experiments which disproved the B.K.S. theory. These authors used the Compton scattering of x-rays which in this theory would only be a continuous beam of virtual radiation with short wavelength. Thus in place of atom A making a transition between two stationary states we have an electron suddenly scattered (according to a probability law similar to the atomic one) and in place of atom B we have the discharge of a counter due to ionization processes. Bothe and Geiger found a very sharp time correlation between electron scattering and x-ray absorption, thereby excluding the possibility that the B.K.S. theory could provide a correct description of the physical world.

These experiments pushed Bohr to reconsider his totally negative opinion toward the wave-particle dualism. The principle of complementarity was his peculiar way to accommodate in his world picture the dualism and was presented in 1927, twentytwo years after Einstein had started to work on the problem.

Heisenberg's discovery of the uncertainty relations was an important bridge between the formalism of quantum theory and the physical world, but did not provide a solution for all difficulties. What was it the composition of the electromagnetic field, particles or waves ? And how could one take into account the oscillatory properties of the electrons ?

Bohr faced such questions directly and found a "solution" consisting of the assumption that we cannot hope to solve this kind of contradictions. Rosenfeld, one of Bohr's pupils, wrote on this : "While the great masters

(Planck, Einstein, Born, Schrödinger) were vainly trying to eliminate the contradictions in Aristotelian fashion by reducing one aspect to another, Bohr realized the futility of such attempts. He knew that we have to live with this dilemma ... and that the real problem was to refine the language of physics so as to provide room for the coexistence of the two conceptions⁽¹³⁾".

Obviously, to live with a dilemma is something fundamentally different from solving it. One cannot avoid to recall, at this point, that there is so much resemblance between this renunciation to solve the fundamental contradiction of atomic physics and the irrationalistic philosophies of Kierkegaard and Høffding to which Bohr had been exposed since his youth and by which he had been so strongly influenced.

Bohr's complementarity can be introduced in the following way⁽¹⁴⁾. The experimenter lives in a macroscopic world and conceptions typical of this condition such as causality and space-time are deeply rooted in all human beings. But it is not necessary and in fact, according to Bohr, it is not true that even conceptions of such a general nature have an unlimited applicability in the study of microphenomena. The key for a correct understanding of this fundamental point is the existence of the quantum of action h .

Let us examine the experimental meaning of causality and of space-time. Causality is for Bohr a synonymous of process taking place according to well defined rules. These rules are in practice those of energy-momentum conservation. Therefore an experimenter wishing to check the rigorous validity of the causality law must perform infinitely precise measurements of energy and momentum. The relations $\Delta E = 0 = \Delta p$ imply however, because of Heisenberg's relations,

$$\Delta t = \infty = \Delta x$$

which mean that absolutely no localization in time and in space is produced during the measurement. Complete lack of localization means for Bohr that space and time in practice do not exist (it should be noted that here, as in many other places, Bohr makes an important concession to the positivistic philosophy assuming that what is not observed does not exist). Therefore one concludes that observation of causality forbids an observation of space and time.

Conversely one may wish to observe space-time correlations : an ideal measurement would now imply $\Delta x = 0$, whence $\Delta p = \infty$. This means that an arbitrarily large momentum is exchanged between apparatus and atomic system. Furthermore such an exchange is *in line of principle* impossible to determine "if the measuring apparatus has to serve its purpose" as Bohr shows in detail in several concrete situations. In these conditions it is obviously impossible to verify the law of causality (that is to check energy-momentum conservation). Thus one concludes that observation of space and time precludes an experimental control of the validity of the law of causality. Therefore it does not make any sense to talk about such a law when one performs space-time observations.

Bohr concludes from these considerations that there is a *complementary relation* (rigid mutual exclusion) between space-time coordination and causality : they can never be used simultaneously.

A similar conclusion is obtained when one considers the conceptions of particle and wave. When studying causality (e.g. in the photoelectric effect or in Compton effect) one finds that the conservation of energy and momentum "finds its adequate expression just in the light quantum idea put forward by Einstein". Conversely the conceptual instrument suitable for pre-

dicting the possible points P' in which a localization of the observed system will manifest itself after a previous localization in P is the wave function whose squared modulus gives the probability density to observe the system in different points P' . It is naturally impossible to know in which point the localization will manifest itself. Therefore the evolution appears as intrinsically stochastic, which is the same as saying once more that one is here talking an ondulatory language. There is also a mutual exclusion between particle and wave, which must be considered complementary descriptions of atomic systems. The impossibility to find a synthesis between these two descriptions leads Bohr to the conclusion that each of them is nothing but an expedient taken from classical physics. No classical idea (wave or corpuscle, causality or space-time) has therefore a secure validity in the atomic domain.

It should be stressed that the wave which represents one of the complementary aspects of atomic entities (the other one is the particle) is daughter of the BKS virtual wave and is conceptually very near, as it will be stressed later, to the probability wave which Born introduced in 1926 in quantum mechanics. In fact, as we stated above, the wave is applicable in studying space-time localizations. Since this excludes the possibility to check the causality law (sinonimous of energy-momentum conservation) one is faced once more, as in the BKS paper, with a wave which does not generate energy conserving transitions. However this wave can modify the probabilities of atomic transitions and this is a feature which we shall reconsider in the last section.

A final remark on complementarity is that recent research on this principle has shown that the difference between the wave and particle aspects is less sharp than Bohr thought and that ondulatory phenomena are easily observable ... even in cases when one is 99% sure that

a particle has propagated⁽¹⁵⁾. In my opinion these recent researches tend objectively to build a bridge between Bohr's complementarity and the Einstein-de Broglie version of dualism, since they point to a probable coexistence of particles and waves.

5 - THE WAVES OF SCHRÖDINGER AND OF BORN

De Broglie's ideas were partly developed and partly modified by Schrödinger who found his famous wave equation for the electron wave-function. The continuity was in the fundamental mathematical development which provided a precise quantitative basis for the evolution of de Broglie's waves. There was however a fundamental difference in the fact that Schrödinger did not accept the presence of particles and reduced both light and matter to purely ondulatory phenomena. Philosophically Schrödinger's ideas were sharply on the realistic side : for instance in a 1926 paper he referred to the "... de Broglie-Einstein ondulatory theory, according to which a moving corpuscle is nothing but the foam on a wave radiation in the basic substratum of the universe⁽¹⁶⁾". In a paper in which he showed the equivalence of matrix mechanics and wave mechanics he refers directly to "ether waves".

The reality of electron-waves is expressed also by the existence in Schrödinger's theory of well defined densities of energy, momentum and electric charge in all points where the wave-function ψ is different from zero. From this point of view Schrödinger's waves represent therefore a complete reversal of the ideas developed by Einstein and Bohr, which contained, as we have seen, energetic particles and extended waves devoid of the usual physical attributes.

The experimental situation is however such that it allows one to exclude that Schrödinger's formu-

lation of dualism (which should rather be called monism in this case) may be correct. In fact a solution of Schrödinger equation ψ should fill the whole space-time region in which $\psi \neq 0$ with a continuous distribution of energy, momentum and electric charge. The same should hold for a nonrelativistic neutron (except obviously for electric charge); for instance in the neutron interferometric experiments described in the first section. But this simply means that the neutron is simultaneously present with part of its energy and momentum on both trajectories. Neutron counters put on these trajectories should therefore show a high coincidence rate, a fact which is contradicted by abundant experimental evidence. Similar considerations can be made for the Davisson-Germer experiment of electron diffraction with electron beam intensity so low that only one electron at a time enters in the apparatus. This electron is then predicted to be present partly in each of the different paths along which diffraction takes place and which can be calculated from Schrödinger's equation. This would imply that parts of the electron should be seen in coincidence measurements on the different paths, a prediction certainly contradicted by experimental evidence.

A reinterpretation of Schrödinger's waves in probabilistic terms was advanced, as it is well known, by Max Born in 1926⁽¹⁷⁾, who brought the waves back to the older proposal of Bohr, Kramers and Slater. This continuity was stressed particularly by Heisenberg who wrote :

"The probability wave of Bohr, Kramers and Slater... was a quantitative version of the old concept "potentia" in Aristotelian philosophy. It introduced something standing in the middle between the idea of an event and the actual event, a strange kind of physical reality just in the middle between possibility and reality. Later when the mathematical frame-work of quantum theory was fixed, Born took up this idea of the probability wave and gave a clear

definition of the mathematical quantity in the formalism ..."⁽¹⁸⁾. In this way the "virtual" waves of BKS became the usual wave-functions of quantum theory.

6 - HEISENBERG BEYOND COMPLEMENTARITY

Heisenberg wrote in 1958 : "... the concept of complementarity introduced by Bohr into the interpretation of quantum theory has encouraged the physicists to use an ambiguous rather than an unambiguous language, to use the classical concepts in a somewhat vague manner in conformity with the principle of uncertainty, to apply alternatively different classical concepts which would lead to contradictions if used simultaneously. In this way one speaks about electronic orbits, about matter waves and charge density, about energy and momentum, etc., always conscious of the fact that these concepts have only a very limited range of applicability.

When this vague and unsystematic use of the language leads into difficulties, the physicist has to withdraw into the mathematical scheme and its unambiguous correlation with the experimental facts"⁽¹⁹⁾.

It is interesting to notice that this withdrawal "into the mathematical scheme" has become a mass phenomenon in contemporary theoretical physics and that Bohr's complementarity and the other forms of dualism are half-forgotten. Therefore the previous statement shows that Heisenberg was a very acute witness of an historical process and that he did advocate such a development. Analyzing the use of descriptive concepts in atomic physics he insisted on the fact that they are often vague and that this vagueness is of the same type as that of "temperature" when used for a single atom.

They are rather correlated with statistical expectations, they are something like tendencies and pos-

sibilities, and can best be described with the concept of "*potentia*" of Aristotelian philosophy. "So the physicists have gradually become accustomed to considering the electronic orbits, etc., not as reality but rather as a kind of "*potentia*". The language has already adjusted itself, at least to some extent, to this true situation. But it is not a precise language in which one could use the normal logical patterns ; it is a language that produces pictures in our mind, but together with them the notion that the pictures have only a vague connection with reality, that they represent only a tendency toward reality"⁽²⁰⁾. The way out from this situation is for Heisenberg either the "withdrawal into the mathematical scheme" quoted above or the development of a different precise language which follows definite logical patterns in complete conformity with the mathematical scheme of quantum theory.

The modifications of classical logic advocated by Birkhoff and von Neumann and by von Weizsäcker are referred to with approval by Heisenberg. Also here it has to be noticed that the development of quantum logic has gone on at a remarkable rate in recent years⁽²¹⁾.

Heisenberg made great discoveries which have shaped the theoretical physics of the present century. His line is however fully characterized by a great fascination for the mathematical language coupled to a philosophically negative attitude toward the material world. For example, Heisenberg stated that during a walk under the stars in a park in Copenhagen in February 1927 "the obvious idea occurred to me that one should postulate that nature allowed only experimental situations to occur which could be described within the framework of the formalism of quantum mechanics"⁽²²⁾.

We see here that Heisenberg gives to the mathematical formalism a logical priority over considerations about the objective reality.

Strong statements of philosophical nature were made by Heisenberg in the paper on the uncertainty relations⁽²³⁾. He stated for instance that if one wants to talk of the position of an object "he has to describe an experiment by which the 'position of an electron' can be measured ; otherwise this term has no meaning at all". Some pages later he stated that "the path comes into existence only when we observe it". One should however notice that there is an element of arbitrariness in Heisenberg's conclusions. The fact that one cannot *measure* position and momentum of an electron simultaneously and with great precision does not necessarily mean that such quantities do not have any physical sense. It is only within a positivistic or an idealistic philosophy that one can draw such a conclusion. The validity of the uncertainty relations still allows one to calculate position and momentum *in the past* with any desired accuracy. About this fact Heisenberg wrote in 1930 : "Then for these past times $\Delta p \Delta q$ is smaller than the usual limiting value, but this knowledge of the past is of a purely speculative character, since it can never ... be used as an initial condition in any calculation of the future progress of the electron and thus cannot be subjected to experimental verification. It is a matter of personal belief whether such a calculation concerning the past history of the electron can be ascribed any physical reality or not"⁽²⁴⁾. Heisenberg's "personal belief", which has become the dominant point of view today, was certainly that one should refrain as much as possible from talking about the physical reality.

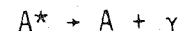
Admiring Heisenberg's discoveries does not necessarily mean that one should accept his *philosophy*.

The set of ideas developed by Einstein, de Broglie, Bohr and Born could finally prove to be more fruitful than an eternal withdrawal into the mathematical scheme.

7 - POSSIBLE INDEPENDENT MANIFESTATIONS OF QUANTUM WAVES

The far from complete review of the fundamental ideas on the nature of quantum waves which we carried out in the previous sections indicates that different authors interpreted the empirical evidence on quantum phenomena in terms of a wave without any associated energy-momentum. Actually de Broglie seemed to favour some very small energy content, but this difference is irrelevant from the point of view of the experiment which we are going to propose, even though it is interesting in itself as it leads to specific predictions. Existence of a wave independent from (even though often associated to) the corpuscular aspect was indicated with compelling clarity by Einstein, de Broglie, Bohr and Born. Moreover the most recent experimental evidence (neutron interferometry) points strongly in the same direction. Einstein called such entities "*ghost waves*" obviously because they seemed to lack the most fundamental qualities which make us call real any phenomenon : energy and momentum. Similarly these waves were called *virtual* by Bohr and had merely the property of inducing energy not conserving atomic transitions with a certain probability proportional to the squared amplitude of the e.m. wave in the point where the atom was located. When Bohr was forced from experimental evidence to accept a dualistic vision of light (which he formulated by means of his complementarity principle) this changed only in part his description of stimulated *emissions*. In fact, no energy needs to be provided to an excited atom A^* in order to make it decay. The energy-momentum balance can be fully satisfied from the energy contained in A^* when

the decay



is considered. Einstein and Bohr could therefore calculate the *induced* probability for this decay starting from an initial electromagnetic field whose energy content was either not needed (in Einstein's case) or not existing (in Bohr's case).

These considerations show that *even a wave which does not carry any energy and momentum can show that it is present by modifying transition probabilities of unstable systems.*

The first proposal in this sense was made in papers by the present author in 1969-1970⁽²⁵⁾ and developed later by Szczepanski⁽²⁶⁾. The basic idea is the following. A beam of photons having such a low intensity that in practice only one photon at a time is present in the apparatus can be generated : in fact, already the by now classical experiment by Janossy and Naray⁽²⁷⁾ satisfied this conditions. A semitransparent mirror splits the beam into two different beams. Photomultipliers put on these two trajectories do not reveal any coincidences⁽²⁸⁾, thus showing that also in the present case, just as in the neutron interferometer, energy and momentum choose only one of the two possible paths. However interference phenomena are perfectly normal even at such low intensities where at any time in average less than one photon is to be found in the arrangement ; this is true even if the dimensions of the arrangement greatly exceed the coherence length of the photons giving rise to the interference pattern. Thus something must propagate on both paths and this something, being an extended phenomenon which carries informations on the phase-shifts of the beams, must necessarily be the wave itself.

How can one ever hope to reveal the presence of a wave which does not carry energy and momentum? This problem can have an answer if one notices that we do not only measure energy changing processes but probabilities as well: therefore the wave could reveal its presence by modifying decay probabilities of an unstable system.

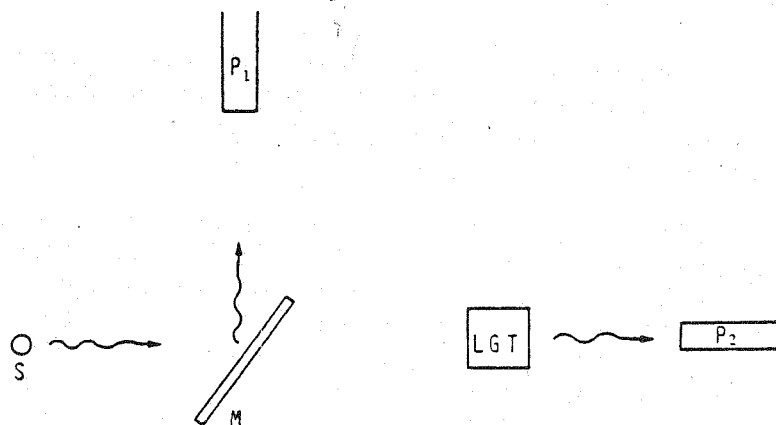


FIG. 2 Schematic diagram for the experimental study of quantum waves: S = photon source; M = semitransparent mirror; LGT = laser gain tube; P_1 and P_2 = phototubes.

Such an effect could probably be seen, if it exists, with existing technology using a modified version of the Pisa experiment⁽²⁹⁾.

A very low intensity photon beam emitted by the source S (FIG. 2) is split by the beam splitter M in two orthogonal beams. On the reflected beam a phototube P_1 is located and one concentrates attention on events in which P_1 does reveal a photon arrival. For such events no energy-momentum can propagate in the transmitted beam since no coincidences above the casual background would be revealed by a second phototube eventually put on this

beam (and not shown in the figure). However, the transmitted beam crosses an organic laser gain tube (LGT) where the eventual wave-packet devoid of energy and momentum has a chance to reveal its existence by generating a zero energy-transfer stimulated emission. The emitted photon could then be revealed by the phototube P_2 put after the LGT. In this way P_1P_2 coincidences would reveal the propagation of a zero-energy ondulatory phenomenon transmitted by M. The space-time propagation of this entity could be studied by checking that P_1P_2 -coincidences disappear whenever an obstacle is put before LGT in the transmitted beam.

* * *

The author is grateful to prof. A. Gozzini and prof. H. Rauch for useful discussions.

BIBLIOGRAPHY

- (¹) U. Bonse and H. Rauch, editors ; Neutron Interferometry, Clarendon Press, Oxford (1979)
- (²) A. Einstein ; Phys. Zs. 18, 121 (1917)
- (³) A.H. Compton ; Phys. Rev. 21, 483 (1923)
- (⁴) A.H. Compton and A. Simon ; Phys. Rev. 25, 306 (1925)
- (⁵) A.H. Compton ; Nobel lecture (1927)
- (⁶) L. de Broglie ; Ann. de Phys. 3, 22 (1925)
- (⁷) L. de Broglie ; Nobel lecture (1929)
- (⁸) N. Bohr ; Kgl. Danske Vid. Selsk., 8 Raekke IV, 1 (1918)
- (⁹) N. Bohr, H.A. Kramers and J.C. Slater ; Phil. Mag. 47, 785 (1924)
- (¹⁰) Ref. 9, page 791
- (¹¹) W. Bothe and H. Geiger ; Zeits.f. Phys. 32, 639 (1925)
- (¹²) See ref. 4
- (¹³) Quoted by A. Landé ; New Foundations of Quantum Mechanics ; Cambridge at the University Press (1965), p. 147
- (¹⁴) N. Bohr ; Atomic Theory and the Description of Nature ; University Press (Cambridge) (1961)
- (¹⁵) W.K. Wootters and W.H. Zurek ; Phys. Rev. 19D, 473 (1979)
- L.S. Bartell ; Phys. Rev. 21D, 1698 (1980)
- (¹⁶) E. Schrödinger ; Phys. Zs. 27, 95 (1926)
- (¹⁷) M. Born ; Zeits. f. Phys. 38, 803 (1926)

- (¹⁸) W. Heisenberg ; Physics and Philosophy ; Harper & broth., New York (1962), p. 41
- (¹⁹) Ref. 18, p. 179
- (²⁰) Ref. 18, p. 181
- (²¹) E.G. Beltrametti and G. Cassinelli ; Riv. Nuovo Cimento 6, 321 (1976)
- (²²) W. Heisenberg in S. Rozenhal, ed. ; Niels Bohr, North-Holland, Amsterdam (1967), p. 105
- (²³) W. Heisenberg ; Zeits. f. Phys. 43, 172 (1927)
- (²⁴) W. Heisenberg ; The Physical Principles of the Quantum Theory, Dover, New York (1949), p. 20
- (²⁵) F. Selleri ; Nuovo Cimento Letters 1, 908 (1969).
See also, Realism and the wave function of quantum mechanics, in Rendiconti della Scuola Internazionale Di Fisica "Enrico Fermi" ; IL Corso, Academic Press, New York (1971)
- (²⁶) A. Szczepanski ; Found. Phys. 6, 425 (1976)
- (²⁷) L. Janossy and Zs. Naray ; Nuovo Cimento Suppl. 9, 588 (1958)
- (²⁸) J.F. Clauser ; Phys. Rev. 9D, 853 (1974)
- (²⁹) A. Gozzini, private communication.