# The Information Interpretation of Quantum Mechanics and the Schrödinger Cat Paradox

Johannes Kofler and Anton Zeilinger

*IQOQI*
*Institute for Quantum Optics and Quantum Information*
*Austrian Academy of Sciences, Vienna, Austria*

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In the first decades of the 20th century, physics has undergone paradigmatic changes in the sense that fundamental notions cherished by physicists had to be modified. One of the new descriptions of Nature – quantum mechanics – is still debated as for example expressed by Richard Feynman who felt “it is safe to say that no one understands quantum mechanics”. Such comments are often dismissed by physicists in view of the overwhelming success of quantum physics. Max Tegmark and John Archibald Wheeler have argued that about one third of the gross national product of the United States is directly based on quantum mechanics. Considering that for example the understanding of the laser or of semiconductors is impossible without quantum physics, this might actually be too low an estimate. Furthermore, in view of the excellent agreement of the predictions of the theory with experimental observation, it is highly unlikely that the theory is in need of modification.

So, where is the problem? Feynman’s remark is underscored by the observation that until today a plethora of different interpretations of quantum physics exist within the scientific community. A central reason for this is that quantum mechanics is still lacking clear foundational principles. Albert Einstein’s theories of special and general relativity, the other fundamentally new descriptions of Nature emerging at the beginning of the 20th century, are based on the fundamental principle that Nature’s laws should have the same form in all reference frames independent of their motion or acceleration. These ideas have strong intuitive appeal and they are basically operational in the sense that there should not be any way to find out if one is moving or at rest, or being accelerated or in a homogenous gravity field without looking out. The consequent changes in our notions of space and time are then readily acceptable once one defines physical quantities only operationally, i.e., space is measured by meter sticks and time is measured by clocks. Quantum theory, however, is built on very abstract and purely mathematical terms.

Another still open issue is the question whether the laws of quantum mechanics, originally established to describe Nature at the microscopic level of atoms, are also valid in the macroscopic domain of every-day experience. This question was already debated in the early years of quantum mechanics. Niels Bohr repeatedly insisted that the distinction between quantum and classical is not the same as the distinction between microscopic and macroscopic. In fact, he was able to refute some attacks of Albert Einstein on the new theory by assuming that quantum laws also apply for large systems in an experiment. In 1935, Erwin Schrödinger has put forward a *gedanken* (i.e. thought) experiment where a *microscopic quantum superposition* of a decayed and non-decayed radioactive atom is transformed into a *macroscopic quantum superposition* of a dead and a living cat – a paradox in sharp contrast to any classical physical intuition (see Box 1). Still it is a challenge for experimental physicists all around the world to show that the quantum laws are also valid in the macroscopic realm.

Quantum superposition is at the heart of the conceptual problems quantum mechanics poses. While this is often discussed in terms of gedanken experiments, technological progress makes it possible now to refer to real experiments already performed. Consider for example a beam of $C_{60}$ molecules – the famous Buckminster fullerene molecules resembling a soccer ball – impinging on a grating (Figure 1). If one measures the distribution of the molecules at some distance – about one meter in the experiment – one observes a characteristic distribution which is very much like the well-known interference pattern of light after passing two slit openings in Young's seminal double-slit experiment. Most interesting are the minima in the distribution. They are explained by destructive interference of waves – in the case of the fullerene experiments: de Broglie waves – passing different slits. In the experiment the intensity of the fullerene beam was so low that in general molecules were passing the grating individually. The observation of the interference pattern then indicates that the wave is associated with each individual molecule, because each molecule "knows" that it should avoid the minima of the interference pattern.

Quantum mechanics tells us that, after the grating, the macro-molecules are in a *superposition of many states* where each state corresponds to a particular path through the grating. The total state then gives the probability of finding a molecule at some location. The appearance of fringes should be compared with the picture for classical soccer balls for which there would only be a broad distribution of balls without the intricate maxima-minima structure. Classically, each molecule passes through a specific slit and the distributions of all slits just add up. So, what is the condition for interference fringes to show up? Interestingly, in the quantum experiment any attempt to determine the path of the individual $C_{60}$ molecules destroys the interference. This was confirmed in a recent experiment where the molecules were heated up to temperatures of about 3000 Kelvin by having them pass through strong laser light. [The experiment was actually performed with $C_{70}$ molecules: L. Hackermüller et al., Nature **427**, 711 (2004).] Then the molecules emit light, i.e., they literally glow. The hotter, the more light they emit. This is encompassed by a gradual disappearance of the interference phenomenon. The peaks in Figure 1 get lower and lower and the valleys are filled up more and more until all interference disappears at some temperature. Why does this happen? We can envisage an experimentalist with a very powerful microscope looking at the molecules while they pass the apparatus. The brighter the light emitted and the shorter the light's wavelength, the better the observer is able to determine which path the molecule takes. It turns out that this is exactly the criterion for appearance and disappearance of the fringes. If there is no *information* present which path the molecule takes, we observe full interference. If full path information is there, no interference occurs, with a gradual transition between both, the two being *complementary*. It is not relevant, whether or not an observer takes notice of that information. The mere existence of the possibility to obtain the path information suffices to destroy the interference. Thus, we have already seen here how important the notion of information is for the understanding of a fundamental quantum phenomenon.

One of the simplest quantum objects is the electron. Electrons possess an intrinsic property called *spin* since it has some similarities with the classical concept of a rotating object. In a Stern-Gerlach type setup (see Box 2 and Figure 2) the spin can be measured along any direction and is always found to have only one out of two possible values, namely "up" or "down" along that direction. If the electron's spin is then measured along a different direction, the outcome is to some degree random. It is completely random along directions orthogonal to the original one. Such measurements are called *complementary.* Furthermore, a spin along any direction can always be considered as a superposition of "up" and "down" along any other chosen direction.

The "primus inter pares" in the interpretations of quantum physics is the Copenhagen interpretation, formed by Niels Bohr and Werner Heisenberg in the early days of quantum mechanics around 1927. In the Copenhagen view the *wavefunction* or *state* of a physical system is a complete *catalogue of knowledge* allowing to compute the *probabilities of outcomes of future measurements*. Individual outcomes can be *objectively random*. They happen without any causal reason, in contrast to the classical or subjective randomness of a thrown dice, which is only due to our ignorance of the exact initial conditions. Moreover, individual properties may be *complementary*, i.e., the knowledge of one excludes the knowledge of the other. This is characterized by the famous Heisenberg uncertainty relation, stating, e.g., that the position and momentum of a particle do not have precise values at the same time. Last but not least, quantum objects can be *entangled* with each other, losing their individual but having well defined joint properties.

The Copenhagen interpretation avoids any definition of reality except for the classical apparatus. Measurement results are just specific features of this classical apparatus. The resulting austerity of that interpretation has led many physicists to search for alternatives trying to salvage reality in one way or another. Yet, maybe there is a deeper message conveyed by the situation?

In this regard, in 1999, one of us (A.Z.) has put forward an idea which connects the concept of *information* with the notion of *elementary systems*. First we note that our description of the physical world is represented by propositions. Any physical object can be described by a set of true propositions. Second, we have knowledge or information about an object only through observations. It does not make any sense to talk about reality without the information about it.

Any complex object which is represented by numerous propositions can be decomposed into constituent systems which need fewer propositions to be specified. The process of subdividing reaches its limit when the individual subsystems only represent a single proposition, and such a system is denoted as an *elementary system*. (This notion is very closely related to Carl Friedrich von Weizsäcker's binary alternative, called the *Ur*, and to the *qubit* of modern quantum physics.) The truth value of a single proposition about an elementary system can be represented by one bit of information with "true" being identified with the bit value "1" and "false" with "0". It is then suggested to assume a principle of quantization of information:

*An elementary system carries one bit of information.*

Disregarding the mass, charge, position and momentum of the electron, its *spin* is such an elementary system. If it is prepared "up along *z*", we have used up our single bit and a measurement along any other direction must *necessarily* contain an element of randomness. This randomness must be objective and irreducible. It cannot be reduced to some unknown hidden properties as then the system would carry more than a single bit of information. Since there are more possible experimental questions than the system can answer definitely, it has to "guess". *Objective randomness is a consequence of the principle lack of information.*

In the extreme case when the measurement direction is orthogonal to the preparation, say along *z* when prepared "up along *x*", the system does not carry any information whatsoever about the measurement result. Due to this full complementarity the outcome is completely random. After the measurement, however, the system is found to be in one of the states "up along *z*" or "down along *z*". This new information was spontaneously created in the measurement, while the old information was lost.

Likewise, *entanglement* can easily be understood in a similar way. Entanglement is the strange feature that measurement on one system immediately changes the quantum state of its entangled siblings. This, according to Einstein, "spooky action at a distance" is readily understood by assuming that the *N* bits of information available to describe the *N* entangled elementary systems are used up for defining *joint properties* of the individuals only.

Footing on the foundational principle of finiteness of information represented by elementary systems, the information interpretation of quantum mechanics provides a new way of understanding objective randomness, complementarity and entanglement. Besides this conceptual advantage compared to the Copenhagen interpretation, the information-theoretic approach takes the philosophical world view one step further (leaving the meaning of the state as a catalogue of knowledge untouched): The quantization of nature is a consequence of the quantization of information. Moreover, reality and information are two sides of the same coin. It does not make sense to talk about reality without the notion of information about it, and it is pointless to talk about information without something where it refers to. *What can be said about reality, defines what can exist.*

Let us finally come back to Schrödinger's cat which is a *macroscopic superposition* of "dead" and "alive". We may indeed consider the cat to be constituted by very many elementary systems, each one representing one bit of information. The state of Schrödinger's cat, however, does not carry any information whatsoever for answering the question "Are you dead or alive?" definitely. If this trivial question is posed, which is usually done by opening the "hell machine" and looking at the cat, *the information about life or death has to be created spontaneously in an objectively random way.*

## Box 1: Schrödinger’s Cat and the Copenhagen Interpretation

In 1935, Erwin Schrödinger constructed a “burlesque” *Gedankenexperiment* of a cat in a “hell machine” together with a radioactive atom. After one hour the atom may have decayed but it is equally likely that it has not decayed at all yet. Detection of the decay triggers the destruction of a tiny flask with hydrocyanic acid that is lethally poisoning the cat.

Quantum physics says that after one hour the state of the system is in a *superposition* of the two possibilities that the atom did or did not decay and did or did not kill the cat. If, as was Schrödinger’s point, quantum mechanics also applies for all macroscopic pieces of the apparatus together with the unfortunate cat, the superposition also includes the cat’s states of *“dead” and “alive”*.

Yet, when opening the box after one hour, we will find no superposition, rather, the cat either alive or dead with equal probability. According to the Copenhagen interpretation of quantum mechanics, as long as no – direct or indirect – measurement of the cat’s state was made, *the cat can neither be said to be dead nor to be alive*. Only upon measurement, this reality is “created”. Which possibility becomes factual is *objectively random* and does not have a causal reason. This gap between potentiality and actuality is sometimes referred to as the *measurement problem* of quantum mechanics.

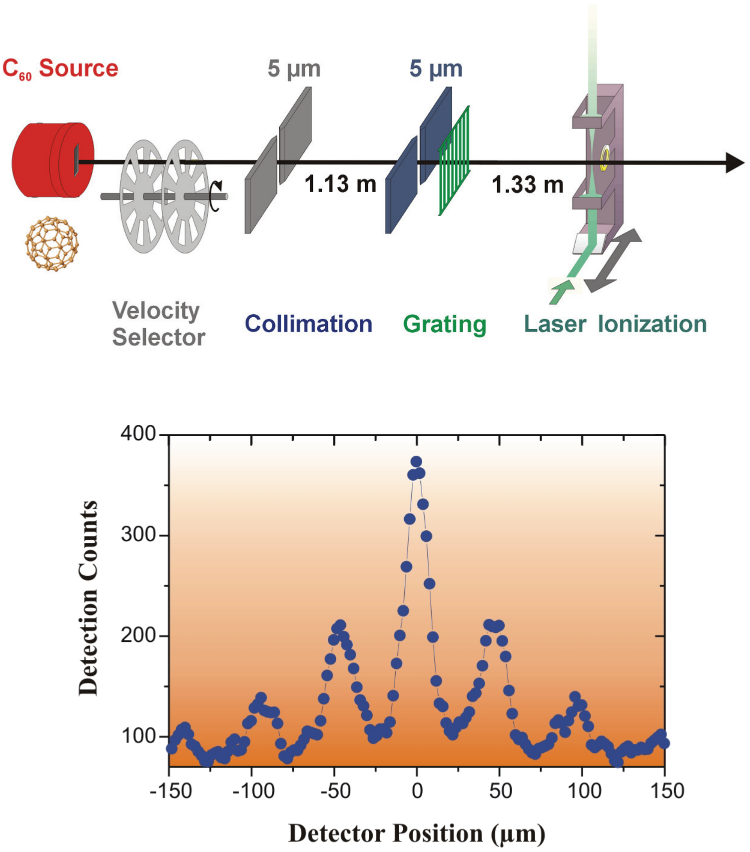
## Box 2: Information in the Stern-Gerlach experiment

In 1922 Otto Stern and Walther Gerlach performed a ground-breaking experiment of physics showing the spin quantization of quantum objects. The spin might be thought as some kind of intrinsic angular momentum or rotation of a particle, represented by a *vector* characterizing the size of the spin and its direction in space.

Consider an individual electron with spin along $x$ incident on the apparatus (Figure 2 top). Classically, we expect it to propagate through the magnet without any influence, as the spin has a vanishing $z$-component. But quantum mechanics predicts, as is confirmed by experiment, that it triggers either detector indicating spin “up” or “down” along the $z$-direction. But which detector will an individual electron trigger? This is objectively random. Quantum mechanics predicts only the probabilities. For a large number of electrons about half will have triggered the upper detector, half the lower one.

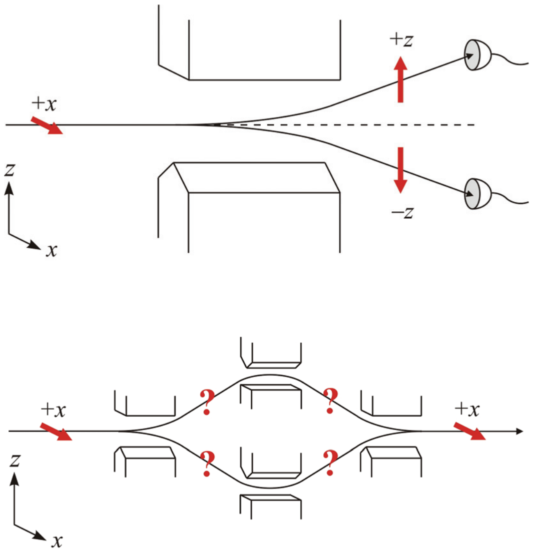
Furthermore does this mean that the spins actually *have* either spin “up” or “down” after leaving the magnet? We can check this by recombining the two beams (Figure 2 bottom). Then an electron emerges which again has its spin oriented along $x$. This is a clear signature of quantum superposition. It only occurs if there exists no possibility whatsoever determining which path the electron took, i.e., which $z$-spin it had. Would we measure the $z$-spin in between, the emerging beam would be just a classical mixture of $+z$ and $-z$ spins.

**Figure 1: Quantum Interference with $C_{60}$ Molecules**



(top) Hot $C_{60}$ molecules (Buckminster fullerenes or “buckyballs”) leave an oven through a nozzle, pass through a velocity selector and two collimating slits, transverse a grating (with a period of 100 nm), and are detected via thermal ionization by a laser. (bottom) According to quantum mechanics, after the grating, the $C_{60}$ molecules are in a superposition of many states, each state corresponding to a particular path through the grating. These paths interfere and produce an interference pattern, where the maxima and minima correspond to constructive and destructive interference, respectively. Most importantly, each molecule “knows” that it should avoid the minima of the interference pattern.

**Figure 2: Information in the Stern-Gerlach Experiment**



(top) In the Stern-Gerlach experiment a beam of electrons passes an inhomogeneous magnetic field oriented along *z*. Such a magnetic field produces a force acting on the spin, depending on the relative orientation of spin and magnetic field, and we are interested in the deflection of the electrons in the *z*-direction due to this force. Classically, an electron with spin along *x* is not deflected and propagates along the dashed line. The experimental result, however, shows that the electron ends up in either detector as shown, never in between. In agreement with quantum theory, this indicates that the spins' *z*-component can only have two values "up" or "down" along *z* even for an incident *x*-spin. (bottom) When the beams are brought together again, the emerging electron recovers the initial *x*-spin if and only if the spin is not measured in between.

## Further Reading

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