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## ***Both quantum and classical – states from the borderland of worlds***

*There is a reason why quantum properties seem extremely exotic: our senses simply cannot see them in the world around us. It turns out, however, that the boundary between exotic quantum reality and classical reality does not have to be as strict as it may seem. Researchers from Cracow, Poland, have shown that there can be quantum states that on one hand exhibit the most characteristic of quantum features, whilst being as close to classical states as is possible in quantum mechanics.*

The everyday, classical world is dramatically different from the world of quantum mechanics. In the former, in principle, everything can be precisely measured and predicted. All classical objects exist here in a specific place in space, in a particular state, and they are not able to react immediately to what is happening to other objects that are distant from them. Meanwhile, in the world of quantum mechanics, instead of certainty, we have only probability. Objects can be in different places and states at the same time and due to the phenomenon of quantum entanglement, they seem to react immediately to what has happened to their partners that can be any distance away from them.

Theoreticians from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Cracow collaborating with mathematicians from the Institute of Mathematics of the Jagiellonian University (IM UJ), however, have shown that both worlds may have more in common with each other than one would suppose. In a publication in *Coherent States and Their Applications: A Contemporary Panorama*, they describe the unique quantum states of a two-particle system simultaneously exhibiting both classical and quantum features.

It is widely believed that in the classical world quantum effects are imperceptible and in describing the classical system they can safely be omitted. Such thinking leads to the naive view that if something behaves classically, it does not behave in a quantum manner – and vice versa. This is not so in reality. The classical world is a world of systems composed of a huge number of quantum objects, and its everyday observable properties are, as the principle of correspondence would suggest, a borderline case of the properties of the latter. Understanding the nature of this borderline is not easy, and physicists still have much to do in this field.

“In our deliberations, we addressed a problem posed over 80 years ago by one of the co-founders of quantum mechanics, Erwin Schrödinger. It deals with the possibility of the co-existence in a single quantum system of properties that are separately considered to be quantum or classical. We tried to find the answer to the question of whether they can occur simultaneously or whether they are mutually exclusive. Together with Prof. Franciszek Szafraniec from the Jagiellonian University’s

Institute of Mathematics we showed that in a system of two quantum particles certain classical and quantum features can indeed coexist amicably,” says Dr. Katarzyna Gorska (IFJ PAN).

The flagship illustration of the non-intuitiveness of the world of quanta is the famous Heisenberg uncertainty principle. It states that for any particle (for simplicity with a fixed mass) it is not possible to simultaneously measure, with any precision, its position or velocity. If we know the exact position of the particle, we will not know anything about its velocity; if we know the exact velocity, we will not be able to indicate the position. Moreover, the uncertainty of the measurements depends on the state in which the particle is, and since quantum particles can be in various states, the uncertainties can be different. States in which the Heisenberg uncertainty principle is minimized are called coherent and are highly similar to states observed in classical systems.

The basic – and at the same time extremely interesting – property of quantum systems is their capability of superposition, that is, being in a state that is a mixture (combination) of certain particular (and at the same time observable) states called base states. In the classical world, such quantum superposition does not exist, but we can try to imagine it with a rather intuitive example: a coin spinning on a table. Here the coin is in a state reminiscent of the superposition of two base states: heads or tails. We can even carry out a “measurement”, that is, press the spinning coin to the table top (or wait for gravity to do this for us). We then destroy the superposition and the coin shifts to one of two, most classical, states: it lies with either heads or tails on top.

“The above analogy is far from complete. The coin is a classical object, and when it spins, heads and tails remain unchanged all the time, and the coin cannot choose between them. So we really have three significantly different states in this system,” explains Dr. Andrzej Horzela (IFJ PAN). “Meanwhile, in quantum superposition there is only one state. Recalling the analogy of the spinning coin, we should see in it some form of head-tails or maybe tails-heads. Something that escapes our imaginations, our classical intuition or maybe even our common sense. And what if our quantum state is additionally a coherent state, and therefore one regarded as closest to the classical states in which we always have either heads or tails?”

Entanglement is considered as being the most important sign of the quantum nature of a system, coherence – as a feature signalling closeness to the classical state. The states found by the Cracow-based physicists are, at least in the mathematical sense, simultaneously coherent and entangled in relation to the entire system of both particles.

“Quantum states of a similar nature have already been considered in the past. They have even been produced experimentally, starting from two coherent states, which were then entangled. The state thus obtained is entangled, but as a whole it does not have to be coherent. Our states are constructed in a way that ensures that they remain simultaneously coherent (i.e. they minimize the uncertainty principle) and entangled. Thus, they can be interpreted as objects that exhibit properties on the one hand close to classical and on the other considered as typically quantum. The manifestation of their quantum nature is that they describe a system of two particles, which cannot be separated even when these particles do not interact with each other,” explains Dr. Horzela.

The result of the Cracow scientists is mathematical in nature. The question remains whether the discovered states can be created in the laboratory. It seems that there are no contraindications preventing their existence. The final answer, however, will only come from experience. The experimentalists, especially scientists dealing with quantum optics, thus have a great scope of activity ahead of them.

The Henryk Niewodniczański Institute of Nuclear Physics (IFJ PAN) is currently the largest research institute of the Polish Academy of Sciences. The broad range of studies and activities of IFJ PAN includes basic and applied research, ranging from particle physics and astrophysics, through hadron physics, high-, medium-, and low-energy nuclear physics, condensed matter physics (including materials engineering), to various applications of methods of nuclear physics in interdisciplinary research, covering medical physics, dosimetry, radiation and environmental biology, environmental protection, and other related disciplines. The average yearly yield of the IFJ PAN encompasses more than 600 scientific papers in the Journal Citation Reports published by the Thomson Reuters. The part of the Institute is the Cyclotron Centre Bronowice (CCB) which is an infrastructure, unique in Central Europe, to serve as a clinical and research centre in the area of medical and nuclear physics. IFJ PAN is a member of the Marian Smoluchowski Kraków

Research Consortium: "Matter-Energy-Future" which possesses the status of a Leading National Research Centre (KNOW) in physics for the years 2012-2017. The Institute is of A+ Category (leading level in Poland) in the field of sciences and engineering.

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#### **SCIENTIFIC PAPERS:**

1. "Coherence, Squeezing and Entanglement: An Example of Peaceful Coexistence"  
K. Górska, A. Horzela, F. H. Szafraniec  
Coherent States and Their Applications. Springer Proceedings in Physics, vol 205. Springer, Cham  
DOI: [https://doi.org/10.1007/978-3-319-76732-1\\_5](https://doi.org/10.1007/978-3-319-76732-1_5)

#### **LINKS:**

<http://www.ifj.edu.pl/>  
The website of the Institute of Nuclear Physics Polish Academy of Sciences.

<http://press.ifj.edu.pl/>  
Press releases of the Institute of Nuclear Physics Polish Academy of Sciences.

#### **IMAGES:**

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Under certain conditions, some quantum states (represented by rotating coins) and classical states (coins lying on the table) may coexist amicably, as demonstrated by scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences and the Jagiellonian University. (Source: IFJ PAN)