Analysis of Principle and State-of-art Implementations of Heisenberg's Uncertainty

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Abstract. As a matter of fact, the Heisenberg's uncertainty principle has important significance and extensive application in microcosmic particle science, is one of the cornerstones of quantum mechanics, proposed by Heisenberg in 1927. The uncertainty principle means that it is impossible to measure a particle's speed and position at the same time. The uncertainty of particle, i.e., the product of uncertainty of position (∆Q) and uncertainty of momentum (∆P), is inevitable greater than or equal to Plank's constant, it expresses the inconsistency between particle behavior in microcosm and macroscopic substance. This study is going to set forth the uncertainty meaning, the research progress of uncertainty principle from the angle of physics, and further exploring the physical significance of Heisenberg's uncertainty principle. According to the analysis, the state-of-art applications will be demonstrated as well as the current limitations and prospects will be discussed. Overall, these results pave a novel path for further investigation in regarding to Heisenberg's uncertainty.

Keywords: Heisenberg's uncertainty, Plank's constant, microcosm and macroscopic substance.

1. Introduction

In retrospect, the German physicist, Werner Heisenberg, put forward the uncertainty principle, was also called paradoxical uncertainty principle. This name is misleading, it will make people think that the particle has certain position and momentum, people cannot measure it accurately. Actually, the uncertainty principle is aimed at showing that some particle physical quantity (for example, position and momentum, energy and time) cannot be accurately determine at the same time. It is the nature of particle that particle cannot has precise position simultaneously, is independent of measurement [1-3]. Therefore, when a particle has a accurate position, its momentum will be not accurate; if the momentum is accurate, the position will be not accurate. It is like holding a water pipe, one pinches more hard, just like the space position be more precise, the water spreads more widely.

In Newton classical theories, if one has advanced measuring tools and techniques, the particle's position and momentum can be measured at the same tine [4]. However, because of wave-particle dualism, particles no longer have a definite position or momentum in quantum mechanics. It's represented as a probability distribution: because of the volatility of particle, its spatial position should be described as the probability wave, and the probability wave can only show the probability of particle appears in some where [5].

The presentation of uncertainty principle marked the ending of Lapras. Its physical meaning means that quantum mechanics already has the complete mathematical form with Heisenberg formula [6-9]:

$$\Delta Q \times \Delta P \geq h/4\pi \tag{1}$$

It also had a rational explanation. The quantum theory has a intrinsic agnostic, one cannot get all the property of a particle at the same time. It is the substantive characteristics of quantum world, which is slightly different from the world of classical physics that one knows. Hawking also mentioned that Heisenberg uncertainty principle is a basic and inevitable property of world in A Brief History of Time, which has far-reaching significance for huamn beings to observe the world [10].

The importance of Heisenberg uncertainty principle is not just in theory, it also was widely applicant in practical usages. It has the essential value in the fields of atomic physics, particle physics, quantum computing and quantum communication. One should use a statistic method to describe the quantum physical system, describing particle's position and momentum by probability distribution.

Uncertainty relations also have important applications in the field of quantum information, such as quantum separability criteria and entanglement detection, security analysis of quantum secret key distribution in quantum encryption, quantum computing, etc. So far, various types of uncertainty relations have been widely studied, including uncertainty relations in the form of product of variance, summation of variance, and entropy [11-13].

2. Uncertainty of the Principle

The Heisenberg uncertainty principle dismissed Newton classical mechanics completely, Newton determinism suggested that everything in our objective world has been fixed be advanced, it's just that one is unable to compute and ensure the state in future. Heisenberg uncertainty principle has the formula listed in Eq. (1). As it entered 21 century, with the development of technology, there were some people pointing out that this principle is not universal, promoting the birth of Professor Ozawa's 'quantum measurement theory'.

The Professor Ozawa, who comes from Japanese Nogoya University, deduce a mathematical formula and verified it has contradiction between Heisenberg uncertainty principle. Ozawa formula is as follows:

$$\Delta Q \times \Delta P + \Delta Q \times \sigma P + \sigma Q \times \Delta P \geq h/4\pi \tag{2}$$

It was proposed in revision uncertainty theory that published in 2003. For Heisenberg inequality, when the position errorΔQ equals 0, the momentum disturbance ΔP will become infinity, so it cannot measure the position and momentum at the same time. Nevertheless, according to the Ozawa inequality, the position and momentum can be measured at the same time (σP or σQ is infinity, as presented in Fig. 1). So, the Ozawa inequality is not only containing the contents of Heisenberg inequality, and it also apply for relation which tested in all experiments [13, 14].

In 2012, Austria Vienna University associate professor Hasegawa's scientific research team reported their experiment in Nature·Physical magazine, this experiment's result also does not conform Heisenberg principle, but conforming to Ozawa inequality. These two discoveries pointed out the basic principle of quantum mechanics, Heisenberg uncertainty principle has a defect, enriching the theory researching of uncertainty relation, and significantly affecting the researching microscopic particle behavior and macroscopic matter, there is strong possibility to play a role in quantum emerging technology.

For example, if one determines the position of an electron in an atom to be on the order of 100pm, the uncertainty in its momentum will be greater than the speed of light, making measurements impossible and meaningless. It is worthy noted that the uncertainty principle does not refer to the error of the measurement instrument or the error of the measurement method. This uncertainty is inherent. A model can be considered problematic if it violates the uncertainty principle, such as Bohr's model of the circular orbit of an electron. The uncertainty principle has an individual name called "uncertainty principle", completely wrong translation, it is not (the instrument is too bad) the measurement experiment itself is not accurate, but the internal cause is not accurate.

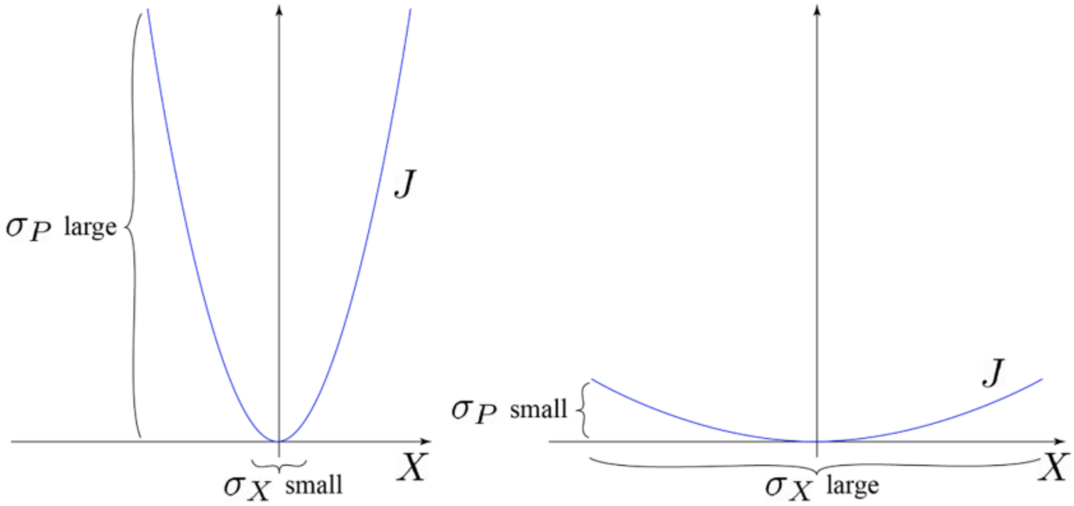

Figure 1. A trade-off between the two values [14].

In some early textbooks, the uncertainty principle is described as the uncertainty principle, but in fact, the uncertainty principle does not involve the measurement problem, and it is not the limitation brought by the measurement, but the principle of quantum mechanics itself, and the uncertainty principle is the inevitable result of wade-particle duality. Boel had a deeper view of the uncertainty principle. He believed that the key to the interpretation of quantum theory was to combine the contradictory wave theory and particle theory. The uncertainty principle was to give the degree to which both descriptions could be applied without falling into contradiction, and the uncertainty principle "protected" quantum mechanics.

A common way of saying this is that you can't accurately measure both the momentum and position of a particle at any given point in time. This uncertainty does not depend on the measurement device or the environment. No matter how well mankind does, it is impossible for us to know the exact values of these two quantities. Firstly, there are multiple uncertainty principles, many of which manifest in the macroworld. In fact, you encounter them all the time, you just don't realize it. Second, the fundamental reason behind Heisenberg's uncertainty principle has nothing to do with quantum physics, but with mathematics. Uncertainty can also explain why the sun shines, or even why the space-time phenomenon of Hawking radiation shrinks black holes. Uncertainty is a purely mathematical phenomenon, but since quantum systems implement some of these mathematical theories, uncertainty is also a physical principle.

3. State-of-art Applications

The quantum uncertainty principle has made new progress in domestic. Heisenberg uncertainty principle shows the incompatibility of different atoms, for this topic, the research has been very systematic and further, and its result has become the basic of quantum information science and quantum measurement. However, the joint measurement of multiple objects has been a long term question. Mao Liya and other researchers have studied this issue in depth from 2019, they cooperated with Professor Yu Sixia, who comes from University of Science and Technology of China, developing the theory and the tool of convex optimization, first discovered the lower bound of joint measurement of multiple physical quantities and corresponding quantum states and experiment measuring operator, invented an innovative measuring tool. In addition, they discussed the relation between multiple physical quantities and continuous measurement and joint measurement further.

This researching result broaden the researching range of Heisenberg’s uncertainty principle, enriching the cognition of quantum mechanics, and providing a new tool to quantum precision measurement, the product of random quantum number and other quantum information science researching orientation.

In a word, Heisenberg uncertainty principle is one of the very important principles in quantum mechanics. It reveals the wonderful and complex microcosmic world, lets one realizes the internal connection between physical quantities, and provides guidance for human beings in the design of quantum computers, quantum communication and other fields. Although the uncertainty principle may seem confusing, it has become one of the foundations of modern science and profoundly affects our knowledge and understanding of the natural world. The application area of Heisenberg's uncertainty principle is very wide, here are some of the main application areas:

- Quantum Mechanics. One of the foundations of quantum mechanics is the uncertainty principle, which is a key principle to explain the behavior of the microscopic world. The uncertainty principle applies not only to the position and momentum of particles, but also to other physical quantities such as energy and time.
- Quantum Computing. The uncertainty principle is one of the foundations for designing quantum computers and quantum algorithms. In quantum computing, the uncertainty principle can help us better understand the behavior of quantum systems and design more efficient algorithms.
- Materials Science. The uncertainty principle can help us better understand the properties and behavior of materials. For example, in materials science, the uncertainty principle can be used to explain the behavior of electrons in materials and thus help us design more efficient electronic devices.
- Communication Technology. The uncertainty principle can help us design more efficient communication systems. For example, in communication technology, the uncertainty principle can be used to explain the behavior of noise and thus help us design better noise reduction algorithms.
- Biomedicine. The uncertainty principle can help us better understand the behavior of living systems. For example, in biomedicine, the uncertainty principle can be used to explain the behavior of proteins and thus help us design better drugs.

In summary, the Heisenberg uncertainty principle is a very important principle, which has a wide range of applications in various fields. With the continuous development of science and technology, it is believed that the application fields of the uncertainty principle will continue to expand.

4. Limitations and Prospects

Nevertheless, it should be noted that there are some retrodictions for the Heisenberg uncertainty based on some novel concepts as well as designs (e.g., shown in Fig. 2). The accuracy of a precise measurement increases with the consumption of resources, which is mathematically described by t-k, where T is the resource (such as measurement time), and k is the most important standard order of accuracy growth to evaluate the pros and pros of different measurement methods. In numerous applications such as phase estimation, magnetometers, and quantum gyroscopes, k has been found to be 0.5 and 1 for the classical and quantum measurement methods, which are called the shot noise limit and the Heisenberg limit, respectively. However, in the presence of many-body interactions or time-dependent evolution, it has been found that k can exceed 1, which is called the "super-Heisenberg limit". At present, these three different precision limits have been realized in single-parameter quantum measurement experiments, but the Heisenberg uncertainty relation is the fundamental limit of quantum mechanics, and whether the "super-Heisenberg limit" is really super-Heisenberg is still controversial.

Using the multi-parameter quantum precision measurement platform developed in recent years, researchers have studied whether the "super-Heisenberg limit" and the Heisenberg limit can be achieved simultaneously in the two parameters of the intensity and frequency of the measured rotation field. By optimizing all parts of the dynamic evolution of the quantum system, they achieved the optimal measurement with two parameters simultaneously reaching the Heisenberg limit and the "super-Heisenberg limit", respectively. They also showed that these two precision limits obey the Heisenberg uncertainty relation, and are both optimal quantum precision limits.

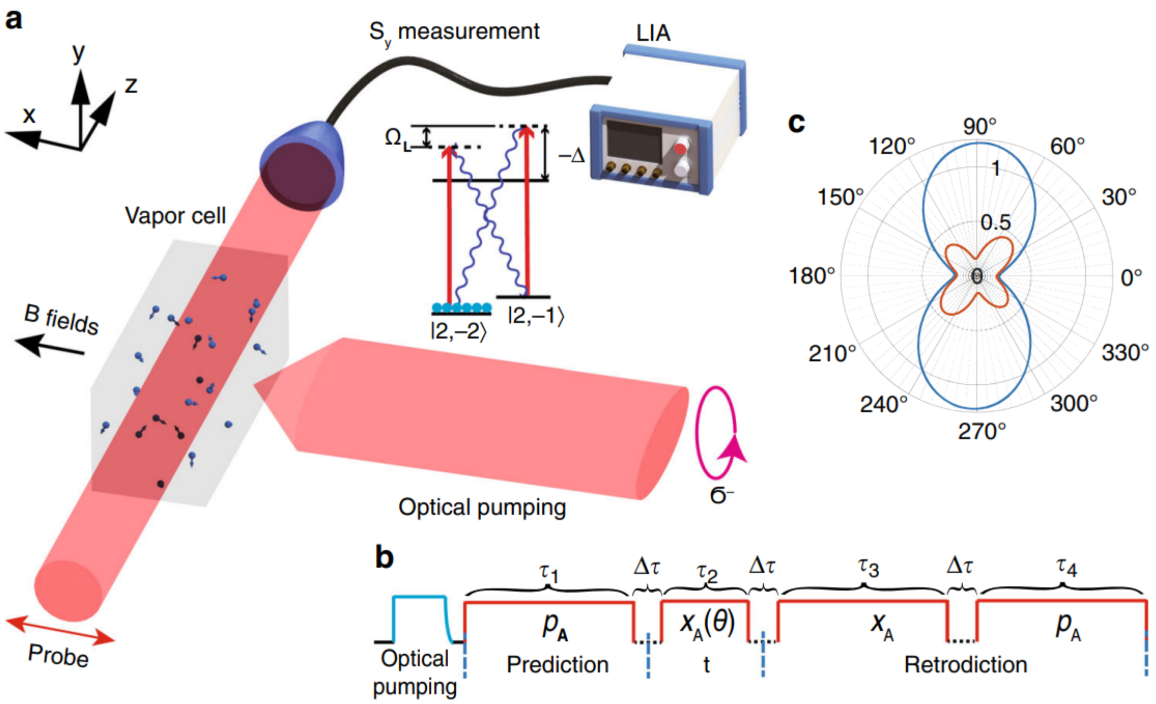

Figure 2. Retrodiction of Heisenberg uncertainty [15].

5. Conclusion

To sum up, Heisenberg's uncertainty principle is a deduction of quantum mechanics system, which means that one cannot finding the position and momentum of particles at the same time, pointing out the probability feature is an essential phenomenon of microscopic particle. Nevertheless, it should be noted that Einstein believed that quantum mechanics can only describe the probability feature of microcosmic object, which means that quantum mechanics is not adequate; Bohr Considered that quantum is a complete system. Nowadays, with the advance of technology, there are many views were proposed, the quantum probability measurement has been broken through. The discussion which lasted for about 90 years produces lots of valuable results, such as quantum communication. Reflecting and questioning this discussion, one can have a better understanding of microcosmos and pursue development in a scientific way.

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