Aalto University
LC-1117-Integrated Oral and Written Skills

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Introduction to Quantum Cheshire Cat

The field of quantum physics is difficult to understand intuitively. Particles, which one tends to imagine as small billiard balls, are in fact described by a superposition of quantum states. This implies that one particle can take two paths at once and interfere with itself like a wave. The field has many seemingly paradoxical phenomena that it may almost be called a wonderland, where physicists are in a continuous search for understanding of the universe. And they have even found a Cheshire Cat!

The Cheshire cat is a famous character from the novel “Alice's Adventures in Wonderland” by Lewis Carroll. [**1**] This peculiar cat is characterized by its mischievous grin, which is left floating in the air as the cat slowly disappears, i.e., the Cheshire Cat and one of its properties can be separated. Surprisingly, an analogical phenomenon has been discovered by current research in quantum mechanics. [**2**] [**3**] The authors have created an experiment, which seems to show evidence for separation of neutron from its spin.

The experimental setup [**2**], depicted in Figure 1, has a structure of a basic interferometer with a few additional pieces. A beam of neutrons enters the apparatus from the left and splits into two equal parts. Path I is the “lower path”, and path II is the “upper path”. After splitting, both beams travel through a spin rotator (SRs), whose effect is to transform the spin into $|S_x, + >$ on path I and into $|S_x, - >$ on path II. Then the beams reflect and come to a phase shifter (PS), which is used to change the relative phase of the beams. Next, the beams combine and the resulting beam is affected by a post-selector device (ST2 + A) that filters out all the $|S_x, + >$ states. Finally, the intensity of the beam is measured by a detector (O-Det.). In addition, the setup has a H-detector for measuring the intensity unaltered by the post-selector.

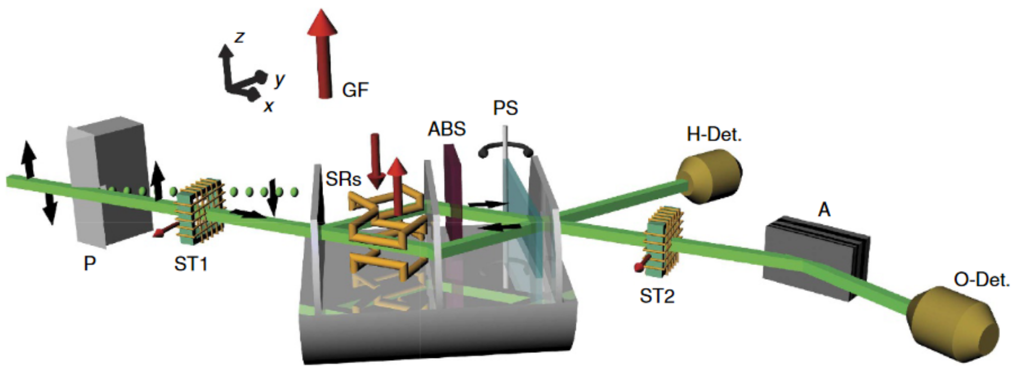

Figure 1: Denkmayer et al. [**2**]

As in most interference experiments, the result is a phase-intensity graph, commonly referred to as an interference pattern. However, the pattern generated by the described setup is a constant line. The intensity is independent of the relative phase. This is caused by a relation between the states $|S_x, + >$ and $|S_x, - >$. Their inner product is zero, i.e., the states are orthogonal. The implication, predicted by the theory of quantum mechanics, is that there is no interference between the states, thus resulting in a constant interference pattern.

The experiment [**2**] itself has two main parts each consisting of two steps. In the first part, a weak absorber is placed in front of the upper path and the arising interference pattern is recorded. The procedure is then applied to the lower path. The results of the first part, obtained by the authors, are shown in Figure 2. As expected, both patterns are still constant, but the intensity is lowered when the absorber has been positioned on path II. Hence, all the particles arriving at the detector must come from the upper path, since the absorber has no effect on the intensity when placed on the lower path.

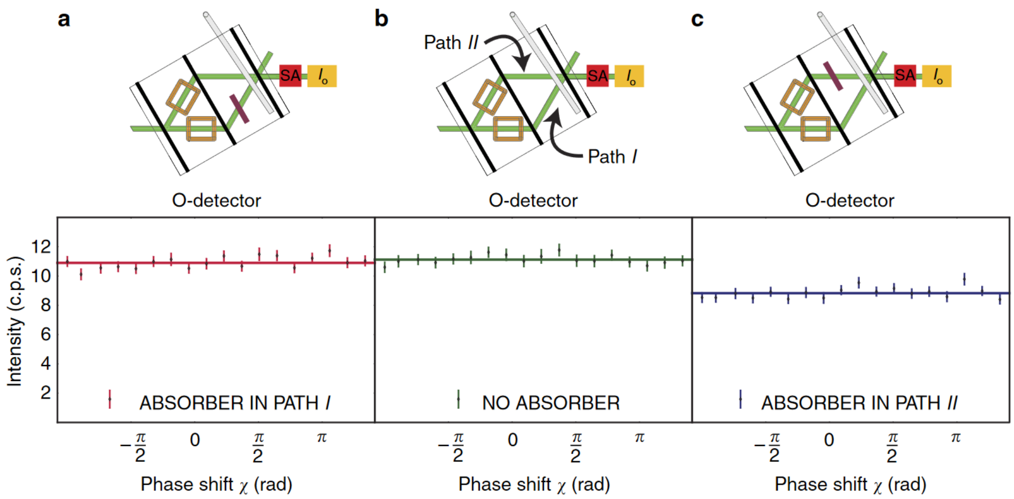

Figure 2: Denkmayer et al. [2]

In the second part of the experiment the absorber is replaced by a weak magnet. The produced magnetic field may then influence the spins of the neutrons. In general, magnetic fields are the best tool to study spin experimentally, because the spin causes the neutron to have a magnetic moment, which then reacts to external magnetic fields. The weak magnetic field has a probabilistic effect on the travelling neutrons. It converts $|S_x, + >$ state into $|S_x, - >$ with some nonzero probability, but leaves the state usually unaltered. The results are shown in Figure 3.

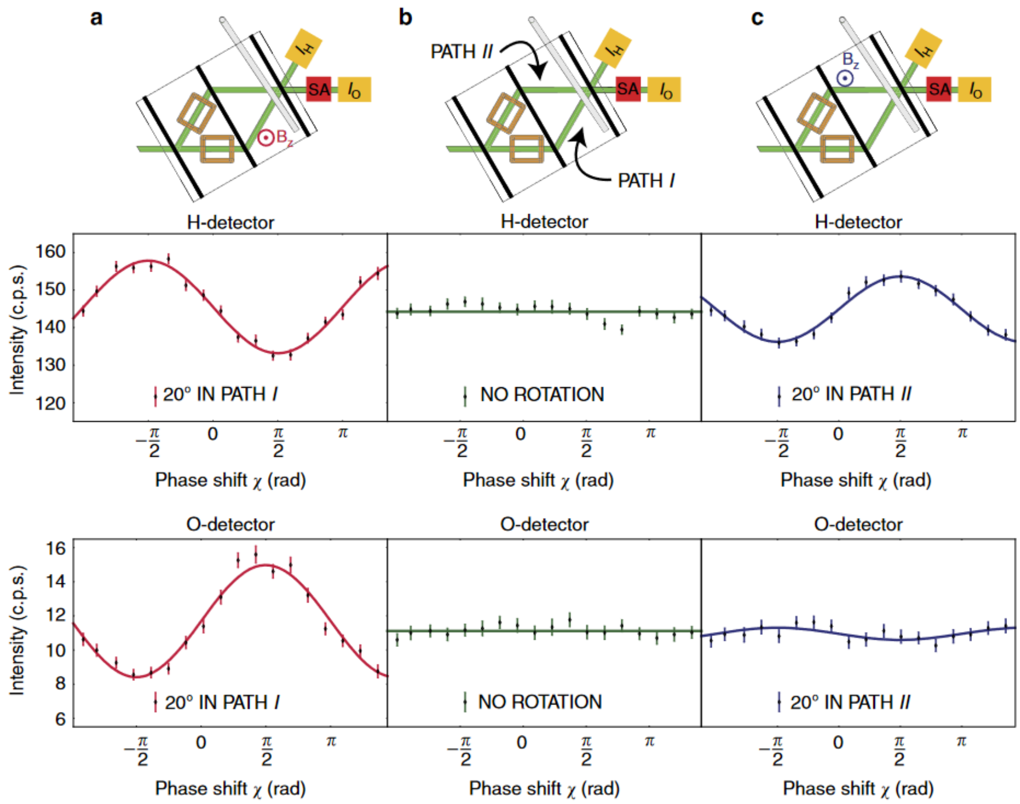

Figure 3: Denkmayer et al. [2]

Unexpectedly, no change in the pattern occurs when the magnet is placed on the upper path, although all the detected particles were previously confirmed to take this path. Even more astonishingly, a strong sinusoidal interference pattern is formed when the magnet is moved on the lower path. Thus, the spins must follow path I and not path II. In other words, the spin has been separated from the neutron. The Cheshire Cat has been caught.

Denkmayer et al. propose that the observed phenomenon generalizes to other quantum systems. They also suggest the use of the phenomenon in making precise observations of quantum systems. They give an example of a scenario, in which the magnetic moment disturbs the precise measurement of another property. The solution would be to apply the quantum Cheshire Cat (QCC) effect.

After the publication of the effect, many physicists have taken a critical view towards it. [**4**] [**5**] The problem lies in the second part of the experiment, in which a weak magnetic field is used to rotate neutron spins. The method is part of the discipline of weak value observations. A recent publication [**4**] concludes that the theoretically predicted QCC phenomenon has not yet been confirmed experimentally, because experiments have not properly implemented the weak measurement protocol. Therefore, new and fresh ideas are needed to invent an experiment, to finally catch the mischievous quantum Cheshire Cat.

References

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