Mysterious quantum Cheshire cat: an illusion

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ABSTRACT

We provide a mystery-free explanation for the experimentally observed facts in the neutron interferometry quantum Cheshire cat experiment of Denkmayr *et al.* [Nat. Comm. 5, 4492, 2014] in terms of a discrete-event simulation model, demonstrating that the quantum Cheshire cat is an illusion.

Keywords: Quantum Cheshire cat, quantum theory, weak measurement, discrete event simulation, single neutron interferometry

1. INTRODUCTION

The Cheshire cat, a grinning cat with mysterious behavior, is one of the characters in the novel "Alice's Adventures in Wonderland" by Lewis Carroll.[1] In this children's story the Cheshire cat is able to slowly vanish beginning with the end of its tail, and ending with its grin, which remains for some time after the rest of the cat has disappeared.

This disembodiment of the cat and her grin inspired Aharonov *et al.* to introduce the concept of a quantum Cheshire cat in the form of a circularly polarized photon, whereby the photon represents the cat and its polarization state the grin.[2] Aharonov *et al.* showed analytically that measuring weak values for the location of the photon and its polarization in a pre- and postselected experiment, the photon can be disembodied from its polarization.[2] According to Aharonov *et al.* the quantum Chesire cat effect is quite general, that is physical properties can be disembodied from the objects they belong to in a pre- and postselected experiment.[2] Soon after the introduction of the quantum Cheshire cat by Aharonov *et al.* proposals for more sorts of quantum Cheshire cats made their appearance in the literature.[3–6]

Quite recently, Denkmayr *et al.* performed weak measurements to probe the location of a neutron and its magnetic moment (z-component only) in a neutron interferometry experiment to demonstrate the quantum Cheshire cat effect.[7,8] In Refs.[7,9] Hasegawa and co-workers give various interpretations of their experimental observations and point out that weak interactions between the probe and the neutron and its magnetic moment have observational effects on average so that it seems as if the neutron and its magnetic moment are spatially separated. These interpretations, not the outcome of the experiment itself, have been criticised on various grounds.[10–13] In this paper, we provide a mystery-free explanation for the experimentally observed facts in terms of a discrete-event simulation (DES) model which reproduces the data of the neutron experiments.[7] We demonstrate that the quantum Cheshire cat is an illusion.

The paper is structured as follows. Section 2 describes the neutron interferometry experiment of Denkmayr *et al.* We explain how, on the basis of the interference patterns that are observed after many neutrons traveled through the interferometer, one could come to the conclusion that neutrons and the z-component of their magnetic moments take different paths in the interferometer. In Section 3, we introduce a DES model for the experiment and show that there exists another, non-mysterious, description in which many neutrons (together with their magnetic moment) travel one-by-one through the interferometer thereby taking only one path or the other and thereby building up count-per-count the interference patterns as those observed in the experiment. Section 4 contains the conclusions and a discussion.

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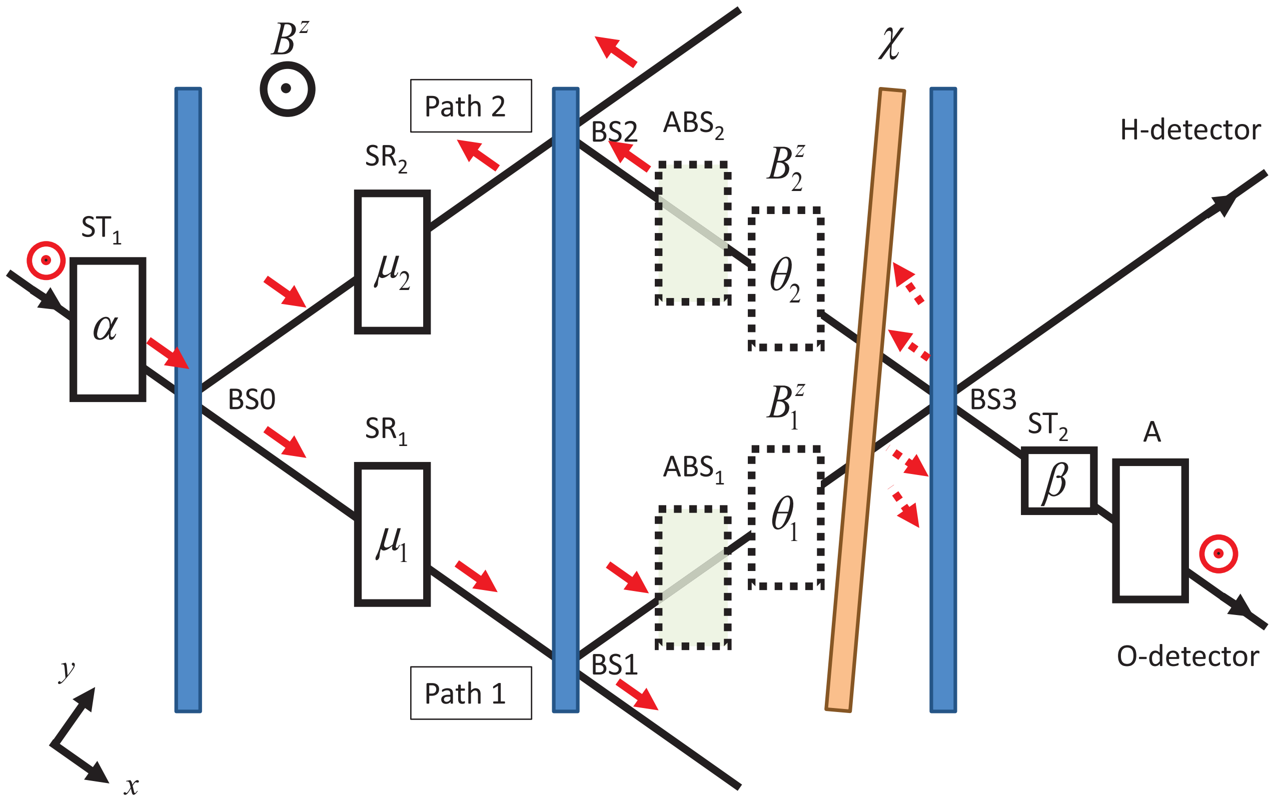

Figure 1. Schematic picture of the single-neutron interferometry experiment for observing the quantum Cheshire cat effect.[7] Polarized neutrons with their magnetic moments aligned parallel to a magnetic guide field B^z first enter a spin turner (ST_1), which rotates the magnetic moment by $\alpha = \pi/2$ about the y-axis before they enter a triple-Laue interferometer.[14] BS0, ..., BS3: beam splitters; neutrons that are transmitted by BS1 or BS2 leave the interferometer; SR_1 and SR_2: spin rotators for rotating the magnetic moment about the z-axis by $\mu_1 = 0$ and $\mu_2 = \pi$, respectively; phase shifter χ: aluminum foil; ABS_1 and ABS_2: absorbers which for weak measurement of the neutron location can be placed in path1 and path 2 (indicated by the dotted lines), respectively; B_1^z and B_2^z: weak additional magnetic fields which for weak measurement of the location of the magnetic moment of the neutron can be applied in path 1 and path 2 (indicated by the dotted lines) for rotating the magnetic moment about the z-axis by θ_1 and θ_2, respectively. For the purpose of postselection a spin turner ST_2 rotating the magnetic moments of the neutrons by $\beta = \pi/2$ about the y-axis and a spin analyzer A is put in the O-beam. Detectors count the number of neutrons in the O- and H-beam. Little (dashed) arrows indicate the orientation of the magnetic moments of the neutrons in the various stages of the interferometer.

2. QUANTUM CHESHIRE CAT EXPERIMENT WITH NEUTRONS

Figure 1 shows a schematic picture of the single-neutron interferometry experiment for demonstrating the quantum Cheshire cat effect.[7] A beam of polarized neutrons with their magnetic moments aligned parallel to the magnetic guiding field **B** oriented along the z-axis, enters a spin turner (ST_1) which rotates the magnetic moment of the neutrons by $\alpha = \pi/2$ about the y-axis such that they become aligned along the x-axis. On leaving the spin turner, the neutron beam impinges on a

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triple-Laue diffraction type silicon perfect single crystal interferometer.[14] The four beam splitters BS0 ... BS3 in the interferometer are identical and have a reflectivity $R = 0.22$ and transmissivity $T = 1 - R = 0.78$. The value of $R = 0.22$ is obtained from a fit of the DES simulation data to the experimental data for the neutron interferometry experiment with a setup only containing the neutron source, a triple-Laue interferometer and two detectors to measure the neutron counts in the O- and H-beam.[15–18] Beam splitter BS0 splits the beam of neutrons with their magnetic moments pointing in the x-direction in a beam following path 1 and one following path 2. Behind beam splitter BS0 and in front of beam splitters BS1 and BS2, spin rotator SR_1 (SR_2) in path 1 (2) rotates the magnetic moment of the neutrons by $\mu_1 = 0$ ($\mu_2 = \pi$) about the z-axis so that they are aligned along the x ($-x$) axis. This corresponds to the preselection process of the weak measurement procedure. Neutrons that are transmitted by beam splitters BS1 and BS2 leave the interferometer and are not considered any further. Behind BS1 and BS2 absorbers ABS_1 and ABS_2 with transmissivity $T_1 = T_2 = 0.79$ can be inserted or additional magnetic fields B_1^z and B_2^z rotating the neutrons' magnetic moments by $\theta_1 = \theta_2 = 20^\circ$ can be applied for the weak measurement of the location of the neutrons or their magnetic moments, respectively.[7] These parameter choices fulfill the condition of a weak measurement, the idea being that due to the weakness of the local coupling between the system and the measurement device, a probe, the subsequent evolution of the system is not significantly altered.[7] A rotatable-plate phase shifter (e. g. aluminum foil[14]) in front of beam splitter BS3 tunes the relative phase χ between path 1 and path 2. BS3 takes as input the two neutron beams following path 1 and path 2 and produces two output beams called the O-beam and H-beam. Neutrons in the H-beam are immediately detected while neutrons in the O-beam undergo a postselection process depending on their magnetic moments. In the postselection process neutrons first pass through spin-turner ST_2, rotating the magnetic moment by $\beta = \pi/2$ about the y-axis, and a spin analyzer A, selecting neutrons with their magnetic moments parallel to the guiding field, before being detected. The neutron detectors have a detection efficiency over 99%.[14] We refer to the interferometer without absorbers ABS_1 and ABS_2 and extra magnetic fields B_1^z and B_2^z as the "reference interferometer". Very important is that the neutron interferometry experiment is performed under the condition that there is at most one neutron in the interferometer while producing, after many single neutron passages through the interferometer, the same interference patterns as if a beam of neutrons would have been used.[14]

The experimental results (kindly provided to us by T. Denkmayr) are presented in Fig. 2 (red circles). The upper two rows of panels clearly show that placing an absorber in path 1 has no effect on the intensity measured by the O-detector, while placing the same absorber in path 2 leads to a reduction of this intensity compared to the one of the reference interferometer.[7] Adopting the reasoning of Denkmayr *et al.*, it seems as if the neutrons follow path 2 in the interferometer. However, for the respective intensities measured by the H-detector we observe that placing an absorber in path 1 or path 2 has a similar effect, namely a reduction of the intensity measured by the H-detector compared to the one of the reference interferometer. If we were to adopt the same reasoning to the H-detector data, then the conclusion would be that neutrons follow path 1 and path 2. Obviously, this reasoning leads to a picture that is self-contradictory. However, in the H-beam the neutrons are not postselected whereas successful postselection is a necessity for the picture to hold.[7]

Following Denkmayr *et al.*, which-way information about the magnetic moment of the neutrons can be obtained by replacing the absorbers by magnetic fields rotating the magnetic moment by a small angle about the z-axis. A magnetic field in one of the paths ensures that the magnetic moments of the neutrons traveling path 1 and path 2 are no longer orthogonal, implying that it is possible to observe interference. As seen from the lower two rows of panels in Fig. 2, a small magnetic field rotating the magnetic moment by 20° in path 1 leads to a periodic variation with significant visibility of the intensities as a function of χ at the O- and H-detector. A small magnetic field in path 2 instead of path 1 leads to a variation with χ of the intensity at the H-detector only. The intensity at the O-detector shows no variation with χ. Based on the changes in the intensity pattern recorded by the O-detector Denkmayr *et al.* argue that the magnetic moments of the neutrons follow path 1.[7] If we were to apply the same reasoning to the H-detector data, then this conclusion cannot be drawn since a periodic variation of the intensity pattern is observed for both cases. In other words, the H-detector data would suggest a picture in which the magnetic moments of the neutrons follow path 1 and/or path 2. As in the case of the weak measurement of the neutron location, the picture that emerges is self-contradictory, but again, in experiment no postselection is performed in the H-beam.[7]

A full quantum theoretical analysis of the above described neutron interferometry experiments shows that quantum theory gives a qualitative description of the observed interference patterns.[18] However, quantum theory cannot give any explanation for the fact that these interference patterns are built up count-by-count. Thus, both the successfully postselected O-beam data and the rigorous quantum theoretical analysis seems to suggest that the neutrons behave as if they were a quantum Cheshire cats. Namely, in the interferometer neutrons and their magnetic moments (z-component only) seem to

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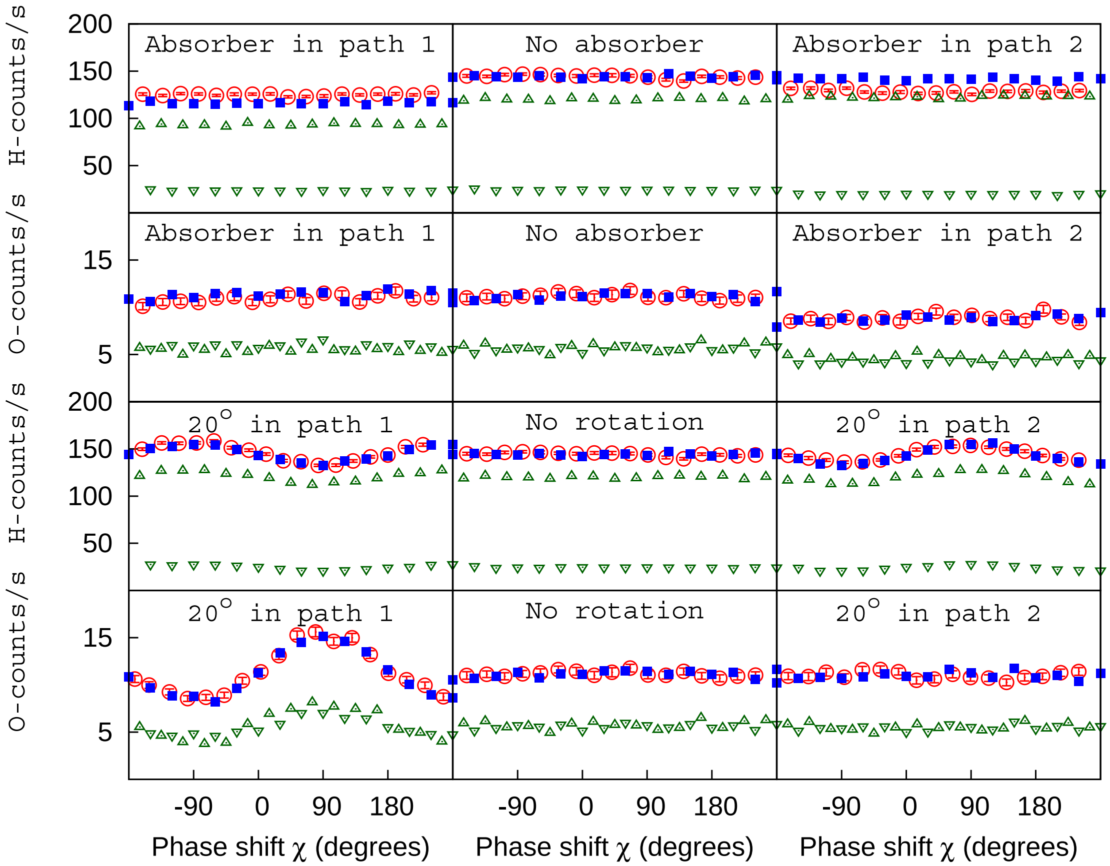

Figure 2. Comparison between the experimental data (open circles with error bars), kindly provided to us by T. Denkmayr, and DES data (solid squares) of the neutron Cheshire Cat experiment.[7] The intensities are given in counts per second. The neutron count in the DES (solid squares) is the sum of the number of neutrons traveling along path 1 (up triangles) and the number of neutrons traveling along path 2 (down triangles). The DES data are normalized by the experimental data obtained for the reference interferometer, i.e. without absorber or rotation. Model parameters: left column, top two rows: $T_1 = 0.79$, $T_2 = 1$, $\theta_1 = \theta_2 = 0$; left column, bottom two rows: $T_1 = T_2 = 1$, $\theta_1 = 20^\circ$, and $\theta_2 = 0$; middle column: $T_1 = T_2 = 1$ and $\theta_1 = \theta_2 = 0$ right column, top two rows: $T_1 = 1$, $T_2 = 0.79$, $\theta_1 = \theta_2 = 0$; right column, bottom two rows: $T_1 = T_2 = 1$, $\theta_1 = 0$, and $\theta_2 = 20^\circ$. Simulation parameters: $\gamma = 0.65$ (see Refs.[15–17]), number of incident neutrons: $N = 72000$, reflectivity of beam splitters: $R = 0.22$.

travel different paths. Note that this picture still holds if an absorber is put in one path and the additional magnetic field in the other and if both an absorber and additional magnetic field are put together in one of the paths.[18] Therefore, the picture that the neutrons and their magnetic moments take different paths in the interferometer is not a result of counterfactual reasoning[2] for the given parameter settings. Thus, following Aharonov *et al.* it may seem that in the interferometer the neutron really becomes disembodied from the z-component of its magnetic moment. This by itself is quite mysterious and requires a rational explanation. However, also the observation that the ensemble needs to be successfully postselected in order to come to this conclusion is mysterious. How is it possible that the future influences the past? This phenomenon reminds of other quantum mysteries like Wheeler's delayed choice and quantum erasure experiments.[19,20]

3. DISCRETE EVENT SIMULATION MODEL

We employ DES, a general form of computer-based modeling that provides a flexible approach to represent the behavior of complex systems in terms of a sequence of well-defined events, to unravel the mystery of the quantum Cheshire cat in the neutron interferometry experiment. In DES the sequence of events is modeled by operations being performed on entities of certain types. The entities are passive (in contrast to agents in agent based modeling) and can have attributes. Typically,

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many details about the entities are ignored. The attributes affect the way entities are handled and they may change as the entity flows through the process.

We use DES to construct an event-based model that reproduces the statistical distributions of quantum theory by modeling physical phenomena as a chronological sequence of events whereby events can be the actions of an experimenter, particle emissions by a source, signal generations by a detector, interactions af a particle with a material and so on. The general idea is that simple rules define discrete-event processes which may lead to the behavior that is observed in experiments, all this without making use of the quantum theoretical prediction of the collective outcome of many events. Evidently, mainly because of insufficient knowledge, the rules are not unique. Hence, the simplest rules one could think of can be used until a new experiment indicates otherwise. Reviews of the method and its application to single-photon experiments and single-neutron interferometry experiments can be found in Refs.[15–17, 21]

A DES of the experiment of Denkmayr *et al.* requires rules for the neutrons and for the various units in the diagram (see Fig. 1) representing the neutron interferometry experiment. We regard a neutron as a messenger (called entity in DES) carrying a message (called attribute in DES). From experiments we know that a neutron has a magnetic moment and that it moves from one point in space to another within a certain time period, the time of flight. Hence, we encode both the magnetic moment and the time of flight in the message. For the technical details we refer to Ref.[16] The neutron source creates messengers one-by-one. The source waits until the messenger's message has been processed by one of the detectors before creating the next messenger. Hence, the messengers cannot directly communicate, but only indirectly through the units in the diagram (see Fig. 1). The messengers interact with the various units representing the beam splitters, the spin turners, spin rotators, absorbers, magnetic fields, phase shifters and spin analyzers. Each of these units interpret, and eventually process and change (part of) the message carried by the messengers. The specific simple rules that each of these units use to emulate their real-world behavior for many neutrons passing through the unit is given in Refs.[15–17] Finally, the messengers trigger one of the detectors in the O- or H-beam. These detectors count all incoming messengers and hence have a detection efficiency of 100%. This is an idealization of real neutron detectors which can have a detection efficiency of 99% and more.[14] Upon detection the messenger is destroyed.

In Fig. 2 we present a comparison of the experimental and DES data of the neutron quantum Cheshire cat experiment. The DES data are generated for 72000 incoming neutrons and are normalized with respect to the experimental data for the reference interferometer. Apart from some small deviations (caused by some experimental details; private communication with T. Denkmayr) in the upper row of panels, the agreement between experimental and simulation data is excellent. Hence, applying the same reasoning as described in the previous section to the DES data obviously leads to the same mysterious conclusion of neutrons behaving as quantum Cheshire cats. However, in the DES we know exactly what the messengers (the neutrons) do in the interferometer: a neutron and its magnetic moment never separate and a neutron follows a definite trajectory, that is it follows either path 1 or path 2. This is also illustrated in Fig. 2 by indicating how many of the neutrons counted by the O- and H-beam detectors have been following path 1 (up triangles) and path 2 (down triangles). From the O-beam data, it is clear that the contributions from path 1 and path 2 to the total count are roughly the same. This is different for the H-beam data, because in the H-beam no postselection on the basis of the magnetic moment is performed. In other words, in the DES the neutron and its magnetic moment never separate and each neutron follows either path 1 or path 2.

4. SUMMARY

We have demonstrated that there exists a non-mysterious scenario in which many neutrons (together with their magnetic moment) travel one-by-one through the interferometer thereby taking only one path or the other that results in the same interference patterns as those observed in the experiment. Since no real which-way information can be obtained from the experiment one has the choice to adopt one or the other scenario. One can adopt the mysterious description of the experiment with the neutrons acting as quantum Cheshire cats whereby the neutrons seem to travel different paths as the z-components of their magnetic moments or one can adopt the rational description with the neutrons together with their magnetic moment simply taking one path or the other. Hence, although the quantum Cheshire cat is not a paradox of counterfactual reasoning, in contrast to the statement made by Aharonov *et al.* that there really is a quantum Cheshire cat,[2] the Cheshire cat is nothing else than an illusion.

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