Scientific Background and results of previous works

Since the first definition by Y. Aharonov, D. Albert, and L. Vaidman[1], weak values have gained an important role in the field of quantum physics. In particular, they have been shown to be strictly related to many fundamental concepts of quantum mechanics, such as: uncertainty relations[8], negative quasi-probability distributions[6], quantum paradoxes[12], and more[5]. Weak values are also an extremely valuable experimental asset, allowing quantum signal amplification for sensitive measurements, wave-function tomography and experimental study of non-classical features [6].

Neutron interferometry has historically been a pillar in studying the foundations of quantum phenomena and weak values[4;9;3]. In a previous experiment performed at S18, we have successfully demonstrated that the full path weak value (real and imaginary part) from a two-path interferometer can be extracted from measurement of the intensity for different relative phases between the paths, i.e. interferograms. The method uses a basic Mach-Zehnder setup and does not require auxiliary quantum states, e.g., spin. The absence of spin manipulation and analysis is a great advantage in neutron interferometry as it preserves a high neutron flux, saving up to an order of magnitude. The effectiveness of the method can be observed in the results presented in Fig. 1.

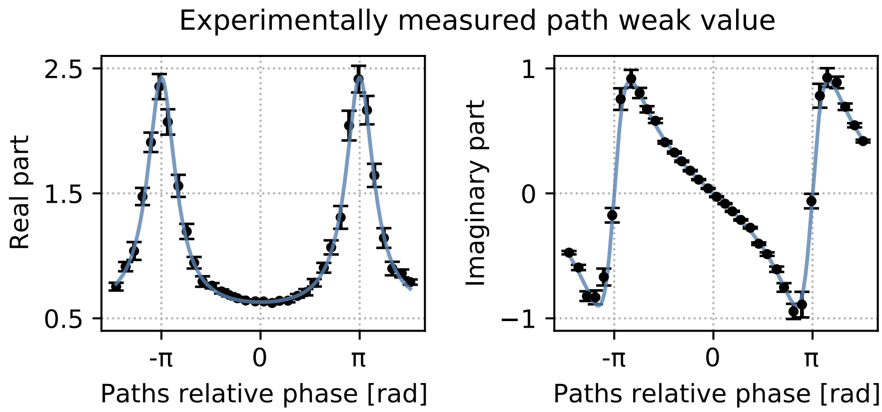

Figure 1: *Resulting weak values (data points) compared with the theoretical prediction (continuous line), plotted as their real and imaginary part for the different values of the relative phase between paths in the initial state.*

Aims and procedures

The first aim of this proposed experiment is to demonstrate that the aforementioned method can be extended to a three-path interferometer, allowing for the study of a three-level quantum system, i.e. a qutrit. The properties of qutrits are of high interest in the field of quantum information and computation[10;7]. The second aim is to use obtained results to investigate a surprising quantum phenomena linked to qutrits: the three-box paradox[2]. In this quantum paradox, we consider a particle pre-selected in an superposition $|\psi\rangle$ of three "boxes" which is successively post-selected in the state $|\phi\rangle$, with

$$|\psi\rangle = \frac{1}{\sqrt{3}}\left(|1\rangle + |2\rangle + |3\rangle\right) \qquad \text{and} \qquad |\phi\rangle = \frac{1}{\sqrt{3}}\left(|1\rangle + |2\rangle - |3\rangle\right) . \tag{1}$$

For a successful post-selection, if we compute the probabilities of finding the particle in box 1 or in box 2 in between states, we get

$$P_1 = \frac{|\langle\phi|\hat{\Pi}_1|\psi\rangle|^2}{|\langle\phi|\hat{\Pi}_1|\psi\rangle|^2 + |\langle\phi|1-\hat{\Pi}_1|\psi\rangle|^2} = 1\,, P_2 = \frac{|\langle\phi|\hat{\Pi}_2|\psi\rangle|^2}{|\langle\phi|\hat{\Pi}_2|\psi\rangle|^2 + |\langle\phi|1-\hat{\Pi}_2|\psi\rangle|^2} = 1\,, \tag{2}$$

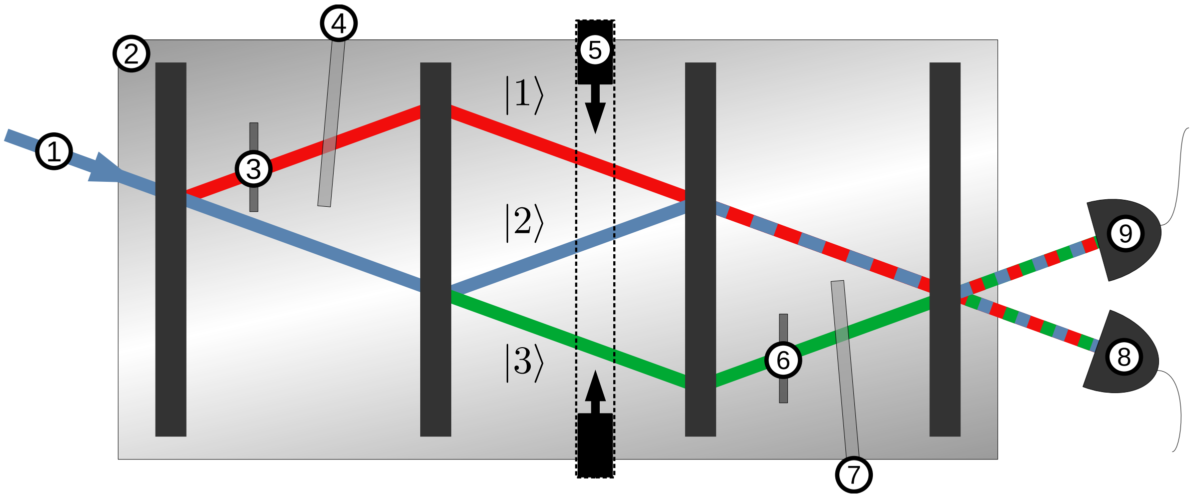

Figure 2: *Schematic drawing of the interferometer setup. Setup elements: unpolarised neutron beam (1), 3-path interferometer (2), indium absorbers (3,6), phase shifters (4,7), Cadmium beam blockers (5), neutron detectors (8,9).*

with $\hat{\Pi}_i = |i\rangle\langle i|$ and $i = 1, 2, 3$. Therefore, it seems like the particle can be found in both boxes with certainty! This atypical result can be understood in terms of weak values and an experimental work on the topic was already performed in a photonic setup[11]. However, we aim for a more complete characterization of the paradox for an arbitrary pre-selected state

$$|\psi\rangle = a_1 |1\rangle + e^{i\alpha_1} a_2 |2\rangle + e^{i\alpha_2} a_3 |3\rangle \ . \tag{3}$$

In particular, we focus on initial states yielding null or purely imaginary weak values, implying no neutron presence in some paths but still an influence on the outcome.

The setup is very basic and requires only a few elements, as shown in Fig. 2. Inside a perfect-crystal neutron interferometer, indium absorbers are used to tune the path amplitudes a_1, a_2, and a_3, while two phase shifters control the relative phases α_1 and α_2. Cadmium path blockers can be inserted to measure the intensity of each path separately.

Required beam time allocation

For the proposed experiment, we expect two main stages: Setup of the interferometer with calibration of the different elements (7 days) and data collection (14 days). In total, we expect to use three weeks (21 days) for the experiment.

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