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Improvement of the polarized neutron interferometer setup demonstrating violation of a Bell-like inequality

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ABSTRACT

For precise measurements with polarised neutrons high efficient spin-manipulation is required. We developed several neutron optical elements suitable for a new sophisticated setup, i.e., DC spin-turners and Larmor-accelerators which diminish thermal disturbances and depolarisation considerably. The gain in performance is exploited demonstrating violation of a Bell-like inequality for a spin-path entangled single-neutron state. The obtained value of $S = 2.365(13)$, which is much higher than previous measurements by neutron interferometry, is $28\,\sigma$ above the limit of $S=2$ predicted by contextual hidden variable theories. The new setup is more flexible referring to state preparation and analysis, therefore new, more precise measurements can be carried out.

1. Introduction

Perfect crystal neutron interferometry was first demonstrated in 1974 at the 250 kW Triga MARK-II reactor in Vienna [1]. Ever since neutron optical experiments, based on interference of matter waves, have provided a power full means of demonstrating effects related to fundamental aspects of quantum physics [2–4], such as measuring the 4π-periodicity of fermions [5], gravitational effects on the neutron [6], spin superposition [7,8] and topological phases [9–11]. Entanglement between different degrees of freedom like the neutron's spin, energy and path have been accomplished [12] and used for testing Bell's inequality [13,14] or measuring the influence of geometric phases [15]. Such an entanglement is achieved within single particles. Further demonstrations of the contextual nature of quantum mechanics (QM) have been performed successfully using neutron interferometry [16–18].

The violation of the Bell inequality can only be shown with high interference contrast and high spin polarisation. In the first experiment [13] a Mu-metal sheet was used as a spin turner, which induced dephasing due to small angle scattering and thereby reducing the interference contrast. The next setup [14] solved the problem of dephasing but the degree of polarisation became problematic.

In this paper we report a significantly improved experimental setup. We designed new DC spin-turners and Larmor-accelerators which allow for very high contrast of the interference fringes and high temperature stability during long measurements. Temperature fluctuations below 0.1 °C over several days are achieved. They also enable high degrees of polarisation and high efficiency spin manipulation. This setup allows a large variety of state preparations and therefore provides capability for many future experiments [18,19]. We performed a test of Bell's inequality using this new setup. The results reveal the substantial improvements achieved by the newly designed setup.

2. Improvement of the polarised interferometer setup

2.1. Overview of the polarised interferometer setup

In our setup high degrees of polarisation, thermal stability, efficient spin-manipulation and spin-analysis are required. Former setups had drawbacks that degrade the quality of the measurement results. Such setups were used for spin-superposition, geometric phase and entanglement measurements [7,15,17]. Spin-turners, which are realized in a way so they put materials in the beam inside the interferometer (IFM) such as Mu-metal sheets [13], anodized aluminum [20] or magnetic foils [21], cause dephasing and therefore loss in contrast. To avoid depolarization the spin-turners need to provide a homogeneous magnetic field over the whole beam cross section. Devices like those used in Refs. [6,14] would cause too much depolarization. For earlier Bell-measurement using single-neutron interferometry two different setups were realized [13,14]. In both setups the spin manipulation

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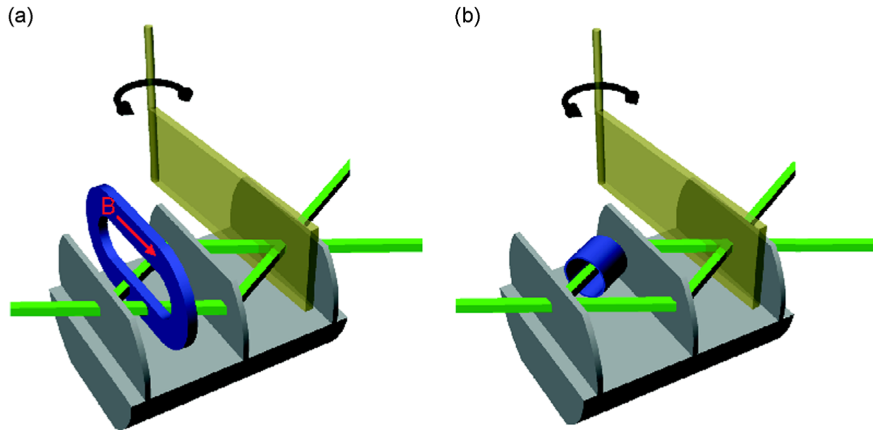

Fig. 1. (a) Setup with Mu-metal inserted in the beam to turn the spin causing dephasing. (b) Setup using a Mu-metal ring to turn the spin causing depolarisation due to inhomogeneity of the field.

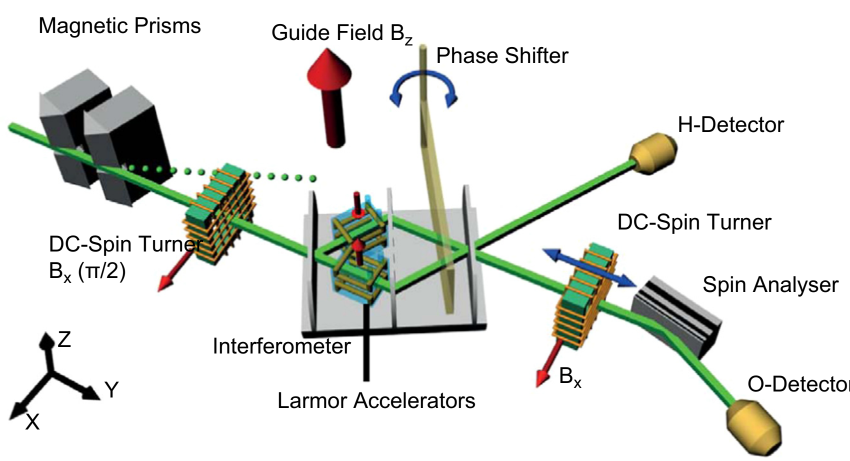

Fig. 2. Experimental setup for measuring Bell inequalities using a triple Laue interferometer. Magnetic prisms are used to polarise the incoming beam. To avoid depolarisation a magnetic guide field B_z is applied around the hole setup. A spin turner before the IFM rotates the spin into the xy-plane. The first plate of the interferometer splits the beam. In each path a Larmor accelerator turns the spin by $\pm\pi/2$. With a phase shifter the relative phase χ can be tuned. The two exit beams are monitored by the O- and H-detectors. The beam arriving at the O-detector is filtered by a spin analyser.

in the IFM was problematic: the contrast and the degree of polarisation were reduced. These two setups are shown in Fig. 1.

Fig, 1(a) shows the IFM with inserted soft magnetic Mu-metal foil as a spin turner. This is achieved by a magnetic field induced into the Mu-metal by a DC-coil outside of the IFM. The Mu-metal foil considerably reduced the contrast of the IFM due to dephasing. To overcome this problem another setup was designed, which does not need any material in the neutron beam in the IFM [14], shown in Fig. 1(b). In one path of the IFM the beam passes a tube of Mu-metal which reduces the strength of the magnetic guide field and thereby inducing a relative spin rotation by different Larmor precessions in the two IFM paths. Since the guide field leaks into the cylinder at its open ends, the field homogeneity is compromised which causes depolarisation of the neutron beam. This setup also requires a spin turner in front of the IFM which additionally reduces the degree of polarisation as described below.

A schematic view of the new setup is shown in Fig. 2. The beam is monochromatised to have a mean wave length of $\lambda_0 = 1.92(2)$ Å by a silicon channel-cut perfect-crystal monochromator. The beam profile is set to $3\times\ 3\ \mathrm{mm}^2$ by an aperture. The incoming neutron beam is polarised by two birefringent magnetic prisms which deflect beams of up- and down-spin neutrons in different directions. The angle between these two beams is 2.3×10^{-5} rad. Since the acceptance width of the interferometer crystal for Laue diffraction is even smaller, we can select one of the spin components (spin-up) by adjusting the rotation angle of the IFM accordingly. Neutrons with spin-down pass the IFM without being reflected and are blocked by a beam stopper afterwards. To avoid depolarisation of the beam a guide field is applied over the entire setup. In front of the IFM the spin is rotated by a DC spin-turner into the *xy*-plane. Within this plane we can adjust the spin by utilizing Larmor precession without putting any material into the beam. This is important to avoid loss of interference contrast due to dephasing. A sapphire phase shifter of 5 mm thickness between second and third plates of the IFM tunes the relative phase χ between the beams in path I and path II. Behind the IFM the spin analysis is carried out using a DC-coil on a translation stage together with a Co–Ti super-mirror array. The neutrons are detected in ^{3}He counters with more than 99% efficiency [22].

2.2. π/2-Spin turner

The $\pi/2$-spin turner is placed between the magnetic prisms and the IFM. Due to the small separation of spin-up and spin-down beams by the magnetic prisms and the fact that the selection of the peak takes place at the first plate of the IFM, wider peaks of the IMF's rocking curves degrade the degree of polarisation of the neutron beam. The peak width at the first IFM plate is determined by the monochromator and the properties of the $\pi/2$-spin turner regarding small-angle scattering. In contrast to