Experimental report

07/09/2022

Proposal: **3-14-422**

Council: 4/2021

Title: Reflection of gravitational UCN quantum states in silicon channels

Research area: Physics

This proposal is a new proposal

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Samples:

Instrument	Requested days	Allocated days	From	To
PF2 TES	54	0		
PF2 EDM	19	16	25/08/2021	15/09/2021

Abstract:

For the upcoming storage of UCN in whispering gallery modes, we need to test the horizontal reflection of vertical gravitational UCN quantum states at walls etched from Si single crystals under different angles. This technique would also allow us to increase the count rate in the present qBounce setup by a factor ~10 , which would improve the impact of the results from a test of the WEP (separate proposal in this round for PF2/UCN). We propose here to perform the required tests at the PF2/EDM beam.

ILL Experimental Report

Reflection of gravitational UCN quantum states in silicon channels

prepared by René Sedmik

Scope

The purpose of the proposed measurements was to demonstrate the disturbance-free reflection of gravitational UCN quantum states off of vertical silicon walls. Such reflections are the basis for a proposed further version of the qBounce setup using a circular storage ring where UCNs can circulate in discrete quantum whispering gallery states. As test setup we used a silicon wafer with curved etched channels in which the neutrons should propagate. The quantum mechanical state distribution with and without channels should be compared to demonstrate that reflections do not influence the state.

Setup

We used the same basic setup for measurements for 3-14-422 and for DIR-245 that resembled the one used for quantum bouncing ball measurements in 2009 [1]. As shown in Figure 1, the EDM neutron guide is attached from the left to a box-shaped Al vacuum chamber. Velocity selection of the neutrons is performed by defining a small range of flight parabolae via an aperture made of borated Al, and the entrance slit of a state selector. The latter consists of a flat polished BK7 glass mirror on the bottom, and an inverted rough mirror from the same material on top. Such stacks are routinely used in qBounce to select the lowest gravitational quantum states [1–4], and are called `absorbers'. After the absorber, we first placed a counter detector to quantify the rate and operation of the absorber. Subsequently, the counter detector was replaced by a position-sensitive CR39 detector [5] to determine the state distribution resulting from the combination of velocity selector and absorber. In later stages, the position-sensitve detector was shifted further away from the reactor and a flat glass mirror of 50 mm length was inserted that served as a reference without channels. Eventually, a silicon wafer with etched channels was mounted using epoxy glue on top of the flat mirror. For both of the latter two configurations, we attempted to use CR39 detectors to determine the state distribution. In order to measure and remove any steps between the mirrors in regions I and II, respectively, an absolute distance fiber-based laser interferometer was

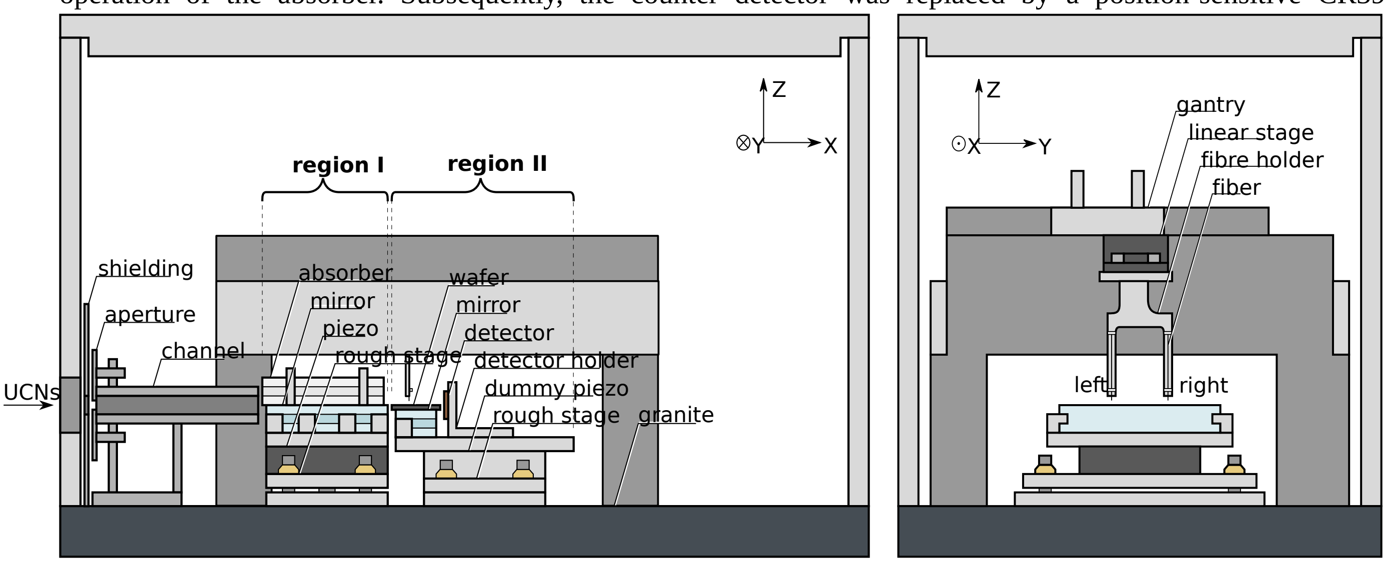

Figure 1: Experimental setup used for all measurements during 3-14-422. Left: side view; Right: cut view at the position of the detector. Graphic courtesy of Janik Trauner

used that measured the distance between the mirror (or wafer) surface and a gantry bridging over the setup. The fibers were continuously moved back and forth between the two regions using a translator stage hanging on the gantry. A simple PID feedback circuit used these readings to adapt the height and tilt of region I to nullify any steps between the regions.
The channels investigated during this beamtime (see Figure 2) were etched into a <110> SOI wafer using the Bosch process. In order to increase UCN reflectivity, the etched wafer was coated with Ni/W (grey areas). Unfortunately, the last step could not be performed in a cleanroom at the time.

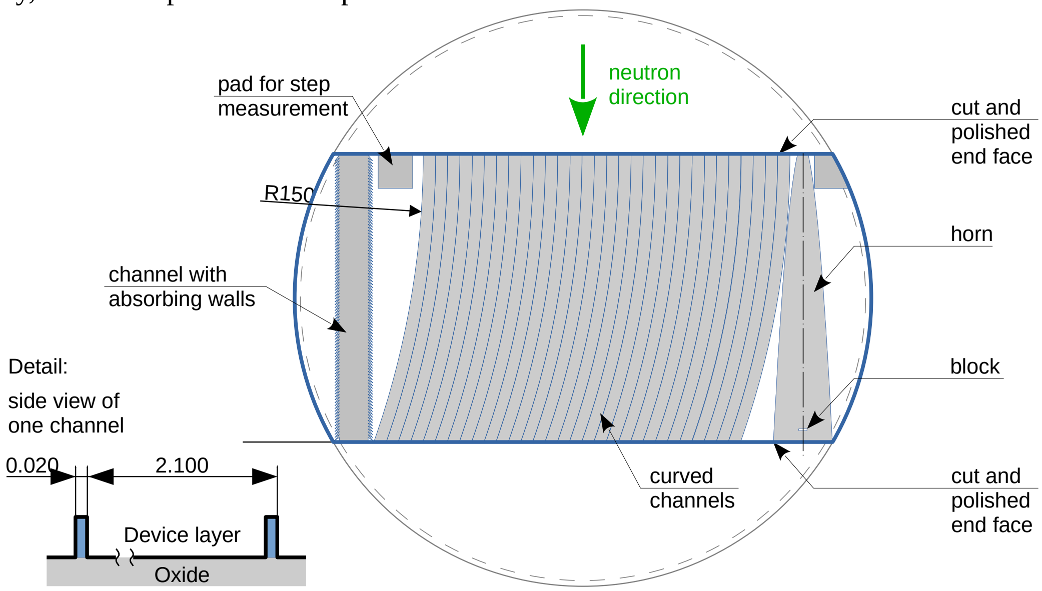

Figure 2: Overview of the different channels on the silicon wafer.

Results

Step measurement and feedback

Due to late availability of the translation stage, its controller, and a number of software problems with the interferometer, the control software for the step feedback could only be written during the beamtime.
After completion, the control circuit achieved a step error of 169±99 nm (over a period of 83 h, see Figure 3) while the intrinsic measurement uncertainty of the interferometers was measured to be 0.37 nm. The reason for this discrepancy were ambient vibrations on Niveau D. Nonetheless, the performance is significantly better than the long-time average of ~500 nm achieved with manual tactile alignment and capacitive sensors in qBounce.

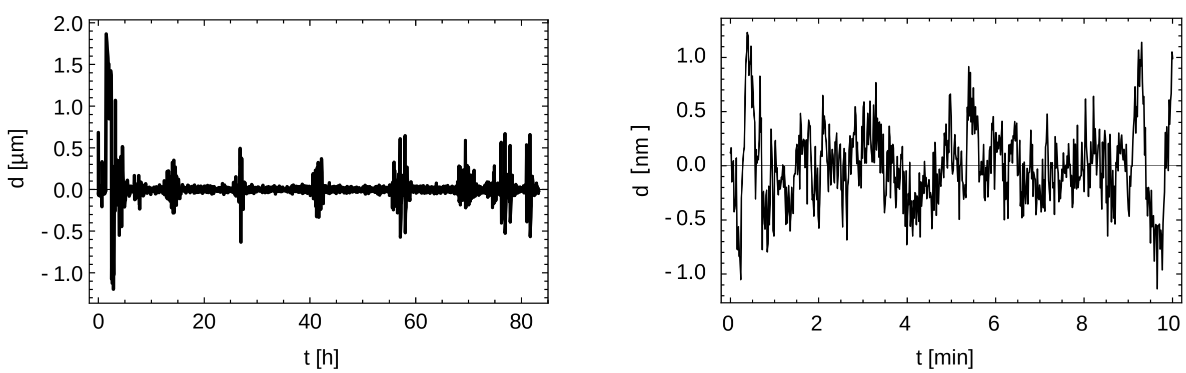

Figure 3: Interferometric measurements. Left: Continuous measurements with active PID feedback during ID 0.024. At around 9:00 each day, strong vibrations occurred on Niveau D. Right: Interferometer stability in a temperature-controlled vibration isolated environment (post beamtime). Figures courtesy of Janik Trauner.

Rate and detection efficiency inconsistencies

The clamped absorber produced a rate of 137±7 mcps at a background of 11.6±1.7 mcps. These values are on the higher side with respect to our long-time experience. Despite this, an exposure of CR39 detector ND-05 resulted in only 20% of the expected neutron counts after 23 h, which was too little to measure the state distribution. Repetition (35 h) with detector ND-07 resulted in a dense stripe, but only on an area of ~20% of the entire detector. Thus, again, no evaluation was possible. Almost no neutrons were detected on detector ND-11 after 13 h. Subsequently the lateral uniformity of the absorber output was tested by measuring the rate when covering parts of the absorber slit with metal. No significant deviation (less than 10%) was found. As the color of the $^{10}B_4C$ coatings on various CR39 detectors varied, we suspected inhomogeneous sensitivity of the CR39 detectors from this batch. This problem, however did not seem to affect all detectors. We tested for spatial inhomogeneities by exposing detector ND-04 directly in the beam tube and analyzing the density of neutron tracks. We measured only 11% variation across the surface, and roughly the expected total number of tracks. The parameters of the chemical development of the detectors [5] were tested by performing a time series on ND-12, which was exposed directly in the beam tube to receive enough neutrons for evaluation. A subsequent analysis confirmed that the previously used parameters already were optimally chosen, for which chemical treatment was ruled out as reason for the inconsistent detection efficiency. In order to be sure to use a detector with nominal efficiency for the final test with the wafer, we exposed small pieces of 6 different detectors directly in the beam tube, which revealed 25% deviation between the average track density of different detectors and up to 45% deviation between different places on the same detector. We selected the detector with the highest efficiency and only 10% deviation between different spots (ND-13). On the basis of the efficiency test of 6 detectors, we expected more than 13000 tracks on the detector. Unfortunately, after the end of measurement (119 h exposure), no neutron track could be identified on the detector, which made further investigations necessary. Analysis using SEM and profilometry revealed several problems with residuals of cleaning liquids and trapped dust, which created a barrier of several micrometers at the entrance edge of the wafer, which is the most probable explanation for the problems. Our investigation also showed that the roughness of the vertical walls is less than a few tens of nm peak, and that the wall faces deviate much less than 1° from 90°. We therefore conclude, that the reason for failure in this test was due to improper preparation and treatment of the wafer. We aim to repeat the test with changed procedures. The coating shall be applied directly in a cleanroom after etching. Mounting of the wafer onto a glass mirror shall also be performed in a cleanroom. The mirror/wafer assembly shall only be taken out of its packaging before placing it into the setup. No cleaning liquids may be applied. In this way, we hope to avoid the problems of experiment 3-14-422, and perform a valid test of the reflection of gravitational UCN quantum states off of vertical walls.

Summary

The ability to reflect gravitational neutron states at vertical walls could not be demonstrated during 3-14-422 due to a multitude of technical and procedural problems. Our CR39 detectors, which were successfully used in the past suffered a quality control problem at the supplier, leading to varying sensitivity. Environmental dust due to long exposure to the air at Niveau D and the implied cleaning steps caused accumulation of crystallites and contaminations at the entrance edge of the wafer for which UCNs were most likely scattered chaotically and could not reach the detector. We therefore conclude that we have to repeat the test with a different procedure for preparations and detection.

References

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