Experimental report

22/09/2016

Proposal: **3-15-85** **Council:** 4/2016

Title: Precision studies of the neutron whispering gallery with a MgF2 concave mirror

Research area: Nuclear and Particle Physics

This proposal is a resubmission of 3-15-83

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Samples: concave MgF2 mirror

Instrument	Requested days	Allocated days	From	To
D17	7	7	20/06/2016	27/06/2016

Abstract:

The neutron whispering gallery effect was discovered in experiments with cold neutrons at D17. An important motivation for precision studies of this effect consists of its extreme sensitivity to extra fundamental short-range forces. Even the very first experiments appeared to be quite competitive from this point of view. Already in these experiments, the interference pattern corresponded to many resolved quantum states. The neutron flux was measured as a function of the longitudinal neutron velocity (measured using the time-of-flight method) and the tangential neutron velocity (calculated using the angle of deflection of neutrons measured in a position-sensitive detector). Our present interest is based on a possibility to obtain by far the best constraint for the extra short-range forces in the particularly interesting range of characteristic distatnces of one - a few nanometers. Our ultimate goal, with the MgF2 concave mirror, to measure about 100th order of such interference with about 10% accuracy for a
line shape.

The present experiment is the first in a series, which have the goal of more precisely investigating neutron whispering gallery in the vicinity of a concave well-polished mirror. A significant improvement in accuracy compared to the very first experiment at D17 with a *Si* mirror [1] can allow better constraining spin-independent and spin-dependent short-range forces [2].

The method consists of measuring the neutron flux at the exit of a precision concave MgF_2-crystal-mirror as a function of the longitudinal neutron velocity (measured using the time-of-flight technique) and the tangential neutron velocity (calculated using the angle of deflection of neutrons measured in a position-sensitive detector).

Already in the first experiment [1], the interference pattern corresponded to many well-resolved quantum states. A typical result is shown in Fig. 1.

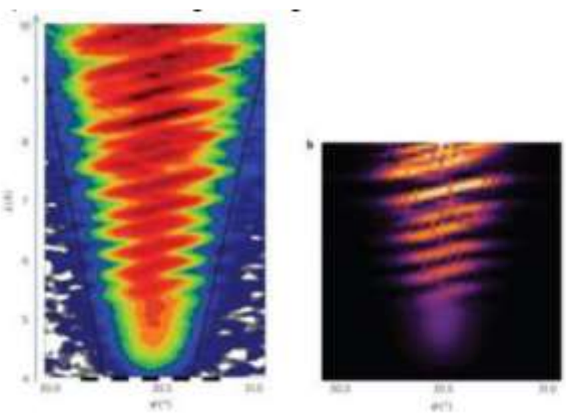

Fig. 1. Interference of whispering gallery quantum states of neutrons measured with a Si-crystal mirror: the scattering probability as a function of neutron wavelength (Å, vertical axis), and deviation angle (degrees, horizontal axis). The maximum probability is shown in red (the experimentally measured interference pattern is shown on the left, and the theoretical expectation for the pattern is given on the right). Neutrons enter through the entrance edge of a cylindrical mirror with the geometrical size of 30.5 degrees.

Attentive comparison of theoretical and experimental patterns in Fig. 1 reveals a deviation. We attribute it to modifications of the mirror surface state caused by a silicon oxide layer. Another feedback of this measurements consisted of a significant probability of parasitic transitions between quantum states and thus false effects associated with the finite accuracy of evaluation of such transitions; the parasitic transitions are caused by non-uniformity of the nuclear potential at the surface of the mirror along the neutron trajectory. Even with these uncertainties, however, the work [1] and further unpublished measurements with this *Si* mirror provided a very competitive constraint.

The new experiment is different in several quantitative aspects; each of them allows decreasing unwanted systematic effects or increasing the statistical accuracy. In particular: 1) a MgF_2 crystal instead of a *Si* crystal used as the substrate allowed to better control the surface state (no oxide layer, significantly lower surface impurities), thus parasitic transitions between quantum states are largely suppressed (in fact, even not observed within the statistical accuracy) and parasitic deformations of the surface potential are largely suppressed as well (no visible deviation between the measured interference pattern and its theoretical calculation), 2) the quality of polishing the mirror is improved (this effect also contributes to the suppression of parasitic transitions and better shaping the surface potential), 3) the angular size of the mirror is equal to 39. 7427(1) degrees compared to 30.5 degrees in the previous experiment (thus quantum states are narrower and the precision of measurements is higher), 4) the optical potential of the substrate material is much higher (134 neV compared to 52 neV), thus significantly more quantum states can be observed and the accuracy is significantly higher, 5) the vertical size of the mirror is significantly larger, thus statistics is higher, 6) the angular and wavelength resolution of D17 was adjusted to maximize useful neutron flux without significantly losing the contrast of the interference pattern, thus the total accumulated statistics is higher.

All these factors were fully realized in the performed experiment. A typical interference pattern is shown in Fig. 2.

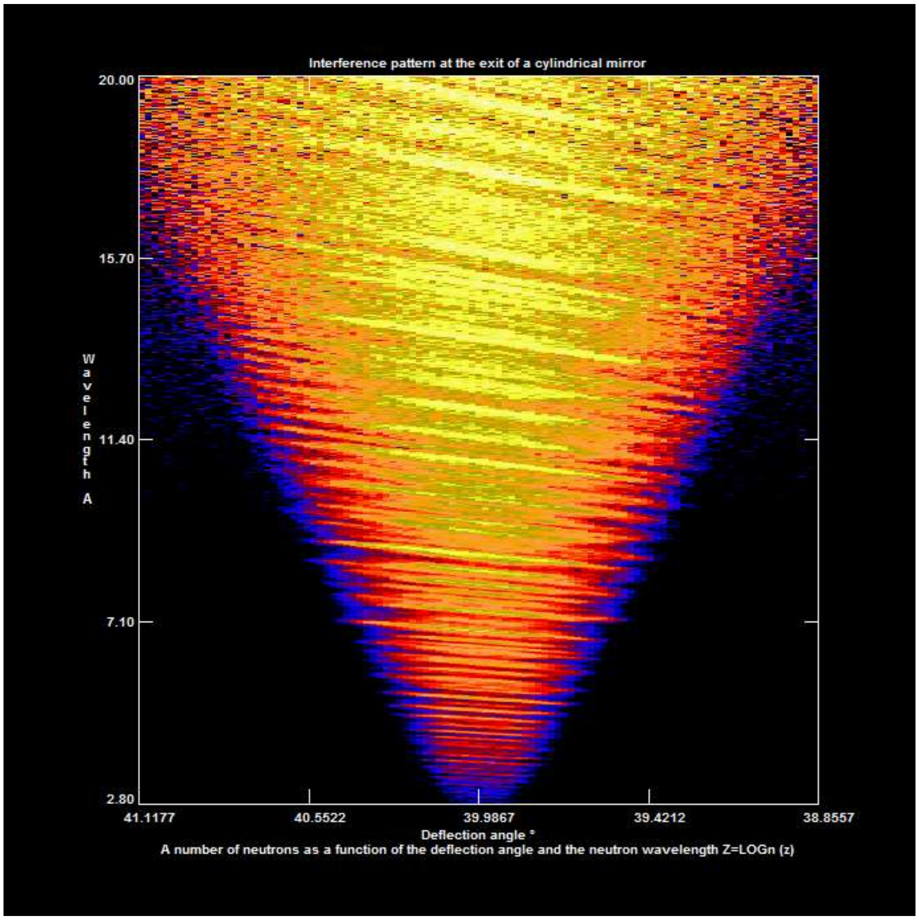

Fig. 2. Interference of whispering gallery quantum states of neutrons measured with a MgF_2-crystal mirror (analogous to Fig. 1). The angular size of the mirror is 39.7427 degrees; the data are normalized to the initial neutron flux.

A major improvement in the resolution is evident. Significantly more interference lines are observed. Lines are significantly narrower. To safe space, we do not show a corresponding theoretical interference pattern, which is visually indistinguishable from the experimental result.

A detailed comparison and analysis of the result will take some time (one theoretical simulation takes a day at a powerful computer but we need hundreds of simulations to explore sensitivity to various possible false effects. However, preliminary estimations show that the current measurement already improves the existing constraints at distance around 10 nm. More detailed analysis will improve the constraints.

Further improvements in the experimental arrangement are also possible. In particular, high-vacuum conditions around the crystal and its special cleaning from traces of surface impurities would improve characterization of the surface potential. A major fraction of time in the present experiment was spend to investigate systematics, thus longer measurement and thus better statistical accuracy and feasible in the future. The vertical axis (the wavelength) is calibrated in the current measurement using Bragg diffraction in *Si* crystals; even better calibration of the vertical axis would further improve the accuracy and reliability.

[1] V.V. Nesvizhevsky, A.Yu. Voronin, R. Cubitt, K.V. Protasov, *Neutron whispering gallery*, **Nature Phys. 6** (2010) 114.

[2] I. Antoniadis, S. Baessler, M. Buchner, *et al*, *Short-range fundamental forces*, **Compt. Rend. Phys. 12** (2011) 755.