LEAP-2018

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Constraints for fundamental short-range forces from the neutron whispering gallery, and extension of the method to atoms and antiatoms

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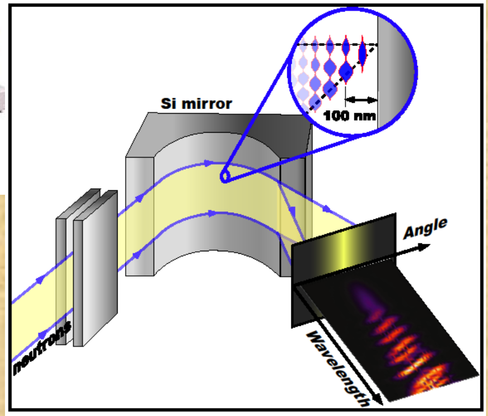
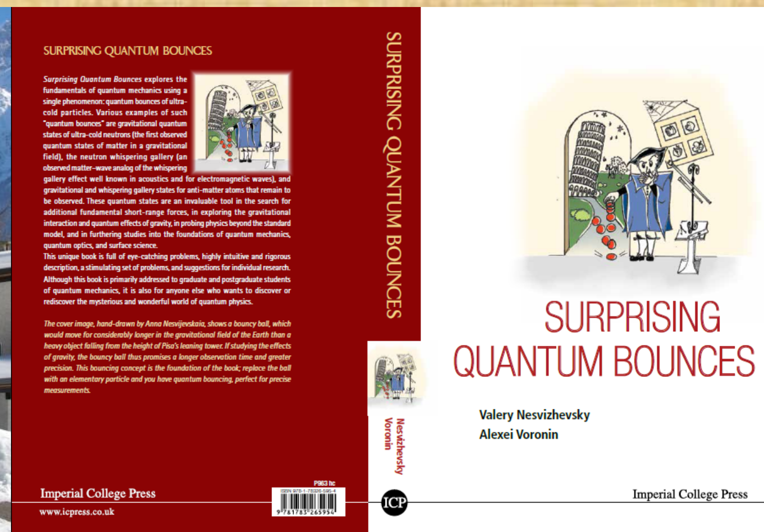
A case of: Gravitational Quantum Interferometry /Spectroscopy with Ultracold Systems

Gravitational quantum spectroscopy with neutrons



Gravitational quantum spectroscopy with antihydrogen atoms (hydrogen, see a poster by S. Vasiliev et al)



Ultracold: gravitational quantum states: 10 nK, ultracold antihydrogen: 100 μK, ultracold neutrons: 1mK

References

Observation of gravitational states of neutrons: [V.V. N., H.G. Boerner, A.K. Petukhov, H. Abele, S. Baessler, F.J. Ruess, T. Stoferle, A. Westphal, A.M. Gagarski, G.A. Petrov, and A.V. Strelkov, *Quantum states of neutrons in the Earth's gravitational field*, Nature 415:297, 2002];

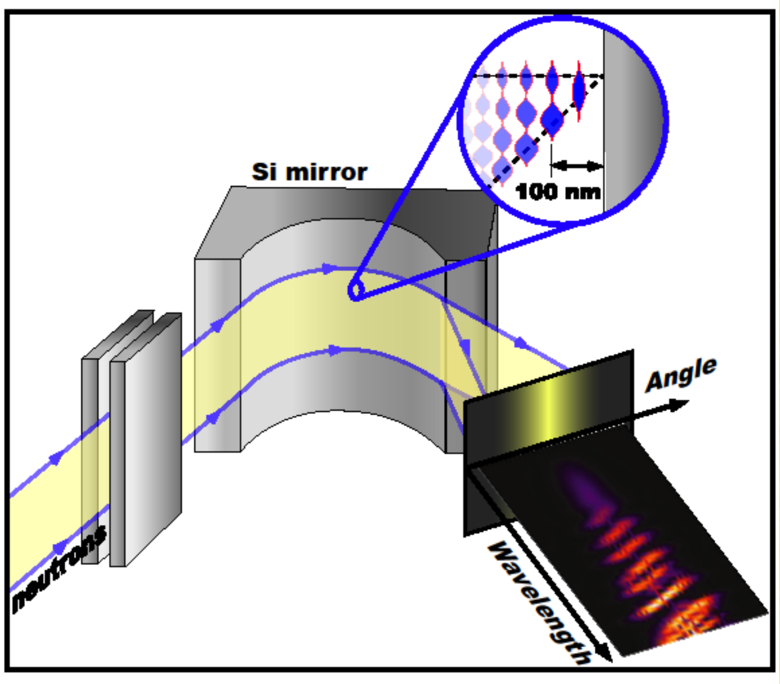
Observation of whispering-gallery states of neutrons: [V.V. N., A.Yu. Voronin, R. Cubitt, and K.V. Protasov, *Neutron whispering gallery*, Nature Physics 6:114, 2010];

Proposal to measure gravitational quantum states of antihydrogen/hydrogen atoms: [A.Yu. Voronin, V.V. N., P. Froelich, *Gravitational quantum states of antihydrogen*, Phys. Rev. A 83:032903, 2011];

Calculations of quantum reflection of (anti)atoms from the surface ([P.-P. Crepin, E.A. Kupriyanova, R. Guerout, A. Lambrecht, V.V. N., S. Reynaud, S. Vasiliev, A.Yu. Voronin, *Quantum reflection of antihydrogen from a liquid helium film*, Europ. Phys. Lett. 119: 33001, 2017];

Also relevant publications of Tokyo, qBounce, GRANIT, GBAR collaborations. Also GRANIT workshop proceedings: [GRANIT-2014, *Gravitational Quantum Spectroscopy*, Adv. High En. Phys. 467409:2, 2014]; [*GRANIT-2010*, Compt. Rend. Phys. 12:703, 2011].

Whispering gallery



1. The phenomenon: quantum states of massive particles (neutrons, atoms, antiatoms), which move in the vicinity of a curved mirror. This is a close analogue to gravitational quantum states (acceleration replaces gravity, and inertial mass plays the role of gravitational mass).

2. The method of observation: an interference pattern (the intensity) is measured as a function of the particle longitudinal velocity (using the time-of-flight method) and the tangential velocity (the angle of exit measured using a position-sensitive detector).

A mirror for neutrons and (anti)atoms

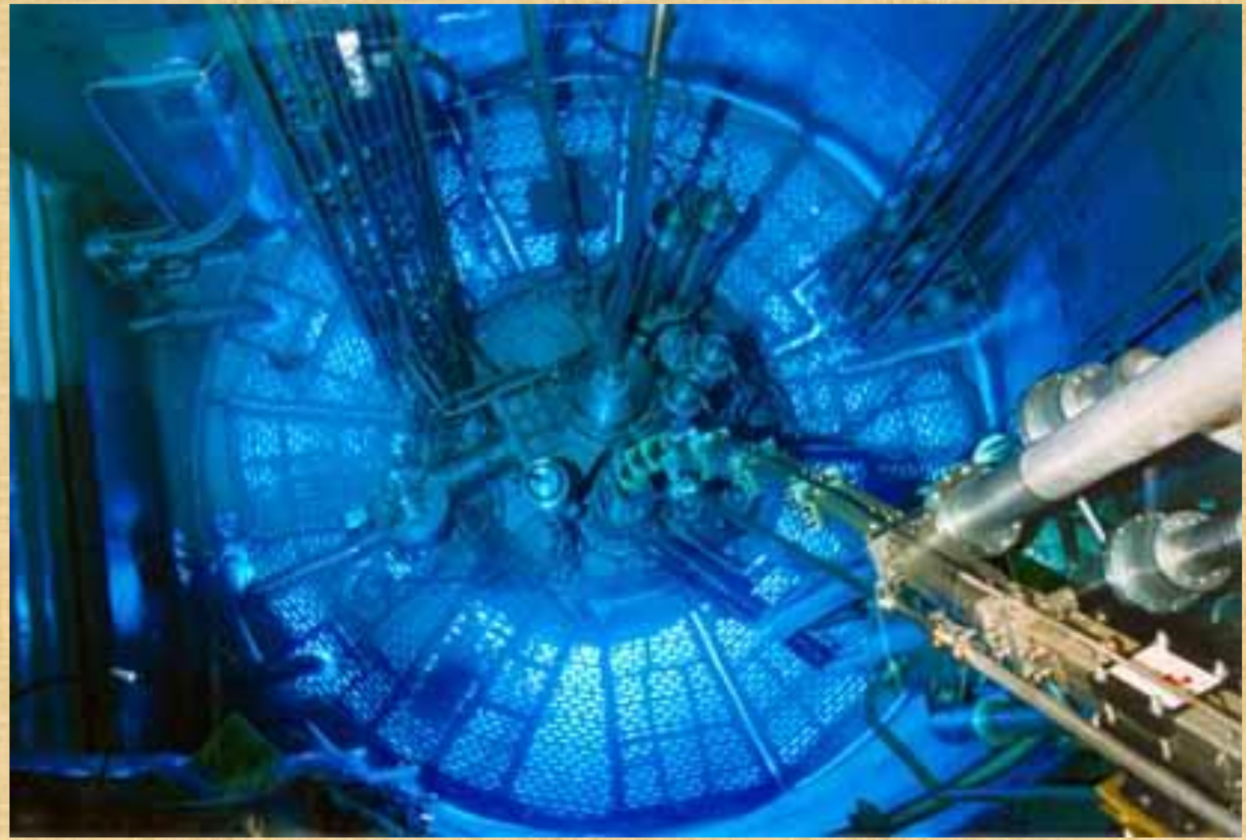
NEUTRONS FOR SCIENCE

- Non-local interaction of an ultracold massive particle with matter due to very large wavelength (much larger than a typical interatomic distance in matter);
- A mirror can be described as a uniform (along the surface) potential barrier, with no internal structure, thus specular reflection;
- An ultracold particle (10 nK !!!) is reflected from the mirror elastically.

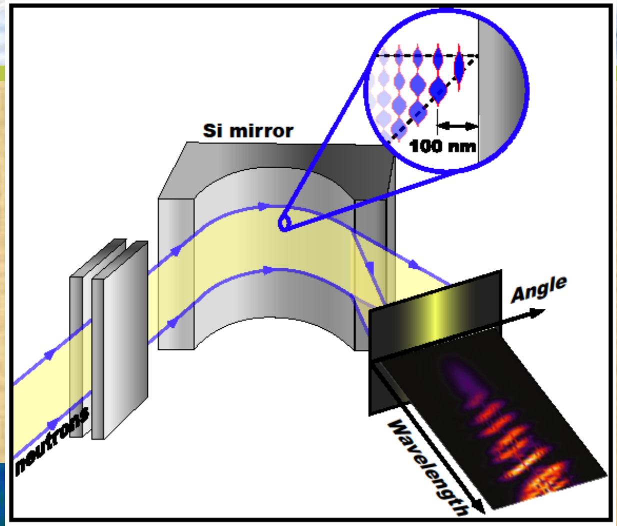
- Ultracold neutrons are reflected from average neutron-nuclei optical potential of the surface [E. Fermi, *Sul moto dei neutroni nelle sostanze idrogenate*, Ric. Sci. 7: 13, 1936];
- (Anti)atoms are reflected from van der Waals/Casimir-Polder potential of the surface [J.E. Lennard-Jones, A.F. Devonshire, Proc. R. Soc. 156: 6, 1936].

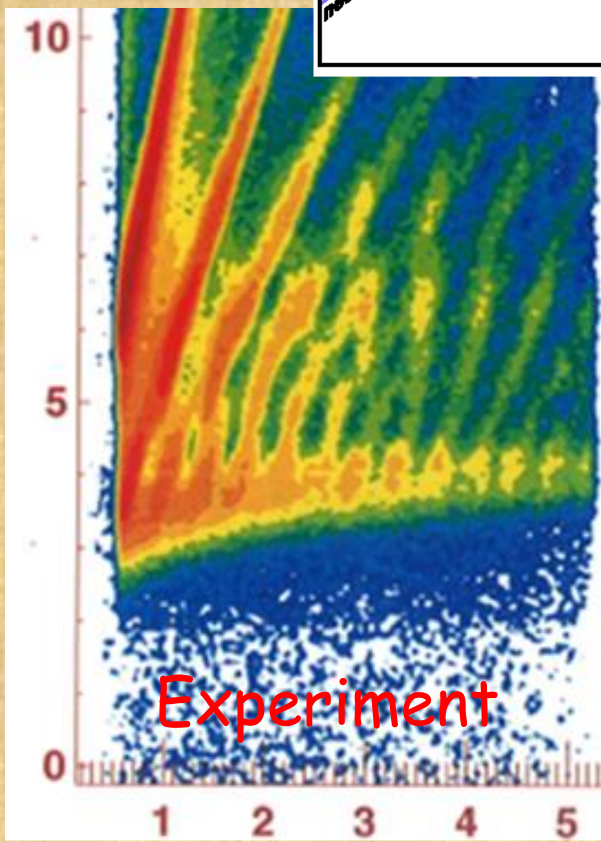
ILL

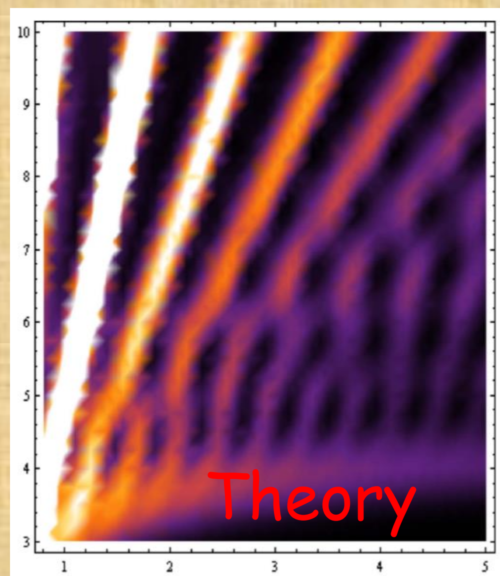
All measurements with neutrons related to the topic of this talk are performed at the Institut Max von Laue - Paul Langevin (ILL), Grenoble, France, and use various ILL facilities (GRANIT, PF1B, PF2, D17 etc).



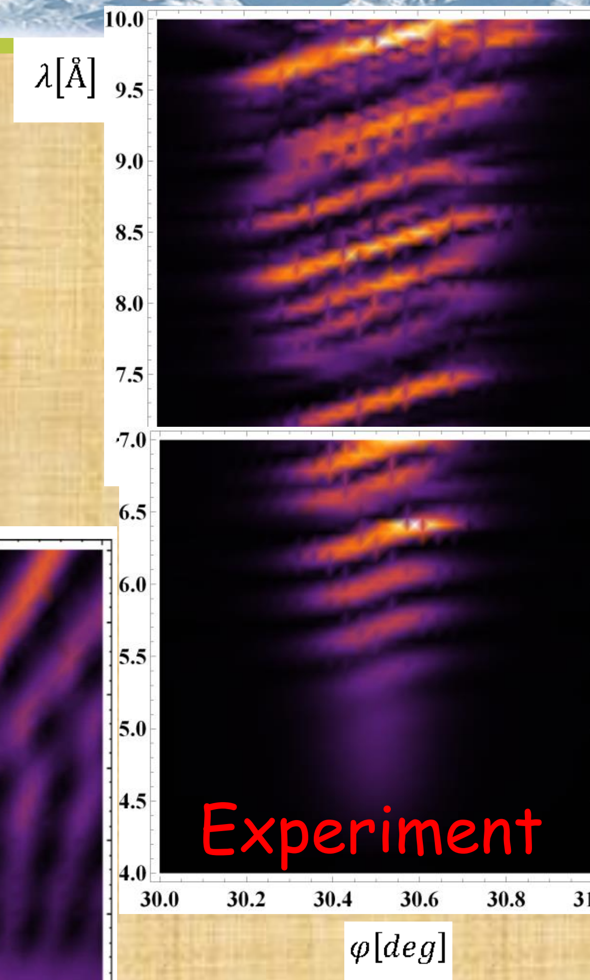
Neutron Whispering Gallery with a Si mirror

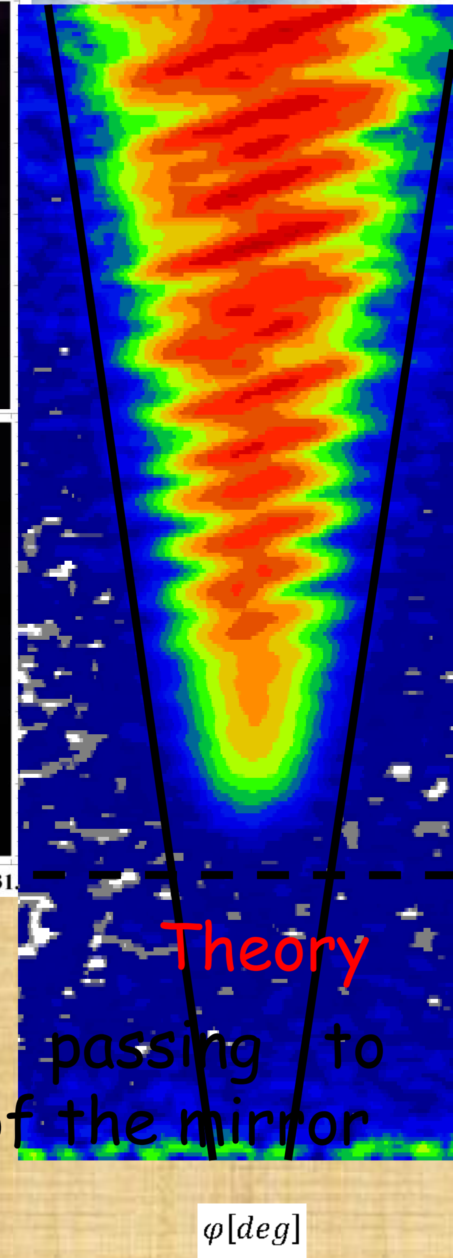






Neutrons tunneling through the mirror

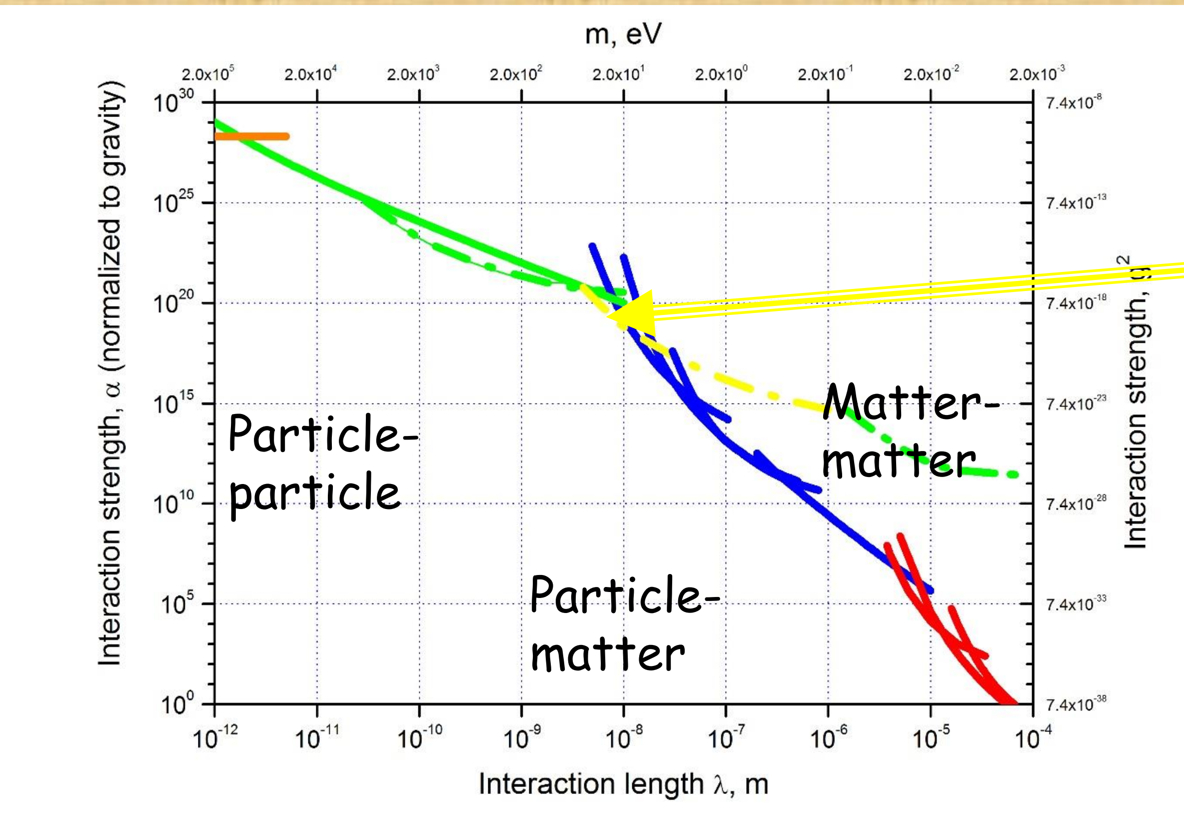


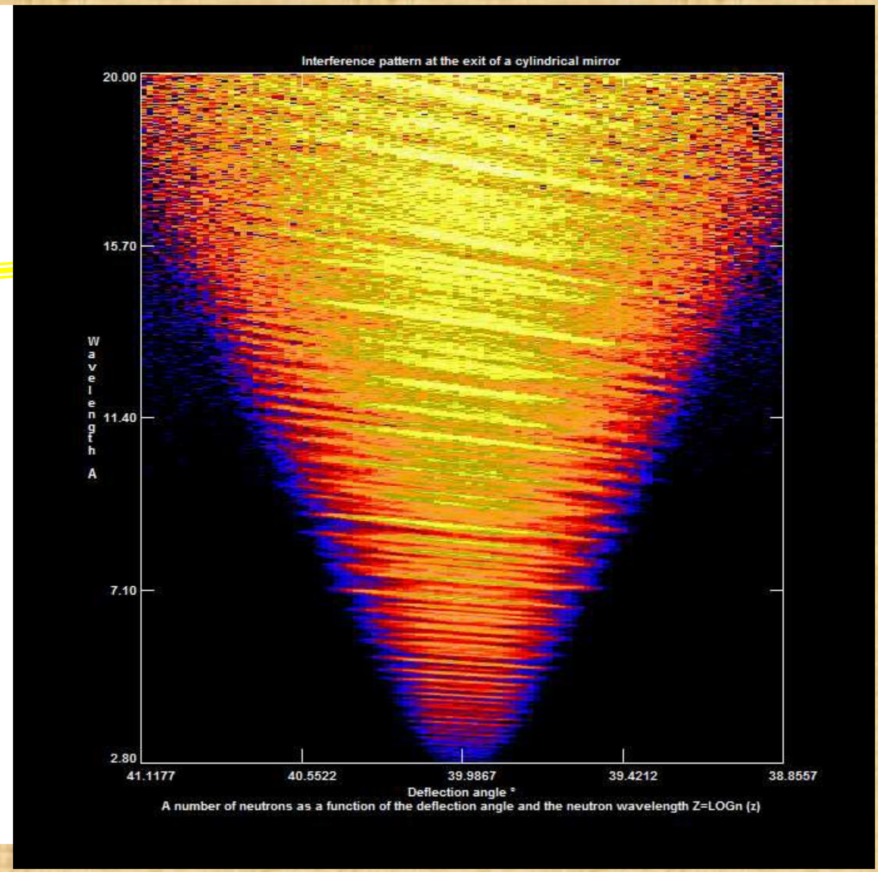


Neutrons passing to the exit of the mirror

NEUTRONS FOR SCIENCE

Neutron Whispering Gallery with a MgF_2 mirror





[I. Antoniadis, S. Baessler, M. Buchner, V.V. Fedorov, S. Hoedl, V.V. N., G. Pignol, K.V. Protasov, S. Reynaud, Yu. Sobolev, *Short-range fundamental forces*, Compt. Rend. Phys. 12: 775, 2011], updated by [Y. Kamiya, K. Itagaki, M. Tani, G.N. Kim, and S. Komamiya, *Constraints on new gravitylike forces in the nanometer range*, ArXiv:hep-ex/1504.02181]

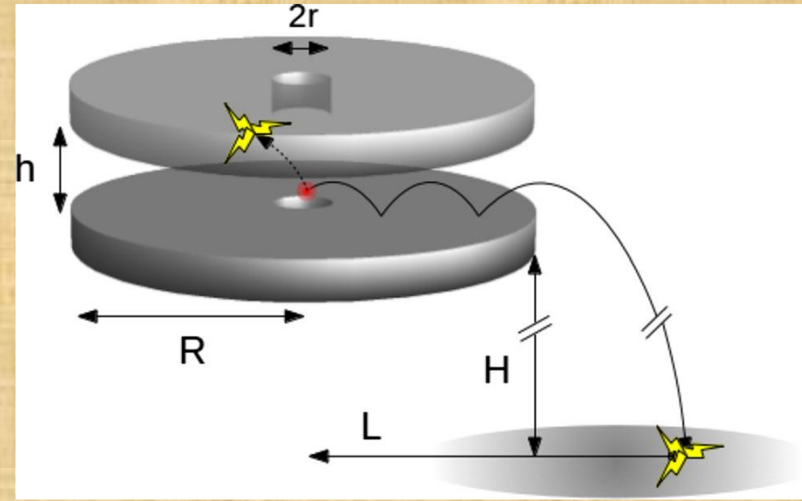
Neutron Whispering Gallery with a MgF_2 mirror

Methodical improvements:

- No Si-oxide layer on the surface (as in the preceding experiment), thus better defined surface potential and smaller systematics;
- Lower impurities on the surface, thus smaller systematics;
- Suppression of parasitic transitions between whispering-gallery states;
- Optimization of the neutron beam shaping and resolutions, thus higher statistics and smaller systematics;
- Better control of false effects;
- Higher critical velocity of the mirror material, thus the access to shorter distances also higher statistics.

To be continued with a closed trap…

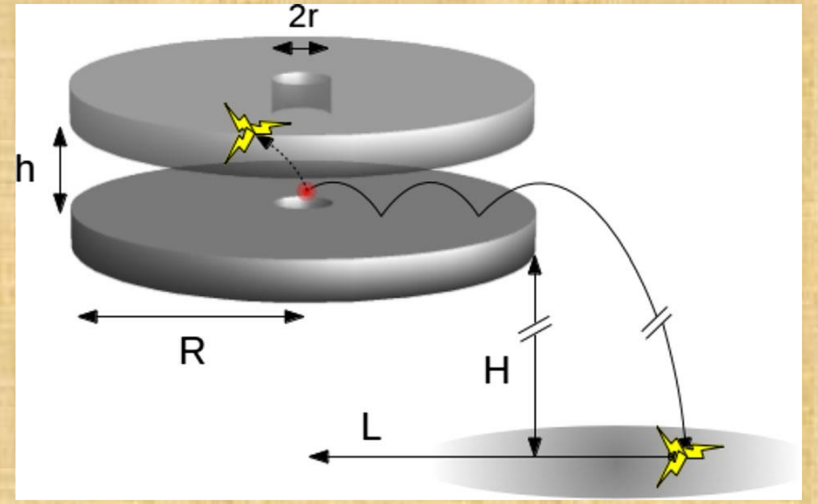
…and extension of the method to (anti)atoms



We propose to use the whispering gallery method, however, applied to a gravity experiment

At the first stage, GBAR is going to measure the free fall of antihydrogen atoms, and thus evaluate a gravitational acceleration for antimatter with an accuracy of $\sim 10^{-2}$;
At the second(first) stage, a spectrum shaping device (for the vertical velocities) will be used to improve the accuracy to $\sim 10^{-3}$;
The third stage is an experiment with gravitational quantum states of antihydrogen atoms, with the goal of 10^{-4}-10^{-6} accuracy.

...and extension of the method to (anti)atoms



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The whispering gallery method!

...and extension of the method to (anti)atoms

- Time-of-flight spectroscopy of antihydrogen longitudinal velocities is provided by precise timing of antihydrogen release from the GBAR precision trap and detection;
- Tangential velocities are measured using GBAR position-sensitive annihilation detector;
- The whispering-gallery method does not require a sharp shaping of the initial vertical spectrum and extreme energy resolution corresponding to a single quantum state;
- Thus, easy to realize;
- Thus, higher statistics (due to measurements of many gravitational quantum states simultaneously) and lower systematics simultaneously.

Conclusion

- The method of neutron whispering gallery with a curved mirror allows competitive constraints for fundamental short-range forces;

- The method of neutron whispering gallery with a curved mirror can be extended to atoms and antiatoms, thus providing probably even better constraints for fundamental short-range forces;

- The method of neutron whispering gallery with a flat mirror can be applied to antihydrogen atoms, thus providing simultaneously easy implementation, higher statistics and smaller systematics in measurement of a gravitational acceleration of antimatter (10^{-4}-10^{-6}).