



Gravitational and other shifts of whispering-gallery and gravitational state interference patterns of light neutral particles.

PSAS-2026, 18-22 May, Vienna

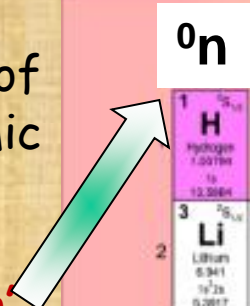


PERIODIC TABLE Atomic Properties of the Elements

NIST
National Institute of
Standards and Technology
U.S. Department of Commerce

Precision Physics of
Simple Atomic
Systems (PSAS):

"Austrian definition"
of Simple Atomic
Systems (Helmut
Rauch), including the
neutron



Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ¹³³Cs

speed of light in vacuum	c	299 792 458 m s ⁻¹ (exact)
Planck constant	h	6.626 070 15 × 10 ⁻³⁴ J s (exact)
elementary charge	e	1.602 176 634 × 10 ⁻¹⁹ C
electron mass	m_e	9.109 383 56 × 10 ⁻³¹ kg
proton mass	m_p	1.672 621 63 × 10 ⁻²⁷ kg
fine-structure constant	α	1/137.035 999 084
Rydberg constant	R_∞	10 973 731.568 162 852 m ⁻¹
Boltzmann constant	k	1.380 658 529 × 10 ⁻²³ J K ⁻¹

- Solids
- Liquids
- Gases
- Artificially Prepared

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	IA	IIA	IIIB	IVB	VB	VIB	VII B	VIII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1	¹ H																	² He
2	³ Li	⁴ Be																¹⁰ Ne
3	¹¹ Na	¹² Mg																¹⁸ Ar
4	¹⁹ K	²⁰ Ca	²¹ Sc	²² Ti	²³ V	²⁴ Cr	²⁵ Mn	²⁶ Fe	²⁷ Co	²⁸ Ni	²⁹ Cu	³⁰ Zn	³¹ Ga	³² Ge	³³ As	³⁴ Se	³⁵ Br	³⁶ Kr
5	³⁷ Rb	³⁸ Sr	³⁹ Y	⁴⁰ Zr	⁴¹ Nb	⁴² Mo	⁴³ Tc	⁴⁴ Ru	⁴⁵ Rh	⁴⁶ Pd	⁴⁷ Ag	⁴⁸ Cd	⁴⁹ In	⁵⁰ Sn	⁵¹ Sb	⁵² Te	⁵³ I	⁵⁴ Xe
6	⁵⁵ Cs	⁵⁶ Ba	⁵⁷ La	⁵⁸ Ce	⁵⁹ Pr	⁶⁰ Nd	⁶¹ Pm	⁶² Sm	⁶³ Eu	⁶⁴ Gd	⁶⁵ Tb	⁶⁶ Dy	⁶⁷ Ho	⁶⁸ Er	⁶⁹ Tm	⁷⁰ Yb	⁷¹ Lu	
7	⁸⁷ Fr	⁸⁸ Ra	⁸⁹ Ac	⁹⁰ Th	⁹¹ Pa	⁹² U	⁹³ Np	⁹⁴ Pu	⁹⁵ Am	⁹⁶ Cm	⁹⁷ Bk	⁹⁸ Cf	⁹⁹ Es	¹⁰⁰ Fm	¹⁰¹ Md	¹⁰² No	¹⁰³ Lr	

Atomic Number: 58
Ground-state Level: ¹G₄
Symbol: Ce
Name: Cerium
Atomic Weight: 140.116
Ground-state Configuration: [Xe]4f¹5d¹6s²
Ionization Energy (eV): 5.5387

¹Based upon ¹²C. (j) indicates the mass number of the longest-lived isotope. For a description of the data, visit physics.nist.gov/data NIST SP 966 (September 2010)

This talk is totally based on our recent publication

V.V. Nesvizhevsky, J.A. Pioquinto, K. Schreiner, S. Baeßler, P. Crivelli, F. Nez, S. Reynaud, P. Yzombard, S.A. Vasiliev, and E. Widmann, *Gravitational and other shifts of whispering-gallery and gravitational state interference patterns of light neutral particles*, *New Journal of Physics*, accepted, 2026.



Gravitational, optical and hyperfine spectroscopy and interferometry with the lightest neutral particles/atoms (neutrons, atoms, antiatoms, positronium, muonium) at lowest kinetic energies



Spectroscopy of gravitational quantum states of ultracold neutrons

AMADEUS grant

More details are given in several articles (to be submitted soon) as well as in the talks and posters at PSAS-2026:

- **J.A. Pioquinto, et al**, *Search for a new spin-dependent short-range interaction at the nanometer scale using whispering gallery states of neutrons* (to be submitted)
- **K. Schreiner, et al**, *Observation of a magnetic shift in neutron whispering-gallery states* (to be submitted)
- **C. Killian, et al**, *GRASIAN: First observation of quantum reflection of atomic hydrogen from a silicon mirror on the journey toward the first demonstration of gravitational quantum states of atoms*, PSAS-2026, Talk, Session 10
- **S. Vasiliev, et al**, *Cold sources of atomic hydrogen and its isotopes*, PSAS-2026, Poster Session 2
- **K. Schreiner, et al**, *Design and construction of a whispering gallery spectrometer for cold atomic hydrogen*, PSAS-2026, Poster Session 1
- **E. Bera, et al**, *A Zeeman decelerator, for enhancing the creation of GQSSs*, PSAS-2026, Poster Session 2

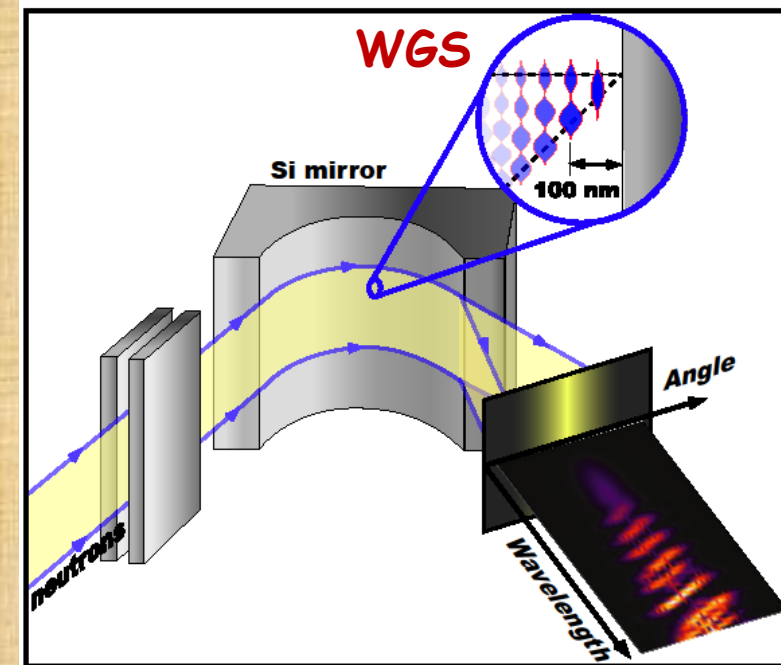
Short history of this long investigation:

- The idea of a “quantum bouncer” [G. Breit, *Phys. Rev.* **32** (1928) 273]
- Several unsuccessful attempts to observe this phenomenon
- Observation of gravitational quantum states (GQS) of neutrons [V. Nesvizhevsky *et al*, *Nature* **297** (2002) 415]
- Observation of whispering gallery states of neutrons (WGS) [V. Nesvizhevsky *et al*, *Nature Phys.* **6** (2010) 114]
- Realization of resonant transitions between GQS of neutrons [T. Jenke *et al*, *Nature Phys.* **7** (2011) 468]
- Observation of WGS of electrons [G. Reecht *et al*, *Phys. Rev. Lett.* **110** (2013) 056802]
- GRASIAN collaboration: Towards observation of GQS and WGS of atoms [C. Killian *et al*, *Europ. Phys. J. D* **78** (2024) 132]

Typical parameters:

GQS: mass **1 at.un.** (neutrons, (anti)hydrogen); energy **~ 0.6 peV**, height **~ 5.9 μm** , effective temperature **~ 10 nK**, formation time **~ 1.1 ms**

WGS: $g \rightarrow a = \frac{v^2}{R}$ (v - velocity, R - mirror radius), thus, a possibility to "tune" parameters by "tuning" v and R



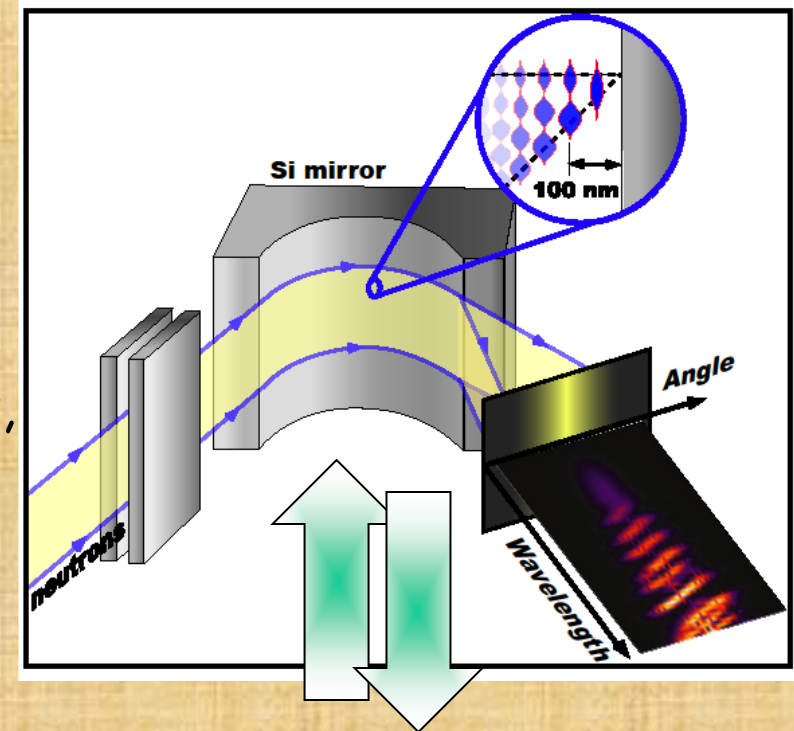
- **Experimental methods** for producing and measuring WGS and GQS are well developed. In particular, several collaborations are (were, will be) measuring **GQS** of **neutrons** using different methods: qBounce, Tokyo, GRANIT, ALSUN etc. GRASIAN is measuring **GQS** of **atoms**. GBAR considers measuring **GQS** of **antiatoms**.
- The accuracy of **theoretical description** of such states can be high. The "theoretical uncertainties" are mainly of the "**experimental**" origin; they are related to the accuracy to which we know parameters of concrete systems.
- **GQS** of **Neutrons**. Limitations: observation times $\sim 10^{-2}-10^{-3}$ s are not much shorter than the formation time $\sim 10^{-3}$ s. So, precision spectroscopy is hard. Advantages: "easy" experiments. **GQS** of **Atoms** and **Antiatoms**. Limitations: The magnetic moment is a factor of thousand larger than the neutron magnetic moment, therefore the control of electromagnetic false effects is harder. Advantages: **Atoms** promise much higher statistics and observation times. **Antiatoms** are an efficient method to measure precisely gravitational properties of antimatter (if ultracold).

For all experiments with **GQS** and **WGS** of **all particles**, there are certain conditions and constraints, in particular:

- The surface reflects **neutrons, atoms, antiatoms, positronium, muonium**, etc, **elastically** due to the condition $l_0 \gg 1 \text{ \AA}$ (a typical size of the quantum state is much larger than an interatomic distance). It means that the thermal motions of individual nuclei/atoms in the surface are effectively averaged out, and
- **specularly**, provided the surface is well-polished and homogeneous (on the spatial scale of the order of l_0) - a condition "easier" to satisfy for **GQS** and more difficult for **WGS**.
- A **characteristic range** of raising the potential should be $\ll l_0$ (the condition of sharpness of the reflecting potential). Otherwise, the raising part of potential modifies **GQS/WGS**, and this modification has to be known precisely.



In [V.V. Nesvizhevsky, J.A. Pioquinto, K. Schreiner, S. Baeßler, P. Crivelli, F. Nez, S. Reynaud, P. Yzombard, S.A. Vasiliev, and E. Widmann, *Gravitational and other shifts of whispering-gallery and gravitational state interference patterns of light neutral particles*, *New Journal of Physics*, accepted, 2026], we develop **a new method** of measuring small shifts of WGS and GQS interference patterns, in [K. Schreiner, et al, *Observation of a magnetic shift in neutron whispering-gallery states* (to be submitted)] we **performed its test**, and in [J.A. Pioquinto, et al, *Search for a new spin-dependent short-range interaction at the nanometer scale using whispering gallery states of neutrons* (to be submitted)] we **improved constraints** on extra interactions.



The experimental test: to add an **additional force** first in the direction of the mirror surface, then in the direction away from the surface; measure the interference pattern in both cases and **compare them**.

The general approach (applied to WGS and GQS of neutrons, hydrogen, antihydrogen, positronium, muonium and other light neutral particles)

Let's start from known parameters of neutron (hydrogen, antihydrogen) GQS :
acceleration

$$a_{GQS} = g \sim 9.8 \text{ m/s}^2 \quad ,$$

$$E_{GQS}^{(n,H,\bar{H})} = \sqrt[3]{\frac{\hbar^2 \cdot m^{(n,H,\bar{H})} \cdot a_{GQS}^2}{2}} \sim 6.0 \cdot 10^{-13} \text{ eV} \quad ,$$

$$l_{GQS}^{(n,H,\bar{H})} = \frac{E_{GQS}^{(n,H,\bar{H})}}{m^{(n,H,\bar{H})} \cdot g} \sim 5.9 \cdot 10^{-6} \text{ m} \quad ,$$

$$\tau_{GQS}^{(n,H,\bar{H})} = \frac{\hbar}{E_{GQS}^{(n,H,\bar{H})}} \sim 1.1 \cdot 10^{-3} \text{ s} \quad .$$

characteristic state energy

characteristic state size

characteristic state formation time

To resolve neutron GQS, the observation time should be, say:

$$t_{GQS}^{(n,H,\bar{H})} = \beta_{GQS}^{(n,H,\bar{H})} \cdot \tau_{GQS}^{(n,H,\bar{H})} \sim 1.1 \cdot 10^{-2} \text{ s} \quad \text{or, for a typical mirror length of}$$

$L_{GQS}^{(n,H,\bar{H})} \sim 0.3 \text{ m}$ the maximum neutron velocity is limited to

$$V_{GQS}^{(n,H,\bar{H})} = \frac{L_{GQS}^{(n,H,\bar{H})}}{t_{GQS}^{(n,H,\bar{H})}} \sim 2.7 \cdot 10^1 \text{ m/s}$$

Thus, for neutrons, we are limited to **ultracold neutrons** (UCN) and, even then, the accuracy is **strongly limited by their available velocity**

The general approach (applied to WGS and GQS of neutrons, hydrogen, antihydrogen, positronium, muonium and other light neutral particles)

Still, we could measure interference of neutron GQS with the existing neutron beams, neutron optics and detectors

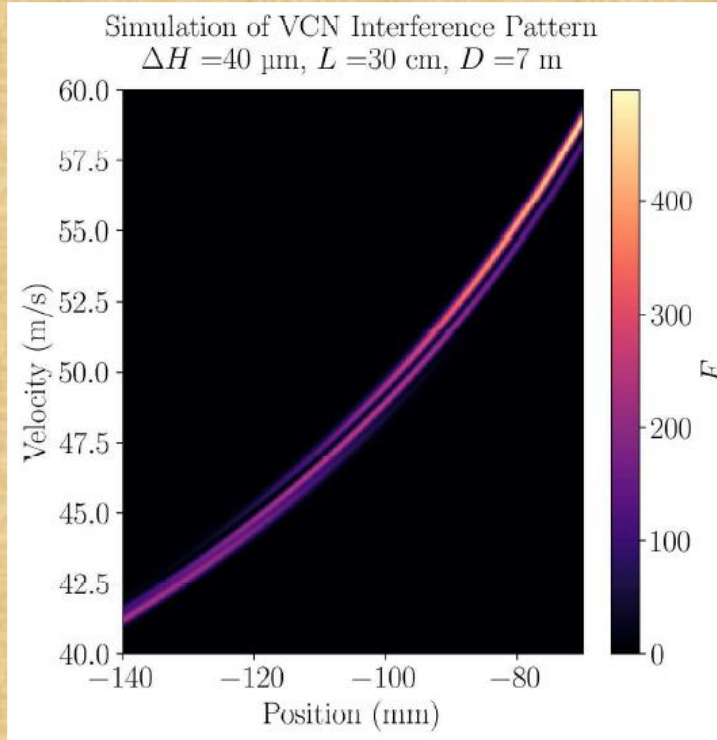
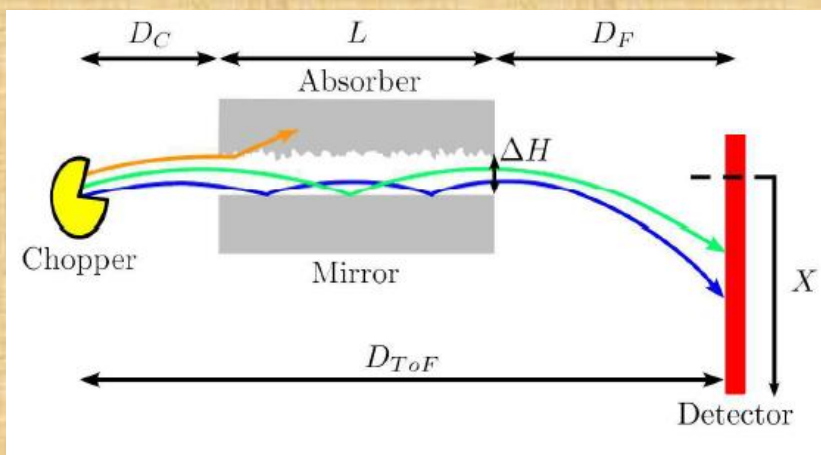


FIG. 3. A simulation of the interference pattern generated by propagating VCN through a mirror-absorber/scatterer system of length $L_{GQS}^{VCN} = 30 \text{ cm}$. The height of the absorber/scatterer is set to $\Delta H_{GQS}^{VCN} = 40 \mu\text{m}$ and the absorber/scatterer is assumed to be very efficient. After exiting the mirror, neutrons enter a free fall region of length $D_{GQS}^{VCN} = 7 \text{ m}$. The velocities presented in the simulation correspond to the peak in the VCN spectrum at the PF2/VCN instrument. Note that a much richer interference pattern can be produced if a position-sensitive detector with better resolution is available or slower neutrons are used.

Simulation, the experiment is scheduled in September 2026.

Comparable in precision to the existing neutron GQS experiments and projects but it's much easier to realize!

GQS of hydrogen atoms ? - nearly the same experimental scheme

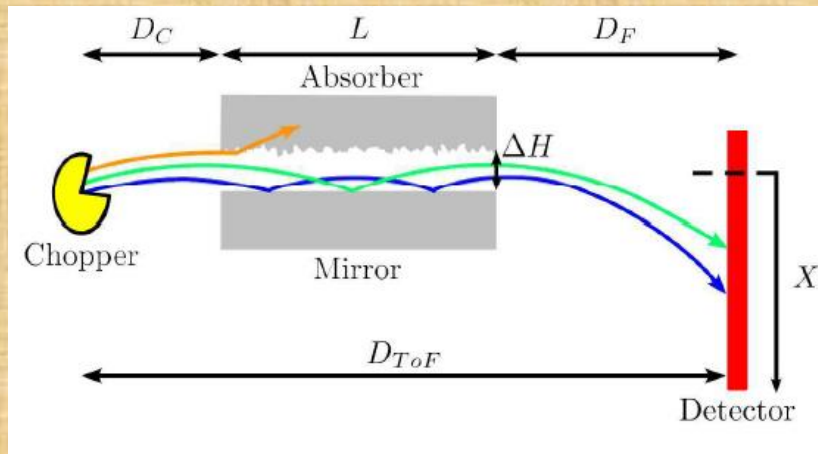
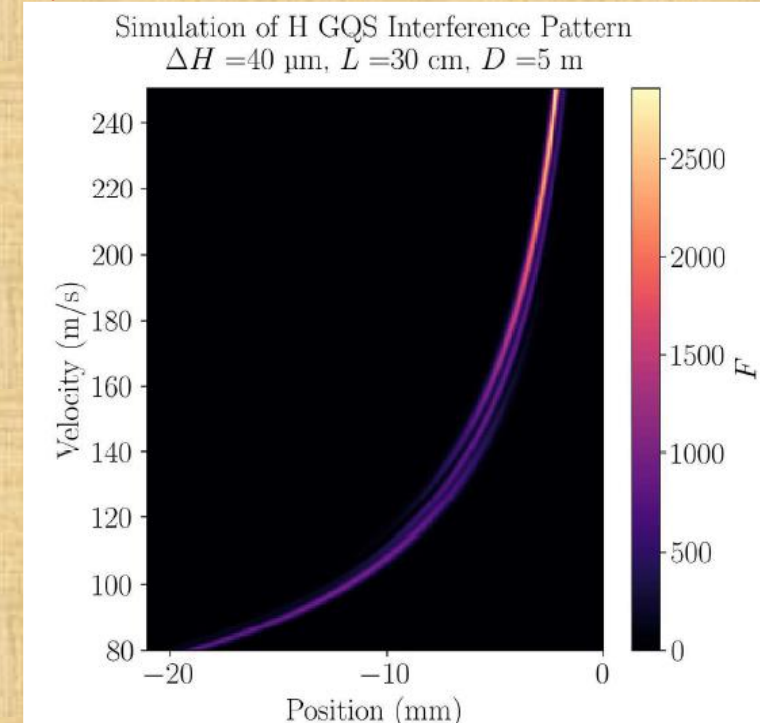


FIG. 8. A simulation of the interference pattern generated by H propagating through a mirror-absorber/scatterer system of the same type as proposed for the VCN GQS measurement. The length of the system is $L_{GQS}^H = 30$ cm and the absorber/scatterer height is $\Delta H_{GQS}^H = 40 \mu\text{m}$. H enters a free fall region of length $D_{GQS}^H = 5$ m after leaving the mirror. Note that, just as it was in the case of proposed experiments with VCN, a much richer interference pattern can be observed if the detector resolution is higher, the distance is larger or/and the velocity is lower.



Simulation

This would be the first demonstration of GQS of atoms. Ongoing experiment, see the talk by Carina Killian.

The characteristic values of acceleration, energy, size and time can be "tuned" by choosing particle mass, velocity as well as mirror radius and inclination (see formulas in slide 10)

We will consider particular applications of this approach

A **motivation** to use **neutron WGS** : a_{WGS} $F_{WGS}^{(n,H,\bar{H})}$ $\tau_{WGS}^{(n,H,\bar{H})}$ until you reach the critical energy (neutron-nuclei optical potential, Fermi potential)

$$a_{WGS} = \frac{v_{WGS}^2}{R_{WGS}}$$

$$E_{WGS} \sim \frac{\hbar}{\tau_{WGS}}$$

$$\tau_{WGS} \sim \left(\frac{2 \cdot \hbar}{m \cdot a_{WGS}^2} \right)^{\frac{1}{3}}$$

$$l_{WGS} \sim \left(\frac{\hbar^2}{2 \cdot a_{WGS} \cdot m^2} \right)^{\frac{1}{3}}$$

$$\gamma_{WGS} \cdot E_{WGS} \sim E_{lim}$$

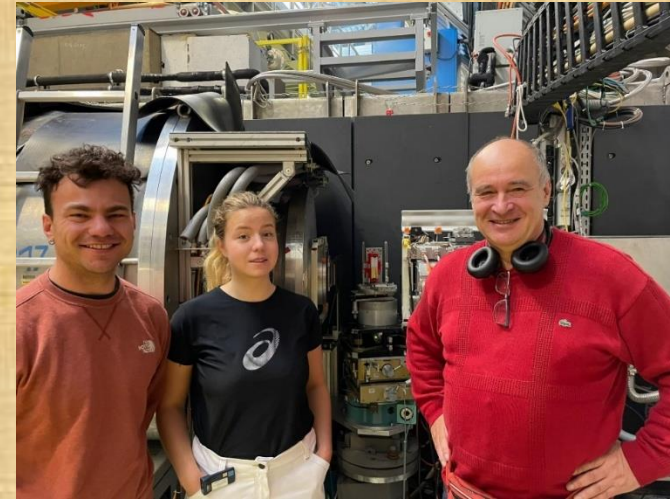
a slight modification for atoms, antiatoms, positronium, muonium: we will define effective critical energy as follows: $(P_{QR}(E_{lim}))^{\beta_{WGS}} \sim 0.5$, in the low energy limit you need to calculate only the effective scattering length. It's sufficient for planning experiments. For the precision analysis, you have to do more sophisticated calculations.

What follows from these very simple arguments?

What follows from these very simple arguments?

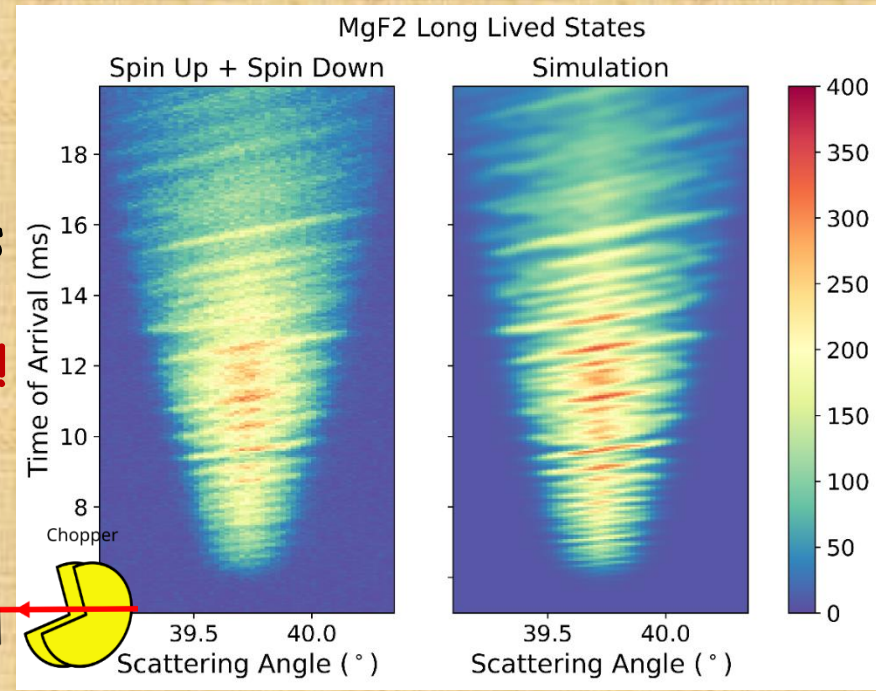
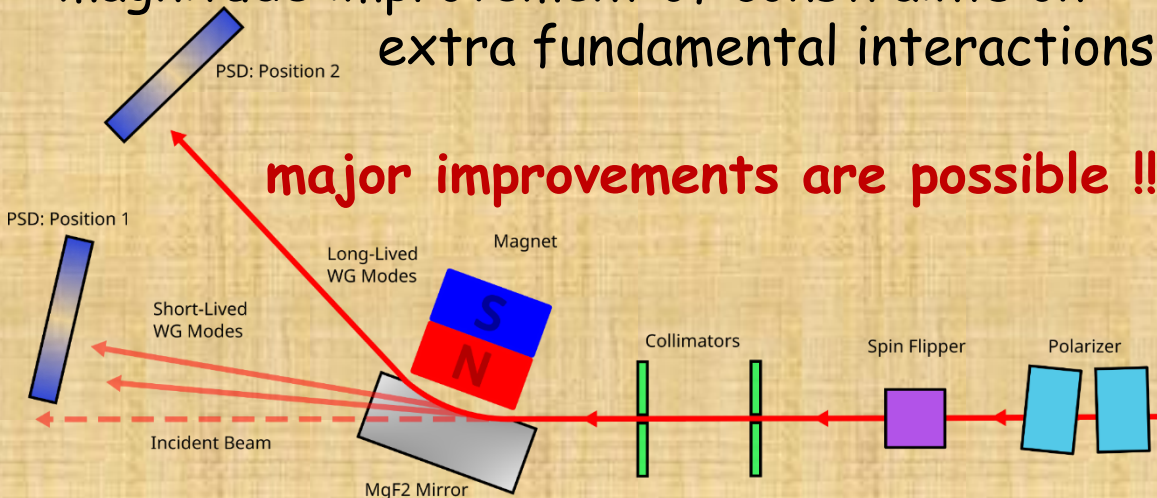
Very detailed interference patterns measured at standard ILL instruments (D17, PF1B, etc)

K. Schreiner PhD, first measurement of a magnetic shift of neutron WGS, the proof of principle for measuring small shifts of $\sim 10^{-6}$ - 10^{-5} .



J. Pioquinto PhD, more than an order of magnitude improvement of constraints on extra fundamental interactions

major improvements are possible !!



The general approach (applied to WGS and GQS of neutrons, hydrogen, antihydrogen, positronium, muonium and other light neutral particles)

The characteristic values of acceleration, energy, size and time can be "tuned" by choosing particle mass, velocity and mirror radius

A motivation to decrease the acceleration value:

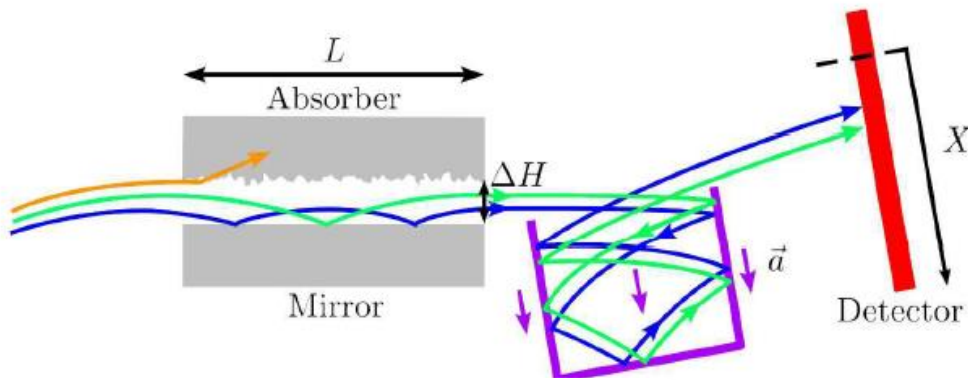
$$l_{GQS}^{UCN} \sim 7.2 \cdot 10^{-5} \text{ m}$$

$$\beta_{GQS}^{UCN} \sim 3 \quad L_{GQS}^{UCN} \sim 1 \text{ m}$$

$$\tau_{GQS}^{UCN} \sim \frac{L_{GQS}^{UCN}}{\beta_{GQS}^{UCN} \cdot V_{GQS}^{UCN}} \sim 1.7 \cdot 10^{-1} \text{ s}$$

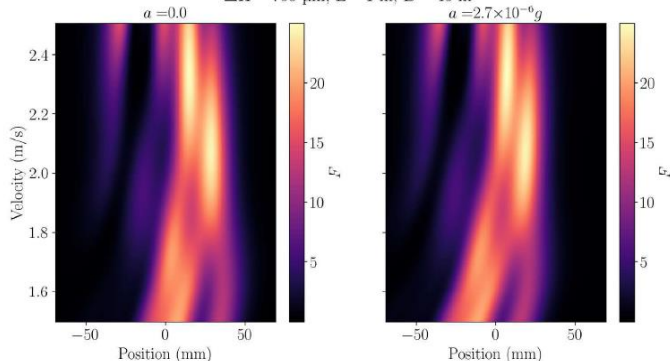
$$g_{reduced} \sim 5.1 \cdot 10^{-3} \text{ m/s}^2$$

$$\Delta\theta \sim 0.52 \text{ mrad}$$



Such an experiment can be built and installed at the PF2/UCN facility at the ILL, or at another UCN facility. It's a long-term project requiring significant efforts; therefore, it might be realized in steps. However, it promises **exceptionally high sensitivity** !

Simulation of UCN Interference Pattern
 $\Delta H = 700 \mu\text{m}$, $L = 1 \text{ m}$, $D = 40 \text{ m}$



Very conservative estimations of its sensitivity:

- A factor of >10 improvement for neutron electric charge $q_n \sim 10^{-22} e$.
- $10^{-4} G$ sensitivity for the gravitational constant

Optimum conditions to measure WGS of hydrogen atoms.

The main difference between atoms and neutrons is **much a lower effective potential**

Therefore, we select

- The lightest atom (hydrogen), thus the most efficient quantum reflection (QR);
- Mirror materials with high effective potential (silica);

Motivations: unprecedented sensitivity and **accuracy of QR measurements**; constraints on **extra fundamental interactions**, etc

PHYSICAL REVIEW A **87**, 012901 (2013)

Quantum reflection of antihydrogen from the Casimir potential above matter slabs

G. Dufour,¹ A. Gérardin,¹ R. Guérout,¹ A. Lambrecht,¹ V. V. Nesvizhevsky,² S. Reynaud,¹ and A. Yu. Voronin³

¹Laboratoire Kastler-Brossel, CNRS, ENS, UPMC, Campus Jussieu, F-75252 Paris, France

²Institut Laue-Langevin (ILL), 6 Rue Jules Horowitz, F-38042, Grenoble, France

³P. N. Lebedev Physical Institute, 53 Leninsky Prospect, Ru-117924 Moscow, Russia

(Received 26 September 2012; published 2 January 2013)

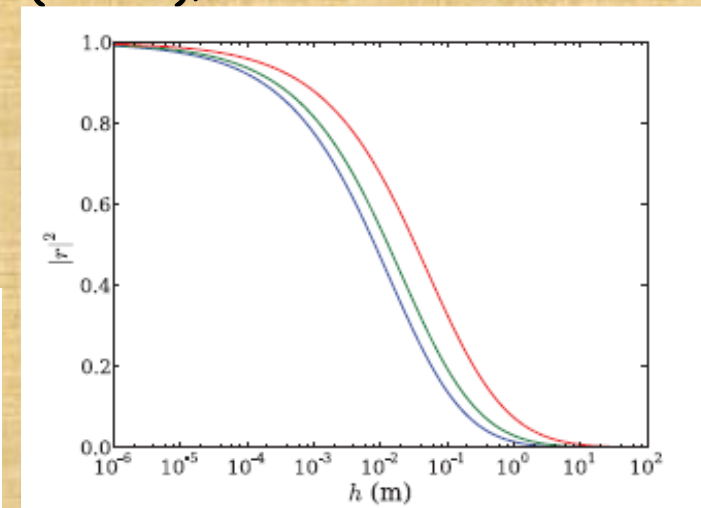


FIG. 2. (Color online) Quantum reflection probability $|r|^2$ as a function of the free-fall height h for $\bar{\text{H}}$ atoms on bulk mirrors; from bottom to top, perfect mirror (blue), silicon (green), and silica (red).

Optimum conditions to measure WGS of hydrogen atoms.

$$E_{lim}^H \sim 1.2 \cdot 10^{-11} \text{ eV}$$

Many quasi-classical bounces and quantum states

$$\beta_{WGS}^H \sim 10$$

$$\gamma_{WGS}^H \sim 3 + N$$

Thus, a short time of formation of WGS

$$\tau_{WGS}^H = \tau_{GQS}^H \frac{\gamma_{WGS}^H \cdot E_{GQS}^H}{E_{lim}^H} \sim 2.5 \cdot 10^{-4} \text{ s}$$

and a huge gravitational shift

$$a_{WGS}^H \sim g \cdot \left(\frac{\tau_{GQS}^H}{\tau_{WGS}^H} \right)^{1.5} \sim 9.0 \cdot 10^1 \text{ m/s}^2$$

$$\frac{g}{a_{WGS}^H} \sim 1.1 \cdot 10^{-1}$$

To use the same experimental setup as that for H GQS :

$$L_{WGS}^H = 0.3 \text{ m}$$

Then

$$V_{WGS}^H \sim \frac{L_{WGS}^H}{\beta_{WGS}^H \cdot \tau_{WGS}^H} \sim 1.2 \cdot 10^2 \text{ m/s}$$

and

$$R_{WGS}^H \sim \frac{(V_{WGS}^H)^2}{a_{WGS}^H} \sim 1.6 \cdot 10^2 \text{ m}$$

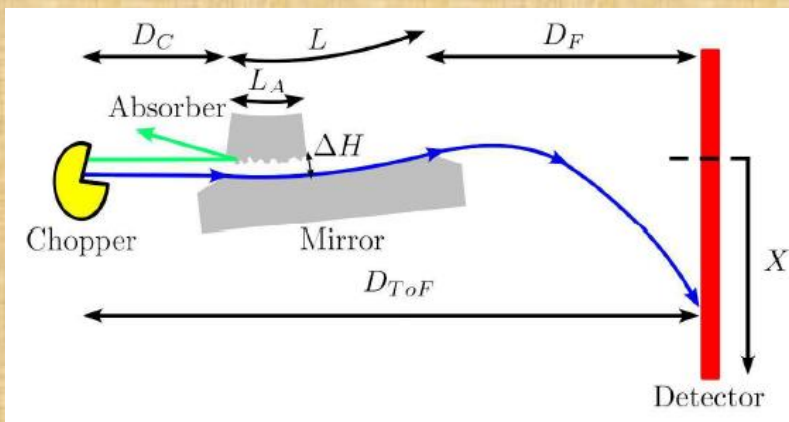


FIG. 7. A schematic of the H WGS experiment. A collimated beam of H enters the system through a chopper, placed a distance D_C away from the entrance of the mirror, which enables the measurement of the velocity of H atoms by the time of flight (ToF) method. The beam then enters the mirror absorber/scatterer system. Lower energy WGS can pass through the initial section where an absorber/scatterer of length L_A is placed a height ΔH above the mirror, while higher WGS are rejected. The lower WGS then propagate along the surface and interfere with each other until reaching the end of the mirror, which has a total length L . The exiting beam enters a free fall region where a time and position sensitive detection system is placed a distance D_F from the exit of the mirror. The position of the H atom on the detector is denoted as X .

To discuss the feasibility and experimental details, please, see the Poster presented by K. Schreiner

Depending on the spatial resolution of the detector and the time resolution of the chopper, we can choose the **slit size** between the mirror and the absorber/scatterer, and thus the complexity of the interference pattern.

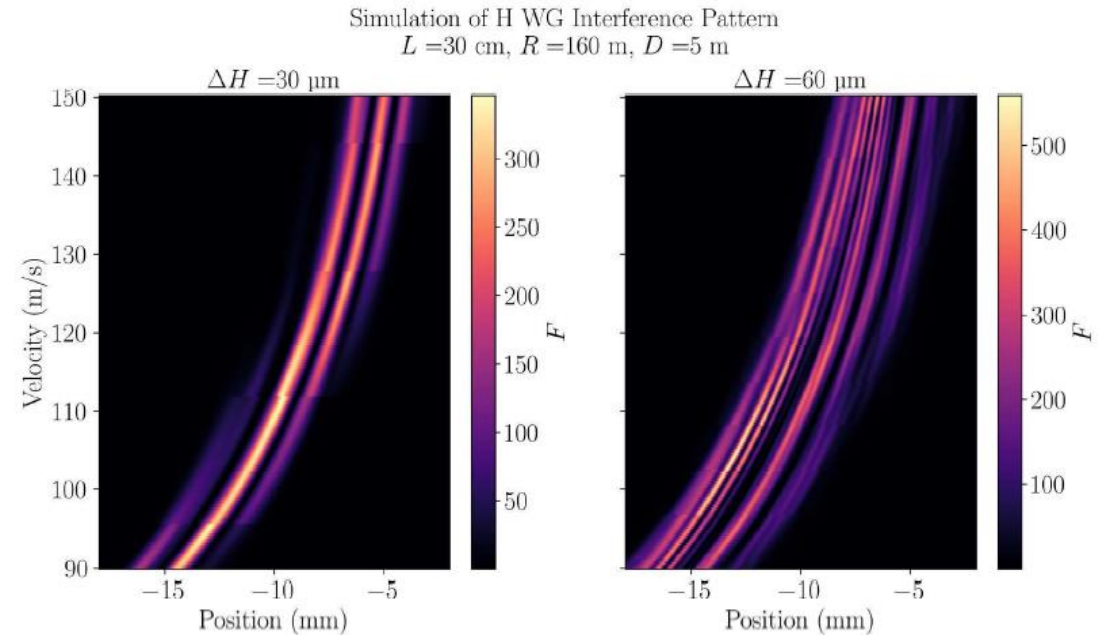


FIG. 6. Simulations of the expected interference pattern for the cylindrical mirror with a radius $R_{WGS}^H = 160$ m and a length $L_{WGS}^H = 30$ cm. Two scenarios are shown, each with an absorber/scatterer of length $(L_A)_{WGS}^H = 3$ cm placed at a height $\Delta H_{WGS} = 30$ μm and $\Delta H_{WGS} = 60$ μm above the beginning of the mirror. An incident plane wave is assumed to enter the gallery with no incidence angle and is propagated through the gallery by solving the Schrödinger equation. The wave packet at the exit of the gallery is then propagated through a free fall region of length $D_{WGS}^H = 5$ m. This image does not consider the velocity distribution of the H beam, nor the resolution effects of the detection system. The gravitational acceleration points downwards, and the origin corresponds to the edge at the exit of the gallery.

Acceptable conditions to measure WGS of antihydrogen atoms.

You have just seen a scheme of an "easy" experiment with WGS of hydrogen atoms and a huge gravitational shift. What is the maximum velocity of hydrogen and antihydrogen which still allows to measure a gravitational shift?

A very large mirror $L_{WGS}^{\bar{H}} \sim 1 \text{ m}$

A very large mirror radius $R_{WGS}^{\bar{H}} \sim 10^4 \text{ m}$

To increase the effective critical energy we limit the number of quasi-classical bounces $\beta_{WGS}^{\bar{H}} \sim 5$ and select $\gamma_{WGS}^{\bar{H}} \sim 3 + 2$

For these parameters of the quantum states:

$$E_{lim}^{\bar{H}} \sim 2.0 \cdot 10^{-10} \text{ eV}; \quad a_{WGS}^{\bar{H}} \sim 5.4 \cdot 10^3 \text{ m/s}^2; \quad V_{WGS}^{\bar{H}} \sim 7.4 \cdot 10^3 \text{ m/s}$$

And the gravitational shift is $\sim 1.8 \cdot 10^{-3}$

Acceptable conditions to measure WGS of antihydrogen atoms.

In contrast to measurements with hydrogen, here we measure the point of annihilation of antihydrogen atom in the mirror; even for the extreme case of largest antihydrogen velocities (simulation on the right) requirements for the spatial resolution of the detector could be easily met

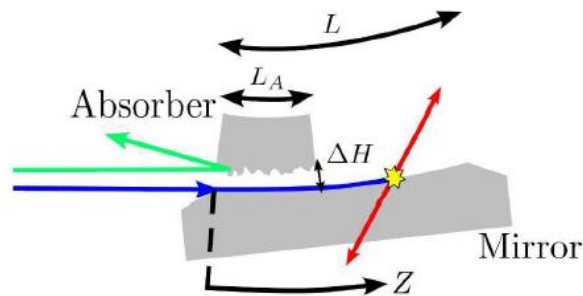
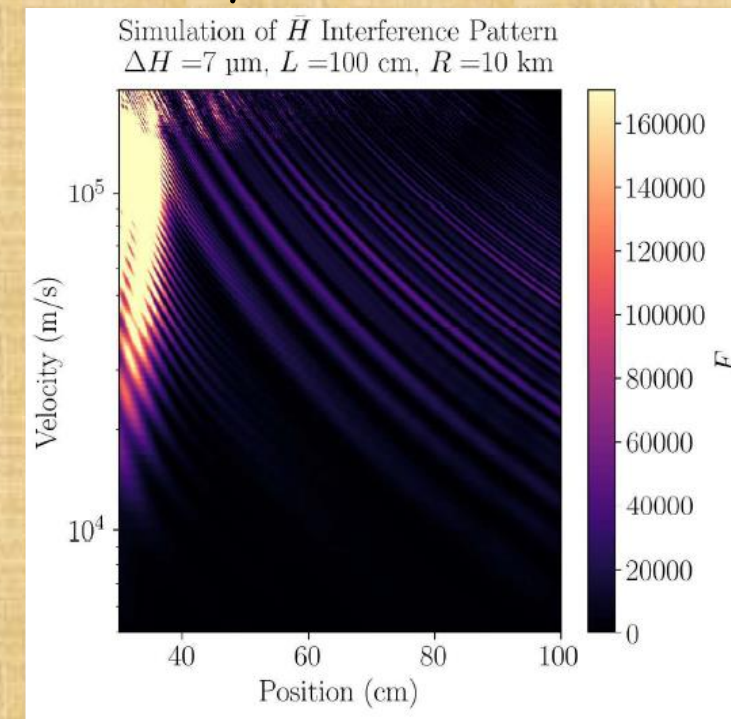


FIG. 9. A schematic of the $\bar{\text{H}}$ WGS experiment. A collimated monochromatic beam of $\bar{\text{H}}$ enters the mirror absorber/scatterer system. Like with the H WGS set-up before, an absorber/scatterer of length L_A is placed a height ΔH above the mirror and filters out higher energy WGS. The surviving WGS propagate along the surface and interfere over the mirror of length L . The $\bar{\text{H}}$ atoms which are not reflected by the Casimir-Polder interaction will reach the surface and annihilate. The position Z of this annihilation event is taken as the signal and is experimentally determined by recording the trajectories of the annihilation products. The predicted annihilation rate can be taken as the probability current of the $\bar{\text{H}}$ wave function at the mirror surface,



Muonium ?

A limitation - its short lifetime

$$\tau^{Mu} \sim 2.2 \cdot 10^{-6} \text{ s}$$

But !! Low velocity

$$V_{WGS}^{Mu} \sim 2.2 \cdot 10^3 \text{ m/s}$$

and sufficient monochromaticity

$$\delta V^{Mu} \sim 5 \cdot 10^1 \text{ m/s}$$

Moreover, due to a smaller mass efficiency of QR and a significantly larger critical energy

$$m^{Mu} \sim 0.113 \cdot m^{n,H,\bar{H}}$$

a largely improved

We can perform our standard optimization procedure and get

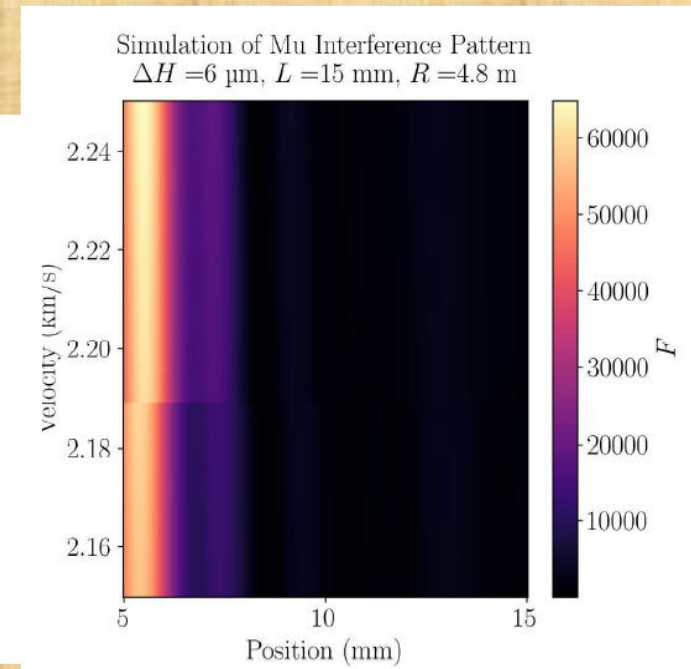
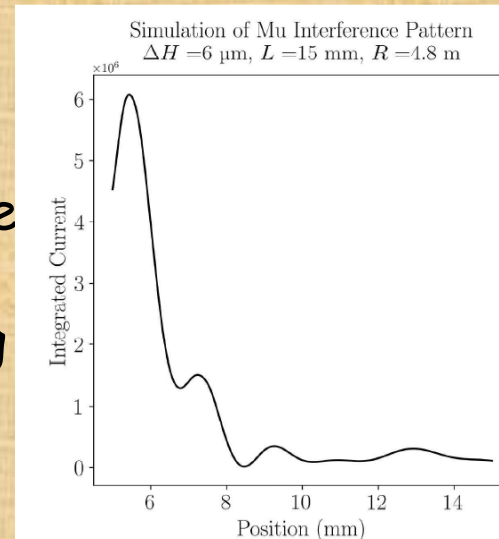
$$R_{WGS}^{Mu} \sim 4.8 \text{ m}$$

$$\frac{g}{a_{WGS}^{Mu}} \sim 10^{-5}$$

WGS measurements are feasible

Gravitational shift is challenging

A detection scheme to be developed



Positronium ?

Lifetimes of highly excited states are sufficiently long

$$\tau^{Ps,n=33} \sim 10^{-5} \text{ s}$$

Available velocities are close to acceptable

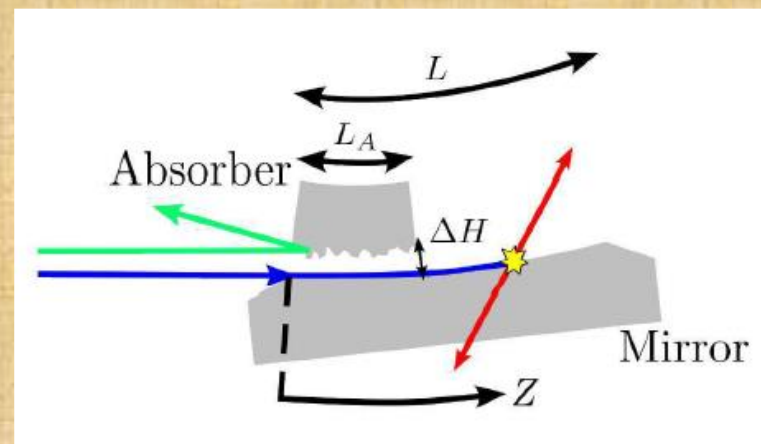
$$V^{Ps} \sim 5 \cdot 10^4 \text{ m/s}$$

Due to the much smaller mass, the QR is very efficient

For $L_{WGS}^{Ps,n=33} \sim 0.5 \text{ m}$ $\beta_{WGS}^{Ps,n=33} \sim 3$ a gravitational shift is $\frac{g}{a_{WGS}^{Ps,n=33}} \sim 5.5 \cdot 10^{-6}$ and $R_{WGS}^{Ps,n=33} \sim 1.4 \cdot 10^3 \text{ m}$

A scheme is the same as for antihydrogen

Promising! A "fine tuning" of parameters is still needed



- We developed a simple **method of optimizing experiments** that rely on various shifts of interference patterns formed by whispering-gallery and gravitational quantum states of various particles and atoms;
- We propose parameters which allow the observation of **whispering gallery states of muonium and positronium**;
- Proposed neutron interferometers can be used to improve constraints on **neutron electric charge** and measure the **gravitational constant**;
- The proposed atomic WGS experiments promise **unprecedented sensitivity and accuracy in studies of quantum reflection**;
- Measurement of a **gravitational shift** are possible with antihydrogen atoms of up to $\sim 10^4$ m/s;
- Measurements of a **gravitational shift** might be possible with available **positronium** sources, however, an optimization of such an experiment is still to be done;
- A major further progress is possible in constraining **extra fundamental interactions** in various realizations discussed in this talk (in particular with neutrons and hydrogen)