A compact penning trapped ion system for precision measurement

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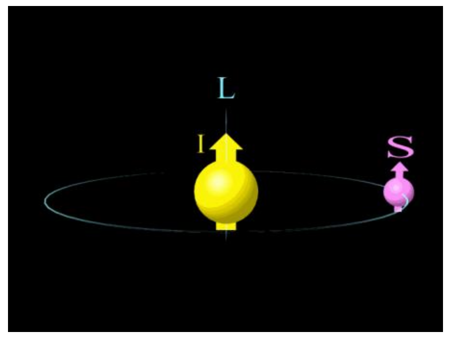
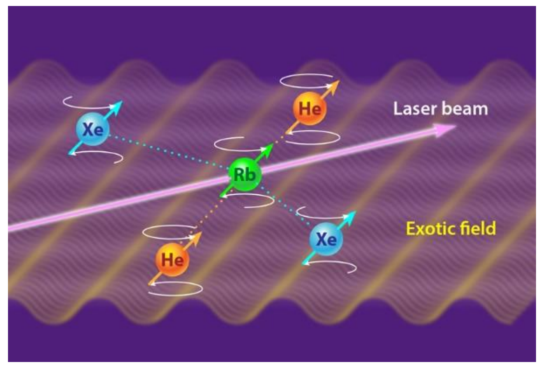
1. Motivation of the study and the basic principle of Penning trapped ions

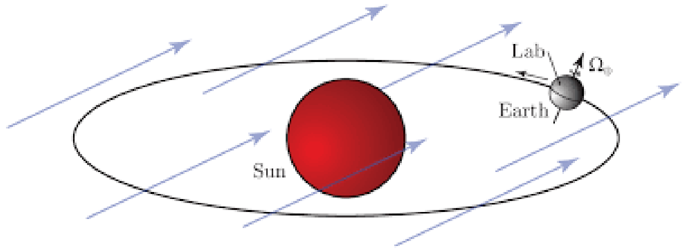
Motivation: Rotation sensing with Quantum sensors.

Atomic Spins as a Gyroscope



1. **Spin owns angular moment. The quantity of the moment is integer or half integer of the Planck constant h.**
2. **The spins are a kind of quantum rotors.**
3. **Nuclear spins could be utilized for rotation sensing. This is the atomic spin gyroscope.**

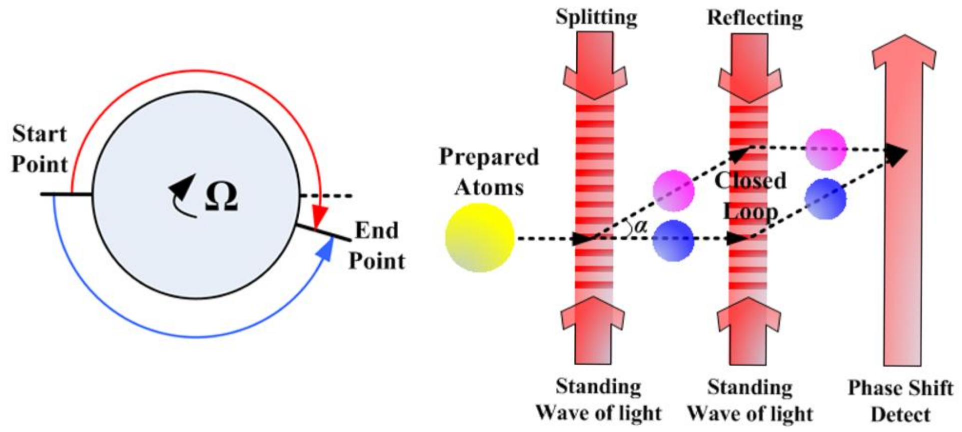




An atomic spin gyroscope could be utilized for testing new physics such as: CPT symmetry.

An atomic interference gyroscope:The Sagnac Effect in cold atoms

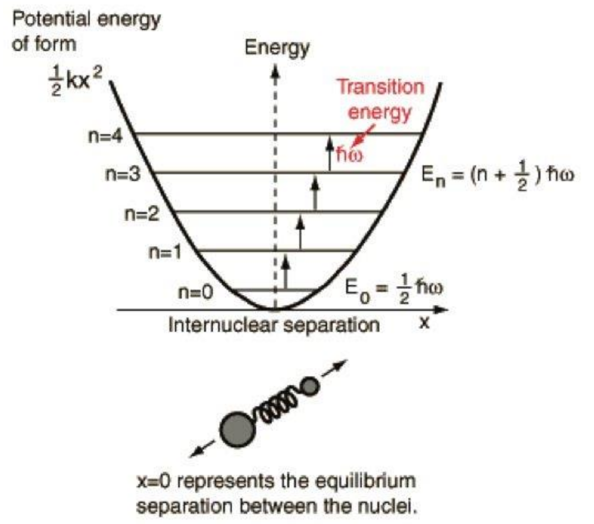
1. **The cold atomic beam -- the matter wave.**
2. **Matter wave just like light could be utilized for interference.**
3. **Rotation induced Sagnac phase shift could be measured.**



An atomic interferometer gyroscope.

Is there a quantum sensor which is similar to the vibration gyroscope?

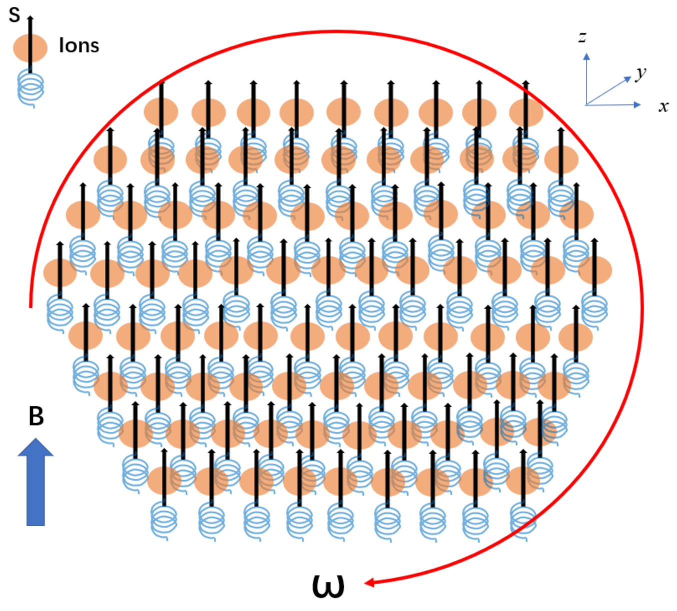
1. **Quantum harmonic oscillators could be used to form a gyroscope.**
2. **Two oscillators should be coupled together to form the gyroscope.**



The quantum harmonic model.

Motivation: New sensor development

Penning trapped ion crystals may form three dimension quantum harmonic oscillators.



1. The ions crystal is trapped by a constant magnetic field B and a quadrupole electric field. The magnetic field traps the ions in the x and y plane.
2. The quadrupole electric field traps the ions in the z direction.
3. Due to the E×B effect, the ions will rotate about B with rotation velocity ω.
4. The Calcium ions utilized in our experiment owns an electron spin S which could be utilized the detect the Coriolis force.

1. Driving oscillators: the x and y direction oscillators(This direction forms spherical oscillator).
2.The sensing oscillator: the z direction, this direction could also form a drum mode.

We can change the traditional harmonical mass into 2D ion crystal. New kind of sensors such as acceleration and rotation measurement could be measured.

2. The design of a quantum vibrational gyroscope

The design of a quantum vibrational gyroscope

Try to start with a single particles

1. **The motion of the particle can be described**

$$m\frac{d^2[x(t),y(t),z(t)]}{dt^2} = eV\frac{\nabla[2z(t)^2-y(t)^2-x(t)^2]}{4{z_0}^2}$$

The acceleration of the ions.

The force from the electric field

$$-e[x(\dot{t}),y(\dot{t}),z(\dot{t})]\times\vec{B} - 2m\vec{\Omega}\times[x(\dot{t}),y(\dot{t}),z(\dot{t})]$$

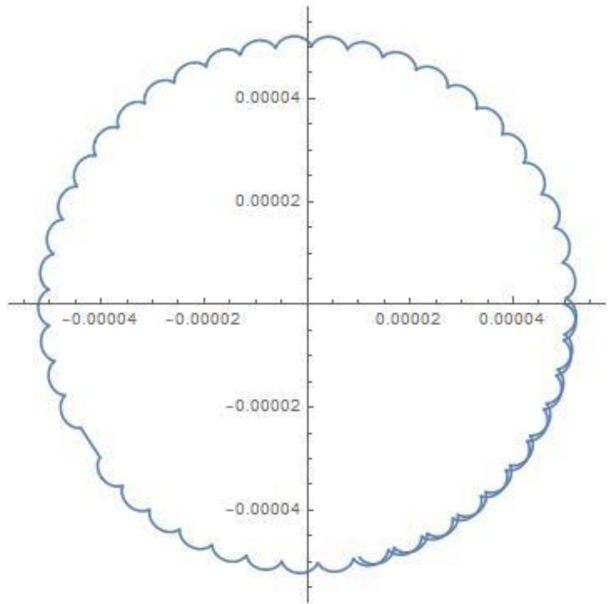
The Lorentz Force

The Coriolis Force

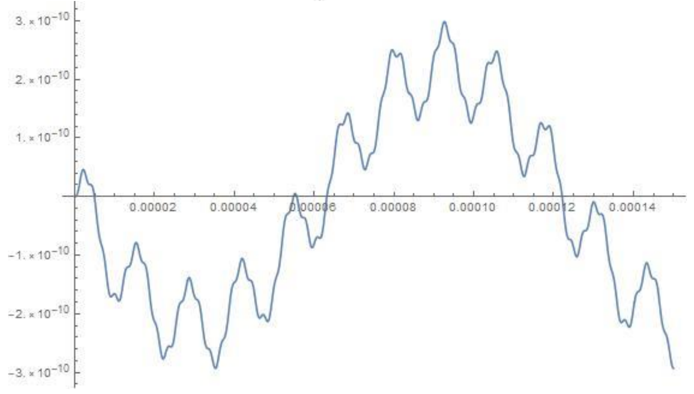
The Numerical solution of the equation:

For Calcium ions,
m=40, V=10V, B=1T,
z_0=0.01m,r_0=2^0.5 z_0

Cyclotron frequency : f_c=383KHz
Axial frequency : f_z=78KHz
Magnetron frequency : f_m= 8KHz



The motion in the x and y plane



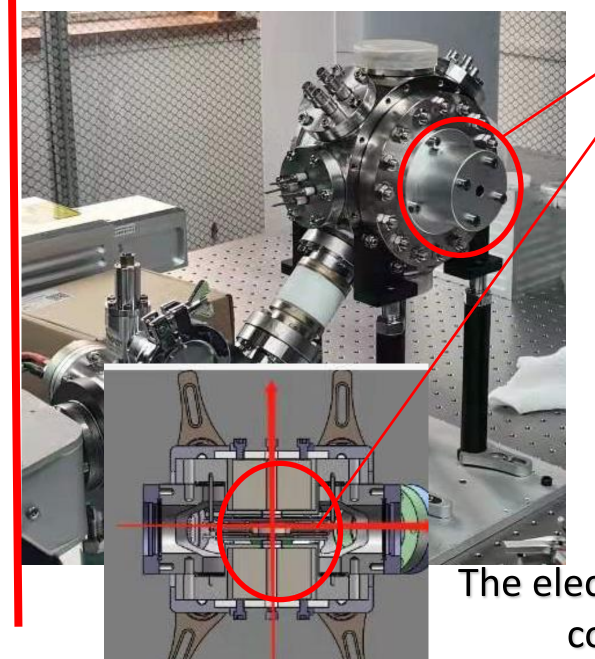
The motion in the z direction

1.The single particle has a problem: The amplitude in the z direction is very small(On the order of 10^{-10} m with a typical angular velocity input).
2. The resonance frequency in the z direction is f_z=78KHz which is much larger than the magnetron motion frequency f_m=8KHz.
3. If f_z=f_m, the motion amplitude in the z direction will be much larger.

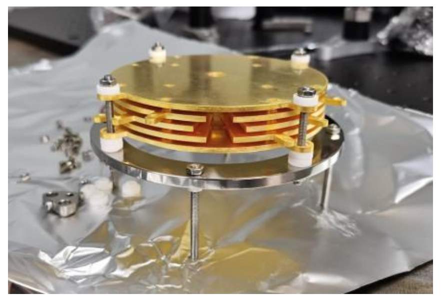
How we can achieve this?

Ion crystal+Rotation Wall driving(the driving frequency is ω_r) of the crystal.

1. The ion crystal frequency could be controlled by the quadrupole rotating wall drive. The ion rotation frequency should be the same as the driving frequency.
2. The driving frequency could be the same as the axial frequency.
3. The axial quantum oscillator owns a high Q wich is on the order of 10^6.



Compact permanent Magnet. 0.001m³.



The electrodes which is used in our compact Penning trap.