Testing the weak equivalence principle using gravitationally bound quantum states of ultracold neutrons

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In the previous PSI 2016 workshop, I got a chance to make a presentation with the title of

Search for new gravity-like interactions and test of the equivalence principle using slow neutrons

Yoshio Kamiya, Koji Yamada, Kenta Uchida, Yoshihiro Sasayama, Keita Itagaki, Misato Tani, Go Ichikawa, Sachio Komamiya, and Guinyun Kim

The Univ. of Tokyo / Kyungpook Nat. Univ.

Physics of fundamental Symmetries and Interactions, Switzerland - 2016 Oct.
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Equivalence Principle

“main target” It is said Sake “酒”

this talk

It is said Sakana “肴”
Special Things on Gravity

Gravity is the very common force experienced in everyday life, however the most unusual from the view of particle physics.

- Extremely weak!

Gravity between protons is weaker than Coulomb force by $10^{-36}$

Electroweak scale $\sim 0.1 \text{ TeV}$ (Vacuum Expectation Value of the Higgs)
Gravitational Interaction scale $\sim 10^{16} \text{ TeV}$ (the Planck mass)

Question 1

Is there any force with intermediate strength? — fifth force search experiment

Special Things on Gravity

Gravity is the very common force experienced in everyday life, however the most unusual from the view of particle physics.

- Geometry! as a result of the equivalence between inertial and gravitational mass
  Weak Equivalence Principle (WEP)

The WEP have been experimentally confirmed by several tests.

Question 2

Is there any observation of quantum effects due to the gravitational field?

There were not so many.

Question 3

Is the weak equivalence principle OK in the framework of quantum mechanics?

- test of WEP with quantum system
- test of quantum effect due to gravity by measuring gravitationally bound quantum state of UCNs

Special Things on Gravity

Gravity is the very common force experienced in everyday life, however the most unusual from the view of particle physics. Very attractive!

• Geometry! as a result of the equivalence between inertial and gravitational mass

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— test of WEP with quantum system

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— test of quantum effect due to gravity by measuring gravitationally bound quantum state of UCNs

How Trapped UCNs in Gravity Look Like?

When you spill UCNs on the floor, they bounce like balls due to their small kinetic energy.

Schrodinger equation for UCNs under the gravity

\[ \left\{ -\frac{\hbar^2}{2m} \frac{d^2}{dz^2} + V(z) \right\} \psi_n(z) = E_n \psi_n(z), \]

where \[ V(z) = \begin{cases} mgz, & z \geq 0 \\ \infty, & z \leq 0 \end{cases} \]

Dimensionless equation is written as a function of \( \xi_n \equiv z/z_0 - E_n/E_0 \)

\[ \left( \frac{d^2}{d\xi_n^2} - \xi_n \right) \psi_n(\xi_n) = 0 \]

where the system’s scales,

\[ z_0 = \left( \frac{\hbar^2}{2m^2 g} \right)^{1/3} \sim 6 \mu m \]
\[ E_0 = \left( \frac{mg^2 \hbar^2}{2} \right)^{1/3} \sim 0.6 \text{ peV} \]

Classical turning points \( z_n \equiv z_0 E_n/E_0 \) \( (\xi_n = 0) \)
Gravitationally Bound Quantum States of UCNs

V. V. Nesvizhevsky et al., Nature 415, 297 (2002)

Exp. Setup

They measured neutron transmission through this thin neutron guide as a function of the height.

Neutron Guide:

- length = 10 cm
- height = ~ several tens microns

The ceiling scatter neutrons on higher energy states.

If the quantum states are formed in the guide,

When the height is equal to the spatial width of the lowest quantum state, the transmission would increase sharply.

The data shows a sharp step around 13 micron height
Gravitationally Bound Quantum States of UCNs


Exp. Setup

They directly measured neutron distribution using a position sensitive neutron detector with the fixed height. to avoid uncertainties which come from a modeling of the ceiling.

Detector: $^{235}\text{U}$ coated CR39 (plastic)

V.V. Nesvizhevsky et al., NIM A 440, 754 (2000)

<Principle>

Daughter nuclei from nuclear fission are make defects on the CR39.

The defects are enlarged by chemical etching.

Measure the points using microscope.

Spatial resolution is said to be about 1 micron.
Gravitationally Bound Quantum States of UCNs


Exp. Setup

They directly measured neutron distribution using a position sensitive neutron detector with the fixed height. to avoid uncertainties which come from a modeling of the ceiling.

Figure 2. Layout of the experiment. The limitation of the vertical velocity component depends on the relative position of the absorber and mirror. To limit the horizontal velocity component we use an additional entry collimator. The relative height and size of the entry collimator can be adjusted.

Figure 4. Position sensitive detector for ultra-cold neutrons.
Gravitationally Bound Quantum States of UCNs

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The defects are enlarged by chemical etching.
Measure the points using microscope.

Spatial resolution is said to be about 1 micron.

We have been impressed by these experiments, so we started new attempts to image this UCN distribution.
Measurement of CCD-based Imaging Detector


Exp. Setup

CCD-based Imaging Detector


Position meas.: 3 microns

Timing meas.: ~ sec

Magnification Rod

magnify the neutron distribution using glass rod by 17~40 times

Exp. Setup

(a) Magnetic shield

Gran ite table

Anti−vibration table

Vacuum chamber

UCN

Helium

Neutron shutter

(b) Collimating guide

Pixelated detector

Magnification rod (3 mm radius)

Ceiling 100 µm

Bottom mirror

Magnification Rod

(calc.)

height

M

0 10 20 30 40 50 60 70 80 90 100

z (µm)

20 40 60 80 100

magnification

15 20 25 30 35 40 45

M (   m)

µmagnification

~ 12 mm

-20

20°

z-axis

~ 2.5 mm

200 mm

100 µm

3 mm
Measurement of CCD-based Imaging Detector

Measurement of CCD-based Imaging Detector


Measurement
(a) expectations from quantum mechanics
(b) expectations from quantum mechanics (zoomed in)
(c) expectations from classical mechanics
consistent with quantum mechanics $\chi^2$/NDF = 0.96

Crosses : data / Histograms : model fittings

Modulated distribution due to quantum effects is clearly measured!!
Treatment of Reflection on a Cylindrical Surface

In the classical manner,
Reflection direction is determined by giving an incident position $z$ and momentum (angle) $P_z$ at the same time.

In the quantum manner?
We cannot give $z$ and $P_z$ simultaneously.
(in usual Hilbert space formulation.)

Utilize the Wigner pseudo probability distribution
(another formulation of quantum mechanics in phase space)

Definition

$$W(z, p_z) \equiv \frac{1}{2\pi\hbar} \int_{-\infty}^{\infty} d\eta \ e^{-\frac{i}{\hbar} p_z \eta} < z + \frac{1}{2}\eta | \hat{\rho} | z - \frac{1}{2}\eta >$$

Characteristics

Probability distribution of the position is given by integrating with momentum (projecting to an axis of position)

$$\int_{-\infty}^{\infty} dp_z W(z, p_z) = < z | \hat{\rho} | z >$$

Expectation value is given by integrated with the weight of the Wigner distribution

$$< \hat{A} > = \text{Tr}(\hat{\rho}\hat{A})$$

$$= \int_{-\infty}^{\infty} dz \int_{-\infty}^{\infty} dp_z A(z, p_z) W(z, p_z)$$

$$A(z, p_z) \equiv \int_{-\infty}^{\infty} d\eta \ e^{-\frac{i}{\hbar} p_z \eta} < z + \frac{1}{2}\eta | \hat{A} | z - \frac{1}{2}\eta >$$

The distribution evolves according to the Liouville equation of classical statistical mechanics.

Liouville - von Neumann Equation

\[ \frac{\partial \hat{\rho}}{\partial t} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] \]

Evaluating the time evolution of the Wigner distribution with

\[ \hat{H} = \frac{\hat{p}_z^2}{2m} + V(\hat{z}) \]

\[ \left( \frac{\partial}{\partial t} + \frac{p_z}{m} \frac{\partial}{\partial z} - \frac{dV(z)}{dz} \frac{\partial}{\partial p_z} \right) W(z, p_z) = \sum_{l=1}^{\infty} U_l(z, p_z) \]

Here, \( U_l(z, p_z) = \frac{(-1)^l (\hbar/2)^{2l}}{(2l + 1)!} \frac{d^{2l+1} V(z)}{dz^{2l+1}} \frac{\partial^{2l+1}}{\partial p_z^{2l+1}} W(z, p_z) \)

Since the right side term contains the higher derivatives of the potential,

in our case, under the gravity of \( V(z) = mgz \), \( \sum_{l=1}^{\infty} U_l(z, p_z) = 0 \)

The distribution evolves according to the Liouville equation of classical statistical mechanics.

\[ \left( \frac{\partial}{\partial t} + \frac{p_z}{m} \frac{\partial}{\partial z} - \frac{dV(z)}{dz} \frac{\partial}{\partial p_z} \right) W(z, p_z) = 0 \]
Description of the Quantum System by the Winger Distribution

(a) Population distribution of the states 
and (b) the Wigner distribution
at the end of the guide (region 3)

Negative probability reflects quantum effects

The time evolution and projection give the spacial distribution on the detector.
Measurement of CCD-based Imaging Detector


**Measurement**
(a) expectations from quantum mechanics
(b) expectations from quantum mechanics (zoomed in)
(c) expectations from classical mechanics

consistent with quantum mechanics  \( \chi^2 / \text{NDF} = 0.96 \)

Crosses: data / Histograms: model fittings

**Now we have got a quantum system which couples to gravity!!**
Measurement of CCD-based Imaging Detector


**Scales of the system**

$$z_0 = \left( \frac{\hbar^2}{2m^2g} \right)^{1/3} \approx 6 \, \mu m$$

$$E_0 = \left( \frac{mg^2\hbar^2}{2} \right)^{1/3} \approx 0.6 \, \text{peV}$$

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consistent with quantum mechanics \( \chi^2 / \text{NDF} = 0.96 \)

Crosses : data / Histograms : model fittings

We can evaluate the mass ratio \( \eta = \frac{m_g}{m_i} \) by measuring length and energy scales simultaneously!!

**Measurement**

\[
\begin{align*}
z_0 & = \left( \frac{\hbar^2}{2m^2g} \right)^{1/3} \sim 6 \text{ µm} \\
E_0 & = \left( \frac{mg^2\hbar^2}{2} \right)^{1/3} \sim 0.6 \text{ peV} \\
\end{align*}
\]

\[
\begin{align*}
\frac{z_0}{\hbar^2} & \sim 6 \text{ µm} \\
\frac{E_0}{\hbar^2} & \sim 0.6 \text{ peV} \\
\end{align*}
\]

\( \hbar \): Planck’s constant
\( m \): mass
\( g \): gravitational acceleration

**Scales of the system**

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\end{align*}
\]

\( m_g \): gravitational mass
\( m_i \): inertial mass
The step changes the eigenstates (basis of the Hilbert space) of this quantum system.

\[
\psi_{(z,t=0)} = a_1 \phi_1(z) + a_2 \phi_2(z)
\]

\[
|\psi_{(z,t)}|^2 = |\psi_{(z,t=0)}|^2 - 4a_1 a_2 \phi_1(z) \phi_2(z) \sin^2 \left( \frac{\varepsilon_2 - \varepsilon_1}{2} t \right)
\]

How to Measure the Two Scales Simultaneously?

- **length scale** is measured by seeing spacial distribution of neutrons directly
- **energy scale** is evaluated by measuring oscillation frequencies between the states

developing with the group of

Giuseppe Iacobucci

Riken

The Geneva University

Yutaka Yamagata

UCNs guide (ceiling) 15 microns step detector

UCNs guide (floor) chopper collimator

non-adiabatic transition

oscillate here

anti-vibration table

feedthrough

[Giuseppe Iacobucci, Yutaka Yamagata]

Time-resolving imaging detector

- length scale
- energy scale
How to Measure the Two Scales Simultaneously?

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Giuseppe Iacobucci
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\[
\psi(z,t=0) = a_1 \phi_1(z) + a_2 \phi_2(z)
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\[
|\psi(z,t)|^2 = |\psi(z,t=0)|^2 - 4a_1a_2\phi_1(z)\phi_2(z) \sin^2 \left( \frac{\varepsilon_2 - \varepsilon_1}{2} \right) t
\]

energy scale
oscillating term

Time-resolving imaging detector
- **length scale** is measured by seeing spacial distribution of neutrons directly.
- **energy scale** is evaluated by measuring oscillation frequencies between the states.

UCN guide (ceiling)
UCN guide (floor)
UCNs
15 microns step
detector
anti-vibration table
feedthrough
Our previous detector: CCD based
- Position resolution: 3 microns
- Readout time: ~ sec

Not enough :-(

Time-resolving Imaging Detector for UCNs
Time-resolving Imaging Detector for UCNs

Our previous detector: CCD based
- Position resolution: 3 microns
- Readout time: ~ sec
- Not enough :-(

New detector design: CMOS based
- Position resolution: a few microns (expected.)
- Readout time: ~ msec
- Looks OK! :-)

Charge sharing? Charge overflow?
Detector Design

We follow the concepts of our previous CCD-based detector: $^{10}$B coated HAMAMATSU back-illuminated CCD

Pixel size : 24 microns

UCN converts to charged particles in the $^{10}$B layer

\[
\text{n}+^{10}\text{B} \rightarrow \begin{cases} 
\alpha(1.47 \text{ MeV}) + ^7\text{Li}^*(0.84 \text{ MeV}) \\
\rightarrow ^7\text{Li}(0.84 \text{ MeV}) + \gamma(0.48 \text{ MeV}) \\
\alpha(1.78 \text{ MeV}) + ^7\text{Li}(1.01 \text{ MeV}) 
\end{cases} \quad (93.9 \%) \\
\quad (6.1 \%)
\]

Position meas.: 3 microns
Timing meas.: $\sim$ sec

Sandwich (double-sides) Configuration

When you measure the two decay products, spatial resolution improves.

two body decay

\[
\begin{align*}
n + ^{10}\text{B} & \rightarrow \begin{cases} 
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\alpha(1.78 \text{ MeV}) + ^{7}\text{Li}(1.01 \text{ MeV})
\end{cases} 
\end{align*}
\]

(93.9 %) (6.1 %)

position resolution (microns)

previous detector (CCD-based)

single-side

double-sides configuration

simulation

readout noise (microns-equiv.)
Thank you!