qBOUNCE: Ultra-cold neutrons bound by Earth’s gravity field, a tabletop search for hypothetical gravity-like interactions

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The Universe

Planck Data 2018

DM: 26.5%
M: 4.9%
DE: 68.6%

F = 10^{-36}
Neutrons in gravitational field

\[ i\hbar \partial_t \psi = -\frac{\hbar^2}{2m_i} \partial_z^2 \psi + m_g g z \psi \]

• No charge

• Small polarizability
  - Rb in 1µm distance of surface: 0.6 peV
  - n in 1µm distance of surface: $10^{-18}$ peV

• Mass interacts with Gravity
 Modifications to Gravity

- No complete Quantum Theory of Gravity $\Rightarrow$ Effective Field Theory
- Theories with $3+n$ space dimensions $\Rightarrow V(r) \sim \frac{1}{r^{1+n}}$
- Additional Yukawa like Potential $\Rightarrow V(r) \sim \frac{\alpha e^{-\frac{r}{\lambda}}}{r}$
- $n$ in gravity field is in $\mu$m range
Neutrons

- Thermal neutrons 25 meV
- (ultra) (very) cold neutrons <25 meV
- Fermi (pseudo) potential: coherent scattering on nuclei in matter => Effective potential for neutron wavefunction $E_F \sim 100$ neV
- Matter can be used to store ultra-cold neutrons
Fermi potentials

• critical velocity: reflection under all angles of incidence
  • $E_F \approx 100 \text{ neV}$
  • $m_N g \approx 100 \text{ neV/m}$
  • $\mu_n \approx 60 \text{ neV/T}$

<table>
<thead>
<tr>
<th>Substance</th>
<th>$E_F$ (neV)</th>
<th>$v_c$ [m/s]</th>
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<tbody>
<tr>
<td>$^{58}\text{Ni}$</td>
<td>335</td>
<td>8.00</td>
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<tr>
<td>Ni</td>
<td>252</td>
<td>6.9</td>
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<tr>
<td>Be</td>
<td>252</td>
<td>6.9</td>
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<tr>
<td>C (diamond)</td>
<td>305</td>
<td>7.74</td>
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<tr>
<td>C (graphite)</td>
<td>175</td>
<td>5.8</td>
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<tr>
<td>Cu</td>
<td>165</td>
<td>5.6</td>
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<tr>
<td>Stainless Steel</td>
<td>$\sim$188</td>
<td>$\sim$6</td>
</tr>
<tr>
<td>Al</td>
<td>54.1</td>
<td>3.22</td>
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<tr>
<td>V</td>
<td>-8.34</td>
<td>-</td>
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<tr>
<td>Ti</td>
<td>-49.7</td>
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PF2 @ ILL

https://www.ill.eu/users/instruments/instruments-list/pf2/description/ultracold-neutron-facility

Tobias JENKE

Public Talk of 103rd Scientific Council of the Institut Laue-Langevin
06/11/2020
Neutrons on a mirror

- Airy functions \( \text{Ai} \left( \frac{z}{z_0} - \frac{E}{mgz_0} \right) \)

- \( z_0 = \frac{3 \sqrt{\frac{\hbar^2}{2m^2g}}}{} \approx 5.87 \mu m \)

- \( mgz_0 \approx 0.60183 \pm 4 \cdot 10^{-5} \text{peV} \)

- \( E_n = -mgz_0 \text{AiZero}(n) \)

- \( f \leq 1 \text{kHz} \sim 4 \text{ peV} \)
Time evolution of states

M. Thalhammer
Ramsey’s Method with qBounce

- UCNs enter from the left
- Neutron detector to the right
- Total length: 0.95 m
Ramsey’s Method with qBounce

- Neutron mirrors, five different sections
- Bound states in gravitational potential
- Oscillations drive transitions

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<td>∞</td>
<td>6</td>
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Ramsey’s Method with qBounce

- II & IV induce transitions
- Free propagation in III
- Oscillation frequency determines final state
State selection

- Rough glass plates
- Scatter high energy states
- Height ≈ 25 µm above mirror
- End of I: \( |\psi>| = |1>\)

- End of II: \( |\psi>| = 50\% |1> + 50\% |6>\)
- III: \( |\psi>| = \frac{1}{\sqrt{2}} (e^{-i\frac{E_1}{\hbar} t} |1> + e^{-i\frac{E_6}{\hbar} t} |6>)\)
- IV: \( |\psi>| = |6>\)
- Transmission is measured
Transitions

\[ i\hbar \partial_t \psi = -\frac{\hbar^2}{2m} \partial_z^2 \psi + mgz\psi + V_0 \Theta \left( -z + a \sin(\omega t + \varphi) \right) \psi \]

• Experimental parameters:
  - Vibration strength \( a\omega_{II}, a\omega_{IV} \)
  - Vibration frequency \( f_{II}, f_{IV} \)
  - Relative phase \( \varphi_{II-IV} \)

• Systematic effects:
  - steps between mirrors - phase offset
  - frequency offset - tilt of mirrors
New Interactions

• Model predicts interaction (with screening)
• Energy shift of a state can be calculated to first order:
  \[ \delta E_n^{(1)} = \langle n | \hat{V} | n \rangle \]
• Difference of energies between two states is measured:
  \[ \delta E_{nm}^{(1)} = \delta E_n^{(1)} - \delta E_m^{(1)} \]
• Comparison with theoretical expectation leads to exclusion or discovery
Symmetron Dark Energy?

\[ i\hbar \partial_t \psi = -\frac{\hbar^2}{2m_i} \partial_z^2 \psi + \left( m_g g z + V_{DE}(z) + V_{DM}(z) \right) \psi \]

\[ V_{\text{eff}} \sim \frac{\lambda}{4} \phi^4 + \left( \frac{\rho}{2M^2} - \frac{\mu^2}{2} \right) \phi^2 + \mu^4 \left( \frac{1}{4\lambda} + \frac{1}{16\pi^2} \right) \]

\[ V_{DE} = \frac{m^2 c^2}{2M^2} \phi^2 \]


https://doi.org/10.1038/s41567-018-0205-x

\[ \nu_{13} = 464 \pm 1.3 \text{ Hz}, \nu_{14} = 649.8 \pm 1.8 \text{ Hz} \]
The Experiment
Velocity selection

![Diagram of velocity selection setup]

- Mirror
- Slit aperture
- Absorber
- $d$, $h_1$, $h_2$, $g$, $z$, $x$, $n$

**Graph**

- $\rho$ vs. $v_x$ [m/s]
- Preliminary data

**Equation**

- Velocity selection

**Notes**

- 06/07/2021
- Jakob Micko
Finding the transition $|1\rangle \rightarrow |6\rangle$

- Highest contrast at $\pi/2$-flip (spoiled by velocity)
Finding the transition $|1>\rightarrow|6>$

- Highest contrast at $\frac{\pi}{2}$-flip" (spoiled by velocity)
Finding the transition $|1\rangle \rightarrow |6\rangle$

- Measure transition around $f_{1\rightarrow 6} \approx 972$ Hz to find true transition frequency
- Keep vibration strength constant
- Avoid steps
- For highest sensitivity use highest slope
|1⟩→|6⟩ 11.8-28.9.2020

Preliminary

$\tilde{f}_{16} \approx 972.68 \pm 0.16 \text{ Hz}$
$|1\rangle \rightarrow |3\rangle$ 11.8-28.9.2020

$P_{13} \approx 463.11 \pm 0.26$ Hz

Preliminary
2021: Jan & May (current) cycles

Jan. 2021 4–14 [m/s]

$f [\text{Hz}]: 972.89 \pm 0.20$

Drop: $42 \pm 6\%$

Jan. 2021 4–9.5 [m/s]

$972.76 \pm 0.11$

$69 \pm 5\%$

May 2021 4–11 [m/s]

$972.77 \pm 0.14$

$44\%$
Summary

- Measured $g = 9.812 \pm 0.001 \text{ m/s}^2$, $\Delta g/g = 1.05 \cdot 10^{-4} \text{ m/s}^2$ with transition $|1\rangle \rightarrow |6\rangle$
- Investigated systematic effects (in progress)
- Improved stability of the experiment
Outlook

• Currently: Measuring transition $|1 \rightarrow |6 >$ with a magnetic field to investigate Torsion.
• Later this year: (classical) measurement of $g$ at PF2
• Testing the WEP with $q\text{BOUNCE}$
• Extend the capabilities to include neutron storage
Thank you

Collaboration between TU Wien and the ILL

- **qBOUNCE:**
  - Atominstitut:
    - Prof. Hartmut Abele
    - Post Doc: R.I.P Sedmik
    - PhD: Joachim Bosina
  - ILL:
    - PF2 Responsible: T. Jenke
    - PF2 Co-Responsible: S. Roccia
    - Technician: T. Brenner

- **Students**
  - Carina Killian
  - Andrej Brandalik
  - Veronika Kraus
  - Richard Bergmayr
  - Hippolyte Bartosz