Gravitational Resonance Spectroscopy with the GRANIT Spectrometer

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Why Spectroscopy?

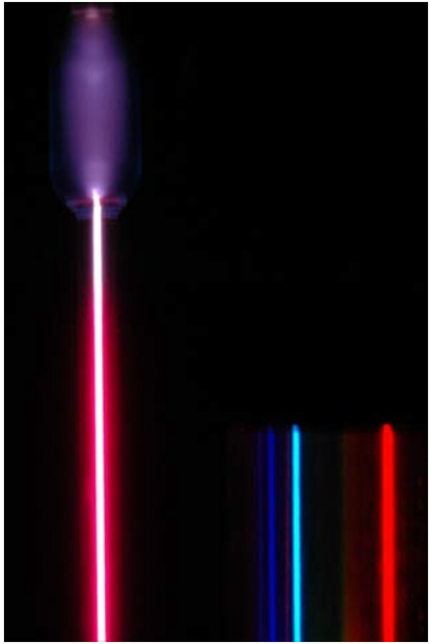
Measuring the spectra of quantum systems can be a useful tool for measuring small effects. Some of the most well-known examples come from the hydrogen atom:

- Quantum Vacuum fluctuations (Lamb Shift)
- Line splitting in electric/magnetic fields (Stark/Zeeman effect)
- Relativistic Effects
- Spin Orbit Coupling

Come from ΔE of bound states of electrons in atomic potential energy.

It is an attractive idea to make similar spectroscopic measurements in a different context to search for other kinds of small effects, like new short-range forces.

This can be done with gravitational bound states of UCNs.



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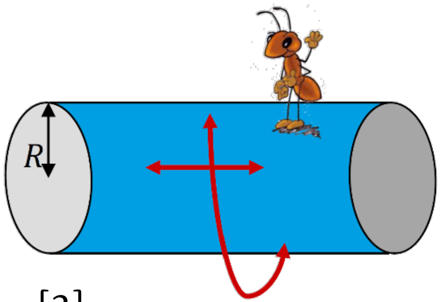
Applications

Gravitational Resonance Spectroscopy (GRS) allows for the precise testing of various principles and theories. An incomplete list is

- Weak Equivalence Principle
- String Theory: Large Extra-Compactified Spatial Dimensions
- Dark Energy Searches: Chameleons

$$\nabla^2\phi + M^2(\rho)\phi = \frac{g}{M_{Pl}}\rho$$



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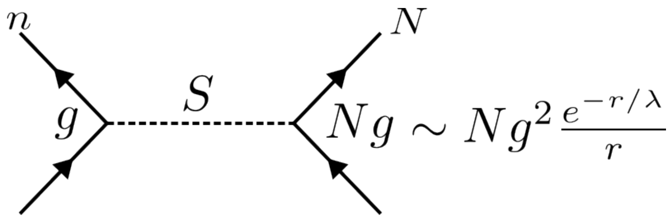
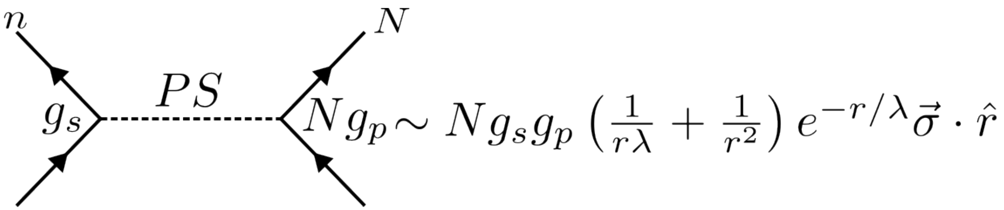
- Dark Matter Searches: Scalar and Pseudo-Scalar Bosons (Axions)





Spectroscopy of H tells you about small electromagnetic effects while GRS can tell you about small modifications to gravity (assuming you have the proper test particle).

Gravitational Bound States

$$i\hbar \frac{\partial|\psi\rangle}{\partial t} = H_0|\psi\rangle$$

$$H_0 = \frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + m_n g x + U_0 \Theta(-x)$$

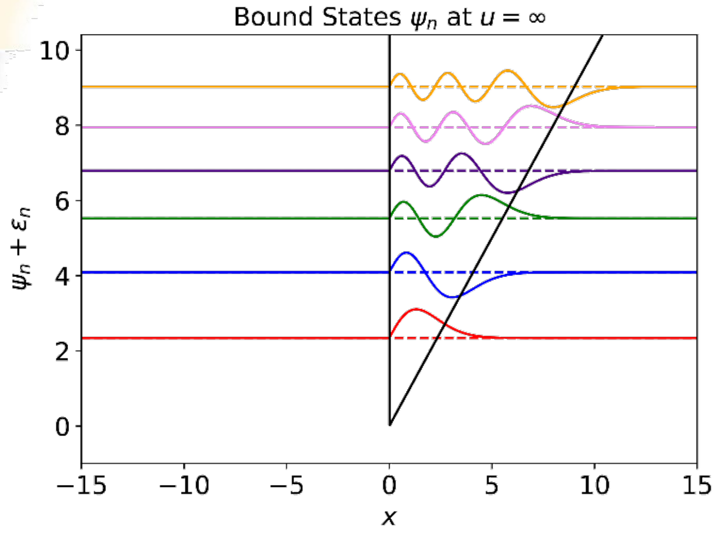
$$U_0 \to \infty$$

$$U_0 \sim 100 \text{ neV} \gg E_0 \sim 0.602 \text{ peV}$$

[3]

$$l_0 = \left(\frac{\hbar^2}{2m_n^2 g}\right)^{1/3} \approx 5.87 \text{ µm}$$

$$E_0 = m_n g l_0 \approx 0.602 \text{ peV}$$



Energy levels are **NOT** equally spaced → transitions can be induced between pairs of states without touching other states.

$$E_n = E_0 \epsilon_n$$

n	1	2	3	4	5
ϵ_n	2.34	4.09	5.52	6.79	7.94

First observed with UCNs at ILL [1].

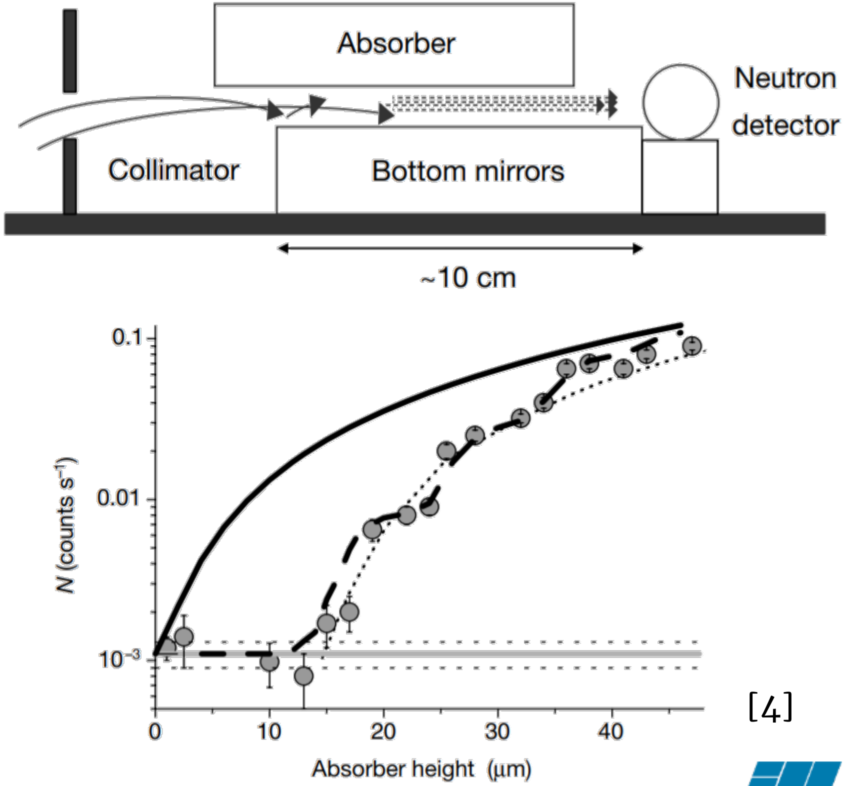
Observation Principle

Use UCNs

- Minimal coupling to static electric fields
- Long observation times→sufficient energy resolution: $\Delta E \sim \hbar/\Delta t$
- Reflects off sufficiently flat surfaces with minimal losses.

Rough absorber/scatter removes high energy modes.

Transmission through system grows in steps as function of absorber height, following the mean position of quantized energy levels.



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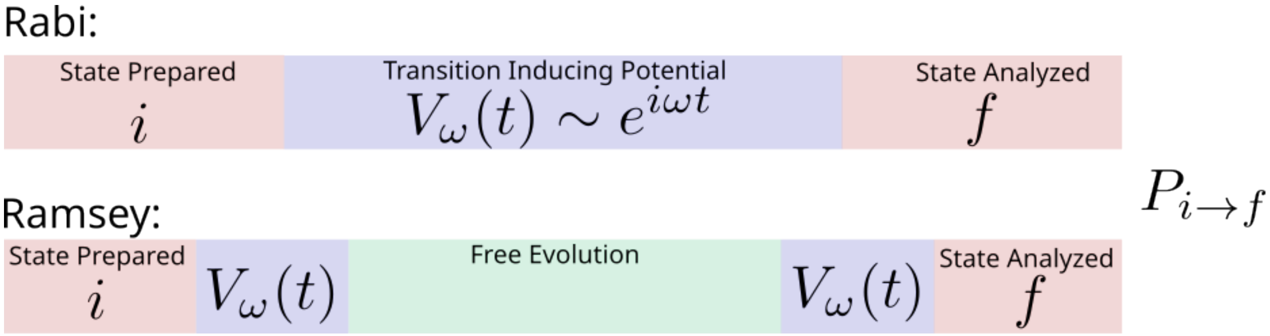
Gravitational Resonance Spectroscopy (GRS)

The general scheme of GRS is to prepare an initial state
→ let it evolve and transition (either with a **Rabi** or **Ramsey** like set-up)
→ measure transmission through the system of the final state



With UCNs, resolution of energy type observables can be high due to long observation times→ stringent constraints on tests of fundamental principles and new physics phenomena.

$$v{\sim}1\frac{\mathrm{m}}{\mathrm{s}} \ \& \ L{\sim}0.1\ \mathrm{m} \rightarrow \Delta t{\sim}0.1s \qquad \Delta E{\sim}\frac{\hbar}{\Delta t}{\sim}7\times 10^{-3}\mathrm{peV}$$

Qbounce: Mechanically Induced Resonances

Installed at PF2 UCN source at ILL.

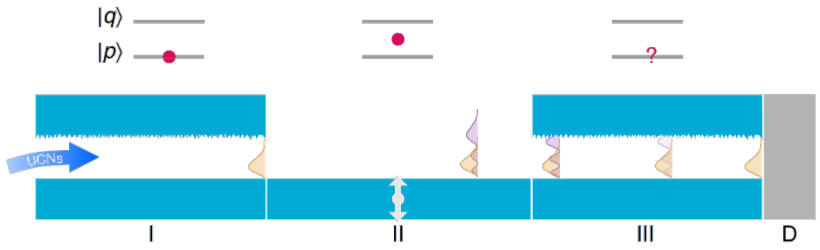
$$i\hbar\frac{\partial|\psi\rangle}{\partial t} = H(t)|\psi\rangle$$
$$H(t) = H_0 + V(t)$$

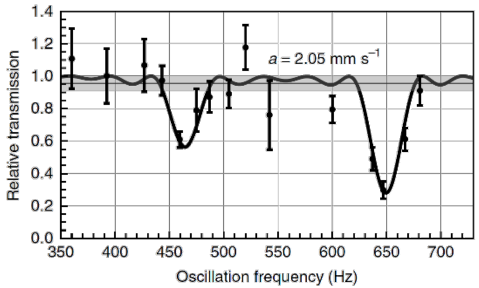
$$|\psi(t)\rangle = \Sigma_n a_n(t) e^{-\frac{i}{\hbar}E_n t}|n\rangle$$

Vibrating table induces transitions

$$V(t) \sim \sin(\omega t)\frac{\partial}{\partial z}$$

Rabi:





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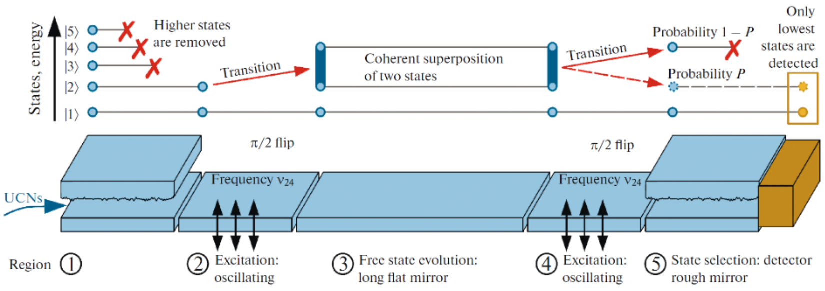
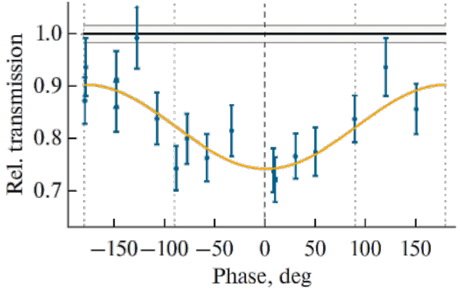
Ramsey:





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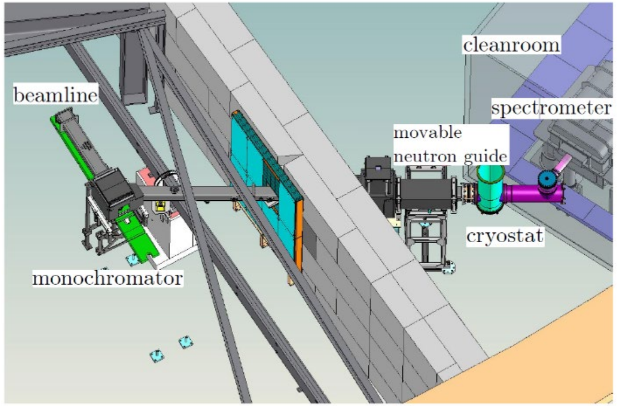
GRANIT Spectrometer was fed with UCNs by the superthermal source SUN1.



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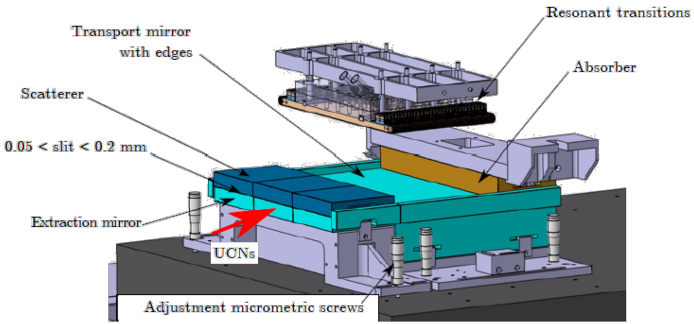

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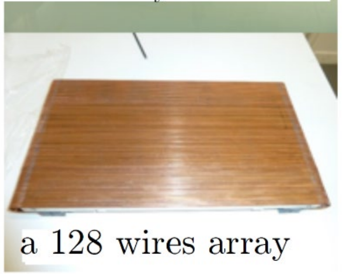
4 modules ready to be connected



a 128 wires array

- Neutrons entered through a slit with a rough absorbing mirror above to remove higher energy states.
- There is then a step down into a region with no absorber, but instead, a wire array which generates an oscillating magnetic field. The step suppresses the ground state, and the field induces transitions.
- Another absorber is present at the end of the set-up, selecting the ground state for a transmission measurement.

GRANIT: Magnetically Induced Resonances

Take advantage of neutron's magnetic moment coupling to external magnetic fields

$$H = H_0 - \vec{\mu} \cdot \vec{B}$$

Transitions come from, to leading order,

$$V_{\pm}(z,t) = \pm\mu|B(z,t)| \approx \pm\mu(\alpha(t) + \beta(t)z + \cdots)$$
$$\approx \pm\mu(\beta_0 + \beta_1 \cos(\omega t + \phi) + \cdots)z$$

Leads to "Stern-Gerlach" shift in energy levels since $m_n g z \to m_n \left(g \pm \frac{\mu\beta_0}{m_n}\right) z$

$$g_{\pm} = g \pm \mu\beta_0 \to \epsilon_{n+} \neq \epsilon_{n-}$$

which results in two, spin-dependent, resonance locations for transitions from $i \to f$, $\omega_{if\pm}$.

$$|\psi(t)\rangle = \sum_{m=1}^{\infty} a_{m\uparrow}(t) e^{-\frac{i}{\hbar}E_m t}|m\uparrow\rangle + a_{m\downarrow}(t) e^{-\frac{i}{\hbar}E_m t}|m\downarrow\rangle$$

$$\frac{da_{m\uparrow}}{dt} = -\frac{i}{\hbar}\sum_{l=1}^{\infty} a_{l\uparrow} e^{-i\omega_{ml}t}\left\langle m\uparrow\middle| -\vec{\mu}_n \cdot \vec{B} \middle| l\uparrow\right\rangle - \frac{i}{\hbar}\sum_{l=1}^{\infty} a_{l\downarrow} e^{-i\omega_{ml}t}\left\langle m\uparrow\middle| -\vec{\mu}_n \cdot \vec{B} \middle| l\downarrow\right\rangle$$

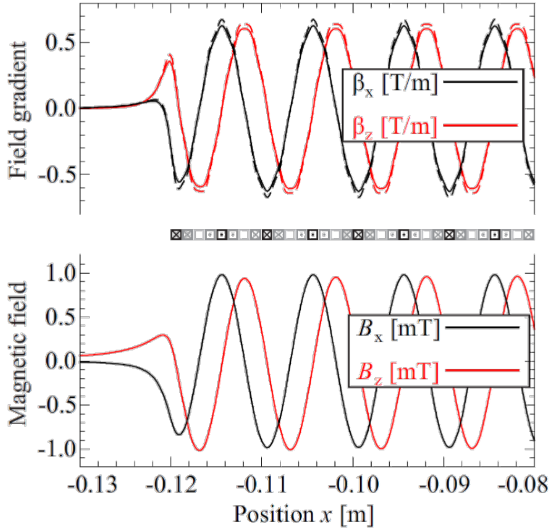
$$\frac{da_{m\downarrow}}{dt} = -\frac{i}{\hbar}\sum_{l=1}^{\infty} a_{l\uparrow} e^{-i\omega_{ml}t}\left\langle m\downarrow\middle| -\vec{\mu}_n \cdot \vec{B} \middle| l\downarrow\right\rangle - \frac{i}{\hbar}\sum_{l=1}^{\infty} a_{l\downarrow} e^{-i\omega_{ml}t}\left\langle m\downarrow\middle| -\vec{\mu}_n \cdot \vec{B} \middle| l\uparrow\right\rangle$$

GRANIT: Magnetically Induced Resonances (DC Mode)

$$V(z,t) = \pm\mu|B(t)| \approx \pm\mu(\alpha(t) + \beta(t)z + \cdots)$$
$$\approx \pm\mu(\beta_0 + \beta_1 \cos\omega t + \cdots)z$$

where $\omega = 2\pi v_x/\lambda$

Spatially oscillating field
resonance condition being met depends on UCN velocity v_x
→ measure fall height to measure spectrum



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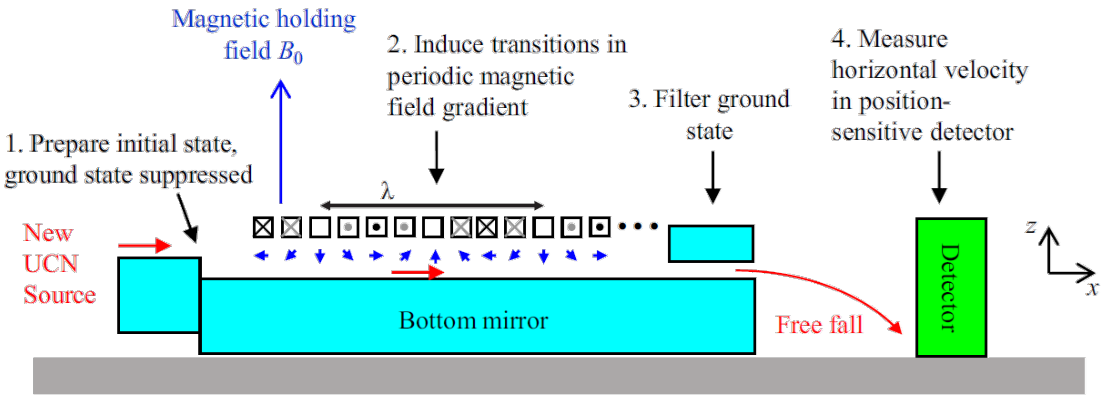


GRANIT: Magnetically Induced Resonances (AC Mode)

$I_1 = I_4 = 1.4$ A $\quad I_2 = I_3 = 3.8$ A, in experiment

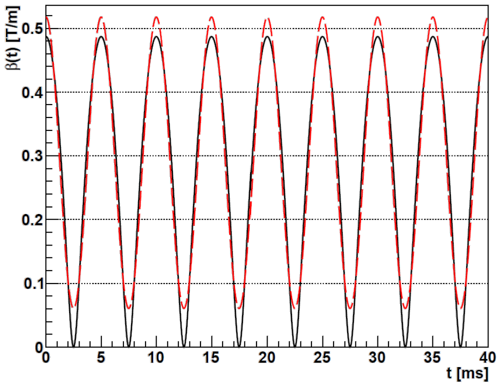
Produces a spatially uniform field gradient over the mirror and oscillates temporally at a chosen frequency.

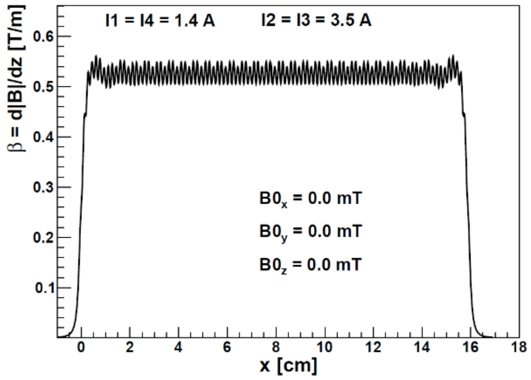
$V(z,t) = (\beta_0 + \beta_1 \cos(4\pi f t + 2\phi) + \cdots)z$

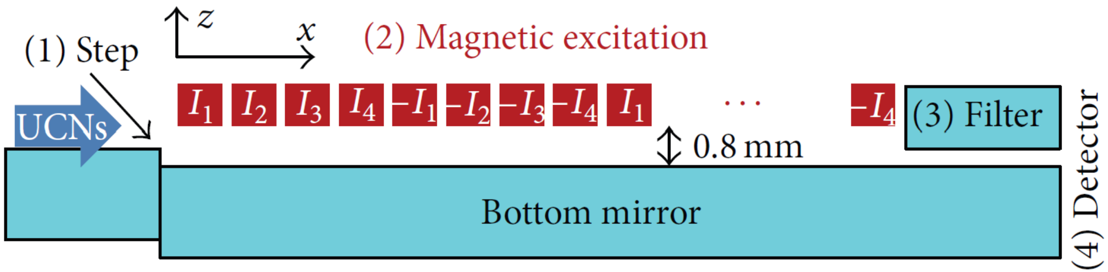
f is a tunable frequency

Velocity not measured with a PSD. Counts measured for all velocities

Last configuration used during experiments.







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GRANIT Simulation: Runge-Kutta

$$\frac{da_{m\uparrow}}{dt} = -\frac{i}{\hbar}\sum_{l=1}^{\infty} a_{l\uparrow} e^{-i\omega_{ml}t}\left\langle m\uparrow\middle|-\vec{\mu}_{\rm n}\cdot\vec{B}\middle|l\uparrow\right\rangle - \frac{i}{\hbar}\sum_{l=1}^{\infty} a_{l\downarrow} e^{-i\omega_{ml}t}\left\langle m\uparrow\middle|-\vec{\mu}_{\rm n}\cdot\vec{B}\middle|l\downarrow\right\rangle$$

$$\frac{da_{m\downarrow}}{dt} = -\frac{i}{\hbar}\sum_{l=1}^{\infty} a_{l\uparrow} e^{-i\omega_{ml}t}\left\langle m\downarrow\middle|-\vec{\mu}_{\rm n}\cdot\vec{B}\middle|l\downarrow\right\rangle - \frac{i}{\hbar}\sum_{l=1}^{\infty} a_{l\downarrow} e^{-i\omega_{ml}t}\left\langle m\downarrow\middle|-\vec{\mu}_{\rm n}\cdot\vec{B}\middle|l\uparrow\right\rangle$$

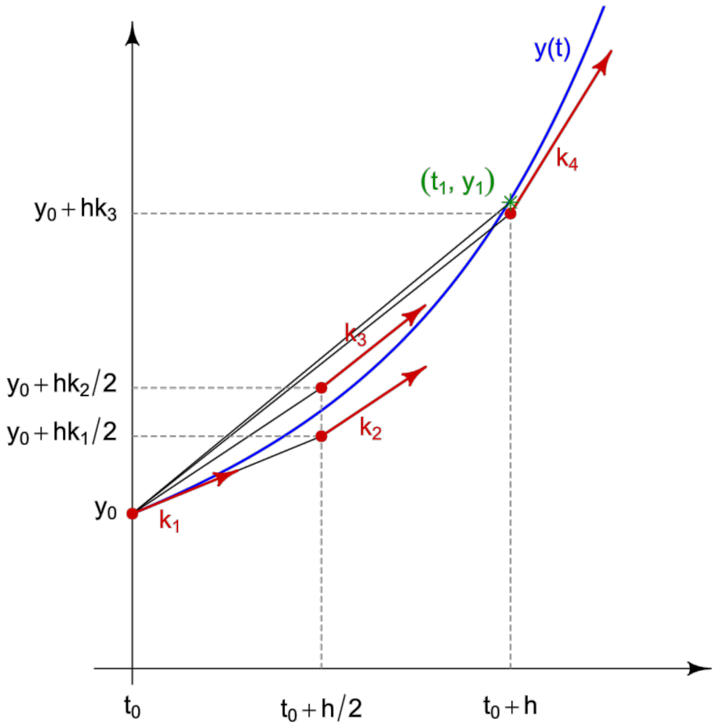
$$\vec{a} = (a_{1\uparrow}, a_{2\uparrow}, \dots, a_{2\uparrow}, a_{2\downarrow}, \dots)$$

4^{th} Order Runge-Kutta Simulation use to solve

$$\dot{\vec{a}} = \boldsymbol{U}(t)\vec{a} = F(t,\vec{a})$$

$$\vec{a}(t+h) = \vec{a}(t) + \frac{1}{6}\left(\vec{k}_1 + \vec{k}_2 + \vec{k}_3 + \vec{k}_4\right) + O\left(h^5\right)$$

$$\vec{k}_1 = F(t,\vec{a})$$
$$\vec{k}_2 = F\left(t+\frac{h}{2}, \vec{a} + \vec{k}_1\frac{h}{2}\right)$$
$$\vec{k}_3 = F\left(t+\frac{h}{2}, \vec{a} + \vec{k}_2\frac{h}{2}\right)$$
$$\vec{k}_4 = F\left(t+h, \vec{a} + +\vec{k}_3 h\right)$$



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GRANIT Simulation: Initial Populations

Initial state populations are determined by a $\Delta z = 21\ \mu\text{m}$ step at the beginning of the GRANIT set-up.

Considering first 4 levels, $a_1 = a_2 = a_3 = a_4 = 1$ before the step.

Assuming a sharp step, the sudden approximation is used to find state populations when inside the transition region

Before step:

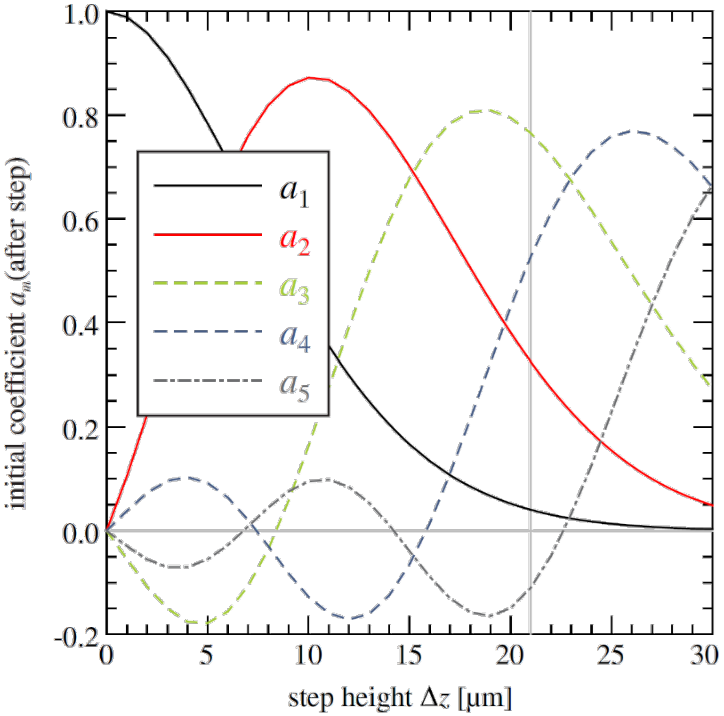
$$\psi_n \sim \text{Ai}(z - z_n)$$

After step:

$$\psi_n \sim \text{Ai}(z - \Delta z - z_n)$$

$$a_m(\text{after step}) := a_{m\uparrow}(\text{after step}) = a_{m\downarrow}(\text{after step})$$

$$= \int_{\Delta z_{\text{step}}}^{\infty} \psi^*_{\text{in}}(z)\psi_m(z)dz.$$



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GRANIT Simulation: Results

Initial populations determined by the projection after the step for each eigen energy, as in previous slide.

Simulation stopped after propagating through transition region $T = L/v_x$ where

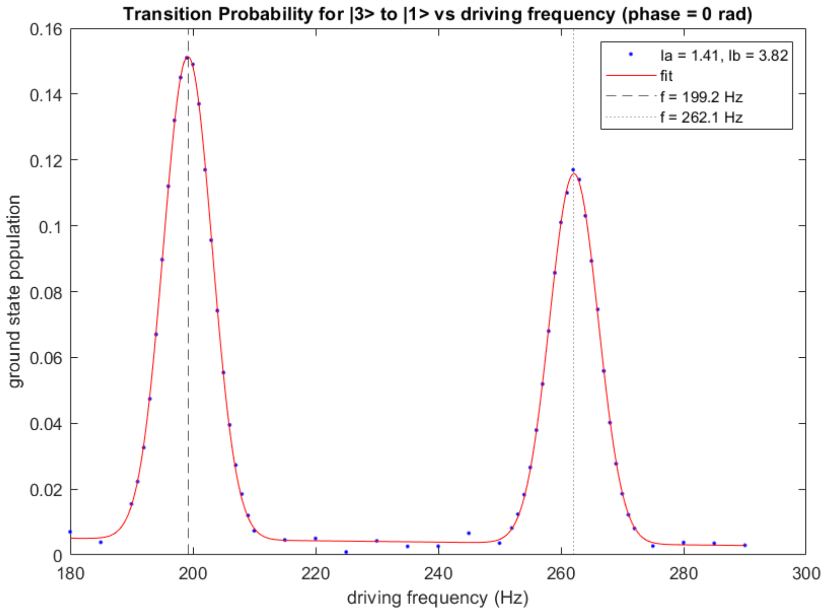
$$L = 16\text{ cm}$$

The result is taken to be the ground state population $|a_1|^2 = |a_{1\uparrow}|^2 + |a_{1\downarrow}|^2$

Simulation run for several v in the GRANIT spectrum and then averaged.

$$\bar{v} = 4\frac{m}{s}, \qquad \sigma = 1.5\frac{m}{s}$$

Several phases of the AC field are also considered and averaged over.



$$\omega_{31+} = 262.1\text{ Hz}$$

$$\omega_{31-} = 199.2\text{ Hz}$$

GRANIT 2020 Experiment

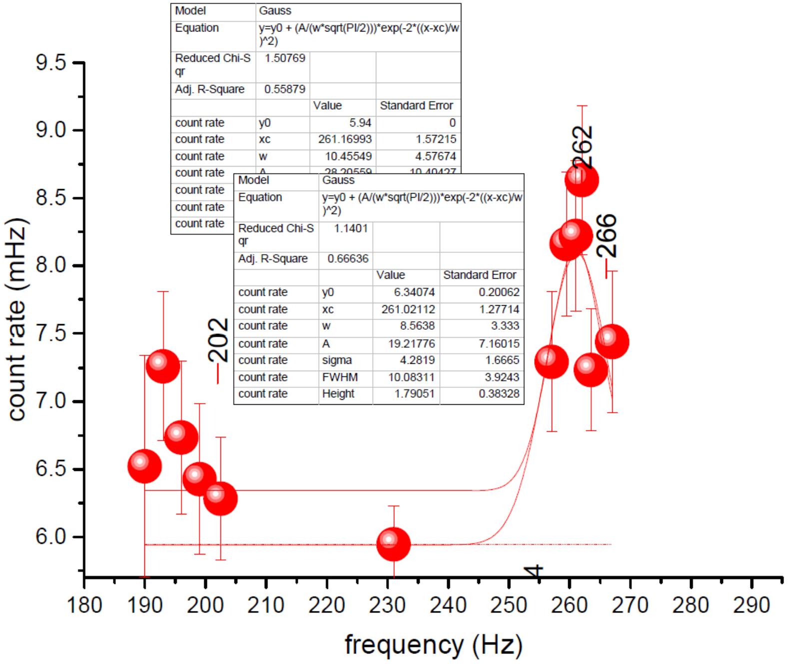
~5 days of measurement time in AC Mode
~20 days of beam time.

It was a struggle to operate the source for longer than a couple days at a time.

$1 \rightarrow 3+$ seen clearly, statistically significant.

$$\omega_{31+} = 262.1$$
$$\omega_{31+}^{measured} = 261.0 \pm 1.3$$

but $1 \rightarrow 3-$ not observed. The data is statistically compatible with no signal.



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GRANIT Improvements

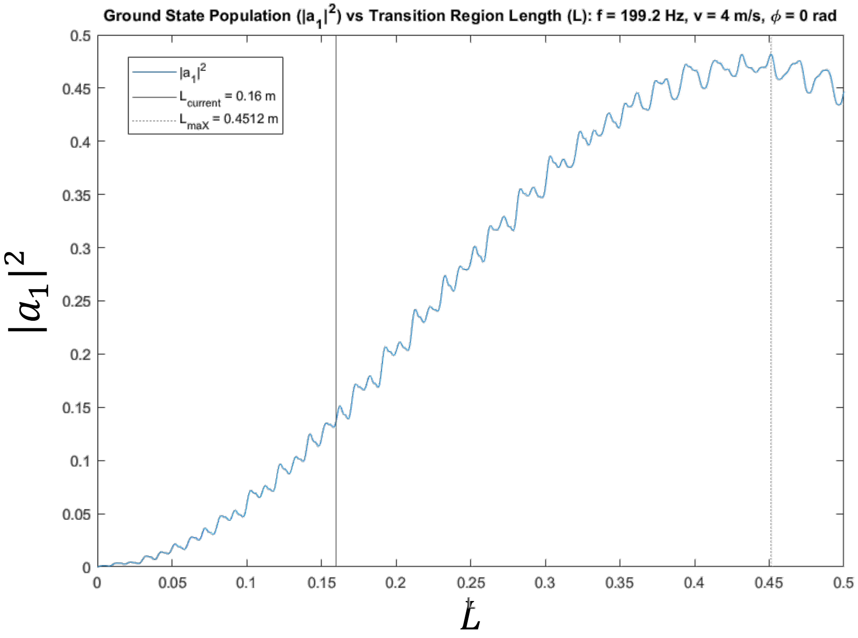
A significant improvement of UCN flux at the input would greatly help statistics and make precisions spectroscopy more feasible.

Improving the reliability of the UCN source would increase usable time.

Making $V(t)$ more sinusoidal than before could also prevent some unintentional transitions induced in high order Fourier terms.

A longer L or larger field strength could help for observation of the ω_{13-} transition

$$\Omega_{nm\pm} = \pm\beta \frac{\mu}{\hbar}\langle n|z|m\rangle$$



Conclusions

Gravitational Resonance Spectroscopy is a promising method of probing new physics models with extreme precision.

UCNs are ideal particles for GRS due to their long observation times

$$\Delta E \sim \frac{\hbar}{\Delta t}$$

To reach the full potential of GRS, and of GRANIT, improvements of the experimental set up and significantly higher flux UCN sources are needed to improve the statistics, signal to noise ratio, and precision of spectroscopy.

People

Many people have contributed to GRANIT, here are some names from the recent work:

Stefan Baessler, Benoit Clement, Valery Nesvizhevsky, Emily Perry, Guillaume Pignol, Konstantin Protasov, Dominique Rebreyend, Damien Roulier, Lingnan Shen, A.V. Strelkov, Francis Vezzu

References

[1] http://hyperphysics.phy-astr.gsu.edu/hbase/hyde.html
[2] “Slow Neutrons as powerful probes in particle physics and cosmology”-Presentation by Tobias Jenke
[3] V. V. Nesvizhevsky, H. G. Börner, A. K. Petukhov, H. Abele, S. Baeßler, F. J. Rueß, T. Stöferle, A. Westphal, A. M. Gagarski, G. A. Petrov, and A. V. Strelkov, Nature (London) 415, 297 (2002).
[4] Nesvizhevsky, V. V. and Alexei Yu. Voronin. “Surprising Quantum Bounces.” (2015).
[5] Cronenberg, G., Brax, P., Filter, H. *et al.* Acoustic Rabi oscillations between gravitational quantum states and impact on symmetron dark energy. *Nature Phys* **14**, 1022–1026 (2018).
[6] Sedmik, R., Bosina, J., Geltenbort, P. *et al.* Ramsey Gravity Resonance Spectroscopy with Ultracold Neutrons. *J. Surf. Investig.* **14** (Suppl 1), S195–S197 (2020).
[7] Damien Roulier, Francis Vezzu, Stefan Baeßler, Benoît Clément, Daniel Morton, Valery V. Nesvizhevsky, Guillaume Pignol, Dominique Rebreyend, "Status of the GRANIT Facility", *Advances in High Energy Physics*, vol. 2015
[8] S. Baeßler, V. V. Nesvizhevsky, G. Pignol, K. V. Protasov, D. Rebreyend, E. A. Kupriyanova, and A. Yu. Voronin Phys. Rev. D **91**, 042006 (2015)
[9] G. Pignol, S. Baeßler, V. V. Nesvizhevsky, K. Protasov, D. Rebreyend, and A. Voronin, Adv. High Energy Phys. 2014, 1 (2014).
[10] https://en.wikipedia.org/wiki/Runge%E2%80%93Kutta_methods#
[11] Correspondence with V. V. Nesvizhevsky

Thank you for listening!

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