Kaluza-Klein spectroscopy from neutron oscillations into hidden dimensions

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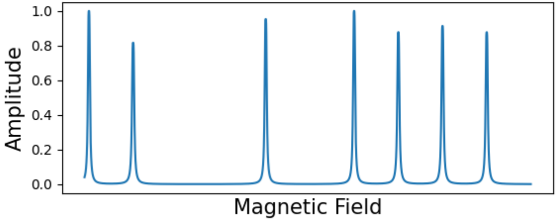
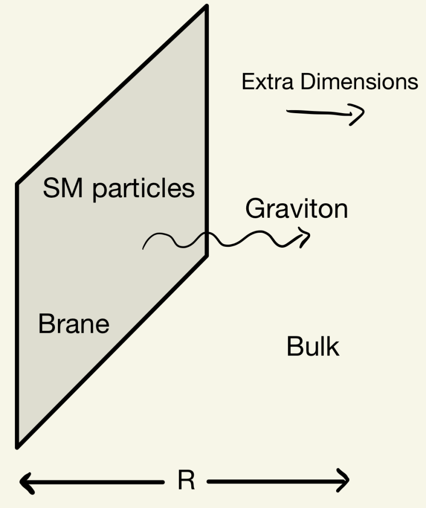
Motivation & Results

- Motivation for large extra dimensions: Hierarchy problem, dark matter, neutrino mass, ...
- Neutrino mass $\rightarrow$ Kaluza-Klein tower of sterile fermion
- Neutron oscillation into extra dimensions $\rightarrow$ magnetic resonance imaging



ADD Model

Arkani-Hamed, Dimopoulos, Dvali ’98, ’99



- Graviton in $4 + N$-dim
- Standard Model on a 4-dim brane
- Parameters:
  Fundamental scale of Quantum Gravity
  $M_f \geq 10\text{TeV}$,
  Size of the extra dimension $R \leq 30\mu\text{m}$

Tan, Yang, Shao, Li, Du, Zhan, Wang, Luo, Tu, Luo ’16
Lee, Adelberger, Cook, Fleischer, Heckel ’20

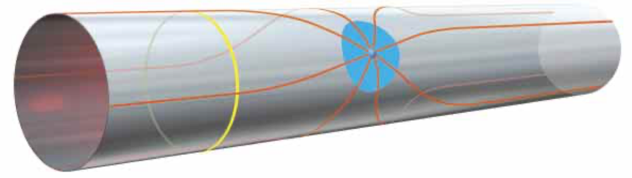
Compactification

Kaluza Klein tower of states with masses $m_k = \sqrt{\frac{k_1^2}{R_1^2} + \cdots + \frac{k_N^2}{R_N^2}}$

$$M_P^2 = M_f^{N+2} V_N$$

where $V_N = (2\pi R)^N$ volume of extra dimensions

Fundamental scale of Quantum Gravity $M_f <$ Planck Scale M_P



Scientific American, Issue August 2000

Neutrino Mass in ADD

Arkani-Hamed, Dimopoulos, Dvali, March-Russell '01, Dvali, Smirnov '99

Sterile bulk fermion

$$\Psi(x,y) = \frac{1}{\sqrt{V_N}} \sum_{k=-\infty}^{k=\infty} \Psi_k(x)\, e^{\frac{iky}{R}}$$

Yukawa Interaction

$$\mathcal{L}_{\rm int} = \frac{1}{\sqrt{M_f^N V_N}} \sum_{k=-\infty}^{k=\infty} H \bar{\nu}_L \Psi_k$$

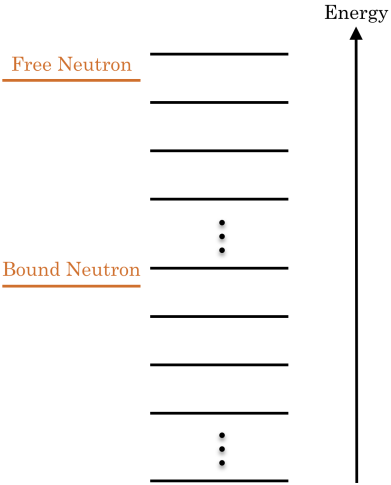
Neutrino Mass

$$m_\nu \sim \frac{\langle H \rangle}{\sqrt{M_f^N V_N}} \sim 10^{-3}\,\mathrm{eV}$$

Neutron Oscillations into Extra Dimensions

Interaction neutron and bulk particle

$$\mathcal{L}_{\rm int} \supset \alpha \sum_{k=-\infty}^{k=\infty} \bar{n}\Psi_k \quad \text{with} \quad \alpha \sim \frac{\Lambda^3_{\rm QCD}}{M_*^2\sqrt{M_*^N V_N}}$$



Probability of Oscillation

$$P_{n\to\Psi_j}(t) = |\langle n|\Psi_j(t)\rangle|^2 = Z\frac{4\alpha^2}{\Delta m^2}\sin^2\left(\frac{\Delta m}{2}t\right)$$

where $\Delta m = m_n - m_k$ and Z degeneracy of states

Constraints from bound neutron

Neutron Disappearance Experiments

$\tau_n > 10^{30}\mathrm{yrs}$ Particle Data Group '22

Bounds on $M_* \neq M_f = 10\text{TeV}$:

N	$M_*[\mathrm{GeV}]$
3	$> 3 \cdot 10^7$
4	$> 1 \cdot 10^7$
5	$> 5 \cdot 10^6$
6	$> 3 \cdot 10^6$

Table: Bound on M_* for one dominant $R = 30\mu\mathrm{m}$.

N	$R[\mu\mathrm{m}]$	$M_*[\mathrm{GeV}]$
2	1.1	$> 7 \cdot 10^9$
3	$1.6 \cdot 10^{-5}$	$> 3 \cdot 10^8$
4	$5.5 \cdot 10^{-8}$	$> 2 \cdot 10^7$
5	$2 \cdot 10^{-9}$	$> 4 \cdot 10^6$
6	$2.2 \cdot 10^{-10}$	$> 8 \cdot 10^5$

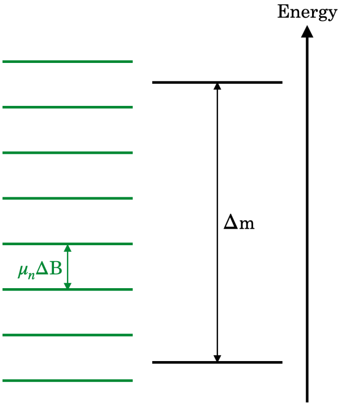
Table: Bound on M_* for equal size extra dimensions.

For $M_* = M_f$ and one dominant extra dimension $R = 30\mu\mathrm{m}$: $M_f \geq 10^{12}\mathrm{GeV}$

Free Neutron Oscillations

- Can evade bounds on bound neutron by mass for bulk particle
- External magnetic field shifts neutron energy by $\mu_n B$
- Oscillation amplitude $\frac{\alpha^2}{|\mu_n B - \Delta m|^2}$
- Resonance when $\alpha \leq |\mu_n B - \Delta m|$
- Scan level-splitting by magnetic field

Scanning with external magnetic field

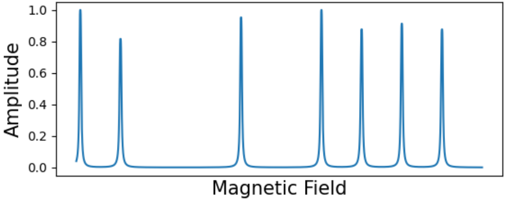


- $N = 1$: level-splitting $\Delta m \sim \frac{1}{R}$ too big for current experiments
- $N \geq 2$: can probe $\Delta m \sim \frac{1}{R^2 m_n}$ with current setups
- Current experiment:
  - $B \sim 50 - 1100\mu$T, $\Delta B \sim 3\mu$T
  - probing 0.8μm $< R < 10\mu$m
  - put bound on $\alpha \lesssim 10^{-14}$eV

Ban et al. '23

Resonance pattern

Resonance pattern: characteristic signature



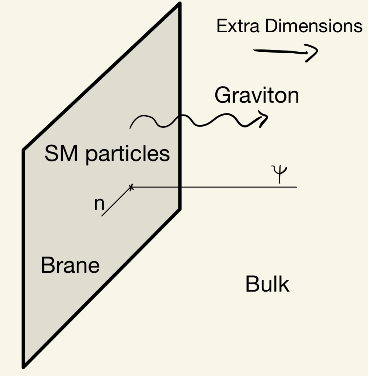
- Resonances with steps $\Delta B = \Delta m / \mu_n$
- One peak for each KK energy level
- Different heights due to degeneracy

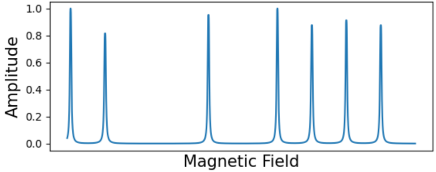
Dark matter candidate

Bulk fermion Ψ can be dark matter:

- similar to KK modes of graviton as dark matter ($m_{\rm grav} < 100$ MeV)
  Arkani-Hamed, Dimopoulos, Dvali '99
- weakly interacting
- long-lived:
  - most important channel $\Psi \to n\pi^0$ has lifetime $\tau \sim 10^{46}/m_\Psi$
  - KK modes with $m_\Psi < 10^5$ GeV can be dark matter
- production mechanism
  - thermal, rescattering of SM particles into Ψ's
  - nonthermal, decay of inflaton field into Ψ's

Summary





- Neutron can oscillate into extra dimensions.
- This can result in spectacular experimental consequences.
- In minimal case: neutron oscillations are correlated with neutrino oscillations.
- Neutron experiments can scan KK tower with external magnetic field.
- Finer scanning, wider range of B can probe physics of extra dimensions.
- Bulk fermion can be dark matter.

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