Super Cool! Neutrons!

(Ultracold Neutrons)

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University of Winnipeg

UM Physics Colloquium, January 16, 2009

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Natural Sciences and Engineering Research Council
Canada Foundation for Innovation
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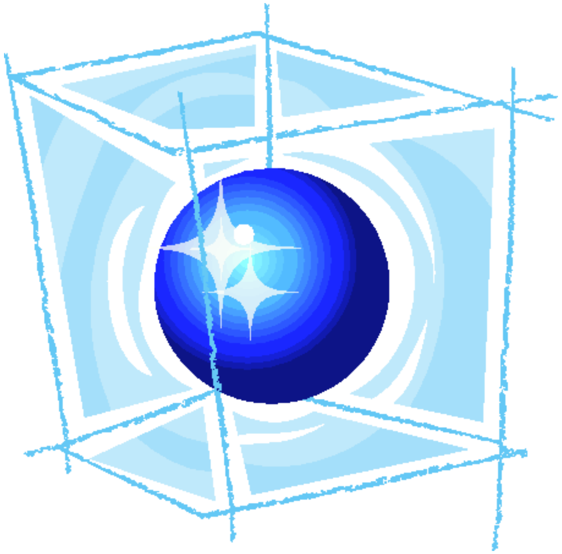
Ultracold Neutrons



- What are neutrons?
- Why are they important?
- How to make lots of neutrons.
- Interesting properties of ultracold neutrons (UCN)
- The world's most intense source of ultracold neutrons.
- Super-cool experiments that we could do there.

Leadership of international collaborations enabled by CFI.
U. Winnipeg submission for this year's CFI NIF competition.

TRIUMF

CANADA'S NATIONAL LABORATORY FOR PARTICLE AND NUCLEAR PHYSICS

Owned and operated as a joint venture by a consortium of Canadian universities via a contribution through the National Research Council Canada

Canadian Spallation Ultracold Neutron Source

Spokesperson: J.W. Martin (U. Winnipeg)

Collaborators: J.D. Bowman, J. Birchall, L. Buchmann, L. Clarke, C. Davis, B.W. Filippone, M. Gericke, R. Golub, K. Hatanaka, M. Hayden, T.M. Ito, S. Jeong, I. Kato, S. Komamiya, E. Korobkina, E. Korkmaz, L. Lee, Y. Masuda, K. Matsuta, A. Micherdzinska, W.D. Ramsay, S.A. Page, B. Plaster, I. Tanihata, W.T.H. van Oers, Y. Watanabe, S. Yamashita, T. Yoshioka

(Winnipeg, Manitoba, ORNL, TRIUMF, NCSU, Caltech, RCNP, SFU, LANL, KEK, Tokyo, UNBC, Osaka, Kentucky)

LABORATOIRE NATIONAL CANADIEN POUR LA RECHERCHE EN PHYSIQUE NUCLÉAIRE ET EN PHYSIQUE DES PARTICULES

Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada

We propose to construct the world's highest density source of ultracold neutrons and use it to conduct fundamental and applied physics research using neutrons.

What are neutrons?

- Neutrons are a basic constituent of matter.
  - The atomic nucleus is made of neutrons and protons.

property	neutron	proton
electric charge	0	1e
mass	1 u	1 u
quark content	udd	uud

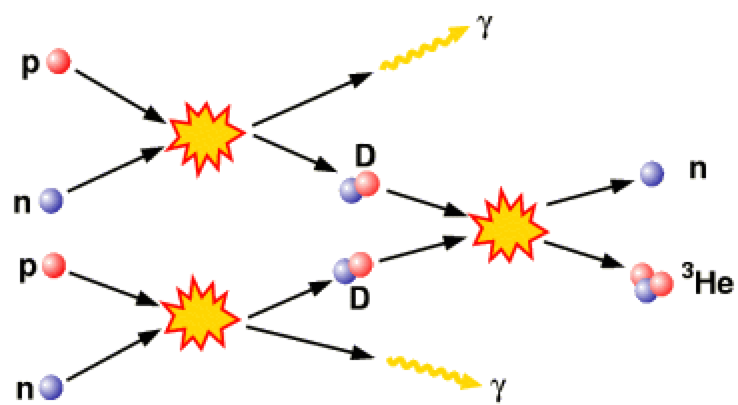
A neutron walks into a bar, sits down, and orders a drink.
Finishing, he asks, “How much?”
The bartender replies, “For you, no charge.”

  - when freed from a nucleus, they decay

- Discovered by Chadwick in 1932 (Nobel Prize).

Why are neutrons important? An historical overview.

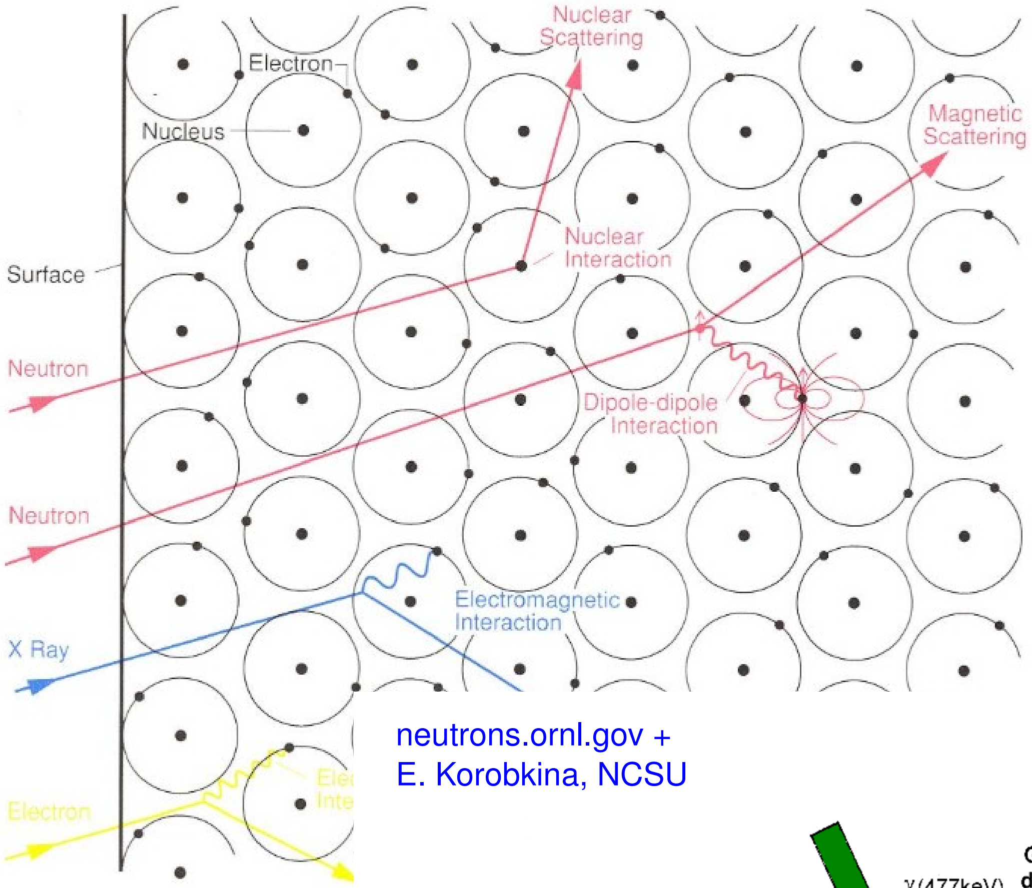
- Free neutrons were one of the first things present in the early universe. How fast they decayed determines how much of various lighter elements are currently present in today's universe. ("Big-Bang Nucleosynthesis")
- Important for many reactions going on in our sun, and in nuclear reactors.
- Consequently, we're made of them.



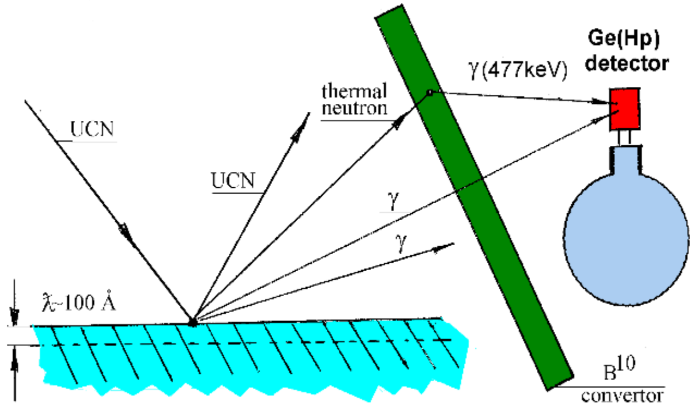
http://www.einstein-online.info

- Nowadays, free neutrons are used to probe the structure of materials
- Fundamental Physics interest in studying neutrons

Technology and Neutrons



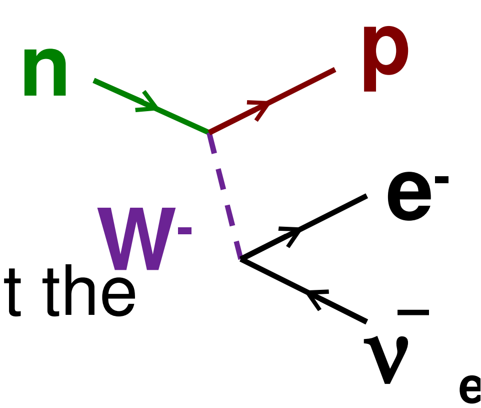
neutrons.ornl.gov +
E. Korobkina, NCSU



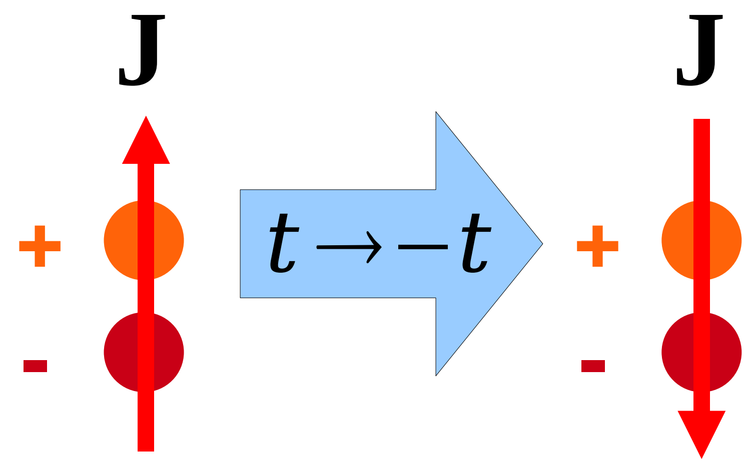
- Neutron scattering is a valuable tool to study the structure of materials.
- Because the neutrons have no charge, they interact mainly via the strong nuclear force with materials, giving a new window into the properties of materials.

Fundamental Physics and Neutrons

- Neutrons and their interactions are a hot topic in particle physics.



  - How fast do neutrons decay?
  - Details about how neutrons decay tell us about the weak nuclear force.
  - Does the neutron possess an electric dipole moment? The predominance of matter over antimatter in the universe.



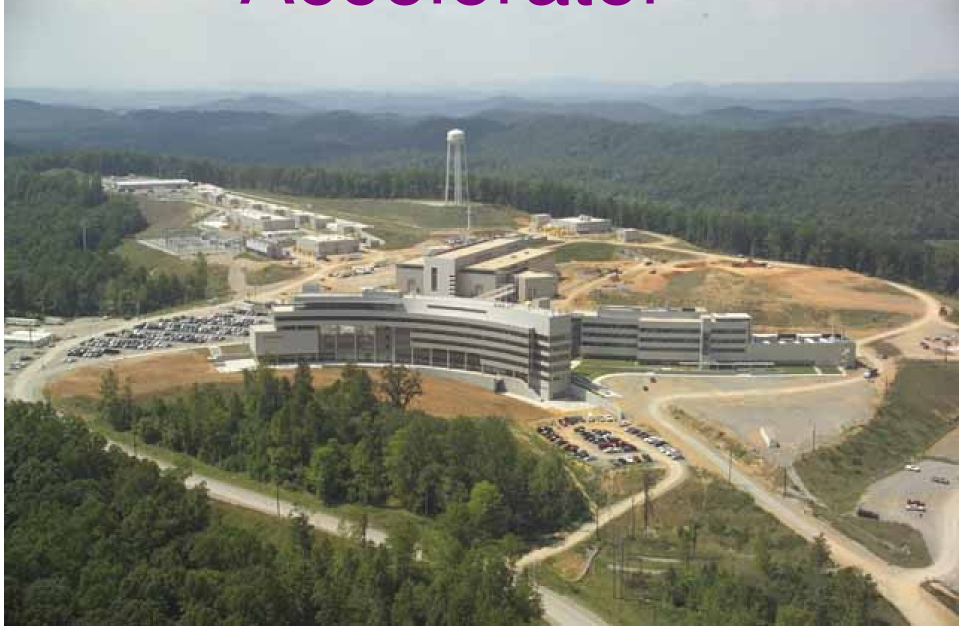
  - Interactions of neutrons with gravity and are there extra dimensions?

How to make lots of neutrons: Liberate them from nuclei!

1) In a nuclear reactor (how the sun does it).

2) In an atom smasher (accelerator).

Accelerator

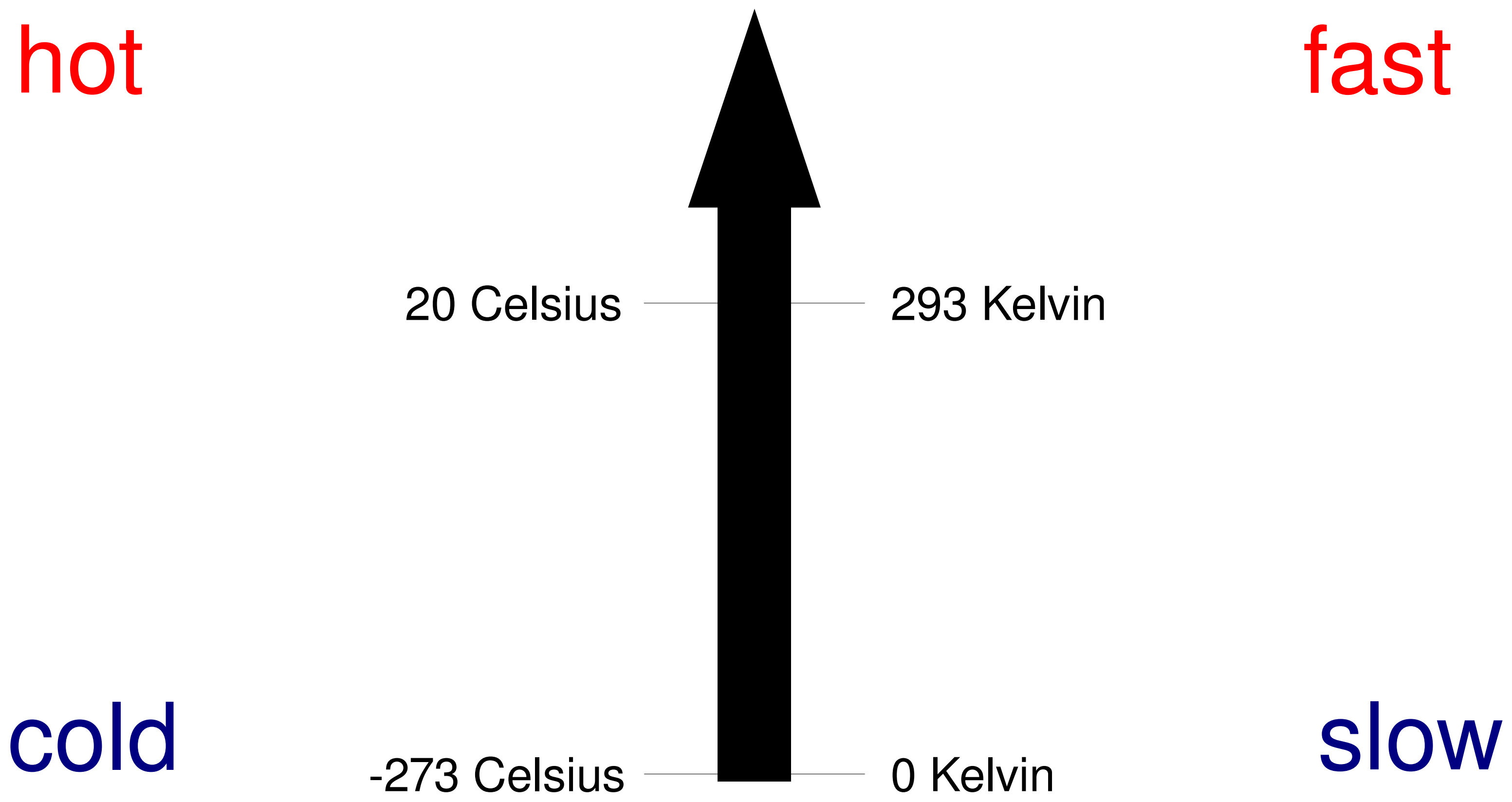


Spallation Neutron Source,
Oak Ridge, Tennessee, www.sns.gov

Reactor

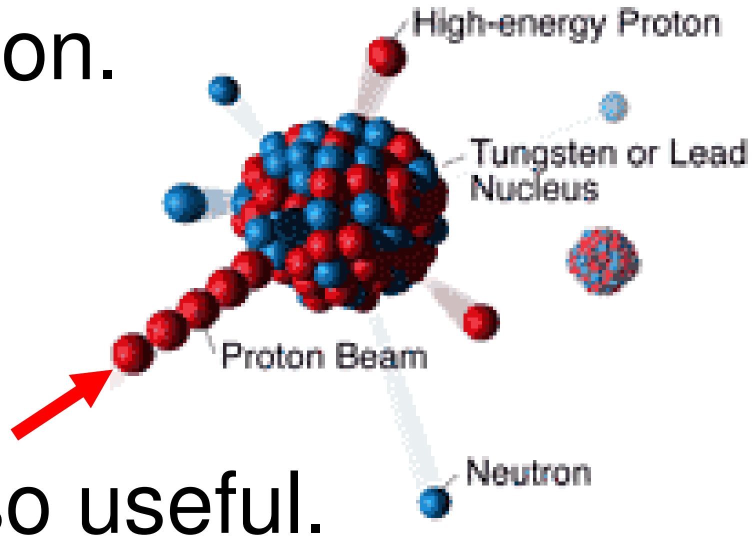
Insititut Laue-Langevin,
Grenoble, France, www.ill.fr

Temperature and Kinetic Energy



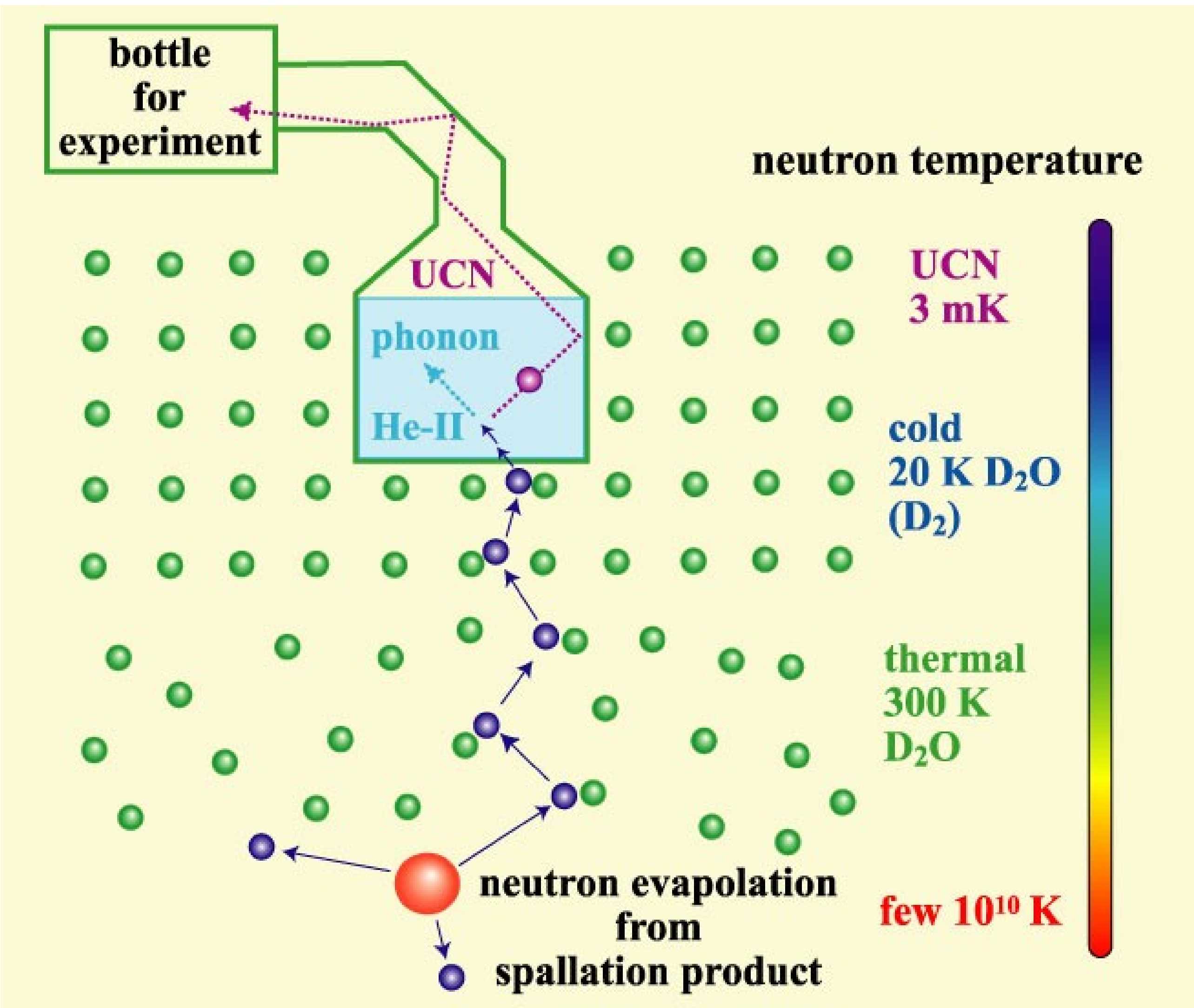
- At absolute zero (0 K) all motion stops!

How we make neutrons.



- Using proton-induced spallation.
- This makes very fast-moving neutrons (T = 1 billion K)
- Such “hot” neutrons are not so useful.
- We need to cool them down to make them useful (I'll show you why in a moment).

How we cool neutrons
Step One: Cold Neutrons

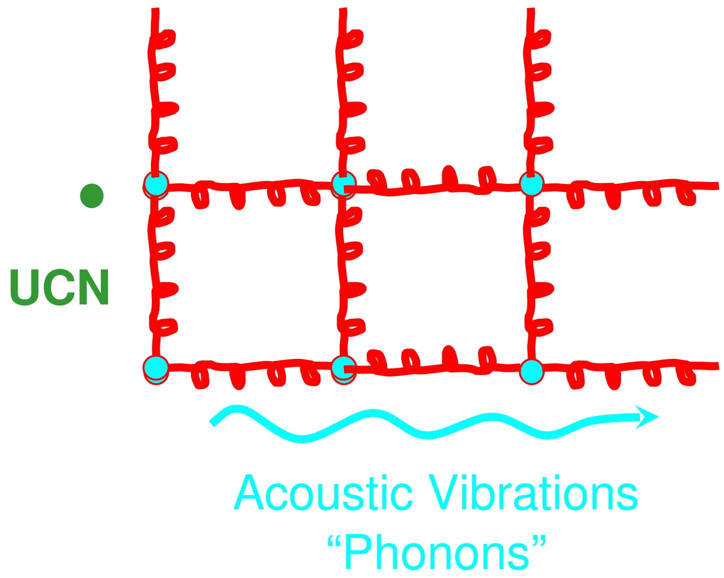


- Bring them into contact with a material at some temperature T.
- The neutrons bounce around for a while and eventually come into equilibrium with the material
- T = 20 K. (20 degrees above absolute zero.)
- But we desire ultracold neutrons

How we cool neutrons
Step Two: Ultracold Neutrons

- Scatter them off a material that doesn't absorb them (e.g. superfluid helium)

How we cool neutrons
Step Two: Ultracold Neutrons



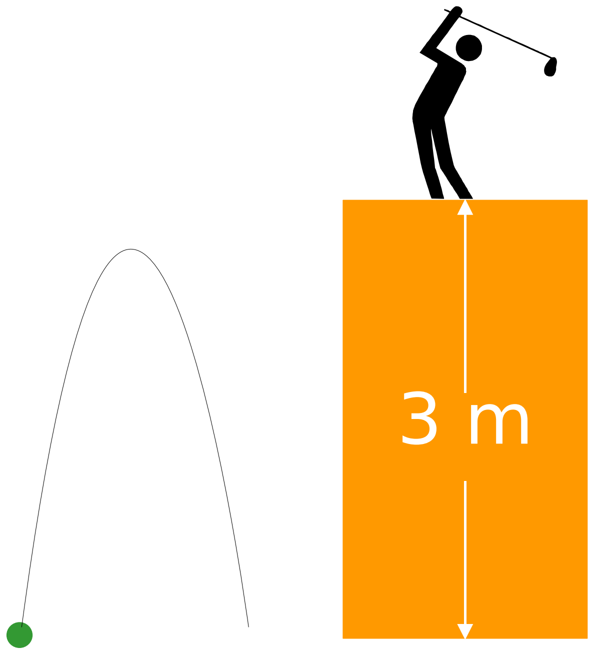
- Scatter them off a material that doesn't absorb them (e.g. superfluid helium) thus creating sound waves ("phonons").

Properties of Ultracold Neutrons

- Once the neutrons are ultracold they have some really very interesting properties.
  - Temperature < 0.004 K (degrees above absolute zero).
  - speed < 30 km/h
- Neutrons interact with the fundamental fields.
  - Strong nuclear force
  - Weak nuclear force
  - Magnetic force
  - Gravity

Gravity

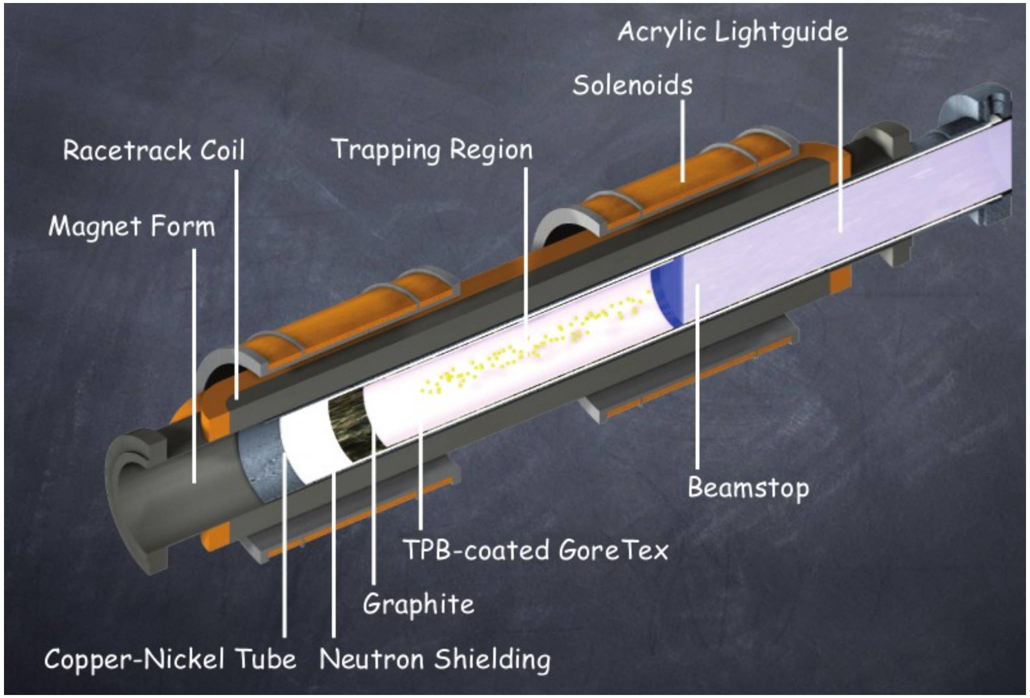
- Question: If I threw something straight up at an initial speed of 30 km/h, how high would it go?
- Answer (from high-school physics):
  - about 3 meters (10 feet).



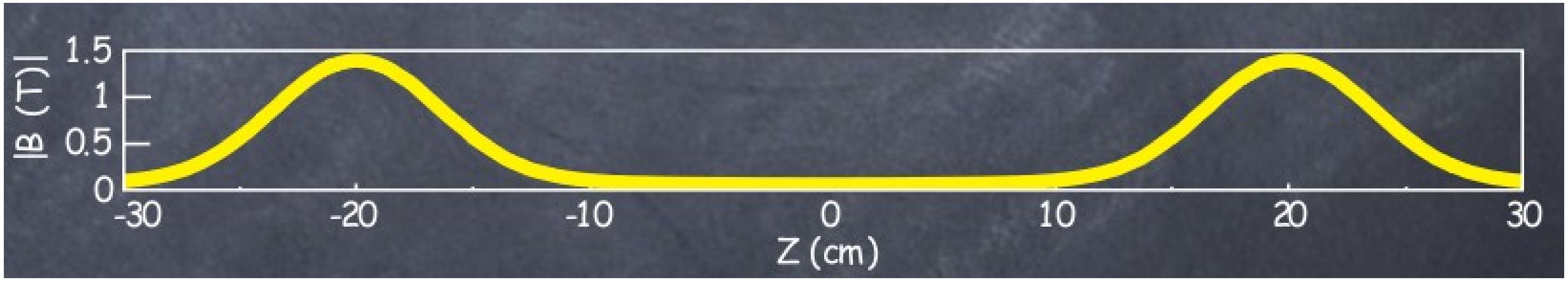
Magnetism

- Neutrons have a "magnetic moment"
  - They behave like a little bar magnets.
- You can trap ultracold neutrons in a magnetic bottle!

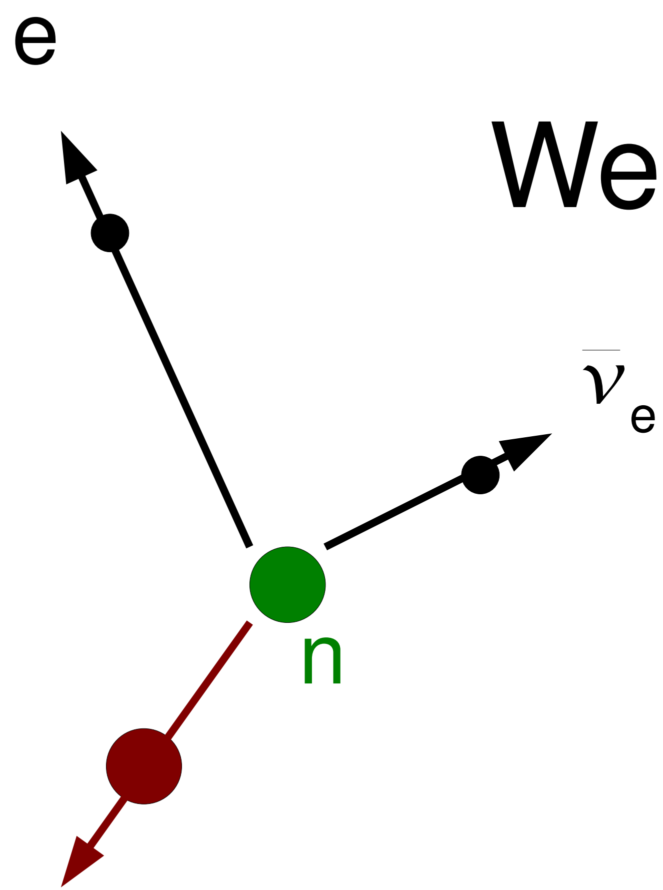
$$V = -\mu \cdot B$$



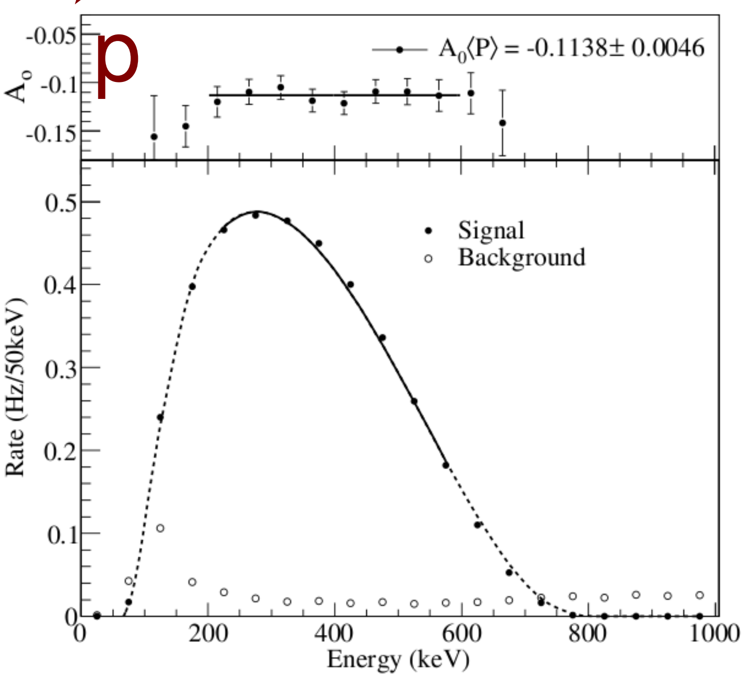
www.nist.gov



Weak Nuclear Force



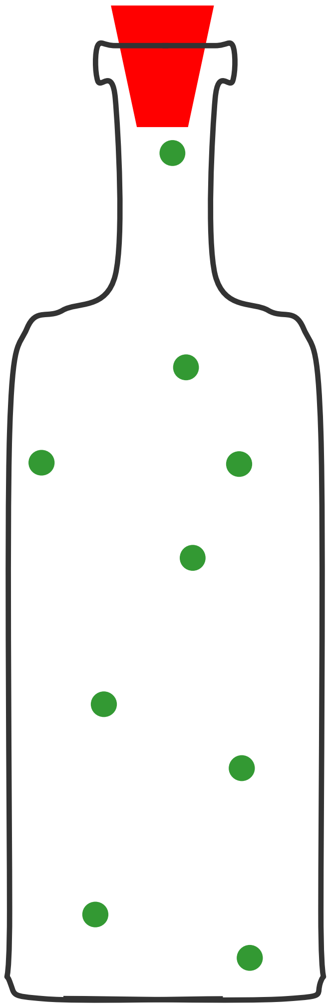
- Causes free neutrons to decay
- Neutrons live for about 15 minutes
- An interesting experiment:
  - Put ultracold neutrons in a bottle
  - Wait a while (about 15 minutes)
  - Open the bottle and see how many neutrons come out
- Also interesting experiment:
  - Measure the beta spectrum



D. Harrison, MSc project

Strong Nuclear Force

- Ultracold neutrons are moving so absurdly slow that they undergo total reflection from surfaces.
- This arises because of the strong nuclear force (the neutrons bumping into atomic nuclei)
- Because of this, you can store them in a material bottle!
- How does this work?



Strong Interaction:
QM in 3D, Central Potential V(r)

$$\frac{-\hbar^2}{2\mathrm{m}}\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial\psi}{\partial r}\right)+\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial\psi}{\partial\theta}\right)+\frac{1}{r^2\sin^2\theta}\frac{\partial^2\psi}{\partial\phi^2}\right]+V(r)\psi=E\psi$$

Solve by separation of variables:

$$\psi(r,\theta,\phi)=R(r)Y_l^m(\theta,\phi)$$

Answer:

$$\left[\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial}{\partial\theta}\right)+\frac{1}{\sin^2\theta}\frac{\partial^2}{\partial\phi^2}\right]Y_l^m=l(l+1)Y_l^m=\frac{1}{\hbar^2}\hat{L}^2Y_l^m$$

$$-i\frac{\partial}{\partial\phi}Y_l^m=mY_l^m=\frac{1}{\hbar}\hat{L}_zY_l^m$$

$$\frac{-\hbar^2}{2\mathrm{m}}\frac{d^2u}{dr^2}+\left[V(r)+\frac{l(l+1)\hbar^2}{2\mathrm{m}r^2}\right]u=Eu$$

$$u(r)=rR(r)$$

QM in 3D
Central Potential V(r)

Some interesting consequences:

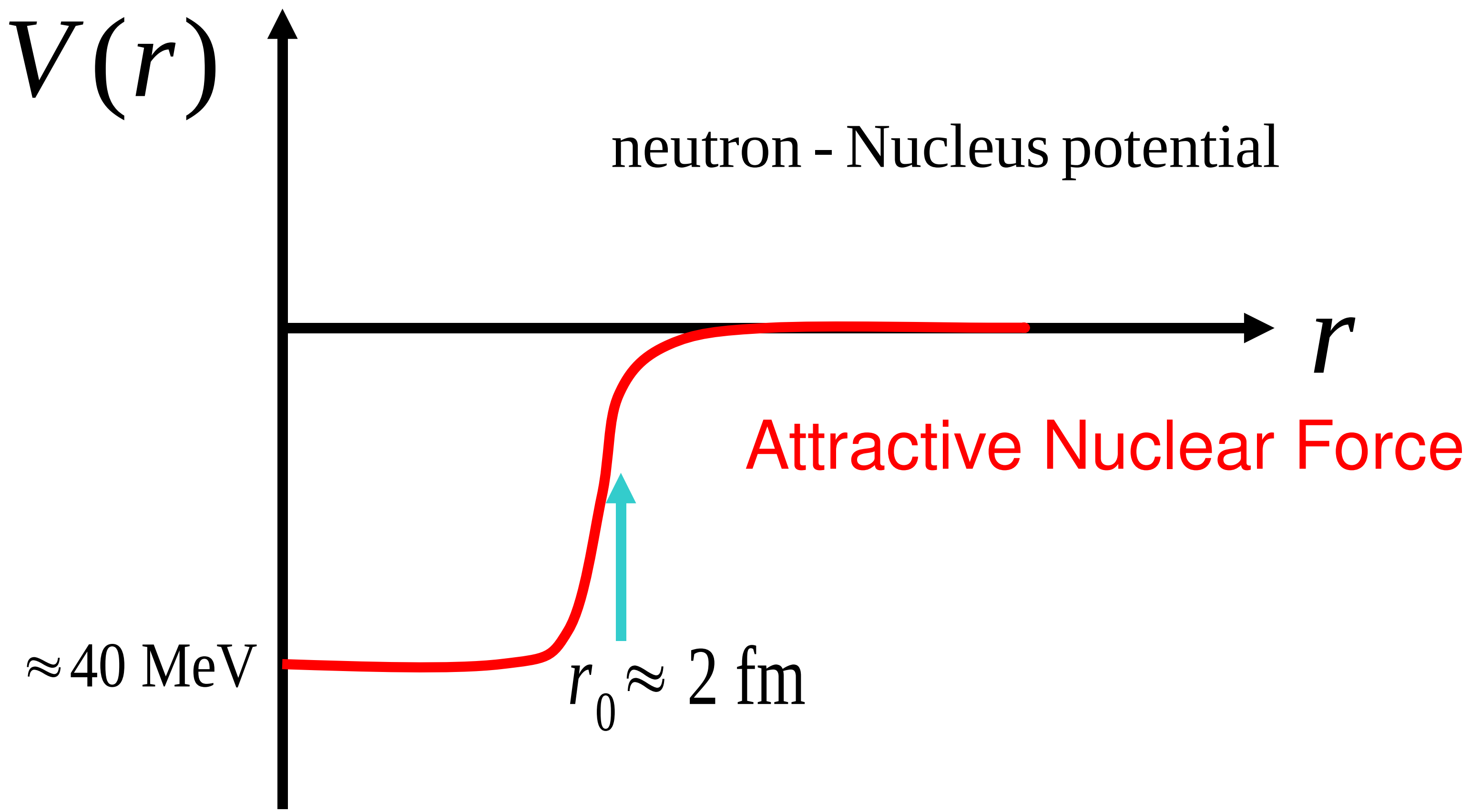
$$l = 0, 1, 2, ... = s, p, d, ...$$

$$m = -l, -l+1, .., l-1, l$$

$$u(r=0) = 0$$

QM in 3D is much like QM in 1D,
but with an infinite wall at the origin.

Strong Interaction



For $T_n \leq 1$ MeV, $l \sim pr_0 \sim 0$, $s-wave$ scattering (isotropic)

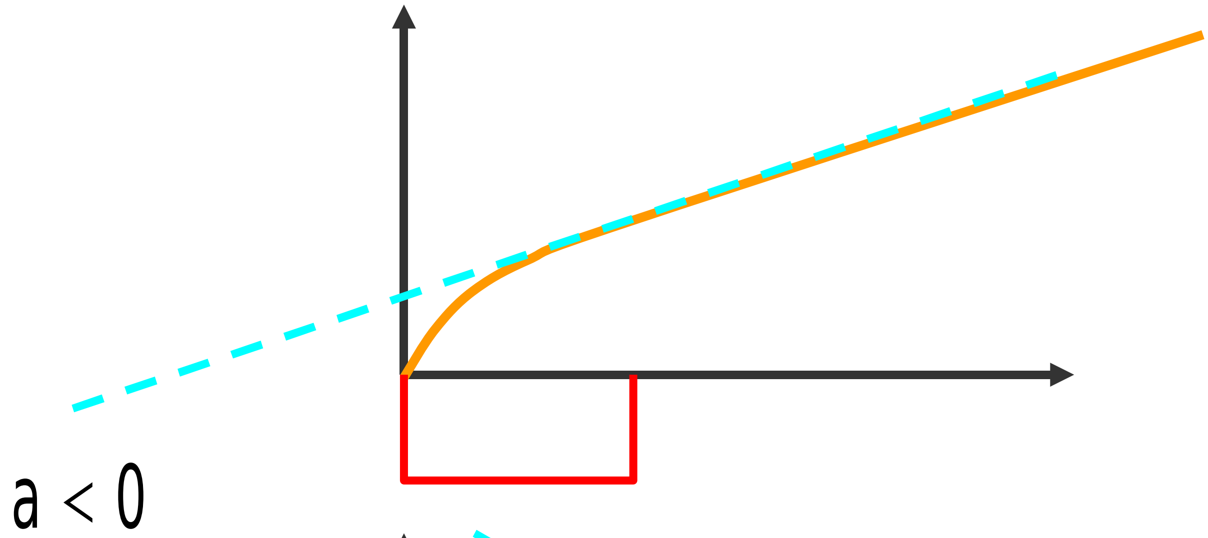
For $T_n \ll 1$ MeV,

$$\sigma_{tot} = 4\pi\ a^2$$

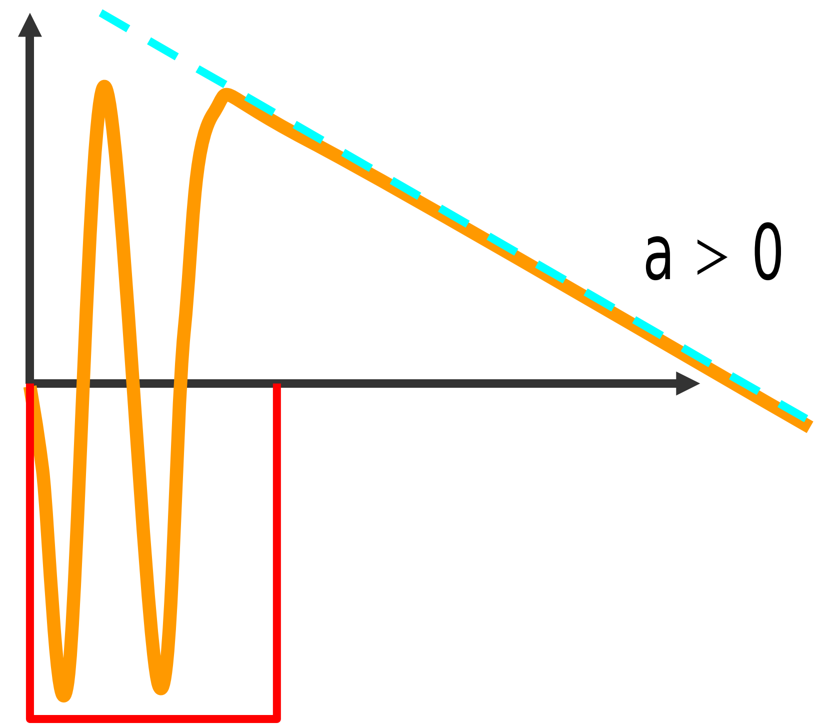
$a \equiv$ scattering length

Scattering Length

Weak potential



Strong potential



Many different potentials can give rise to the same value for “a”

Odds are, a > 0

Fermi Potential

Let's replace *V(r)* by an effective potential with the same *a*:

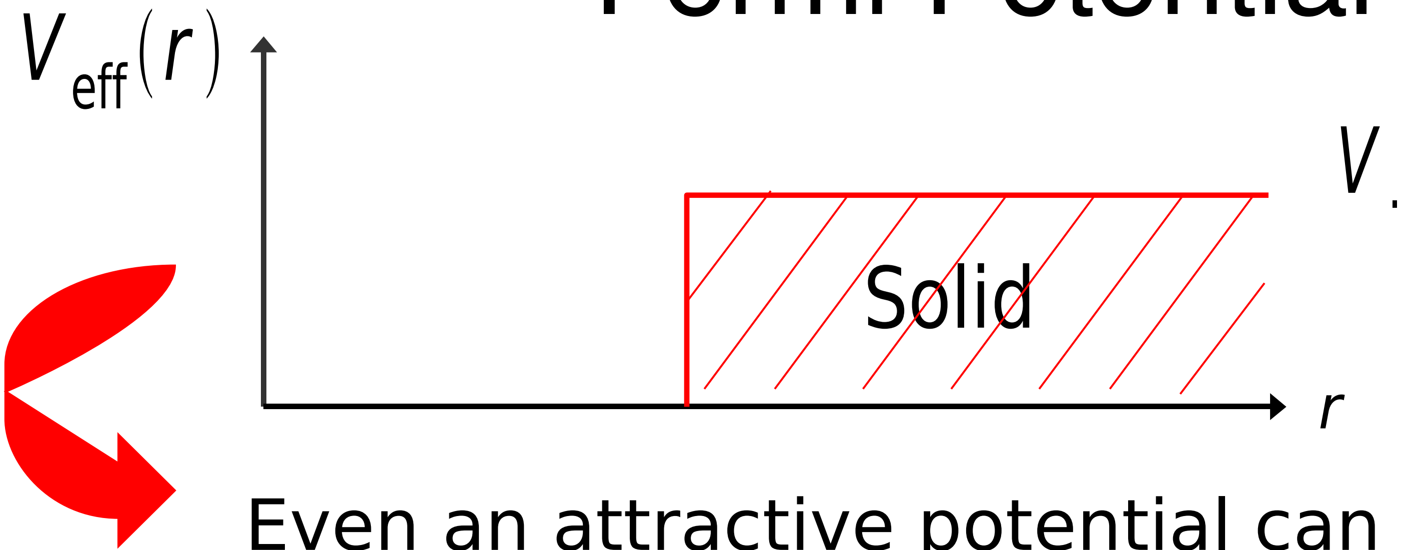
$$V_{eff}(r) = \frac{2\pi\hbar^2 a}{m}\delta(r)$$

For many nuclei in a solid, $V_{eff}(r) = \frac{2\pi\hbar^2}{m}\sum_i a_i \delta(r - r_i)$

For *a* all the same, and small lattice spacing cf. neutron λ ,

$$V_{eff}(r) = \frac{4\pi a\hbar^2}{2m} N_0 \int \frac{d^3 r'}{V}\delta(r - r') = \frac{2\pi a\hbar^2 n_0}{m}\theta(r \notin V) \equiv V_0\theta(r \notin V)$$

Fermi Potential



Even an attractive potential can lead to repulsive effective potential!
(the “Fermi Potential”)
Just as long as a > 0

Largest Fermi potential is for Nickel-58 (^{58}Ni)
V_0 = 335 neV

The World's Highest Density Source of Ultracold Neutrons

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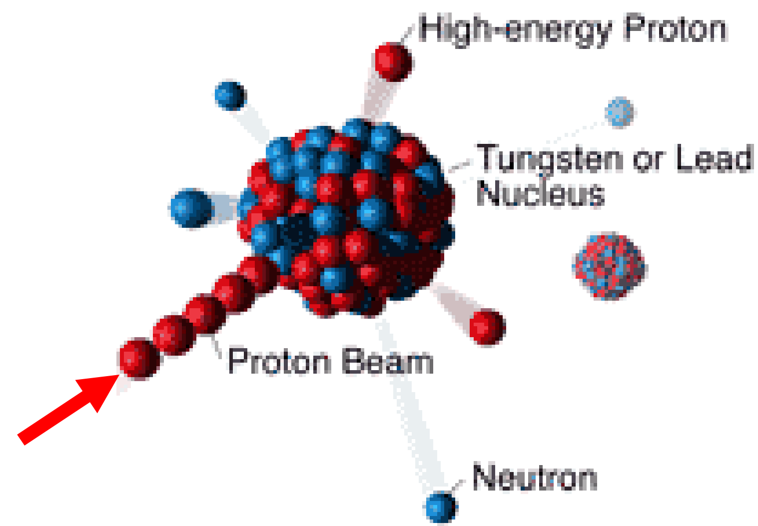
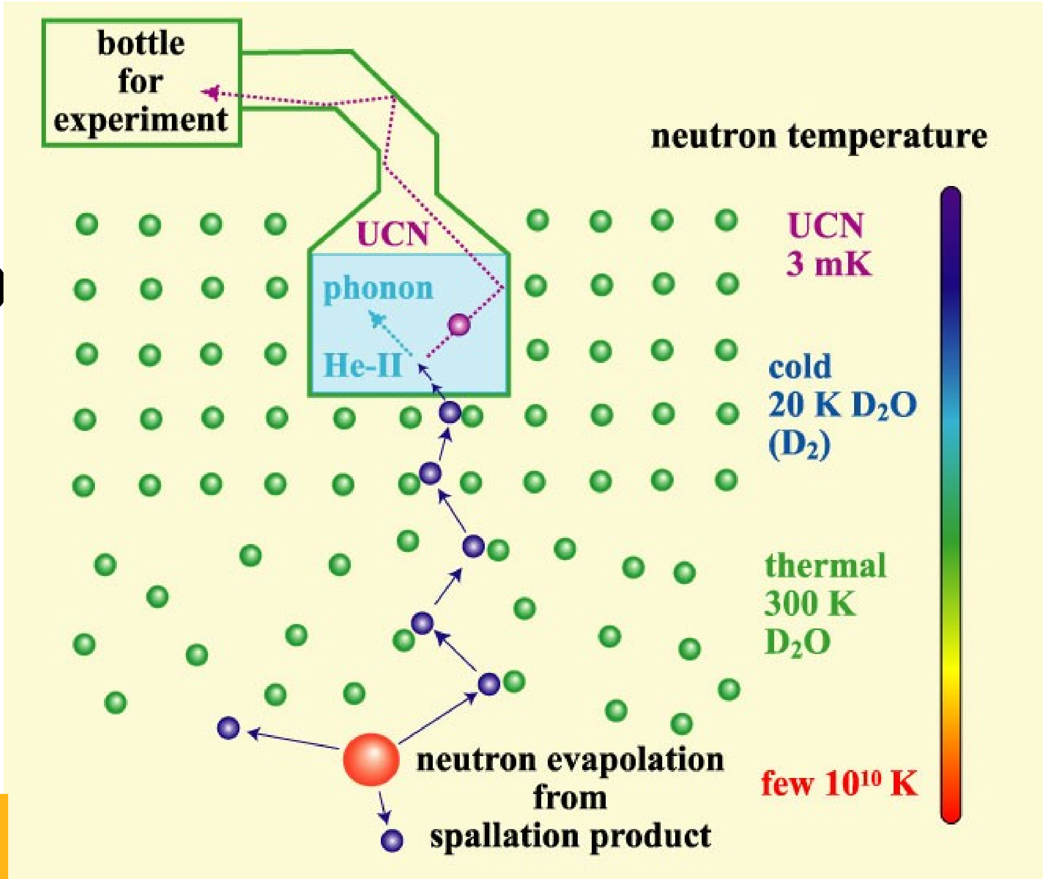
(Winnipeg, Manitoba, ORNL, TRIUMF, NCSU, Caltech, RCNP, SFU, LANL, KEK, Tokyo, UNBC, Osaka, Kentucky)

How to make UCN

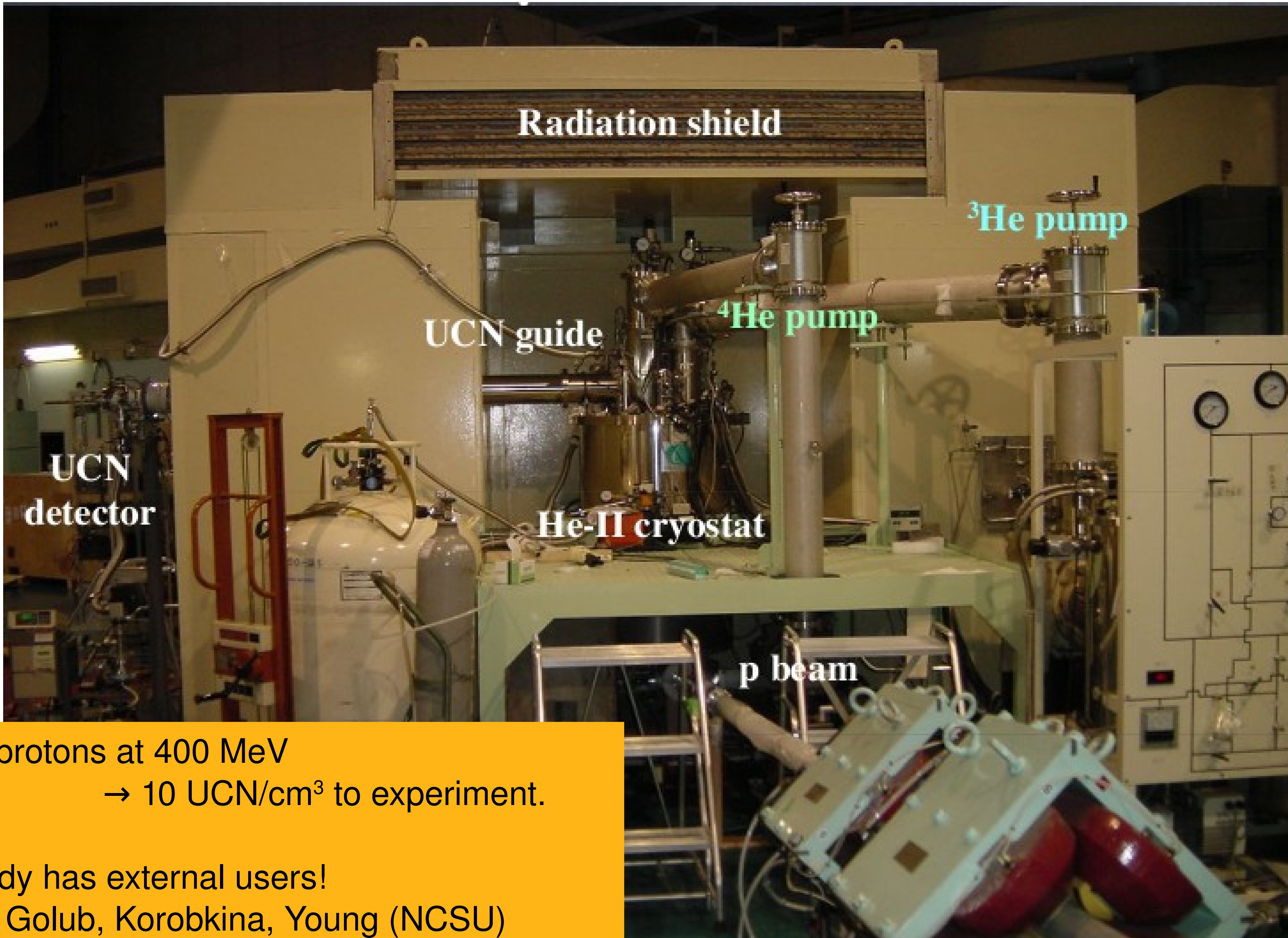
- Liberate neutrons by proton-induced spallation.
- Moderate (thermalize) in cold (20 K) D_2O.
- Cold neutrons then "downscatter" to near zero energy (4 mK) in superfluid helium through phonon production.





<u>Unique to TRIUMF!</u> Most others use SD_2

Osaka UCN Source (Masuda, et al)



1 μa protons at 400 MeV
→ 10 UCN/cm^3 to experiment.

Already has external users!
- e.g. Golub, Korobkina, Young (NCSU)

Gain Factors for TRIUMF

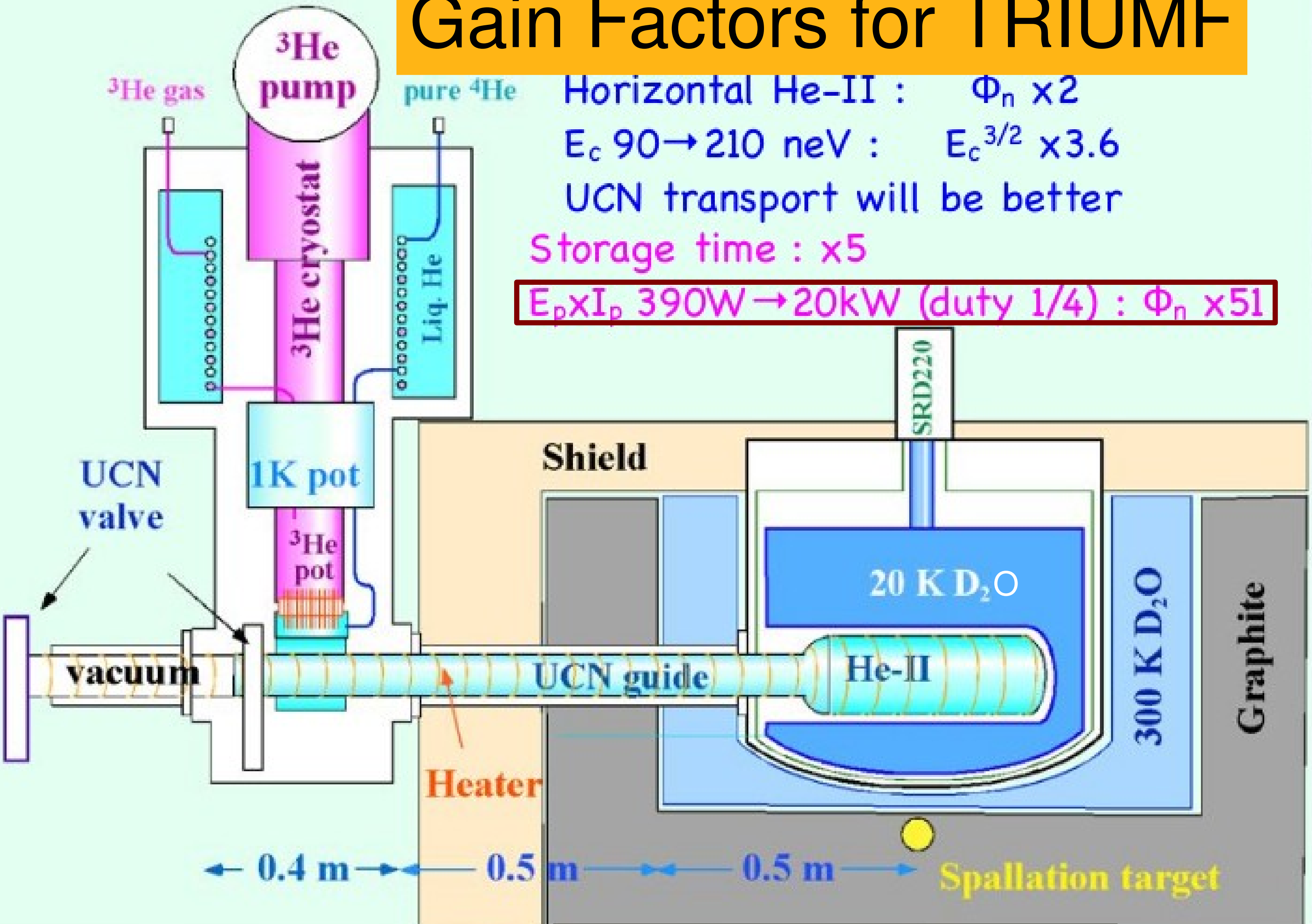
Horizontal He-II : Φ_n x2

E_c 90→210 neV : $E_c^{3/2}$ x3.6

UCN transport will be better

Storage time : x5

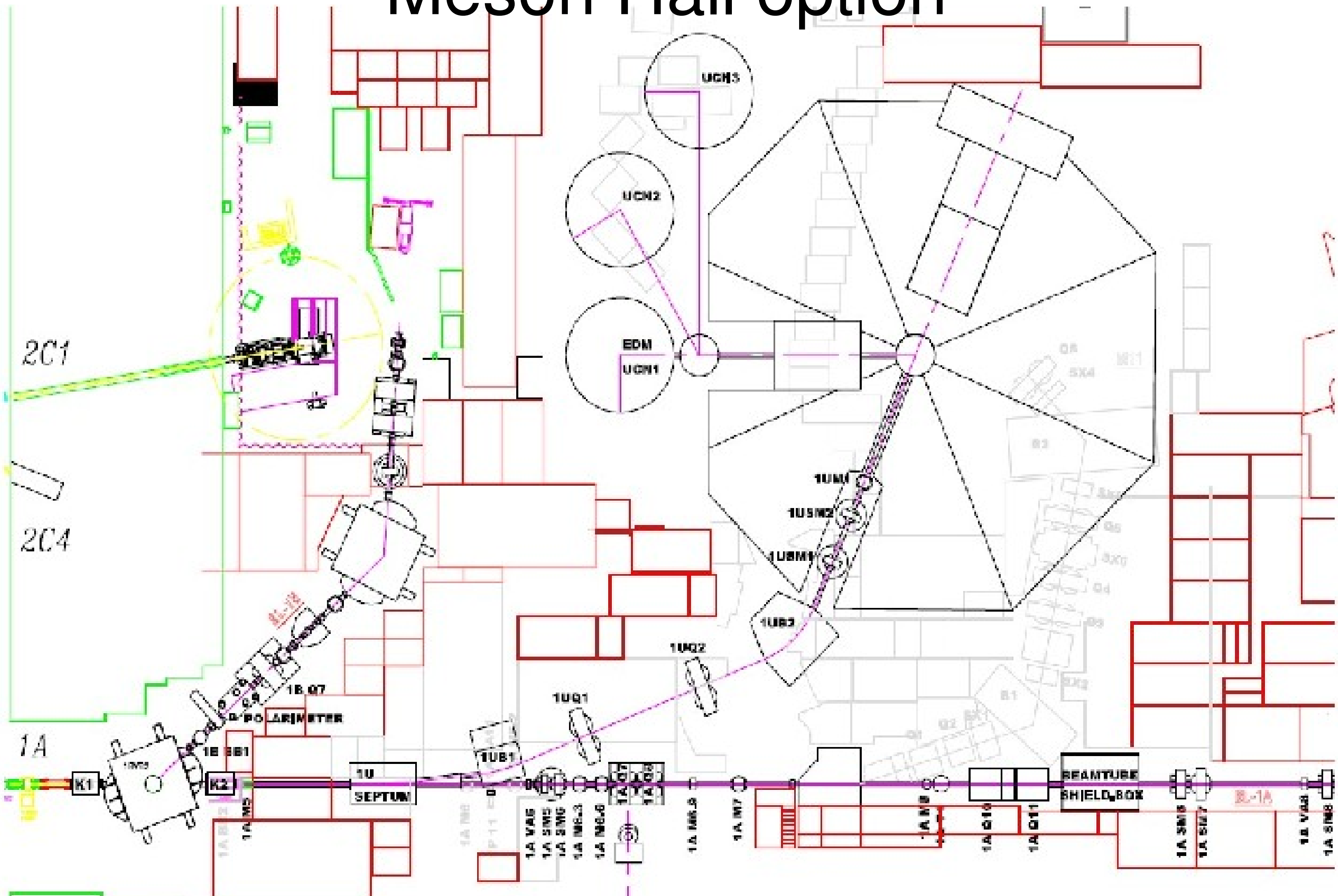
$E_p x I_p$ 390W→20kW (duty 1/4) : Φ_n x51



Future Upgrade: D_2O ice → LD_2 : x5

CSUNS Implementation at TRIUMF

Meson Hall option



- Beamline design (J. Doornbos, G. Clark)
- Kicker feasibility, design (M. Barnes)
- Shielding estimates (A. Trudel)
- Layout (above) (S. Austen, C. Davis)

- Cost/Sched/Manpower (V. Verma, W.D. Ramsay, C. Davis)
- ...and many useful discussions with E. Blackmore, R. Baartman, ...

World's UCN projects

	source type	E_c neV	P_{UCN} /cm^3/s	T_s s	ε_{ext}	ρ_{UCN} /cm^3 source/exp.
TRIUMF	spallation He-II	210	0.4×10^4 (10L)	150	~1	3×10^5 (20L) **$1\text{-}5 \times 10^4$**
ILL	n beam He-II	250	10	150	~1	**/1000
SNS	n beam He-II	134	0.3 (7L)	500	1	**/150
LANL *	spallation SD2	250	4.4×10^4 (240cm^3)	1.6	1.3×10^3/ 4.4×10^4	**/120
PSI	spallation SD2	250	2.9×10^5 (27L*)	6	0.1	2000 (2m^3) /1000
NCSU	reactor SD2	335	2.7×10^4 (1L)	**	**	1300/**
Munich	reactor SD2	250	**	**	**	1×10^4/**

Super-cool Physics Experiments

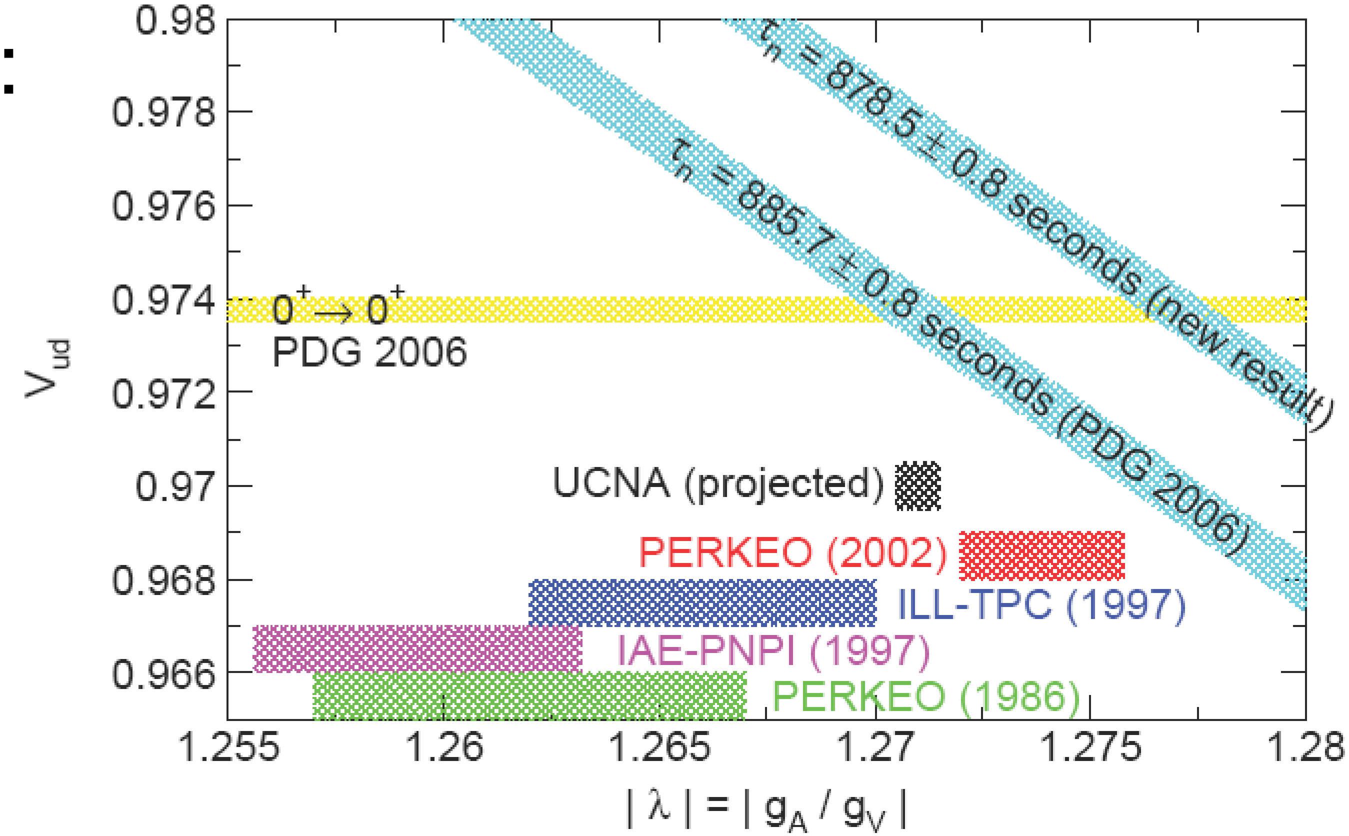
- Neutron lifetime
- gravity levels
- surface science
- n-EDM

near term (Neutron lifetime, gravity levels, surface science)

longer term (n-EDM)

Neutron Lifetime

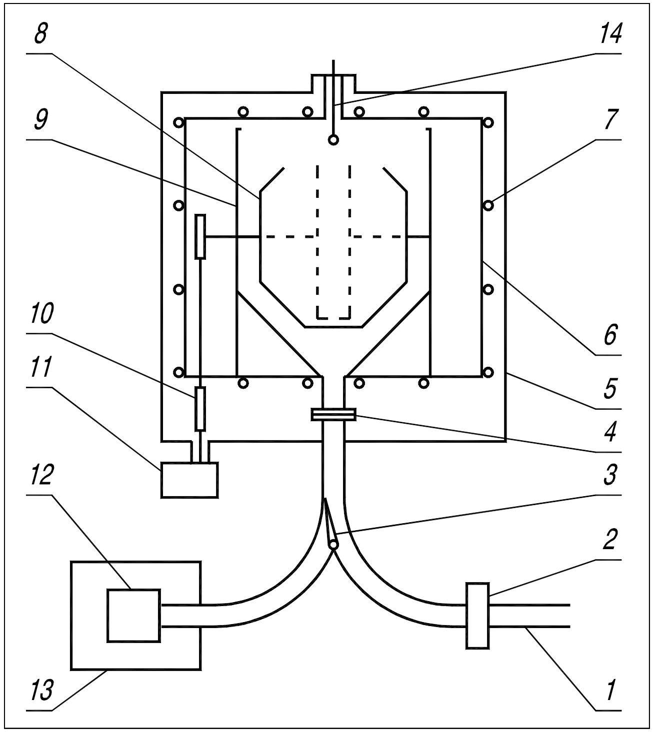
- Physics interest:
  - BBN
  - V_{ud}



- Currently a 6.5 sigma discrepancy between n-lifetime experiments

Neutron Lifetime

- Basic experiment: trap UCN for varying amounts of time
- All previous precise experiments used material traps
- Wall effects give dominant systematic effects

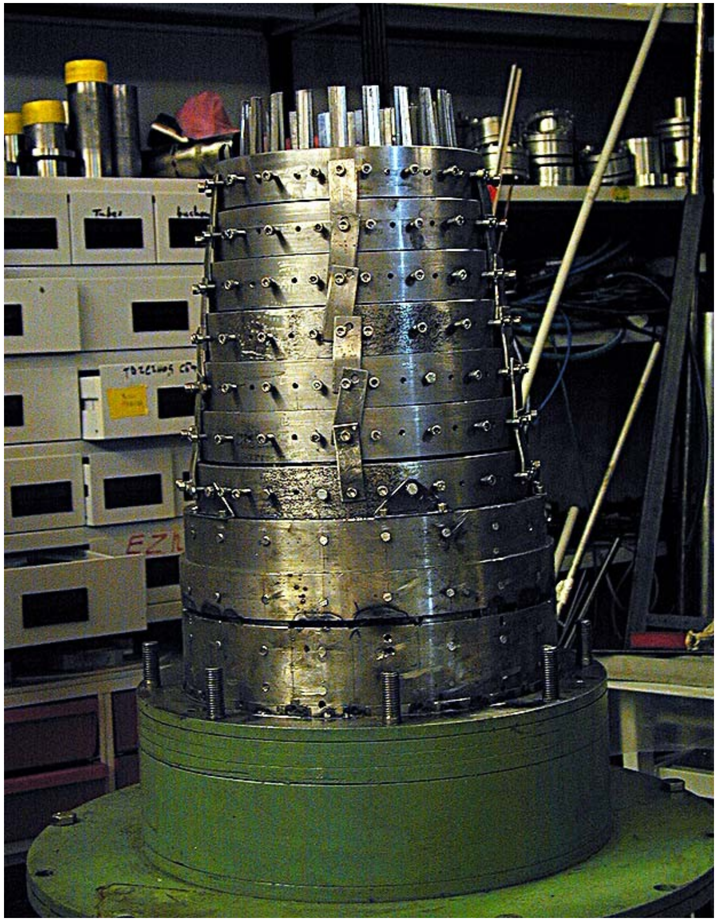


- New efforts to trap UCN magnetically
- marginally trapped orbits
- NEED MORE UCN!!!

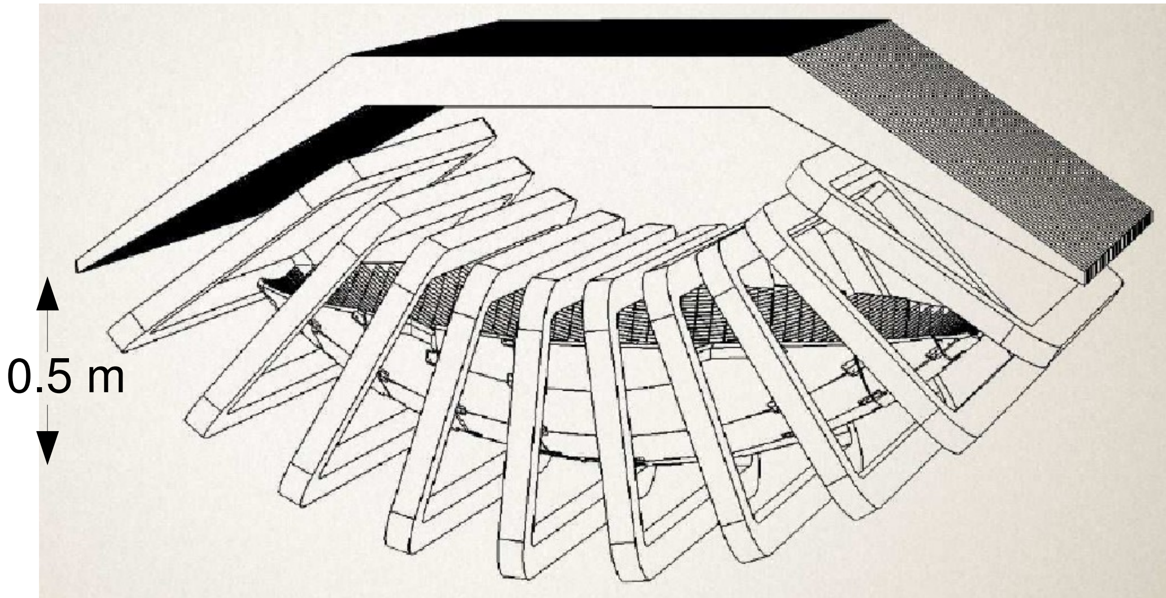
<- Gravitrap

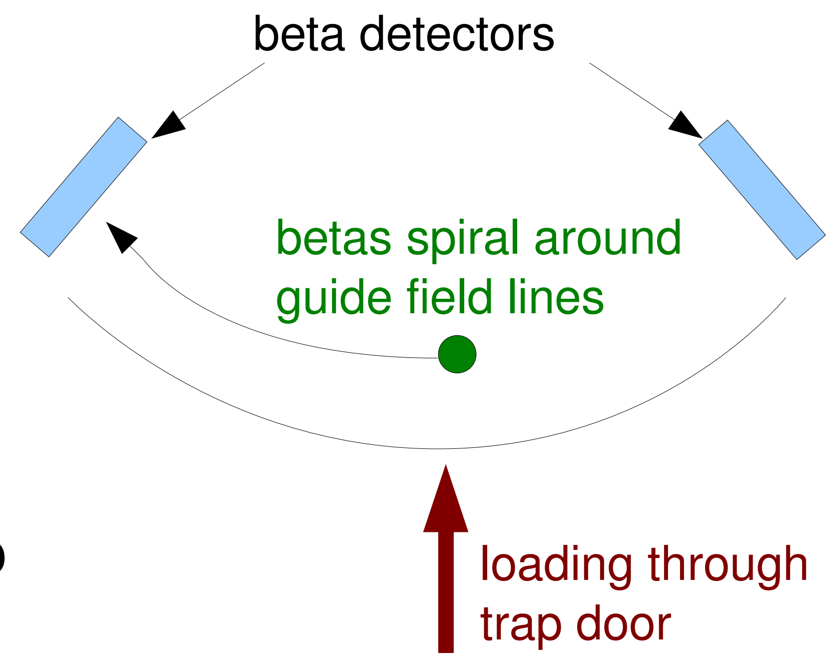
Permanent magnet trap ->

(both at ILL)



Magneto-Gravitational Trap for Neutron Lifetime (Bowman et al)





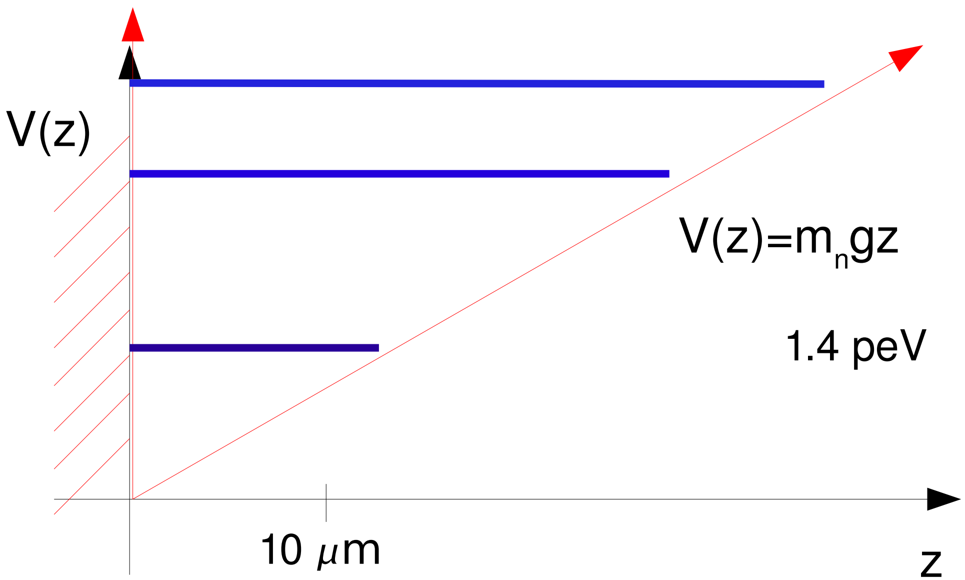
- Shallow Halbach array + gravity for trap
- Guide field for decay betas
- Marginally trapped neutrons experience chaotic orbits and are ejected rapidly
- Goal precision $\delta\tau_n$ ~ 0.1 s
- Require: Efficient trap loading, effective n-“cleaning”, high UCN density

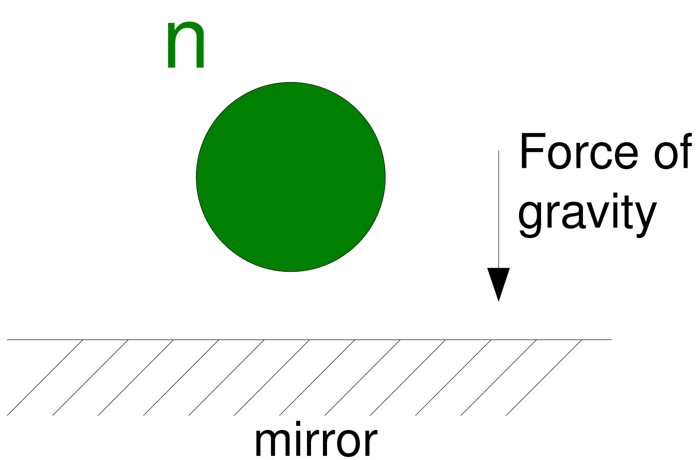
N-lifetime Plans for TRIUMF

- Theoretical work on trap dynamics completed at LANL recently published in NIM A.
- Prototype under construction at LANL
- Goal is for test experiment at LANL UCN source
- TRIUMF experiment would build on preliminary work done at LANL
- Candidate for a first physics experiment using the TRIUMF UCN source
- Current common collaborators:
  - J.D. Bowman, B. Filippone, T. Ito, B. Plaster

Quantum Physics, Gravity, and Neutrons

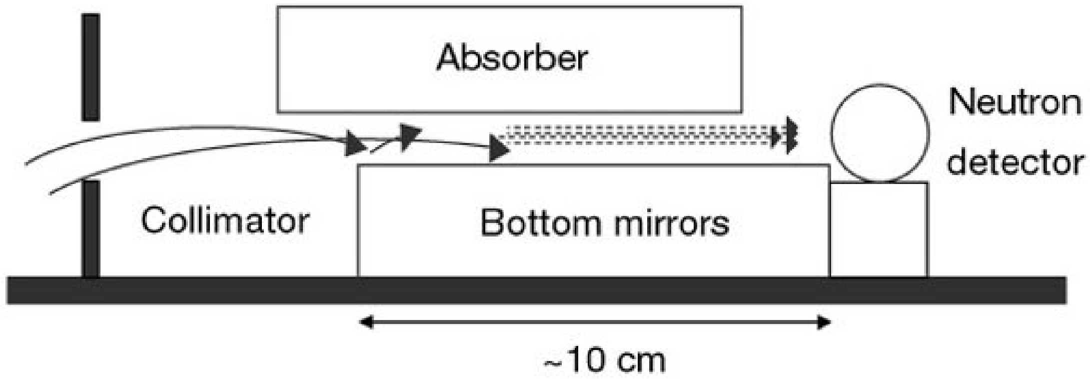
- Ultracold neutrons can be confined in the Earth's gravity field.

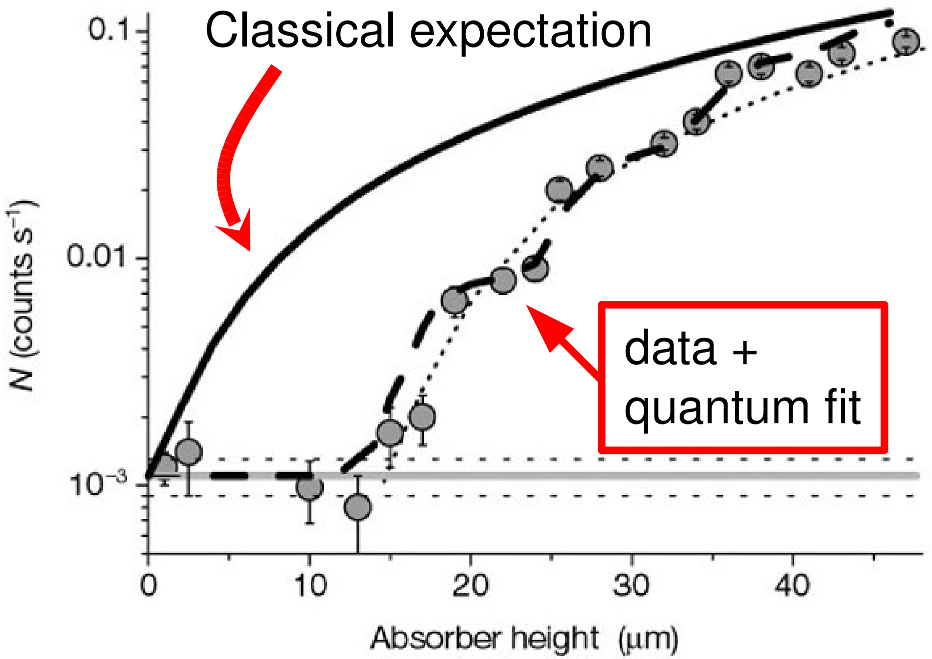




- Recently, the first observation of quantized energy-levels in the Earth's gravity field was made.

Experiment on Quantum Mechanics and Gravity



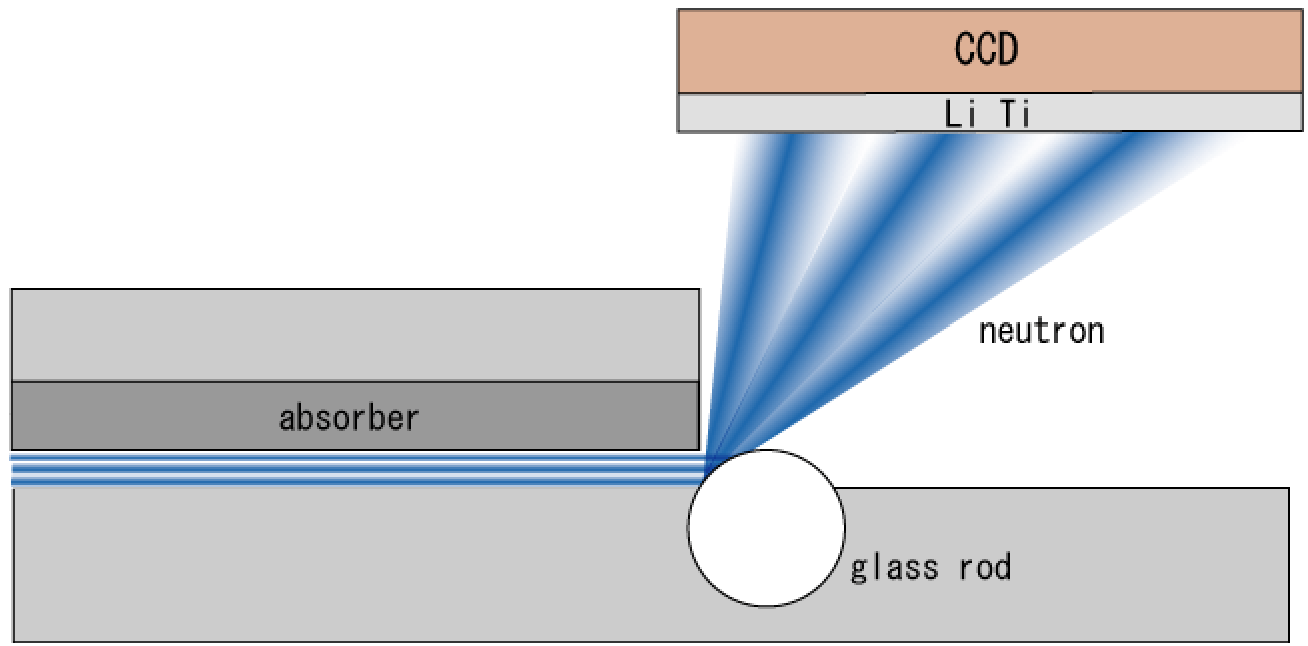


- Experimental results have been used to place limits on
  - 10 um scale modifications to gravity
  - extra dimensions
  - axions

- Conducted in Grenoble, France.

Concept for Improved Experiment (Komamiya group)

UCN in



Komamiya et al, NIM A (2009)

- Features:
  - glass rod “magnifier”
  - Li-coated CCD readout

Plans for TRIUMF

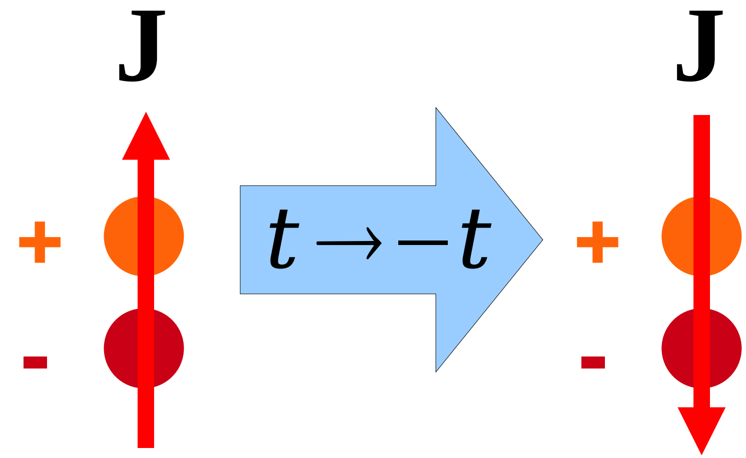
- Experiment would be initiated and led by Japanese groups (S. Komamiya, et al).
- Because development work is already underway, this is a good candidate for a first experiment (along with n-lifetime).

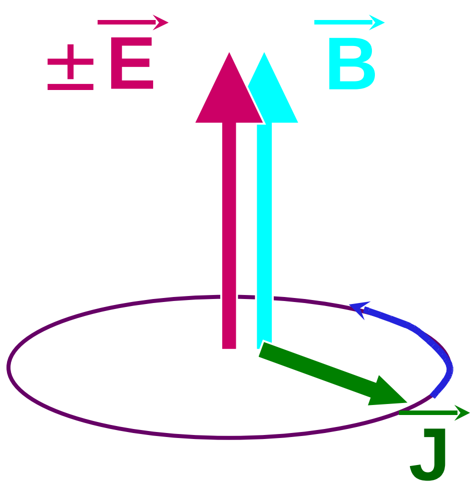
Further experiments:

- Bottle the UCN to increase time the UCN is contact with the mirror.
- Excite resonant transitions between quantum states.
- Increase purity of states by preselection.
- Goal: improve precision on energy of state and hence increase sensitivity to modifications to gravity.

Neutron Electric Dipole Moment (n-EDM)

- Existence of EDM implies violation of Time Reversal Invariance
- CPT Theorem then implies violation of CP conservation





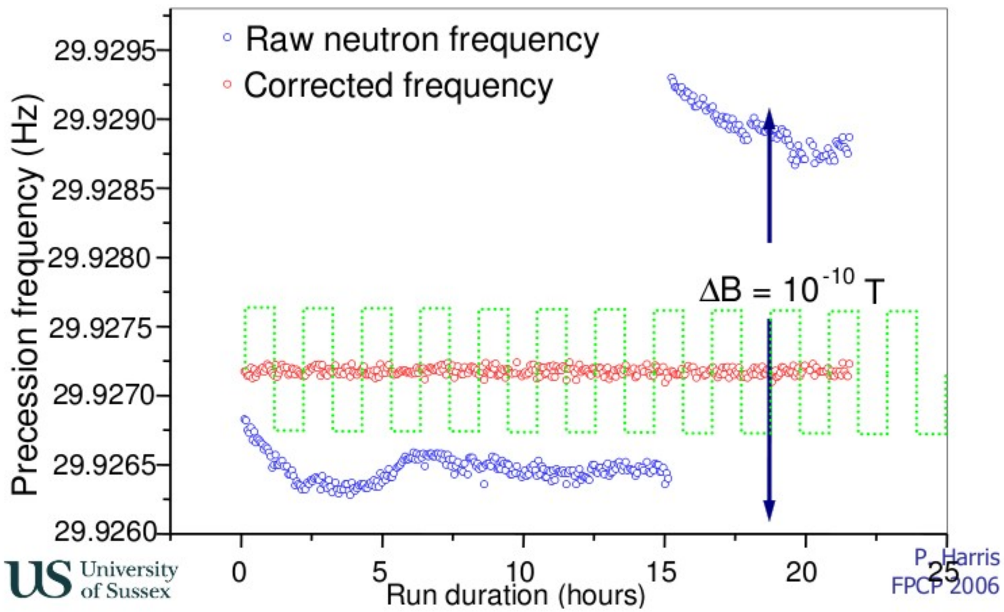
$$h\nu = 2\mu_n B \pm 2\mathrm{d}_e E$$

- Present Exp. Limit < 3×10^{-26} e-cm
- Standard Model value: 10^{-31} e-cm
- Supersymmetry or Multi-Higgs models can give 10^5xSM
- Significant discovery potential with new high sensitivity *n*-EDM experiment

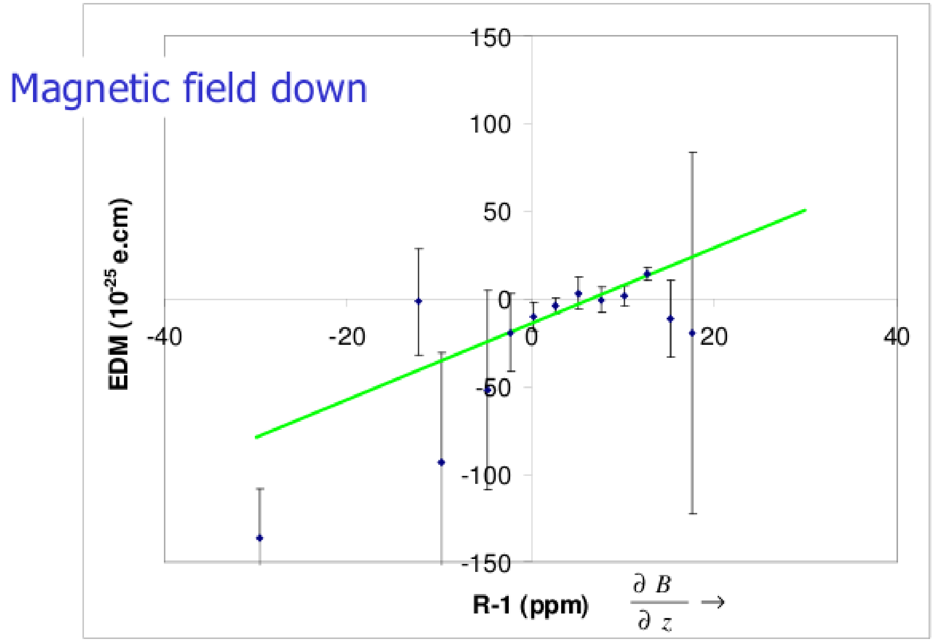
n-EDM Systematics

- magnetic field variations
- leakage currents
- geometric phase effect
  - false EDM arising from field inhomogeneity and E x v.

(co)magnetometry



comagnetometry



false EDM (GP) effect

Past and Future n-EDM efforts

- OILL expt. ($d_n < 3\times10^{-26}$ e-cm)
  - 0.7 UCN/cc, room temp, in vacuo
- CryoEDM (ILL, Sussex, RAL)
  - 1000 UCN/cc, in superfluid 4He
- SNS
  - 430 UCN/cc, in superfluid 4He
- PSI
  - 1000 UCN/cc, in vacuo
- TRIUMF: 1-5 x 10^4 UCN/cc

Plans for TRIUMF

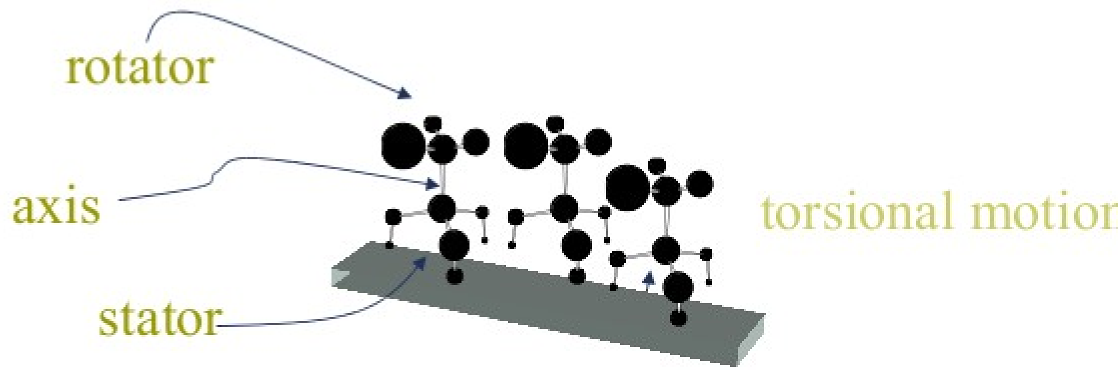
- Begin with modified ILL, SNS, or PSI setup
  - higher UCN density allows smaller cell size
    - smaller GP effect
  - development of magnetometers, Ramsey-resonance technique (Masuda)
- proposal ~ 2011
- expect number of EDM-experienced collaborators to grow if UCN source is approved:
  - B. Filippone, R. Golub, T. Ito, E. Korobkina, M. Hayden, B. Plaster

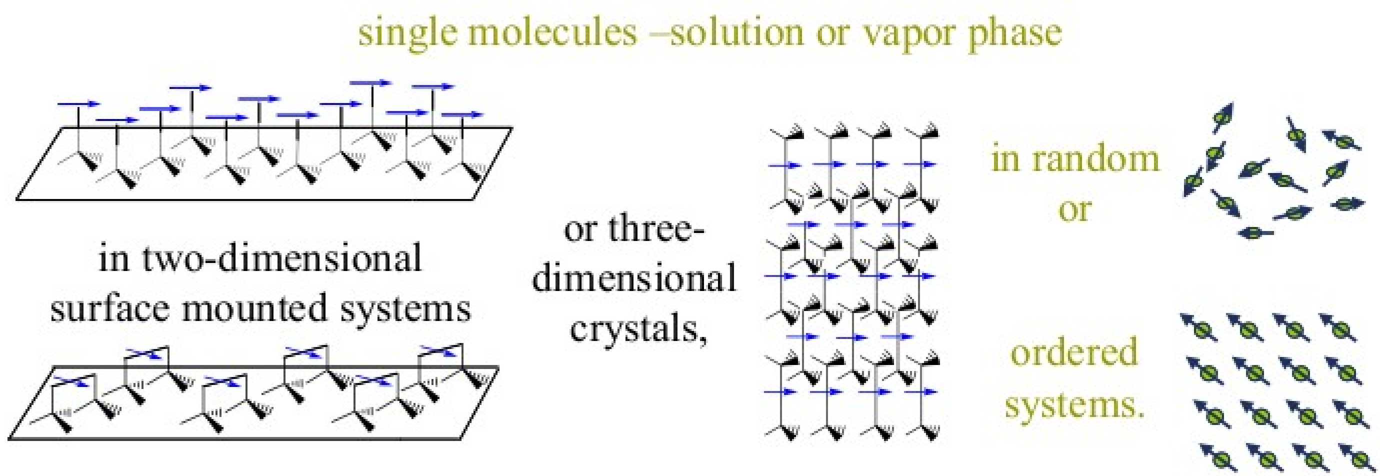
Surface Physics

- Use UCN to study 10 nm thin surface films
  - e.g. our application: "inelastic scattering reflectometry" (UCN ISR), sensitive to low-energy excitations, particularly of hydrogen-containing materials
  - compare two methods of inelastic scattering detection:
    - UCN loss measurements
    - detect upscattered neutrons
- High intensity UCN source is needed for this new field to be opened up.

Application of UCN ISR: Artificial Molecular Rotors

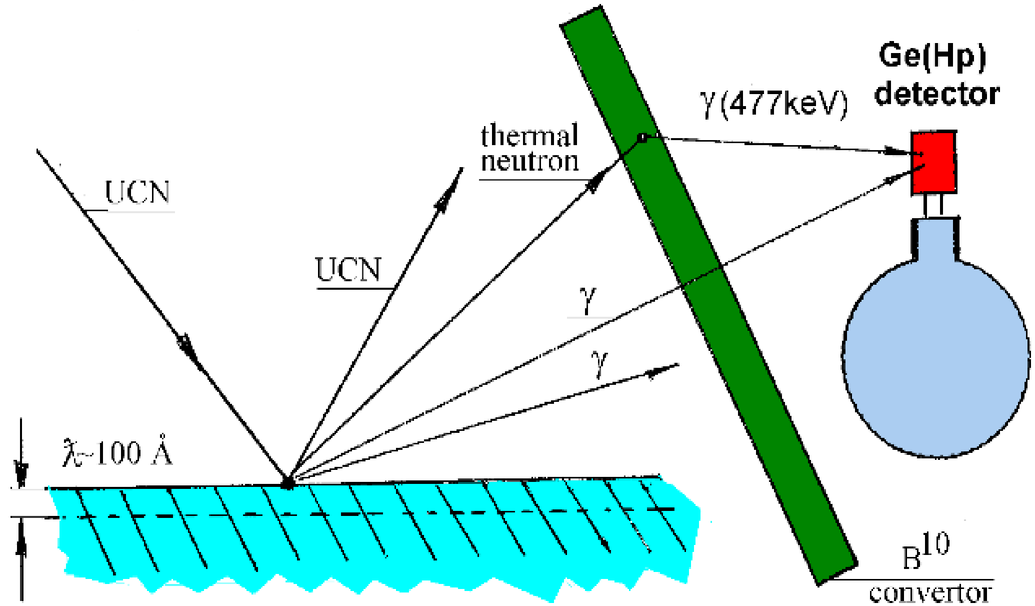
"low-energy excitations"
=
rotations and vibrations of big molecules





- "Smart surfaces" research – surfaces that change their properties when subjected to external stimuli (drug delivery example)

Basic Apparatus



- Simultaneous measurement of UCN loss rate and converter gammas isolates UCN ISR from e.g. (n,gamma) losses.

UCN ISR apparatus for TRIUMF

- Design of cryostat and first proof-of-principle experiments have been carried out. (Hahn-Meitner Inst., ILL)
- Need higher UCN flux.
- R. Golub, E. Korobkina, L. Clarke (NCSU)
- Potentially large user-base in “smart surfaces” community

CSUNS timeline

- 2008: CFI NIF proposal submitted
  - In-kind contributions from Japan, TRIUMF
- 2009-12:
  - develop UCN source in Japan
  - preparations and design in Canada
  - develop neutron lifetime collaboration, proposal, and experiment
- 2012-13: Install, commission at TRIUMF
- 2012-15: First experiments (n-lifetime, gravity)
- 2015-: n-EDM and beyond

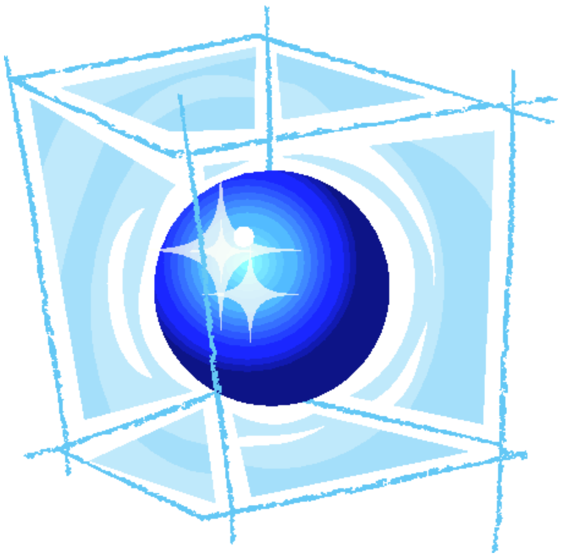
Canadian Spallation Ultracold Neutron Source

- Canada has an opportunity to construct a world-leading UCN facility at TRIUMF.
- Proposal to CFI NIF submitted through U. Winnipeg with several Canadian universities involved. Matching supplied by Japan and TRIUMF.
- Involvement of private industry: Acsion Industries – for neutron moderator optimization and training of HQP (matched by MB Gov't)

Troy Dawson, UWpg hons. thesis, April 2009

Summary

- Ultracold neutrons are super cool.
- We can use them for a variety of purposes, for example to test quantum gravity.



- We want to build the world's most intense source of ultracold neutrons, and locate it in Canada.

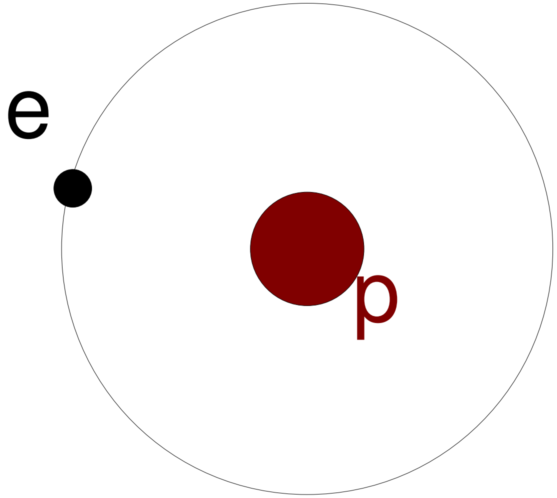
References

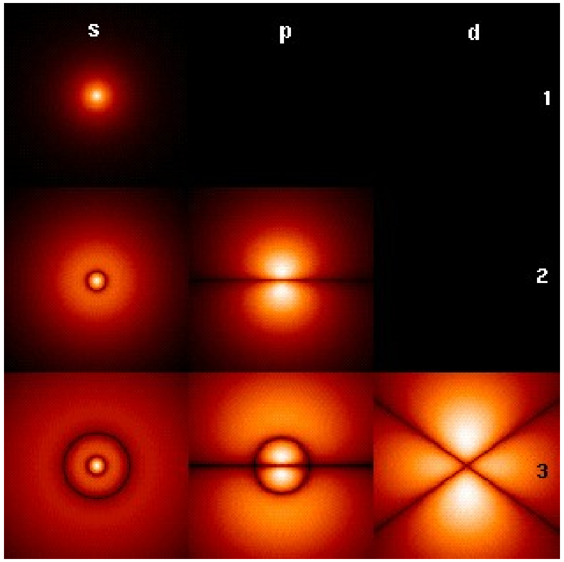
- My research group:
  - http://nuclear.uwinnipeg.ca
- Canadian Spallation Ultracold Neutron Source:
  - http://nuclear.uwinnipeg.ca/ucn/triumf
- The Particle Adventure:
  - http://www.particleadventure.org

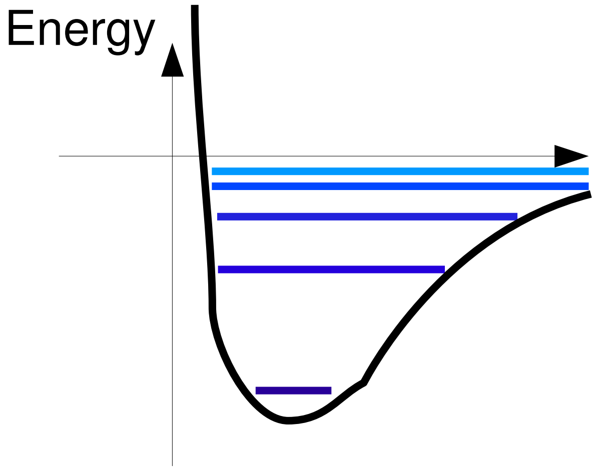
jmartin@nuclear.uwinnipeg.ca

Quantum Physics

- We think that everything in the universe is governed by the laws of quantum physics.
- However, quantum physics effects are only seen, generally, in really small things. (e.g. atoms ~ 0.1 nm = one-billionth of ten centimeters)
- One successful prediction of quantum mechanics is the “quantization” of energy levels for particles bound in potential wells. (e.g. H-atoms)

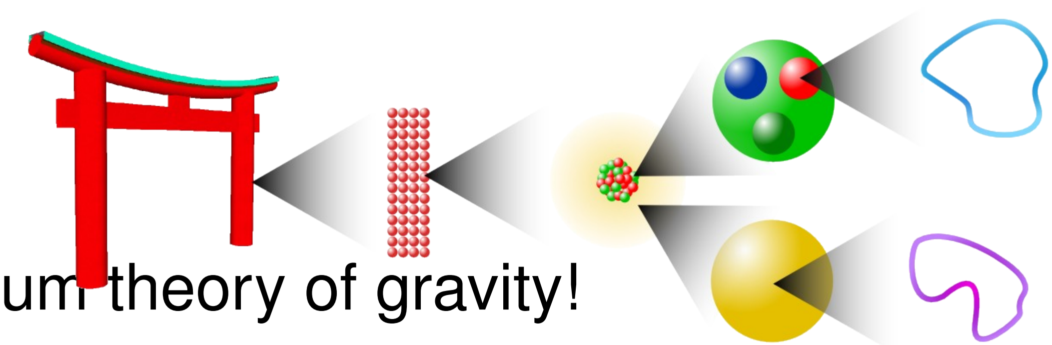






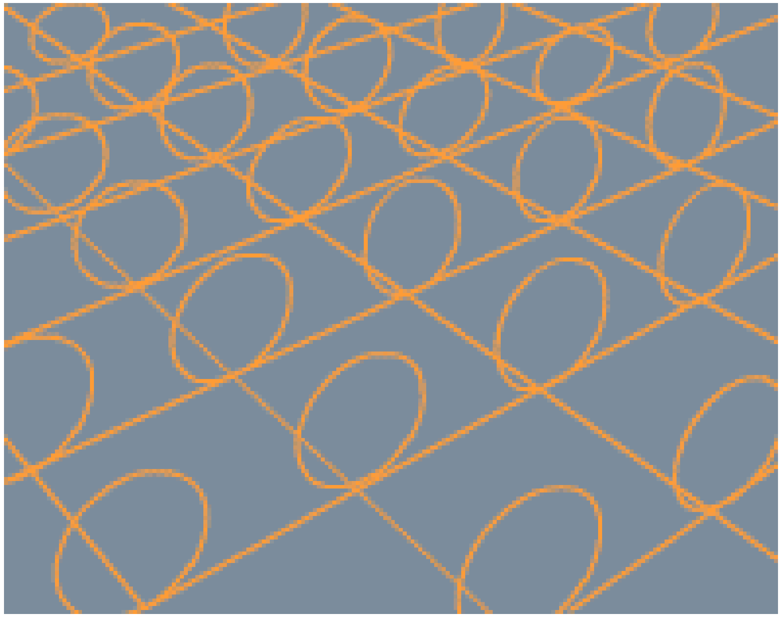
Quantum Physics and Gravity: They Don't Work Well Together

- So far, no one has figured out how to make gravity work with quantum physics.
- But people are trying:



  - string theory
    - might be the real quantum theory of gravity!
  - models of quantum behavior in black holes
    - J. Ziprick, G. Kunstatter, and R. Kobes, U. Winnipeg

Extra Dimensions?



- One "prediction" of string theory is extra dimensions.
- If they exist, where are they?
- Clever theorists have suggested that maybe they are "curled up" or "compactified".
- These curled up dimensions would modify gravity at scales below the size of the curling.
- If gravity is modified at these scales, neutron gravity experiments should see it.

The Future of Ultracold Neutrons in Canada (I hope)

TRIUMF

CANADA'S NATIONAL LABORATORY FOR PARTICLE AND NUCLEAR PHYSICS

Owned and operated as a joint venture by a consortium of Canadian universities via a contribution through the National Research Council Canada

- I am proposing, along with others, to construct the world's most intense source of ultracold neutrons (at Canada's National Nuclear and Particle Physics Lab, TRIUMF, Vancouver).
- We hope to use these neutrons to provide:
  - new windows into materials science
  - the most precise test of quantum mechanics as applied to gravity and extra dimensions.

LABORATOIRE NATIONAL CANADIEN POUR LA RECHERCHE EN PHYSIQUE NUCLÉAIRE ET EN PHYSIQUE DES PARTICULES

Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada