

Ultracold Neutrons in Canada and Japan

Jeff Martin

The University of Winnipeg

February 2009



NSERC
CRSNG



Canada Foundation
for Innovation

Fondation canadienne
pour l'innovation

research supported by

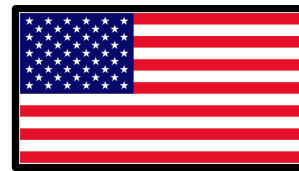
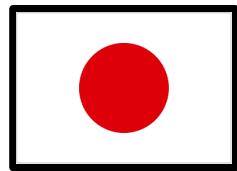
Natural Sciences and Engineering Research Council Canada

Canada Foundation for Innovation

Manitoba Research & Innovation Fund

Japan Society for the Promotion of Science

International Spallation Ultracold Neutron Source



Spokespeople: Y. Masuda (KEK), J.W. Martin (Winnipeg)

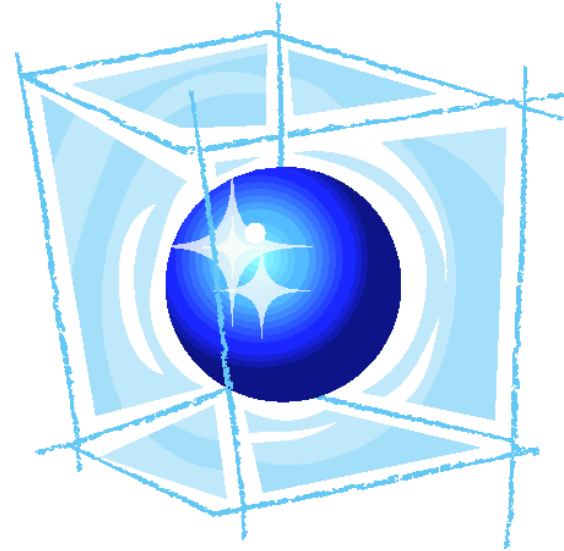
Collaborators: J.D. Bowman, J. Birchall, L. Buchmann, L. Clarke, C. Davis, B.W. Filippone, M. Gericke, R. Golub, K. Hatanaka, M. Hayden, T.M. Ito, S. Jeong, I. Kato, S. Komamiya, E. Korobkina, E. Korkmaz, L. Lee, K. Matsuta, A. Micherdzinska, W.D. Ramsay, S.A. Page, B. Plaster, I. Tanihata, W.T.H. van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

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

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.

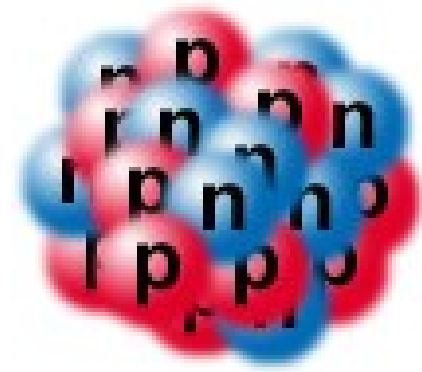
Ultracold Neutrons (UCN)

- What are neutrons?
- Why are they important?
- What are UCN?
- Interactions of UCN.
- How to make UCN.
- Plans for the International Spallation Ultracold Neutron Source (InterSUNS).
- Experiments that we would do there.



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

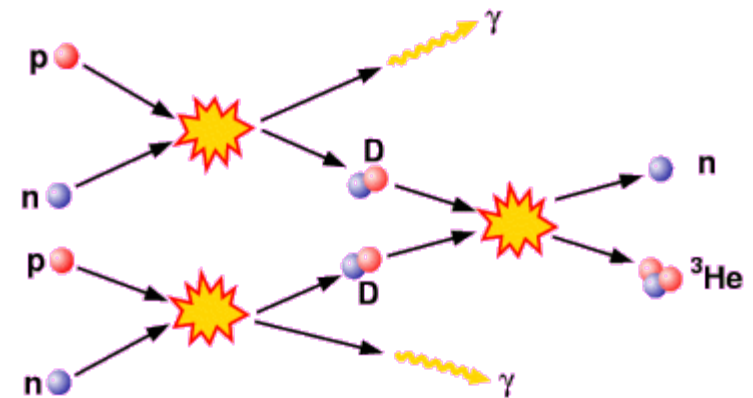
- when freed from a nucleus, they decay
- Discovered by Chadwick in 1932 (Nobel Prize).

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.

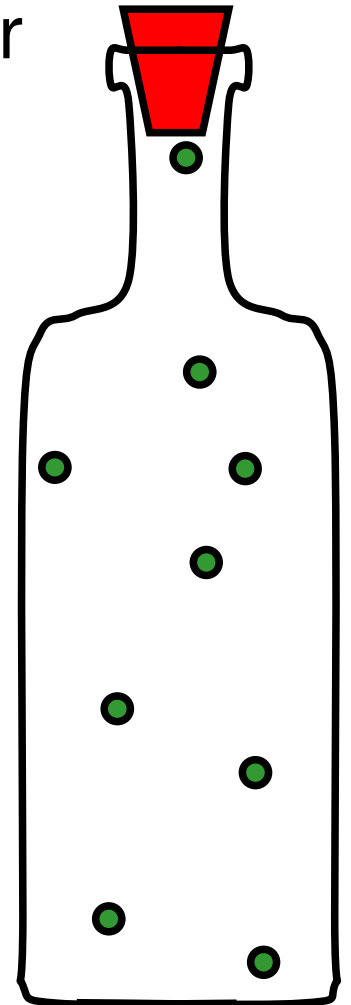


<http://www.einstein-online.info>

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

Ultracold Neutrons (UCN)

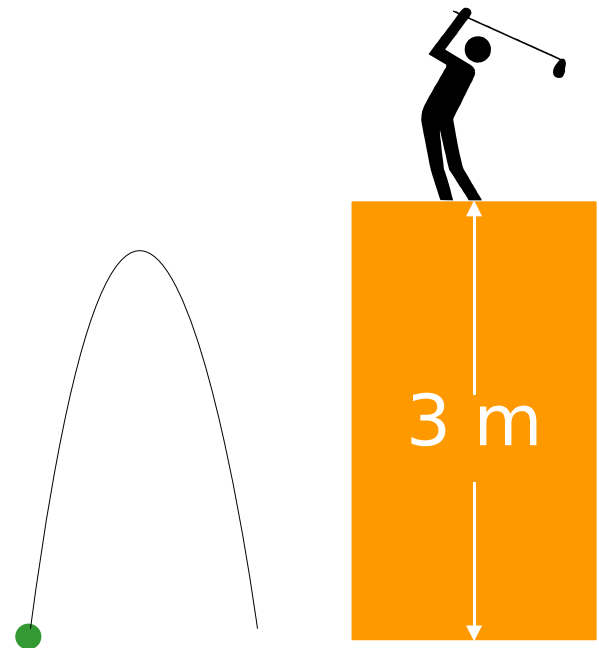
- UCN are neutrons that are moving so slowly that they are totally reflected from a variety of materials.
- So, they can be confined in material bottles for long periods of time.
- Typical parameters:
 - velocity $< 8 \text{ m/s} = 30 \text{ km/h}$
 - temperature $< 4 \text{ mK}$
 - kinetic energy $< 300 \text{ neV}$
- Interactions:
 - gravity: $V=mgh$
 - weak interaction (allows UCN to decay)
 - magnetic fields: $V=-\mu \cdot B$
 - strong interaction



Gravity

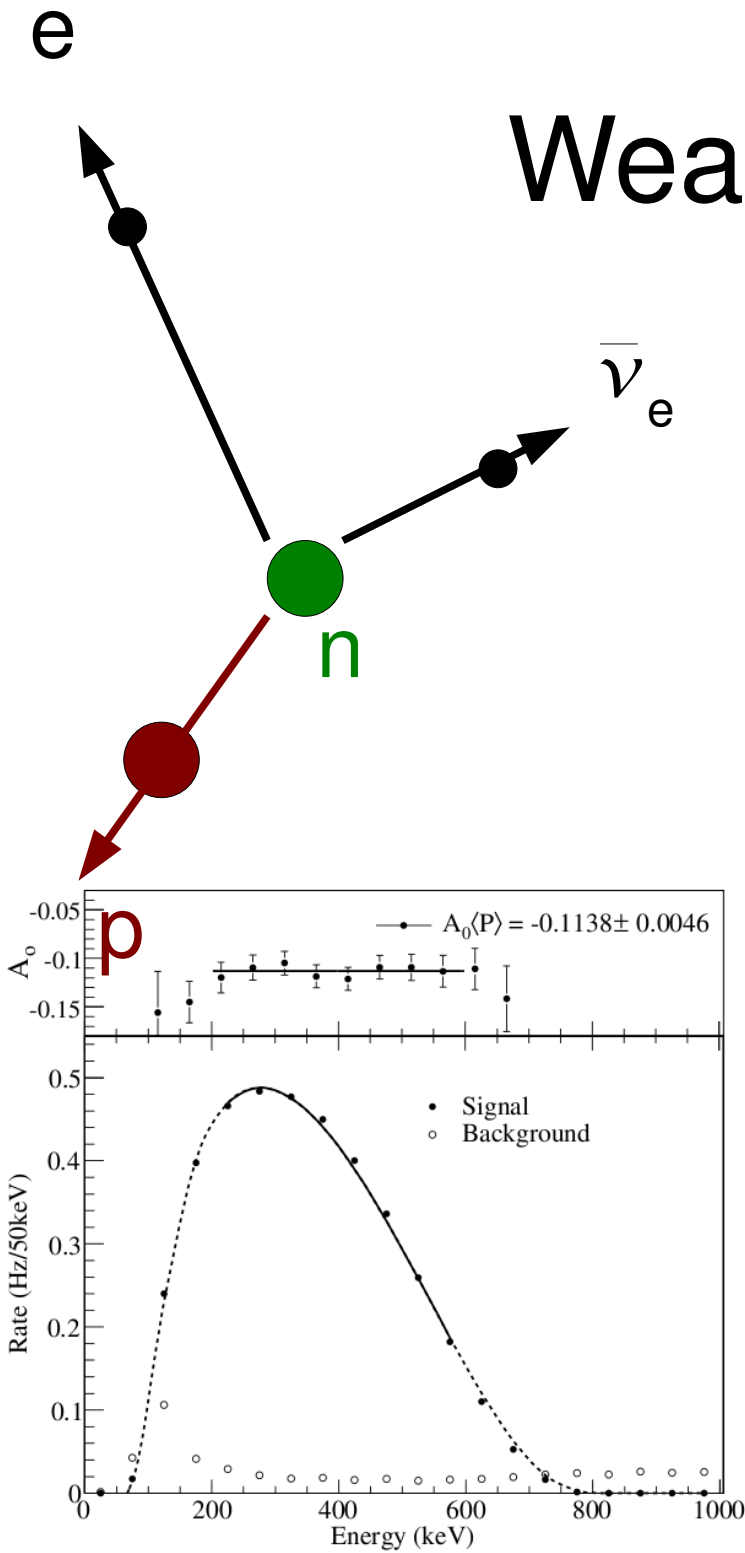


- Question: If I threw something straight up at an initial speed of 30 km/h, how high would it go?
- Answer (from high-school physics):
 - about 3 meters.
- Application:
 - UCN gravity spectrometer.



Weak Nuclear Force

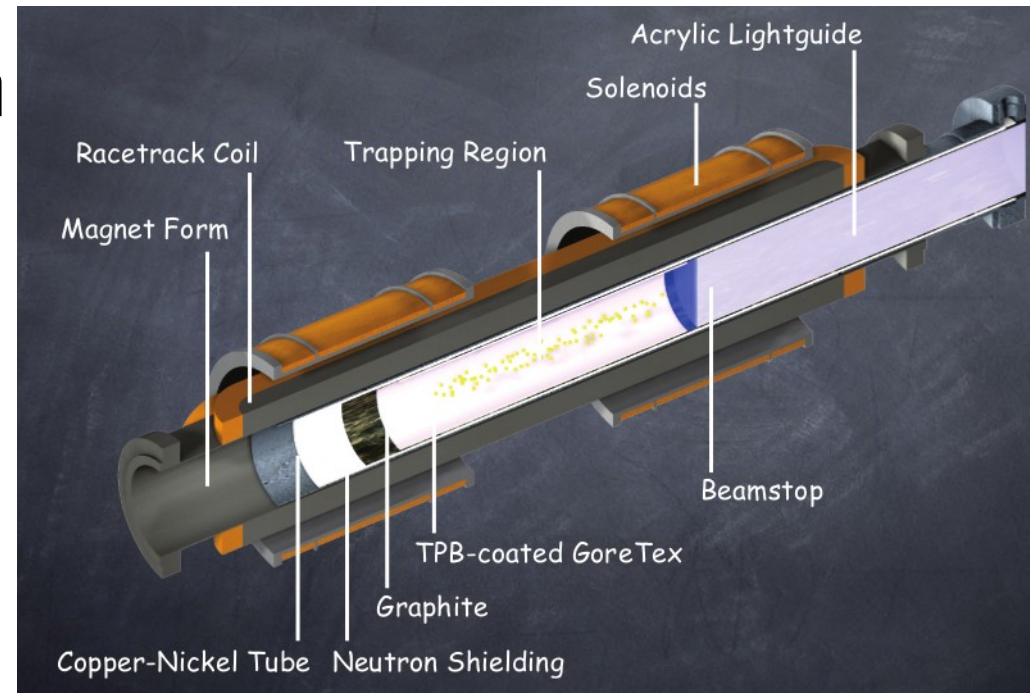
- Causes free neutrons to decay
- Neutrons live for about 15 minutes
- An interesting experiment:
 - Put ultracold neutrons in a bottle
 - Wait a while (about 15 minutes)
 - Open the bottle and see how many neutrons come out
- Also interesting experiment:
 - Measure the beta spectrum



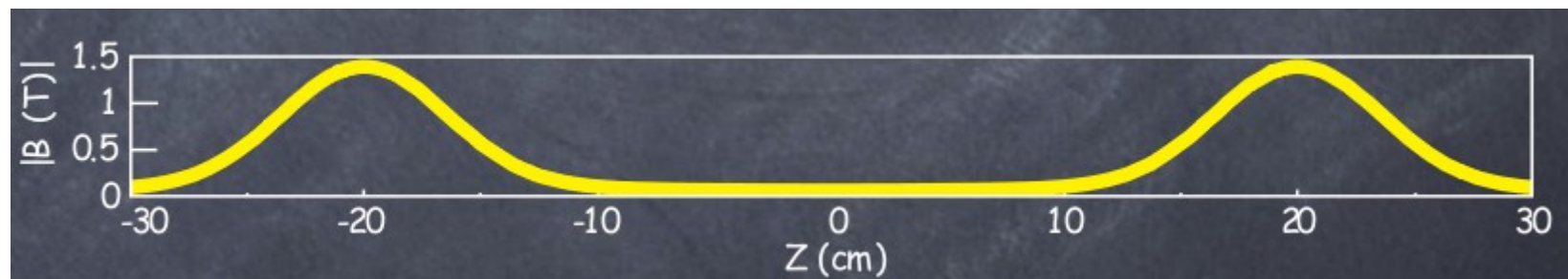
Magnetic Fields

- Neutron magnetic moment is 60 neV/T
- UCN 100% polarization achieved by passage through 7 T field.
- You can trap ultracold neutrons in a magnetic bottle!

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

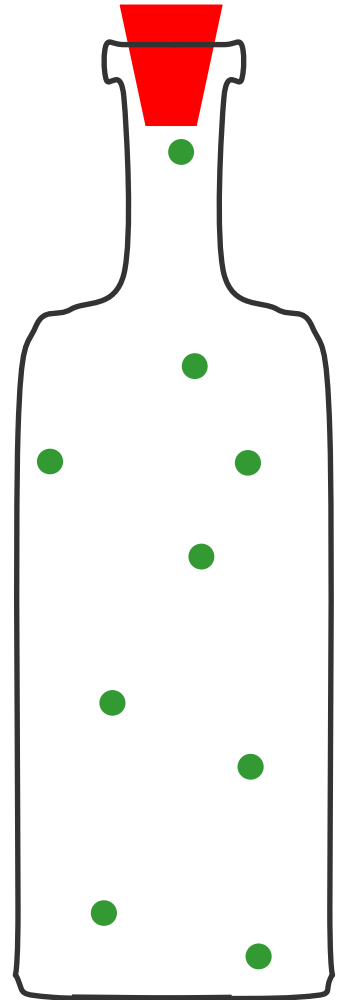


www.nist.gov

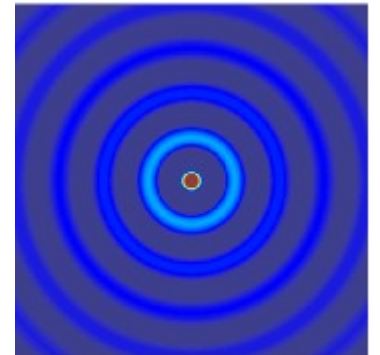
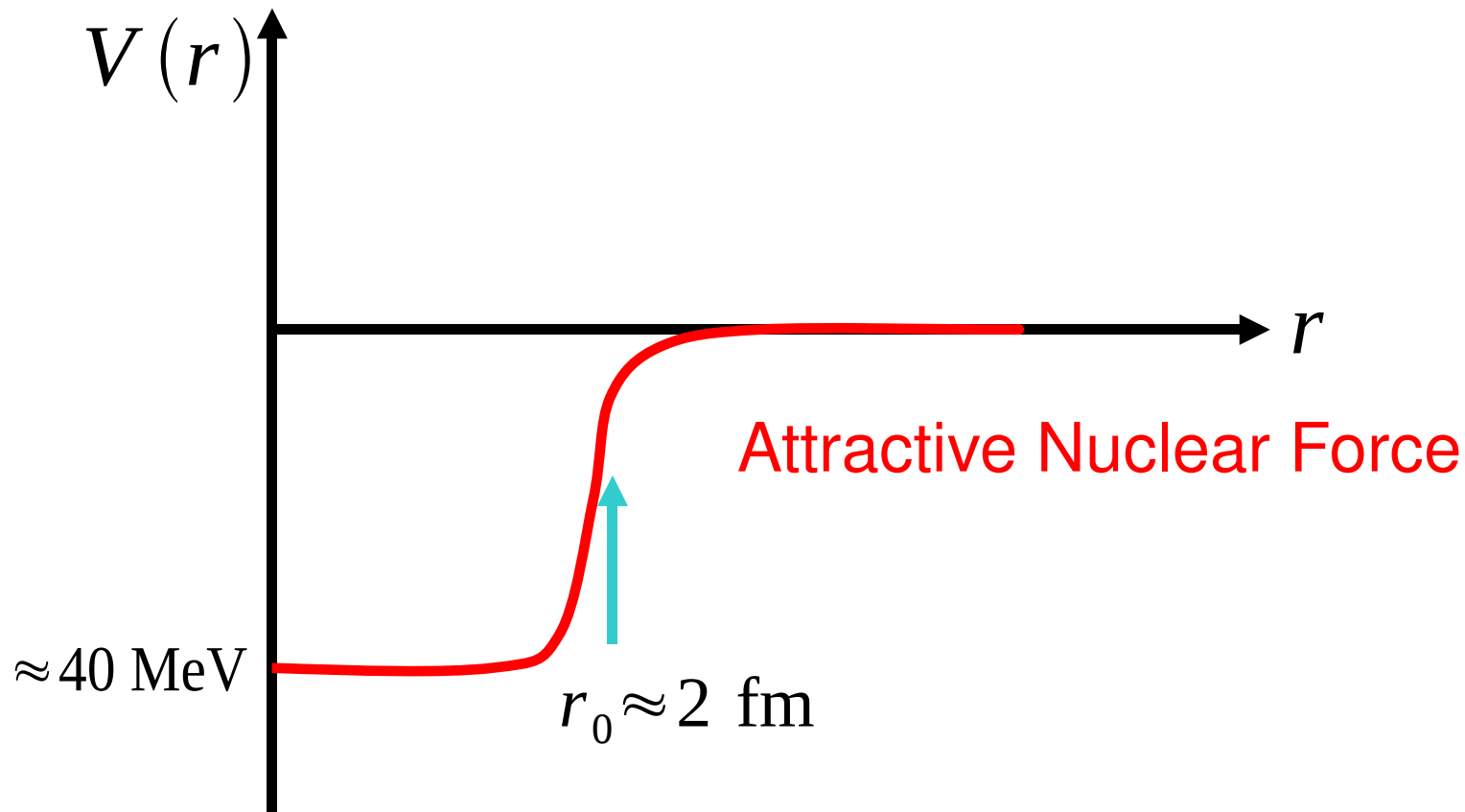


Strong Nuclear Force

- Ultracold neutrons are moving so absurdly slowly 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

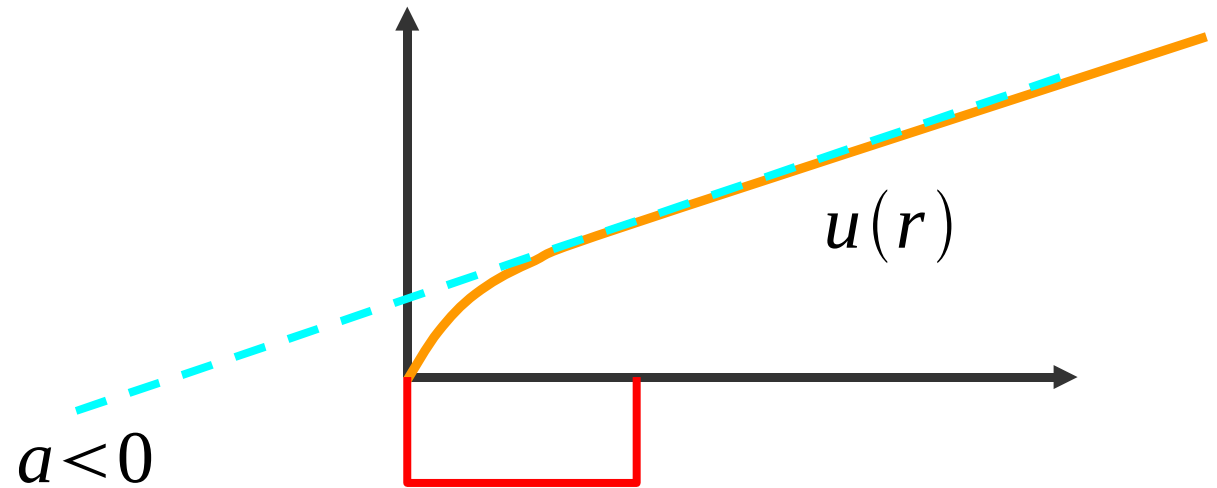


For $T_n \leq 1 \text{ MeV}$, $l \sim pr_0 \sim 0 \Rightarrow$ s-wave scattering (isotropic)

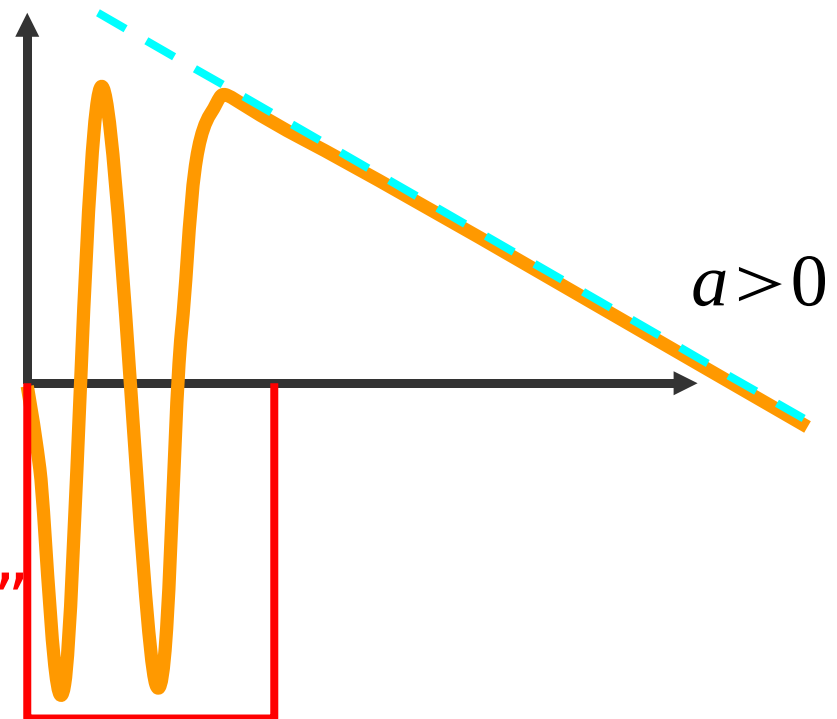
For $T_n \ll 1 \text{ MeV}$, $\sigma_{\text{tot}} = 4\pi a^2$, where $a \equiv$ scattering length

Scattering Length

Weak potential



Strong potential



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

Odds are, $a > 0$

Fermi Potential

- Replace $V(r)$ by a potential with the same a :

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

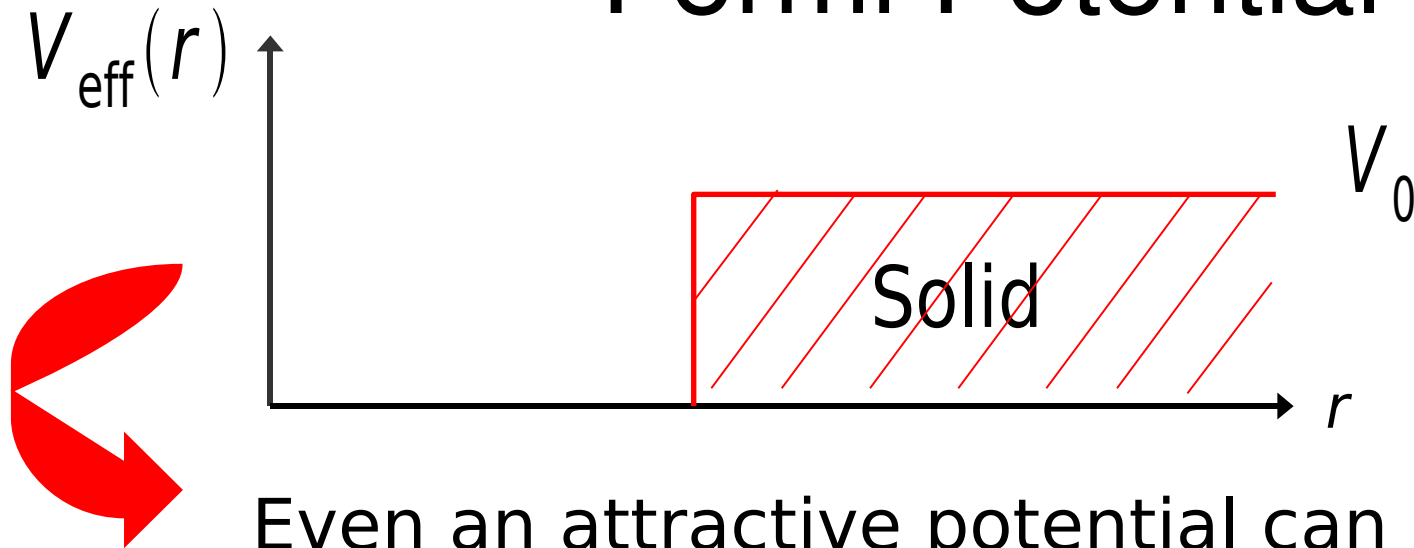
- For many nuclei in solid:

$$V_{\text{eff}}(r) = \frac{2\pi\hbar^2}{m} \sum_i a_i \delta(r - r_i)$$

- For lattice spacing \ll neutron wavelength

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

Fermi Potential



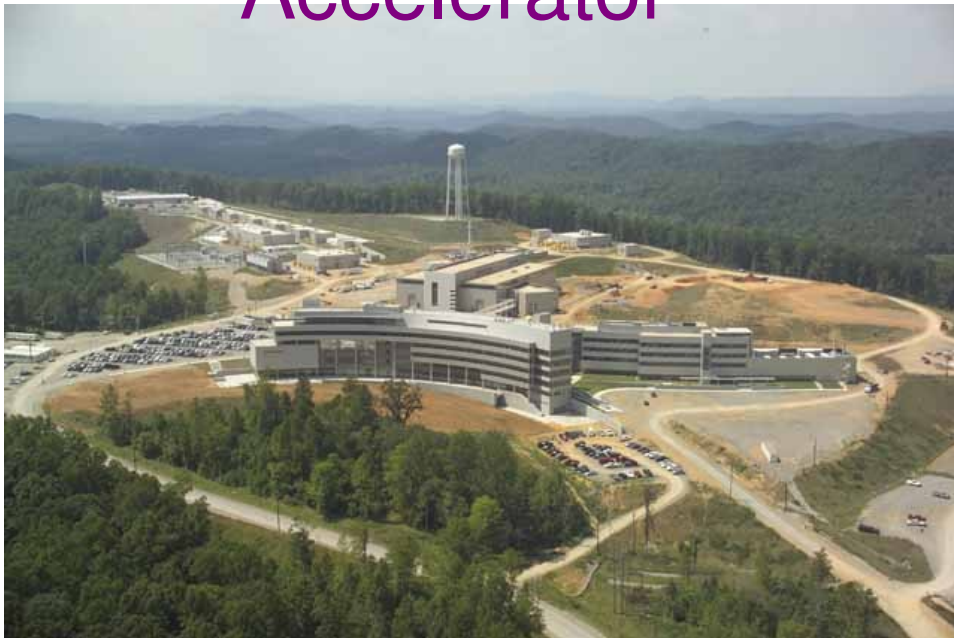
Even an attractive potential can lead to
repulsive effective potential!
(the "Fermi Potential")
Just as long as $a > 0$

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

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

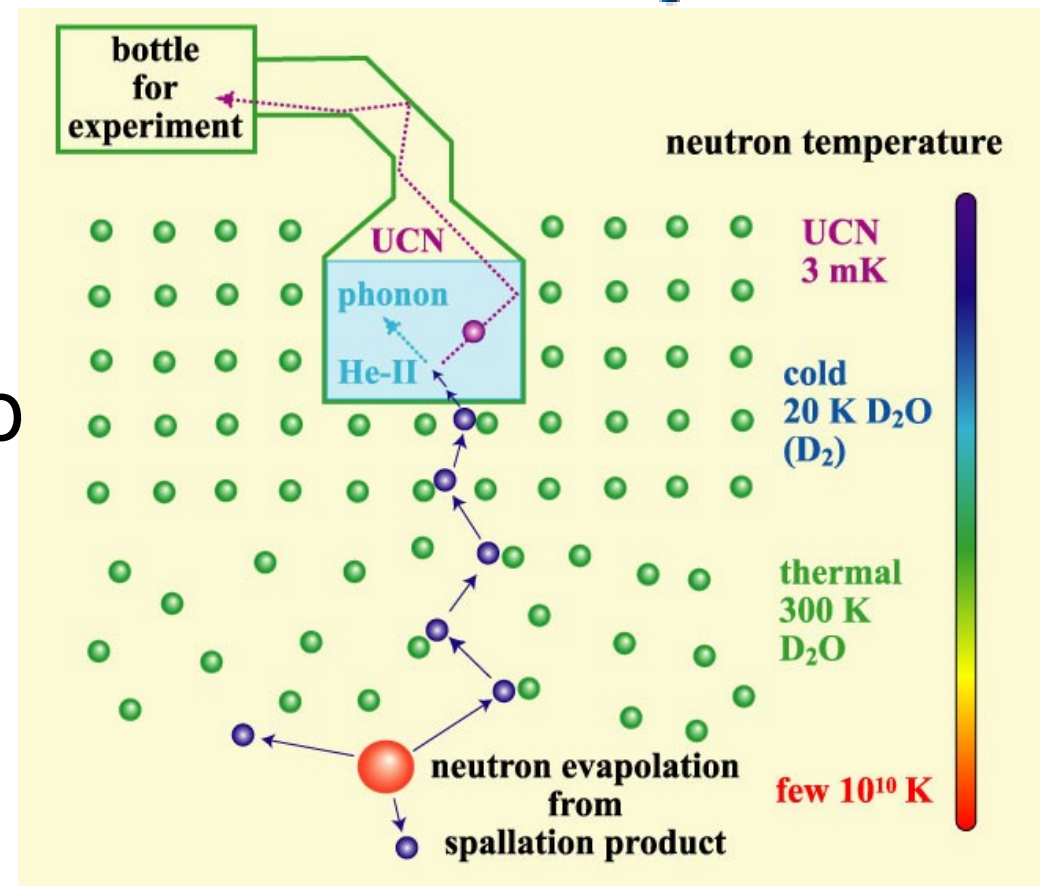
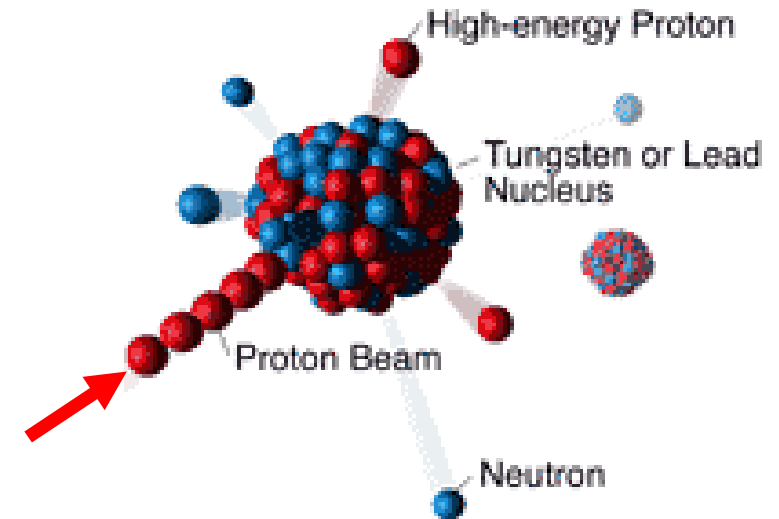
Reactor



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

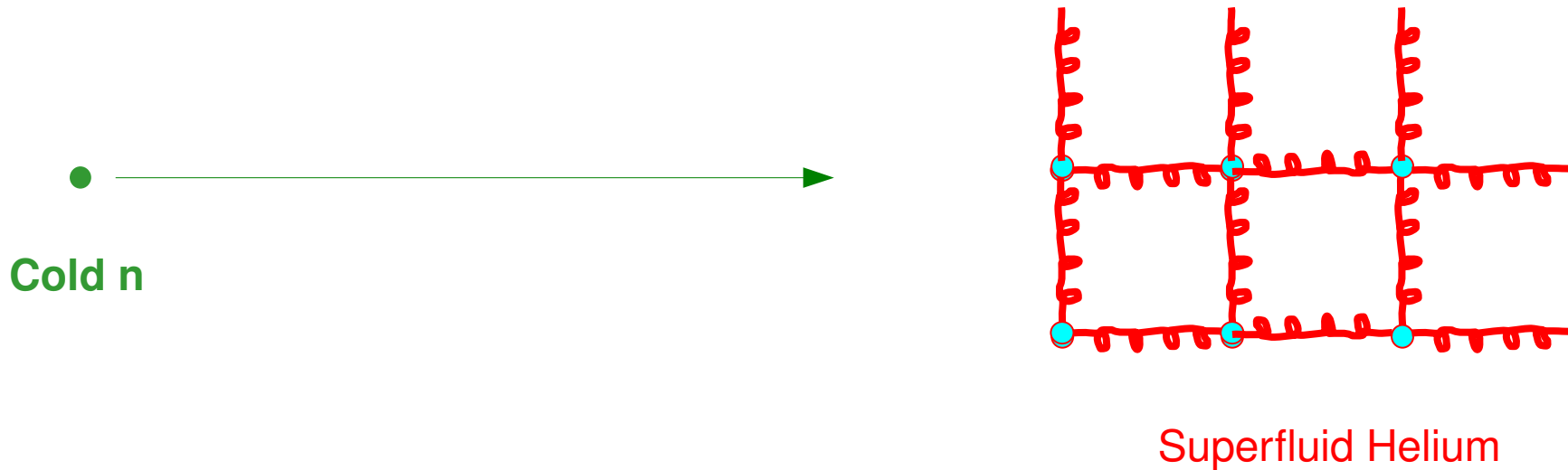
How to make UCN

- 1) Liberate neutrons by proton-induced spallation.
 - However $T = 10^{10}$ K !!!
- 2) Moderate (thermalize) in cold (20 K) D_2O .
- 3) Cold neutrons then “downscatter” to near zero energy (4 mK) in superfluid helium through phonon production.



How we cool neutrons

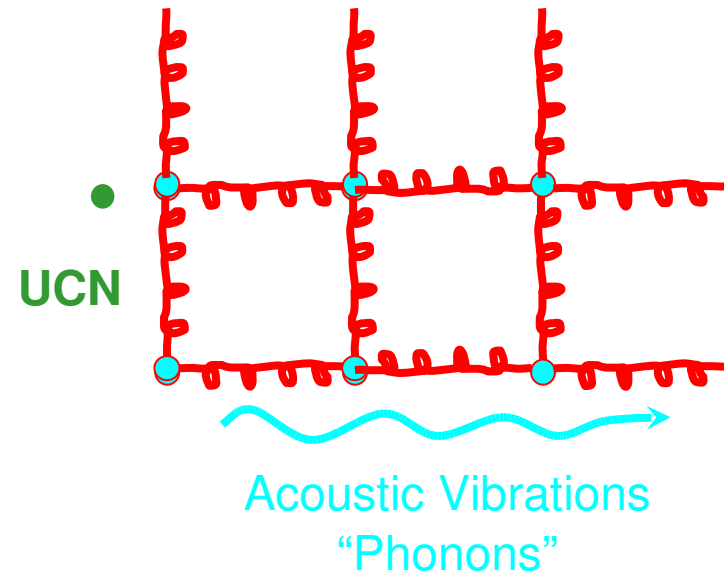
Step 3: Ultracold Neutrons



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

How we cool neutrons

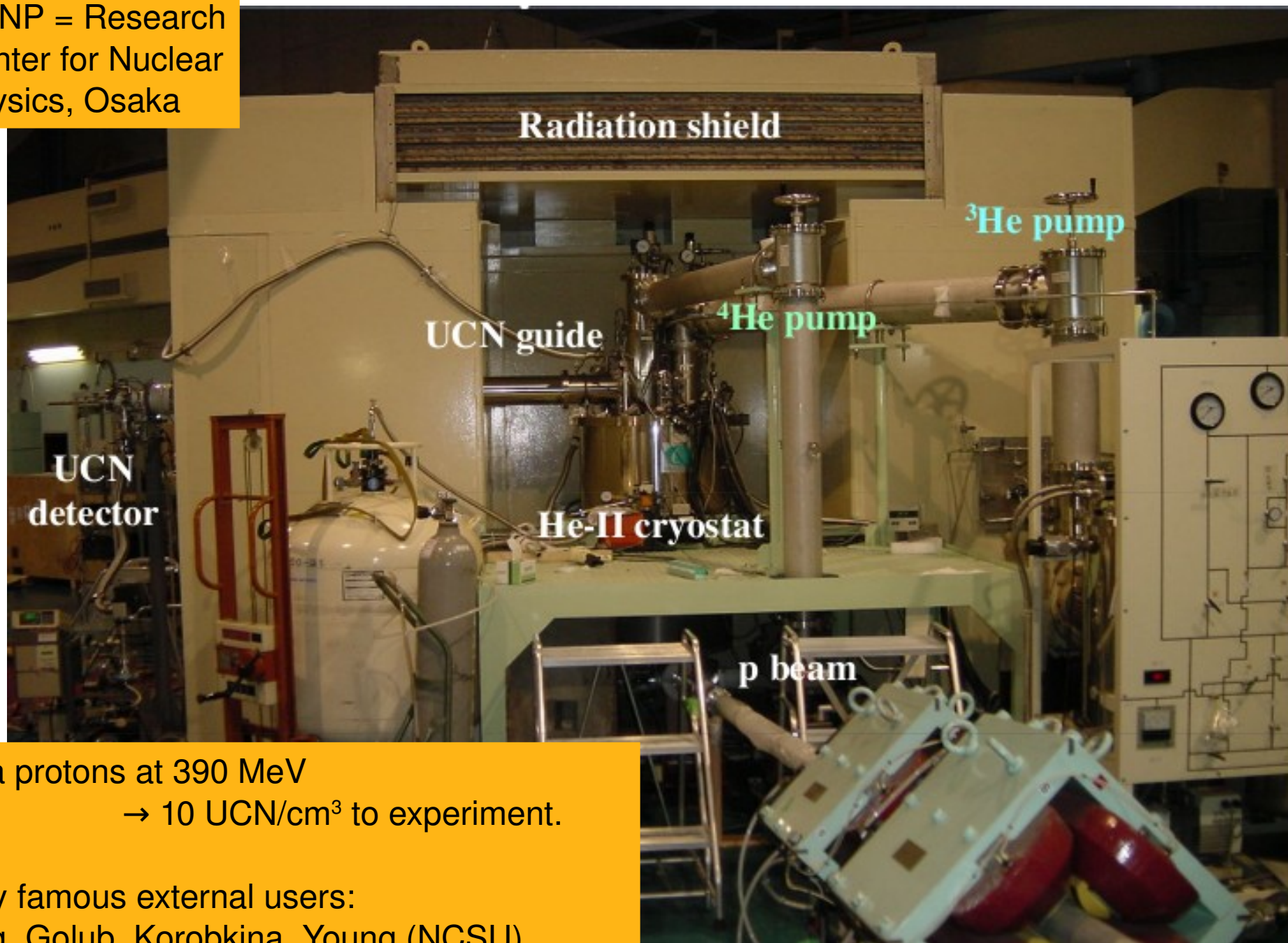
Step 3: Ultracold Neutrons



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

KEK/RCNP UCN Source (Masuda, et al)

RCNP = Research
Center for Nuclear
Physics, Osaka



1 μa protons at 390 MeV
→ 10 UCN/cm³ to experiment.

Very famous external users:
- e.g. Golub, Korobkina, Young (NCSU)



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

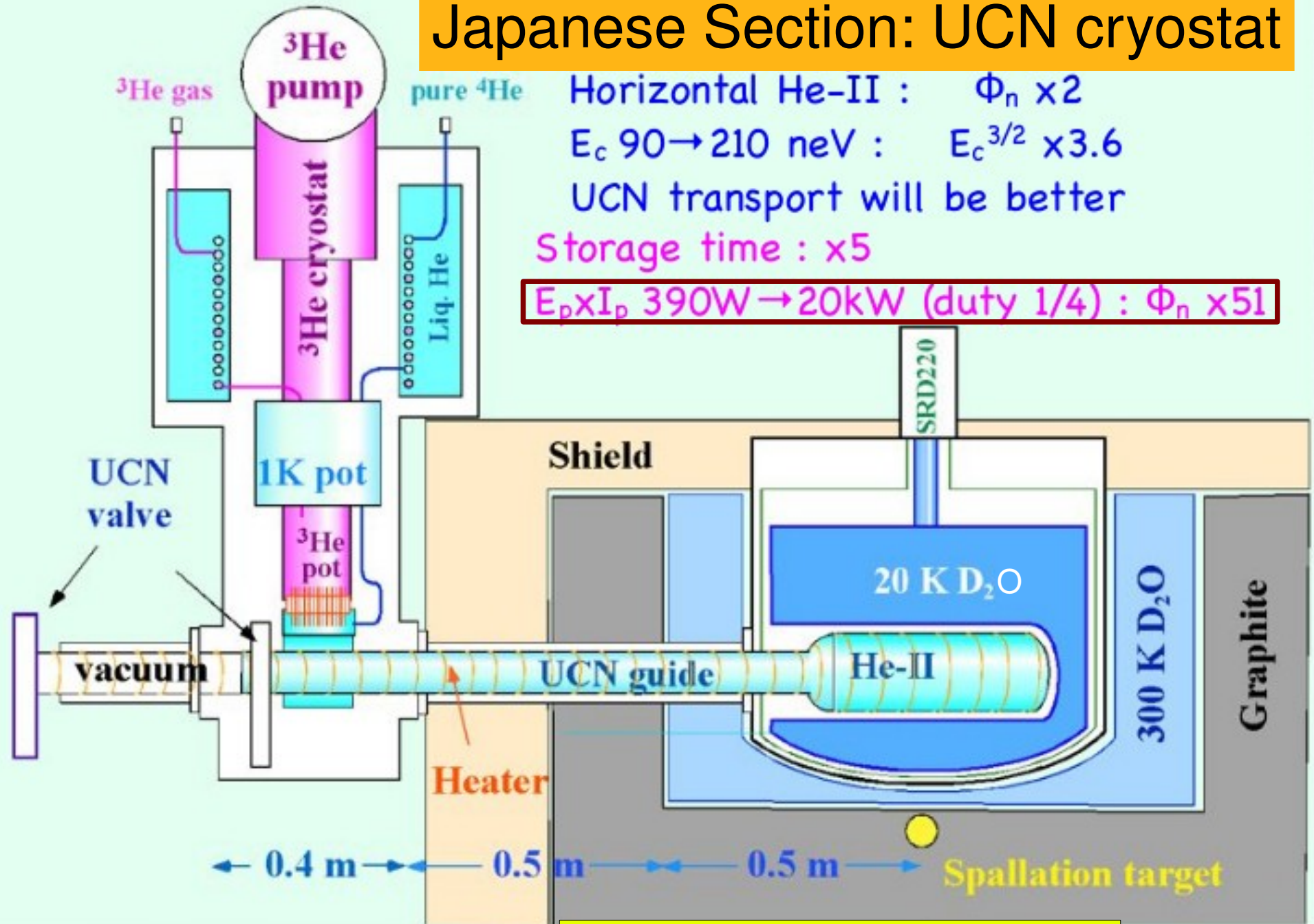
- TRIUMF UCN source:
 - 500 MeV protons at 40 μA
- Recall RCNP, Osaka:
 - 390 MeV protons at 1 μA
- A fifty-fold increase in beam power means 50 x UCN!!!
- Cyclotron operates 8 months/yr.



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

Japanese Section: UCN cryostat

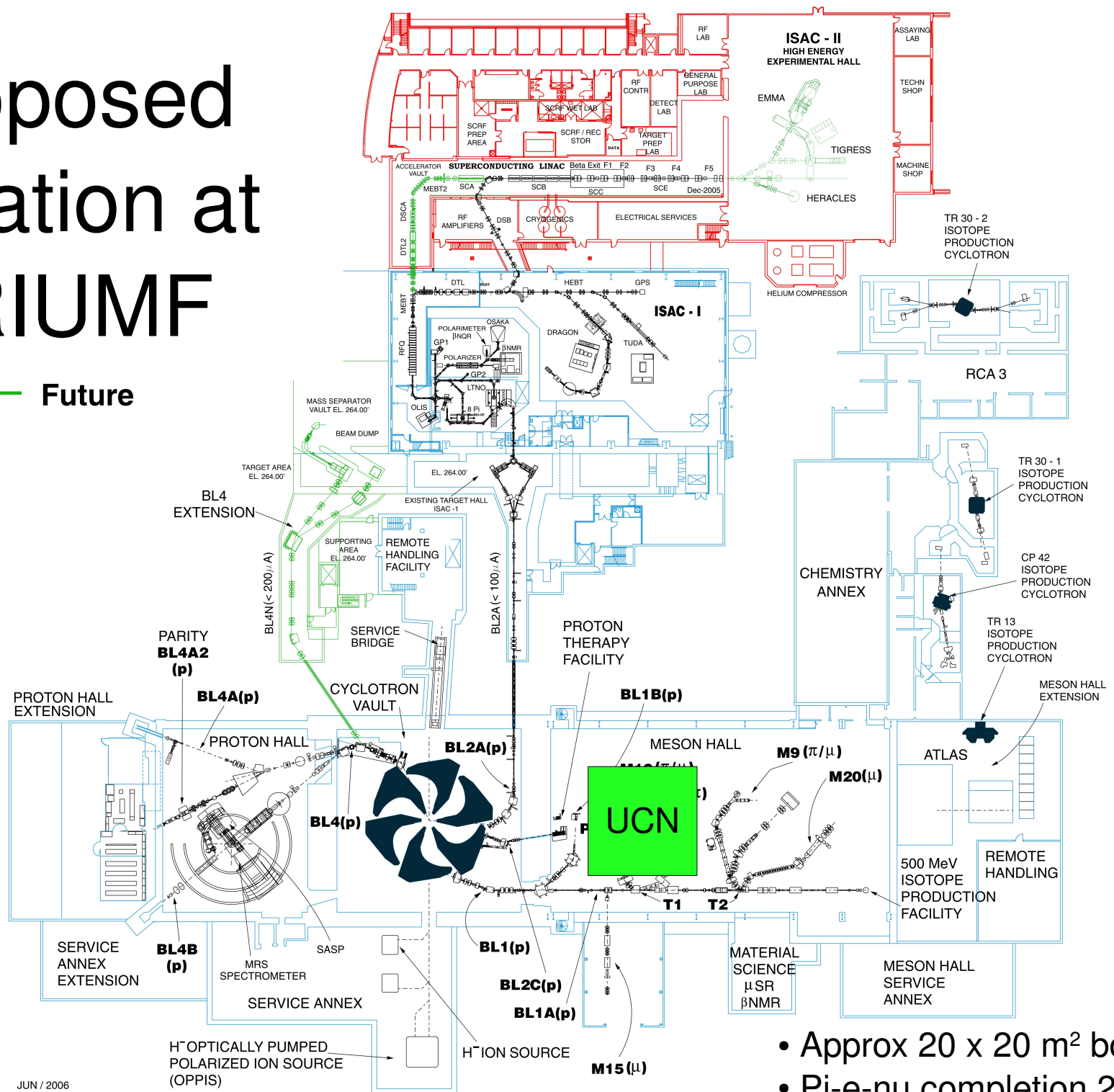


Future Upgrade: D_2O ice \rightarrow LD_2 : $\times 5$

Future



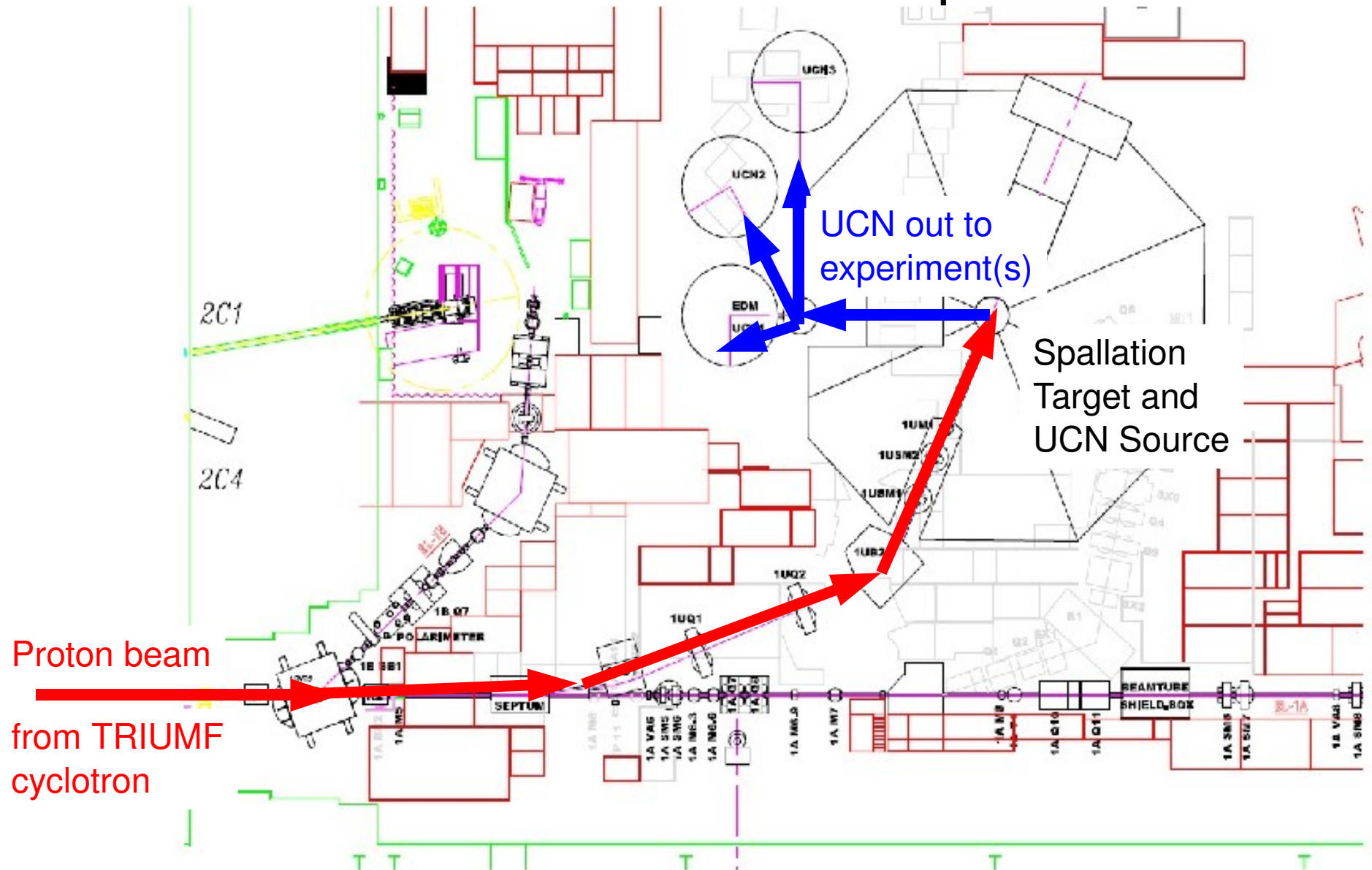
A compass rose with a red needle pointing towards the top, labeled 'NORTH'. The cardinal directions are labeled: 'NORTH' at the top, 'SOUTH' at the bottom, 'EAST' on the right, and 'WEST' on the left. The rose is drawn with concentric circles and radial lines.



- JUN / 2006

i-SUN Implementation at TRIUMF

Meson Hall concept



World's UCN projects

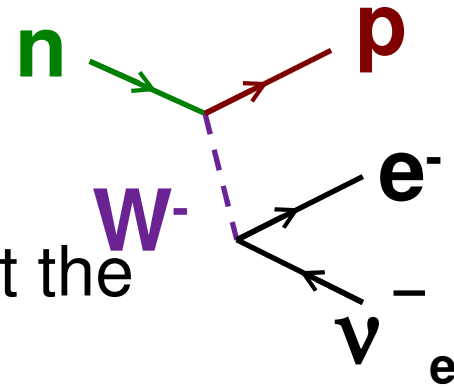
	source type	E_c neV	P_{UCN} /cm ³ /s	T_s s	ϵ_{ext}	ρ_{UCN} /cm ³ source/exp.
TRIUMF	spallation He-II	210	0.4×10^4 (10L)	150	~1	3×10^5 (20L) $1-5 \times 10^4$
ILL	n beam He-II	250	10	150	~1	**/1000
SNS	n beam He-II	134	0.3 (7L)	500	1	**/150
LANL *	spallation SD2	250	4.4×10^4 (240cm ³)	1.6	$1.3 \times 10^3 / 4.4 \times 10^4$	**/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 /**

Fundamental Physics Experiments with UCN

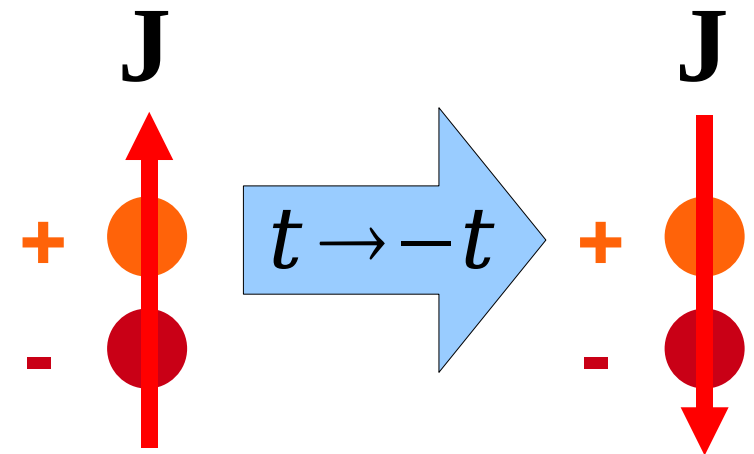
Fundamental Physics and Neutrons

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

- How fast do neutrons decay? (BBN)
- 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?

Physics Experiments for i-SUN

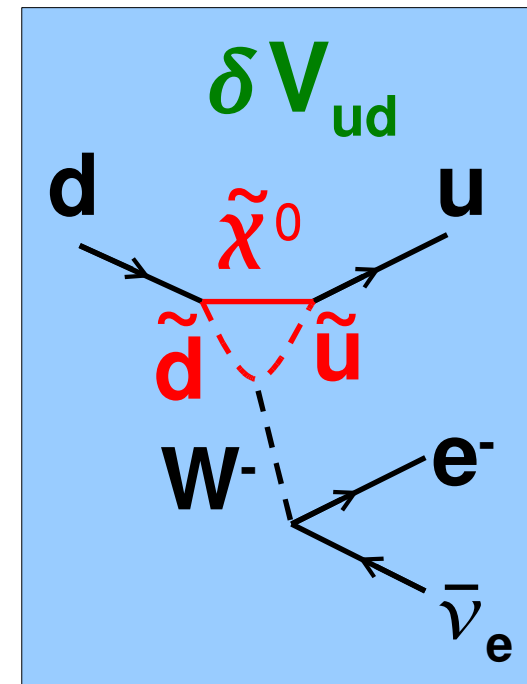
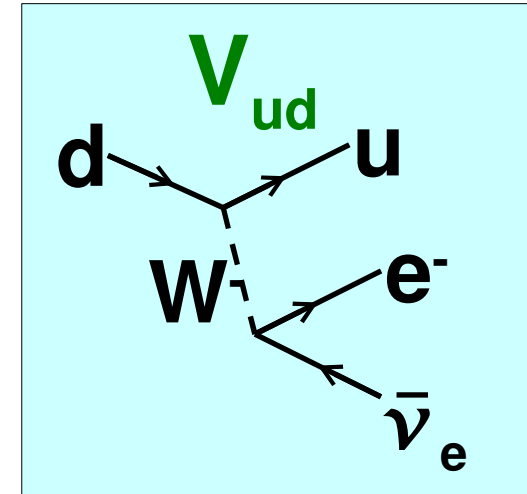
- neutron lifetime
 - gravity levels
 - surface science
 - n-EDM
 - $n\bar{n}$?
 - Free n target?
-
- near term
- longer term

Neutron Beta-Decay

- Sensitive to KM matrix parameter V_{ud}
- A precise test of unitarity:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1?$$

- If not, the discrepancy could be caused by new particles beyond the standard model.

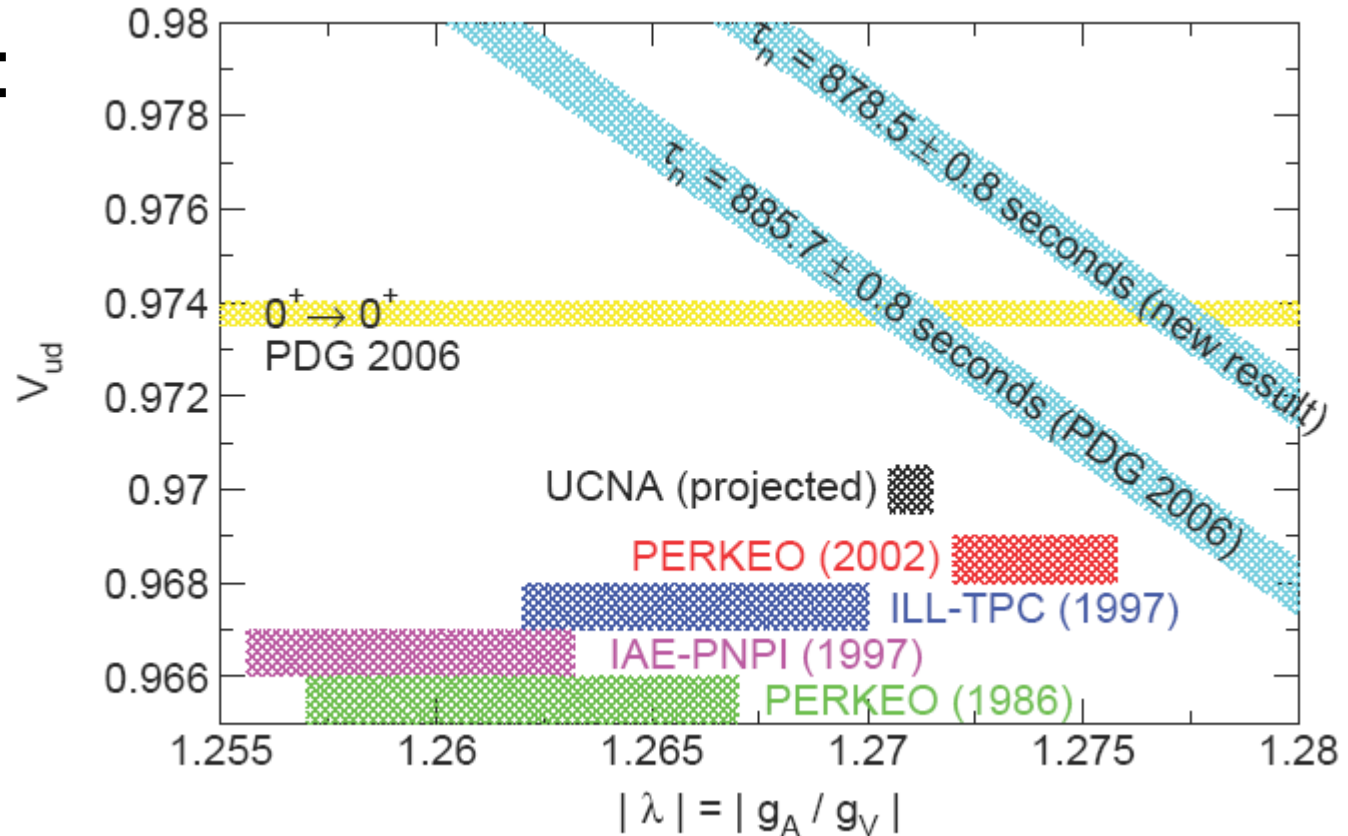


Neutron Lifetime

- Physics interest:

- BBN

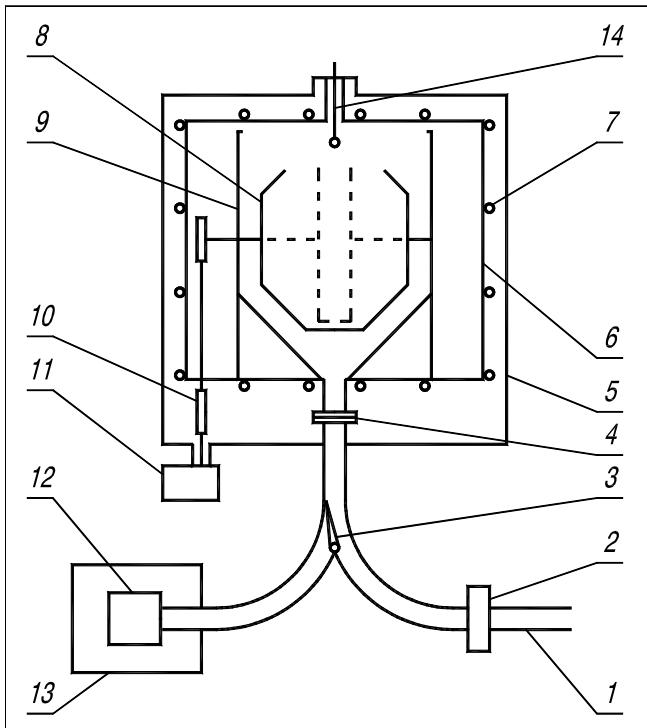
- V_{ud}



- Currently a 6.5σ discrepancy between neutron lifetime experiments!
- Claimed precision is 0.8 s.

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!!!

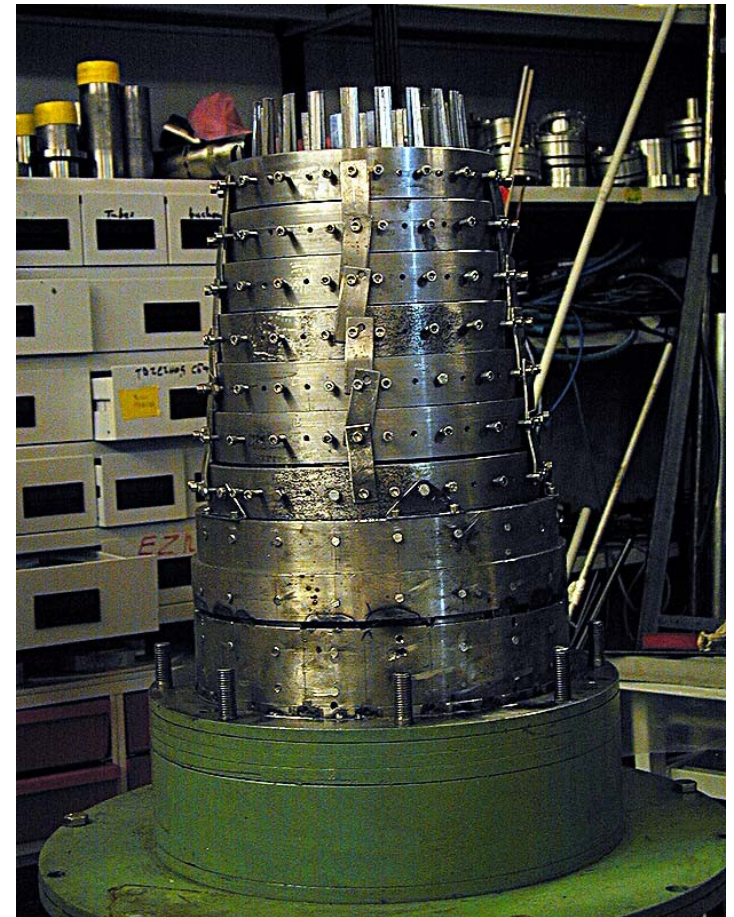


<- Gravitrapp

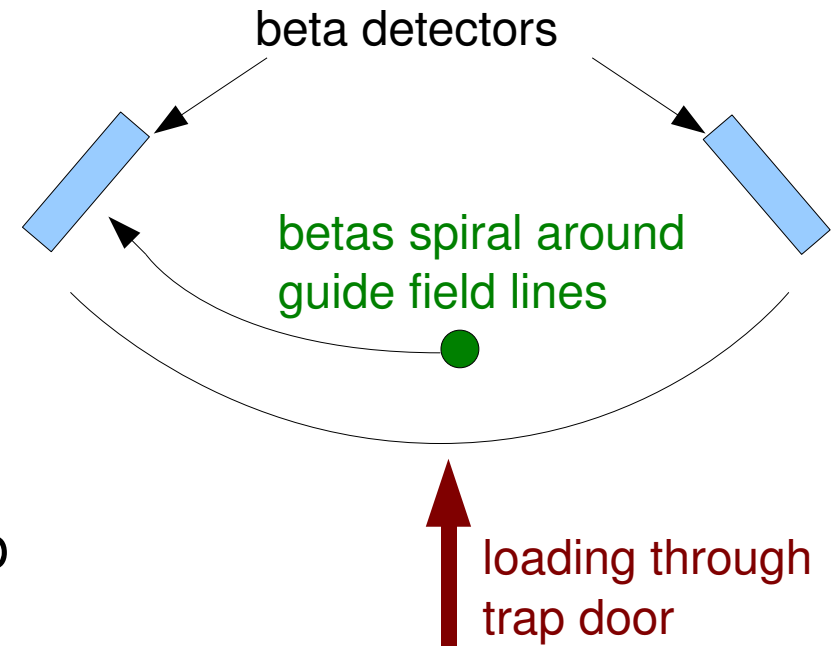
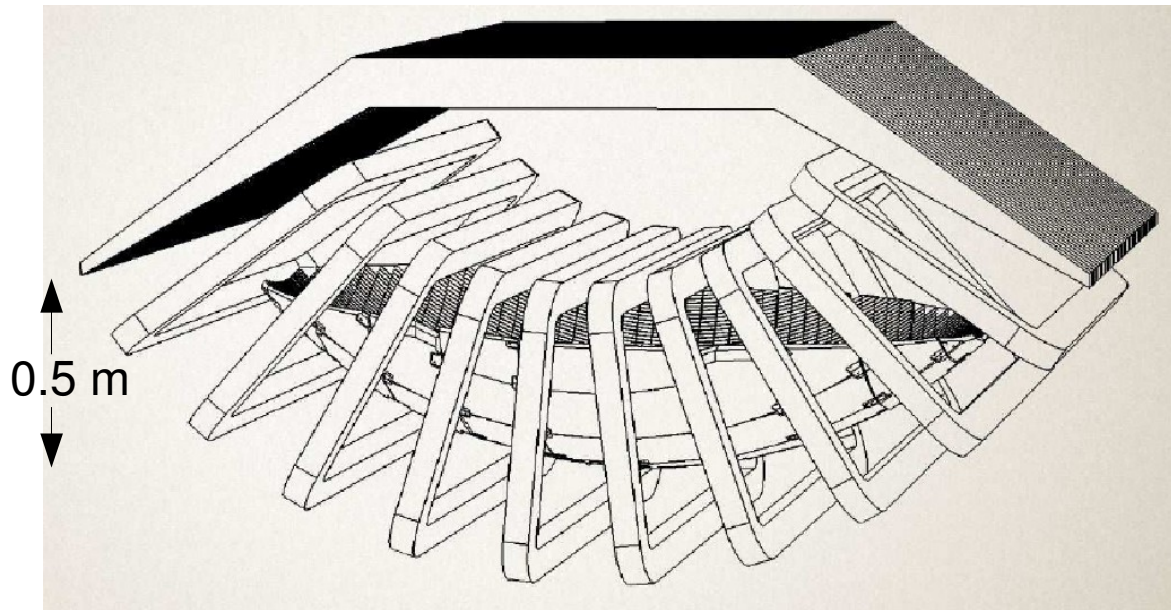
Permanent
magnet trap

->

(both at ILL)



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



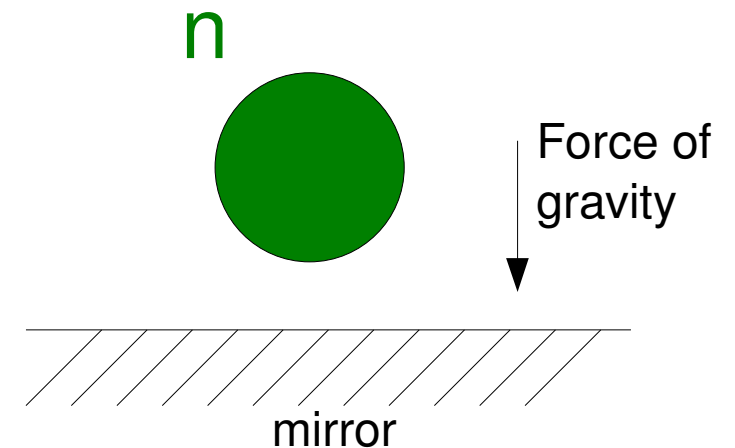
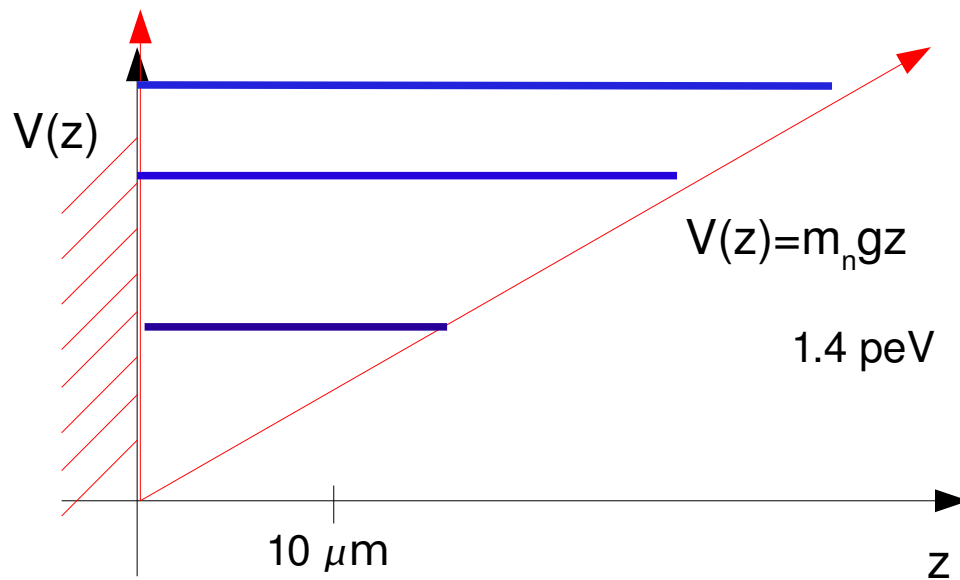
- Shallow Halbach array + gravity for trap
- Guide field for decay betas
- Marginally trapped neutrons experience chaotic orbits and are ejected rapidly
- Goal precision $\delta\tau_n \sim 0.1$ s
- Require: Efficient trap loading, effective n-“cleaning”, high UCN density

n-lifetime Plans for Canada

- Theoretical work on trap dynamics completed at LANL recently published in NIM A, Feb. 2009.
- Prototype under construction at LANL
- Goal is for test experiment at LANL UCN source
- TRIUMF experiment would build on preliminary work done at LANL
- Collaborators:
 - J.D. Bowman, B. Filippone, T. Ito, B. Plaster

Quantum Mechanics, Gravity, and Neutrons

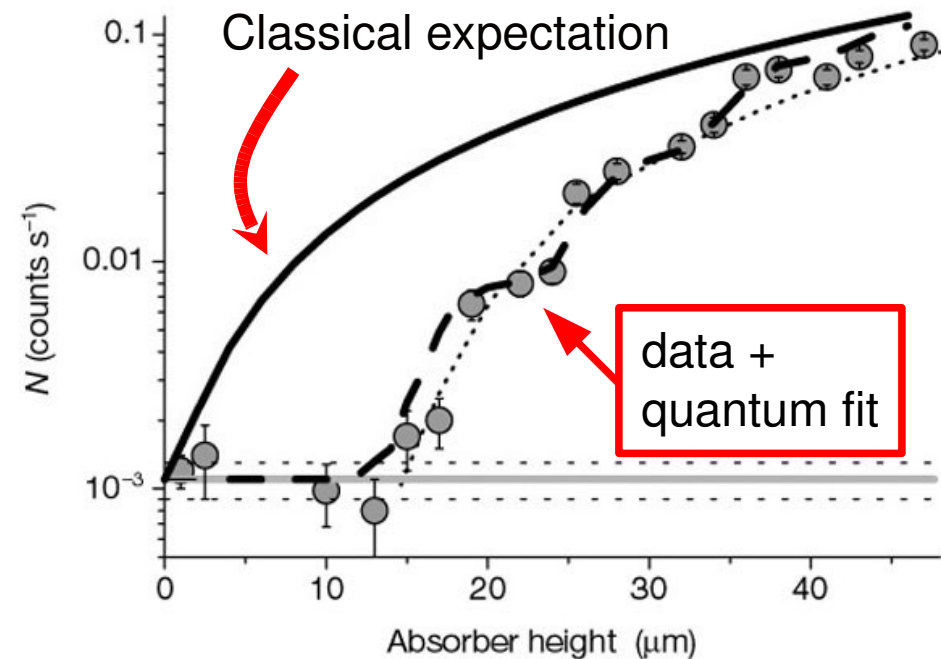
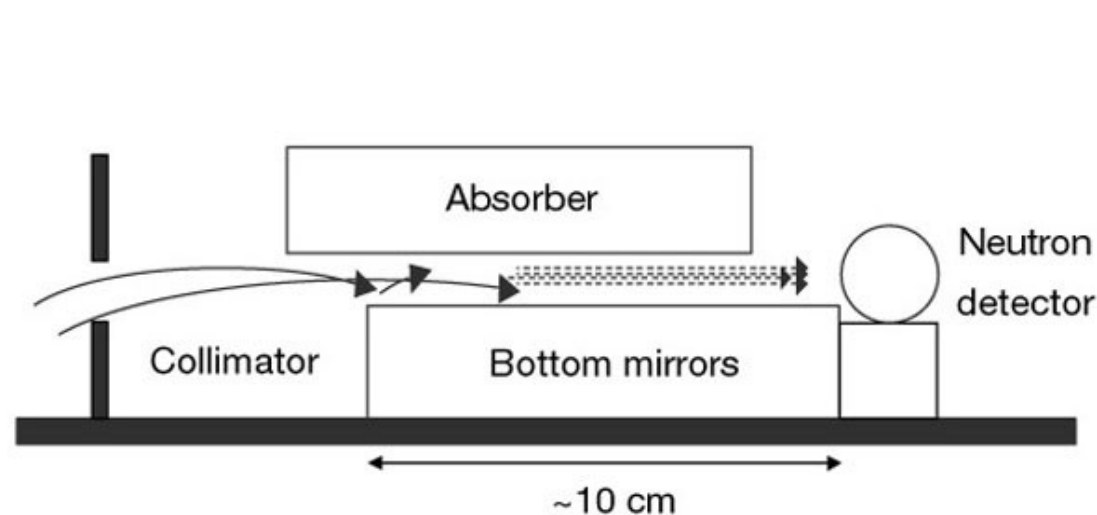
- Ultracold neutrons can be confined in the gravitational field of Earth.



Quantum mechanically, only
particular energies are allowed

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

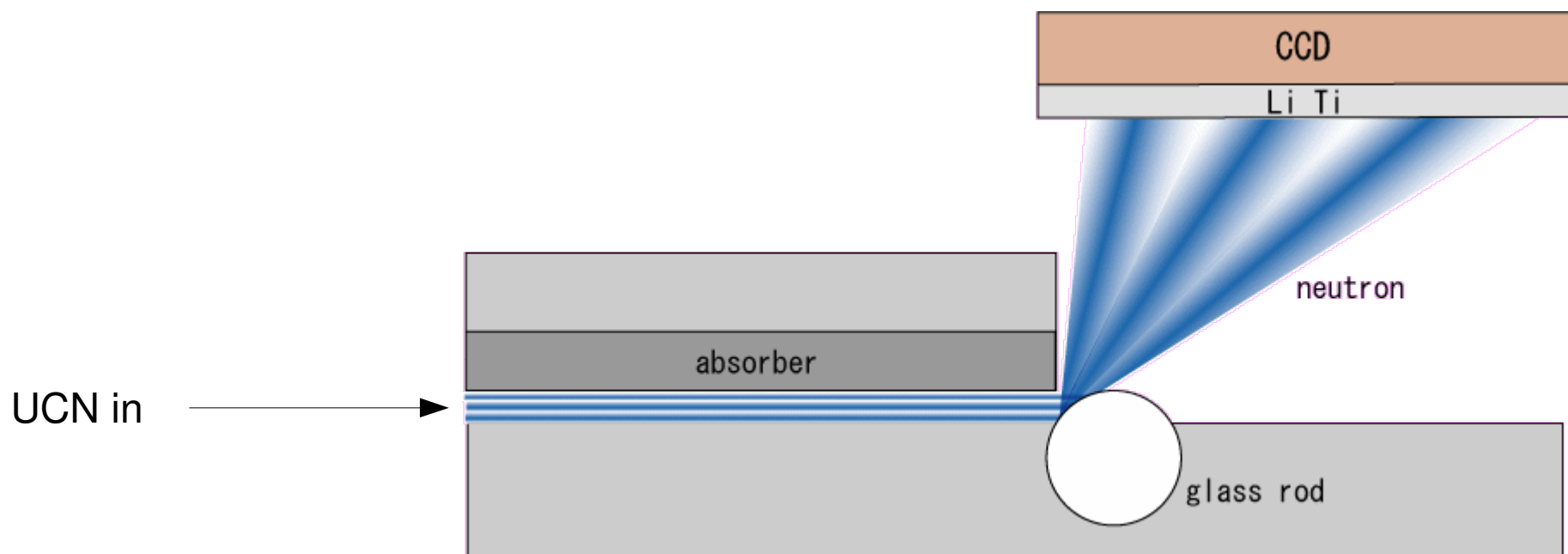
Experiment on Quantum Mechanics and Gravity



- Experimental results have been used to place limits on
 - 10 μm scale modifications to gravity
 - extra dimensions
 - axions
 - “fifth force”

- ILL, Grenoble, France, 2002.

Proposal for Improved Experiment (Japanese group)



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

Recently reported in:
T. Sanuki, S. Komamiya,
S. Kawasaki, S. Sonoda,
NIM A (2009)

Plans for Canada

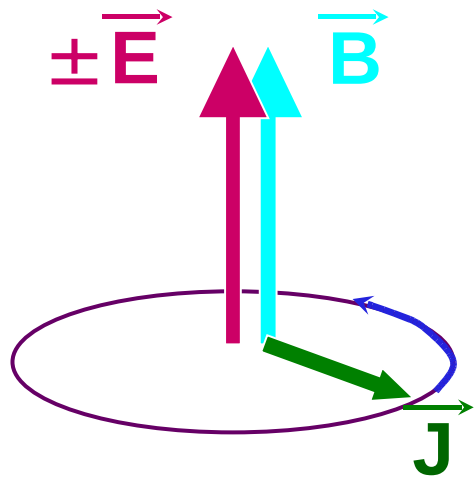
- We hope the experiment would be initiated and led by Japanese groups (S. Komamiya, et al).

Further experiments:

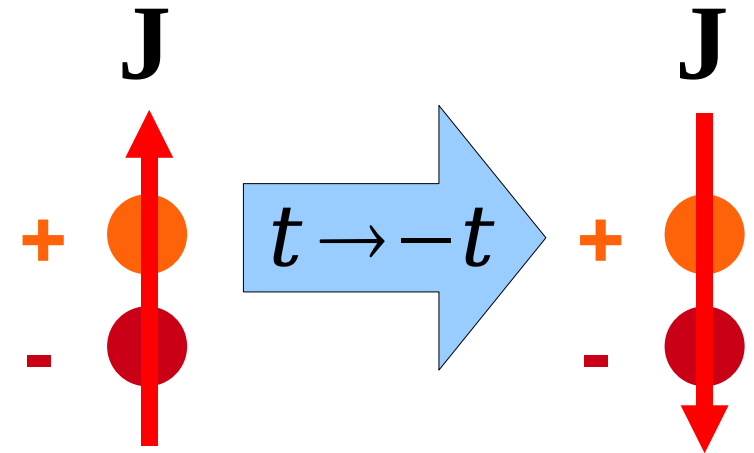
- Bottle the UCN to increase time the UCN is contact with the mirror.
- Excite resonant transitions between quantum states.
- Increase purity of states by preselection.
- Goal: improve precision on energy of state and hence increase sensitivity to modifications of the gravitational force.

Neutron Electric Dipole Moment (n-EDM)

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



$$h\nu = 2\mu_n B \pm 2d_e E$$

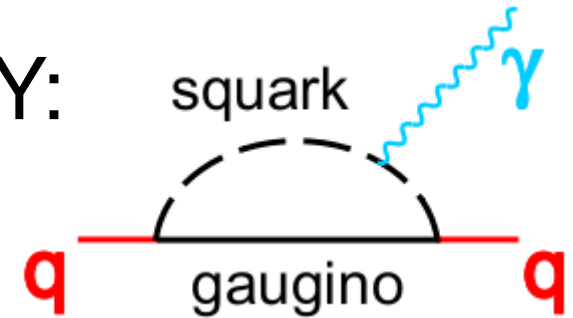


- Present Exp. Limit $< 3 \times 10^{-26}$ e-cm
- Standard Model value: 10^{-31} e-cm
- Supersymmetry or Multi-Higgs models can give $10^5 \times \text{SM}$
- Significant discovery potential for new sources of CP-violation beyond the standard model with new experiment

EDM's and SUSY

- Scale of EDM's for quarks in SUSY:

$$d_q \sim \frac{\alpha}{\pi} \times \frac{m_q}{\Lambda_{SUSY}} \times \sin \theta_{CP}$$



from P. Harris, Sussex

- For “reasonable” values of new parameters:

$$d_q \sim 3 \times 10^{-27} e \cdot cm$$

- According to neutron EDM measurements:

$$d_u \sim 2 \times 10^{-25} e \cdot cm \quad d_d \sim 5 \times 10^{-26} e \cdot cm$$

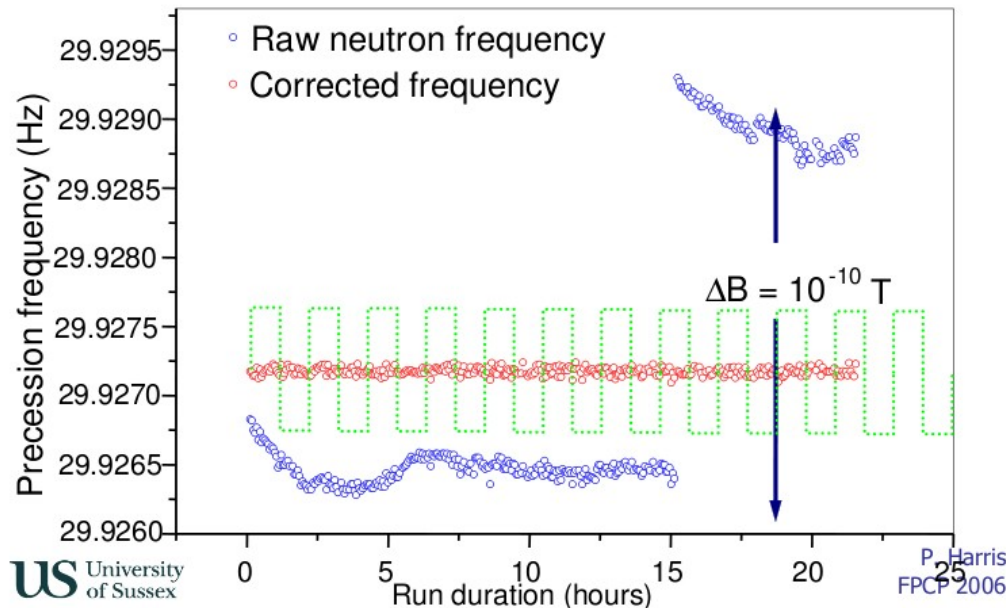
- Unattractive solution:

- $\Lambda_{SUSY} > 2 \text{ TeV}$ and/or $\theta_{CP} < 0.01$
- “SUSY CP problem”

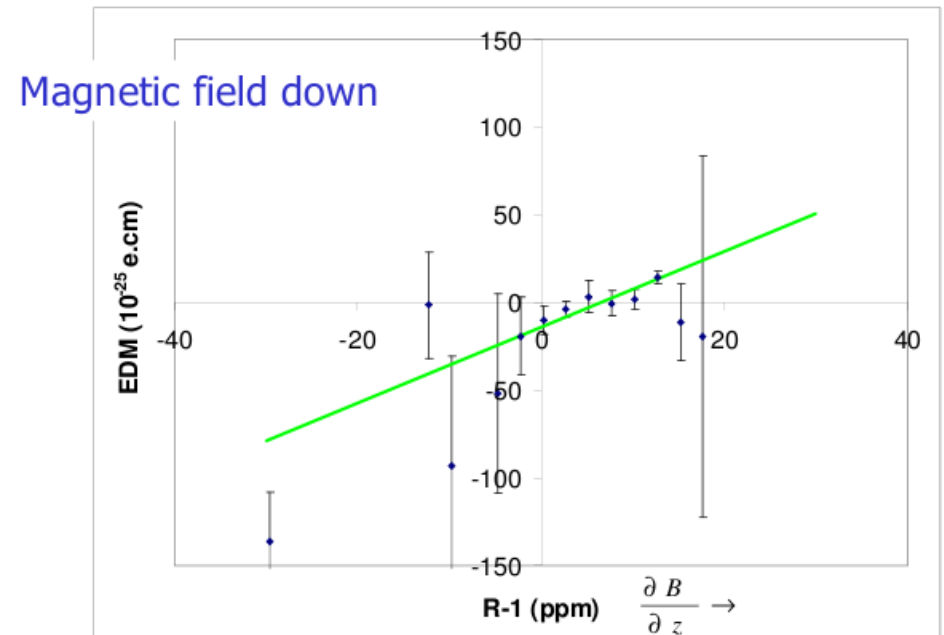
n-EDM Systematics

- magnetic field variations
- leakage currents
- geometric phase effect
 - false EDM arising from field inhomogeneity and $\mathbf{E} \times \mathbf{v}$.

(co)magnetometry



comagnetometry

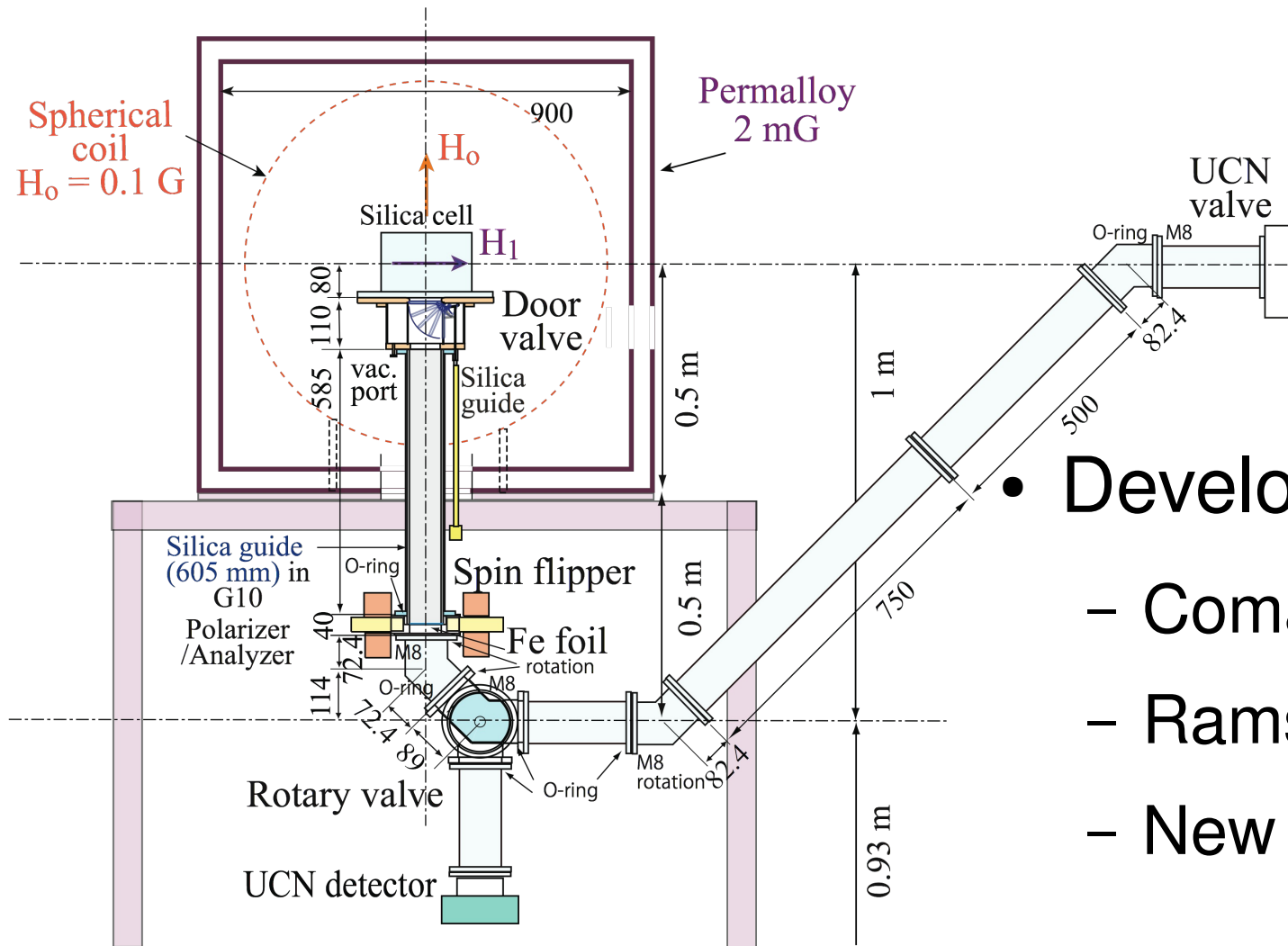


false EDM (GP) effect

Past and Future n-EDM efforts

- OILL expt. ($d_n < 3 \times 10^{-26}$ 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: $1\text{-}5 \times 10^4$ UCN/cc

n-EDM Experiment in Japan



- Development of:
 - Comagnetometers
 - Ramsey-resonance
 - New B-field geometry

- Masuda, et al. First experiments this summer at RCNP.

Plans for Canada

- Complete experiments in Japan, 2009-2011.
- Develop proposal for TRIUMF ~ 2011.
 - higher UCN density allows smaller cell size
 - smaller GP effect
- Expect number of EDM-experienced collaborators to grow if UCN source is approved:
 - e.g. B. Filippone, R. Golub, T. Ito, E. Korobkina, M. Hayden, B. Plaster (all work on SNS EDM project)

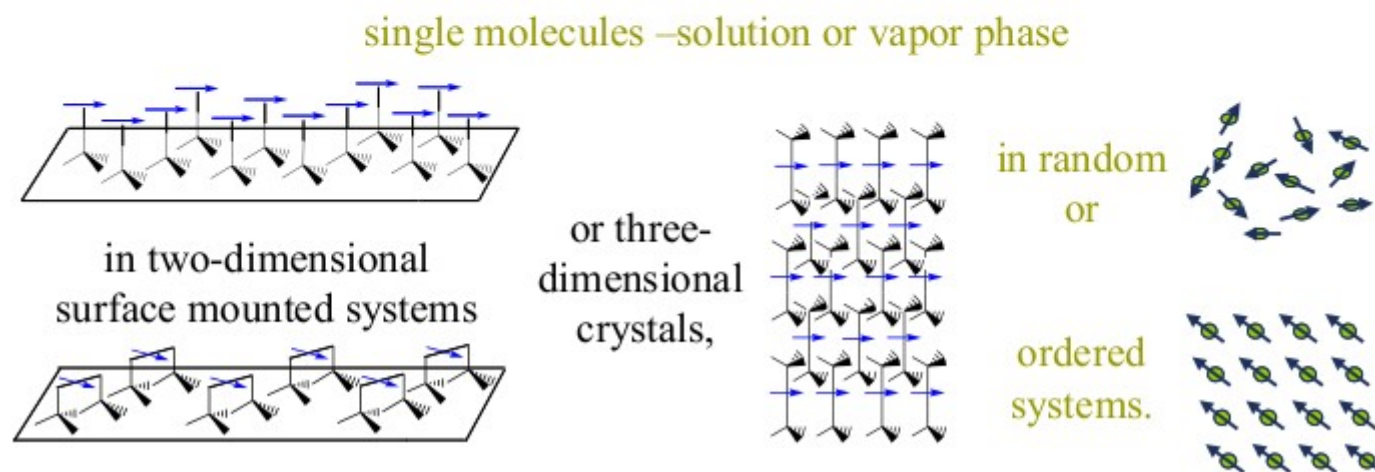
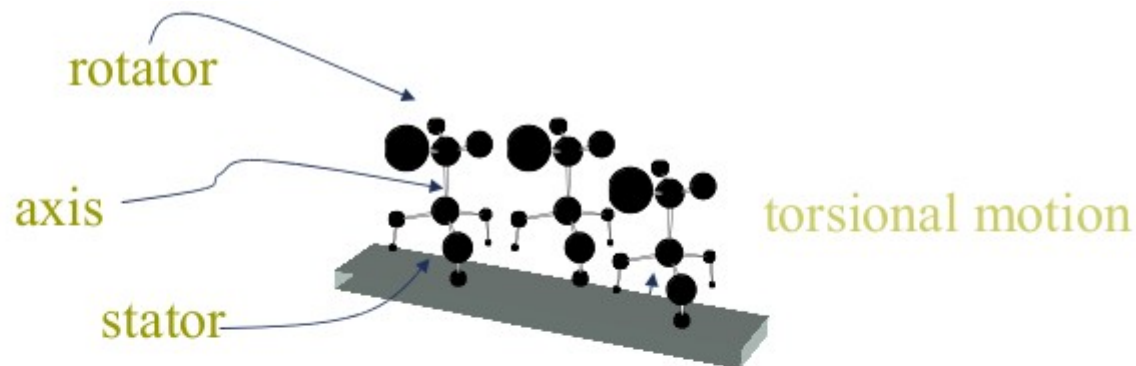
Involvement from more Japanese collaborators in this exciting experiment is very welcome!

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.

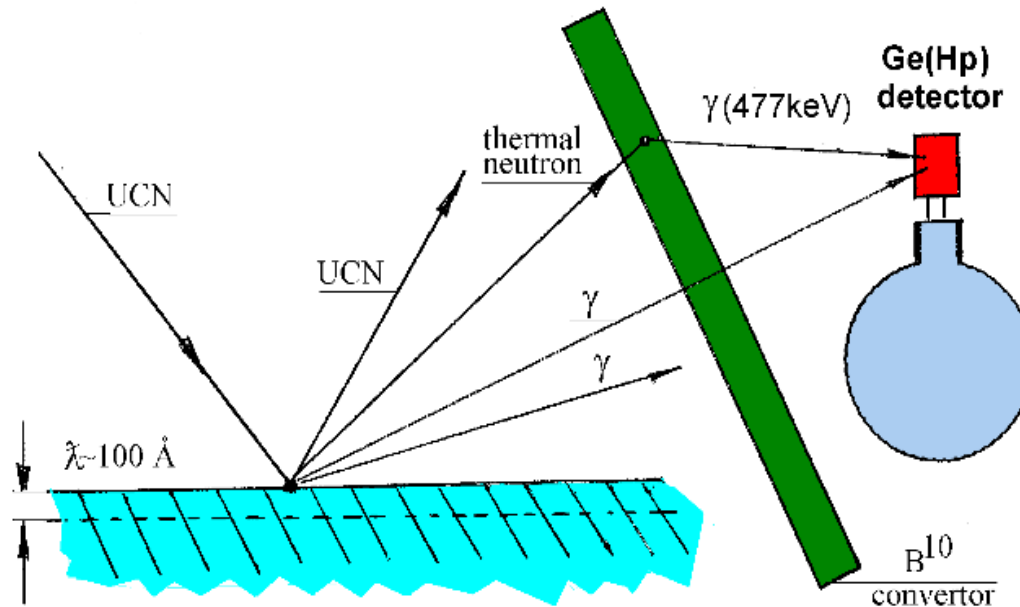
Application of UCN ISR: Artificial Molecular Rotors

“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 Canada

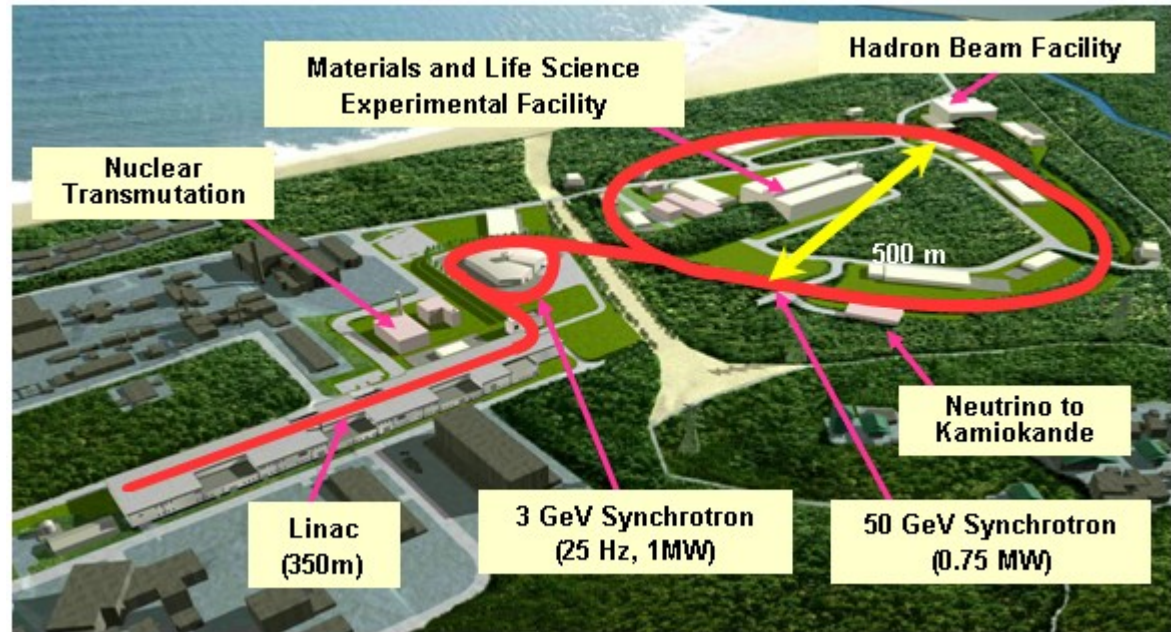
- Design of cryostat and first proof-of-principle experiments have been carried out. (Hahn-Meitner Inst., ILL)
- Need higher UCN flux.
- R. Golub, E. Korobkina, L. Clarke (NCSU)
- Potentially large user-base in “smart surfaces” community
- Other ideas and interest from Japan are very welcome!

i-SUN timeline

- 2007-8: UCN source supported by TRIUMF committees, included in plan for TRIUMF
- 2008: CFI NIF proposal submitted
 - In-kind contributions from Japan, TRIUMF
- 2009-12:
 - develop UCN source in Japan, EDM experiments
 - preparations and design in Canada
 - develop collaborations and proposals for experiments
- 2012-13: Install, commission at TRIUMF
- 2012-15: First experiments

Beyond Canada

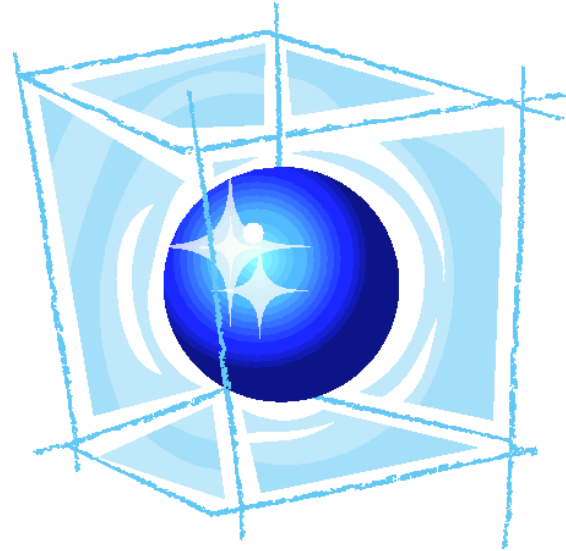
- Scaling by beam power, JPARC (1 MW) could achieve an additional factor of 50 over TRIUMF, or 2,500,000 UCN/cc.



- This could make experiments like searches for $nn\bar{b}$ oscillations, and the dream of a free neutron target, a reality.
- The success of the Canadian project should prove the feasibility of a JPARC UCN project.
- We look forward to a future UCN source at JPARC.

Summary

- Ultracold neutrons are very interesting objects.
- We can use them for a variety of fundamental physics experiments with a long-term future.
- We want to build the world's most intense source of ultracold neutrons.



References

- My research group:
 - <http://nuclear.uwinnipeg.ca>
- International Spallation Ultracold Neutron Source:
 - <http://nuclear.uwinnipeg.ca/ucn/triumf>

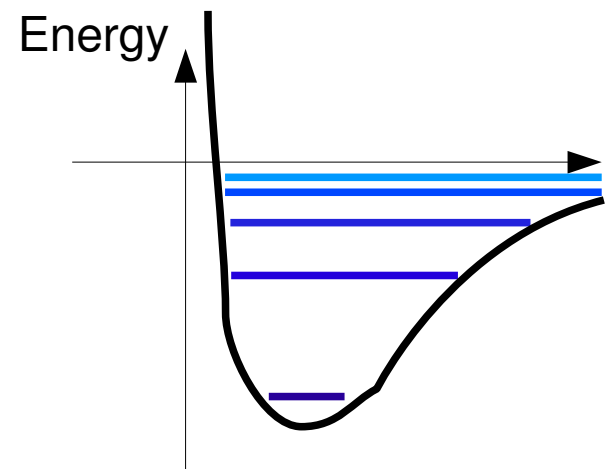
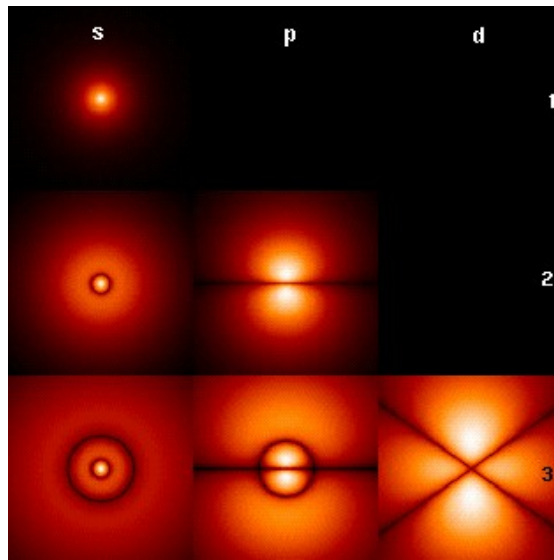
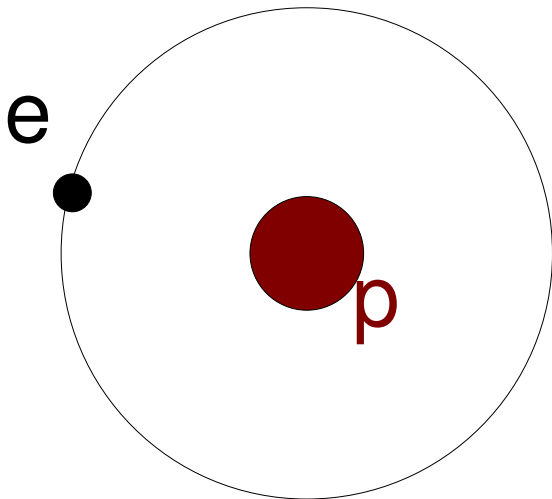
Budget Summary

Item	Cost	Funding Source
UCN cryostat system	\$4M	Japanese collaborators
Beamline	\$2M	TRIUMF
Kickers, shielding, spallation target	\$4.225M	CFI NIF
Moderator design	\$0.675M	Manitoba + Acision Industries
Total	\$10.9M	

- UCN cryostat system includes:
 - Existing UCN source (\$2M)
 - Modifications to source for TRIUMF (\$2M)
 - Horizontal extraction, improved guide technology, etc.

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.

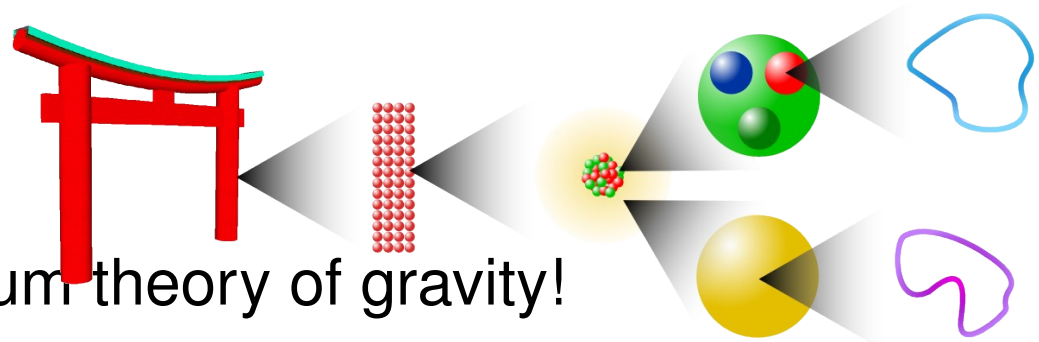
- But people are trying:

- string theory

- might be the real quantum theory of gravity!

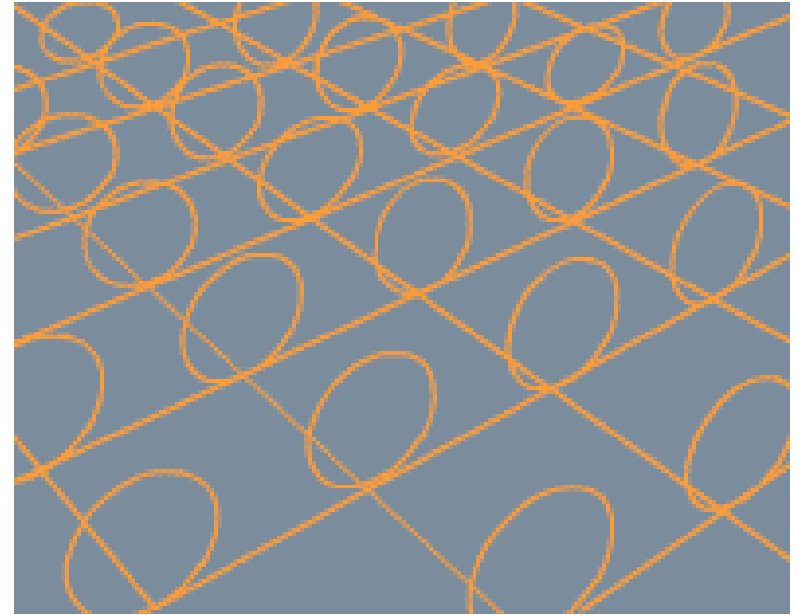
- models of quantum behavior in black holes

- J. Ziprick, G. Kunstatter, and R. Kobes, U. Winnipeg



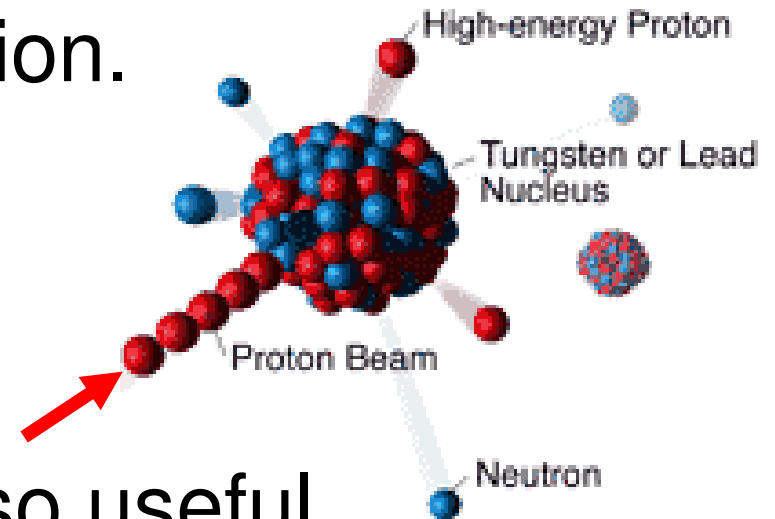
Extra Dimensions?

- 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.



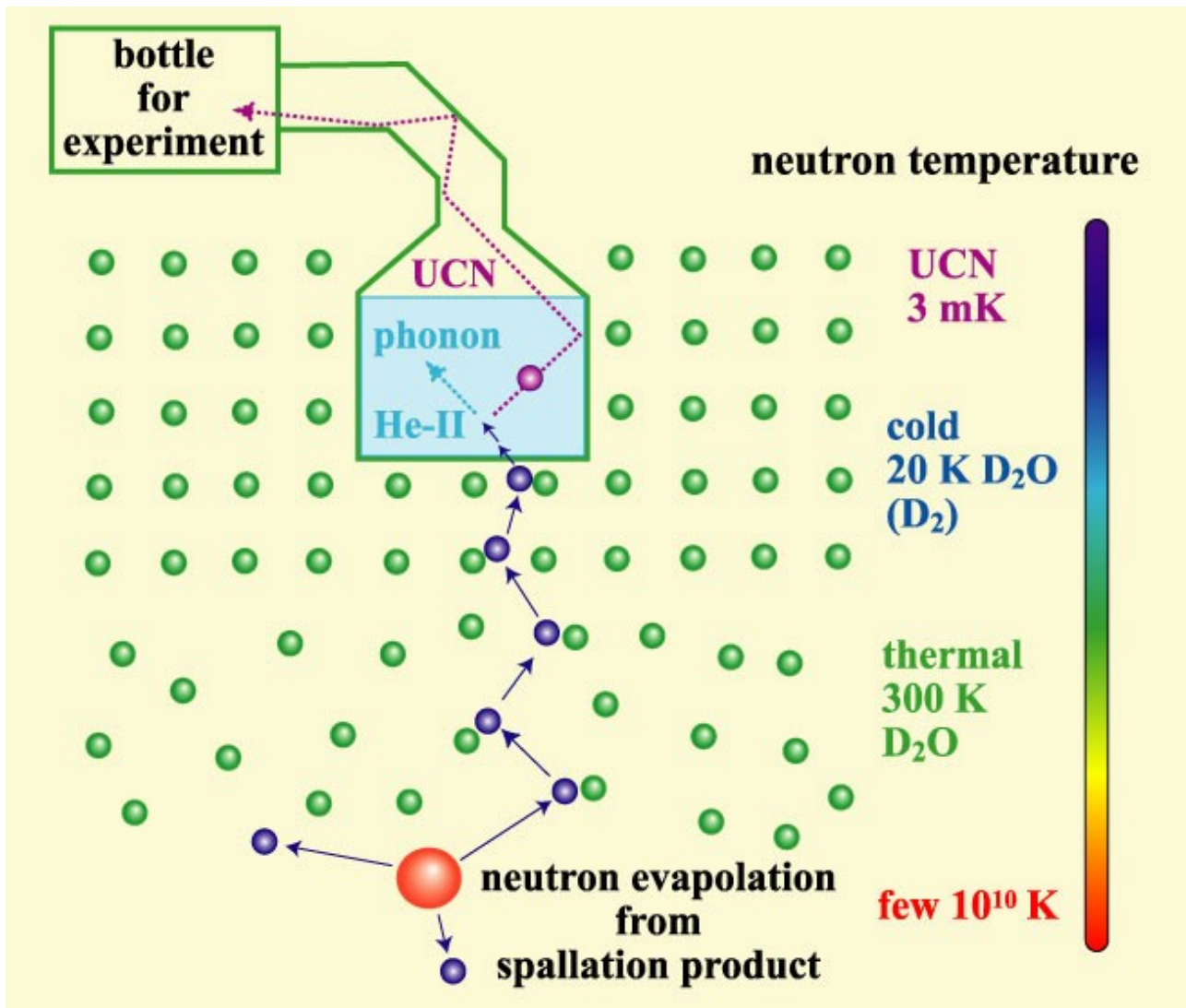
How we will make neutrons.

- 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