Ultracold Neutrons in Canada and Japan

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TRIUMF

International Spallation Ultracold Neutron Source

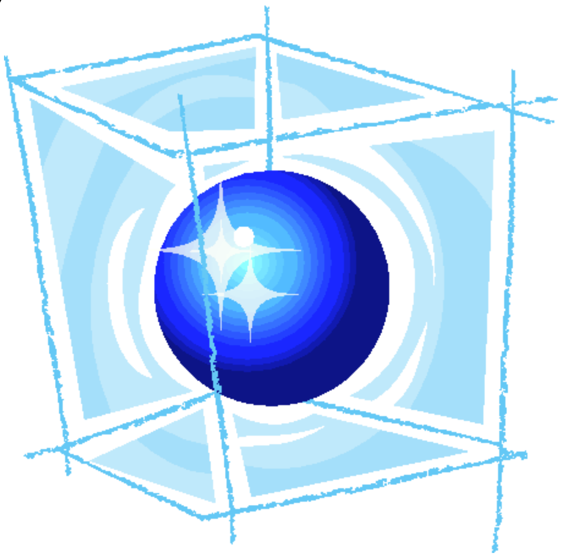
Spokespeople: Y. Masuda (KEK), J.W. Martin (Winnipeg)

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.

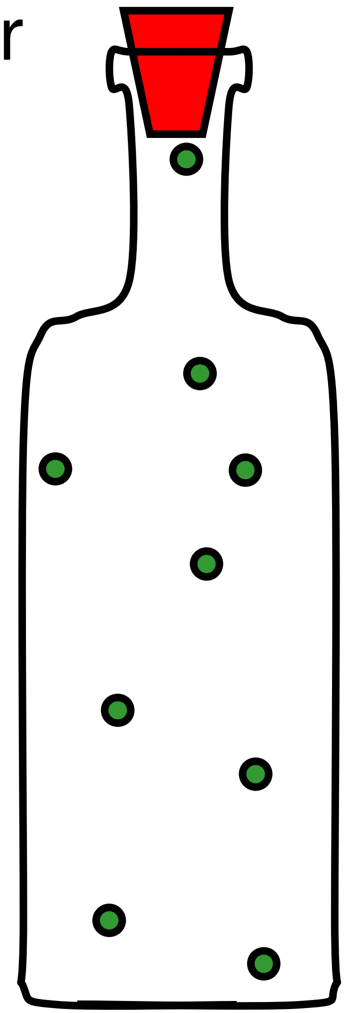
Ultracold Neutrons (UCN)



- What are UCN?
- Interactions of UCN.
- How to make UCN.
- Plans for the International Spallation Ultracold Neutron Source (i-SUN).
- Experiments that we would do there.

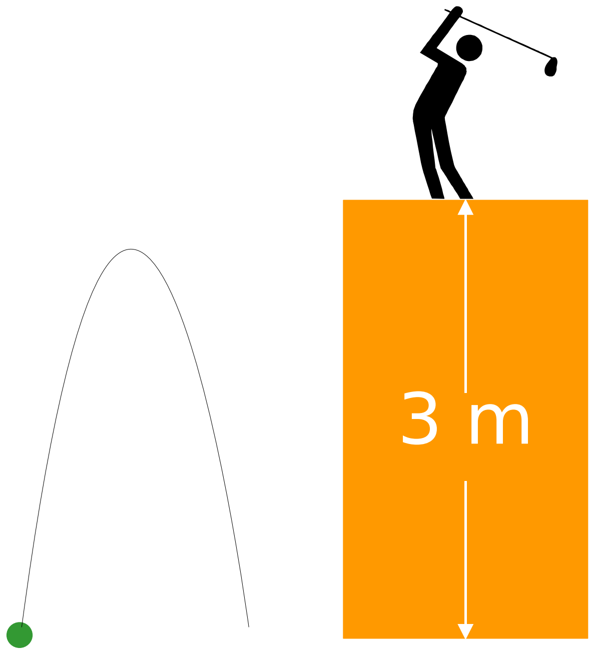
Ultracold Neutrons (UCN)

- 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 m/s = 30 km/h
  - temperature < 4 mK
  - kinetic energy < 300 neV
- Interactions:
  - gravity: $V = mgh$
  - weak interaction (allows UCN to decay)
  - magnetic fields: $V = -\mu \bullet B$
  - strong interaction



Gravity

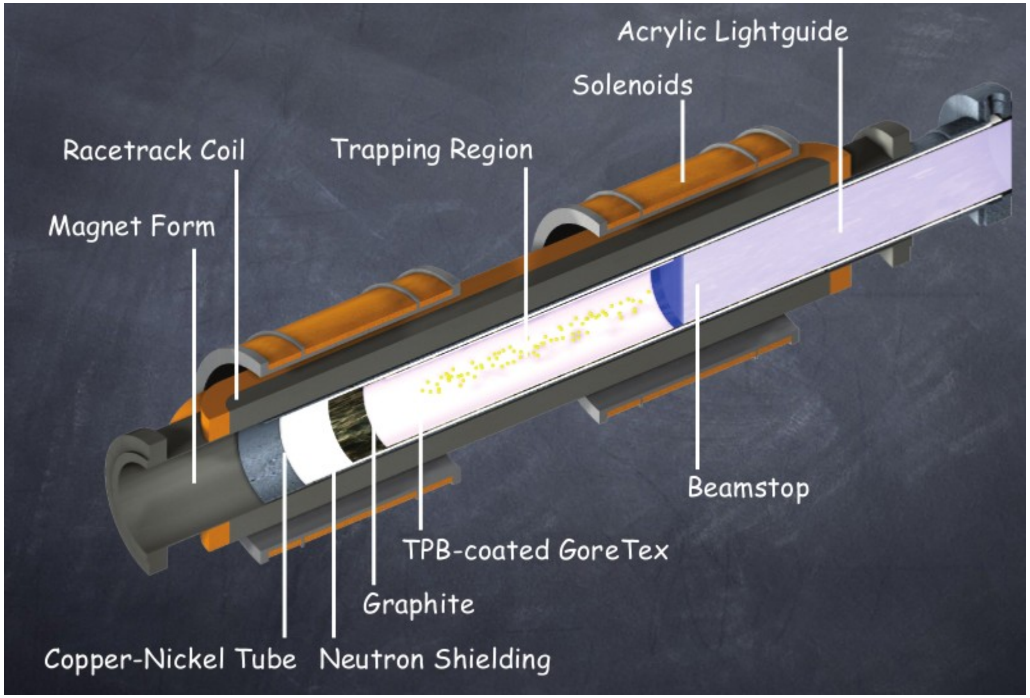
- Question: If I threw something straight up at an initial speed of 30 km/h, how high would it go?
- Answer (from high-school physics):
  - about 3 meters (10 feet).



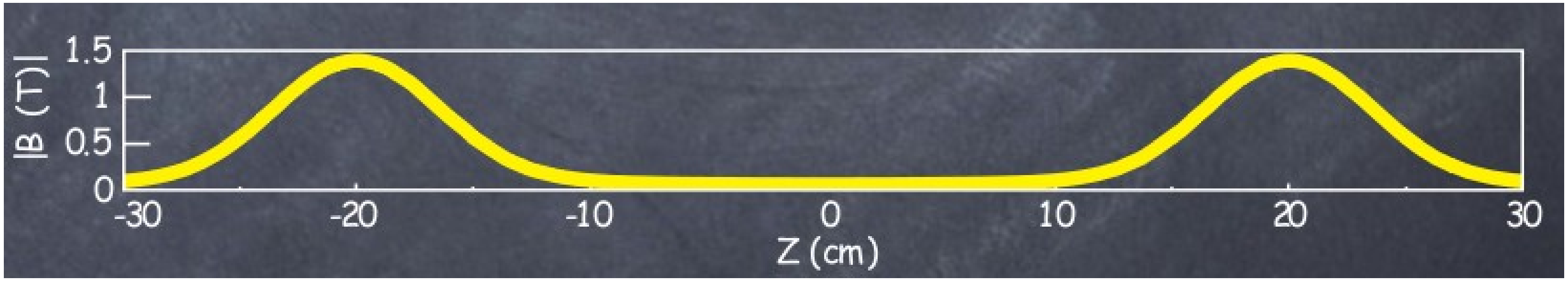
Magnetic Fields

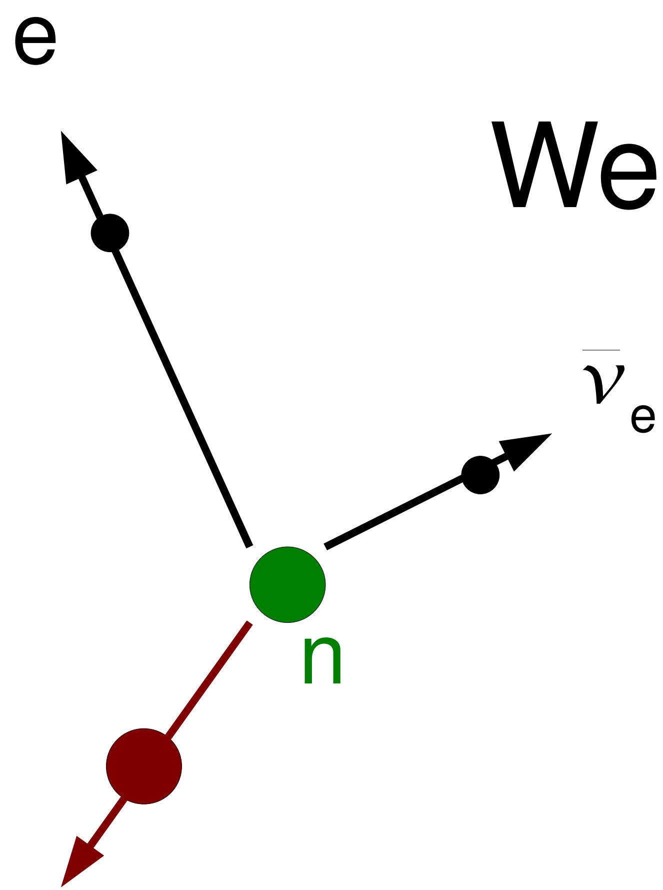
- Neutrons magnetic moment is 60 neV/T
- UCN 100% polarization achieved by passage through 7 T field.
- You can trap ultracold neutrons in a magnetic bottle!

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



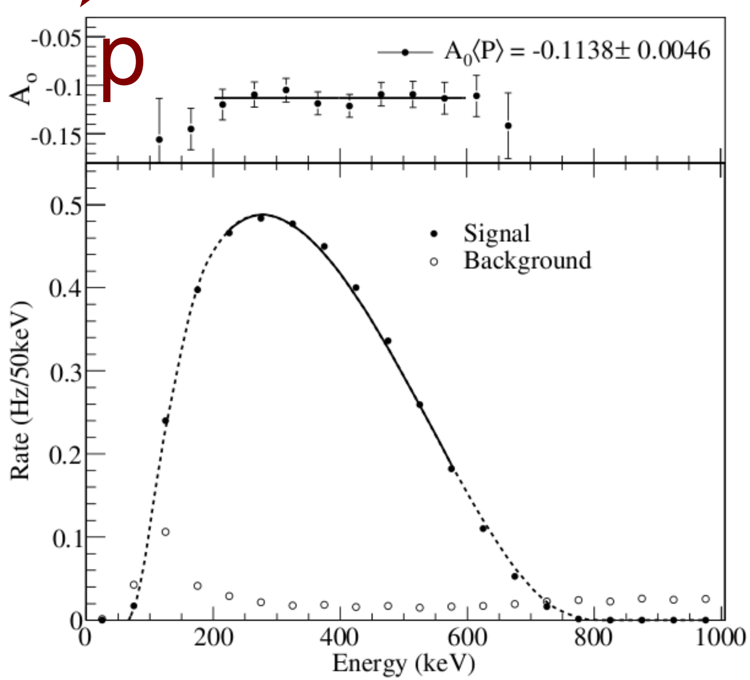
www.nist.gov





Weak Nuclear Force

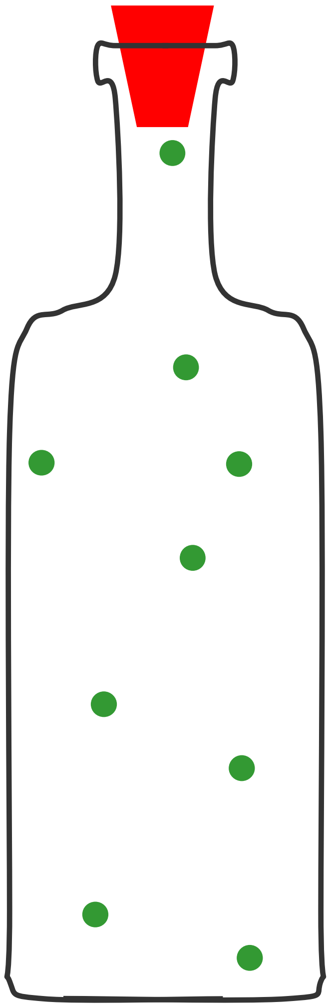
- Causes free neutrons to decay
- Neutrons live for about 15 minutes
- An interesting experiment:
  - Put ultracold neutrons in a bottle
  - Wait a while (about 15 minutes)
  - Open the bottle and see how many neutrons come out
- Also interesting experiment:
  - Measure the beta spectrum



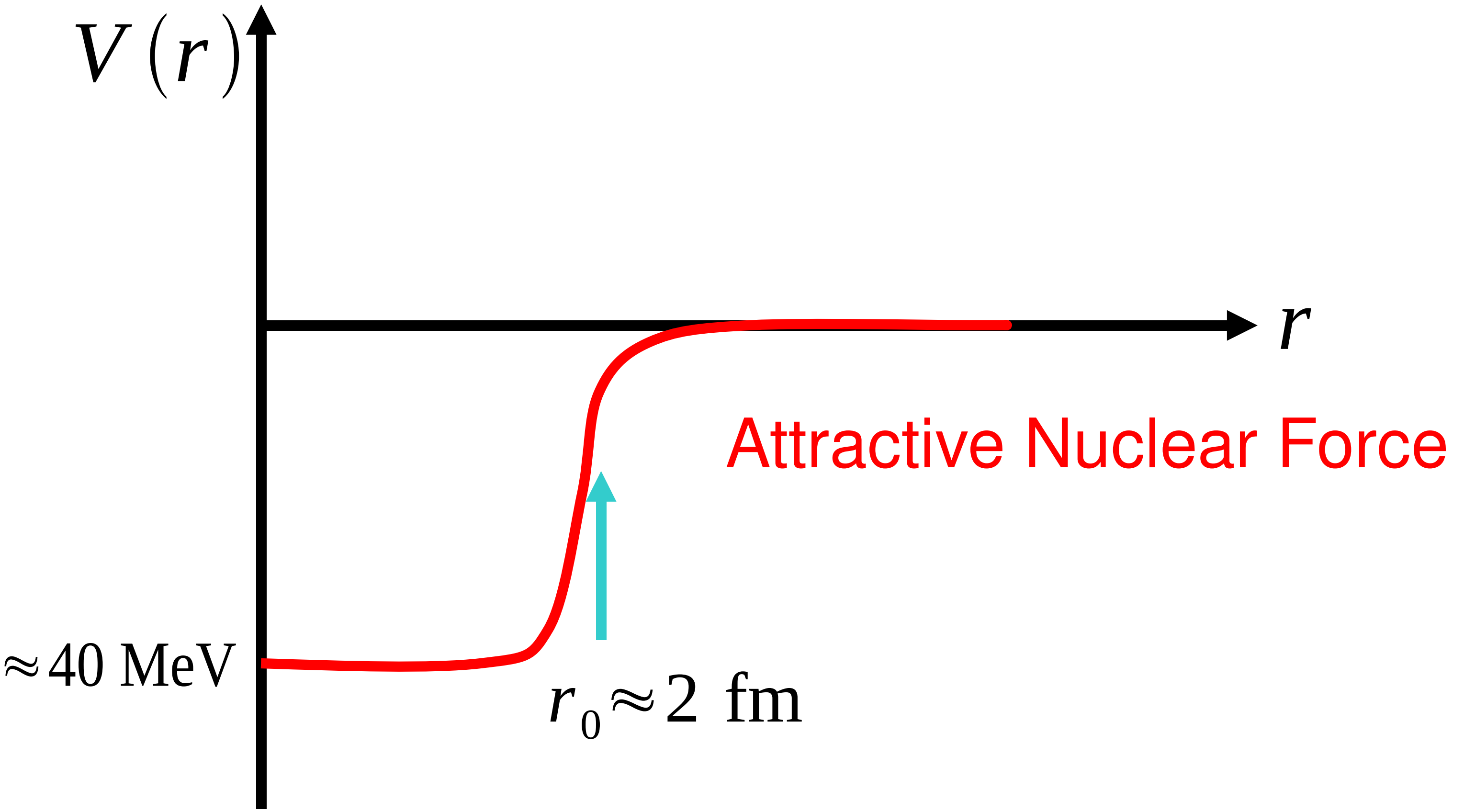
D. Harrison, MSc project

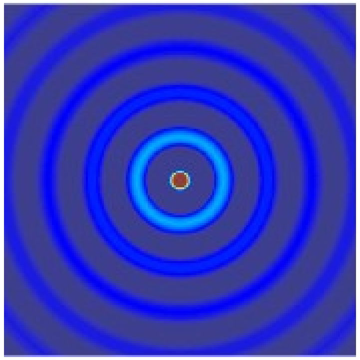
Strong Nuclear Force

- Ultracold neutrons are moving so absurdly 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



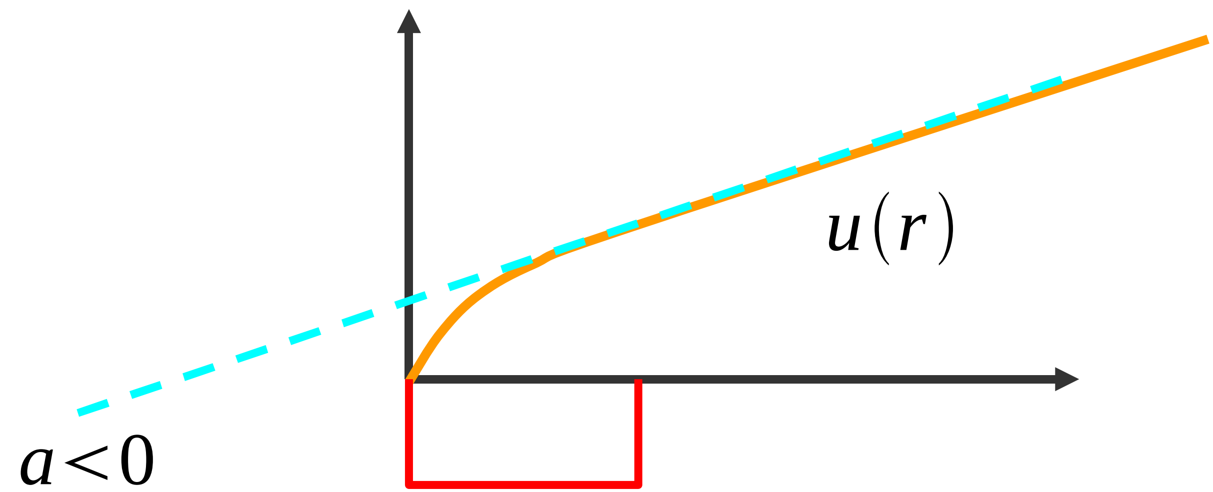


For $T_n \leq 1$ MeV, $l \sim pr_0 \sim 0 \Rightarrow$ s-wave scattering (isotropic)

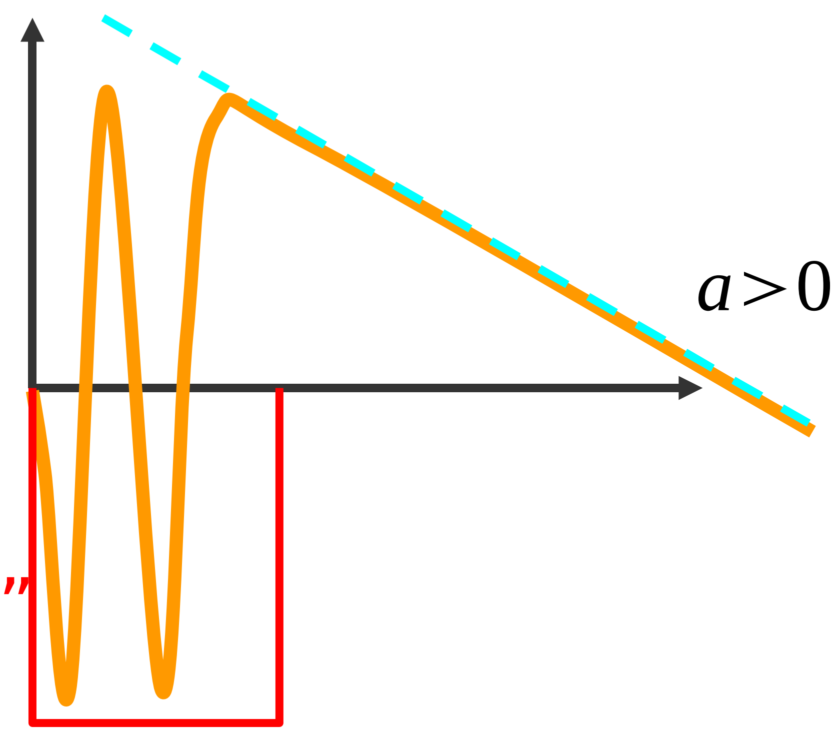
For $T_n \ll 1$ MeV, $\sigma_{\text{tot}} = 4\pi a^2$, where $a \equiv$ scattering length

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:

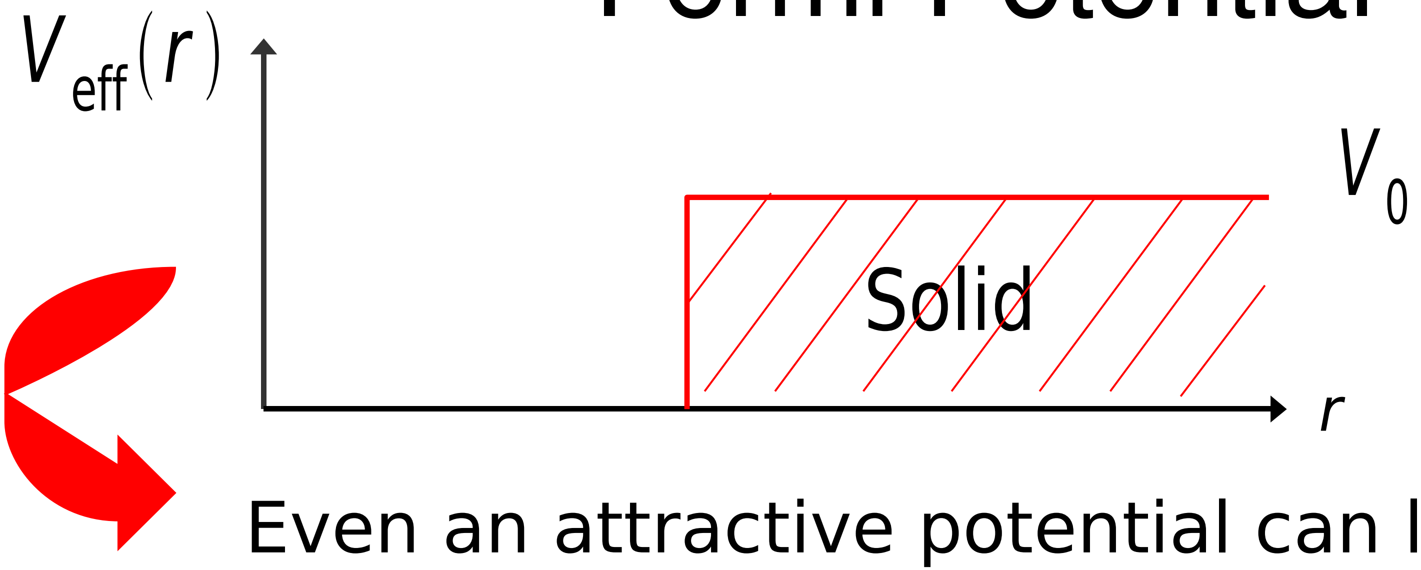
$$V_{\text{eff}}(r) = \frac{2\pi\hbar^2}{m}\sum_i a_i \delta(r - r_i)$$

- For lattice spacing << neutron wavelength

$$V_{\text{eff}}(r) = \frac{2\pi\pi\hbar^2}{m} N_0 \int \frac{d^3 r'}{V}\delta(r - r')$$

$$= \frac{2\pi\pi\hbar^2 n_0}{m}\theta(r \notin V) \equiv V_0 \theta(r \notin V)$$

Fermi Potential



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

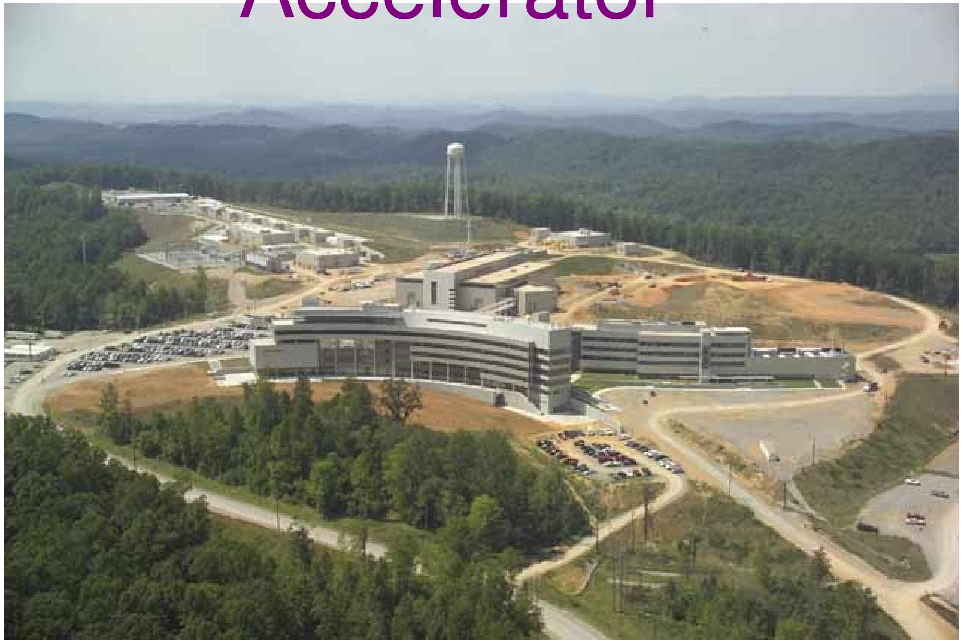
Largest Fermi potential is for Nickel-58 (^{58}Ni)
V_0 = 335 neV

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

1) In a nuclear reactor.

2) In an atom smasher (accelerator).

Accelerator



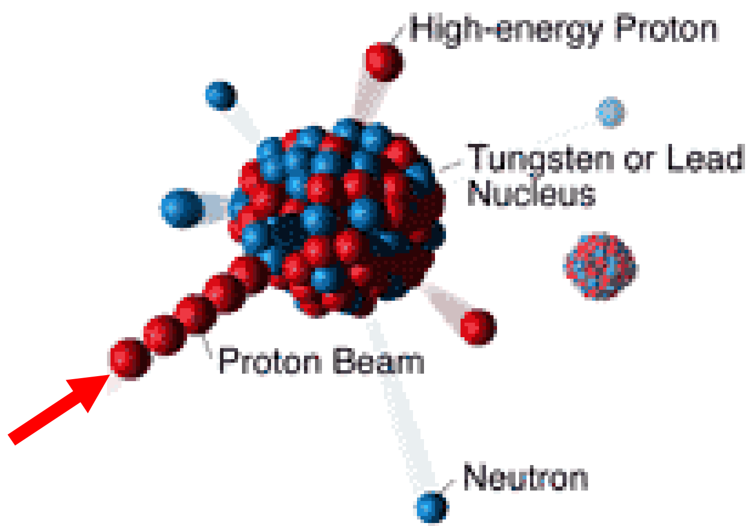
Spallation Neutron Source,
Oak Ridge, Tennessee, www.sns.gov

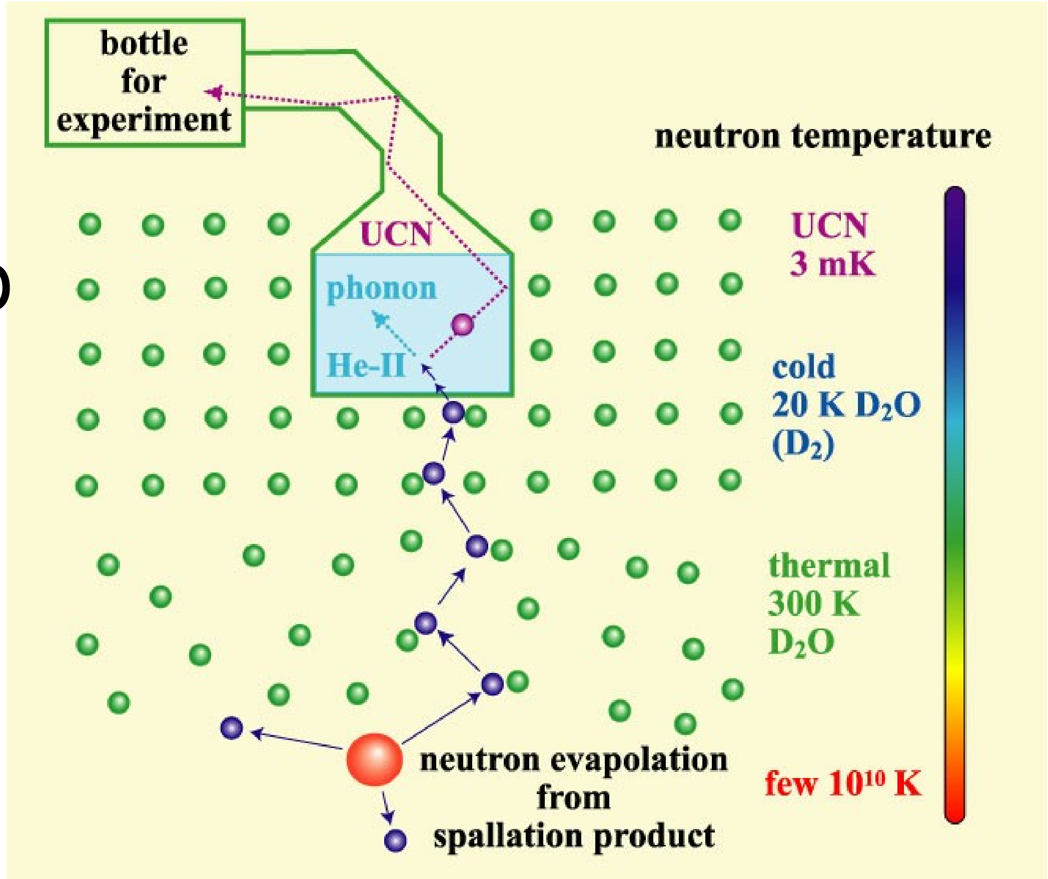
Reactor

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

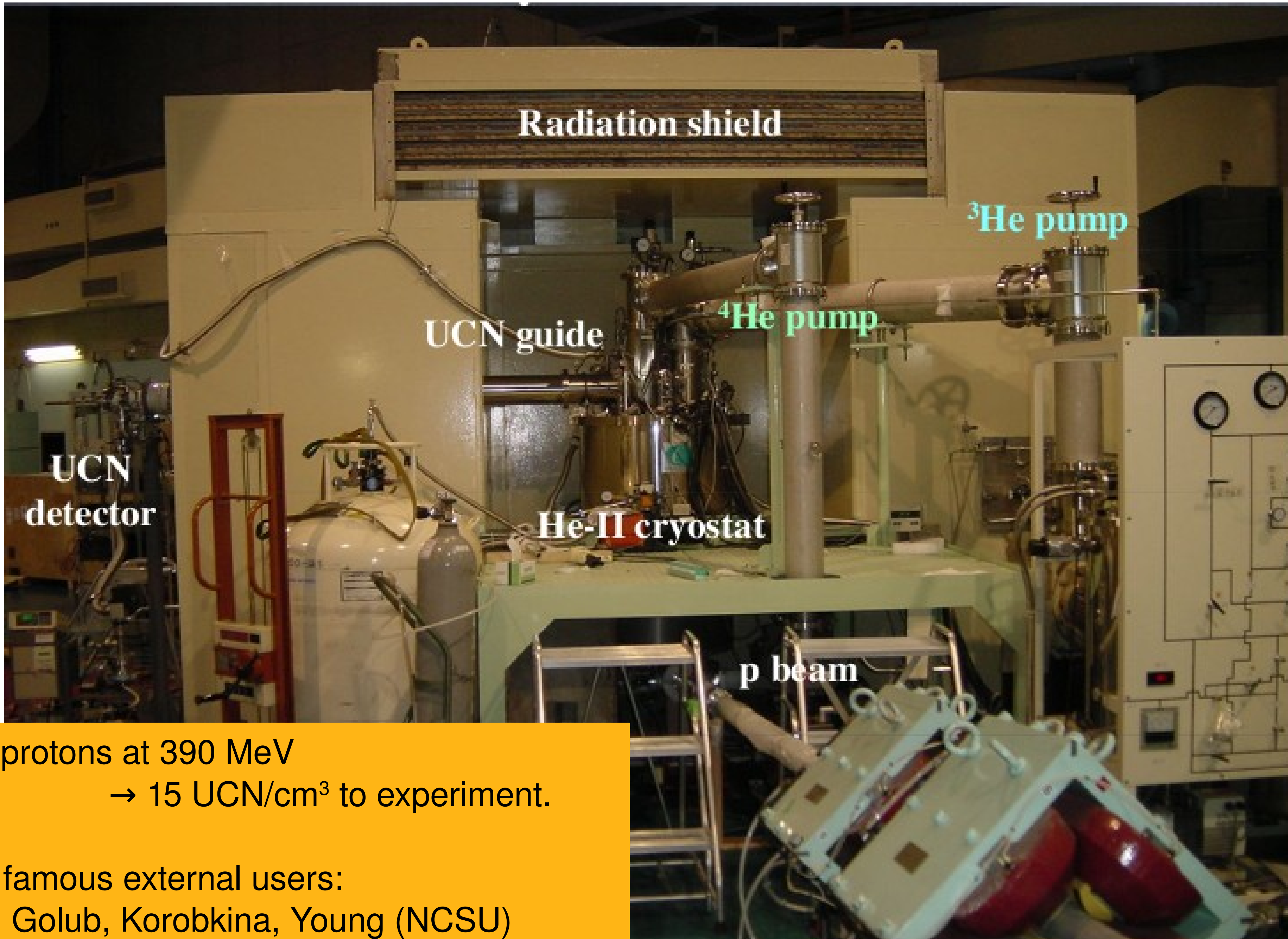
How to make UCN

- 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.





KEK/RCNP UCN Source (Masuda, et al)



1 μa protons at 390 MeV
→ 15 UCN/cm^3 to experiment.

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

- Proposed beam parameters for TRIUMF UCN source:
  - 500 MeV protons at 40 uA
- Recall RCNP, Osaka:
  - 390 MeV protons at 1 μA
- A fifty-fold increase in beam power.
- Cyclotron operates ~ 8 months/yr.

Japanese Section: UCN cryostat

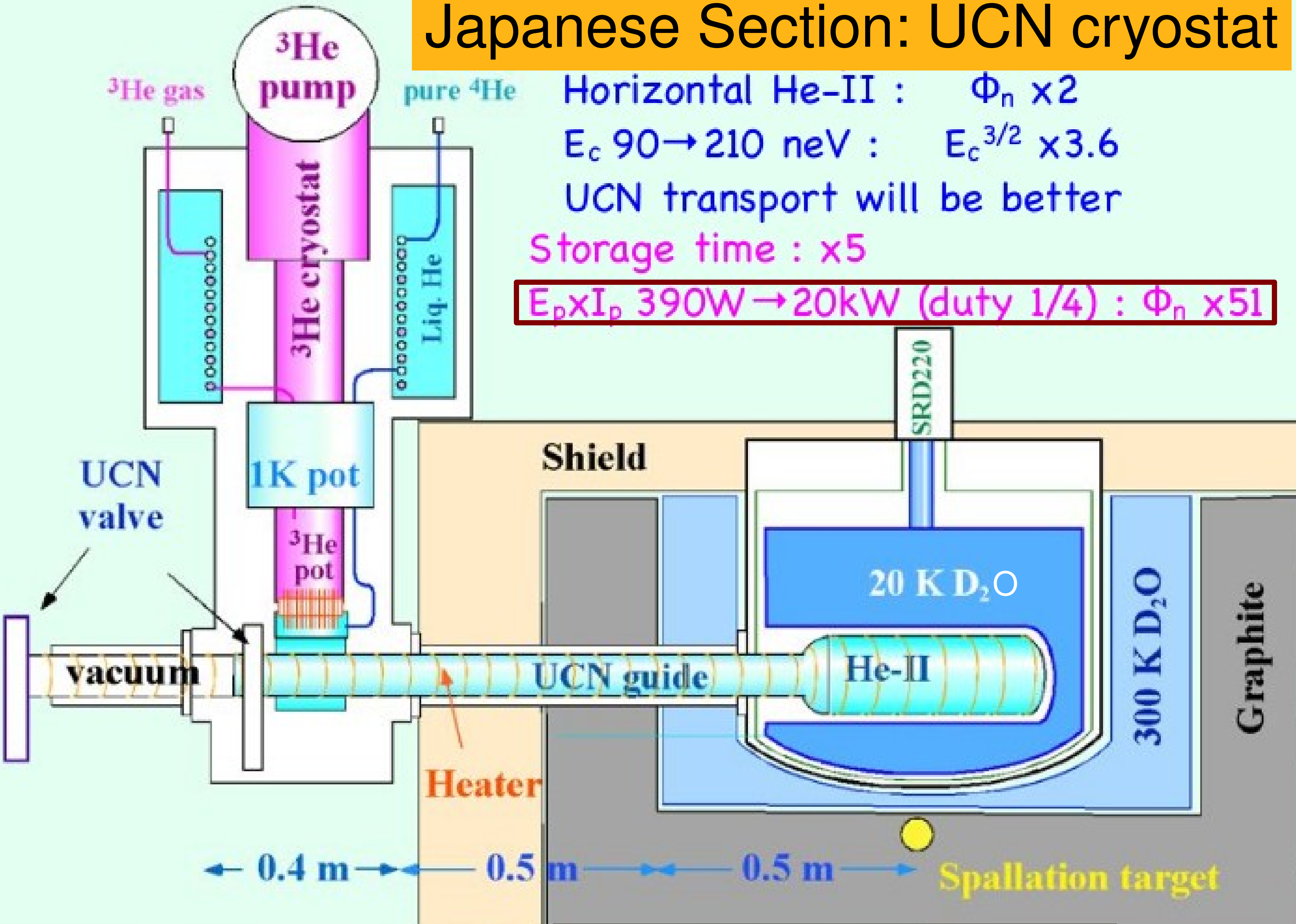
Horizontal He-II : Φ_n x2

E_c 90→210 neV : $E_c^{3/2}$ x3.6

UCN transport will be better

Storage time : x5

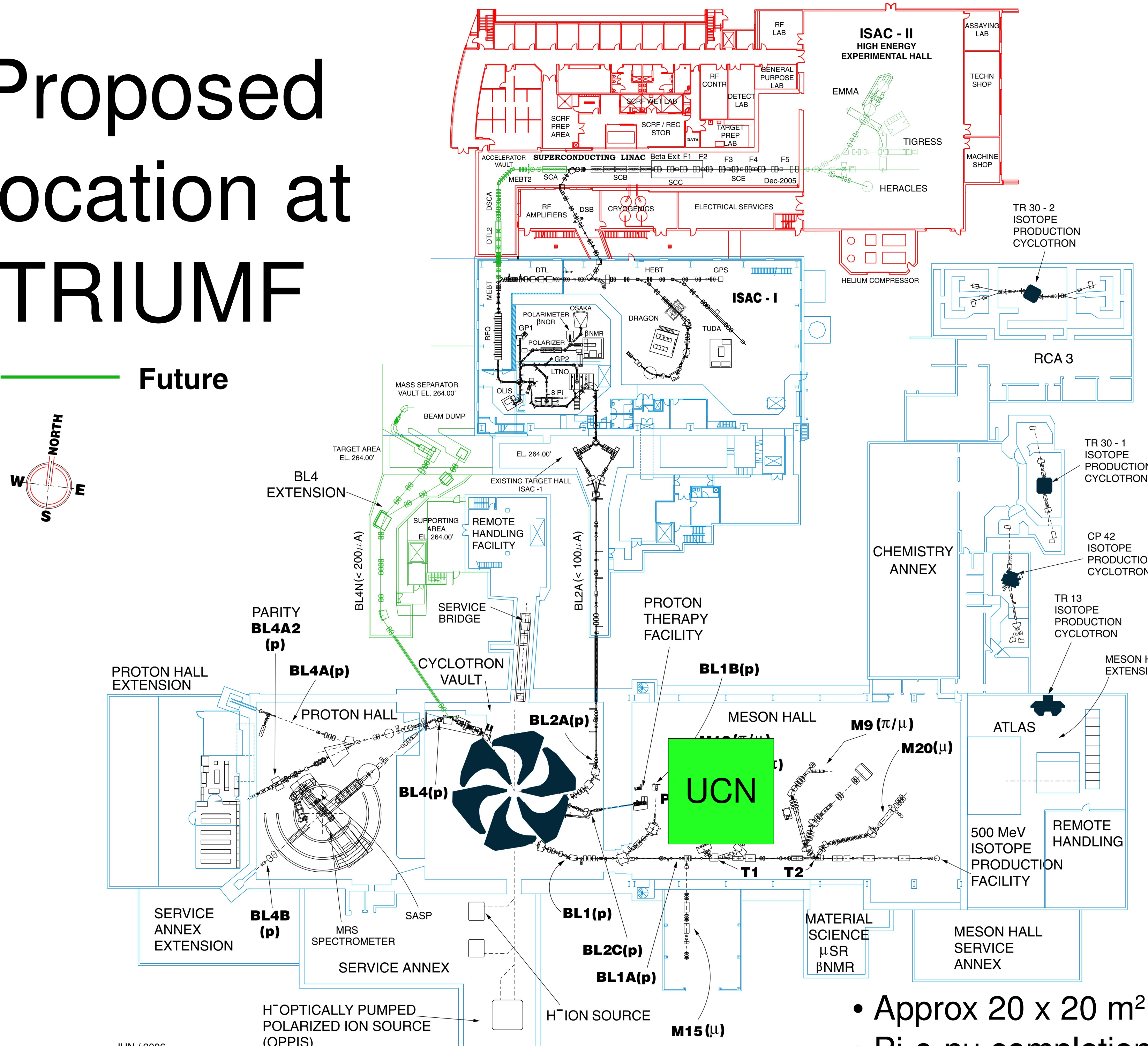
E_pxI_p 390W→20kW (duty 1/4) : Φ_n x51



Future Upgrade: D_2O ice → LD_2 : x5

Proposed Location at TRIUMF

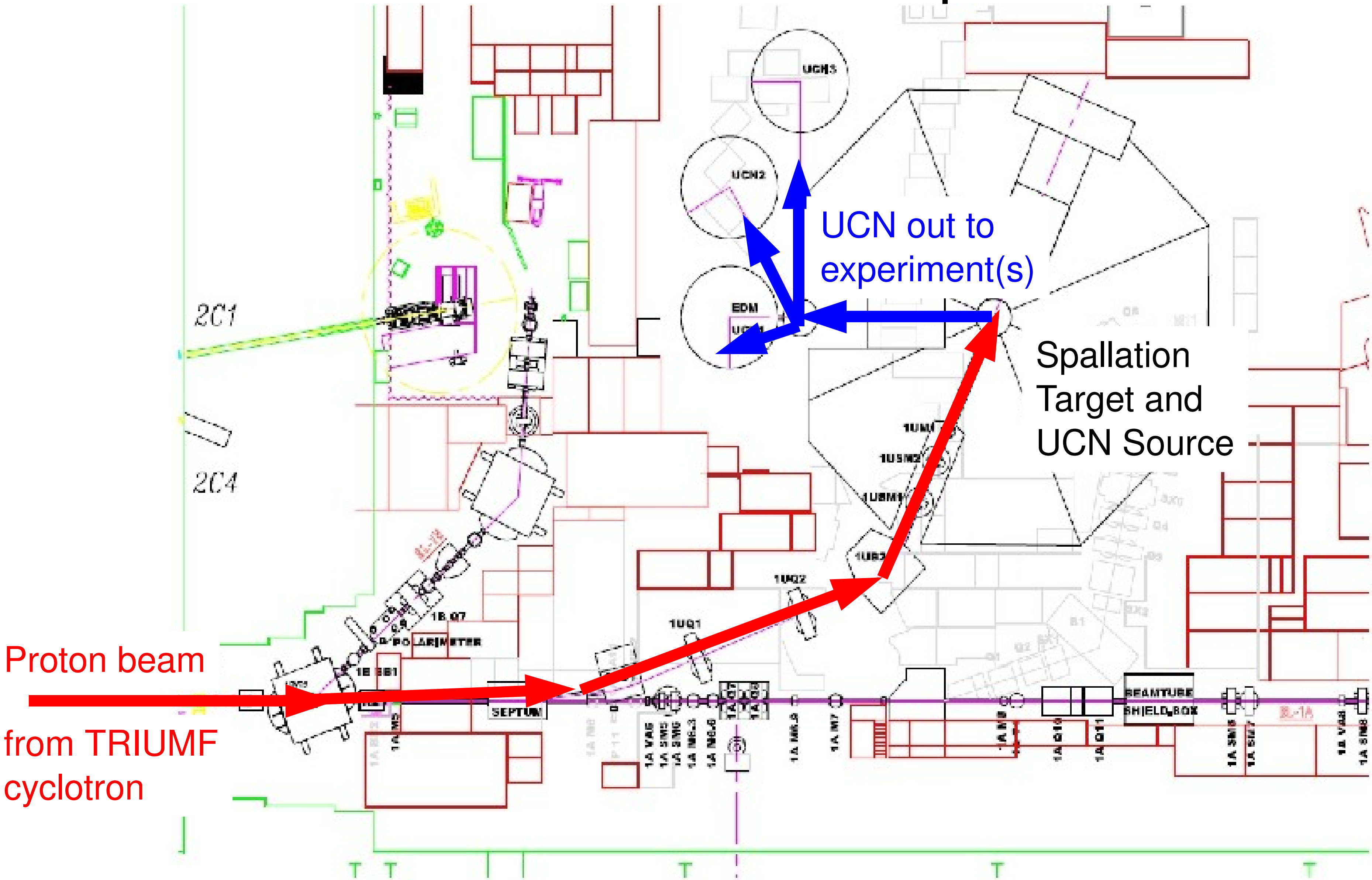
Future



- Approx 20 x 20 m^2 box
- Pi-e-nu completion 2011

i-SUN Implementation at TRIUMF

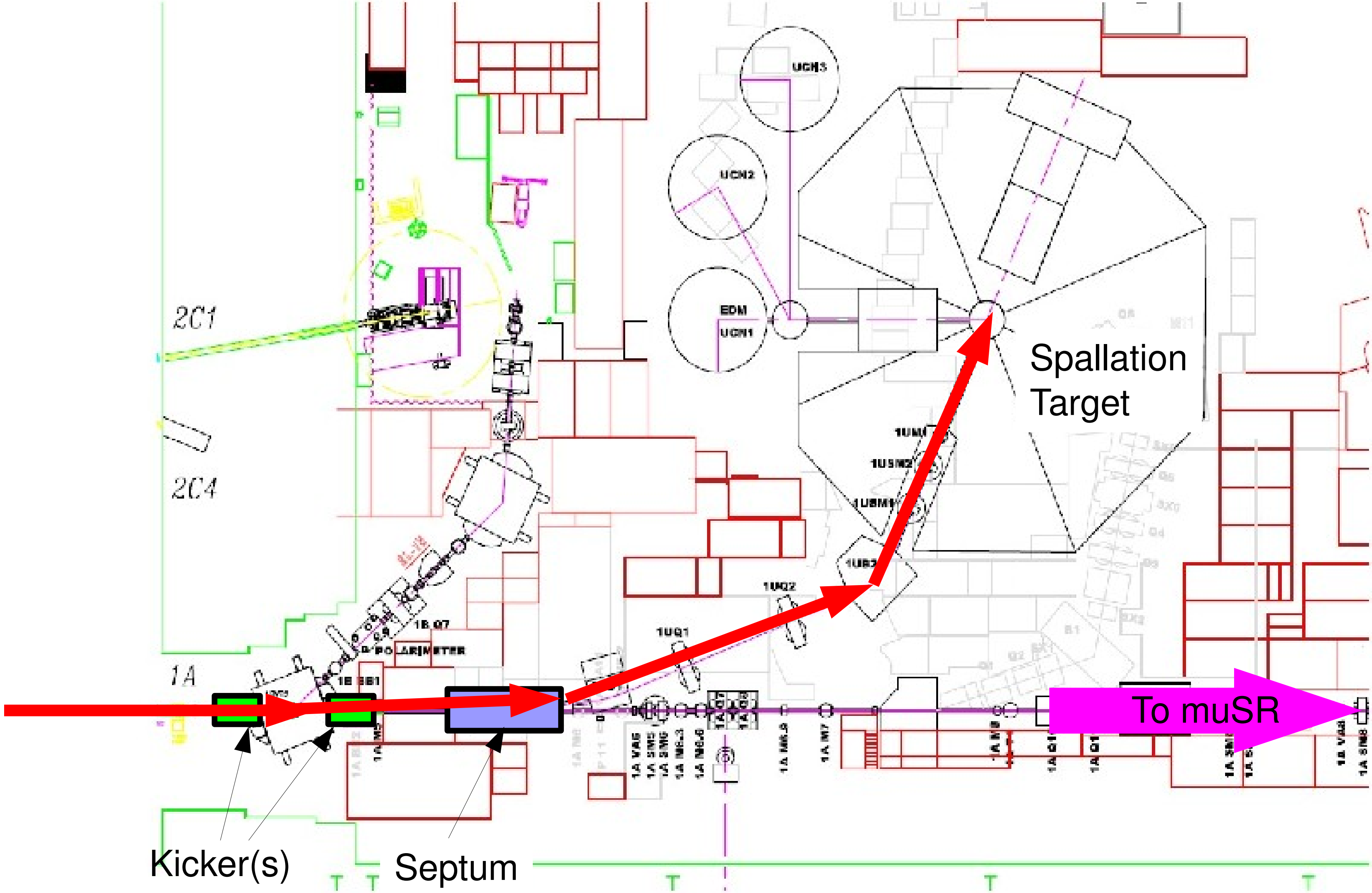
Meson Hall concept



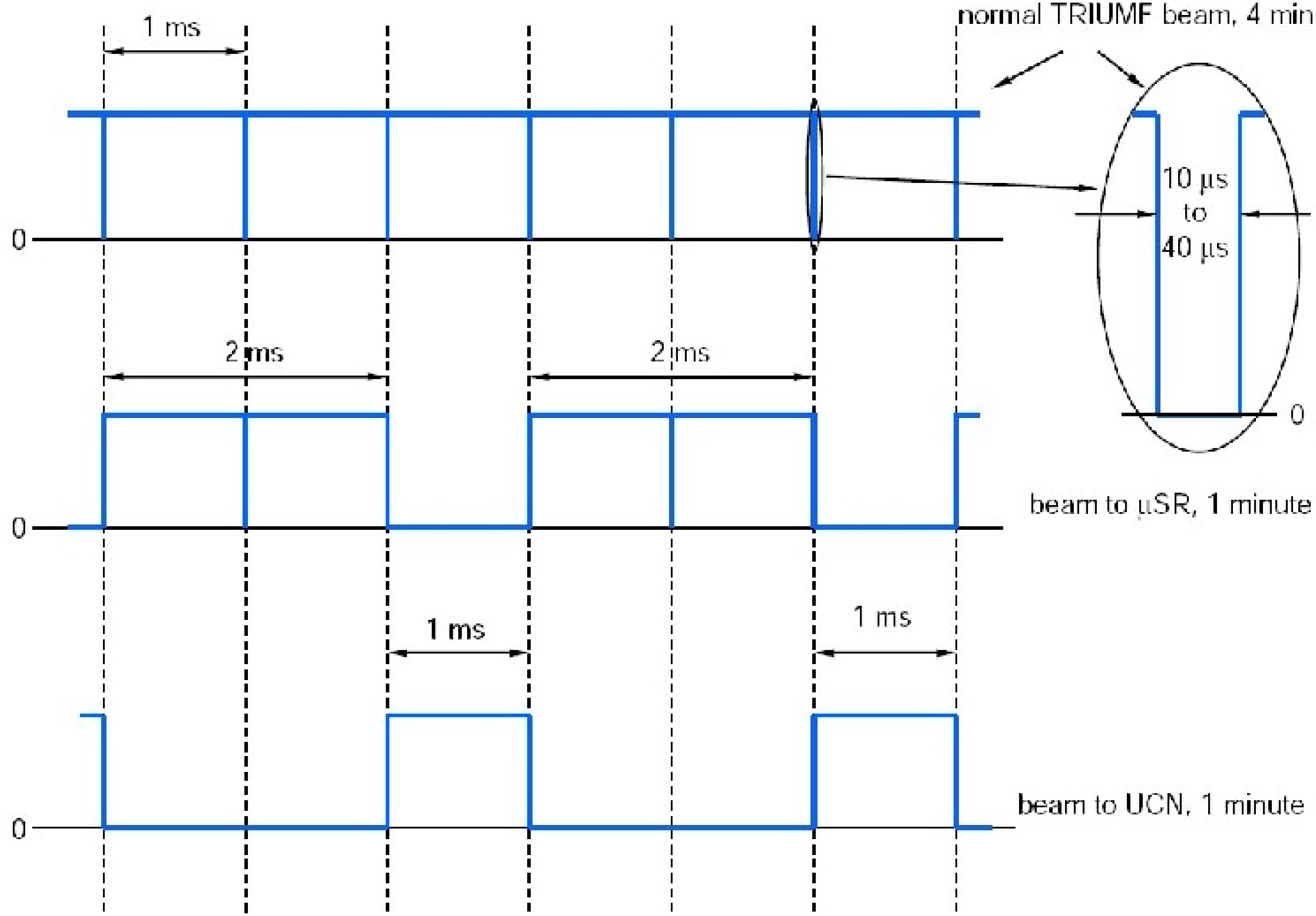
Challenges in Implementation

- For counting-mode physics experiments, it can be highly advantageous to switch the beam off.
- E.g. At RCNP:
  - 1 min beam on, 3 mins beam off.
- At TRIUMF, we will use a fast kicker to achieve this pulsing.
- Constraints of beam structure from cyclotron.
- We must also be careful to not affect downstream users (muSR CMMS facility)

Kicker Concept



Kicker Concept



- Downstream users affected only at 7% level.
- UCN data when cyclotron is on (8 months/yr.)

Other Technical Progress

- Beamline design (J. Doornbos, G. Clark)
- Kicker feasibility, design (M. Barnes)
- Shielding estimates (A. Trudel)
- Layout (S. Austen, C. Davis)
- Cost/Sched/Manpower (V. Verma, W.D. Ramsay, C. Davis)
- ...and many useful discussions with E. Blackmore, R. Baartman, P. Schmor ...

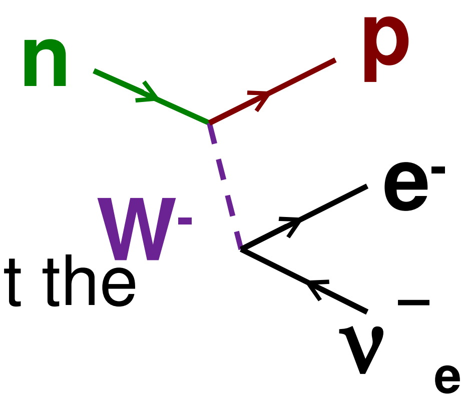
World's UCN projects

	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 x 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/**

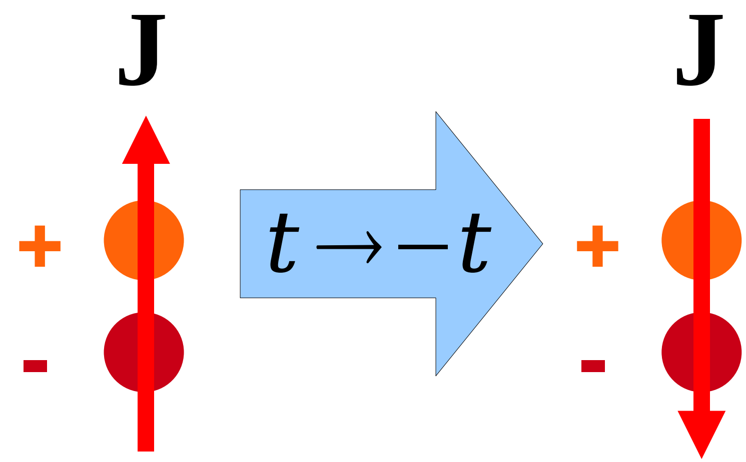
Physics Experiments with UCN

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

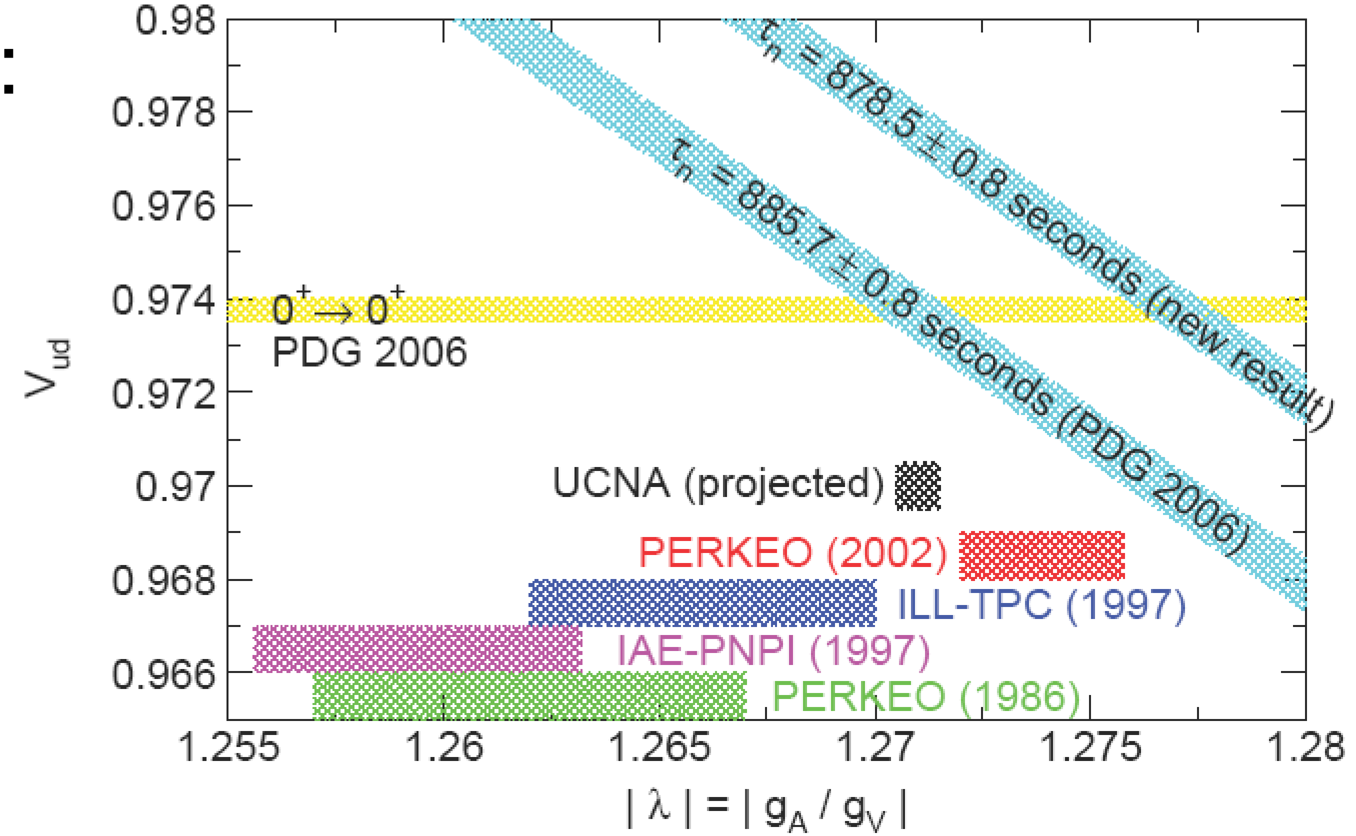
near term

- nnbar?
- Free n target?

longer term

Neutron Lifetime

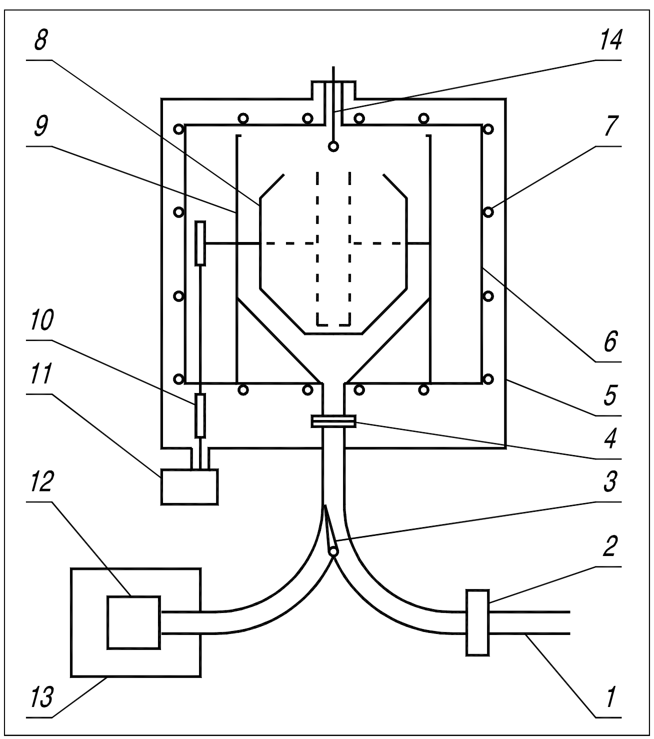
- Physics interest:
  - BBN
  - V_{ud}



- 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

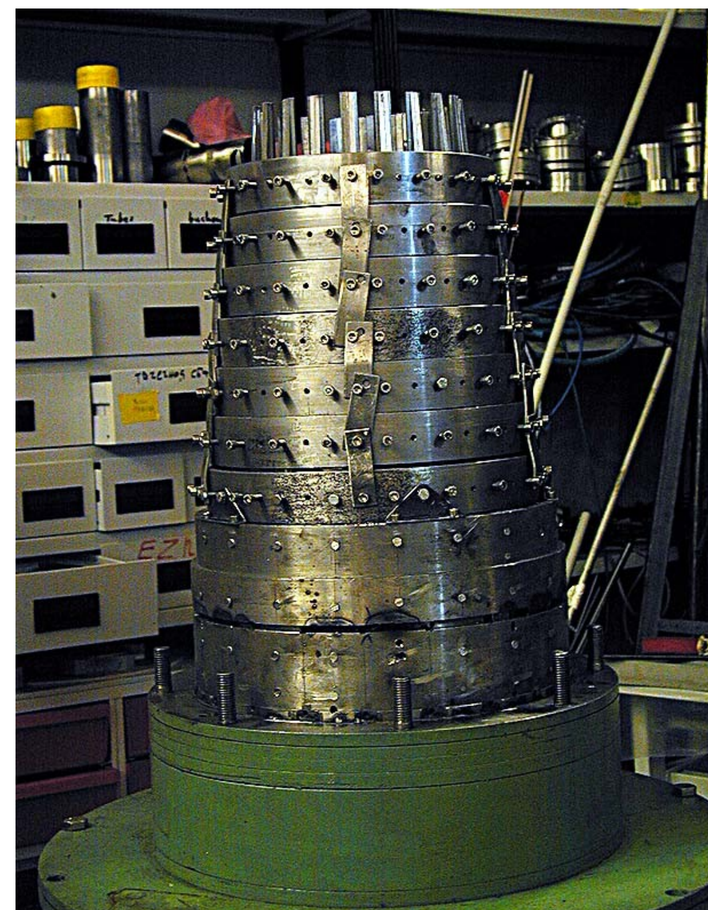


<- Gravitrap

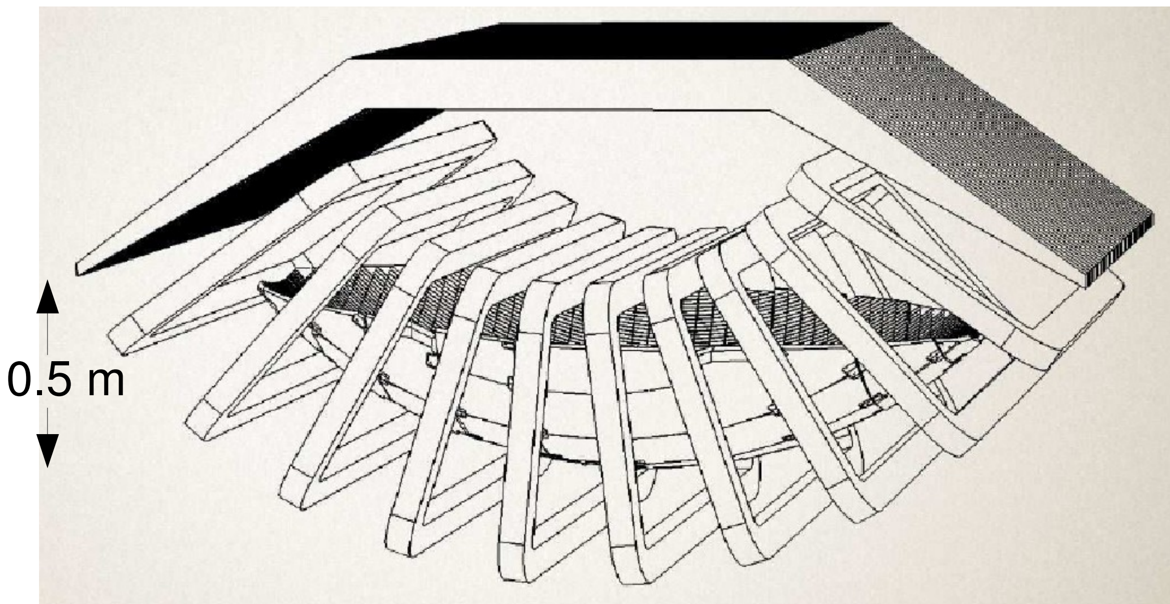
Permanent magnet trap ->

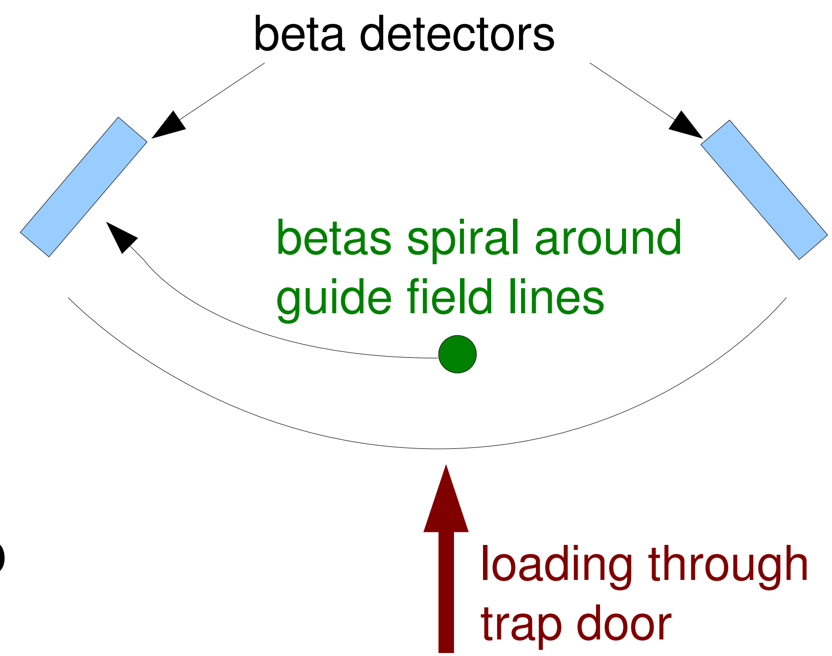
(both at ILL)

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



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





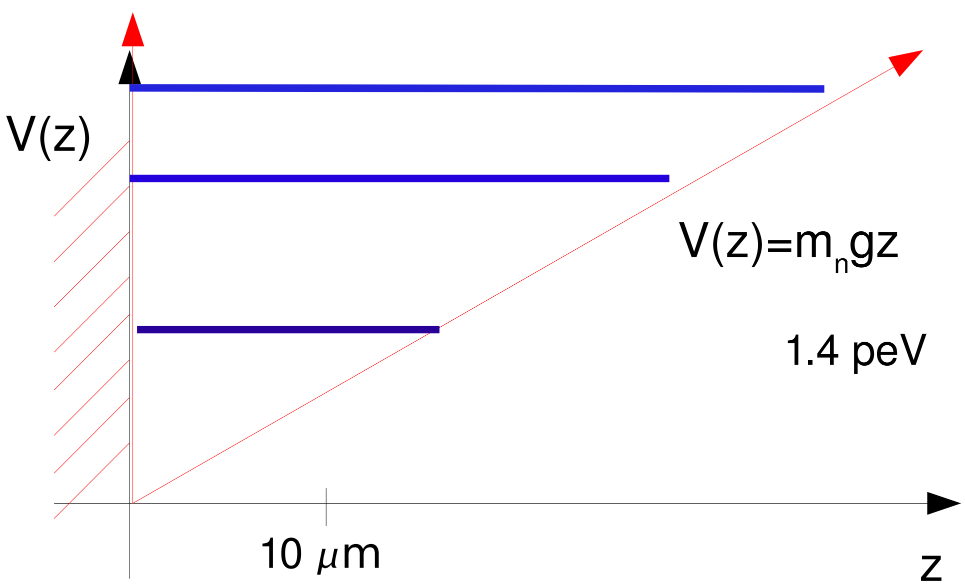
- Shallow Halbach array + gravity for trap
- Guide field for decay betas
- Marginally trapped neutrons experience chaotic orbits and are ejected rapidly
- Goal precision $\delta\tau_n$ ~ 0.1 s
- Require: Efficient trap loading, effective n-“cleaning”, high UCN density

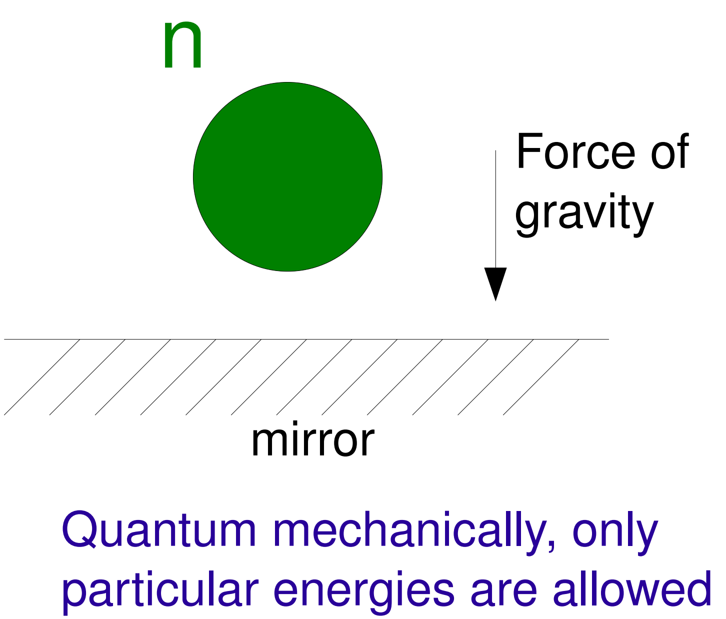
n-lifetime Plans for Canada

- 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

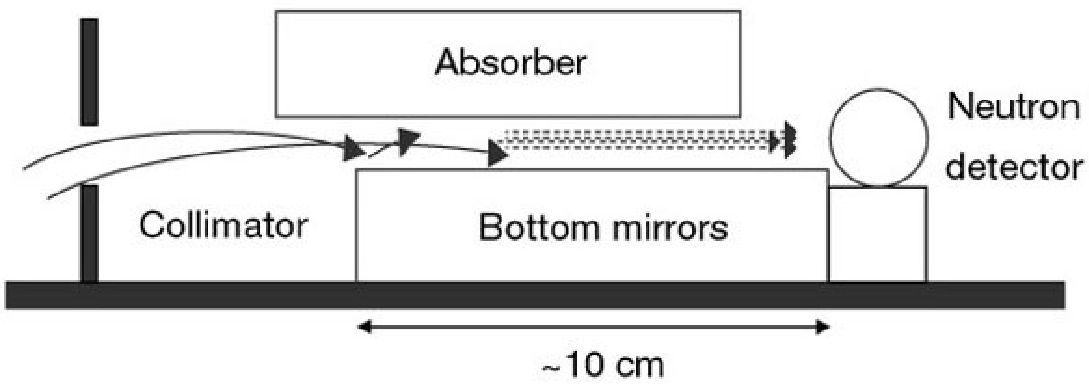
- Ultracold neutrons can be confined in the gravitational field of Earth.

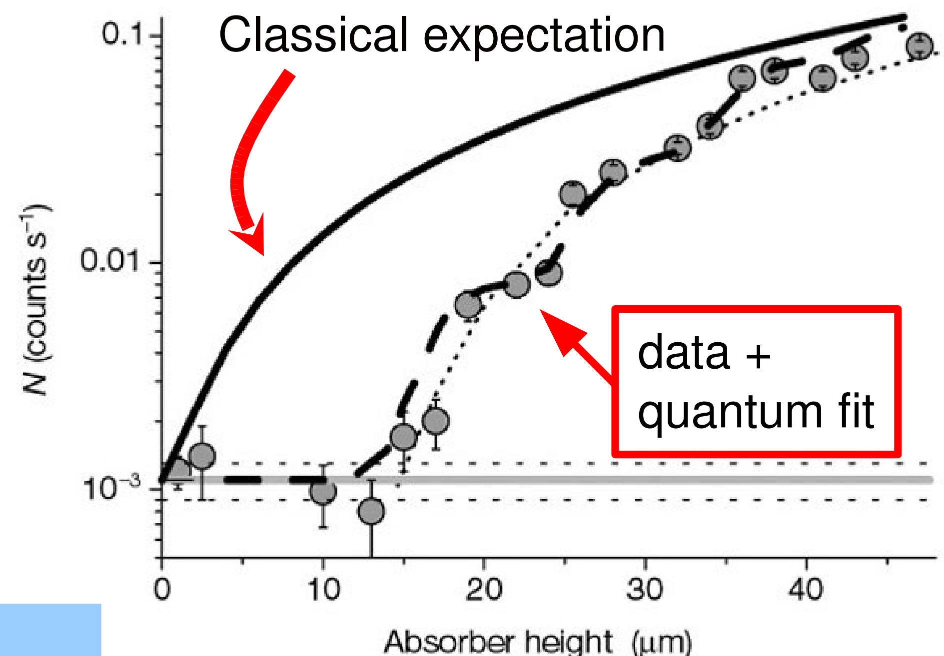




- Recently, the first observation of quantized energy-levels in the Earth's gravity field was made.

Experiment on Quantum Mechanics and Gravity

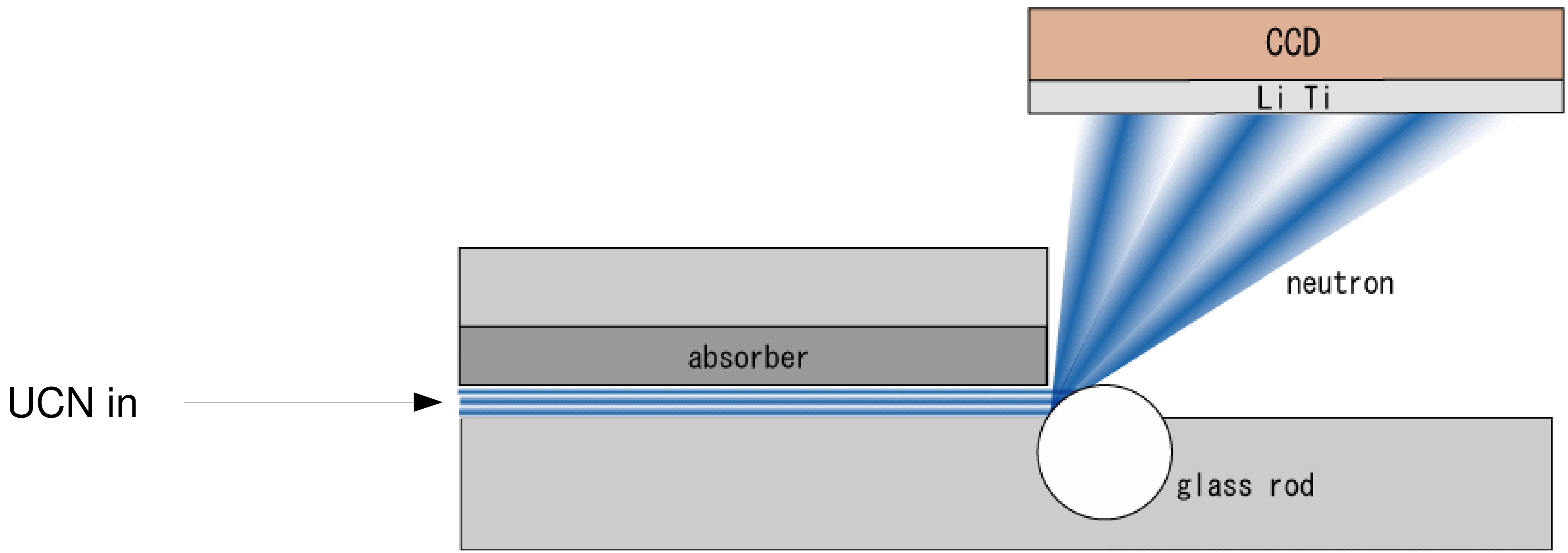




- Experimental results have been used to place limits on
  - 10 um scale modifications to gravity, "fifth force"
  - extra dimensions
  - axions

- 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 (Jan. 2009)

Plans for TRIUMF

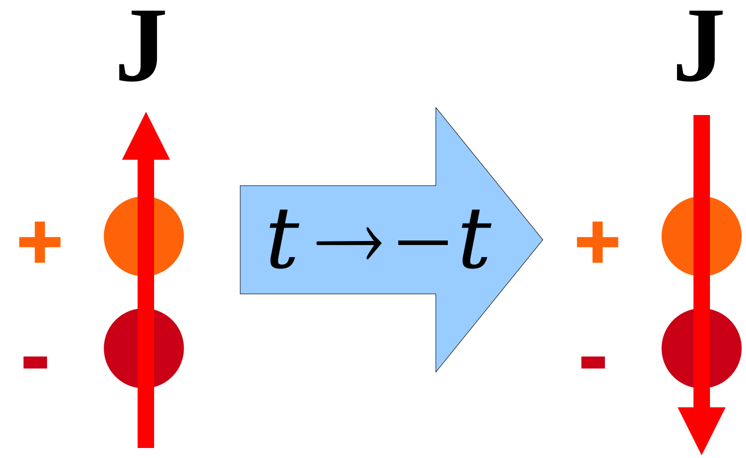
- We hope the experiment would be initiated and led by Japanese groups (S. Komamiya, et al).

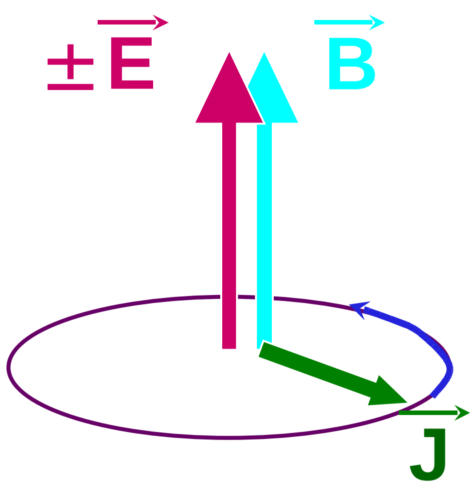
Further experiments:

- 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.
- Direct imaging of neutron wavefunction.
- 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





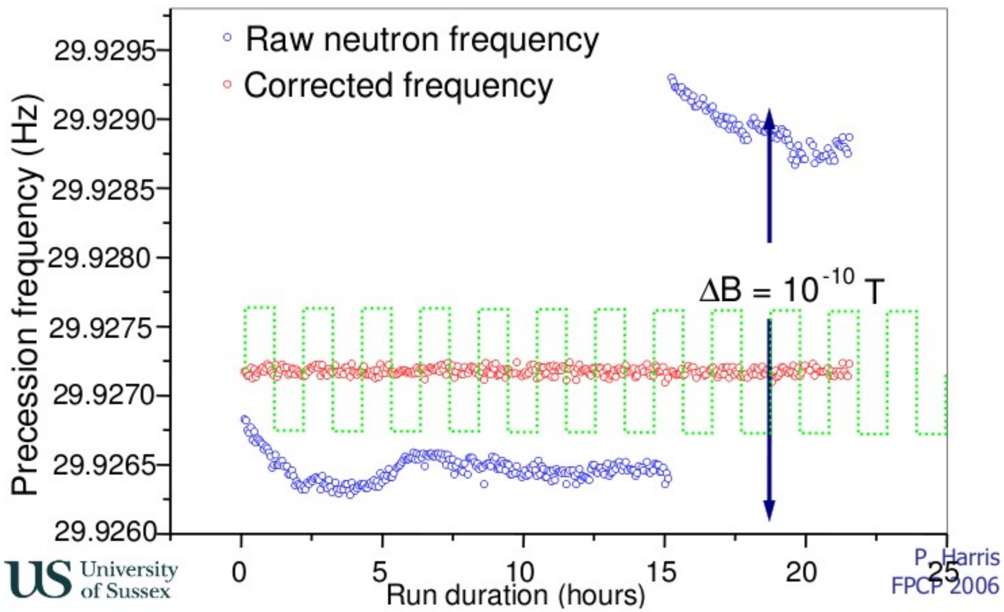
$$h\nu = 2\mu_n B \pm 2 d_e E$$

- Present Exp. Limit < $3\text{x}10^{-26}$ 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

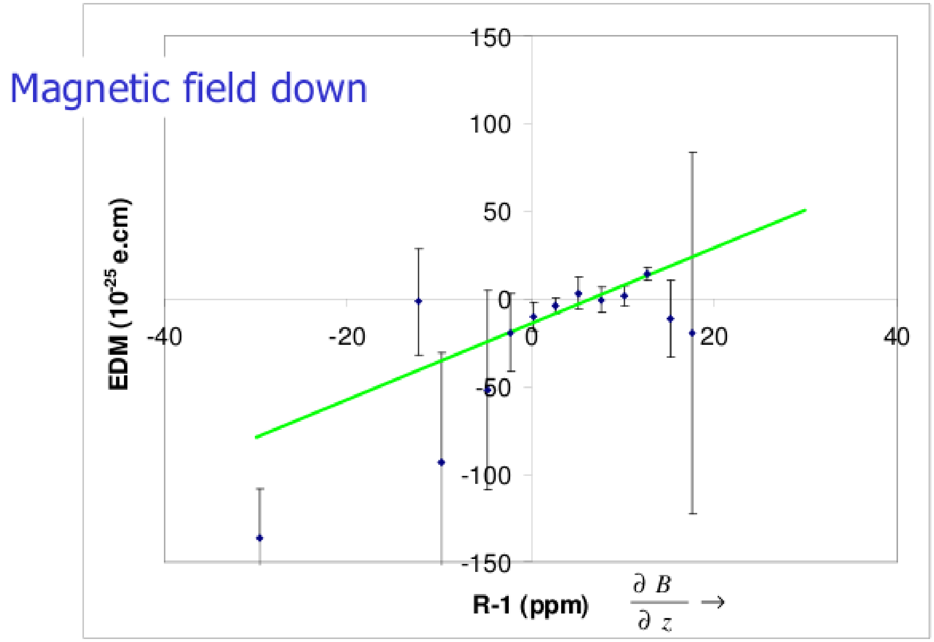
n-EDM Systematics

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

(co)magnetometry



comagnetometry

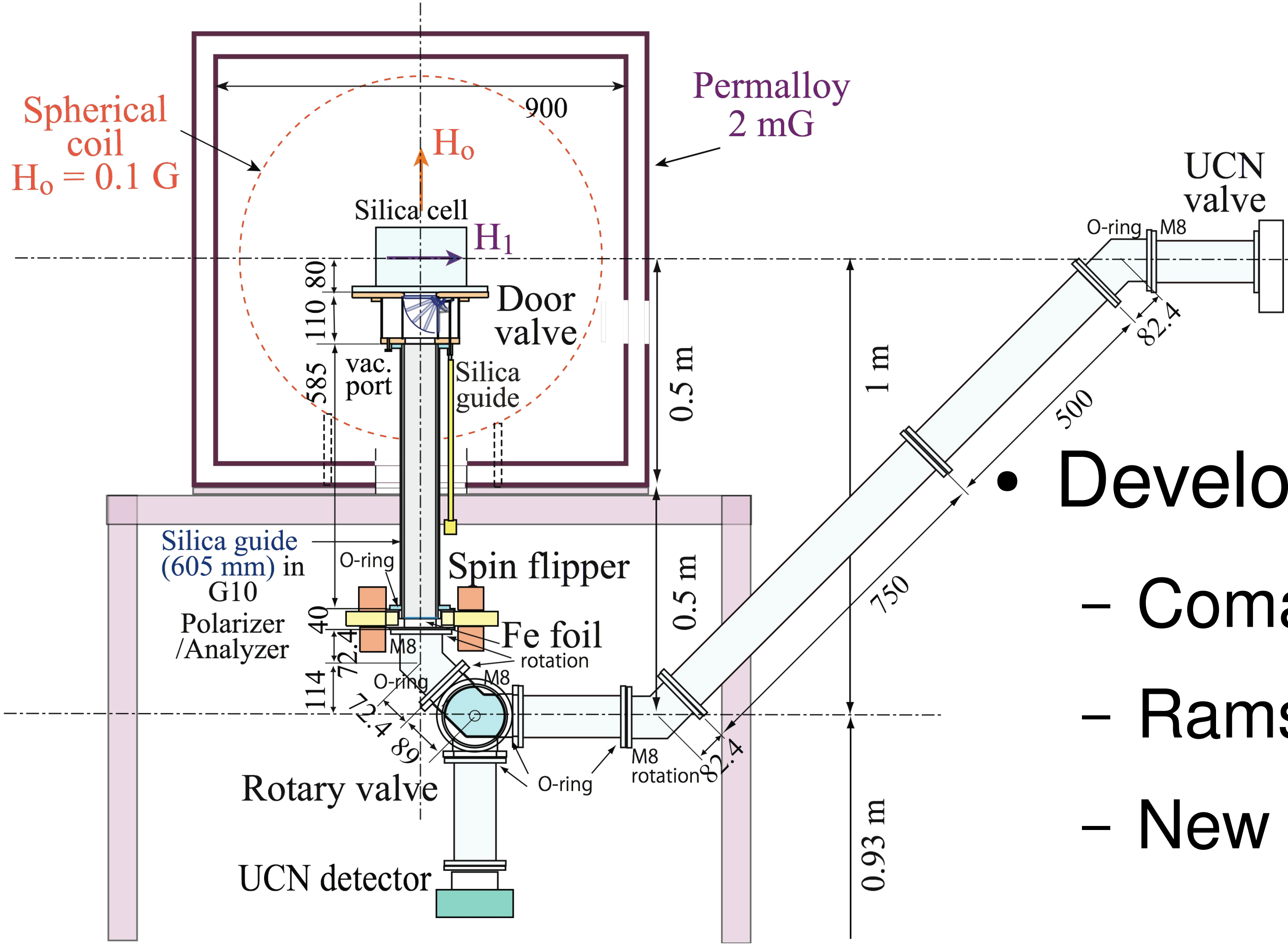


false EDM (GP) effect

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

n-EDM Experiment at RCNP



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

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

Seeking PAC approval on Monday.

Plans for TRIUMF

- 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)

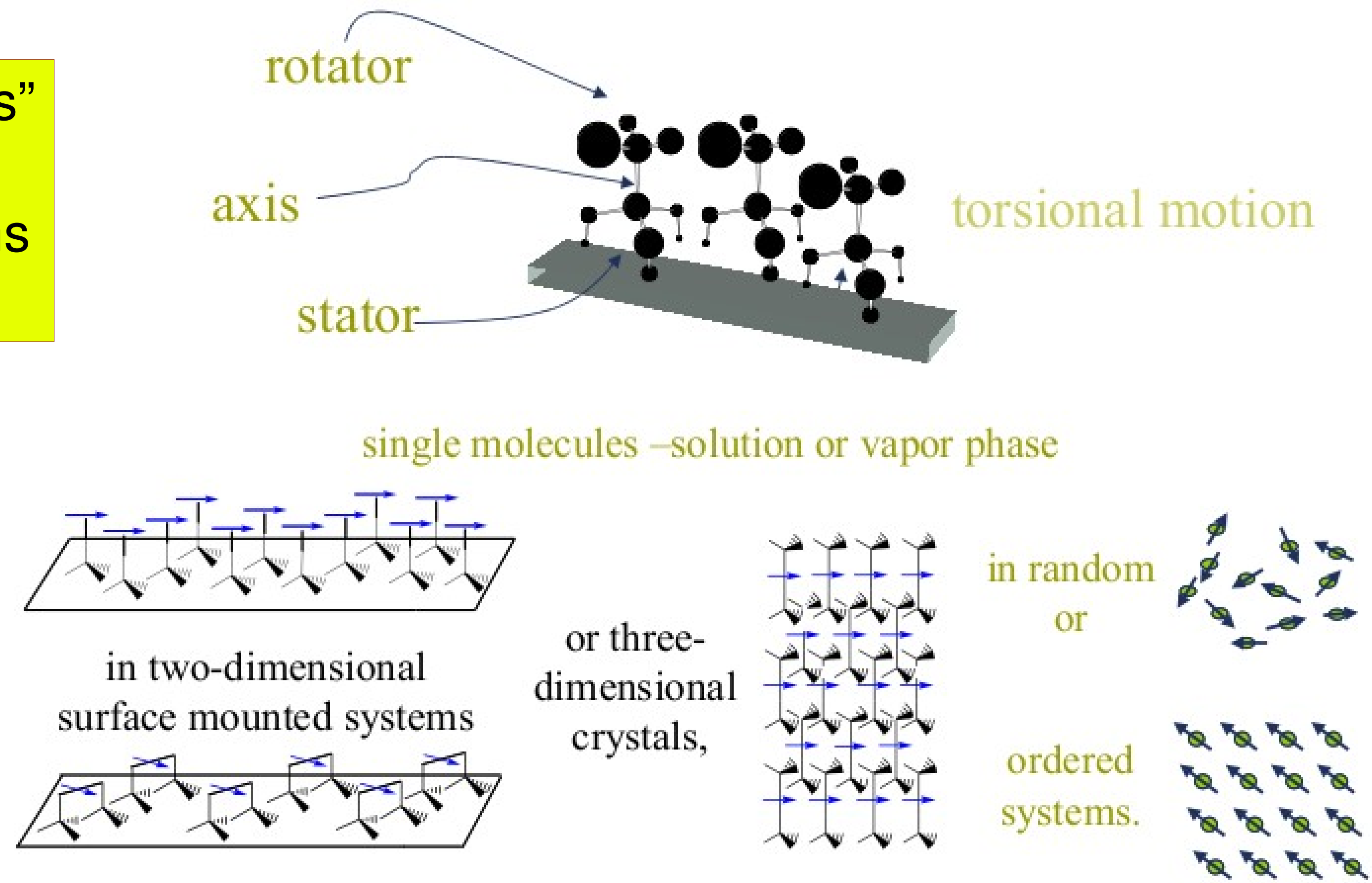
Involvement from more Japanese collaborators in this exciting experiment is very welcome!

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.

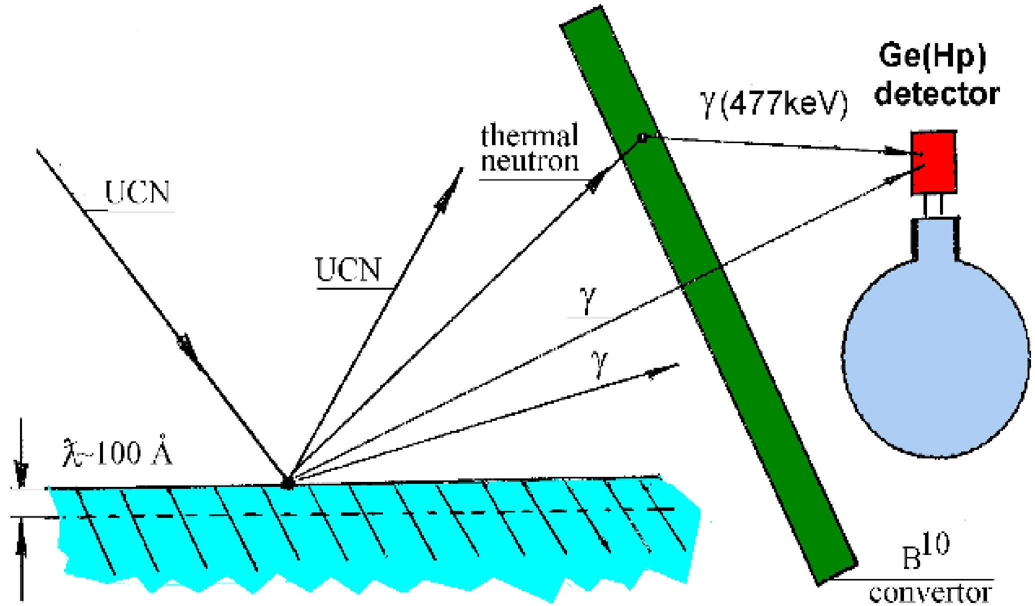
Application of UCN ISR: Artificial Molecular Rotors

"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 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
- 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

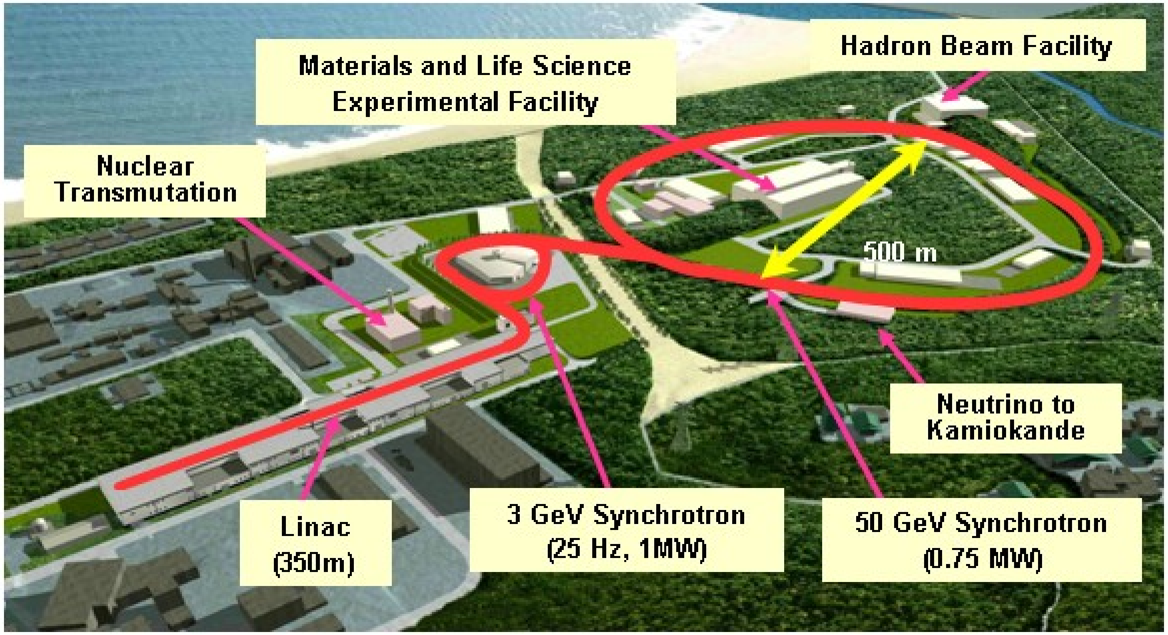
Budget Summary

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 + Acsion Industries
Total	$10.9M	

- UCN cryostat system includes:
  - Existing UCN source ($2M)
  - Modifications to source for TRIUMF ($2M)
    - Horizontal extraction, improved guide technology, etc.
- Canadian money for physics experiments:
  - separate budget from NSERC.

Beyond Canada

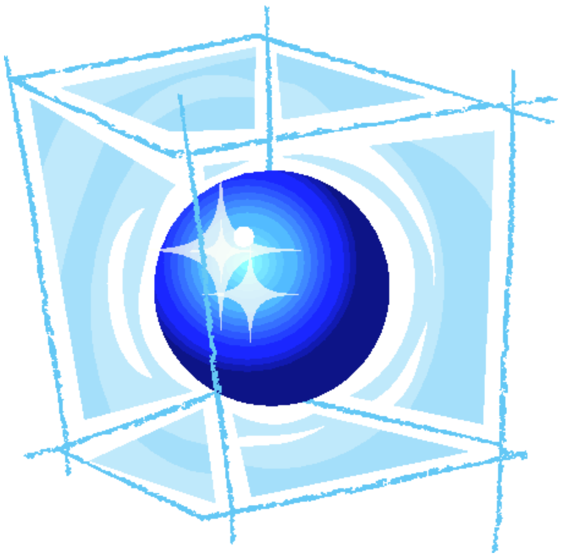
- Scaling by beam power, JPARC (1 MW) could achieve an additional factor of 50 over TRIUMF, or 2,500,000 UCN/cc.



- This could make experiments like searches for nnbar oscillations, and the dream of a free neutron target, a reality.
- Work at TRIUMF 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

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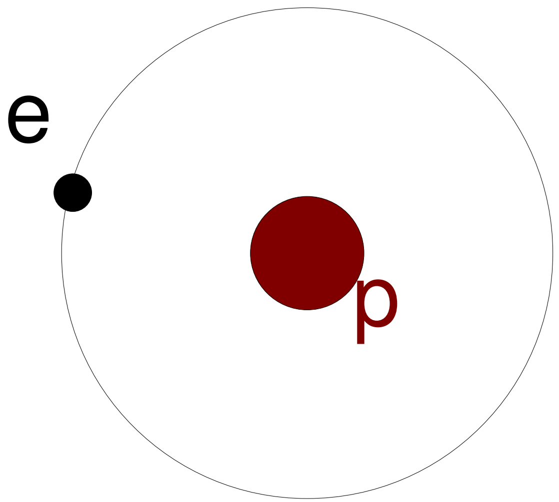
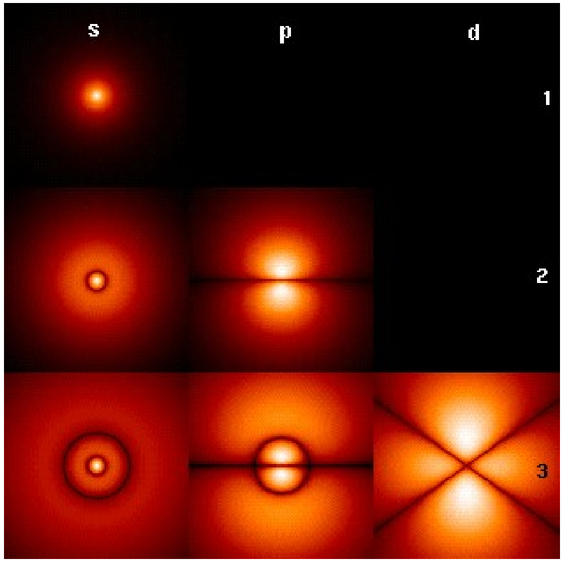
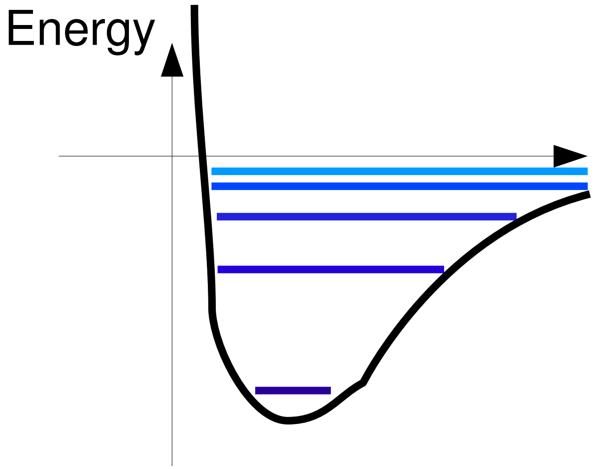
Quantum Physics

- 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)

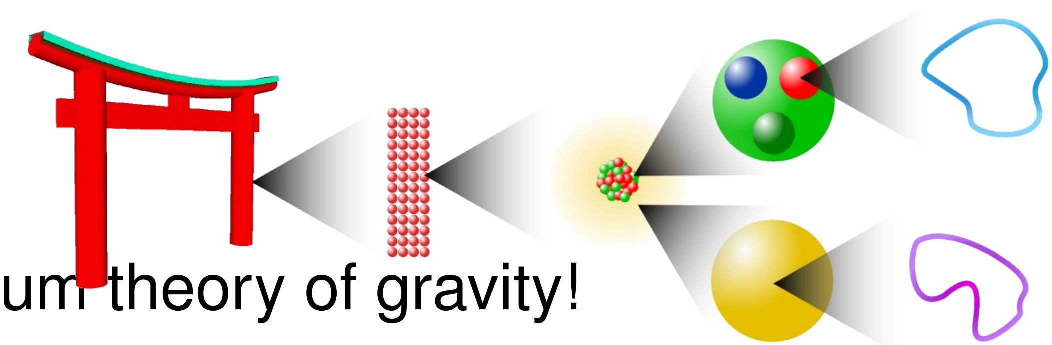




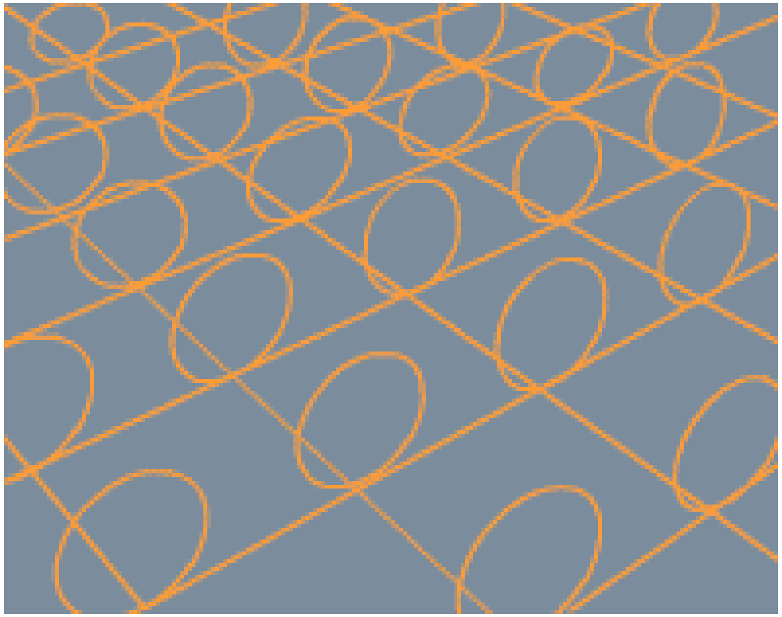


Quantum Physics and Gravity: They Don't Work Well Together

- 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



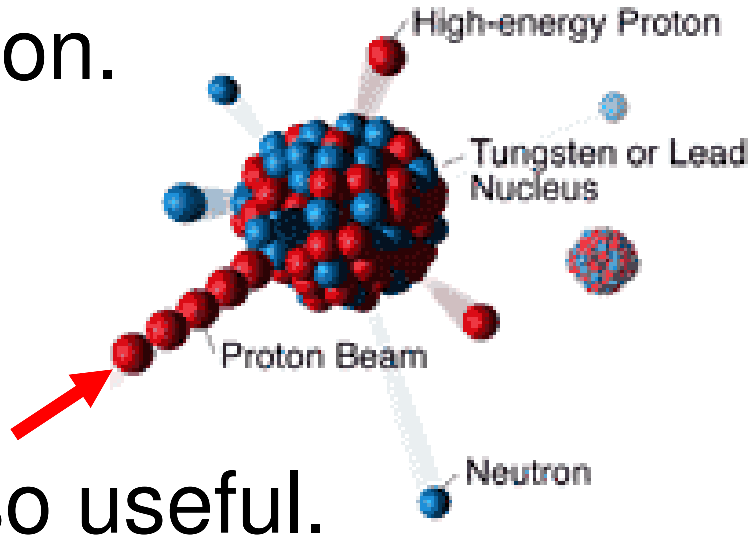
Extra Dimensions?



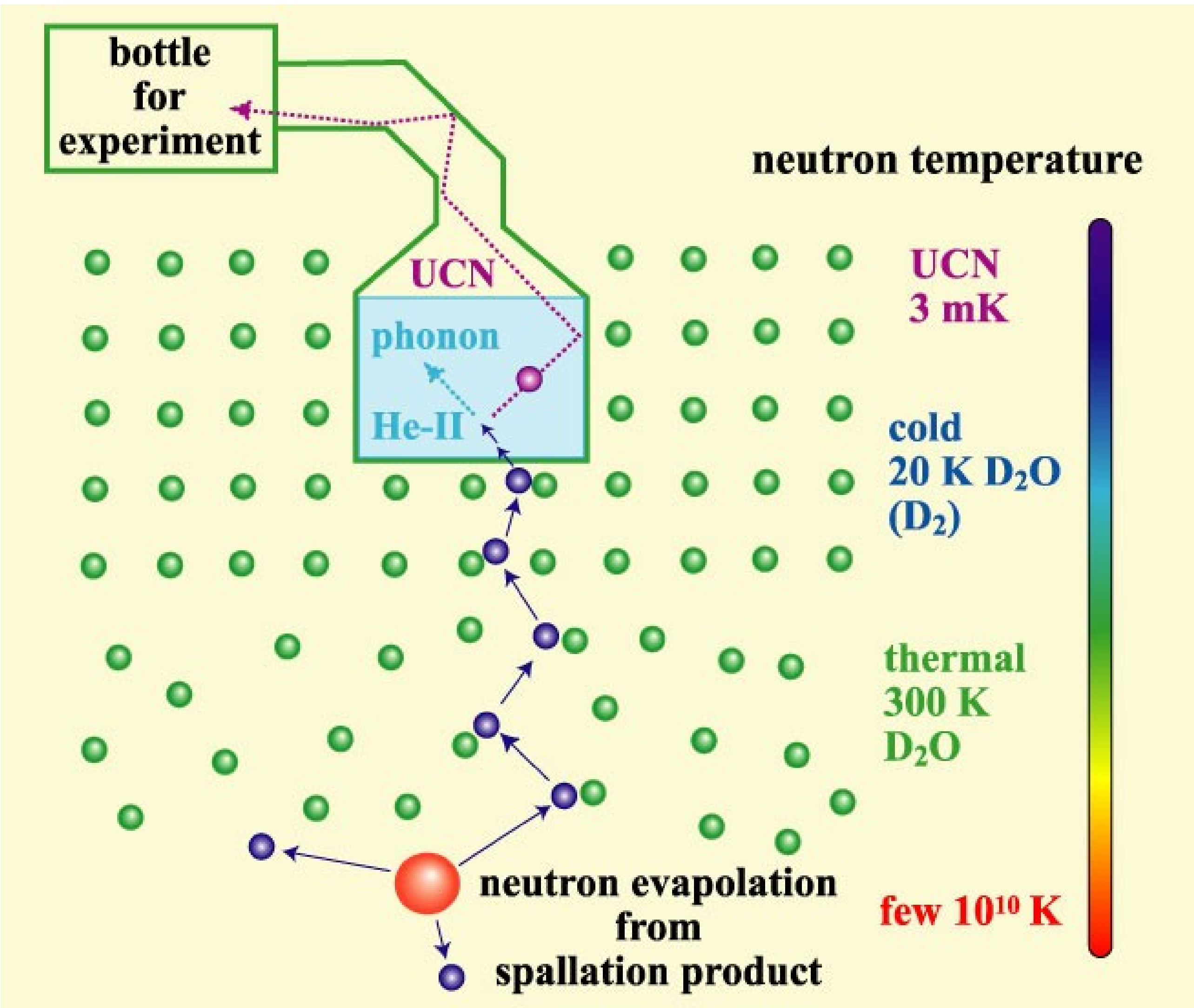
- One “prediction” of string theory is extra dimensions.
- If they exist, where are they?
- Clever theorists have suggested that maybe they are “curled up” or “compactified”.
- These curled up dimensions would modify gravity at scales below the size of the curling.
- If gravity is modified at these scales,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

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”).