Search for Neutron-Antineutron Oscillation

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Antineutron

Anti-neutron discovered in 1956

Exactly same gravitational/inertial mass as a neutron.

Magnetic and electric dipole moments different from a neutron.

Why there would be oscillation between a neutron and an anti-neutron?

Particle and Anti-particle are considered eigenstates of
a mass matrix.

$$\begin{pmatrix} m & 0 \\ 0 & m \end{pmatrix}\begin{pmatrix} n \\ \overline{n} \end{pmatrix} = m\begin{pmatrix} n \\ \overline{n} \end{pmatrix}$$

From time dependent Schrodinger equation

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} n \\ \overline{n} \end{pmatrix} = \begin{pmatrix} m & 0 \\ 0 & m \end{pmatrix}\begin{pmatrix} n \\ \overline{n} \end{pmatrix}$$

Plane wave solution. Population of particle, anti-particle should
not change with time.

In the presence of external interaction, the mass
matrix would be modified.

Time dependent Schrodinger equation would look like

$$i\hbar \frac{\partial}{\partial t}\begin{pmatrix} n \\ \bar{n} \end{pmatrix} = \begin{pmatrix} m+A & 0 \\ 0 & m-A \end{pmatrix}\begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$

Still no particle to anti-particle transition

$$\langle n | \bar{n} \rangle = 0$$

Particle-antiparticle transition is possible only if there are
Off-diagonal terms in the mass matrix.

Time dependent Schrodinger equation should look like

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} n \\ \bar{n} \end{pmatrix} = \begin{pmatrix} E_n & \delta m \\ \delta m & E_{\bar{n}} \end{pmatrix}\begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$

CPT invariance demands that the off-diagonal terms must be
The same.

Let us assume En =Enbar = m (no external field)

Then we get

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix} n \\ \bar{n} \end{pmatrix} = \begin{pmatrix} m & \delta m \\ \delta m & m \end{pmatrix}\begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$

In this case $\langle n | \bar{n} \rangle = \delta m$

There is a small probability for particle to anti-particle transition.

However charge conservation has to be respected.

No transition for electron to positron or proton to antiproton.

δm =0 for such cases.

GUT (electro-weak+strong interaction) allows for baryon

Neutron-antineutron oscillation possible because of such non-zero off-diagonal terms δm in the neutron mass matrix.

Physical states

$$\left| n_{\pm} \right\rangle = \left(\alpha \left| n \right\rangle \pm \beta \left| \bar{n} \right\rangle \right)$$

With masses (m± δm)

Probability for neutron to antineutron transition

$$P_{n \to \bar{n}} = \sin^2 (\delta m) t$$

Oscillation time period

$$\tau = \frac{h}{\delta m}$$

In an external field, let En and Enbar are the energies of the particle and anti-particle. Let ΔE= En-Enbar, then the probability of transition from particle to anti-particle is given by

$$P_{n\to\bar{n}}(t) = \frac{4(\delta m)^2}{(\Delta E)^2 + 4(\delta m)^2} \sin^2\left(\sqrt{(\Delta E)^2 + 4(\delta m)^2}\, t\right)$$

For δm<<ΔE, we get

$$P_{n\to\bar{n}}(t) \approx \left(\frac{\delta m}{\Delta E}\right)^2 \sin^2(\Delta E t)$$

$$\Delta E.t << 1,$$

Free n to nbar transition

$$P_{n\to\bar{n}}(t) \approx (\delta m.t)^2$$

$$\Delta E.t >> 1$$

Bound neutrons in a nucleus

$$P_{n\to\bar{n}}(t) \approx \left(\frac{\delta m}{\Delta E}\right)^2$$

Transition inhibited

Expt using free neutrons

$$\tau \geq 10^{8}\,\mathrm{sec}$$

$$\delta m \leq 6\times 10^{-33}\,GeV$$

Bound neutrons in a nucleus, ΔE□ 100 MeV

$$\tau_{nucleus} \approx 10^{34}\,years$$

Considering detailed nuclear physics effects

$$\tau_{nucleus} \approx 10^{32} years$$

Model dependent

From large solar neutrino experiments (SNO, Super-K etc.)

Stability of 16O known up to

$$\tau_{16O} \geq 1.77 \times 10^{32}\, years$$

Impli
es

$$\tau_{n \to \bar{n}} \geq 2.3 \times 10^{8}\,\mathrm{sec}$$

Nuclear model dependent number

Limit on stability of matter cannot be improved much from those
experiments due to irreducible atmospheric neutrino background

Free neutron experiments required

Experiment with free neutrons to search for neutron-antineutron oscillation

Very simple basic idea

Allow neutrons to pass through vacuum shielded from all possible
External interactions.

Watch for neutrons to be converted to anti-neutrons which will
Annihilate by striking a detector and produce 4 -5 pions in coincidence.

Average kinetic Energy of each pion about 250-300 MeV.

Easy to detect. Background signal level should be very low because of

Difficulties of the experiment

Very good shielding from external interactions . Earth’s magnetic field (0.5 Gauss) has to be shielded very well

By μ-metal shield.

Even due to the earth’s magnetic field, the difference in the

Interaction energy of neutron and anti-neutron is $\Delta E \approx 3\times10^{-21} GeV$

Ou r $\delta m \le$ GeV

So (n to nbar transition) would be inhibited very strongly in Earth’s magnetic field.

Reduce magnetic field < nano-Gauss level.

Use cold/ultracold neutrons.

Why

Speed of a neutron with 1 MeV kinetic energy $\approx 1.4\times 10^{7}\, meters/\sec$

Put neutrons in a box of dimension 10 meters.

A neutron with 1 MeV kinetic energy will strike the other end of the container in a micro-second.

Initial state $(\alpha|n\rangle \pm \beta|\overline{n}\rangle)$

After striking the wall, it will collapse to either |n> or |nbar> state.

Starting with neutrons, after a micro-second, they will essentially remain neutrons.

Slow down neutron speed to 6-8 meters/sec. They will strike the wall every second. Watch for transitions in a second with a large number of neutrons. Requires ultra-cold neutrons

Trapping of neutrons

Trapping of charged particles requires a electromagnetic
field (Penning or Paul trap).

Neutrons can be trapped magnetically.

However ultra-cold neutrons can be trapped by reflection also.

Usually neutrons pass through material without reflection.

E. Fermi and Zeldovich realized that the coherent scattering
of very slow neutrons (wavelength >> many lattice lengths;
500 Angstrom) would result in an effective potential for
Neutrons travelling through matter.

Production of cold/ultra-cold neutrons

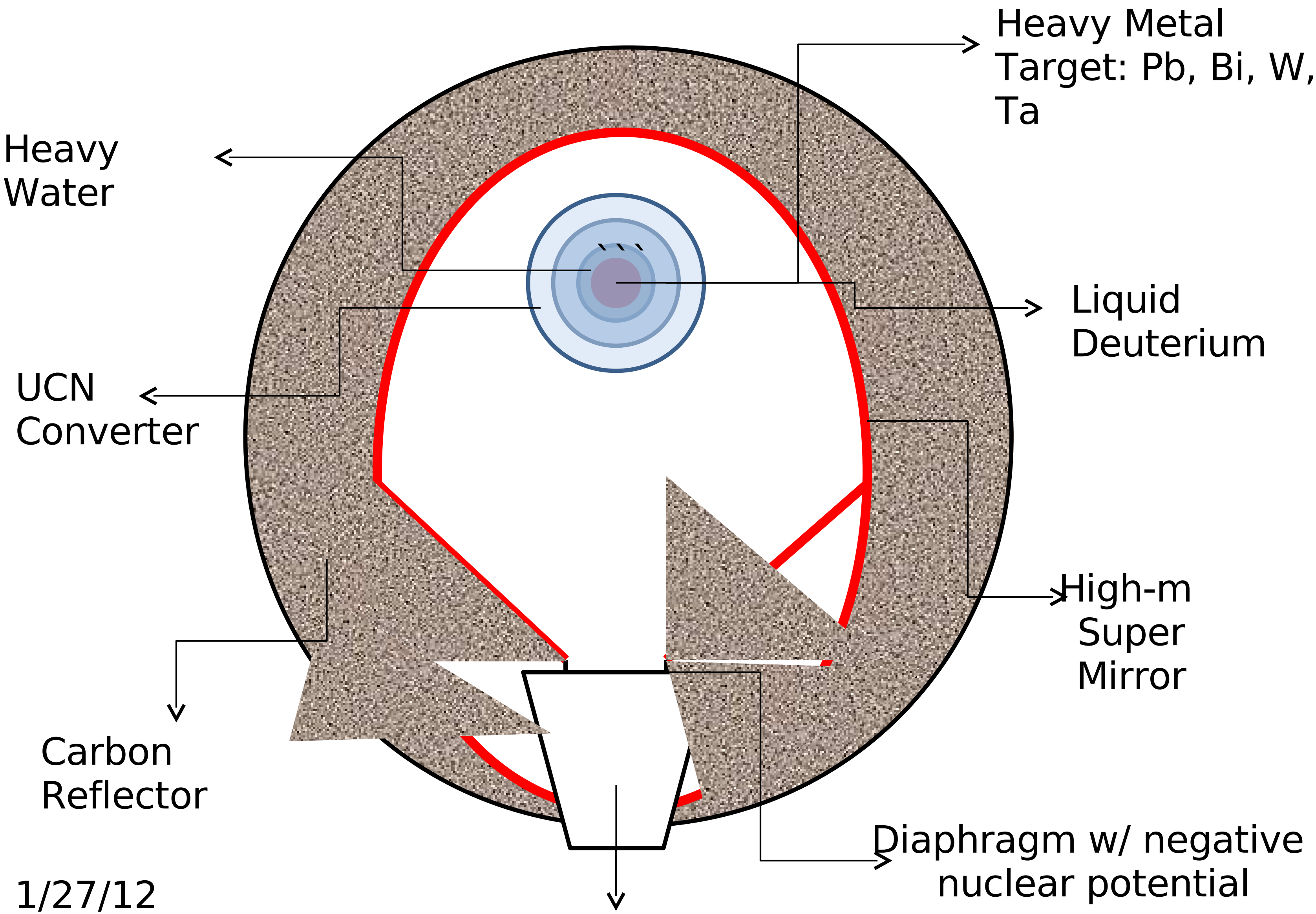
High intensity proton/electron beam strikes a target to produce
neutrons.

Target surrounded by room temperature heavy water moderator to
make the neutrons thermal.

In the next layer, it is surrounded by liquid D2 (20 K)
(cold neutrons)
and then by solid D2 (8 K) to produce ultra-cold neutrons.

Cold/ultra-cold neutrons reflected by metal reflector and a
Parallel beam is made.

Schematic of spallation target with UCN converter (view along the beam)



Present Status

Neutron-antineutron oscillation time period 2×10^{8} sec

ILL experiment and stability of matter studies

Future studies

Using strong neutron source

Problems with reactor-based neutron source

Need > 20 MW research reactor and close access to reactor core.

Future possibility

Intense cold neutron source

Sensitivity of cold neutron experiments can be increased by a factor ~ 1000.

Using existing cold neutron technology
Recent Improvements in neutron optics
Longer observation time > 3 years.
Large scale experiment

Neutron-antineutron oscillation

If Discovered

This will violate (B-L) by 2 units.
Establish a new force of nature.
Illuminate beyond Standard Model
Matter-antimatter asymmetry

If Not Discovered

New limit on the stability of matter > 10^{35} years

In combination with LHC results, can eliminate many
Possible B- violating models below elctro-weak
phase transition

Possibilities in India

Experiment might be done in several stages

First stage

Get a moderately strong neutron source $\approx 10^{12}\text{-}10^{14}\, neutrons/\sec$ intensity

Pass through heavy water and liquid D2 moderators to produce
Cold neutrons and then ultra-cold neutrons by using solid D2.

Cold/ultra-cold neutrons useful for condensed matter research.

Used for imaging.

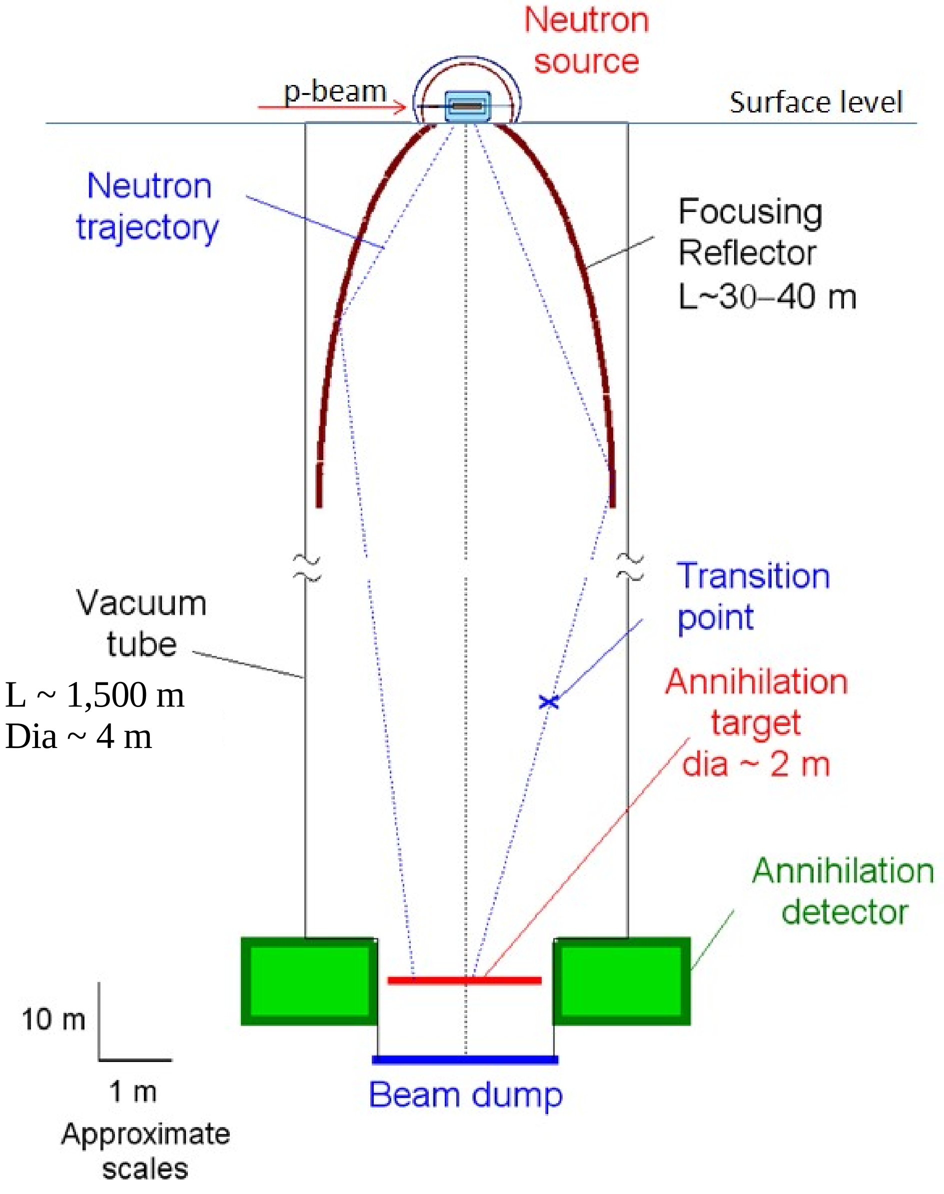
In future, the experiment could be done elsewhere in
India using a spallation neutron source.

Intensity $\approx 10^{17}$ neutrons/sec

With a long vertical flight path using cold neutrons.

Conceptual sketch

Schematic view of the vertical NNbar experiment



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Thank you for your attention

Possible connection between neutrino mass and neutron-antineutron oscillation

Proton decay

$$p \rightarrow e^{+} + \pi^{0}$$

Violets both B and L number conservation.
Conserves (B-L)

Neutrinoless double beta decay

$$A_Z \rightarrow A_{Z+2} + 2e^{-}$$

Violets (B-L)

Violets L by 2 units

Neutron-antineutron oscillation

$$n \rightarrow \overline{n}$$

Violets (B-L)

Violets B by 2 units

In standard model,

Neither B nor L are good symmetry.

(B-L) considered conserved in SM

Neutrino mass=0 in standard model

Scale of (B-L) symmetry breaking believed to be associated
With the origin of neutrino mass.

In some models, neutron-antineutron oscillation
related to the neutrino mass.

There are models that use Neutron-Antineutron oscillation to explain the observed mass symmetry (more matter than antimatter)
in the Universe today.

As a result of big bang, equal amount of matter and anti-matter created.

At high temperature, in equilibrium,

$$\Gamma(n \rightarrow \overline{n}) = \Gamma(\overline{n} \rightarrow n)$$

CPT invariance

As the universe started expanding and cooling, it was in non-equilibrium
condition.

Matter-antimatter asymmetry probably developed as the universe
Started expanding and cooling and was in non-equilibrium condition.

A Model to explain matter-antimatter asymmetry

Postulate (n to nbar transition) through heavy intermediate particles
S1 and S2 (More than one mass hierarchy).

Let M(S2)>M(S1).

In equilibrium, T>M(S2), due to CPT invariance

$$\Gamma(n \rightarrow S1 \& S2 \rightarrow \bar{n}) = \Gamma(\bar{n} \rightarrow S1 \& S2 \rightarrow n)$$

However, in general,

$$\Gamma(n \rightarrow S1 \rightarrow \bar{n}) \neq \Gamma(\bar{n} \rightarrow S1 \rightarrow n)$$

So for M(S1)<T<M(S2), transition through S2 not allowed for
Phase-space reason. Then transition through S1 only took place
Causing baryon asymmetry

UCN Energy Scales

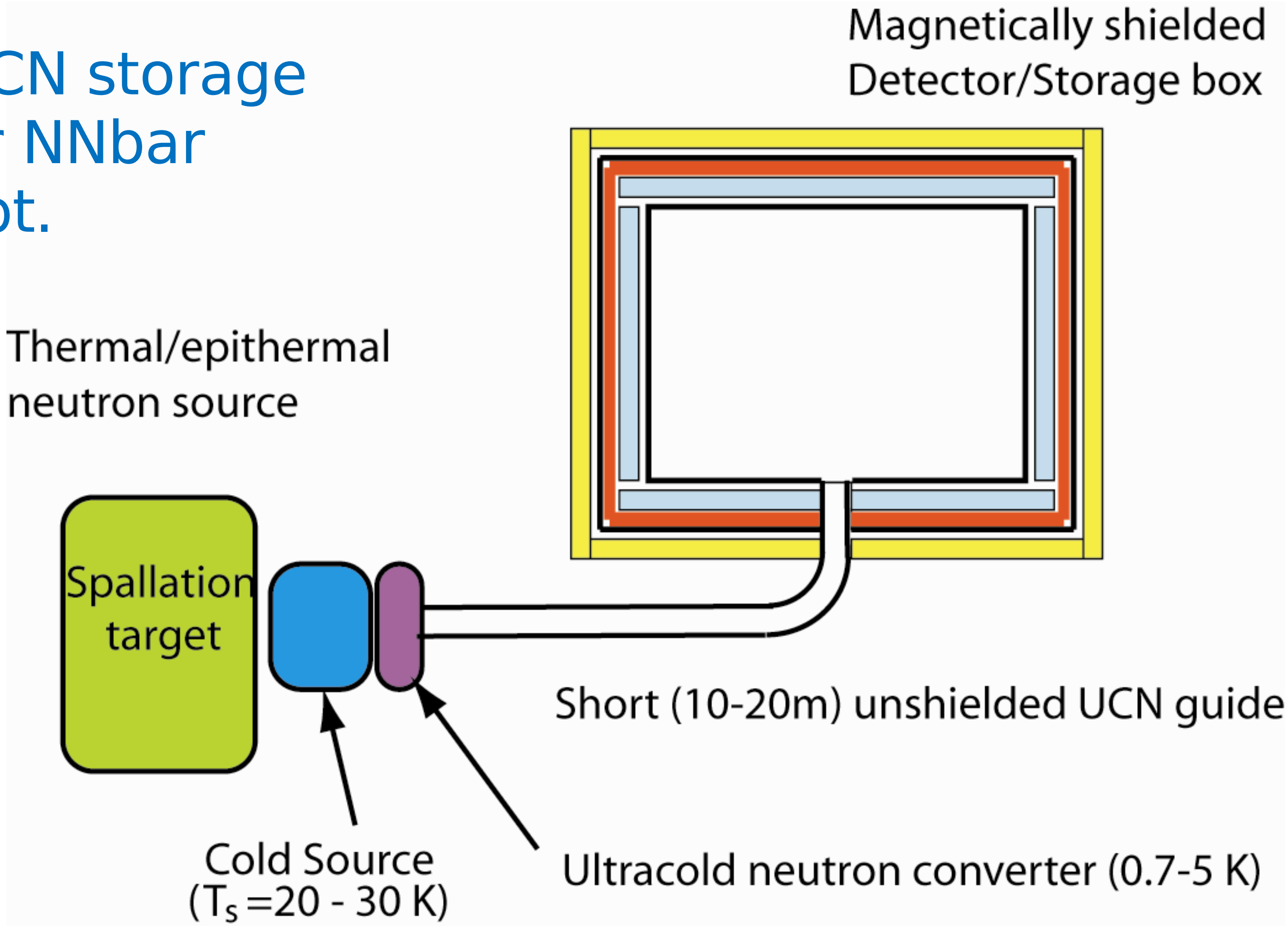
Energy of UCN moving 8 m/sec: 340 neV (nano-eV)
3.6 mK

Energy of UCN in 1T magnetic field: 60 neV

Energy change associated with a 1 m rise: 104 neV

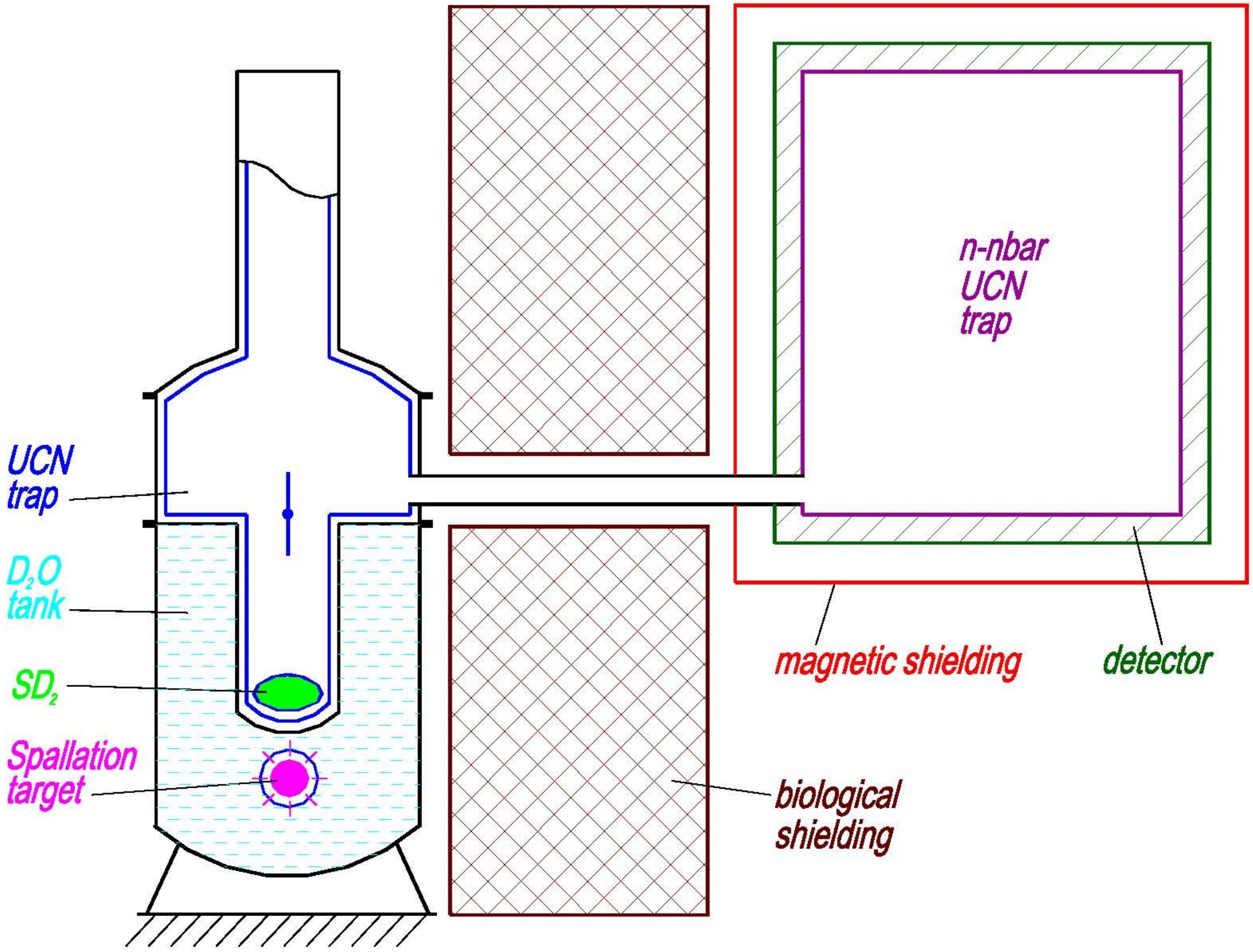
→ implications for optimized design of N-Nbar…
UCN can be polarized and stored using magnetic fields
Typical UCN can bounce no higher than about 3m!

UCN storage for NNbar expt.



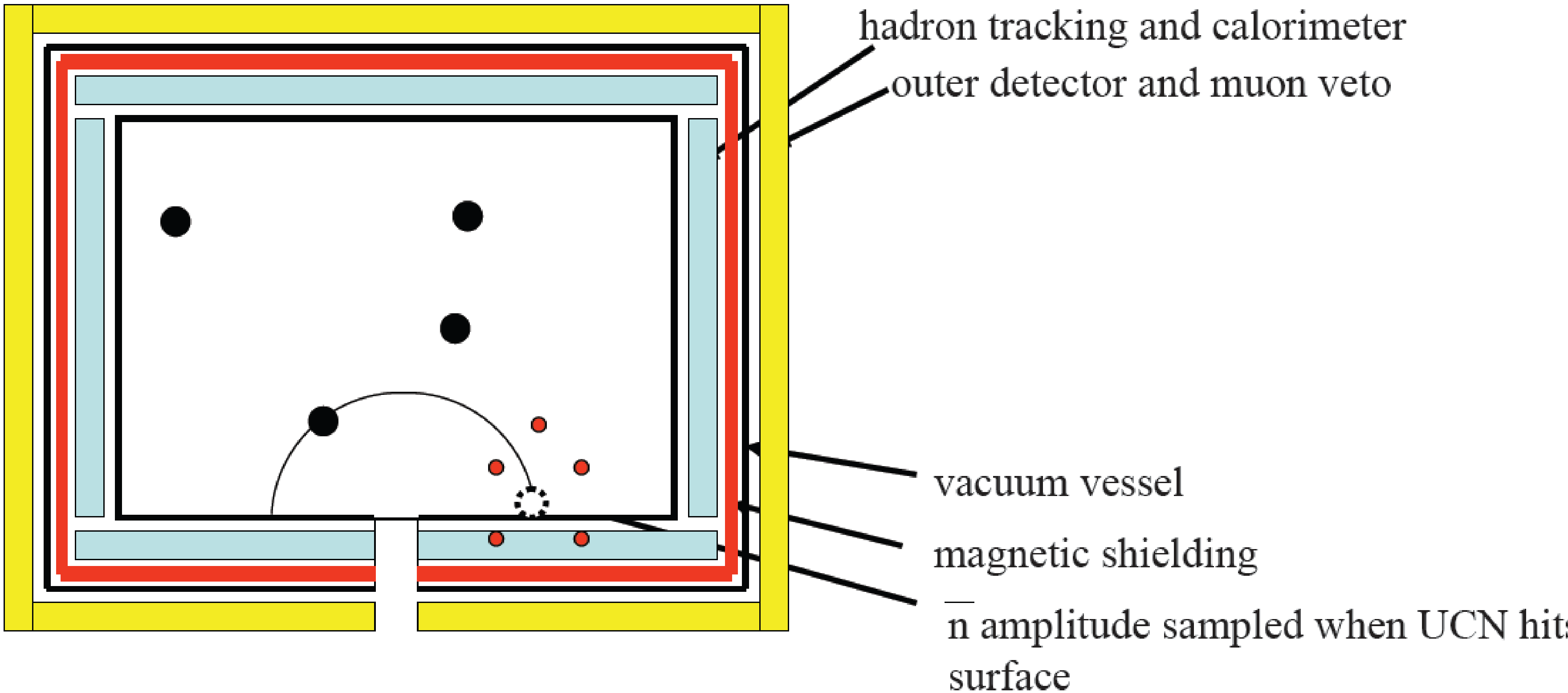
Spallation neutrons are produced in 4□ but used for ucn conversion only in
a small fraction of a solid angle.
In best A. Young's (NCSU) scenario with dedicated 1.9K, 200 kW source:
3.3□108 ucn/s can be made available in the transport tube.

Systematic studies of the PSI UCN source optimized for NNbar by A. Serebrov and V. Fomin



Mode of operation: beam pulsed w/ valve open, then valve closed and UCN stored in system (can, in principle, accumulate)

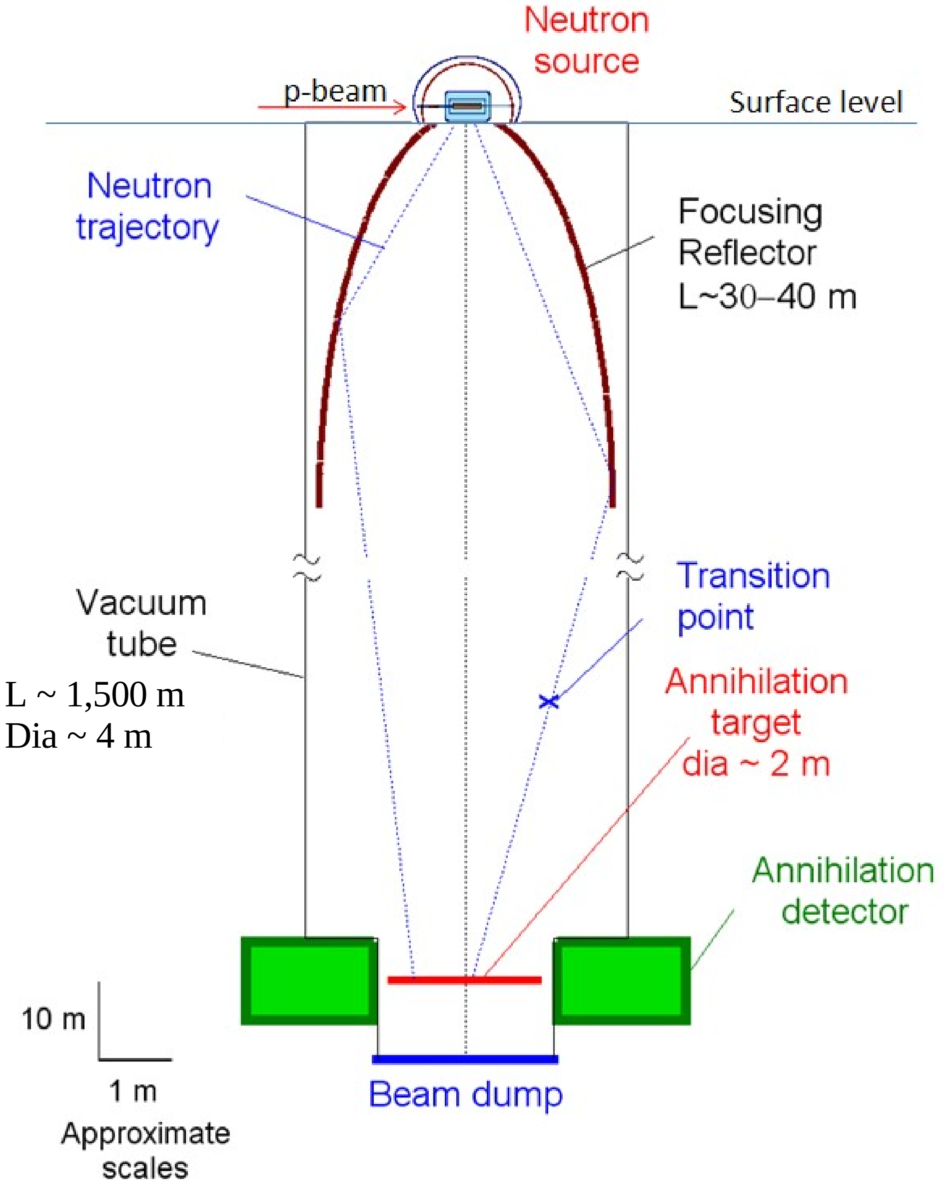
NNbar with UCN



Box filled with UCN gas…many samples/neutron
longer average flight times (~1/3 sec)
large neutron current required

Albert

Schematic view of the vertical NNbar experiment at DUSEL with spallation neutron source
provided by dedicated high-current accelerator, e.g. by a CW cyclotron 0.2 – 1 MW proposed by DAE�ALUS Collaboration



The conceptual scheme
of antineutron detector

$\bar{n} + C$ □ $\langle 5p \rangle$