Neutron – antineutron oscillation

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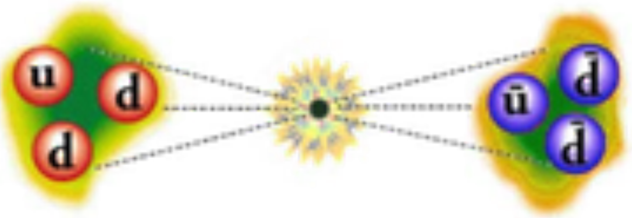
What is neutron – antineutron oscillation?

- Neutron – antineutron oscillation is exactly what the name would insinuates, a neutron turning into an antineutron



$$n \longrightarrow \bar{n}$$

- Observation of electrically neutral particles into other species are no longer a surprising phenomenon in particle physics
    - Ex. Neutrino and neutral meson oscillations

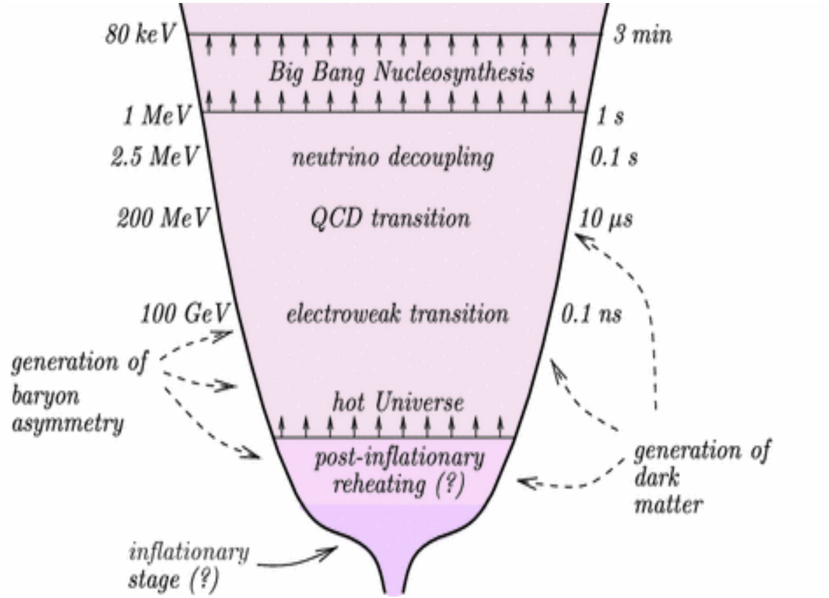
- Only conservation of baryon number forbids a neutron from transforming to an anti-neutron
    - This conservation law does not follow from any known physical principle but is inferred from experiment.

Why is it important?

- Simple answer: baryon asymmetry
  - Observe more matter than anti-matter in the universe

- To produce matter and antimatter at different rates, a set of three necessary conditions that a baryon-generating interaction must satisfy (Sakharov conditions):
  - Baryon number B violation
  - C-symmetry and CP-symmetry violation
  - Interactions out of thermal equilibrium

- However there are a number of other reasons to study $n - \bar{n}$ oscillations including:
  - Majorana neutrinos
  - Baryogenesis mechanisms
  - Theory independent



$n - \bar{n}$ transition probability

- The time evolution of a system in which a neutron state can transform into an antineutron follows:

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

- where δm is the $n - \bar{n}$ mixing rate of the process that violates baryon number conservation
- From this you can extract the antineutron transition probability using the boundary conditions that at time zero $P_n(0) = 1$ and and $P_{\bar{n}}(0) = 0$

$$P_{\bar{n}}(t) = \left(\frac{t}{\tau_{n-\bar{n}}}\right)^2 \quad \text{where} \quad \tau_{n-\bar{n}} = \frac{1}{|\delta m|}$$

oscillation lifetime

$n-\bar{n}$ transition probability (II)

- $n-\bar{n}$ oscillation can occur in two different settings:
  - **Free**: neutron propagates while not being bound within and a nucleus
  - **Bound**: Neutron propagates while bound in a nucleus

- These two settings have different transition probabilities because there is a suppression factor within the nucleus which affects the oscillation lifetime
  - Situation complicated by neighboring nucleons

- The suppressed oscillation lifetime in the nuclei and the free oscillation lifetime are then related by:

$$\tau_{nucl} = R \times (\tau_{n-\bar{n}})^2$$

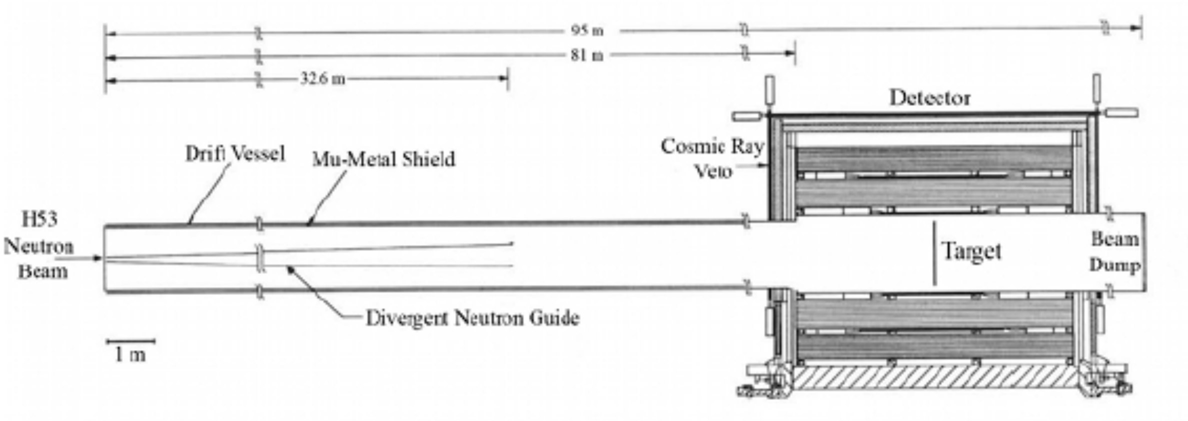
- where R is a nucleus dependent suppression factor (order of $10^{22\text{-}23}$ sec)

Experimental methods

- Two methods for observing $n - \bar{n}$ oscillations:
  - Oscillations of a beam of neutrons against an annihilation target
  - Oscillations of neutrons to antineutrons in bound nuclei

Experimental methods

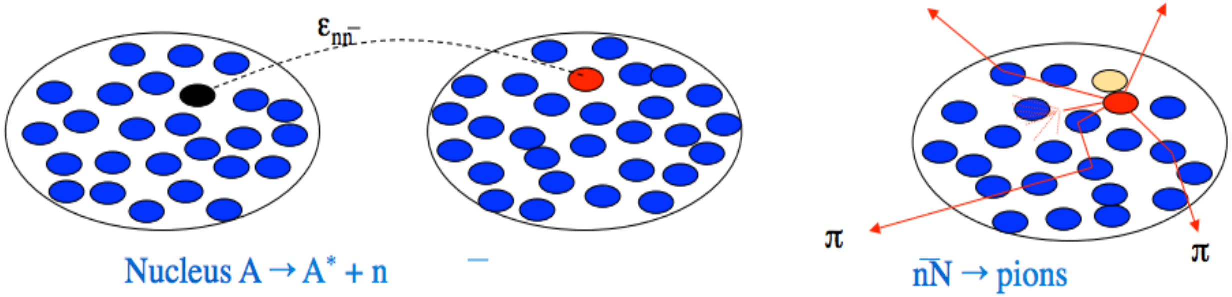
- Two methods for observing $n - \bar{n}$ oscillations:
  - **Oscillations of a beam of neutrons against an annihilation target**
    - Beam of slow neutron which propagate freely from the exit of a neutron optical guild to a distant antineutron annihilation target



  - Pros:
    - Robust background suppression
    - Control signal with magnetic field
    - Can achieve orders of magnitude improvement in sensitivity with updated technology
  - Cons:
    - Difficult to find source of neutrons tailored for this search
    - Small overlap with other neutron experiments

Experimental methods

- Two methods for observing $n - \bar{n}$ oscillations:
  - **Oscillations of neutrons to antineutrons in bound nuclei**
    - Look for spontaneous transition of neutron to antineutron in nuclei in large underground detectors which are mainly built for proton decay and neutrino oscillation studies
      - SNO, DUNE, etc.



$$T_{\text{intranuclear}} = \tau_{n\bar{n}}^2 R$$

Measurable in detector

Evaluated from nuclear models

- Pros:
  - Overlap with other proton and neutrino experiments
  - Large number of neutrons to help overcome suppression factor
- Cons:
  - Considerable backgrounds to account for (10-50%)

Previous search with free neutrons

- Current best limit performed at the Institut Laue-Langevin in Grenoble in the early 1990's

Ran for one year
Zero candidate events
Zero background events
$\tau_{n-\bar{n}} > 0.86{\times}10^{8} sec$

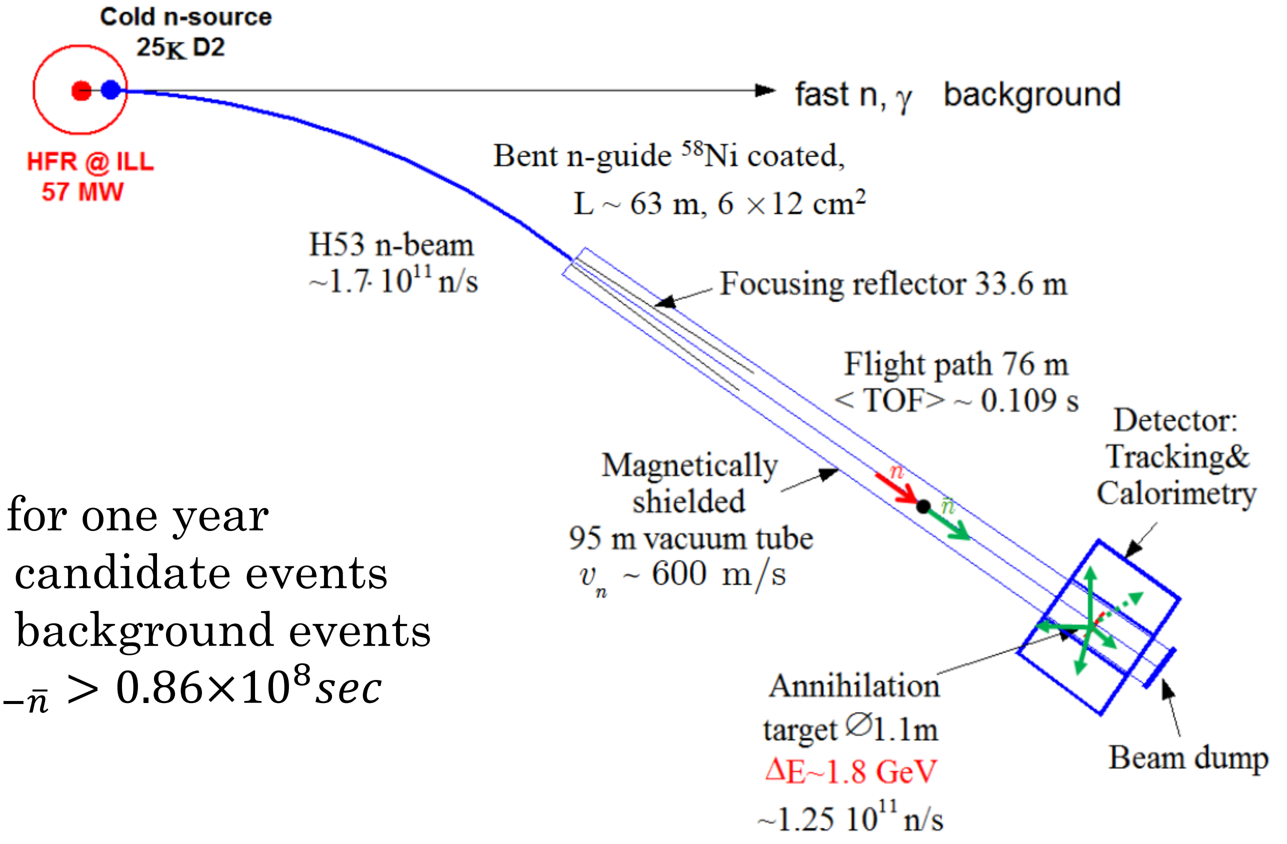
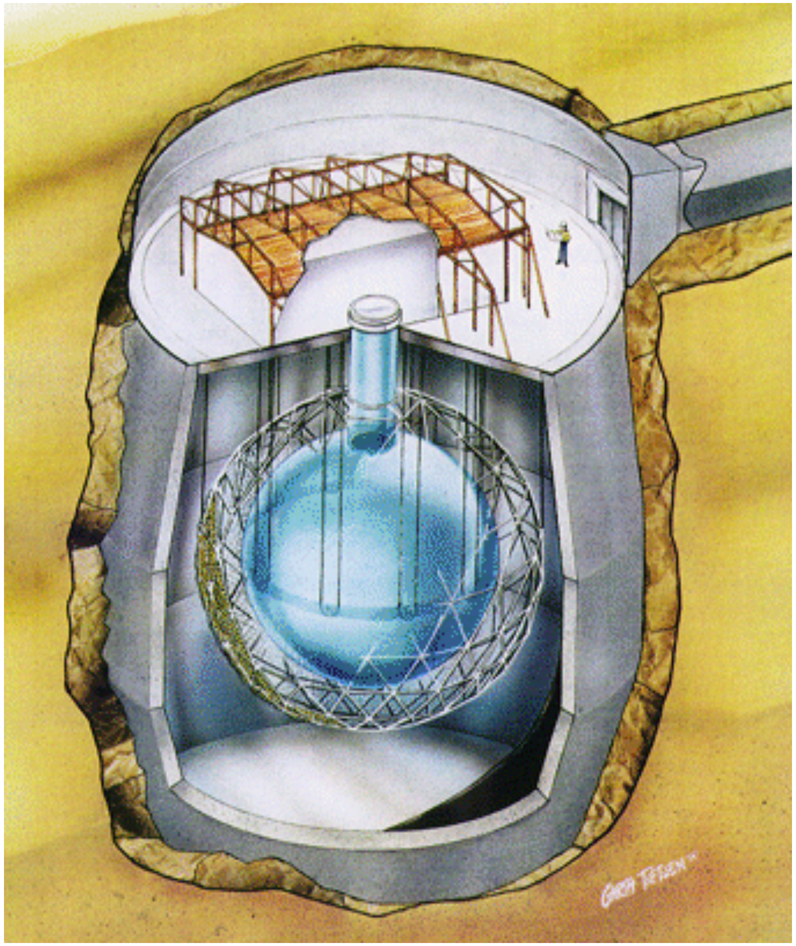


Figure 2: Configuration of the horizontal $n - \bar{n}$ search experiment at ILL/Grenoble [63].

SNO results with bound nuclei

- SNO (Sudbury Neutrino Observatory) was a heavy water (2H2O or D2O) Cherenkov imaging detector that was in operation from November 2, 1999 to November 28, 2006



- Deuteron is an intra-nuclear source for neutron – antineutron oscillations
  - Has lower suppression factor by factor of 4 compared with Oxygen
- Looking for signature of multi-prong events with multiple charged and neutral pions from nbar-p or nbar-n interactions

SNO results with bound nuclei (II)

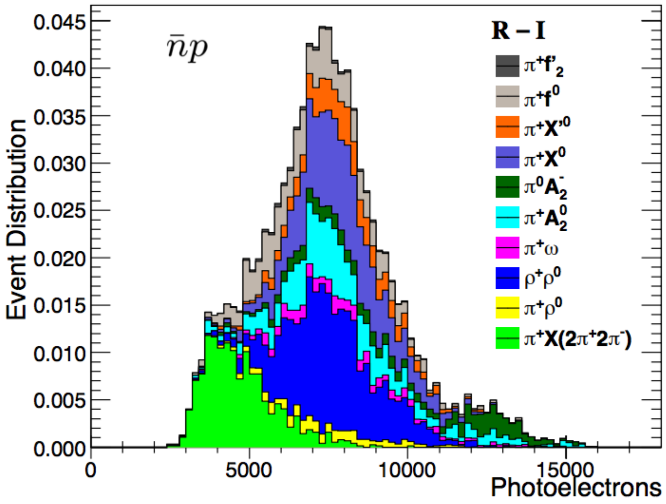
- **Momentum regime I (at rest)**

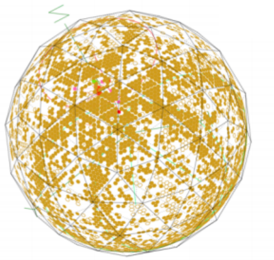
A study of channels of an antiproton colliding with a neutron near rest showed a majority of 2-body intermediate states*. These intermediate states can then decay into channels including multiple pions.

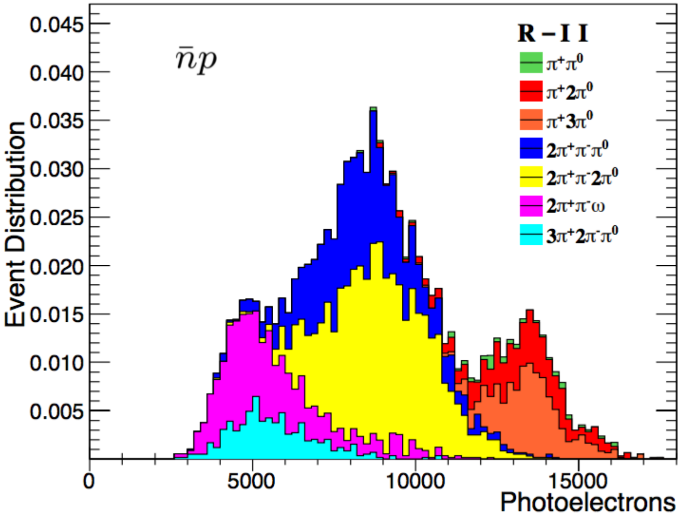
- **Momentum regime II (~ 250 MeV)** :

Alternative interaction channels [**] for n̄p annihilation have also been modeled using beam data of p̄n collisions at momenta comparable to the ^{16}O

Both models are investigated and **give similar results.** Weighted average of both is used in analysis







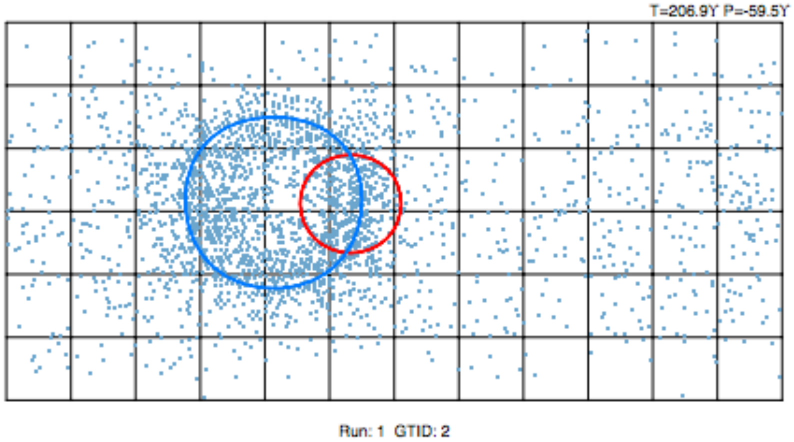
Multiple rings
Mainly pion final states

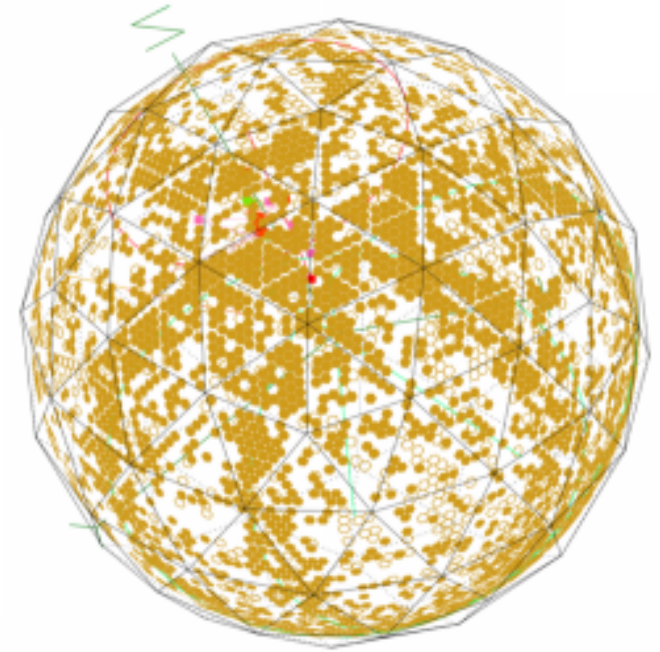
Energy Range
2,000 pe ~ 250 MeV
18,000 pe ~ 2.0 GeV

*R. Bridges et al., Phys. Rev. Lett. 56, 215 (1986)
**K. Abe et al., Phys. Rev. D 91, 072006 (2015)

SNO results with bound nuclei (III)

- They look for evidence of the pion decays by reconstructing rings left on detector

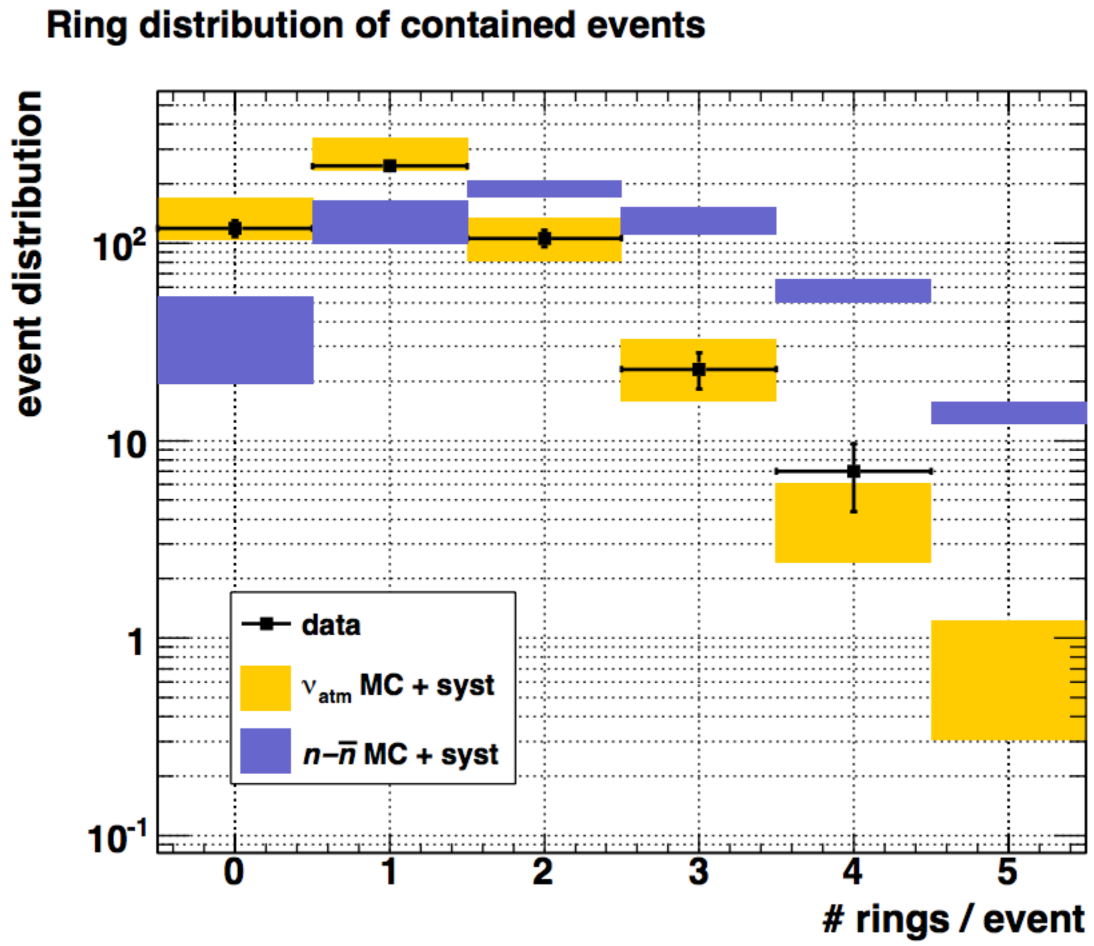




Simulation of a neutron-antineutron oscillation event in SNO

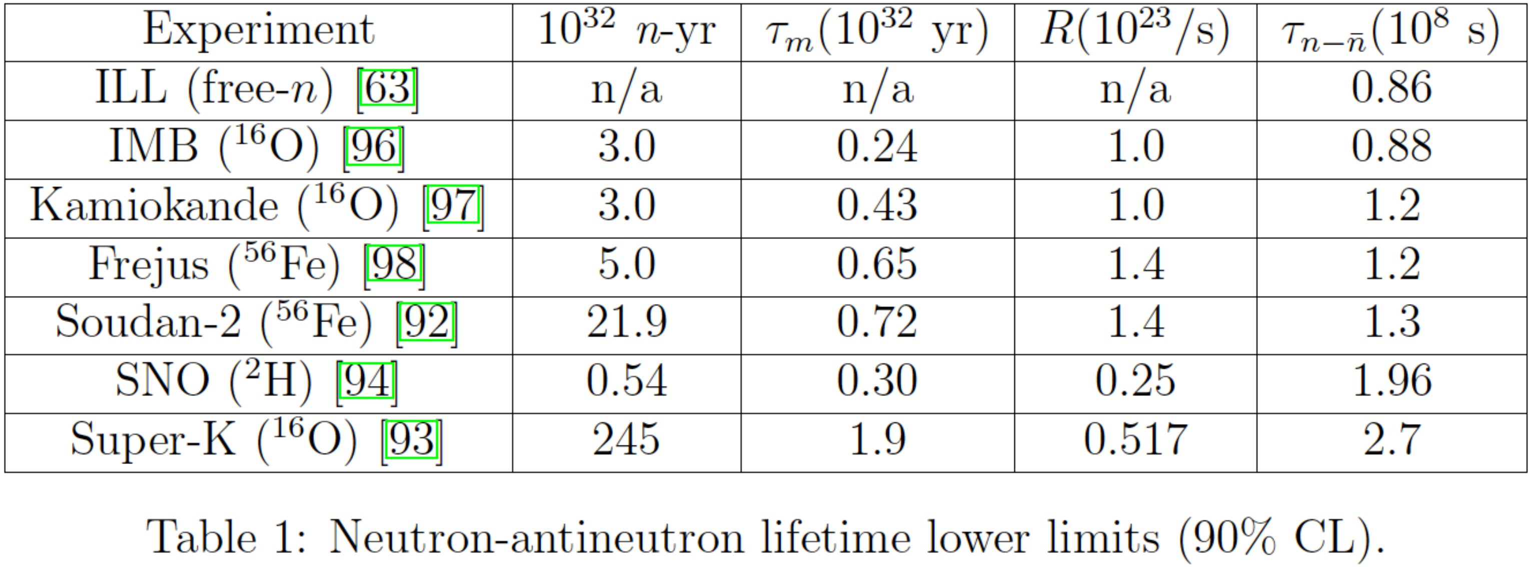
SNO results with bound nuclei (IV)

- Data events compared with MC simulations for signal and background are consistent with the background



Bound nuclei limits on oscillation lifetime

- A number of different experiments have set limits on the free neutron – antineutron oscillation lifetime using bound neutrons in nuclei



Experiment	10^{32} n-yr	$\tau_m(10^{32}$ yr)	$R(10^{23}/\mathrm{s})$	$\tau_{n-\bar{n}}(10^8$ s)
ILL (free-n) [63]	n/a	n/a	n/a	0.86
IMB (^{16}O) [96]	3.0	0.24	1.0	0.88
Kamiokande (^{16}O) [97]	3.0	0.43	1.0	1.2
Frejus (^{56}Fe) [98]	5.0	0.65	1.4	1.2
Soudan-2 (^{56}Fe) [92]	21.9	0.72	1.4	1.3
SNO (^{2}H) [94]	0.54	0.30	0.25	1.96
Super-K (^{16}O) [93]	245	1.9	0.517	2.7

Table 1: Neutron-antineutron lifetime lower limits (90% CL).

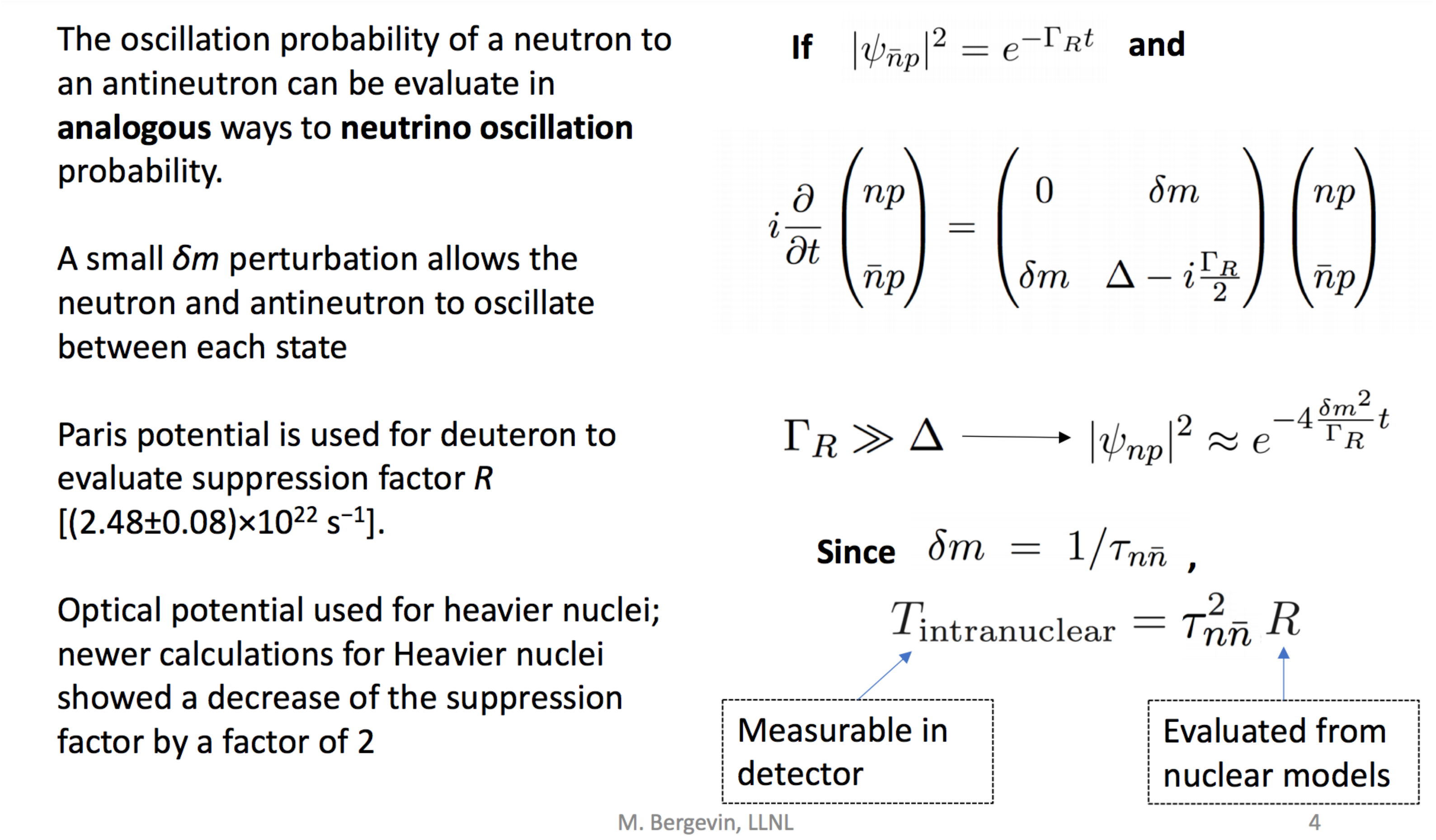
- Somewhat surprisingly, all results have been consistent with the limit set by the ILL free neutron experiment

What does this all mean?

- It means that we haven’t observed neutron – antineutron oscillation yet, and we haven’t set a limit that deviates far enough from what is expected to show evidence of new physics
  - The current lower limits set on the neutron – antineutron oscillation lifetime are lower than the upper bound set by the seesaw theory (which sets the upper – bound at 10^{10} seconds)

- Given that the experiments looking for oscillation in bound nuclei have yet to observe the interaction, it may be worth pursuing free neutron experiments with more seriously.
  - ESS and FNAL have both proposed such experiments

Extra slides



The oscillation probability of a neutron to an antineutron can be evaluate in **analogous** ways to **neutrino oscillation** probability.

A small *δm* perturbation allows the neutron and antineutron to oscillate between each state

Paris potential is used for deuteron to evaluate suppression factor *R* [(2.48±0.08)×10^{22} s^{-1}].

Optical potential used for heavier nuclei; newer calculations for Heavier nuclei showed a decrease of the suppression factor by a factor of 2

If $|\psi_{\bar{n}p}|^2 = e^{-\Gamma_R t}$ **and**

$$i\frac{\partial}{\partial t}\begin{pmatrix} np \\ \bar{n}p \end{pmatrix} = \begin{pmatrix} 0 & \delta m \\ \delta m & \Delta - i\frac{\Gamma_R}{2} \end{pmatrix}\begin{pmatrix} np \\ \bar{n}p \end{pmatrix}$$

$$\Gamma_R \gg \Delta \longrightarrow |\psi_{np}|^2 \approx e^{-4\frac{\delta m^2}{\Gamma_R}t}$$

Since $\delta m = 1/\tau_{n\bar{n}}$ **,**

$$T_{\text{intranuclear}} = \tau_{n\bar{n}}^2 \, R$$

Measurable in detector

Evaluated from nuclear models

M. Bergevin, LLNL

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Impact of B-L-conserving SM interaction on B asymmetry

Sphaeleron mechanism in Standard Model lead to violation of lepton and baryon number ('t Hooft, 1976)

- "On anomalous electroweak baryon-number non-conservation in the early universe" (Kuzmin, Rubakov, Shaposhnikov, 1985)

Sphaelerons conserve ($B\!-\!L$) but violate ($B\!+\!L$). Rate of ($B\!+\!L$)-violating processes at T > TeV exceeds the Universe expansion rate. If $B\!=\!L\neq 0$ is set at GUT scale due to $B\!-\!L$ conserving process, B asymmetry can be wiped out by ($B\!+\!L$)-violating process

Thus, for the explanation of universe B asymmetry, B-L-violating mechanisms (leptogenesis, NNbar, some nucleon decay modes…) seem to be required

"Proton decay is not a prediction of baryogenesis" [Yanagida'02]

Experimental searches for B Violation: Nucleon Decay and Neutron-Antineutron Oscillations

Mode	Nucleon decay	N-Nbar oscillations
Effect on B and L	ΔB=1, ΔL=1, others Δ(B-L)=0,2,…	ΔB=2, ΔL=0, Δ(B-L)=2
Effective operator	$L = \frac{g}{M^2} QQQL$	$L = \frac{g}{M^5} QQQQQQ$
Mass scale probed	~GUT	>~EW