Understanding the retaining of the oscillation phase in reflection from highly absorbing materials for $n - \bar{n}$ system

Discussed at the meeting with Fankang Li, Peter Jiang and Mike Fitzsimmons on June 30, 2022

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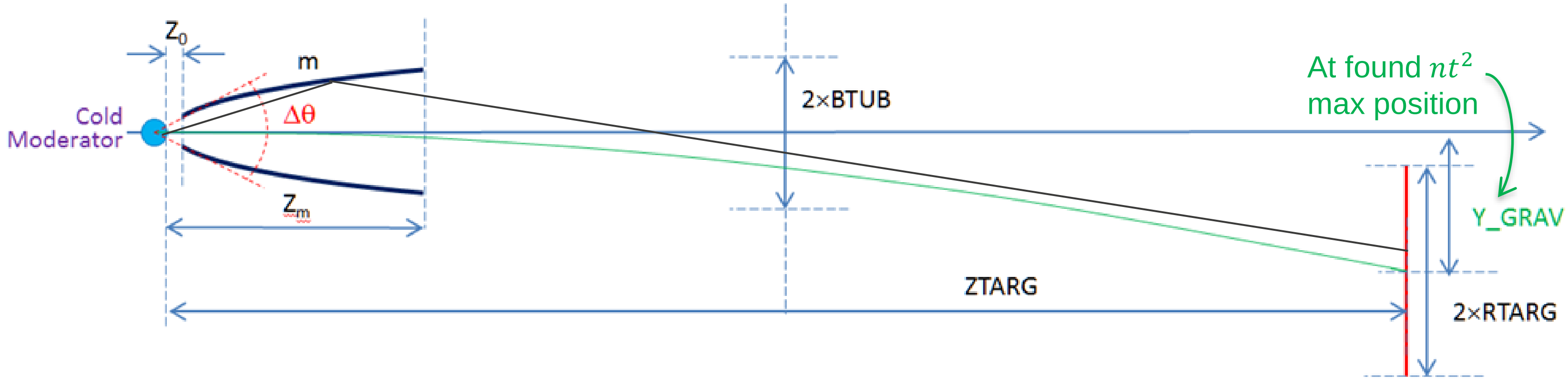
Large elliptical focusing reflector with m=6 was proposed for ESS $n \to \bar{n}$ experiment to search for baryon number violation

$n \to \bar{n}$ Baseline Configuration for Simulation (2015)



- Elliptical Reflector
  - Minor Radius (BTUB) — 2.00 m
  - Source-to-Target Distance (ZTARG) — 200 m
  - Entrance/Exit Position (Z_o/ Z_m) — 10/50 m
  - Reflectivity (m) — m=6
  - RTARG (annihilation target radius) — 1.00 m
  - *cold* source model — variable

Focusing idea:
Neutrons emitted withing large $\pm 5°$ aperture by single reflection should be directed to annihilation target

In vacuum with B=0
($\mu_n = -\mu_{\bar{n}}$ from CPT)

$$P(n \to \bar{n}) = \left(\frac{t}{\tau_{osc}}\right)^2$$

Known Challenges
! cost
! Will be difficult to assemble
+ 200m × dia 4m vacuum tank
+ magnetic compensation screen
+ large volume → rad. shielding
+ needs building with floor and crane

According to classical paper S. Marsh and K.W. McVoy (1983) oscillation phase of mixed $n \to \bar{n}$ system is reset due to collapse of the wave function under the collision either to n or to $\bar{n}$ interaction state

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Theory of neutron-antineutron oscillation using bottled ultracold neutrons

S. Marsh and K. W. McVoy
Physics Department, University of Wisconsin, Madison, Wisconsin 53706
(Received 6 June 1983)

We contrast the quantum-mechanical treatment of neutron oscillations in a "bottle" with the usual free-space formalism. The quantum-mechanical corrections appear to reduce the figure of merit for the bottled-neutron experiments, and also place constraints on the experimental arrangement.

Therefore, one should not allow the number of collisions of the system to be > 1.
If # $\gg$ 1 there will be no quadratic time dependence (e. g. in UCN trap), but rather only linear dependence and the sensitivity of experiment will be reduced.

Recent conjecture of Valery Nesvizhevsky/ILL et al. (2019) is that reset of the oscillation wave function occurs because the complex potential of interaction for n and $\bar{n}$ with reflecting surface is very different, e. g. due to large annihilation (imaginary) potential of $\bar{n}$ interaction with the reflector.

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Experimental Approach to Search for Free Neutron-Antineutron Oscillations Based on Coherent Neutron and Antineutron Mirror Reflection

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An observation of neutron-antineutron oscillations $(n-\bar{n})$, which violate both B and $B-L$ conservation, would constitute a scientific discovery of fundamental importance to physics and cosmology. A stringent upper bound on its transition rate would make an important contribution to our understanding of the baryon asymmetry of the Universe by eliminating the postsphaleron baryogenesis scenario in the light quark sector. We show that one can design an experiment using slow neutrons that in principle can reach the required sensitivity of $\tau_{n-\bar{n}} \sim 10^{10}$ s in the oscillation time, an improvement of $\sim 10^4$ in the oscillation probability relative to the existing limit for free neutrons. The improved statistical accuracy needed to reach this sensitivity can be achieved by allowing both the neutron and antineutron components of the developing superposition state to coherently reflect from mirrors. We present a quantitative analysis of this scenario and show that, for sufficiently small transverse momenta of $n/\bar{n}$ and for certain choices of nuclei for the $n/\bar{n}$ guide material, the relative phase shift of the n and $\bar{n}$ components upon reflection and the $\bar{n}$ annihilation rate can be small enough to maintain sufficient coherence to benefit from the greater phase space acceptance the mirror provides.

The next conjectured points are:

- If $U_n = V_n - iW_n \equiv U_{\bar{n}} = V_{\bar{n}} - iW_{\bar{n}}$ there will be no oscillation reset. (V_n is real part of optical potential, $W_{\bar{n}}$ imaginary part due to absorption)

- If U_n and $U_{\bar{n}}$ potentials are about the same, then $(n\bar{n})$ system can be reflected coherently many times from the surfaces

→ if the coherence is maintained under many collisions, then one can build a very long reflecting tube of a small diameter (e. g. 20 cm) and
(a) dramatically reduce cost of experiment.
(b) achieve higher sensitivity of $n\bar{n}$ search.

Most recent found published paper on that is https://pos.sissa.it/380/428/pdf

Implementations of neutron/antineutron ($n/\bar{n}$) guides in experiments searching for $n - \bar{n}$ oscillations

Identified example for reflector:

$$nCu \Rightarrow V_n - iW_n = (168. - i \cdot 0.026)\ neV$$
$$\bar{n}Cu \Rightarrow V_{\bar{n}} - iW_{\bar{n}} = (\ 94. - i \cdot 27.0\ )\ neV$$

U_n potentials are NOT the same however, theoretically, reflection coefficients are large for both n and $\bar{n}$

- this is *m=1* reflection with $v_{\perp} \sim 4.2\ m/s$
- super-mirrors with m>1 are not considered

Even if $U_n \equiv U_{\bar{n}}$, the fact of retaining the phase (coherence) under reflection is not experimentally established.

Is it possible to model reflection of 2-level $n \rightarrow \bar{n}$ oscillating system with two-spin states precession in magnetic field?

If the reflection would collapse nnbar system to either n or $\bar{n}$
the reflection should also "measure" polarization of reflected spin of n

Hamiltonians are similar:

(a) Two-state system $H = \mu\boldsymbol{\sigma}\cdot\boldsymbol{B}$; $n = \begin{pmatrix}\uparrow\\ \downarrow\end{pmatrix}$; $H = \mu\begin{pmatrix}B_z & B_x + iB_y\\ B_x - iB_y & -B_z\end{pmatrix} \Longrightarrow \mu\begin{pmatrix}0 & B_x\\ B_x & 0\end{pmatrix}$

Longitudinally polarized
beam along z

$$E_{1,2} = \pm\mu B_x$$

$$\boldsymbol{B} = (B_x, 0, 0); \quad n(0) = \begin{pmatrix}1\\0\end{pmatrix}$$

$$P_{\begin{pmatrix}0\\1\end{pmatrix}}(t) = sin^2\,(\mu B_x t/\hbar)$$

(b) Two-state system $\mathrm{N} = \begin{pmatrix}n\\ \bar{n}\end{pmatrix}$ $\quad H = \begin{pmatrix}E & \epsilon\\ \epsilon & E\end{pmatrix}$ $\quad E_{1,2} = \pm\epsilon$

$$\boldsymbol{B} = (0, 0, 0); \quad \mathrm{N}(0) = \begin{pmatrix}1\\0\end{pmatrix}$$

$$P_{\bar{n}}(t) = sin^2\,(\epsilon t/\hbar)$$

For $n \to \bar{n}$ oscillation beam polarization is not essential, since $B = 0$ is required

Calculation of Optical Potentials in QM Scattering Theory

$$U_{\text{opt}}(p_{rel}) = -2\pi\hbar^2 \frac{\nu}{m_*}\langle f_0(k_{rel})\rangle = V - iW$$ where m_* is reduced mass $(\hbar = c = 1)$

If $b = -\langle f_0(k_{rel})\rangle$ is bound coherent scattering length, then instead m_* one can use $m_n \equiv m$ (See UCN book of Golub),
ν – number density of the material, v – velocity

$$ReU_{opt} = 2\pi\hbar^2 Re(b)\frac{\nu}{m} \equiv V \qquad ImU_{opt} = 2\pi\hbar^2 Im(b)\frac{\nu}{m} \equiv W$$

For s-wave elastic scattering: $f_{\theta=0} = -b(1 - ik_{rel}b)$

More generally: $\mathrm{Im} f_{\theta=0} = \frac{k}{4\pi}\sigma_{tot}$ optical theorem

$\hookrightarrow$ (including elastic, inelastic, absorption)

$$\boxed{W = \frac{\hbar(\sigma_{tot}v\,)}{2}\nu; \quad V = 2\pi\hbar^2 Re(b_{coh})\frac{\nu}{m}}$$

ν – is number density of material

Let’s look at the non-magnetic reflector materials

- Reflector should be absorptive like $\bar{n}Cu \Rightarrow 94. - i \cdot 27.0 \ \ neV$
- Material properties should allow production of mirror surface (e.g. Cd is very soft)

Absorber	V	W
	neV	neV
B4C	199	6.1
BN	194	2.84
Ni	335	0.03
Cu	168	0.026
Cd	58.8	8.5
Gd	46.4	102.3
Sm	6.0	11.8
Eu	37.8	6.8
Dy	134.2	2.3
nbar Cu	94	27

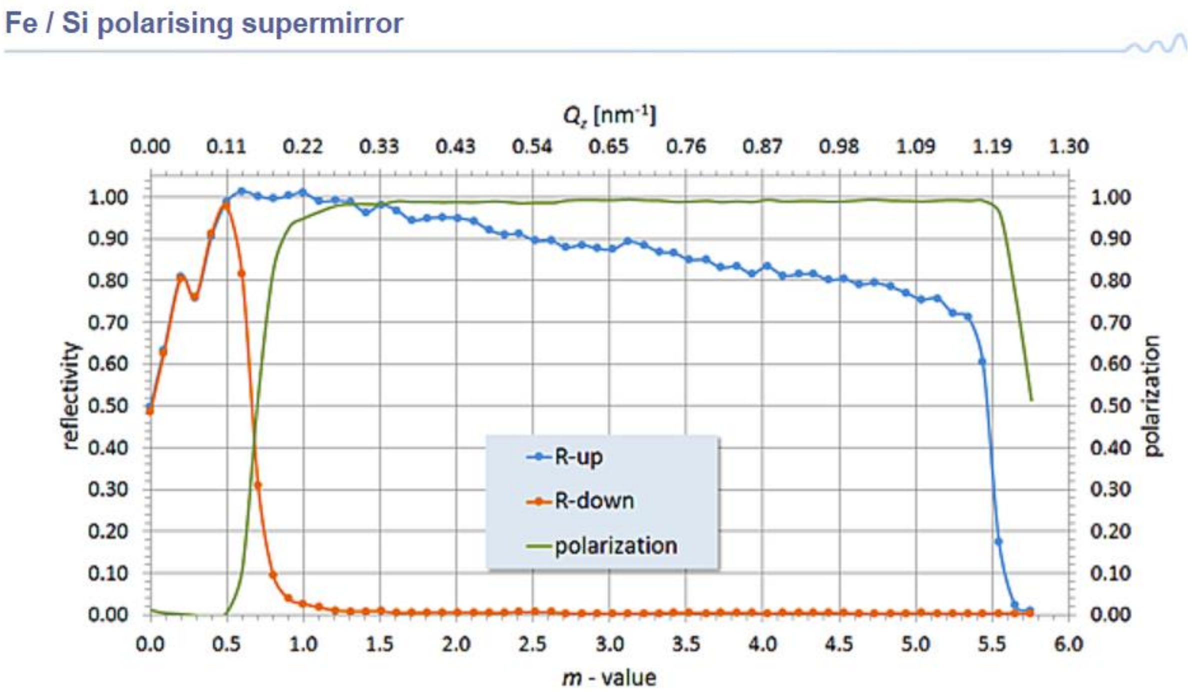
Gd (ferromagnetic < 20℃, paramagnetic > 20℃

Program of experiment

1. For two polarizations of neutrons the Re and Im parts of the optical potential will be equal, that makes a perfect condition for testing the hypothesis of the oscillation phase non-reset.

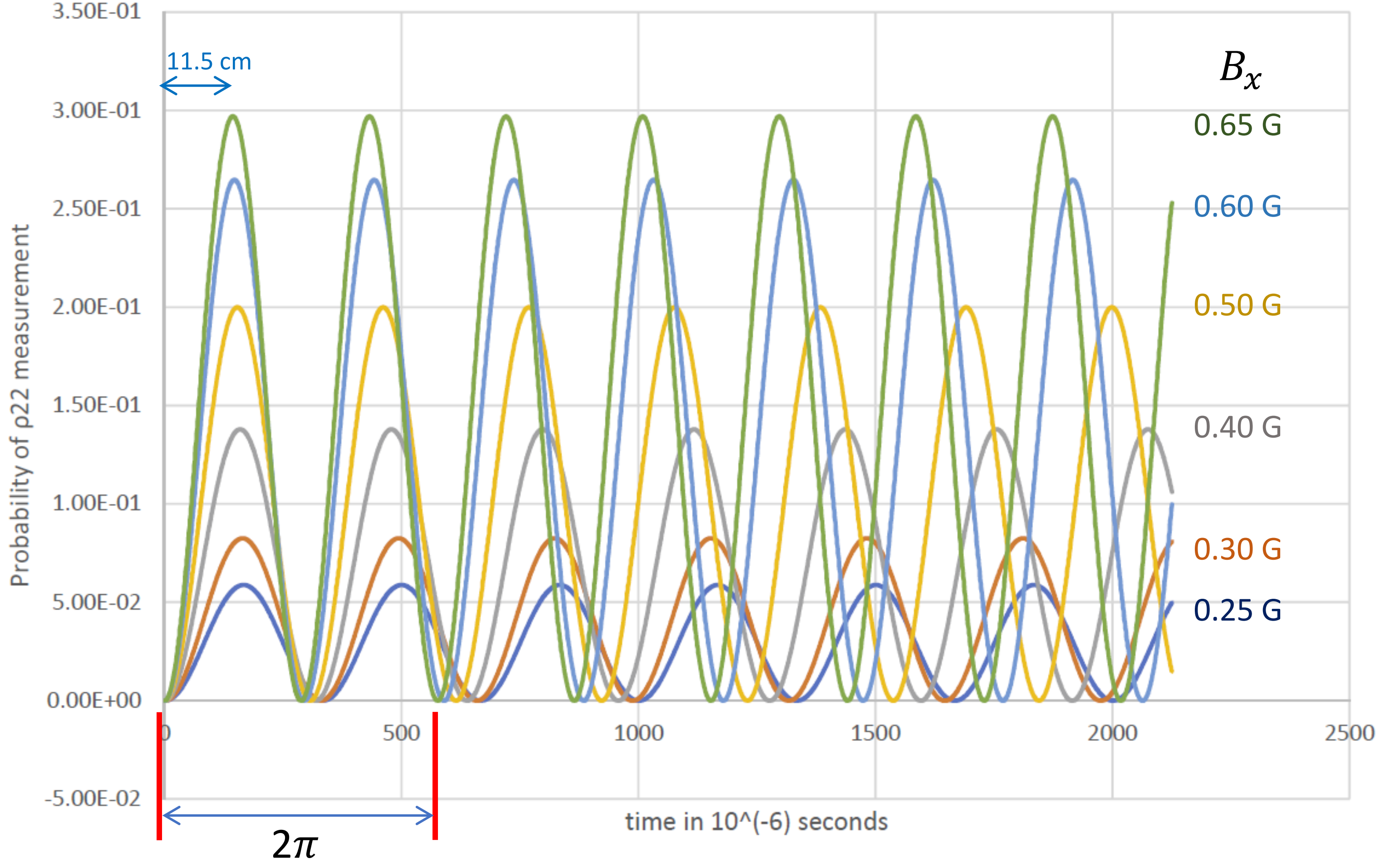
2. By measuring reflection phase change for two materials with complex optical potential close to $n\ \&\ Cu$ and to $\bar{n}\ \&\ Cu$ one can calculate the phase shift for $n \leftrightarrow \bar{n}$ system reflection from Cu.

3. How in reflection one can make Interaction potential different for two neutron polarizations? Polarizing reflector? Cold Gd?



Spin dependent reflectivity and polarization of a Fe/Si polarizing supermirror m = 5.5

Spin precession in uniform field



calculated by grad student Erich Bermel / UT / 2021

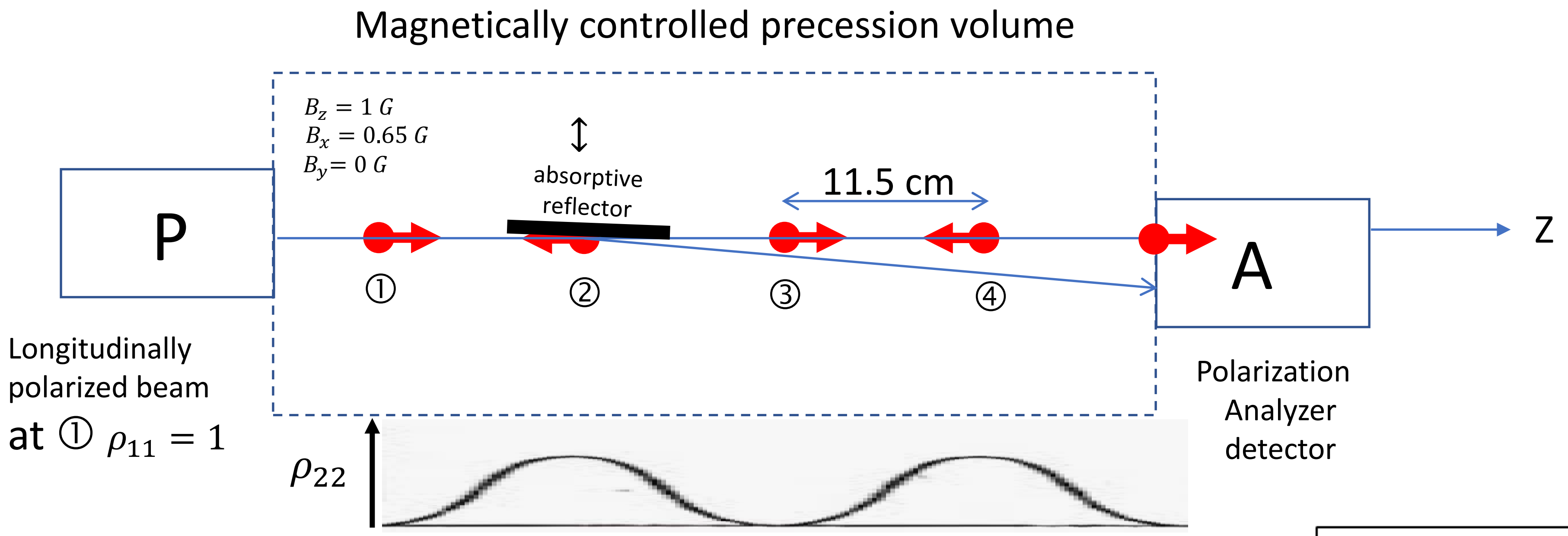
Probability of ρ22 measurement
Initial state Polarzed ρ11 =1
Bz = 1 Gauss. Bx =.25 -.65 Gauss
$\lambda = 5\text{Å}$ Velocity 800 m/s

$$\rho_{22} = sin^2(\omega t)$$

$$\omega = \mu B/\hbar$$

$$\mu = 60.3\, neV/T$$
$$B_z = 1G = 10^{-4}T$$
$$B_x = 0.65G$$
$$B_t = 1.193G = 1.193 \cdot 10^{-4}T$$
Frequency $\sim 1.6\ kHz$

Idea of experiment: measure phase shift due to reflection from absorbing mirror material



Range of reflection angles 0.05 – 0.35° for $\lambda = 5\text{Å}$

- For fixed λ max of ρ_{22} defines the position of beam reflection point
- Spectrum of λ (TOF) can be used for simultaneous measurements.
- absorbing/non-absorbing reflectors can be compared
- Reflectors with different $U_1 \neq U_2$ to study ΔV and ΔW effect on phase shift
- One reflector can be chosen with O.P. like nA and another like $\bar{n}A$.

Difference of phase differences for two cases will determine the answer for $(n\bar{n})$ reflection

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