Antineutron Optics

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(1) N-Nbar relative phase shifts in gas transmission and mirror reflection
(2) N-Nbar decoherence in gas transmission and mirror reflection

V.V. Nesvizhevsky, V. Gudkov, K.V. Protasov, W. M. Snow, and A.Yu. Voronin, **A new operating mode in experiments searching for free neutron-antineutron oscillations based on coherent neutron and antineutron mirror reflection,** Phys. Rev. Lett. **122**, 221802 (2019). arXiv: 1810.04988.

V. Gudkov, V.V. Nesvizhevsky, K.V. Protasov, W.M. Snow, and A.Yu. Voronin, **A new approach to search for free neutron-antineutron oscillations in coherent neutron propagation in gas,** Phys. Lett. B **808**, 135636 (2020). arXiv:1912.06730

K. V. Protasov, V. Gudkov, E. A. Kupriyanova, V. V. Nesvizhevsky, W. M. Snow, and A. Yu. Voronin, **Theoretical Analysis of Antineutron-Nucleus Data needed for Antineutron Mirrors in Neutron-Antineutron Oscillation Experiments,** accepted for publication in Phys. Rev. D (2020). arXiv: 2009.11467.

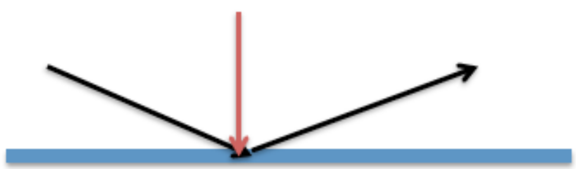
Neutron Optical Potential for n and nbar

$$U = V - iW = (2\pi\hbar^2/m)\sum_l N_l(b_{l,r} - ib_{l,i}),$$

$$|R^2| = \frac{E_\perp - \sqrt{E_\perp(2\alpha - 2(V - E_\perp) + \alpha}}{E_\perp + \sqrt{E_\perp(2\alpha - 2(V - E_\perp) + \alpha}}$$

where

$$\alpha = \sqrt{(V - E_\perp)^2 + W^2}$$



Mirror reflection

$$\begin{bmatrix} n \\ \overline{n} \end{bmatrix} \rightarrow \begin{bmatrix} n \\ \rho e^{i\varphi}\overline{n} \end{bmatrix}$$

Real and imaginary parts of U_{opt} reflect

Potential scattering:

Im(b)<<Re(b) for n,

Im(b)~Re(b) for nbar

Validity of neutron optics for highly-absorbing neutron mirrors is known for decades, Gadolinium reflection used for test

I Gurevich and P. E. Nemiovskii, Zhurnal Eksp. And Theo. Fiz. 41, 1175 (1961).

V. I. Morozov, M. I. Novopoltsev, Yu. N. Panin, Yu. N. Pokotilovskii, and E. V. Rogov, Pis'ma Zh. Eksp. Teor. Fiz. 46, 301 (1987).

Nbar scattering lengths from theory

Batty-Friedman-Gal approach

The interaction of low-energy antiprotons with nuclei, as well as the interaction of antiprotons bound in an atomic system, is described in this work by the conventional '$t\rho$' potential [8]

$$2\mu V_{\mathrm{opt}}(r) = -4\pi\left(1 + \frac{A-1}{A}\frac{\mu}{m}\right) b_0 \rho(r), \tag{3}$$

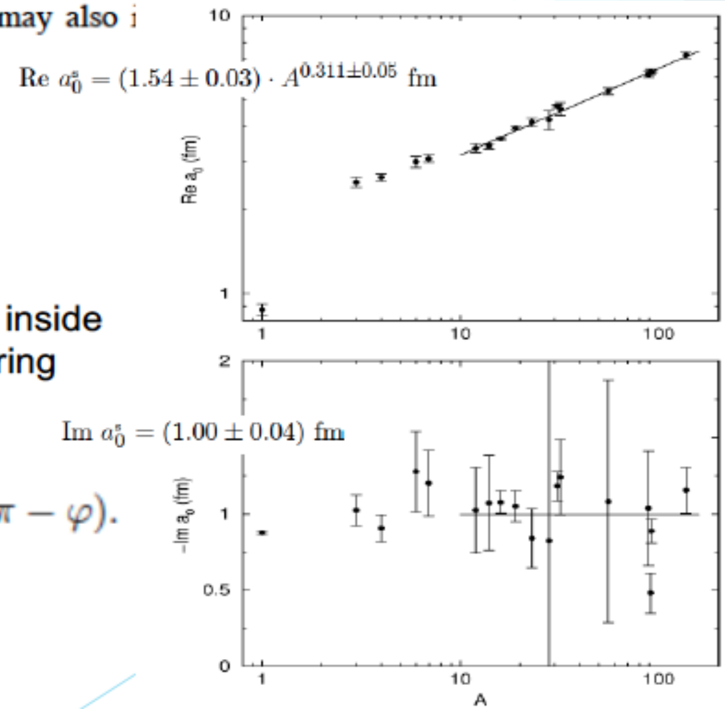
where m is the nucleon mass, μ is the $\bar{p}$–nucleus reduced mass, b_0 is an 'effective scattering length' complex parameter obtained from fits to the data and $\rho(r)$ is the nuclear density distribution normalized to A. The density $\rho(r)$ may also i

$$\rho_{p,n}(z) = \frac{\rho_{p_0,n_0}}{1 + \exp\left(\frac{z - R_{p,n}}{a_{p,n}}\right)},$$

Very strong annihilation "kills" the wave function inside the nucleus and the imaginary part of the scattering length becomes sensitive to diffuseness only

$$U(r) = -U_0 e^{-r/r_0}, \qquad \lim_{|z_0|\to\infty} \mathrm{Im}\, a_s = -r_0(\pi - \varphi).$$

Karmanov, Protasov, Voronin, Eur Phys J **A8**, 429 (2000)



For nbar: Re(b)~$1.5A^{1/3}$ fm, Im(b)~ 1 fm

See K. Protasov et al, arXiv: 2009.11467

$$\psi_n(x) = \begin{cases} e^{ikx} - A_n(k)e^{-ikx}, & x < 0, \\ B_n(k)e^{-\kappa_n x}, & x > 0, \end{cases}$$

where $k = \sqrt{2mE}$, $\kappa_n = \sqrt{2m(U_n - E)}$. One has

$$A_n(k) = e^{i\varphi_n(k)}, \quad \varphi_n(k) = 2 \arctan \frac{k}{\kappa_n},$$

or,

$$A_n(k) = \varrho_n(k)e^{i\varphi'_n(k)}, \quad \varrho_n(k) = 1, \quad \varphi'_n(k) = \arctan \frac{2k\kappa_n}{\kappa_n^2 - k^2}.$$

For the antineutron component with $E < V_{\bar{n}}$ similar equations read

$$\psi_{\bar{n}} = (k) \begin{cases} e^{ikx} - A_{\bar{n}}(k)e^{-ikx}, & x < 0, \\ B_{\bar{n}}(k)e^{-\kappa_n x}, & x > 0, \end{cases}$$

where $\kappa_{\bar{n}} = \kappa'_{\bar{n}} - i\kappa''_{\bar{n}} = [2m(V_{\bar{n}} - iW_{\bar{n}} - E)]^{1/2}$. One gets

$$A_{\bar{n}}(k) = \frac{\kappa_{\bar{n}} + ik}{\kappa_{\bar{n}} - ik} = \varrho_{\bar{n}}(k)e^{i\varphi_n(k)},$$

$$\varrho_{\bar{n}}^2(k) = \frac{(\kappa''_{\bar{n}} - k)^2 + \kappa'^2_{\bar{n}}}{(\kappa''_{\bar{n}} + k)^2 + \kappa'^2_{\bar{n}}}, \quad \varphi_{\bar{n}}(k) = \arctan \frac{2k\kappa'_{\bar{n}}}{\kappa'^2_{\bar{n}} + \kappa''^2_{\bar{n}} - k^2}.$$

Difference between n and nbar phase shifts
for glancing angle reflection (Nesvizhevsky et al)
use usual formulae of neutron optics

Phases shifts for n and nbar (separately) from n optics.

nbar U_{opt} from theory

Quasifree condition CAN be met! (Nesvizhevsky et al, PRL)

This is phase shift of n and nbar separately. OK in the presence of oscillations?

↓

$$\theta(k) \simeq \frac{2k}{\kappa_n \kappa'_{\bar{n}}}(\kappa'_{\bar{n}} - \kappa_n).$$

Quantum Decoherence and Neutron Optics

Neutron optics describes the coherent interactions of the neutron with matter

Incoherent interactions of <u>single</u> neutron state with environment:
diffuse scattering, reduces amplitude

Incoherent interactions of <u>coherent superposition</u> of neutron states: can damp oscillations from off-diagonal terms in H (environment "measures" the system)

Standard method of analysis in quantum decoherence theory uses Lindblad operators for evolution of density matrix

$$\dot{\hat{\varrho}}(t) = \frac{d\hat{\varrho}(t)}{dt} = -i[\hat{H}, \hat{\varrho}(t)] + \sum_n [L_n \hat{\varrho}(t) L_n^\dagger - \frac{1}{2} L_n^\dagger L_n \hat{\varrho}(t) - \frac{1}{2} \hat{\varrho}(t) L_n^\dagger L_n],$$

NOTE: "nothing new": Lindblad treatment is known to reduce to usual Van Hove expressions for n scattering theory. But a much more convenient way to analyze effects of interest.

for Lindblad->Van Hove: see L. Lanz, et al., Phys. Rev. A **56,** 4826 (1997).

Quantum Decoherence and Neutron Optics

$$\dot{\hat{\varrho}}(t) = \frac{d\hat{\varrho}(t)}{dt} = -i[\hat{H}, \hat{\varrho}(t)] + \sum_n [L_n \hat{\varrho}(t) L_n^\dagger - \frac{1}{2} L_n^\dagger L_n \hat{\varrho}(t) - \frac{1}{2} \hat{\varrho}(t) L_n^\dagger L_n],$$

For the n-nbar two-state system: one gets

$$\hat{H} = \begin{pmatrix} E + \Delta_1 - \frac{2\pi}{k} n v Re f_1(0) - i\frac{\gamma}{2} & \varepsilon \\ \varepsilon & E + \Delta_2 - \frac{2\pi}{k} n v Re f_2(0) - i\frac{\gamma}{2} \end{pmatrix}. \quad L = \sqrt{nv}\, F, \quad F = \begin{pmatrix} f_1(\theta) & 0 \\ 0 & f_2(\theta) \end{pmatrix}.$$

For nnbar in a gas medium one can calculate the damping factor to be:

$$\lambda \simeq 4\pi\, n\, v\, \mathrm{Im} \frac{f_2(0)}{2k} = n\, v\, \sigma_a/2 \equiv \Gamma_a.$$

for λt>>1

$$|\Psi_{\bar{n}}(t)|^2 \simeq \frac{4\varepsilon^2}{\lambda^2} \exp\left(-\frac{4\varepsilon^2}{\lambda} t\right),$$

for λt<<1

$$|\Psi_{\bar{n}}(t)|^2 \simeq \varepsilon^2 t^2 - \frac{1}{2}\varepsilon^2 \lambda t^3.$$

Small effect for ILL experiment given residual gas pressure

B. O. Kerbikov, **Lindblad and Bloch Equations for a conversion of a neutron into an antineutron ,** Nucl. Phys. A **975**, 59-72 (2018). arXiv: 1810.04988

Quantum Decoherence in Neutron Reflection

Kerbikov 2: decoherence in nbar reflection from Cu mirror with τ the collision time, Γ the nbar annihilation rate.

$$H = \begin{pmatrix} E_n & \varepsilon \\ \varepsilon & E_{\bar{n}} - i\frac{\Gamma}{2} \end{pmatrix}$$

In the short collision time limit τε<<1, nbar is just depleted due to annihilation. Kerbikov estimated τ<~10-8 sec in Cu

$$\Psi_{\bar{n}}(t) = \varepsilon\tau \exp\left(-iE_{\bar{n}}t - \frac{\Gamma}{2}t\right), \quad |\Psi_{\bar{n}}(t)|^2 = \varepsilon^2\tau^2 e^{-\Gamma t}$$

small effect for τε<<1

$$|\Psi_{\bar{n}}(t)|^2 = \frac{4\varepsilon^2}{\Gamma^2}\exp\left(-\frac{4\varepsilon^2}{\Gamma}t\right)$$

In the τε>>1 limit however, quantum decoherence strongly attenuates the nbar reflection probability.

B.O. Kerbikov**, "The effect of collisions with the wall on neutron-antineutron transitions",** Phys. Lett. B **795,** 362 (2019)

Obvious question: what is the collision time for neutron-antineutron reflection, and how does one measure it?

Observation of the Goos-Hänchen Shift with Neutrons

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(Received 27 August 2009; revised manuscript received 24 October 2009; published 8 January 2010)

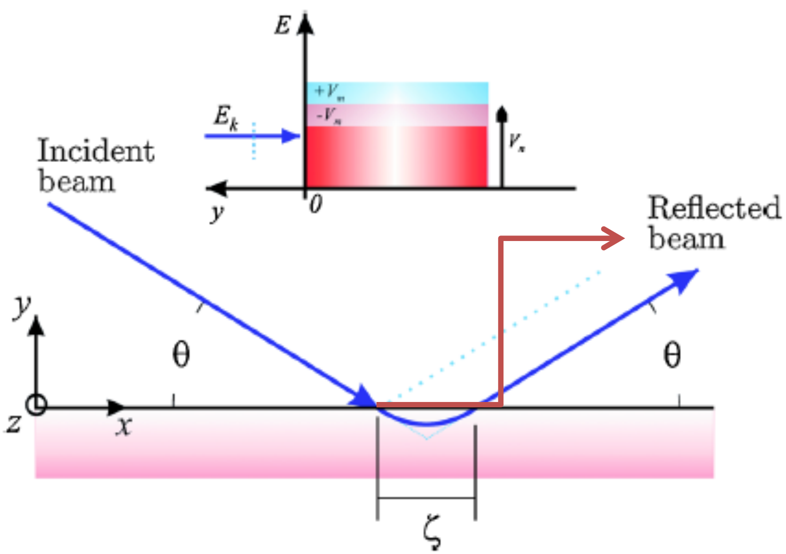


FIG. 1 (color online). Reflection of a plane wave with incident angle θ on a substrate boundary at $y = 0$ indicating the Goos-Hänchen shift, ζ. Inset: nuclear V_n and magnetic $\pm V_m$, scattering potential and kinetic energy E_k associated with neutron velocity component perpendicular to the surface.

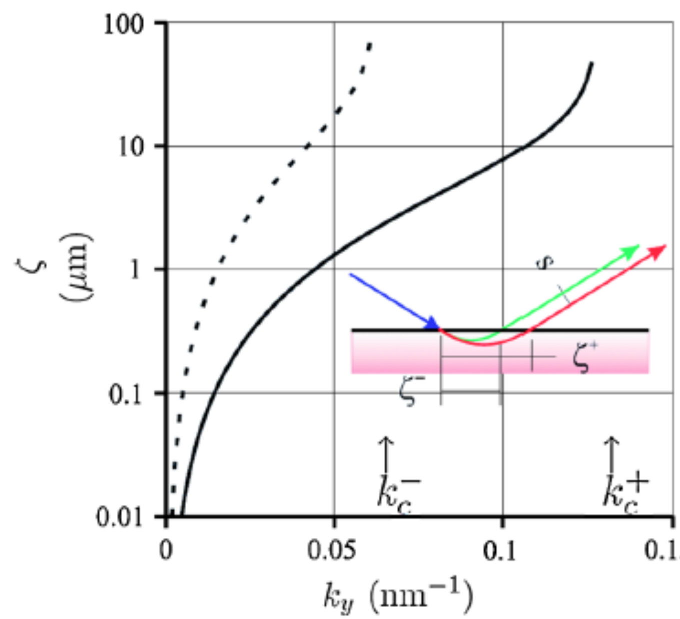


FIG. 2 (color online). Goos-Hänchen shift, ζ along the interface for an incident angle of 2 mrad as function of the wave vector component perpendicular to the surface, k_y for up (full line) and down (dashed line) spin state for fully magnetized iron. Inset: Splitting, s of the neutron wave function at the interface.

Goos-Hanchen phase shift and displacement neutrons polarized along sample magnetization:

$$\phi^{\pm} = -i \ln(\rho^{\pm}) = 2 \arccos(k_y/k_c^{\pm})$$

$$\tau^{\pm} = \frac{m}{\hbar (k_c^{\pm})^2} \frac{2k_y}{\sqrt{(k_c^{\pm})^2 - k_y^2}}.$$

This determines also the time delay between the two neutron spin states associated with the different rays. This was ~10^{-7} seconds near the critical angle for the magnetized Permalloy ($Fe_{0.2}Ni_{0.8}$) sample used

$$\zeta^{\pm} = \frac{k}{(k_c^{\pm})^2} \frac{2k_y}{\sqrt{(k_c^{\pm})^2 - k_y^2}}.$$

Experiment done on Offspec spin echo instrument at ISIS using polarized neutron spin-echo reflectometry, which directly measured the phase difference

$$\frac{P}{P_0} = \cos N\delta(k_y)$$

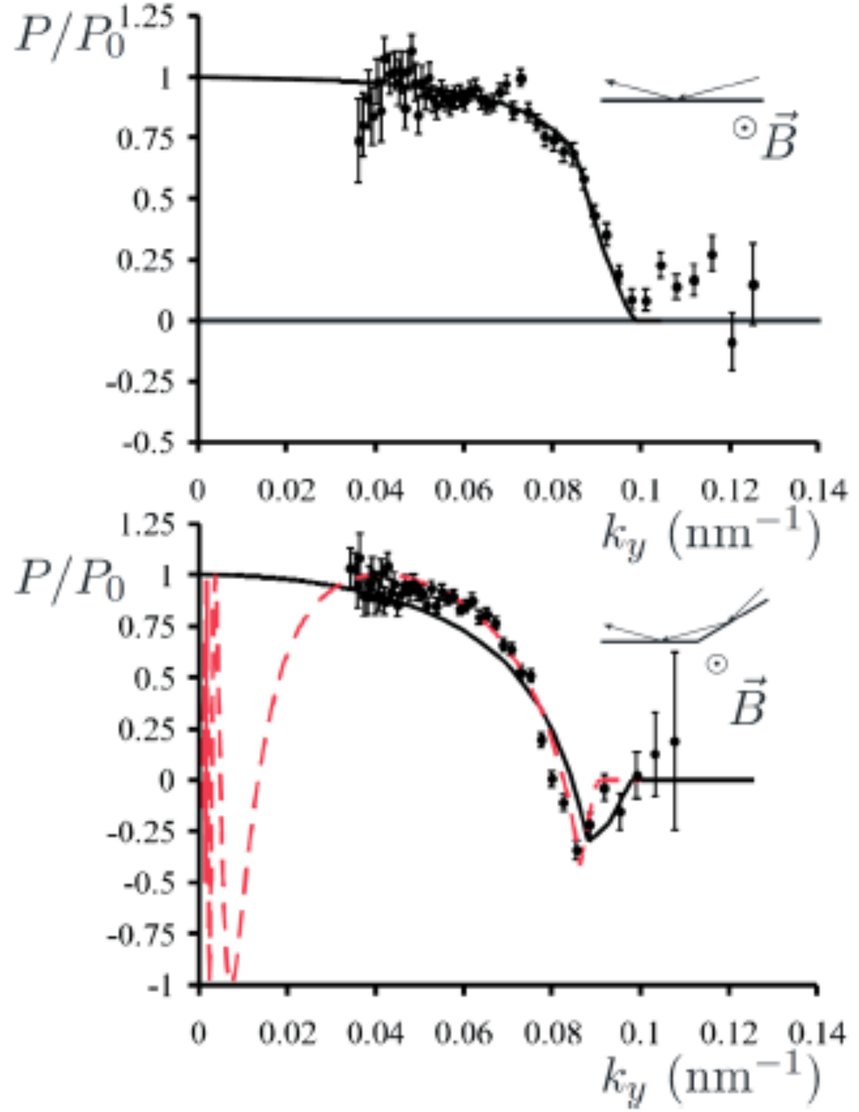


FIG. 3 (color online). Measured normalized polarization, P/P_0 as function of perpendicular wave vector, k_y representing the Larmor pseudo precession due to the Goos-Hänchen shift along the interface for a single (top) and double (bottom) reflection from a Permalloy thin film. The black lines represent the theoretical predictions. The (red) dashed line in the lower graph represents a simulation (see text).

(2) Does quantum decoherence from time in mirror kill the oscillations?

$$\begin{bmatrix} n \\ \overline{n} \end{bmatrix} \rightarrow \begin{bmatrix} n \\ \rho e^{i\varphi} \overline{n} \end{bmatrix}$$

No in short collision time limit $\tau\varepsilon \ll 1$

Collision time as inferred through Goos-Hanchen effect agrees with n optics calculation

Therefore, this effect can be calculated with confidence using n optics, given U_{opt}

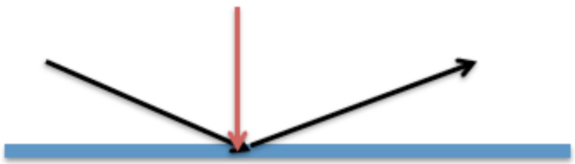
Also: coherent neutron optics works fine for neutron spins with large off-diagonal terms in H (polarized neutron reflectometry, pseudomagnetic precession,…)

Next steps:

Calculate $\tau\varepsilon$ for mirrors made of stable nuclei using Kerbikov/Lindblad theory+neutron optics

Investigate antineutron supermirror optics

How can we get info on nbar reflection physics?



Can we use

$$\begin{bmatrix} \uparrow \\ \downarrow \end{bmatrix} \rightarrow \begin{bmatrix} \uparrow \\ \rho e^{i\varphi} \downarrow \end{bmatrix}$$

To learn about

$$\begin{bmatrix} n \\ \overline{n} \end{bmatrix} \rightarrow \begin{bmatrix} n \\ \rho e^{i\varphi} \overline{n} \end{bmatrix}$$

In future: low energy pbar/antihydrogen mirror reflection is a possibility

For now: no direct method (no slow nbar beams)

However: polarized slow neutron beams available, also instruments to bounce them from mirrors.

Two state systems with the same Hamiltonian have the same dynamics

We could engineer a “poor man's” n-nbar reflection test using polarized neutrons from a well-chosen mirror material with large absorption for one neutron spin state (Gd?)

Conclusions

$$\begin{bmatrix} n \\ \overline{n} \end{bmatrix} \rightarrow \begin{bmatrix} n \\ \rho e^{i\varphi}\overline{n} \end{bmatrix}$$

(1) Neutron optics theory can be used to calculate ρ and φ for n-bar oscillating system given U_{opt} . Theory for nbar U_{opt} implies quasifree condition can be met in mirror reflection and gas transmission in certain regimes.

(2) Quantum decoherence from imaginary part of U_{opt} can suppress oscillations. Effect is calculable given nbar optical potential from theory, can be small.

(3) Calculate decoherence for mirrors made of stable nuclei and investigate antineutron supermirrors

(3) Use resonances in Gd

$$b_{res} = \sum_j \frac{1}{2k'_j} \frac{\Gamma_{n,j}}{[(E' - E_j) + i\Gamma_j/2]}$$

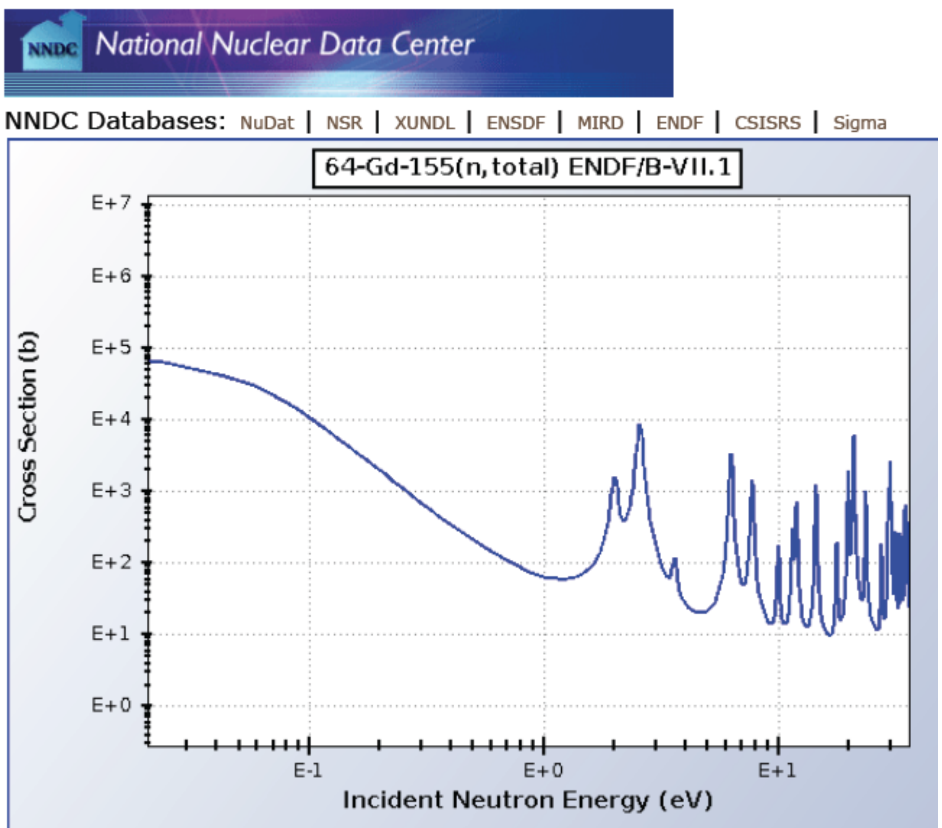
Both ^{155}Gd and ^{157}Gd: I=3/2
and lowest-energy resonance J=2

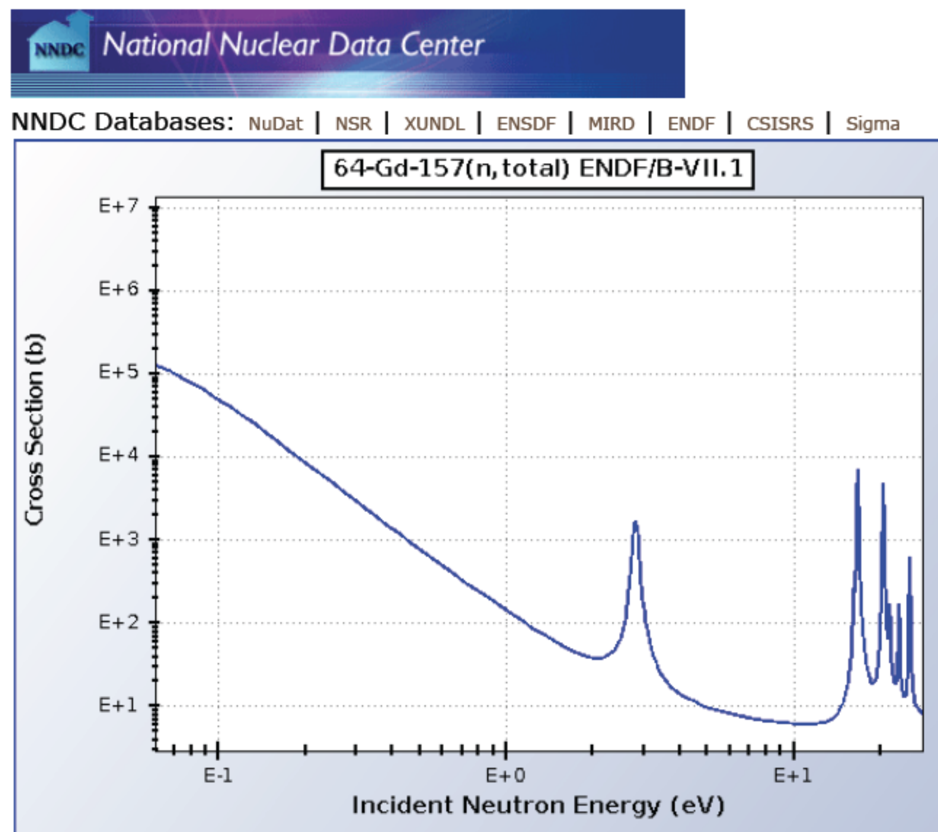
To emulate n-nbar, we want:

Im(b)<<Re(b) for |↑>,

Im(b)~Re(b) for |↓>. How?

on n-A resonance, $Re(b_{res})=0$, and $Im(b_{res})$ large





Experimental determination of gadolinium scattering characteristics in neutron reflectometry with reference layer

Physica B: Condensed Matter 552 (2019) 58–61

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Unpolarized reflectometry on Gd evaporated on a silicon substrate. Results in good agreement with neutron optics calculations including the large imaginary part of the optical potential from the Gd resonances.

b_{real}

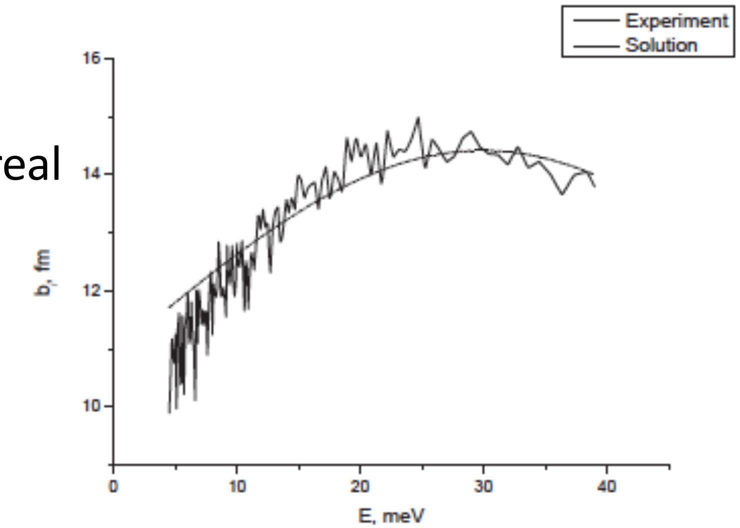

Fig. 3. Approximation of the experimental values of the scattering length.

Real part of b and imaginary part of b are comparable due to the resonance contributions

Polarized neutron scattering on magnetized Gd?

$b_{imaginary}$

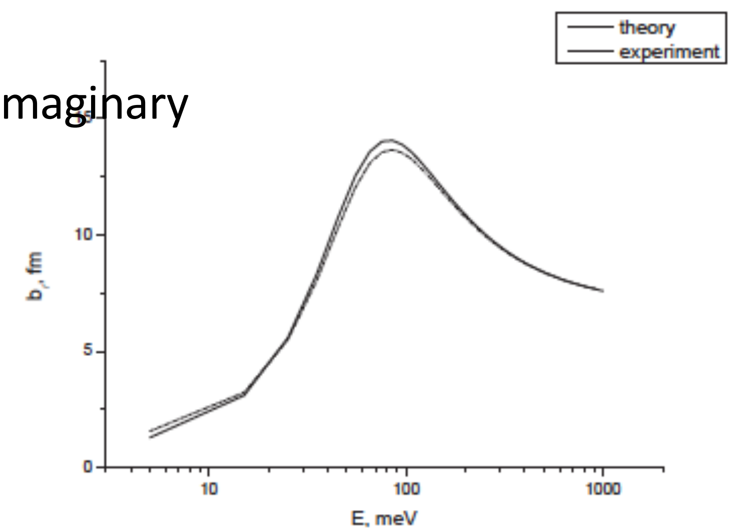

Fig. 4. Real (a) and imaginary (b) parts of the gadolinium scattering length.

Im(b) is large, but about the same for |↑> and |↓>.

For Im(b) (|↑>) large and Im(b) [|↓>] small?

Use polarized neutrons and polarized Gd nuclei
Exploit spin-dependence of resonance

Neutron scattering lengths and cross sections

ZSymbA	p or $T_{1/2}$	I	b_c	b_+	b_-	c	σ_{coh}	σ_{inc}	σ_{scatt}	σ_{abs}
64-Gd-155	14.9	3/2	13.8(3)			E	40.8(4)	25.0(6.0)	66.0(6.0)	61100.0(400.0)
64-Gd-156	20.6	0	6.3(4)				5.0(6)	0	5.0(6)	1.5(1.2)
64-Gd-157	15.7	3/2	4.0(2.0)			E	650.0(4.0)	394.0(7.0)	1044.0(8.0)	259000.0(700.0)

No evidence that anyone has ever scattered neutrons from nuclear polarized Gd: no spin-dependent scattering lengths in the latest table I have

I=3/2 Gd nuclear spins->no so easy to “flip” nuclear spin: need to worry about behavior of tensor components

“brute force” nuclear polarized Gd: needs low T (~mK regime), high B (several T). Large B effect on neutron spin would need to be understood.

Enhancement of field at nucleus is possible in certain materials, but they tend to be highly magnetic -> may depolarize n beam

Neutron-Antineutron transition probability

For $H = \begin{pmatrix} m_n + V & \alpha \\ \alpha & m_{\bar{n}} - V \end{pmatrix}$ $\quad P_{n\to\bar{n}}(t) = \frac{\alpha^2}{\alpha^2 + V^2} \times \sin^2\left[\frac{\sqrt{\alpha^2 + V^2}}{\hbar} t\right]$

where V is the potential difference for neutron and anti-neutron

For $\left[\frac{\sqrt{\alpha^2 + V^2}}{\hbar} t\right] \ll 1$ ("quasifree condition") $\quad P_{n\to\bar{n}} = \left(\frac{\alpha}{\hbar} \times t\right)^2 = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$

$\tau_{n\bar{n}} = \frac{\hbar}{\alpha}$ is characteristic oscillation time. Present limit -> $\alpha < 10^{-23} eV$!