NEUTRON OSCILLATIONS in a TRAP: INSIGHTS and OPEN PROBLEMS

(# of Op. Pr-s ≫ # Ins-s)

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work in progress

The plan:

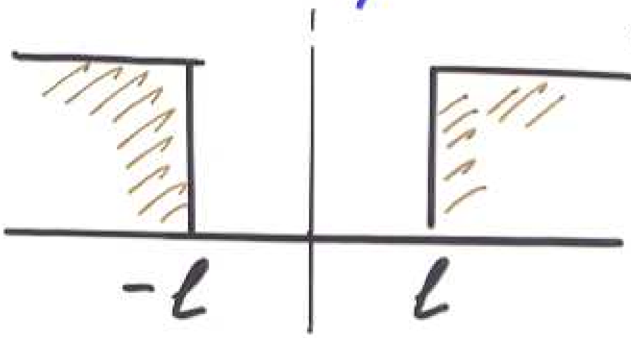
1. A toy model of a trap
2. Wave packets – standing waves duality
3. Hitting the trap wall: $n-\bar{n}$ phase difference and/or quantum dephasing
4. Antineutron production probability
5. Wave packet revival
6. Possible localization inside the wall
7. A remark on mirror neutrons

A TOY MODEL OF A TRAP

UCN: $E < 10^{-7}\,\mathrm{eV}$, $T \simeq 10^{-3}\,\mathrm{K}$,

$v \lesssim 5\cdot 10^{2}\,\mathrm{cm/s}$, $\lambda = \frac{2\pi}{k} \simeq 10^{-5}\,\mathrm{cm}$.

1D trap



$U \simeq 200\,\mathrm{neV}$

$l = 50\,\mathrm{cm}$

$\tau_l = \frac{2l}{v} \cong 0.2\,\mathrm{s}$

$E_n = 0.8\cdot 10^{-7}\,\mathrm{eV}$, $v = 3.9\cdot 10^{2}\,\mathrm{cm/s}$, $j \simeq \frac{2l}{\pi}\sqrt{2mE} \simeq$

$\simeq 2\cdot 10^{7}$.

$\frac{\Delta E}{E} \simeq 10^{-3} \Rightarrow \Delta j \simeq 10^{4}$

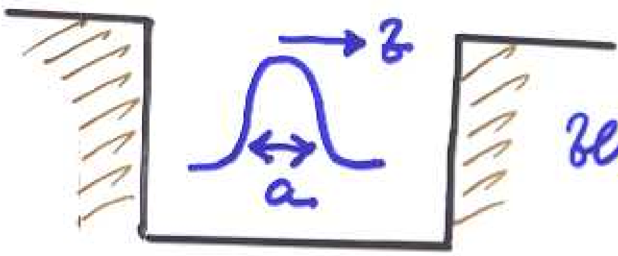
↖ w. packet

$j_0 \simeq 2\cdot 10^{7}$ $\left.\begin{array}{c}\text{———}\\\text{———}\\\text{———}\\\text{———}\end{array}\right\}\Delta j \simeq 10^{4}$

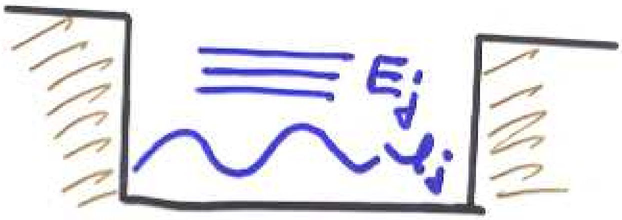
$j \gg 1$ – semiclassical regime, the level spacing δE_j is almost constant within Δj,

$\delta E_j \simeq 10^{-14}\,\mathrm{eV}$.

WAVE PACKETS - STANDING WAVES DUALITY



versus



$$\psi_j \simeq \sqrt{\frac{1}{\ell}} \begin{cases} \cos k_j x \\ \sin k_j x \end{cases}$$

billiards vs guitar

Wave packet decomposition of the UCN Maxwell flux

$$\omega_k = \sum_q C(q-k)\,\Psi_q$$

Gaussian w.p. in coordinate space

$$\Psi_k(x, t=0) = (\pi a^2)^{-1/4} \exp\left\{ ikx - \frac{(x-x_0)^2}{2a^2} \right\},$$

$$a = 1/\Delta k\,, \quad \frac{\Delta E}{E} = 10^{-3} \Rightarrow a \simeq 3\cdot 10^{-3}\,\mathrm{cm}$$

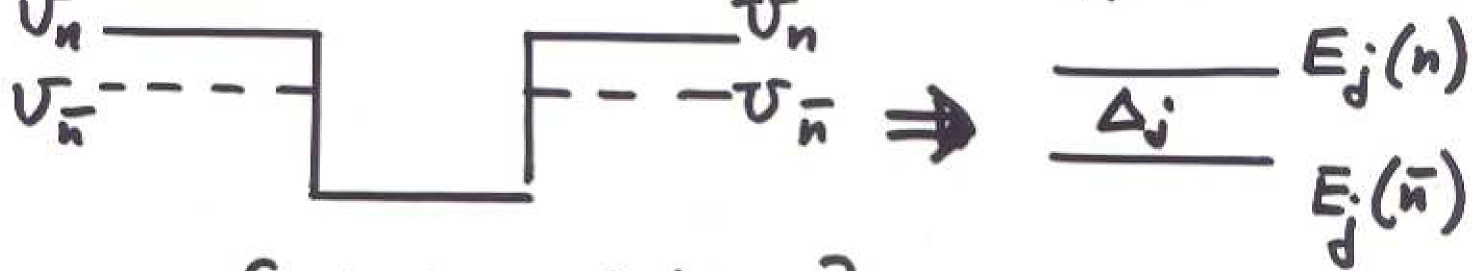
Spreading

$a' = 2\ell$ at $\tau_f \simeq 500\,\mathrm{s}$

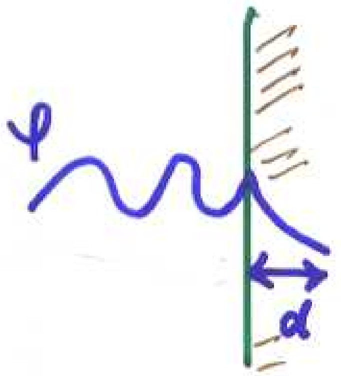
Flattering (collapse) time $\tau_f \sim$ UCN holding time

STATIONARY APPROACH

Spurious (?) $n-\bar{n}$ damping of oscillations inside the trap in the standing waves approach



$$\Delta_j \simeq \int_{x \lesssim d \simeq \lambda} dx\,(U_n - U_{\bar{n}})\,|\psi(x)|^2$$



d - penetration depth

$$d \lesssim \lambda \sim 10^{-6}\,cm$$

$$\Delta_j \sim \delta U \frac{\lambda}{\ell} \sim \delta U \frac{1}{k\ell} \sim \frac{\delta U}{j} \sim 10^{-14}\,eV$$

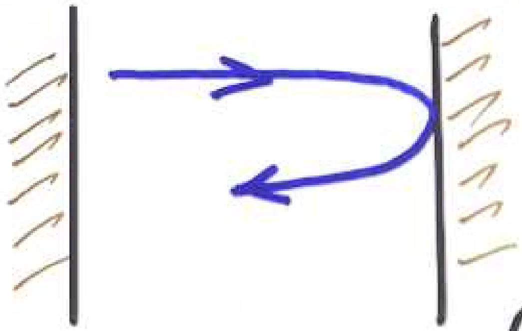
Then inside the trap

$$|\psi_{\bar{n}}(t)|^2 = \frac{4\varepsilon^2}{(\Delta_j)^2} \sin^2 \frac{\Delta_j}{2} t\,, \quad \varepsilon \lesssim 10^{-23}\,eV$$

$$\left(\frac{\varepsilon}{\Delta_j}\right)^2 \sim 10^{-18}\,!$$

WAVE PACKET APPROACH

($t < \tau_f \sim$ holding time)



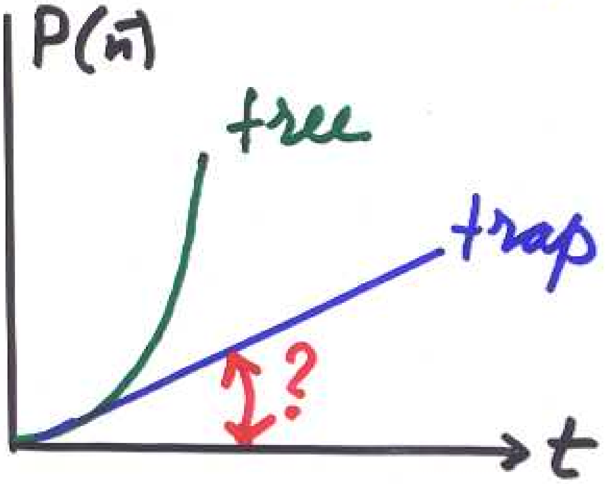
On the wall: annihilation of $\bar{n}$ or decoherence of $n-\bar{n}$.
Collision may stop the clock

Annihilation rate:

$$P(\bar{n}) \propto \underbrace{\varepsilon^2 \tau_\ell^2}\left(\frac{t}{\tau_\ell}\right), \quad \tau_\ell = \frac{2\ell}{g} \simeq 0.2\,s$$

free space oscillations

Kerbikov, Kudryavtsev, Lensky 2004



$$\Psi_{refl} = \rho e^{i\varphi} \Psi_{inc}$$

$$d\varphi/dk \simeq \hbar \tau_{coll}$$

$$\tau_{coll} \simeq 10^{-8}\,s$$

$$\tau_{coll}(n) \neq \tau_{coll}(\bar{n})$$

After N collisions

$$P_a(N) = \frac{\varepsilon^2 \tau_e^2}{1+g^2-2g\cos\theta}\left\{N(1-g^2)+1-\frac{(1-g^2)}{1+g^2-2g\cos\theta}\right\}$$

$\theta = \varphi_{\bar{n}} - \varphi_n$ the key quantity

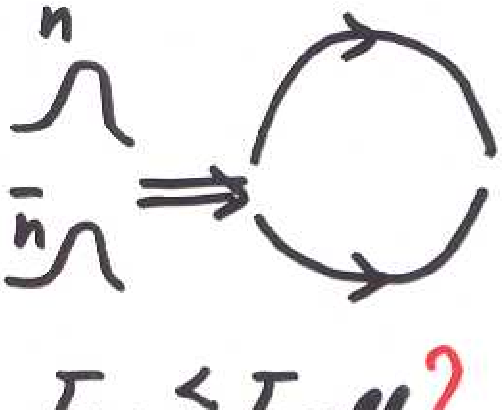
$$P_a(N) \Rightarrow \begin{cases} \varepsilon^2 \tau_e \tau, & g \ll 1 \\ \frac{1-g}{1+g}\varepsilon^2\tau_e\tau, & \theta = \pi \text{ superdamping} \\ \frac{1+g}{1-g}\varepsilon^2\tau_e\tau, & \theta = 0 \text{ enhancement} \end{cases}$$

the plot p7

QUANTUM DEPHASING

The wall register particle trajectory (e.g., spin - flip)

τ_φ - phase breaking time



$\Rightarrow \langle \delta(\varphi_n - \varphi_{\bar{n}})^2 \rangle$

$\langle\ \rangle$ thermodynamical averaging

Also coll. with rest gas

$\tau_\varphi \lesssim \tau_{coll}$?

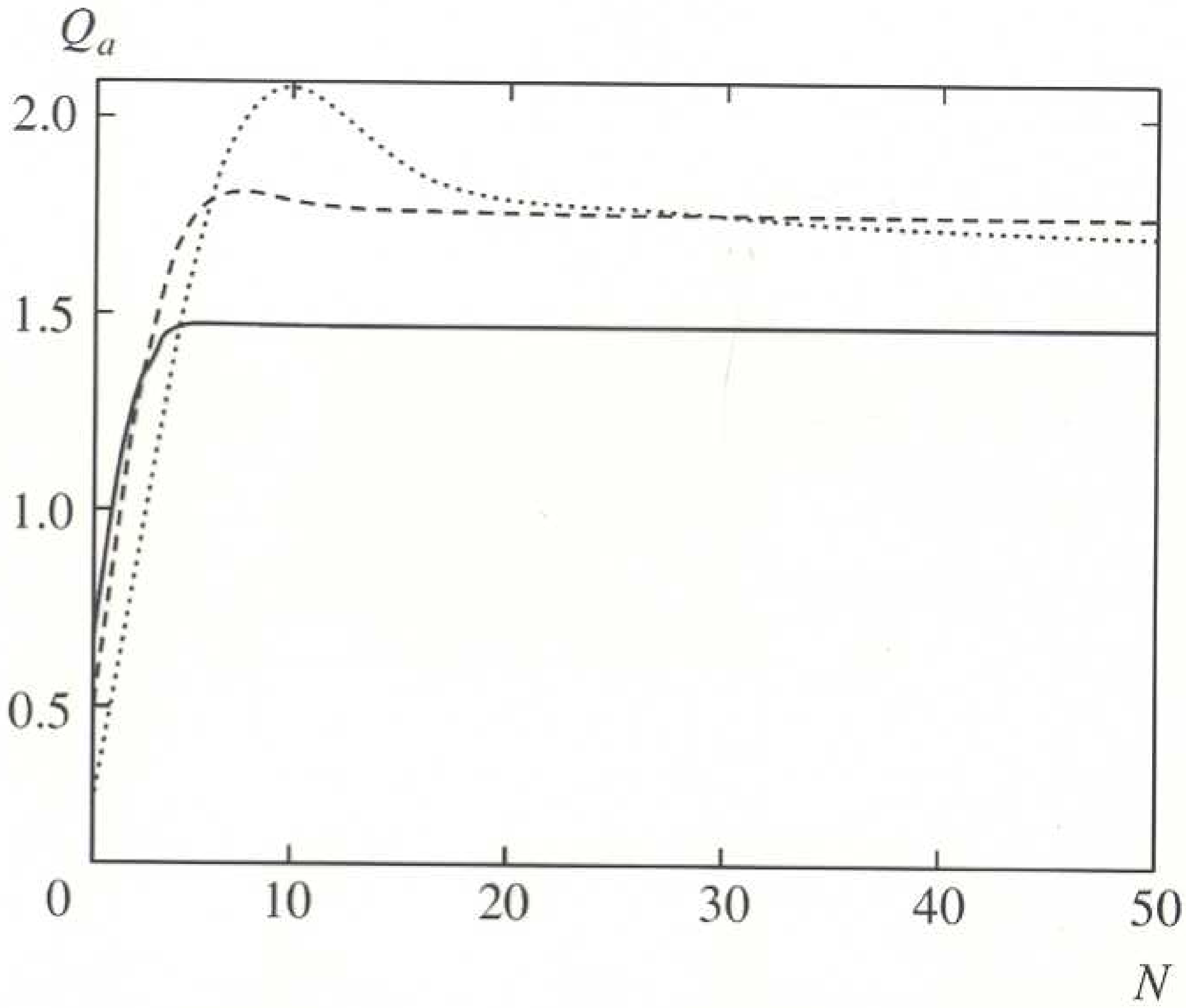
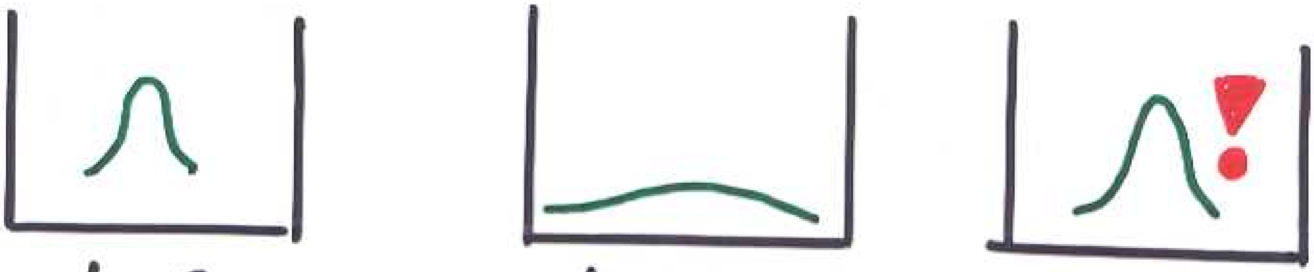


Fig. 1. Plot of the $Q_a(N) = (\epsilon^2\tau_L t)^{-1}P_a(N)$ dependence vs. N. The solid line corresponds to ^{12}C (graphite); the dashed one, to ^{12}C (diamond); and the dotted one, to Cu.

Wave Packet Revival



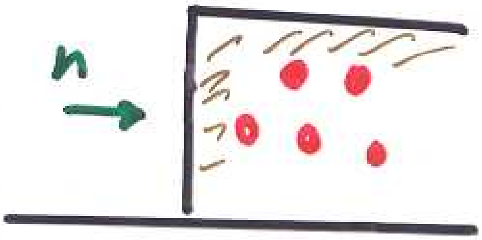
$t=0$ $\quad t=\tau_f$ $\quad t=2j_0\tau_l$

Large number of $\simeq$ equidistant levels within the wave packet → revival

$$\tau_{rev} = \begin{cases} \sim 1 \text{ year} & 2l = 10^{2}\text{ cm} \\ \sim 30\text{ s} & 2l = 10^{-1}\text{ cm} \end{cases}$$

Localization of UCN inside the walls

→ anomalous loss + quantum dephasing
(original idea of Serebrov)



Impurities in disorder →
→ Anderson localization
→ UCN loss +
+ dephasing

random barriers

Mirror Neutron Transitions

$$P(n') = 4\delta^2 \frac{t}{(\mu B)^2 \tau_\ell} \sin^2\left(k\ell\sqrt{1+\frac{\mu B}{E}}\right)$$

① weak B : $\mu B \ll \pi/\tau_\ell$

$$P(n') = 4\delta^2 \frac{t}{(\mu B)^2 \tau_\ell} \sin^2\left(\frac{\mu B m \ell}{k}\right) = \delta^2 \tau_\ell t$$

② $\mu B \gg \pi/\tau_\ell$

$$P(n') = \frac{2\delta^2}{(\mu B)^2 \tau_\ell} t .$$