Puzzling Neutron: A Window to New Physics?

A Detective Story in two parts

Zurab Berezhiani

University of L'Aquila and LNGS

TSU, Tbilisi, Aug. 20-24, 2018

Contents

Useful information

Neutrons – long known particles making 50% of atomic mass in our bodies ...

They are stable in nuclei but decay in free state as $n \to pe\bar{\nu}_e$ and in unstable nuclei (β-decay)

Fermi Theory of V-A form conserving baryon number – Standard Model

$$\frac{G_F\,|V_{ud}|}{\sqrt{2}}\;\overline{p}(1-g_A\gamma^5)\gamma^\mu n\;\overline{\nu}_e(1-\gamma^5)\gamma_\mu e$$

Yet, we do not know well enough its decay features and lifetime

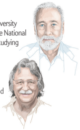
The lifetime puzzle

PARTICLE PHYSICS

the neutron enigma

Two precision experiments disagree on how long neutrons live before decaying. Does the discrepancy reflect measurement errors or point to some deeper mystery?

By Geoffrey L. Greene and Peter Geltenbort



Geoffrey L. Greene is a professor of physics at the University of Tennessee, with a joint appointment at the Oak Ridge National Laboratory's Spallation Neutron Source. He has been studying the properties of the neutron for more than 40 years.

Peter Geltenbort is a staff scientist at the Institut Laue-Langevin in Grenoble, France, where he uses one of the most intense neutron sources in the world to research the fundamental nature of this particle.

IN BRIEF

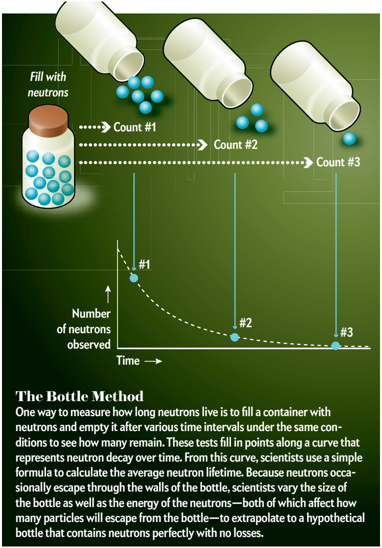
The best experiments in the world cannot agree on how long neutrons live before decaying into other particles.

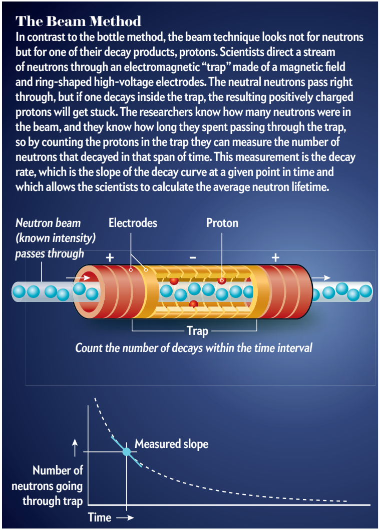
Two main types of experiments are under way: bottle traps count the number of neutrons that survive after various intervals, and beam experiments look for the particles into which neutrons decay.

Resolving the discrepancy is vital to answering a number of fundamental questions about the universe.

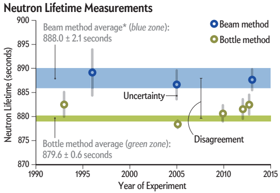
Illustration by Bill Mayer

Two methods to measure the neutron lifetime





Problems to meet ...



A few theorists have taken this notion seriously. Zurab Berezhiani of the University of L'Aquila in Italy and his colleagues have suggested such a secondary process: a free neutron, they propose, might sometimes transform into a hypothesized "mirror neutron" that no longer interacts with normal matter and would thus seem to disappear. Such mirror matter could contribute to the total amount of dark matter in the universe. Although this idea is quite stimulating, it remains highly speculative. More definitive confirmation of the divergence between the bottle and beam methods of measuring the neutron lifetime is necessary before most physicists would accept a concept as radical as mirror matter.

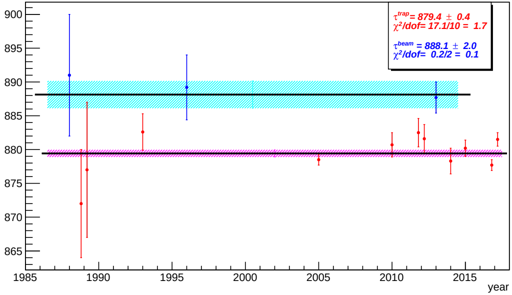
Why the neutron lifetime measured in UCN traps is smaller than that measured in beam method ? $n \to n'$ conversion can be plausible explanation: β-decay in invisible channel $n \to n' \to p' e' \bar{\nu}'$

Two methods to measure the neutron lifetime

Beam method measures neutron β-decay ($n \to pe\bar{\nu}_e$) width $\Gamma_\beta = \tau_\beta^{-1}$

Trap method measures neutron total decay width $\Gamma_n = \tau_n^{-1}$

Standard Model (and common wisdom of baryon conservation) tell that both should be the same, $\Gamma_n = \Gamma_\beta$ But ...



$\tau_{\rm trap} = 879.4 \pm 0.5$ s $\tau_{\rm beam} = 888.0 \pm 2.0$ s

$\Delta\tau = \tau_{\rm beam} - \tau_{\rm trap} = (8.6 \pm 2.1)$ s   more than 4σ discrepancy

Chapter I

Into the Darkness

The Neutron Dark Decay

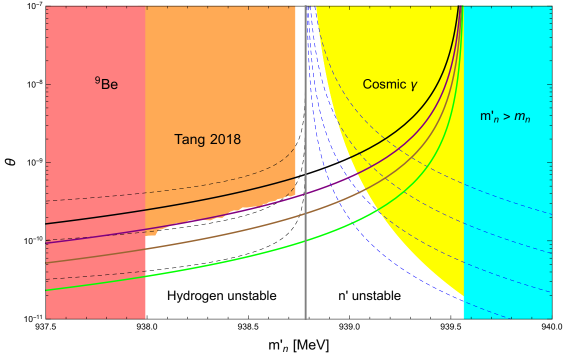
If this discrepancy is real (not due to some yet unknown systematics)

then New Physics should be invoked which could consistently explain the relations between the neutron decay width Γ_n, β-decay rate Γ_β, and the measured values $\tau_{\rm trap}$ and $\tau_{\rm beam}$

Some time ago I proposed a way out assuming that the neutron has a new decay channel $n \to n'X$ into a 'dark neutron' n' and light bosons X among which a photon, due to a mass gap $m_n - m_{n'} \simeq 1$ MeV. Then $\Gamma_\beta = \tau_{\rm beam}^{-1}$ and $\Gamma_n = \Gamma_\beta + \Gamma_{\rm new} = \tau_{\rm trap}^{-1}$,

$\tau_{\rm trap}/\tau_{\rm beam}$ discrepancy could be explained by a branching ratio $\mathrm{Br}(n \to n'X) = \Gamma_{\rm new}/\Gamma_n \simeq 0.01$.

Status of the Neutron Dark Decay



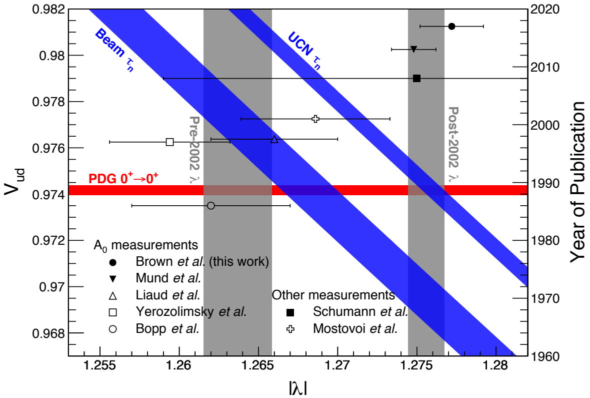
$\mathrm{Br}(n \to \chi\gamma) = 0.01$ $\quad \mathrm{Br}(n \to n'\gamma) = \mathrm{Br}(n \to n'\gamma') = 0.004$

$\mathrm{Br}(n \to n'\gamma) = 0.001, \mathrm{Br}(n \to n'\gamma') = 0.009$

$m_{n'} > m_p + m_e$, DM decays $n' \to pe\bar{\nu}_e$ $(\tau = 10^{14}, 10^{15}, 10^{16}, 10^{17}$ yr)

$m_{n'} < m_p + m_e$, Hydrogen atom decays $pe \to n'\nu_e$ $(\tau = 10^{20}, 10^{21}, 10^{22}$ yr)

τ_n vs. superallowed $0^+ - 0^+$ and β-asymmetry

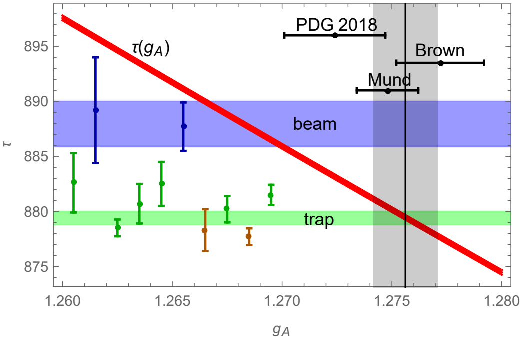


$|\lambda| = g_A$

$\tau_{\rm beam} = \tau_\beta$ seems incompatible with Standard Model

May indicate towards BSM physics? E.g. new contribution to β decay $n \to pe\bar{\nu}_e$? E.g. scalar form factor – mediated by exchange of charged Higgs (from extra Higgs doublet) – Does not help!

τ_n vs. β-asymmetry



$$\tau_\beta(1 + 3g_A^2) = (5172.0 \pm 1.1)\ \mathrm{s}$$

$$g_A = 1.2755 \pm 0.0011 \quad \longrightarrow \quad \tau_\beta^{\mathrm{SM}} = 879.5 \pm 1.3\ \mathrm{s}$$

$$\tau_{\mathrm{beam}} = 888.0 \pm 2.0\ \mathrm{s} \qquad \tau_{\mathrm{trap}} = 879.4 \pm 0.5\ \mathrm{s}$$

So experimentally we have $\tau_{\mathrm{trap}} = \tau_n = \tau_\beta < \tau_{\mathrm{beam}}$

while dark decay predicts $\tau_{\mathrm{trap}} = \tau_n < \tau_\beta = \tau_{\mathrm{beam}}$ Not Good!

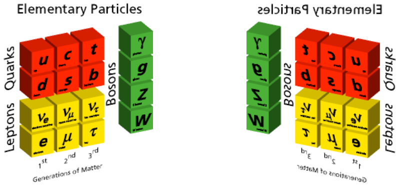
Chapter II

In and Out of the Darkness

$SU(3) \times SU(2) \times U(1) \quad + \quad SU(3)' \times SU(2)' \times U(1)'$

$$G \times G'$$

Regular world — Mirror world



- Two identical gauge factors, e.g. $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$
- Exact parity $G \to G'$: no new parameters in dark Lagrangian $\mathcal{L}'$
- MM is dark (for us) and has the same gravity
- MM is identical to standard matter, (asymmetric/dissipative/atomic) but realized in somewhat different cosmological conditions: $T'/T \ll 1$.
- New interactions between O & M particles $\quad \mathcal{L}_{mix}$

$SU(3) \times SU(2) \times U(1)$ vs. $SU(3)' \times SU(2)' \times U(1)'$

Two parities

Fermions and anti-fermions :

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}; \qquad u_R,\ d_R, \qquad e_R$$

B=1/3   L=1   B=1/3   L=1

$$\bar{q}_R = \begin{pmatrix} \bar{u}_R \\ \bar{d}_R \end{pmatrix}, \quad \bar{l}_R = \begin{pmatrix} \bar{\nu}_R \\ \bar{e}_R \end{pmatrix}; \qquad \bar{u}_L,\ \bar{d}_L, \qquad \bar{e}_L$$

B=-1/3   L=-1   B=-1/3   L=-1

Twin Fermions and anti-fermions :

$$q'_L = \begin{pmatrix} u'_L \\ d'_L \end{pmatrix}, \quad l'_L = \begin{pmatrix} \nu'_L \\ e'_L \end{pmatrix}; \qquad u'_R,\ d'_R, \qquad e'_R$$

B′=1/3   L′=1   B′=1/3   L′=1

$$\bar{q}'_R = \begin{pmatrix} \bar{u}'_R \\ \bar{d}'_R \end{pmatrix}, \quad \bar{l}'_R = \begin{pmatrix} \bar{\nu}'_R \\ \bar{e}'_R \end{pmatrix}; \qquad \bar{u}'_L,\ \bar{d}'_L, \qquad \bar{e}'_L$$

B′=-1/3   L′=-1   B′=-1/3   L′=-1

$$(\bar{u}_L Y_u q_L \bar{\phi} + \bar{d}_L Y_d q_L \phi + \bar{e}_L Y_e l_L \phi) + (u_R Y_u^* \bar{q}_R \phi + d_R Y_d^* \bar{q}_R \bar{\phi} + e_R Y_e^* \bar{l}_R \bar{\phi})$$

$$(\bar{u}'_L Y'_u q'_L \bar{\phi}' + \bar{d}'_L Y'_d q'_L \phi' + \bar{e}'_L Y'_e l'_L \phi') + (u'_R Y'^*_u \bar{q}'_R \phi' + d'_R Y'^*_d \bar{q}'_R \bar{\phi}' + e'_R Y'^*_e \bar{l}'_R \bar{\phi}')$$

Doubling symmetry $(L, R \to L, R$ parity$)$: $\quad Y' = Y \qquad B - B' \to -(B - B')$

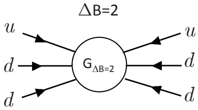
Mirror symmetry $(L, R \to R, L$ parity$)$: $\quad Y' = Y^* \qquad B - B' \to B - B'$

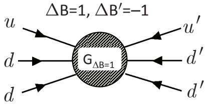
B violating operators between O and M particles in $\mathcal{L}_{\rm mix}$

Ordinary quarks $u,\ d$ (antiquarks $\bar{u},\ \bar{d}$)
Mirror quarks $u',\ d'$ (antiquarks $\bar{u}',\ \bar{d}'$)

- Neutron -mirror neutron mixing – (Active - sterile neutrons)

$$\frac{1}{M^5}(udd)(udd) \text{ and } \frac{1}{M^5}(udd)(u'd'd') \quad (+\text{ h.c.})$$



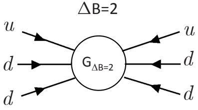


Oscillations $n(udd) \leftrightarrow \bar{n}(\bar{u}\bar{d}\bar{d})$ $(\Delta B = 2)$
$n(udd) \to \bar{n}'(\bar{u}'\bar{d}'\bar{d}'),\ n'(udd) \to \bar{n}(\bar{u}\bar{d}\bar{d})$ $(\Delta B = 1,\ \Delta B' = -1)$

Can co-generate Baryon asymmetries in both worlds
of the same sign, $B, B' > 0$, with $\Omega'_B \simeq 5\,\Omega_B$

Neutron– antineutron oscillation

Majorana mass of neutron $\epsilon(n^T C n + \bar{n}^T C \bar{n})$ violating B by two units comes from six-fermions effective operator $\frac{1}{M^5}(udd)(udd)$



It causes transition $n(udd) \to \bar{n}(\bar{u}\bar{d}\bar{d})$, with oscillation time $\tau = \epsilon^{-1}$

$$\varepsilon = \langle n|(udd)(udd)|\bar{n}\rangle \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \sim \left(\frac{100\ {\rm TeV}}{M}\right)^5 \times 10^{-25}\ \text{eV}$$

Key moment: *$n - \bar{n}$ oscillation destabilizes nuclei:*
$(A, Z) \to (A-1, \bar{n}, Z) \to (A-2, Z/Z-1) + \pi$'s

Present bounds on ϵ from nuclear stability

$\varepsilon < 1.2 \times 10^{-24}$ eV $\;\to\;$ $\tau > 1.3 \times 10^8$ s $\quad$ Fe, Soudan 2002

$\varepsilon < 2.5 \times 10^{-24}$ eV $\;\to\;$ $\tau > 2.7 \times 10^8$ s $\quad$ O, SK 2015

Free neutron– antineutron oscillation

Two states, n and $\bar{n}$

$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \varepsilon \\ \varepsilon & m_n - \mu_n \mathbf{B}\sigma \end{pmatrix}$$

Oscillation probability $P_{n\bar{n}}(t) = \frac{\varepsilon^2}{\omega_B^2} \sin^2(\omega_B t), \quad \omega_B = \mu_n B$

If $\omega_B t \gg 1$, then $P_{n\bar{n}}(t) = \frac{1}{2}(\varepsilon/\omega_B)^2 = \frac{(\varepsilon t)^2}{(\omega_B t)^2}$

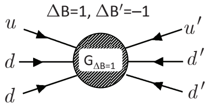
If $\omega_B t < 1$, then $P_{n\bar{n}}(t) = (t/\tau)^2 = (\varepsilon t)^2$

"Quasi-free" regime: for a given free flight time t, magnetic field should be properly suppressed to achieve $\omega_B t < 1$.
More suppression makes no sense !

Exp. Baldo-Ceolin et al, 1994 (ILL, Grenoble) : $t \simeq 0.1$ s, $B < 100$ nT
$\tau > 2.7 \times 10^8 \quad \rightarrow \quad \varepsilon < 7.7 \times 10^{-24}$ eV
At ESS 2 orders of magnitude better sensitivity can be achieved, down to $\varepsilon \sim 10^{-25}$ eV

Neutron – mirror neutron mixing

Effective operator $\frac{1}{M^5}(udd)(u'd'd') \quad \rightarrow \quad$ mass mixing $\epsilon n C n' + \mathrm{h.c.}$
violating B and B' – but conserving $B - B'$



$$\epsilon = \langle n|(udd)(u'd'd')|\bar{n}'\rangle \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \sim \left(\frac{1\ \rm TeV}{M}\right)^5 \times 10^{-10}\ \rm eV$$

Key observation: *$n - \bar{n}'$ oscillation cannot destabilise nuclei:*
$(A, Z) \rightarrow (A-1, Z) + n'(p'e'\bar{\nu}')$ forbidden by energy conservation
(In principle, it can destabilise Neutron Stars)

Even if $m_n = m_{n'}$, $n - \bar{n}'$ oscillation can be as fast as $\epsilon^{-1} = \tau_{n\bar{n}'} \sim 1$ s, without contradicting experimental and astrophysical limits.
(c.f. $\tau_{n\bar{n}'} > 2.5 \times 10^8$ s for neutron – antineutron oscillation)

Neutron disappearance $n \rightarrow \bar{n}'$ and regeneration $n \rightarrow \bar{n}' \rightarrow n$
can be searched at small scale 'Table Top' experiments

$n - n'$ mixing and transitional moments

$n - n'$ mass mixing $\epsilon \bar{n} n' + \mathrm{h.c.}$
Let us assume $\epsilon \sim 10^{-10}$ eV and $m_n - m_{n'} = \Delta m \sim 10^{-7}$ eV

transitional magn. moment/EDM $\mu_{nn'}(F_{\mu\nu} + F'_{\mu\nu})\bar{n}\sigma^{\mu\nu} n' + \mathrm{h.c.}$

Hamiltonian of n and n' system becomes

$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \epsilon + \mu_{nn'}(\mathbf{B} + \mathbf{B}')\sigma \\ \epsilon + \mu_{nn'}(\mathbf{B} + \mathbf{B}')\sigma & m_{n'} + \mu_n \mathbf{B}'\sigma \end{pmatrix}, \quad x = \frac{\mu_{nn'}}{\mu_n}$$

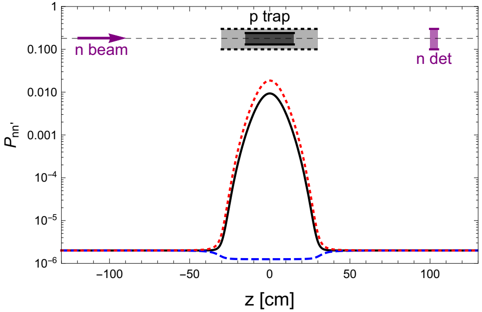
If $B, B' \ll \Delta m$, oscillation probability is $P_{nn'} \simeq (\epsilon/\Delta m)^2 \sim 10^{-6}$
... Allowed by evaluation of UCN losses in traps

Interplay of ϵ, $\mu_{nn'}$ and $d_{nn'}$ can take place .... the latter is also interesting since in beam experiments also large electric fields are used

Beam Experiments

$n - n'$ conversion probability depends on magn. field in proton trap

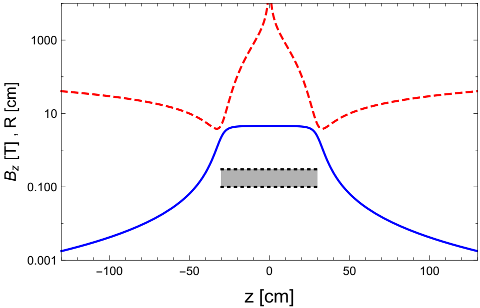
$$N_n = P^{\rm tr}_{nn} L \int_A da \int dv\, I(v)/v \quad \text{and} \quad N_{n'} = P^{\rm tr}_{nn'} L \int_A da \int dv\, I(v)/v$$



$$\dot N_p = e_p \Gamma_\beta P^{\rm tr}_{nn} L \int_A da \int dv \frac{I(v)}{v}, \qquad \dot N_\alpha = e_\alpha \bar v P^{\rm det}_{nn} \int_A da \int dv \frac{I(v)}{v}$$

$$\tau_{\rm beam} = \left(\frac{e_p L}{e_\alpha \bar v}\right)\left(\frac{\dot N_\alpha}{\dot N_p}\right) = \frac{P^{\rm det}_{nn}}{P^{\rm tr}_{nn}}\,\tau_\beta$$

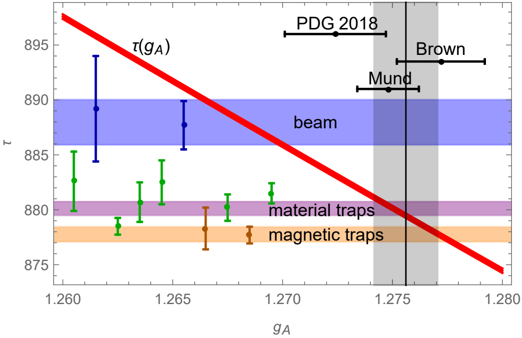
Adiabatic or non-adiabatic (Landau-Zener) conversion ?



$$P^{\rm tr}_{nn'} \approx \frac{\pi}{4}\xi \simeq 10^{-2}\left(\frac{2\ \rm km/s}{v}\right)\left(\frac{P^0_{nn'}}{10^{-6}}\right)\left(\frac{B_{\rm res}}{1\ \rm T}\right)\left(\frac{R_{\rm res}}{10\ \rm cm}\right)$$

$R(z) = (d\ln B/dz)^{-1}$ – characterises the magnetic field gradient at the resonance

τ_n vs. β-asymmetry: $\tau_\beta(1 + 3g_A^2) = (5172.0 \pm 1.1)$ s



$g_A = 1.2755 \pm 0.0011 \quad \longrightarrow \quad \tau_\beta^{\rm SM} = 879.5 \pm 1.3$ s

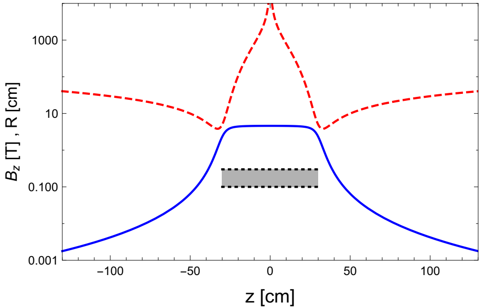
$\tau_{\rm beam} = 888.0 \pm 2.0$ s $\qquad \tau_{\rm trap} = 879.4 \pm 0.5$ s

$\tau_{\rm mat} = 880.2 \pm 0.5$ s, $\quad \tau_{\rm magn} = 877.8 \pm 0.7$ s (2.6σ discrepancy)

So experimentally we have $\quad \tau_{\rm magn} < \tau_{\rm mat} = \tau_n = \tau_\beta < \tau_{\rm beam}$

what s exactly predicted by my scenario **So far so Good!**

Adiabatic or non-adiabatic (Landau-Zener) conversion ?



$$P^{\rm tr}_{nn'} \approx \frac{\pi}{4}\xi \simeq 10^{-2}\left(\frac{2~{\rm km/s}}{v}\right)\left(\frac{P^0_{nn'}}{10^{-6}}\right)\left(\frac{B_{\rm res}}{1~{\rm T}}\right)\left(\frac{R_{\rm res}}{10~{\rm cm}}\right)$$

$R(z) = (d \ln B/dz)^{-1}$ – characterises the magnetic field gradient at the resonance

Adiabatic or non-adiabatic (Landau-Zener) conversion ?

If my hypothesis is correct, a simple solenoid with magnetic fields $\sim$ Tesla can be very effective machines that transform neutrons into dark matter.

Some groups in LANL, ORNL and NIST already think how to prepare simple experiments that could test this

Adiabatic conditions can be improved and 50 % transformation can be achieved

$$P^{\rm tr}_{nn'} \approx \frac{\pi}{4}\xi \simeq 10^{-2} \left(\frac{2 \text{ km/s}}{v}\right) \left(\frac{P^0_{nn'}}{10^{-6}}\right) \left(\frac{B_{\rm res}}{1 \text{ T}}\right) \left(\frac{R_{\rm res}}{10 \text{ cm}}\right)$$

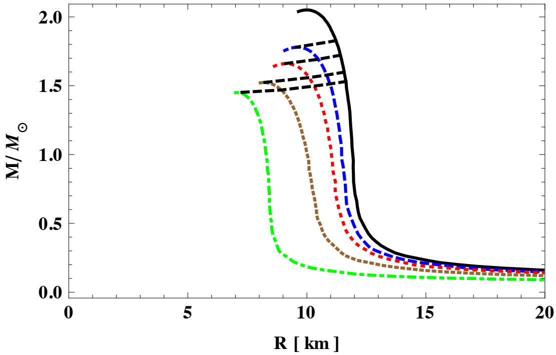
$R(z) = (d \ln B/dz)^{-1}$ – characterises the magnetic field gradient at the resonance

Neutron Stars

By $n \to n'$ conversion ordinary neutron star slowly transforms into mixed (50% - 50%) ordinary-mirror neutron star ....

O and M "neutrons" have same equation of state $p(n) = F[\rho(n)]$)

$\sqrt{2}$ rule: $\quad R^{\rm mix}(M) = \frac{1}{\sqrt{2}} R^{\rm ord}(M), \quad M^{\rm mix}_{\rm max} = \frac{1}{\sqrt{2}} M^{\rm ord}_{\rm max},$



... solving "mixed" OV equations