Neutron disappearance and regeneration from mirror state

Louis Varriano
University of Tennessee, Knoxville

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Mirror matter hypothesis

- for a review, see L. B. Okun, Phys. Usp. 50 380-389 (2007)

- Mirror matter (MM) is a hypothetical form of matter and is a copy of the Standard Model particle content in a hidden “mirror” sector, with identical self-couplings and possibly new interactions between the two sectors.

- MM sector has identical forces and self-interacting particles which are dark to ordinary matter (OM), with gravity as a common force.

- Exact symmetry between the two sectors means no new parameters, except for possible mixing parameters.

- In \( \mathcal{L}_{\text{tot}} \), MM might restore global parity between left-right in weak sector.

Two identical gauge sectors (ex. \( SU(5) \times SU(5)' \)) with identical field contents, couplings, and Lagrangians:

\[
\mathcal{L}_{\text{tot}} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\text{mix}}
\]

\( \mathcal{L}_{\text{mix}} \) could contain new particle interactions between sectors for neutral particles (e.g. \( \gamma, \nu, n, \) etc.).
Mirror matter as dark matter

– No DM has yet been observed, despite popularity of existing models and experimental searches for new particles.

– **Alternative DM models should be explored.**

– MM is a natural dark matter (DM) candidate since its particles do not interact with OM except through gravity (and perhaps some new mixing force).

– MM is currently not excluded by any experiment and is consistent with cosmological observation.


– MM is similar to OM, but, because its temperature $T' < T$, has $\sim 25\%$ mirror H and $\sim 75\%$ mirror He by mass.

No DM direct detection experiments of MM yet

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Neutral particles could oscillate between sectors

- Free neutrons (no charge and colorless) could oscillate between OM and MM sectors via new mechanism.

- \( n-n' \) could be fast (\( \tau_{nn'} \gtrsim 1 \text{ s} \)) compared to \( n-\bar{n} \) (\( \tau_{n\bar{n}} > 2.4 \times 10^8 \text{ s} \)), which could be a second-order effect.

\[ n \rightarrow n' \]

\[ G_{\Delta B=1} = \frac{1}{M_D M_S^4} \]

\[ n \rightarrow \bar{n} \]

\[ G_{\Delta B=2} = \frac{\langle \chi \rangle}{M_D} \frac{1}{M_D M_S^2} \]

small
Magnetic resonance in $n-n'$ oscillations

- The $n-n'$ Hamiltonian $\hat{H} = \left( m + \mu (\vec{\sigma} \cdot \hat{\vec{B}}) \right) \left( m + \mu (\vec{\sigma} \cdot \hat{\vec{B}}') \right)$.

- Enhancement of oscillation probability if magnetic fields in each sector are aligned and same magnitude ("resonance" behavior).

- Direction and magnitude of $B'$ unknown.

- When $\mu B \gg \varepsilon$, the dependence of the probability of oscillation on angle $\beta$ between the two magnetic field can be written:

$$P_{n\rightarrow n'}(t) = \frac{\sin^2\left(\frac{\mu B}{2} - \frac{\mu B'}{2}\right)t}{2\tau^2\left(\frac{\mu B}{2} - \frac{\mu B'}{2}\right)^2} \left[1 + \cos(\beta)\right] + \frac{\sin^2\left(\frac{\mu B}{2} + \frac{\mu B'}{2}\right)t}{2\tau^2\left(\frac{\mu B}{2} + \frac{\mu B'}{2}\right)^2} \left[1 - \cos(\beta)\right]$$
Previous $n-n'$ oscillation searches

- Three ultra-cold neutron experiments performed previously

- One neutron beam regeneration-type experiment performed previously (unpublished)
  1. U. Schmidt (Heidelberg), BLNV Workshop 2007
Most persuasive experiment with ultra-cold neutrons

- 190L volume stores $\sim 500,000$ UCN with wall collision rate of $\sim 10$ per neutron per second.

- Magnetic field varied: $\sim 0$ Gauss or $\pm 0.2$ Gauss (up or down).

- Neutron lifetime in the trap is measured with a cycle of 130 s filling, 300 s storage, and 130 s counting survivors.

- Comparison of applied magnetic field counting with shielded field ($\sim 0$ G) counting can reveal $n-n'$ effect.

- Assuming $B' = 0$, $n-n'$ oscillation time $\tau > 448s$ (90% CL).
Most persuasive experiment with ultra-cold neutrons

\[ n \rightarrow n' \text{ UCN search at ILL / Grenoble (2007)/ A. Serebrov et al.} \]
Reanalysis discovered magnetic anomaly!


- Asymmetry
  \[ A^\text{det}_B(t) = \frac{N_{-B}(t) - N_B(t)}{N_{-B}(t) + N_B(t)} \]

- Reanalysis shows the asymmetry has a 5.2\(\sigma\) deviation from zero, dependent on the applied magnetic field direction.

- This could be indication of non-zero \(B'\) field present at Earth!

- Fitted parameter indicate \(B \sim 0.1\) G and \(\tau_\beta \sim\) few seconds.

- A new experiment should be performed by an alternate method to be sensitive to this anomaly.
UCN experiment with scanning magnetic field

- Scanning over the magnetic field from $+12.5 \mu T$ to $-12.5 \mu T$ in $2.5 \mu T$ increments.

- Data shows that step size is too coarse to observe resonance.

- Data could be fit equally well with straight line.

- Low significance fit, however, indicates that $B' \sim 11 \mu T$, $\beta \sim 25^\circ$, $\tau \sim 20$ s.

- Experiment with finer steps in magnetic field could reveal resonance!

FIG. 1: (colour online) Combined fit to the normalised UCN counts as a function of applied magnetic field $B$ for 75 s (dark green squares and solid line) and 150 s (light green triangles and dashed line). Positive (negative) $B$ values correspond to $B$ field up (down).
UCN scattering can have ambiguous interpretation

- UCN scattering on trap walls leads to higher loss coefficients than predicted by calculation - not well understood.
  - E. A. Goremychkin and Yu. N. Pokotilovski, JGU Mainz, Germany (2016)

- Asymmetry anomaly might be some other, unexplained phenomenon, not mirror transformation.

- Neutron beam regeneration experiment without neutron reflections eliminates potentially anomalous effects.
Previously - cold neutron beam regeneration at $B = 0$

- U. Schmidt (Heidelberg), BLNV Workshop 2007

- Previous cold neutron beam experiment compared neutron counts with applied magnetic field to counts with suppressed, zero field.

- New, proposed experiment revives previous beam technique with added component - scanning over lab magnetic field.

“Neutron disappearance and regeneration from mirror state”
Z. Berezhiani, M. Frost, Y. Kamyshkov, B. Rybolt, and L. Varriano
New, proposed regeneration experiment

- Proposed regeneration experiment to be sensitive to $\tau \sim 10 - 20$ s, independent of angle $\beta$.

- Paper examines SNS as possible site of experiment as an example → Leah Broussard (next) to talk about real experiment at HFIR.
Conclusions

- Mirror matter offers an attractive theory to help explain several big problems in physics, including nature of dark matter, and could also shed light on the baryonic asymmetry problem.

- A neutron regeneration experiment can check the anomalous UCN signal unambiguously, with good control of magnetic fields and by eliminating neutron wall reflections, which lack a satisfactory theoretical understanding.

- The unique character of the resonance signal is different than simply measuring a UCN asymmetry, which might be attributed to different effects.

- By enhancing/suppressing the resonance signal, it could be possible to determine mirror magnetic field vector at Earth.
Questions?

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Mirror matter as dark matter

- T. Tait, Snowmass 2013

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Parameters affecting experiment

\( n-n' \) disappearance is influenced by six parameters:

- \( \tau \) - \( n-n' \) oscillation period
- \( B \) - lab magnetic field strength
- \( B' \) - mirror magnetic field strength
- \( \beta \) - angle between lab magnetic field and mirror magnetic field
- \( \varphi \in \mathbb{C} \) - Fermi pseudo-potential of residual lab gas (\( H_2 \))
  \( \Rightarrow \) residual gas pressure
- \( \varphi' \in \mathbb{C} \) - Fermi pseudo-potential of mirror gas (\( H'_2 \) or \( \bar{H}'_2 \))
  \( \Rightarrow \) mirror gas pressure (\textit{neglected here})