Astrophysical Constraints on Neutrino Magnetic Moments

Timur Rashba

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Weak Interactions and Neutrinos, Delphi, 2005

Outline

1. Introduction
    - Astrophysical motivations
    - Theoretical grounds
2. Astrophysical constraints
    - μ_ν in cosmology and astrophysics
    - Present bounds
    - Some future hopes
3. Summary

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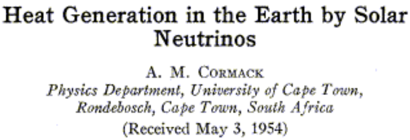
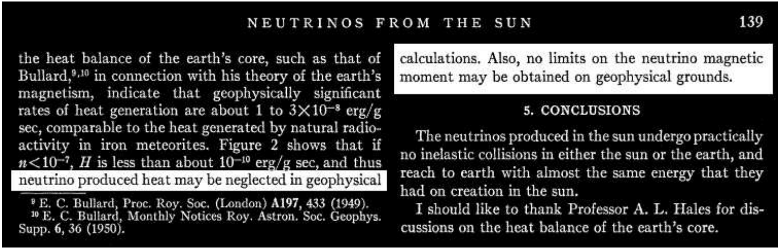
One of early attempts to astrophysical search for μ_ν



Heat Generation in the Earth by Solar Neutrinos

A. M. Cormack
Physics Department, University of Cape Town,
Rondebosch, Cape Town, South Africa

(Received May 3, 1954)



NEUTRINOS FROM THE SUN 139

the heat balance of the earth's core, such as that of Bullard,[9,10] in connection with his theory of the earth's magnetism, indicate that geophysically significant rates of heat generation are about 1 to 3×10^{-8} erg/g sec, comparable to the heat generated by natural radioactivity in iron meteorites. Figure 2 shows that if $n<10^{-7}$, H is less than about 10^{-10} erg/g sec, and thus neutrino produced heat may be neglected in geophysical calculations. Also, no limits on the neutrino magnetic moment may be obtained on geophysical grounds.

5. CONCLUSIONS

The neutrinos produced in the sun undergo practically no inelastic collisions in either the sun or the earth, and reach to earth with almost the same energy that they had on creation in the sun.

I should like to thank Professor A. L. Hales for discussions on the heat balance of the earth's core.

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[9] E. C. Bullard, Proc. Roy. Soc. (London) **A197**, 433 (1949).
[10] E. C. Bullard, Monthly Notices Roy. Astron. Soc. Geophys. Supp. **6**, 36 (1950).

[A.M. Cormack'54 and '55]

μ_ν: astrophysical motivations

Search for ν electromagnetic properties

"the weak interactions have produced so many surpises that it is worthwhile, from time to time, to study the experimental limits (both weak-interaction results and astrophysical data) that have been set on the neutrino properties." [*Bernstein, Ruderman & Feinberg'63*]

$\mu_\nu < 10^{-10}\mu_B$ *(based on plasmon decay rate and solar energy loss)*

Solar neutrino problem

- ν spin flip in solar magnetic field to explain Homestake data [*Cisneros'71*]
- Anti-correl. of ν data with sol. magn. activity [*Voloshin, Visotsky & Okun'86*]
- ν spin flavor precession in matter [*Akhmedov'88, Lim & Marciano'88*]

Cosmological bounds

- ν_R exitation may affect BBN [*Morgan'81, Shapiro & Wasserman'81, . . .*]

Supernova 1987A

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μ_ν: more astrophysical motivations

Present laboratory bounds (at 90% C.L.)

- $\mu_{\nu_e} < 1.0 \times 10^{-10} \mu_B$ $\bar{\nu}_e$-e scatt. MUNU
- $\mu_{\nu_\mu} < 6.8 \times 10^{-10} \mu_B$ ν_μ-e and $\bar{\nu}_\mu$-e scatt. LSND
- $\mu_{\nu_\tau} < 3.9 \times 10^{-7} \mu_B$ ν_τ-e scatt. DONUT

Astrophysical and cosmological bounds

$$\mu_\nu \sim 10^{-12} - 10^{-11} \mu_B$$

However, the situation can be changed in near future due to many new experimental proposals and project activities
⇒ see next talk by Henry Wong

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ν electromagnetic properties: theoretical grounds

Standard Model with $m_\nu \neq 0$

- SM with right handed neutrino singlet *[Lee & Shrock'77]*

$$\mu_\nu = 3.2 \times 10^{-19} \mu_B \frac{m_\nu}{1 \text{ eV}}$$

Extensions beyond the Standard Model

- However in extended electroweak models there are no direct relations between μ_ν and m_ν and, e.g., μ_ν might be proportional to the mass of heavy charge lepton interacting with charge scalar
- e.g. in MSSM with horizontal symmetry between e and μ transition magnetic moments might be up to

$$\mu_\nu \sim 10^{-11} - 10^{-10} \mu_B$$

keeping neutrino masses and splittings small

[Babu & Mohapatra'89, Leurer & Marcus'90,. . .]

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[Babu & Mohapatra'89, Leurer & Marcus'90,...]

ν electromagnetic interactions

Effective hamiltonians

$$H_{em}^{Dirac} = \frac{1}{2}\bar{\nu}_R \lambda \sigma^{\mu\nu} \nu_L F_{\mu\nu} + \text{H.c.}$$

$$H_{em}^{Majorana} = -\frac{1}{4}\nu_L^T C^{-1} \lambda \sigma^{\mu\nu} \nu_L F_{\mu\nu} + \text{H.c.}$$

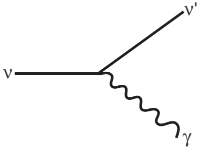
In Dirac case: λ is an arbitrary matrix

In Majorana case: $\lambda^T = \lambda$, only transition moments are non-zero, may be parametrized as $\lambda_{\alpha\beta} = \varepsilon_{\alpha\beta\gamma}\Lambda_\gamma$

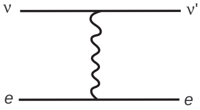
$\lambda = \mu - id$, μ – magnetic moment matrix, d – electric dipole moment matrix

ν electromagnetic processes relevant in astrophysics

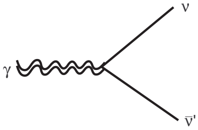
[*See for details and refs Raffelt'96*]



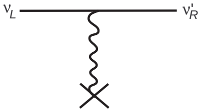
ν decay or Cherenkov radiation



$\nu - e$ scatt. or e^+-e^- annigilation



Plasmon decay



Spin (flavor) precession

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Neutrinos in astrophysics and cosmology

μ_ν can be of some importance in ...

- Early Universe, in particular for BBN
- Cosmic neutrino background
- Supernovae explosion
- Star cooling
- Solar neutrinos propagation and detection

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Early Universe neutrinos

Big-bang nucleosynthesis

Spin-flip collisions would populate the sterile Dirac neutrino components in Early Universe and thus encrease the effective number of thermally excited neutrino degrees of freedom at the time of BBN. Consequently it would change primordial abundances of light elements, in particular, helium.

Two types of processes are relevant:

- $\nu + e \to \nu + e$, $\gamma \to \nu\bar{\nu}$, $e^+e^- \to \nu + \bar{\nu}$. Plasma effects are important!

  [Elmfors et al'97]

  $$\mu_\nu^{(D)} < 6 \times 10^{-11} \mu_B \quad \text{for } T_d = 100MeV$$

  [Ayala et al'99]

  $$\mu_\nu^{(D)} < 3 \times 10^{-10} \mu_B \quad \text{for } T_d = 100MeV$$

- neutrino spin flip in primordial magnetic fields
  - Spin flip in large scale primordial fields ⇒ bounds on $\mu_\nu^{(D)} \times B$
  - Spin flip in random primordial fields ⇒ $\mu_\nu^{(D)} < 10^{-19} - 10^{-16} \mu_B$ ⇒ but strongly depends on random field parameters! [Pastor et al.'95]

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Supernova neutrinos

Supernova 1987A bounds

Left handed neutrinos trapped in SN dense core may convert to sterile ν-s via Dirac $\mu_\nu^{(D)}$ and freely escape.

This would lead to three possible effects:

- Energy release to right sterile ν-s
  $\mu_\nu^{(D)} < 10^{-12} - 10^{-11} \mu_B$ [Barbieri & Mohapatra'88, Ayala et al'98,...]
- Shorten in time signal of observed left-handed ν_e
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SN bounds depend very much on SN explosion modelling, $\nu_L \to \nu_R$ suppressed by matter effects, SN magnetic field is unknown, ...

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Star cooling neutrinos

Red giant bounds

Nonstandard neutrino looses would delay the helium ignition in the cores of red giant globular cluster stars. The main process is a plasmon decay $\gamma \to \nu\bar{\nu}$, ν-s freely escape from the core.

$$\mu_\nu < 3 \times 10^{-12} \mu_B$$

[*Raffelt'90*]

Observation of color-magnitude diagrams of globular cluster stars provides a restrictive limit on red giants core mass, corresponding to the restriction of new neutrino energy loss

- Important note: this limit applies equally to all electric dipole and magnetic transition moments both in Dirac and in Majorana neutrino cases!
- Note: only for $m_\nu < 5$keV that $\gamma \to \nu\bar{\nu}$ is kinematically allowed.

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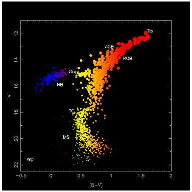

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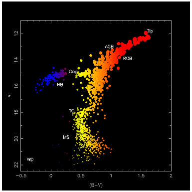

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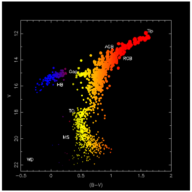
Nonstandard neutrino looses would delay the helium ignition in the cores of red giant globular cluster stars. The main process is a plasmon decay $\gamma \to \nu\bar{\nu}$, ν-s freely escape from the core.

$$\mu_\nu < 3 \times 10^{-12} \mu_B$$

[*Raffelt'90*]

Observation of color-magnitude diagrams of globular cluster stars provides a restrictive limit on red giants core mass, corresponding to the restriction of new neutrino energy loss



- Important note: this limit applies equally to all electric dipole and magnetic transition moments both in Dirac and in Majorana neutrino cases!
- Note: only for $m_\nu < 5$keV that $\gamma \to \nu\bar{\nu}$ is kinematically allowed.

Solar neutrinos

Plasmon decay in solar plasma

$\mu_\nu < 4 \times 10^{-10} \mu_B$ based on present helioseismic data

[Raffelt'99, present day update of Bernstein et al.'63]

Spin flip and spin flavor conversion in solar magnetic field

only $\mu_\nu \times B$ may be constrained → poor knowledge of solar field

Spin-flavor conversion in solar turbulent field

allows to avoid magnetic field uncertainties up to some extent

$\mu_{12}^{(M)} < 5 \times (10^{-12} - 10^{-11}) \mu_B$

Solar neutrino detection

Using solar neutrinos instead of reactor and artificial ν sources

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Majorana μ_ν bound in solar turbulent magnetic field

KamLAND bound on $\bar{\nu}_e$ flux

$$\Phi_{\bar{\nu}_e} < 2.8 \times 10^{-4} \Phi_{\nu_e}^{^8B}$$

Majorana $\bar{\nu}_e$ appearance in solar turbulent field

[Miranda et al'04]

$$P(\bar{\nu}_e)_{Earth} \sim \mu_{12}^2 \frac{b_{max}^2}{L_{max}^{2/p}}$$

Turbulent field scales as $b \sim L^{1/p}$

"Realistic" bound: $\mu_{12}^{(M)} < 5 \times 10^{-12} \mu_B$

"Conservative": $\mu_{12}^{(M)} < 4 \times 10^{-11} \mu_B$

[For discussion see also Friedland'05]

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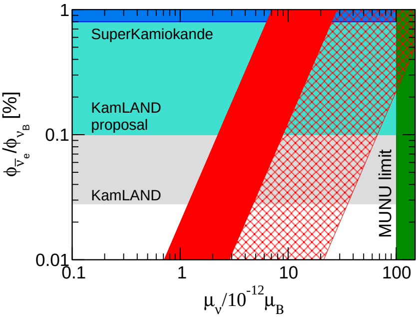

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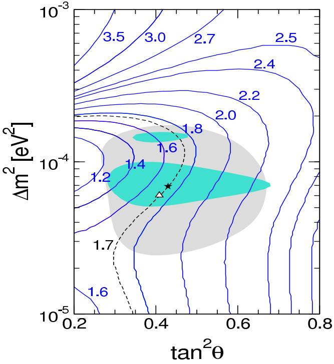
Constraining $\mu_\nu^{(M)}$ from solar and reactor data

By the courtesy of Mariam Tortola [Grimus et al'03]

Bounds on $|\vec{\Lambda}|$ from solar and reactor data

- **method I** → $|\vec{\Lambda}| < 1.8 \times 10^{-10}\ \mu_B$ at 90% C.L.
- **method II** → contours of 90% C.L. bound on $|\vec{\Lambda}|$ $(10^{-10}\mu_B)$:



⇒ reactor data **very sensitive to θ**: drastic improvement in the bound for low Δm^2 values.

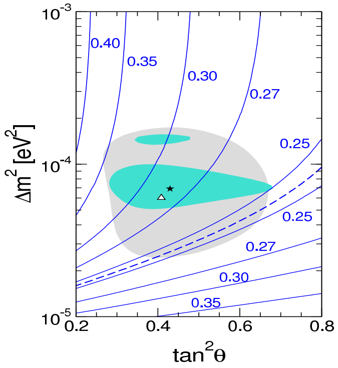
⇒ upper-left part: no significant improvement.

Constraining $\mu_\nu^{(M)}$: sensitivity of Borexino

By the courtesy of Mariam Tortola [*Grimus et al'03*]

Sensitivity on $|\vec{\Lambda}|$ of Borexino

- **Best fit point** (3 years data taking): $|\vec{\Lambda}| < 0.28 \times 10^{-10}\ \mu_B$ at 90% C.L.
- **LMA region** → contours of 90% C.L. bound on $|\vec{\Lambda}|$ $(10^{-10}\mu_B)$:



⇒ **strongest** attainable **limit** $\sim 0.24 \times 10^{-10}\ \mu_B$, for $P_{e1} = 0.5$ (dashed line).

⇒ **Borexino** is more sensitive to MMs because of **lower energies observed**:

- bigger e.m. contribution expected.
- P_{e1} closer to optimal value 0.5.

Outline

1. Introduction
   - Astrophysical motivations
   - Theoretical grounds
2. Astrophysical constraints
   - μ_ν in cosmology and astrophysics
   - Present bounds
   - Some future hopes
3. Summary

Some future hopes

- *In Dirac case:* it's very difficult to pull down astrophysical and cosmological μ_ν bounds since the "missing" effects are becaming so small to produce any astrophysically significant phenomena
- *In Majorana case:* the crucial point is the search for or would be a detection of $\bar{\nu}_e$ in future experiments ("appearance" observation)
  - $\bar{\nu}_e$ from the Sun, converted in solar magnetic field [*Balantekin & Loreti'92,. . . .*]
  - $\bar{\nu}_e$ from future Supernova 20xx arriving together with the prompt neutrinization burst [*Akhmedov & Fukuyama'03*]

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- Some of astrophysical bounds on μ_ν are very reliable and still stronger than laboratory ones
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