Neutrinos and the Stars
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Lectures at JIGSAW 07, 12–23 Feb 2007, TIFR, Mumbai, India

Where do Neutrinos Appear in Nature?

- Nuclear Reactors
- Sun
- Supernovae (Stellar Collapse)
- Particle Accelerators
- Earth Atmosphere (Cosmic Rays)
- Astrophysical Accelerators
- Earth Crust (Natural Radioactivity)
- Cosmic Big Bang (Today 330 km/s^2)

Indirect Evidence

- Nuclear Reactors
- Particle Accelerators
- Earth Atmosphere (Cosmic Rays)
- Sun
- Earth Crust (Natural Radioactivity)
- Cosmic Big Bang (Today 330 km/s^2)

Neutrinos from the Sun

- Solar radiation: 98% light, 2% neutrinos
- At Earth 66 billion neutrinos/cm^2 sec

Thermonuclear reaction chains (1938)

Bethe’s Classic Paper on Nuclear Reactions in Stars

No neutrinos from nuclear reactions in 1938 ...

The combination of four protons and two electrons can occur essentially in two ways. The first mechanism starts with the combination of two protons to form a deuterium nucleus with positron emission, viz.

\[ H + H = D + e^+ \]  

The deuterium is then transformed into He^+ by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

\[ C^7 + H = N^8 + e^- \]
\[ N^8 + H = C^7 + e^- \]
\[ C^7 + H = C^7 + He^+ \]
The Possible Role of Neutrinos in Stellar Evolution

It can be considered at present as definitely established that the energy production in stars is caused by various types of thermonuclear reactions taking place in their interior. Since these reaction chains usually contain the processes of $\beta$-disintegration accompanied by the emission of high-speed neutrinos, and since the neutrinos pass almost without difficulty through the body of the star, we must assume that a certain part of the total energy produced escapes into interstellar space without being noticed as the actual thermal radiation of the star. Thus, for example, in the case of the carbon-nitrogen cycle in the sun, about 7 percent of the energy produced is lost in the form of neutrino radiation. However, since, in such reaction chains, the energy taken away by neutrinos represents a definite fraction of the total energy liberation, these losses are of but secondary importance for the problem of stellar equilibrium and evolution.

We want to indicate here that the situation becomes entirely different in cases where, as the result of the pro-

More detailed calculations on this collapse process are now in progress.

G. Gamow

The George Washington University, Washington, D. C.

M. Schoenberg

University of São Paulo, São Paulo, Brazil

November 21, 1940.

* Fellow of the Guggenheim Memorial Foundation. Now in Washington, D. C.

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Sun Glasses for Neutrinos?

8.3 light minutes

100 light years of lead needed to shield solar neutrinos

Bethe & Peterls 1934: “... this evidently means that one will never be able to observe a neutrino.”

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First Detection (1954 - 1956)

Fred Reines

Clyde Cowan

(1918 – 1974)

(1919 – 1998)

Nobel prize 1995

Detector prototype

Anti-Electron Neutrinos from Hanford Nuclear Reactor

\[ \bar{\nu}_e + p \rightarrow e^+ + \gamma + \bar{\nu}_e \]

3 Gammas in coincidence

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Neutrino Theory of Stellar Collapse

G. Gamow, George Washington University, Washington, D. C.

M. Schoenberg, University of São Paulo, São Paulo, Brasil

(Received February 6, 1941)

At the very high temperatures and densities which must exist in the interior of contracting stars during the later stages of their evolution, one must expect a special type of nuclear processes accompanied by the emission of a large number of neutrinos. These neutrinos penetrating almost without difficulty the body of the star, must carry away very large amounts of energy and prevent the central temperature from rising above a certain limit. This must cause a rapid contraction of the stellar body ultimately resulting in a catastrophic collapse. It is shown that energy losses through the neutrinos produced in reactions between ordinary nuclei, and probably above 30,000°C for supernovae, and the rapid expansion of the stellar atmosphere which is evidently blown up by the increasing radiative pressure. In the case of Nova Aquilae 1918, for example, the star was surrounded by a luminous gas shell expanding with a velocity of 2000 kilometers per second, whereas the gas masses expelled by the galactic supernova of the year A.D. 1054 (observed by Chinese astronomers) form at present an en-
First Measurement of Solar Neutrinos

Inverse beta decay of chlorine

\[ V_e \] -> $^{37}$Cl -> e

600 tons of Perchloroethylene

Homestake solar neutrino observatory (1967–2002)

Cherenkov Effect

Elastic scattering or CC reaction

Neutrino

Electron or Muon (Charged Particle)

Light

Cherenkov Ring

Water

Super-Kamiokande Neutrino Detector

42 m

39.3 m
Super-Kamiokande: Sun in the Light of Neutrinos

I. Stellar Evolution and Particle Limits
II. Neutrinos and Axions from the Sun
III. Supernova Neutrinos

Basics of Stellar Evolution
Equations of Stellar Structure

- Assume spherical symmetry and static structure (neglect kinetic energy)
- Excludes: Rotation, convection, magnetic fields, supernova-dynamics, ...

Hydrostatic equilibrium
\[
\frac{dP}{dr} = -\frac{G_N M_r \rho}{r^2}
\]

Energy conservation
\[
\frac{dL_r}{dr} = 4\pi r^2 \varepsilon \rho
\]

Energy transfer
\[
L_r = \frac{4\pi r^2 d(aT^4)}{3\varepsilon}
\]

Literature
- Clayton: Principles of stellar evolution and nucleosynthesis (Univ. Chicago Press 1968)
- Kippenhahn & Weigert: Stellar structure and evolution (Springer 1990)

Virial Theorem and Hydrostatic Equilibrium

- Hydrostatic equilibrium
- Integrate both sides
- L.h.s. partial integration with \( P = 0 \) at surface \( R \)
- Classical monatomic gas: \( P = \frac{2}{3} U \) (U density of internal energy)
- Average energy of single "atoms" of the gas

Convection in Main-Sequence Stars

Dark Matter in Galaxy Clusters
**Dark Matter in Galaxy Clusters**

**Fritz Zwicky:**
*Die Rotverschiebung von Extragalaktischen Nebeln*  
(The redshift of extragalactic nebulae)  

In order to obtain the observed average Doppler effect of 1000 km/s or more, the average density of the Coma cluster would have to be at least 400 times larger than what is found from observations of the luminous matter. Should this be confirmed one would find the surprising result that dark matter is far more abundant than luminous matter.

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**Virial Theorem Applied to the Sun**

Approximate Sun as a homogeneous sphere with

- Mass $M_{\text{sun}} = 1.99 \times 10^{33}$ g
- Radius $R_{\text{sun}} = 6.96 \times 10^{10}$ cm

Gravitational potential energy of a proton near center of the sphere

$$\langle E_{\text{grav}} \rangle = -\frac{3}{2} \frac{G N_{\text{sun}} m_{p}}{R_{\text{sun}}} = -3.2 \text{ keV}$$

Thermal velocity distribution

$$\langle E_{\text{kin}} \rangle = \frac{3}{2} k_{B} T = -\frac{3}{2} \langle E_{\text{grav}} \rangle$$

Estimated temperature

$$T = 1.1 \text{ keV}$$

Central temperature from standard solar models

$$T_{C} = 1.56 \times 10^{7} \text{K} = 1.34 \text{ keV}$$

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**Nuclear Binding Energy**

*Mass Number*  
*Proton*  
*Neutron*

- $\langle E_{\text{grav}} \rangle = -0.420 \text{ MeV}$  
- $\langle E_{\text{kin}} \rangle = -1.442 \text{ MeV}$  
- $\langle E_{\text{grav}} \rangle = 0.384 \text{ MeV}$  
- $\langle E_{\text{grav}} \rangle = 18.8 \text{ MeV}$

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**Hydrogen burning: Proton-Proton Chains**

$$p + p \rightarrow ^{2}\he + e^{+} + \nu_{e} < 0.420 \text{ MeV}$$

$$p + e^{-} + p \rightarrow ^{2}\he + \nu_{e} 1.442 \text{ MeV}$$

- $^{2}\he + ^{3}\he \rightarrow ^{4}\he + 2p$  
- $^{3}\he + ^{4}\he \rightarrow ^{7}\be + \gamma$  
- $^{7}\be + e^{-} \rightarrow ^{7}\li + \nu_{e} 0.862 \text{ MeV}$

- $^{3}\he + p \rightarrow ^{4}\he + e^{+} + \nu_{e}$  
- $^{7}\be + e^{-} \rightarrow ^{7}\li^{*} + \nu_{e} 0.384 \text{ MeV}$

- $^{4}\he + ^{4}\he$  
- $^{8}\be \rightarrow ^{8}\be^{*} + e^{+} + \nu_{e} < 15 \text{ MeV}$
Hydrogen Burning: CNO Cycle

- Hydrogen burning: $4p + 2e^- \rightarrow ^4He + 2\nu_e$
  - Proceeds by pp chains and CNO cycle
  - No higher elements are formed because no stable isotope with mass number 8
  - Neutrinos from $p \rightarrow n$ conversion
  - Typical temperatures: $10^7$ K (~1 keV)

- Helium burning: $^4He + ^4He + ^4He \leftrightarrow ^8Be + ^4He \rightarrow ^{12}C$
  - "Triple alpha reaction" because $^8Be$ unstable, builds up with concentration $\sim 10^{-9}$
  - Typical temperatures: $10^8$ K (~10 keV)

- Carbon burning: Many reactions, for example $^{12}C + ^{12}C \rightarrow ^{23}Na + p$ or $^{20}Ne + ^4He$ etc
  - Typical temperatures: $10^8$ K (~100 keV)

Thermonuclear Reactions and Gamow Peak

- Coulomb repulsion prevents nuclear reactions, except for Gamow tunneling
- Tunneling probability $p \propto e^{-\frac{E}{2m}}$
- With Sommerfeld parameter
  $$\eta = \left(\frac{m}{2E}\right)^{1/2} Z_1 Z_2 e^2$$
- Parameterize cross section with astrophysical S-factor
  $$S(E) = a(E) E e^{2\pi \eta(E)}$$

Hydrogen Exhaustion

- Main-sequence star
- Helium-burning star
### Burning Phases of a 15 Solar-Mass Star

<table>
<thead>
<tr>
<th>Burning Phase</th>
<th>Dominant Process</th>
<th>$T_C$ [keV]</th>
<th>$\rho_c$ [g/cm$^3$]</th>
<th>$L_\gamma$/$L_\nu$</th>
<th>Duration [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>$H \rightarrow \text{He}$</td>
<td>3</td>
<td>5.9</td>
<td>2.1</td>
<td>1.2 x $10^7$</td>
</tr>
<tr>
<td>Helium</td>
<td>$\text{He} \rightarrow C, O$</td>
<td>14</td>
<td>1.3 x $10^3$</td>
<td>6.0</td>
<td>1.7 x $10^5$</td>
</tr>
<tr>
<td>Carbon</td>
<td>$C \rightarrow \text{Ne, Mg}$</td>
<td>53</td>
<td>1.7 x $10^5$</td>
<td>8.6</td>
<td>1.0 x $10^3$</td>
</tr>
<tr>
<td>Neon</td>
<td>$\text{Ne} \rightarrow O, \text{Mg}$</td>
<td>110</td>
<td>1.6 x $10^7$</td>
<td>9.6</td>
<td>1.8 x $10^3$</td>
</tr>
<tr>
<td>Oxygen</td>
<td>$O \rightarrow \text{Si}$</td>
<td>160</td>
<td>9.7 x $10^7$</td>
<td>9.6</td>
<td>2.1 x $10^4$</td>
</tr>
<tr>
<td>Silicon</td>
<td>$\text{Si} \rightarrow Fe, Ni$</td>
<td>270</td>
<td>2.3 x $10^8$</td>
<td>9.6</td>
<td>9.2 x $10^5$</td>
</tr>
</tbody>
</table>

### Neutrinos from Thermal Plasma Processes

- **Photo (Compton)**
- **Plasmon decay**
- **Pair annihilation**

These processes first discussed in 1961-63 after V-A theory.

### Effective Neutrino Neutral-Current Couplings

- **Neutrinon**
- **Charged current**

\[
H_{\text{int}} = \frac{G_F}{\sqrt{2}} \Psi_\nu \gamma_\mu (C_V - C_A \gamma_5) \Psi_\nu \Psi_\nu \gamma^\mu (1 - \gamma_5) \Psi_\nu
\]

- $G_F = 1.166 \times 10^{-5} \text{ GeV}^{-2}$
- $\sin^2 \theta_W = 0.231$

### Neutrino Energy Loss Rates
### Existence of Direct Neutrino-Electron Coupling

**JOURNAL OF PHYSICS** 10, 12-23 March 1970

**Title:** Astrophysical Determination of the Coupling Constant for the Electron-Neutrino Weak Interaction

**Authors:** Richard B. Stothers

**Abstract:**

The existence of the $\mathcal{V}_{lL}(l,e)$ weak interaction is confirmed by the results of some astrophysical tests. The value of the coupling constant is equal to, or close to, the coupling constant of beta decay, namely, $g^2 - 10^{-15}$.

Of all the astrophysical tests applied so far for the inference of a direct electron-neutrino interaction in nature, none has unambiguously provided a useful upper limit on the coupling constant, which in the $\nu$-$A$ theory of Feynman and Gell-Mann is taken to be equal to the “universal” weak-interaction coupling constant measured from beta decays (called $g_\nu$ hereafter). However, it is important to point out that these tests, made by the author and his colleagues during the past eight years, do provide a nonzero lower limit, and therefore establish at least the existence of the $\mathcal{V}_{lL}(l,e)$ interaction. It should be emphasized, nonetheless, that all of these tests rely on the validity of various stellar model calculations. These models, while not subject to scrutiny in the same sense as a laboratory experiment, have relative theoretical lifetimes, calculated with and without the inclusion of neutrino emission.

In this Letter, the unmodified term “luminosity” will mean the photon luminosity $L$ radiated by the star. The “neutrino luminosity” will be designated $L_\nu$. Quantities referring to the sun are subscripted with an unterlined dot.

The most accurate available data on white dwarfs are those collected by Eggen for the two clusters Hyades and Pleiades and for the nearby general field. Of chief interest here are the hot white dwarfs, for which the observational data have been reduced following the procedure of Van Horn. The resulting luminosities are estimated to have a statistical accuracy of $0.1$ in log$L/L_\odot$, which is adequate here. Models of cooling white dwarfs have been computed.

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### Self-Regulated Nuclear Burning

**Title:** Virial Theorem

**Form:** $\langle E_{\text{kin}} \rangle = -\frac{1}{2} \langle E_{\text{grav}} \rangle$

**Key Points:**
- Small Contraction
  - Heating
  - Increased nuclear burning
  - Increased pressure
  - Expansion
- Additional energy loss ("cooling")
  - Loss of pressure
  - Contraction
  - Heating
  - Increased nuclear burning

**Main-Sequence Star**

- Hydrogen burning at a nearly fixed $T$
- Gravitational potential nearly fixed
- More massive stars bigger

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### Modification of Stellar Properties by Particle Emission

**Title:** Degenerate Stars ("White Dwarfs")

**Inverse mass-radius relationship for degenerate stars:**

$$R = 10,500 \text{ km} \left( \frac{0.6 M_\odot}{M} \right)^{1/3} \left( \frac{Y_e}{5} \right)^{5/3}$$

**For sufficiently large mass, electrons become relativistic:**
- Velocity = speed of light
- Pressure

**Chandrasekhar mass limit**

$$M_{\text{Ch}} = 1.457 M_\odot \left( \frac{2Y_e}{5} \right)^2$$
Degenerate Stars ("White Dwarfs")

Inverse mass-radius relationship for degenerate stars: \( R \propto \frac{1}{M^{1/3}} \)

Chandrasekhar mass limit
\( M_{\text{Ch}} = 1.457 \ M_{\odot} (2Y_e)^2 \)

Stellar Collapse

Main-sequence star

Helium-burning star

Hydrogen Burning

Helium Burning

Hydrogen Burning

Stellar Collapse

Onion structure

Collapse (implosion)

 Degenerate iron core:
\( \rho \approx 10^9 \ \text{g cm}^{-3} \)
\( T \approx 10^{10} \ \text{K} \)
\( M_{\text{He}} = 1.5 \ M_{\odot} \)
\( R_{\text{He}} \approx 8000 \ \text{km} \)

Giant Stars

Main-sequence star \( 1M_{\odot} \)

(Hydrogen burning)

Helium-burning star \( 1M_{\odot} \)

Large surface area → low temperature → "red giant" → huge L(H)

Large luminosity → mass loss

"Envelope" fully convective

\( e_{\text{nuc}}(\text{He}) \) relates to
\( T \propto \Phi_{\text{grav}} \propto \frac{M}{R} \) of core

\( e_{\text{nuc}}(\text{H}) \) relates to
\( T \propto \Phi_{\text{grav}} \propto \frac{M}{R} \) of full star

\( e_{\text{nuc}}(\text{H}) \) determined by
\( T \propto \Phi_{\text{grav}} \) of core → huge L(H)
Evolution of a Low-Mass Star

- **Main-Sequence**
- **Giant Branch**
- **He**
- **RGB**
- **HB**
- **AGB**

Evolution of Stars

<table>
<thead>
<tr>
<th>Mass Range</th>
<th>Fate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M \leq 0.08 , M_{\odot}$</td>
<td>Brown dwarf</td>
</tr>
<tr>
<td>$0.08 &lt; M \leq 0.8 , M_{\odot}$</td>
<td>Hydrogen burning not completed in Hubble time</td>
</tr>
<tr>
<td>$0.8 &lt; M \leq 2 , M_{\odot}$</td>
<td>Degenerate helium core after hydrogen exhaustion</td>
</tr>
<tr>
<td>$2 \leq M \leq 8 , M_{\odot}$</td>
<td>Helium ignition non-degenerate</td>
</tr>
<tr>
<td>$5 - 8 , M_{\odot}$</td>
<td>All burning cycles → Onion skin structure with degenerate iron core</td>
</tr>
<tr>
<td>$M_{\odot}$</td>
<td>Core collapse supernova</td>
</tr>
<tr>
<td>$&gt; 8 , M_{\odot}$</td>
<td>Neutron star (often pulsar)</td>
</tr>
</tbody>
</table>

Planetary Nebulae

- **Hour Glass Nebula**
- **Eskimo Nebula**
- **Planetary Nebula IC 418**
- **Planetary Nebula NGC 3132**
Globular Clusters of the Milky Way

http://www.dartmouth.edu/~chaboyer/mwgc.html

Globular clusters on top of the FIRAS 2.2 micron map of the Galaxy

The galactic globular cluster M3

Color-Magnitude Diagram for Globular Clusters

- Stars with M so large that they have burnt out in a Hubble time
- No new star formation in globular clusters

Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Particle-Phsycis Limits from Globular Cluster Stars: Axions

Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)
Basic Argument

- Invisible axions have very small mass
- Emission from stellar plasma not suppressed by threshold effects (analogous to neutrinos)
- New energy-loss channel
- Back-reaction on stellar properties and evolution

What are the emission processes?
- What are the observable consequences?

Axion Properties

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Lagrangian</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( L_{\text{ay}} = \frac{g_{\text{ay}}}{2f_a} F_{\mu\nu} a_{\mu} a_{\nu} = g_{\text{ay}} F_{\mu\nu} a_{\mu} a_{\nu} )</td>
</tr>
</tbody>
</table>

Conversion rate (screening effects, no nuclear recoil)

- \( \Gamma_{\gamma \rightarrow a} = \frac{g_{\text{ay}}^2 T_k S_k^2}{32\pi} \left[ \left( 1 + \frac{k_S^2}{4E^2} \right) \ln \left( 1 + \frac{4E^2}{k_S^2} \right) - 1 \right] \)

Screening scale (non-relativistic non-degenerate)

- \( k_S^2 = \frac{k_S^2}{4T^2} = \frac{\alpha_{\text{em}}}{3T} \left( \sum_j Z_j^2 Y_j \right) \)
- \( \text{Sun} \quad k_S^2 \approx 12 \)
- \( \text{HB Star} \quad k_S^2 \approx 2.5 \)

- Consistent with results from FTD methods, see Altherr, Petitgirard & del Rio Gaztelurrutia, Astropart. Phys. 2 (1994) 175
Energy-Loss Rate of the Sun

\[ \gamma \rightarrow a = \frac{g_a^2 T k_s^2}{2 \pi} \left( \left[ 1 + \frac{k_s^2}{4 e^2} \right] \ln \left( 1 + \frac{4 e^2}{k_s^2} \right) - 1 \right) \]

\[ \approx \frac{g_{10}^2}{10^{-15}} \text{ s}^{-1} \quad \text{for few keV-energy photons (Sun)} \]

\[ g_{10} = \frac{g_{\gamma}}{10^{-10} \text{ GeV}^{-1}} \]

\[ Q = \int \frac{2 d^3 k_s}{(2 \pi)^3} \left( \frac{g_a^2}{4 \pi} \right) F(k_s) \]

\[ F(k_s) = \frac{k_s^2}{2 \pi^2} \int_0^\infty dx \left( x^2 + k_s^2 \right) \ln \left( 1 + \frac{x^2}{k_s^2} \right) - x^2 \]

\[ = \frac{g_{10}^2}{1.85 \times 10^{-3} L_{\text{sun}}} \]

Solar Axion Luminosity

\[ L_a = g_{10}^2 1.85 \times 10^{-3} L_{\text{sun}} \]

\[ 10^{-10} \text{ GeV}^{-1} \]

Helium-Burning Lifetime of Horizontal-Branch Stars

Number ratio of HB-Stars/Red Giants in 15 galactic globular clusters (Buzzoni et al. 1983)

Helium-burning lifetime established within ±10%
Globular Cluster Limit on Axion-Photon Coupling

Helium-burning star

- Helium-burning luminosity
  \[ L_{3\alpha} \approx 20 \, L_\odot \]
  \[ T \approx 10 \, \text{keV} \]
  \[ \rho \approx 10^4 \, \text{g cm}^{-3} \]

- Core-average nuclear energy generation rate
  \[ \varepsilon_{3\alpha} \approx 80 \, \text{erg g}^{-1} \text{s}^{-1} \]

- Core-average Primakoff emission rate
  \[ \varepsilon_{\text{Primakoff}} \approx g_{10}^2 \times 30 \, \text{erg g}^{-1} \text{s}^{-1} \]

- Reduction of helium-burning lifetime
  \[ \tau_0 = \frac{1}{1 + 0.4 \, g_{10}^2} \]

- Adopt nominal limit \[ g_{10} < 1 \]
  (More restrictive limit if using 10% precision for helium burning lifetime)

Free Streaming vs Trapping of New Particles

<table>
<thead>
<tr>
<th>Free Streaming</th>
<th>Trapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Free Path</td>
<td>Stellar Radius</td>
</tr>
<tr>
<td>Hydrostatic Equilibrium</td>
<td>Energy transfer</td>
</tr>
</tbody>
</table>

Weakly interacting particles constitute a new energy-loss channel in addition to neutrinos and thus violate “energy conservation,” reducing the available nuclear energy

\[ \varepsilon = \varepsilon_{\text{nuc}} - \varepsilon_{\gamma} - \varepsilon_{x} \]

Strong effect on stellar evolution when \( \varepsilon_{x} \) comparable to \( \varepsilon_{\text{nuc}} \)

Injection of weakly interacting particles achieves local thermal equilibrium and thus contribute an energy-transfer channel in addition to photons and conduction

\[ \kappa^{-1} = \kappa_{c}^{-1} + \kappa_{\gamma}^{-1} + \kappa_{x}^{-1} \]

Relation to average mean free path

\[ (\kappa_{\gamma} \rho)^{-1} = \lambda_{\text{Rosseland}} \]

Strong effect on stellar structure when \( \lambda_{x} \geq \gamma \)

What if axion-like particles are “trapped”?

Radiative energy transfer

Photons transport energy over a distance ~ 1 mean free path (mfp)

To be harmless, a “trapped” low-mass particle species, e.g., axion-like particles, must have a mfp approximately less than photons (in the Sun ~ few cm)

A new low-mass particle has the strongest effect on a star when its mfp is of order the geometric dimensions of the star!

CAST Phase I Results (2003–2004)

CAST Collaboration:
An improved limit on the axion-photon coupling from the CAST experiment

hep-ex/0702006
Particle-Physics Limits from Globular Cluster Stars: Neutrino Dipole Moments

Neutrinos from Thermal Plasma Processes

**Plasmon Decay in Neutrinos**

- Vacuum:
  - Photon massless
  - Can not decay into other particles, even if they themselves are massless

- Propagation in a medium:
  - Photon acquires a “refractive index”
  - In a non-relativistic plasma (e.g. Sun, white dwarfs, core of red giant before helium ignition, ...) behaves like massive particle:
    - $\omega^2 - k^2 = \omega_p^2$
    - Massless neutrinos do not couple to photons
    - May have dipole moments or even “millicharges”

**Neutrino-Photon-Coupling in a Plasma**

- In a medium:
  - Neutrinos interact coherently with the charged particles which themselves couple to photons
  - Induces an “effective charge”
  - In a degenerate plasma (electron Fermi energy $E_F$ and Fermi momentum $p_F$)
    - $e_V = 16\sqrt{2}C_V G_F E_F p_F$
    - Degenerate helium core (and $C_V = 1$)
    - $e_V = 6 \times 10^{-11} e$

**Neutrino-Photon-Coupling**

For vector-current analogous to photon polarization tensor

$$\Lambda_{\mu\nu} = e \mu \Pi_{\mu\nu}$$

$$\Lambda_{\mu\nu} = 4eG_F \int \frac{d^3p}{2E(2\pi)^3} \left[ f_e - (\beta) + f_e + (\beta) \right] \left[ \frac{(PK)^2 g_{\mu\nu} + K^2 p_{\mu\nu} - (PK)^2}{(PK)^2 - 1/4(K^2)^2} \right] (PK)^2 - 1/4(K^2)^2$$

$$\Lambda_{\mu\nu}^{\text{eff}} = 2e \mu \Lambda_{\mu\nu}^{\text{eff}}$$

- Usually negligible
Neutral-Current Couplings and Plasmon Decay

A neutral-current process that was never useful for "neutrino counting" unlike big-bang nucleosynthesis (of course today $Z^0$-decay width fixes $N_V = 3$)

\[ G_F = 1.166 \times 10^{-5} \text{ GeV}^{-2} \]

As the standard-model plasmon decay produces almost exclusively $v_e v_e$

\[ \sin^2 \theta_W = \frac{1}{2} \]

\[ H_{\text{int}} = \frac{G_F}{\sqrt{2}} \bar{\psi}_i \gamma_\mu (C_V - C_A \gamma_5) \psi_j \bar{\psi}_j \gamma_\mu (1 - \gamma_5) \psi_j \]

Neutrino Fermion $C_V$ $C_A$

$v_e$ Electron $+\frac{1}{2}$ $+\frac{1}{2}$

$v_{\mu}, v_{\tau}$ $-\frac{1}{2}$ $-\frac{1}{2}$

Proton $+\frac{1}{2}$

Neutron $-\frac{1}{2}$

Plasmon Decay vs. Cherenkov Effect

Photon dispersion in a medium can be

\[ \omega^2 - k^2 > 0 \] ("Time-like"

\[ \omega^2 - k^2 < 0 \] ("Space-like"

Refractive index $n$

\[ (k = n \omega) \]

$n < 1$ $n > 1$

Example

- Ionized plasma
- Normal matter for large photon energies

Allowed process that is forbidden in vacuum

Plasmon decay to neutrinos

\[ \gamma \rightarrow v \bar{v} \]

Cherenkov effect

\[ e \rightarrow e + \gamma \]

Neutrino Electromagnetic Form Factors

Effective coupling of electromagnetic field to a neutral fermion

\[ L_{\text{eff}} = -F_1 \bar{\psi}_i \gamma_\mu A^\mu \psi_j \]

Charge $e_V = F_1(0) = 0$

Anapole moment $G_1(0)$

Magnetic dipole moment $\mu = F_2(0)$

Electric dipole moment $s = G_2(0)$

- Charge form factor $F_1(0^2)$ and anapole $G_1(0^2)$ are short-range interactions if charge $F_1(0) = 0$
- Connect states of equal chirality
- In standard model they represent radiative corrections to weak interaction

- Dipole moments connect states of opposite chirality
- Magnetic or electric dipole moments can connect different flavors or different mass eigenstates ("Transition moments")
- Usually measured in "Bohr magnetons" $\mu_B = e/(2m_e)$

Consequences of Neutrino Dipole Moments

Spin precession in external $E$ or $B$ fields

\[ \frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi} \left[ (C_V + C_A)^2 + (C_V - C_A)^2 \right] \left( 1 - \frac{T}{E_\gamma} \right)^2 \]

Scattering

\[ \frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi} \left( C_V - C_A \right)^2 \]

Electron recoil energy

\[ \Gamma = \frac{2m_e^2 - m_V^2}{8m_e^3} \]

Decay or Cherenkov effect

\[ \frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi} \left( \frac{m_V^2 - m_\gamma^2}{m_\gamma^2} \right) \]
**Plasmon Decay And Stellar Energy Loss Rates**

Assume photon dispersion relation like a massive particle (nonrelativistic plasma)

\[ \frac{E_y^2 - m_e^2}{E_y} = a_{pl}^2 = \frac{4\pi\varepsilon_0 n_e}{m_e} \]

Decay rate of photon (transverse plasmon) with energy \(E_y\)

\[ \Gamma(\gamma \to \nu \nu) = \frac{4\pi}{3} \frac{1}{E_y} \times \left[ \frac{\alpha\left(a_{pl}^2/4\pi\right)}{2} \right] \]

Dipole moment

\[ \frac{\varepsilon_0 E_y^4}{2\alpha} \left(\frac{a_{pl}^2/4\pi}{2}\right) \]

Standard model

Energy-loss rate of stellar plasma (temperature \(T\) and plasma frequency \(\alpha_{pl}\))

\[ Q(\gamma \to \nu \nu) = \int \frac{2d^3p}{(2\pi)^3} \frac{E_y}{E_y - 1} \times \left[ \frac{\alpha\left(a_{pl}^2/4\pi\right)}{2} \right] \]

Millicharge

\[ \frac{\varepsilon_0 E_y^4}{2\alpha} \left(\frac{a_{pl}^2/4\pi}{2}\right) \]

**Color-Magnitude Diagram for Globular Clusters**

Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W. Harris, 2000)

- Hot, blue
- Cold, red
- Asymptotic Giant
- Red Giant
- White Dwarfs
- Horizontal Branch
- Main-Sequence

**Measurements of Globular Cluster Observables**

- Number ratio of HB vs. RGB stars in 15 globular clusters
- Brightness difference between HB (RR Lyrae stars) and brightest red giant in 26 globular clusters

**Core-Mass at Helium Ignition**

Core mass at helium ignition established to ±0.02 \(M_{\odot}\) or ± 4%
Globular Cluster Limits on Neutrino Dipole Moments

Compare magnetic-dipole plasma emission with standard case

\[ Q_\mu = \frac{2\mu_\nu^2}{Q_{SM}} \]

For red-giant core before helium ignition \( \epsilon_{pl} = 18 \text{ keV} \)

\[ Q_\mu = 9 \times 10^{-22} \left( \frac{\mu_\nu}{\mu_B} \right)^2 \]

Require this to be \( \mu_\nu < 3 \times 10^{-12} \mu_B \)

Globular-cluster limit on neutrino dipole moment

\( \mu_\nu < 2 \times 10^{-12} \mu_B \)

Standard Dipole Moments for Massive Neutrinos

In standard electroweak model, neutrino dipole and transition moments are induced at higher order

Massive neutrinos \( \nu_i \) \( (i = 1,2,3) \), mixed to form weak eigenstates

\[ \nu_2 = \sum_{i=1}^3 U_{i2} \nu_i \]

Explicit evaluation for Dirac neutrinos
(Magnetic moments \( \mu_{ij} \), electric moments \( \epsilon_{ij} \))

Neutrino Radiative Lifetime Limits

\[ \Gamma_{\nu \gamma} = \frac{2\mu_{\text{eff}}^2 m_\nu^3}{3\pi} \]

\[ \Gamma_{\nu \gamma} = \frac{2\mu_{\text{eff}}^2 \omega_{\text{pl}}^3}{24\pi} \]

For low-mass neutrinos, plasmon decay in globular cluster stars yields most restrictive limits

Standard Dipole Moments for Massive Neutrinos

Diagonal case
(Magnetic moments of Dirac neutrinos)

\[ \mu_{ii} = \frac{3\sqrt{2} G_F}{(4\pi)^2} m_i \left( m_i + m_j \right) \sum_{\ell=e,\mu,\tau} U_{ij} U_{i\ell}^* \delta \left( \frac{m_\nu}{m_W} \right) \]

\[ \epsilon_{ii} = 0 \]

Off-diagonal case
(Transition moments)

First term in \( f(m_\nu/m_W) \) does not contribute
(“GIM cancellation”)

\[ \mu_{ij} = \frac{3\sqrt{2} G_F}{4(4\pi)^2} \left( m_i + m_j \right) \left( \frac{m_\nu}{m_W} \right) \sum_{\ell=e,\mu,\tau} U_{ij} U_{i\ell}^* \frac{m_\ell}{m_\ell} \]

\[ \epsilon_{ij} = \ldots (m_i - m_j) \ldots \]

Largest neutrino mass eigenstate \( 0.05 \text{ eV} < m < 0.7 \text{ eV} \)
For Dirac neutrino expect

\[ 1.6 \times 10^{-20} \mu_B < \mu_\nu < 2.2 \times 10^{-19} \mu_B \]
Limits on Milli-Charged Particles

Davidson, Hannestad & Raffelt
JHEP 5 (2000) 3

Figure 1: Regions of mass-charge space ruled out for milli-charged particles. The solid and dashed lines apply to the model with a paraphoton; solid and dotted lines apply in the absence of a paraphoton. The bounds arise from the following constraints: AC — accelerator experiments; Op — the Tokyo search for the invisible decay of ortho-protonium [27]; SLAC — the SLAC milli-charged particle search [28]; L — the Lamb shift; BBN — nucleosynthesis; Ω — Ω < 1; Lp — muon decay; WD — white dwarf; DM — dark matter; SN — Supernova 1987A.

Globular cluster limit most restrictive for small masses

Further Reading on Particle Limits from Stars

Georg Raffelt:
Stars as Laboratories for Fundamental Physics (University of Chicago Press, 1996)

Particle Physics from Stars

Astrophysical Methods to Constrain Axions and Other Novel Particle Phenomena
Phys. Rept. 198 (1990) 1-113

Physical Review

Electromagnetic Properties of the Neutrino
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I. INTRODUCTION

Most physicists now accept the prospect that there are two neutrinos, with identical exception for neutrinos with masses and the mass of the muon neutrino is the least well known of the parameters associated with either neutrino. The best measurements of it come from the energy-momentum balance in neutrino experiments give

\[ m_{\nu} < 200 \text{ eV}, \]

and the experiments are consistent with \( m_{\nu} = 0 \).

(2) \( \tau \rightarrow \mu \tau \): The mass of the muon neutrino is the only parameter associated with either neutrino. The best measurements of it come from the energy-momentum balance in neutrino experiments give

\[ m_{\nu} < 3.5 \text{ MeV}. \]

(3)

The reason for this uncertainty lies in the kinematic fact that the small neutrino mass is given as the difference between measured quantities of order 1. In the \( \tau \rightarrow \mu \tau \) decay, the accuracy with which the neutrino mass can be determined is given by

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