Coherent neutrino scattering theory, dark matter implications, and searches for new physics

Louis E. Strigari
Texas A&M University
Mitchell Institute coherent neutrino scattering workshop
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Coherent effects of a weak neutral current

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(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process \( e + A \rightarrow e + A \) should have a sharp coherent forward peak just as \( e + A \rightarrow e + A \) does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about \( 10^{-33} \) cm\(^2\) on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes \( \nu + A \rightarrow \nu + A^* \) provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapses and neutron stars.

NEUTRINO OPACITIES AT HIGH TEMPERATURES AND DENSITIES

David L. Turris and David N. Schramm
University of Chicago, Enrico Fermi Institute
Received 1975 February 28; revised 1975 April 18

ABSTRACT

A detailed calculation is made of the major cross sections contributing to neutrino opacities at high temperatures and densities such as those encountered in gravitational collapse. These calculations include the effects of neutral currents, where applicable, and electron degeneracy. The processes considered are electron-neutrino scattering (including both electron and muon neutrinos and antineutrinos), neutrino-nucleon absorption and scattering, and coherent neutrino scattering. Results for these interactions are also given for the average energy transferred by the neutrino as well as the mean scattering angle (thus yielding momentum transfer).
Principles and applications of a neutral-current detector
for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik,
Munich, Federal Republic of Germany
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of
the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a
detector would be relatively light and suggests the possibility of a true “neutrino observatory.” The recoil energy
which must be detected is very small (10–100 eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible
through extension and extrapolation of currently known techniques. Such a detector could permit
determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations
since it detects all neutrino types. Various applications and tests are discussed, including spallation
sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the
most difficult backgrounds is attempted.

Bolometric Detection of Neutrinos

Blas Cabrera, Lawrence M. Krauss, and Frank Wilczek
Department of Physics, Stanford University, Stanford, California 94305
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 01238
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 14 December 1984)

Elastic neutrino scattering off electrons in crystalline silicon at 1–10 mK results in measurable
temperature changes in macroscopic amounts of material, even for low-energy (< 0.41 MeV)

pp ν's from the sun. We propose new detectors for bolometric measurement of low-energy ν
interactions, including coherent nuclear elastic scattering. A new and more sensitive search for oscillations of reactor antineutrinos is practical (∼ 100 kg of Si), and would lay the groundwork for a
more ambitious measurement of the spectrum of pp, 7Be, and 8B solar ν's, and supernovae any-
where in our galaxy (∼ 10 tons of Si).
Coherent neutrino-nucleus scattering

- **Coherent neutrino scattering will produce a signal similar to a WIMP**

  Friedman 1974; Tubbs & Schramm 1977, Donnelly 1985

- Proportional to the number of neutrons\(^2\) due to vector current coupling

\[
\frac{d\sigma_{CNS}(E_\nu,T_R)}{dT_R} = \frac{G_f^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N T_R}{2 E_\nu^2}\right) F^2(T_R)
\]

- Compare to spin-independent WIMP-nucleus cross section which is proportional to \(A^2\)

- Straightforward prediction of Standard Model. Though not yet detected.

\[\text{ neutrino } \rightarrow \text{ neutrino} \]
Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^5$ GeV; or strongly interacting particles of masses $1-10^4$ GeV.

<table>
<thead>
<tr>
<th>Experimental source</th>
<th>Event rate in kg$^{-1}$ day$^{-1}$</th>
<th>Recoil energy range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spallation source</td>
<td>$10^2-10^3$</td>
<td>10—100 keV</td>
</tr>
<tr>
<td>Reactor</td>
<td>10</td>
<td>50—500 eV</td>
</tr>
<tr>
<td>Solar neutrinos</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$pp$ cycle</td>
<td>$10^{-3}-10^{-2}$</td>
<td>1—10 eV</td>
</tr>
<tr>
<td>$^7$Be</td>
<td>$10^{-2}-5\times10^{-2}$</td>
<td>5—50 eV</td>
</tr>
<tr>
<td>$^8$B</td>
<td>$10^{-3}-10^{-2}$</td>
<td>100 eV—3 keV</td>
</tr>
<tr>
<td>Galactic halo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>coherent $m \sim 2$ GeV</td>
<td>50—1000</td>
<td>10—100 eV</td>
</tr>
<tr>
<td>$m \geq 100$ GeV</td>
<td>up to $10^4$</td>
<td>10—100 keV</td>
</tr>
<tr>
<td>Spin dependent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m \sim 2$ GeV</td>
<td>0.1—1</td>
<td>10—100 eV</td>
</tr>
<tr>
<td>$m \geq 100$ GeV</td>
<td>up to 1</td>
<td>10—100 keV</td>
</tr>
</tbody>
</table>
Direct dark matter searches: progress

Evolution of the WIMP–Nucleon $\sigma_{SI}$

Adapted from SNOWMASS
Going beyond the neutrino background: Ideas

1. Build a big DM detector
(Ruppin, Billard, Figueroa-Feliciano, Strigari 2014)

2. Annual modulation
(Davis 2014)

3. Directional detectors
(O’Hare et al. 2015)

4. Non-relativistic EFT models
(Dent, Dutta, Newstead, Strigari to appear)
Solar neutrinos: Outstanding issues

1. Solar Metallicity problem

New 3D rotational hydrodynamical simulations suggest lower metallicity in Solar core [Asplund et al. 2009]

However the low metallicity appears in conflict with helioseismology data

2. Intermediate energy survival probability

SK, Borexino, SNO CC data seem to not indicate an ‘upturn’ in the electron neutrino survival probability
Solar neutrinos

<table>
<thead>
<tr>
<th>High metallicity metallicity</th>
<th>Low metallicity metallicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ flux</td>
<td>$E_{\nu}^{\text{max}}$ (MeV)</td>
</tr>
<tr>
<td>p+p→$^2$H+e$^+$+ν</td>
<td>0.42</td>
</tr>
<tr>
<td>p+e$^-$+p→$^2$H+ν</td>
<td>1.44</td>
</tr>
<tr>
<td>$^7$Be+e$^-$→$^7$Li+ν</td>
<td>0.86 (90%)</td>
</tr>
<tr>
<td></td>
<td>0.38 (10%)</td>
</tr>
<tr>
<td>$^8$B→$^8$Be+e$^+$+ν</td>
<td>~15</td>
</tr>
<tr>
<td>$^3$He+p→$^4$He+e$^+$+ν</td>
<td>18.77</td>
</tr>
<tr>
<td>$^{13}$N→$^{13}$C+e$^+$+ν</td>
<td>1.20</td>
</tr>
<tr>
<td>$^{15}$O→$^{15}$N+e$^+$+ν</td>
<td>1.73</td>
</tr>
<tr>
<td>$^{17}$F→$^{17}$O+e$^+$+ν</td>
<td>1.74</td>
</tr>
<tr>
<td>$\chi^2/\nu_{\text{dof}}$</td>
<td></td>
</tr>
</tbody>
</table>

SNO NC measurement (5.25 x 10$^6$) right in between predictions of low and high metallicity SSMs
Solar neutrinos

Table 3: Results from global fits

<table>
<thead>
<tr>
<th>ν</th>
<th>Flux</th>
<th>E_{\nu}^{\text{max}} (MeV)</th>
<th>GS98-SFII</th>
<th>AGSS09-SFII</th>
<th>Solar</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+p→2H+e^++ν</td>
<td>0.42</td>
<td>5.98(1 ± 0.006)</td>
<td>6.03(1 ± 0.006)</td>
<td>6.05(1.003^{+0.003}_{-0.011})</td>
<td>10^{10}/cm^{2}s</td>
<td></td>
</tr>
<tr>
<td>p+e^-+p→2H+ν</td>
<td>1.44</td>
<td>1.44(1 ± 0.012)</td>
<td>1.47(1 ± 0.012)</td>
<td>1.46(1.010^{+0.010}_{-0.014})</td>
<td>10^{8}/cm^{2}s</td>
<td></td>
</tr>
<tr>
<td>7Be+e^-→7Li+ν</td>
<td>0.86 (90%)</td>
<td>5.00(1 ± 0.07)</td>
<td>4.56(1 ± 0.07)</td>
<td>4.82(1.05^{+0.05}_{-0.04})</td>
<td>10^{9}/cm^{2}s</td>
<td></td>
</tr>
<tr>
<td>8B→8Be+e^++ν</td>
<td>~15</td>
<td>5.58(1 ± 0.14)</td>
<td>4.59(1 ± 0.14)</td>
<td>5.00(1 ± 0.03)</td>
<td>10^{6}/cm^{2}s</td>
<td></td>
</tr>
<tr>
<td>3He+p→4He+e^++ν</td>
<td>18.77</td>
<td>8.04(1 ± 0.30)</td>
<td>8.31(1 ± 0.30)</td>
<td>—</td>
<td>10^{3}/cm^{2}s</td>
<td></td>
</tr>
<tr>
<td>13N→13C+e^++ν</td>
<td>1.20</td>
<td>2.96(1 ± 0.14)</td>
<td>2.17(1 ± 0.14)</td>
<td>≤ 6.7</td>
<td>10^{8}/cm^{2}s</td>
<td></td>
</tr>
<tr>
<td>15O→15N+e^++ν</td>
<td>1.73</td>
<td>2.23(1 ± 0.15)</td>
<td>1.56(1 ± 0.15)</td>
<td>≤ 3.2</td>
<td>10^{8}/cm^{2}s</td>
<td></td>
</tr>
<tr>
<td>17F→17O+e^++ν</td>
<td>1.74</td>
<td>5.52(1 ± 0.17)</td>
<td>3.40(1 ± 0.16)</td>
<td>≤ 59.</td>
<td>10^{6}/cm^{2}s</td>
<td></td>
</tr>
</tbody>
</table>

χ^2/ν | 3.5/90% | 3.4/90% |

Haxton et al, 2013

SNO NC measurement (5.25 x 10^6) right in between predictions of low and high metallicity SSMs
Evidence for a ~ 1 eV sterile neutrino?

- **electron neutrino disappearance** experiments: Gallium, reactor anomaly (Giunti & Lavedar 2006; Mention et al. 2011)

- **muon to electron neutrino appearance** experiments (LSND, MiniBooNE)

No hints for sterile neutrino from:

- **muon neutrino disappearance** experiments (Super-K, MiniBooNE, MINOS)

Kopp et al., sterile neutrino review 2013
Extracting new physics from Coherent neutrino scattering (talk by Joel Walker)

- Magnetic moment interactions off of protons or electrons (Vogel & Engel 1989)

\[
\frac{d\sigma}{dT_R} \bigg|_{\mu_\nu} = \frac{\pi \alpha^2 \mu^2_\nu}{m^2_e} \left[ \frac{1 - T_R/E_\nu}{T_R} + \frac{T_R}{4E^2_\nu} \right]
\]
Extracting new physics from Coherent neutrino scattering
(talk by Joel Walker)

- Sensitivity to Z-prime of order a few TeV, complementary to LHC in the near term