Supernovae and Neutrino Elastic Scattering

SN1998S, April 2, 1998 (8” SCT homemade CCD)

Trento, June, 2003
Keywords (Prof. Fujita)

- Weak magnetism corrections to the $\beta$ decay of supernovae as observed via $\nu$-A elastic scattering in solar $\nu$, double $\beta$ decay, and dark matter detectors,
- Implications for neutrino oscillations, nucleosynthesis, and close in massive planets.
- The FINESE accelerator experiment on elastic $\nu$-p scattering to determine the strange quark contribution to the spin of the nucleon.
Supernovae and Weak Interactions

- Core collapse SN dominated by weakly interacting neutrinos. Unique chance for macroscopic manifestations of symmetries and features of standard model weak interactions.
- Example: Large P violation related to large C viol. $$\nu$$-N interaction fundamentally stronger than anti-$$\nu$$-N.
- Difference between $$\nu$$ and anti-$$\nu$$ is of recoil order, $$E_\nu/M$$, but has a large coefficient from weak magnetism,
  $$J_\mu = F_1 \gamma_\mu + F_2 i \sigma_{\mu\nu} q^\nu / 2M$$
  and is important for both charged and neutral currents.
Core Collapse Supernova

>8M_☉ Star

Envelope

Shock

Hot bubble

Proto-neutron star: hot, e rich

July 5, 1054

Crab nebula
ν Spectra (Before Osc.)

Structure:
Charged Currents split $\nu_e$ from $\nu_x$

Fine Structure:
Weak Magnetism splits $\nu_x$ from $\overline{\nu_x}$

Hyper-fine:
Muons split $\nu_\mu$ from $\nu_\tau$?
Measure Energy of $\nu_x$

- $E(\nu_x)-E(\nu_e)$ is “lever arm” for neutrino osc.
- Measure total E of SN. This is binding energy of neutron star.
  - Most of SN energy in $\nu_x$.
  - N Star binding E $\sim M^2/R$.
  - Mass of NS interesting, could later collapse to black hole.
  - Nucleosynthesis depends on “compactness” M/R. Larger value gives higher entropy for escaped material.
Existing SN ν Detectors

- Measure E of anti-ν_e well: \( \overline{\nu}_e + p \rightarrow n + e^+ \).
- Detect ν_x without direct E information.
  - \(^{16}\text{O}(\nu_x,\nu_x')^{16}\text{O}^* \rightarrow \gamma + {^{16}\text{O}} \) in SK.
  - d(ν_x,ν_x')np → count n in SNO.
- To directly measure E(ν_x) need two body final state: ν-e (small cross section), ν-p elastic (perhaps possible in Kamland –J. Beacom), ν-A elastic.
- Coherent ν-A cross section very large and spectrum of recoils gives ν_x spectrum. But E is low ~ 50 keV.
Huge Elastic Signal

- Assume SN at 10 kpc, $3 \times 10^{53}$ ergs total energy, equal partition of energy among six flavors, and $T(\nu_x), T(\text{anti-}\nu_e), T(\nu_e) = 8, 5, 3.5$ MeV see astro-ph/0302071.

- Yield much larger than existing detectors (100s of \text{anti-}\nu_e and 10s of \nu_x per kilo-ton).

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Events/ton</th>
<th>&lt;E&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^4\text{He}$</td>
<td>0.9</td>
<td>240 keV</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>2.5</td>
<td>83</td>
</tr>
<tr>
<td>$^{20}\text{Ne}$</td>
<td>4.0</td>
<td>46</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>18.6</td>
<td>9.5</td>
</tr>
<tr>
<td>$^{132}\text{Xe}$</td>
<td>31.1</td>
<td>4.8</td>
</tr>
</tbody>
</table>
Recoil Spectra for Different Targets

Dotted curve for $^{20}\text{Ne}$ assumes $T$ for $\nu_x = 5$ MeV others use 8 MeV.
Detecting Low E Recoils

- Physics of detecting low E solar $\nu$, dark matter via nuclear recoils, and double $\beta$ decay similar to SN $\nu$-A elastic.
- Lots of work on large mass, low threshold, low background detectors.
- Background for SN $\nu$ much less severe than others because of high count rate.
- $\beta\beta$ decay: Proposed Majorana and Genius detectors will involve $\frac{1}{2}$-1 ton of $^{76}$Ge. [Existing Ge exps have needed threshold and background rates.] These should be sensitive to a galactic SN!
- Dark Matter: It may take ton quantities of Xe or other materials coupled with extraordinary background rejection to probe most of SUSY parameter space.
CLEAN Detector

- Cryogenic Low Energy Astrophysics with Noble gases.
- Based on liquid Ne which scintillates in UV and is easy to purify (little intrinsic background).
- Sensitive to dark matter.
CNO cycle captures 4 protons on CNO nuclei with two beta decays to produce an alpha particle. No net change in C, N, O.

CNO cycle is energy source for stars slightly hotter than sun. In sun CNO is only about 1-2% of pp burning.

CNO ν flux very sensitive to both T and metal abundance. Central metal abundance also important for opacity which determines temperature.

Measure both $^8\text{B}$ and CNO ν fluxes. Allows determination of both central T and metal abundance of sun.

Can test for contamination of outer convection zone with metals from fallen “hot Jupiters”.

Final search for the planet Vulcan???
Kevin Coakly, Dan Mckinsey, CJH, astro-ph/0302071.

Phototubes with wavelength shifters view 100 tons of liquid Ne.

Assume background dominated by U, Th, K… in phototubes, shifters and support structure.

Find event position from hit pattern in phototubes.

Assume quenching factor of $\frac{1}{4}$ for light from Ne ions compared to e.
Supernova at 10 kpc in CLEAN

- Simulation of full 100 ton active mass.
- Threshold (no position resolution) about 5 keV.
- Green curve is total low energy background in 10 seconds.
- Black or red curves are SN signal (≈ 400 events) for different $\nu_x$ temperatures.
Simulation of Inner 70 Tons

- Can reduce background with position cuts. Most background events on outside edges.
- Threshold, if position resolution, ~ 25 keV.
- If background matches simulations don’t need cuts.
- Many ways to reduce background further.
- Supernova detection in CLEAN looks robust.

Very large elastic cross section may allow larger statistics in future.
Supernova $\nu$ detectors

- Important to make model independent measurements!
- Do not assume everything is known but one parameter in your model!
- One wants a simple well known detector response.
- Elastic scattering has almost no theoretical uncertainty in cross section.
- Important to have multiple redundant experiments.
- Important to hope for surprises! This is how we will learn the most.
“Ultimate Flux Normalization”

- The ν-A elastic cross section is both very accurately known and very large.
- If the recoil ions can be detected, they could provide a very accurate absolute calibration of the neutrino flux.
- Micropattern gas detectors may observe reactor antineutrinos via elastic ν-A scattering, see P. Barbeau et al, hep-ex/0212034.
R-Process Nucleosynthesis

- As neutron rich medium cools, nuclei capture n to make heavy nuclei.
- Results depend on initial n/p ratio, entropy and expansion time scale.
- Need large n excess and high entropy
- Is ν-driven wind in supernovae r-process site?

Solar system heavy element abundances divided into s-process (red giant) and r-process
R-process in Neutrino driven wind

- Low density region above proto-neutron star dominated by large ν flux.

- Initial neutron to proton ratio and $Y_e$ in wind set by relative rates:

  \[ \nu_e + n \rightarrow p + e^- \quad (1) \]
  \[ \bar{\nu}_e + p \rightarrow n + e^+ \quad (2) \]

- Cross section for (1) > (2) because of n-p mass difference and because of weak magnetism. For fixed ν flux, weak magnetism increases $Y_e$ by 20%.

In neutrino driven wind, ν eject a few baryons from surface of protoneutron star.
n/p ratio in $\nu$-driven wind

For wind to be neutron rich must be above dark $Y_e=0.5$ line and below SN1987A limit line. This requires cold $\nu_e$ temperatures, top scale.
Neutrino Driven Wind is Not Significantly Neutron Rich

- Not site for r-process?
- New neutrino physics such as oscillations to sterile neutrinos that decreases $Y_e$.
- R-process occurs at much higher entropies (somehow) with $Y_e$ just below 0.5.
- Example, very strong magnetic fields $\sim 10^{15}$G keep material in $\nu$ heating region longer to greatly increase $S$. 
ν-n Elastic Important for Opacity

- Significant energy transport by $\nu_x (\equiv \nu_\mu, \nu_\tau)$ because twice as many as $\nu_e$ and without charged currents, $\nu_x$ have longer mean free paths.
- Opacity of $\nu_x$ mostly from ν-n elastic.
- Incorrect elastic cross sec caused Oak Ridge simulation to explode when it did not with correct one.
- Uncertainty in ν-n cross sec from strange quarks relevant for SN simulations.
FINESE: Fermi Lab Intense ν Scattering Experiment

- Proposed near detector on MiniBooNE beam line.
- Measure Δs via ratio of neutral to charged current.

D. H. Potterveld, P. E. Reimer
Argonne National Laboratory

B. T. Fleming, R. Stefanski
Fermi National Accelerator Laboratory,

C. Horowitz, T. Katori, H.-O. Meyer,

R. Tayloe
Indiana University

G. Garvey
Los Alamos National Laboratory

J.-C. Peng
University of Illinois
Strange quark content of nucleon

- Three form factors
  - $F_1^s$, $F_2^s$, $G_a^s$
- Low Q limits:
  - $F_1^s(0)=0$, $dF_1^s/dQ^2 \to$ strangeness radius $\rho_s$,
  - $F_1^s=(\rho_s+\mu_s)\ Q^2/4M^2$ for small $Q^2$
  - $F_2^s(0)=\mu_s$ strange magnetic moment,
  - $G_a^s(0)=\Delta s$, fraction of nucleon spin carried by $s$
A Future $\nu$-p Elastic Experiment

- Physics goals are compelling:
  - $G_a^s(Q^2)$ and $\Delta s$.
  - $F_2^s$ independent of PV radiative correction.
- Very attractive $\nu$ fluxes at beam lines for long baseline $\nu$-oscillation exp.
- Measuring ratio of neutral to charged currents is simple and controls many systematic errors.
Measure $\Delta s$ via Ratio of Neutral to Charged Current Scattering

- Ratio of protons from: $\nu + p \rightarrow \nu + p$ to protons from: $\nu + n \rightarrow \mu^- + p$.
- Note, both are quasielastic scattering from an $N=Z$ nucleus such as $^{12}$C.
- Very simple observable: ratio of protons of a given $E$ without muons to those with muons.
Example: $E_\nu = 0.8$ GeV, $Q^2 = 0.5$

- Neutral to CC ratio $R \approx 0.14$
- Error in extracted $\Delta s$
  - 5% measurement of $R$ 0.04
  - $\pm 0.03$ GeV uncer. in $M_A$ 0.01
  - $\pm 0.3$ uncer. in $\mu_s$ 0.07
  - $\pm 2$ uncer. in $\rho_s$ 0.002

  [Assume $G_a^s = \Delta s / (1 + Q^2 / M_A^2)^2$]

- 5% ratio sensitive to $\Delta s$ at $\pm 0.04$
- Determine one combination of $\Delta s$ and $\mu_s$ from $\nu$ and another from anti-$\nu$. 
Experimental Considerations

- Many systematics, such as absolute flux, proton efficiency, cancel in ratio.

- Need to identify pions to separate elastic from inelastic events. [This may require a segmented detector.]

- Possible backgrounds from neutrons and multiple nucleon knockout.

- Many nuclear structure issues also cancel in ratio, however don’t go too low in $Q^2$. Want proton recoil energy to be large compared to giant resonances $T_{\text{lab}}>50-100$ MeV (can use more calculations).

- Note, more counts and closer to $Q^2=0$ limit for $\Delta s$ at low $Q$. Tradeoff in $Q^2$ choice.
Conclusions

- Important to measure $\nu_\mu$, $\nu_\tau$ since they contain most of E and benchmark for $\nu$ oscillation measurements.

- $\nu$-$A$ elastic scattering has large yield, information on $\nu_\mu$, $\nu_\tau$ energy spectrum, and very clean theoretical interpretation.

- Good way to measure total E of SN which is important and interesting.

- Liquid Ne [CLEAN] looks very good, 4 events/ton for galactic SN. This is a factor of 20 or more greater yield than large yield $\nu_e$-bar capture in $H_2O$. 