

Electroweak Elastic Scattering in Heaven and Earth

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Neutrino-nucleon elastic scattering is the largest opacity source for mu and tau neutrinos in a core collapse supernova and sets the time scale for neutrinos to diffuse out of the core. Elastic neutrino-proton or neutrino-nucleus scattering is a very promising way to detect supernova neutrinos. The coherent nuclear cross section is very large and the spectrum of recoiling ions provides crucial information on the energy spectrum of mu and tau neutrinos. Finally it is important to measure neutrino-nucleon elastic scattering using laboratory neutrinos in order to determine strange quark contributions to the nucleon structure and spin. There are now a number of attractive neutrino beam lines. Measuring the ratio of neutral to charged current scattering allows strange quark contributions to be extracted with reduced systematic errors.

1. INTRODUCTION

Core collapse supernovae are gigantic explosions of a single massive star. They are dominated by weakly interacting neutrinos that radiate 99% of the binding energy of the newly formed neutron star. This provides a unique opportunity to search for macroscopic manifestations of the symmetries and features of the standard model weak interactions [1][2]. Significant energy is transported from the interior by mu and tau neutrinos because these have longer mean free paths than electron neutrinos since ν_e also have charged current interactions.

The opacity for ν_μ and ν_τ is dominated by ν -nucleon elastic scattering. In this paper we discuss $\nu - N$ elastic scattering in both supernovae and laboratory experiments. In section II we discuss neutrino interactions in core collapse supernovae. We also discuss the detection of supernova neutrinos in new underground detectors. The liquid Ne based CLEAN proposal can measure the spectrum of mu and tau neutrinos via neutrino-nucleus elastic scattering.

In section III we discuss neutrino-nucleon elastic scattering in the laboratory. This allows one to measure strange quark contributions to both the vector and axial form factors of the nucleon. First we review present results from parity vio-

lating electron scattering. Then we discuss a very promising measurement of the neutral current to charged current ratio that can accurately determine strange quark contributions to the nucleon. Finally, we mention the proposed FINESE detector at Fermi Lab that is ideally suited for this measurement.

2. Core Collapse Supernovae

A core collapse supernova is the violent death of a large star. A single massive star, larger than about 8 solar masses, successively burns heavier elements until its core is converted into Fe. At this point no more energy can be released by nuclear reactions. Without the thermal pressure from reactions, the core, a planet sized object of about 1.5 solar masses, collapses in less than a second. This forms a protoneutron star with a radius of only about 20 km.

The very high incompressibility of nuclear matter starts a shock as the collapse abruptly stops. However this shock loses so much energy dissociating the Fe and radiating neutrinos that it, very likely, stalls. Over a longer time scale, perhaps as long as a second, the intense neutrino radiation from the hot lepton rich protoneutron star is thought to reenergize the shock and eventually explode the star.

Unfortunately the best simulations of this neutrino reheating mechanism do not presently explode [3]. However there is much more energy radiated in neutrinos than is needed to explode the star. Therefore, the explosion may depend on some of the fine details of neutrino-nucleon interactions. Furthermore, recent advances in computer simulations allow neutrino transport to be calculated with realistic neutrino interactions [4][5][6].

Neutrino-nucleon elastic scattering is an important opacity source that determines how quickly mu and tau neutrinos can diffuse out of the star. There is some uncertainty in the elastic cross section because of possible strange quark contributions to the axial form factor of a nucleon, see below. This uncertainty is relevant for supernova simulations. Indeed, one supernova simulation with an erroneously too small cross section did indeed incorrectly explode. It would be useful to have better laboratory measurements of the neutrino-nucleon cross sections.

2.1. Supernova neutrino detection

The Kamioka and IMB detectors, in a historic first, observed about 20 events from Supernova SN1987A. These were, very likely, all from $\bar{\nu}_e$ capture on protons. Present detectors such as Superkamiokanda should observe thousands of $\bar{\nu}_e$ events from a core collapse supernova in our galaxy. Thus $\bar{\nu}_e$ should be well measured.

However, the energy of mu and tau neutrinos will not be directly observed in present detectors. For example, SuperK can observe mu and tau neutrinos via $^{16}\text{O}(\nu, \nu)^{16}\text{O}^*$ followed by detection of a gamma ray from the de-excitation of ^{16}O [7]. Because the outgoing neutrino is not observed, the energy of the neutrino is not directly measured. Likewise SNO can observe ν_μ and ν_τ via neutral current breakup of deuterium followed by detection of the neutron [8]. Again direct energy information is lost.

It is important to directly measure the spectrum of ν_μ and ν_τ , which we collectively call ν_x , for a number of reasons. First, most of the energy in a supernova is radiated in mu and tau neutrinos. This is because there are twice as many as ν_e . The total energy radiated in neutrinos is equal

to the gravitational binding energy of the newly formed neutron star. This binding energy is of order,

$$E \approx \frac{3}{5} \frac{GM^2}{R}, \quad (1)$$

where G is Newtons constant and M is the mass and R the radius of the neutron star. Thus measuring the ν_μ and ν_τ can set important limits on the mass of the new neutron star. Alternatively, one can check for a small radius that could indicate exotic forms of matter such as strange quark matter or a color superconductor. These may have softer equations of state and lead to radii smaller than the 10-13 km expected for stars made of conventional neutron rich matter.

Supernovae provide important cooling limits on additional weakly interacting particles such as axions. If a new particle interacts weakly, it may escape quickly from the star and carry off some of the energy. Better measurements of ν_x energies will allow a better accounting of the total energy radiated in neutrinos and provide a tighter constraint on any “missing energy.”

Finally, it is important to search for oscillations of supernova neutrinos. The large matter effects in a supernova allow sensitivity to small θ_{13} mixing angles and the sign of the $m_3 - m_2$ mass difference. These quantities may be difficult to measure in terrestrial or solar neutrino experiments. However, the signature of supernova neutrino oscillations is a change in energy of the detected ν_e . It is expected that ν_x are emitted with higher energies than ν_e because ν_x interact more weakly and decouple from matter at higher densities and temperatures. Oscillations can convert some of these high energy ν_x into high energy ν_e . Thus the “lever arm for observing neutrino oscillations is the expected energy difference between the original ν_x and ν_e spectra. Therefore it is important to accurately measure the ν_x spectrum.

2.2. Elastic scattering detectors

Supernova detection via elastic neutrino-nucleon or neutrino nucleus scattering can provide unique information on the ν_x spectrum via the spectrum of recoiling ions. Neutrino proton scattering may be possible in Kamland [9].

Neutrino-nucleus scattering has a very large coherent cross section that is accurately known with little theoretical uncertainty. This allows very large yields of a few or more events *per ton* for a galactic supernova at 10 kpc distance. This is a large improvement on the ν_x yields of existing detectors of 10s of events *per kiloton*.

However, the energy of the recoiling ions is very low, typically below 100 kilovolts. It is very challenging to detect these low energy recoils in the presence of many sources of backgrounds. However, great progress is being made in large mass, low threshold, and low background detectors for low energy solar neutrinos, weakly interacting dark matter particles (WIMPS), and double beta decay. Large detectors for low energy solar neutrinos, WIMPS or double beta decay should soon be sensitive to galactic supernovae via elastic scattering [10].

For example, CLEAN is a proposed detector for pp solar neutrinos that will use liquid neon as a scintillator [11]. The great advantage of liquid Ne is that it can be easily purified of radioactive impurities. Figure 1 shows the expected signal from a supernova at 10 kpc in CLEAN. This signal is much larger than the radioactive background and is very sensitive to the temperature of the ν_x . Furthermore, one can use position information inside the detector to reduce the background further [10]. We conclude that CLEAN can make important measurements of the ν_x spectrum.

3. Neutrino-nucleon elastic scattering in the laboratory

Neutrino scattering in the laboratory can provide information on strange quark contributions to the nucleon form factors. The weak neutral current of a nucleon can be written,

$$J_\mu = \bar{U}(p')[\gamma_\mu F_1(Q^2) + i\frac{\sigma_{\mu\nu}q^\nu}{2M}F_2(Q^2) + \gamma_\mu\gamma_5 G_A(Q^2)]U(p), \quad (2)$$

with $q_\mu = p'_\mu - p_\mu$ the momentum transferred to the nucleon and $Q^2 = -q_\mu^2$. The Dirac, F_1 , Pauli, F_2 , and axial, G_A , form factors can have contributions from strange quarks: F_1^s , F_2^s and G_A^s . The nucleon has no valence strange quarks

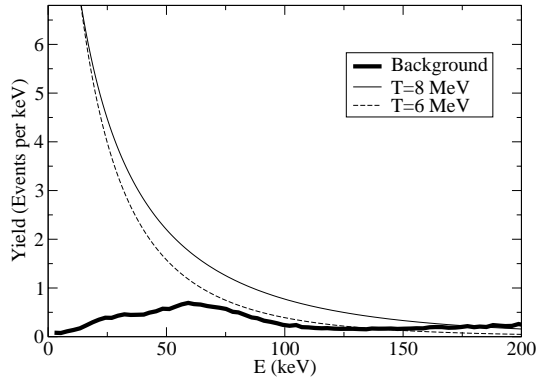


Figure 1. Yield for full 100 ton fiducial mass of CLEAN versus recoil kinetic energy E . The solid curve is the expected supernova signal assuming a distance of 10 kpc and a ν_x temperature $T_{\nu_x} = 8$ MeV. The dashed curve assumes $T_{\nu_x} = 6$ MeV. Finally, the thick curve is the predicted background from the Monte Carlo simulation assuming an observing time of 10 seconds [10].

so $F_1^s(Q^2 = 0) = 0$. The derivative of F_1^s at $Q^2 = 0$ is related to the strangeness radius of the nucleon ρ_s while $F_2^s(Q^2 = 0) = \mu_s$, with μ_s the strange anomalous moment of the nucleon. Finally the axial form factor reduces to the fraction of the nucleon spin Δs carried by strange quarks $G_A^s(Q^2 = 0) = \Delta s$.

The form factors F_1 , F_2 and G_A have contributions from up and down quarks in addition to strange quarks. Therefore three independent measurements are needed to separate the form factors into up, down and strange contributions and isolate the strange quarks. If one assumes the nucleon has good isospin, one can use the measured electromagnetic form factor of the proton and neutron plus weak information from either parity violating electron scattering or neutrino scattering to separate the quark contributions.

The SAMPLE experiment at MIT Bates measured the parity violating asymmetry for elastic electron scattering at large angles and low Q^2 from both hydrogen and deuterium [12]. This is sensitive to F_2^s . They find that F_2^s is consistent

with zero, however the errors are large. The experiment is also sensitive to radiative corrections. For example the nucleon can have a parity violating electromagnetic coupling known as an anapole moment. This arises from parity violation in the hadronic system. Both hydrogen and deuterium are sensitive to radiative corrections while hydrogen is much more sensitive to F_2^s than deuterium. Therefore one can use the two measurements to separate F_2^s from radiative corrections. However this separation has relatively large errors. An early SAMPLE result suggested that the radiative corrections were surprisingly large. However, a more recent correction for backgrounds from pion production may lead to radiative corrections consistent with theoretical estimates.

Unfortunately, parity violating electron scattering can not measure G_A^s well because of radiative corrections and a small suppression factor $1 - 4\sin^2\theta_W$ involving the weak mixing angle θ_W . Therefore elastic neutrino scattering may be one of the few practical ways to directly measure G_A^s . Furthermore, neutrino scattering has much smaller radiative corrections than parity violating electron scattering because the neutrino is uncharged. Note, Δs can be extracted from polarized deep inelastic scattering, however the analysis involves many assumptions such as SU3 symmetry. Also Δs can be extracted from semi-inclusive deep inelastic scattering, but again with many model assumptions.

The best neutrino-nucleon elastic scattering experiment was done several years ago at Brookhaven [13]. This experiment suggested that Δs is nonzero and negative, however the systematic errors are large. Now there are very attractive neutrino fluxes at a number of beam lines designed for neutrino oscillation experiments. It is very promising to design a new elastic scattering experiment that can accurately measure strange quark contributions to G_A^s . It is important to cleanly isolate elastic events and control systematic errors.

At low Q^2 there are large nuclear structure corrections while at high neutrino energies it is difficult to isolate the elastic events from the large inelastic background. Therefore there is a broad region of intermediate neutrino energies around

one GeV that is good for an elastic experiment. One should be able to isolate elastic events in a segmented scintillator or similar detector. Here one can detect and measure the energy of a recoiling proton track and separate it from pions or muons.

Ratio measurements can be very effective at controlling systematics. One possibility is to measure the ratio of $\nu - n$ to $\nu - p$ elastic scattering from a target containing carbon. This ratio is very sensitive to strange quarks. However, it requires neutron detection which is difficult at these intermediate energies (the neutron recoil energy is around 100 MeV). Furthermore, one is very sensitive to the efficiency of detecting neutrons which may be poorly known.

We focus on the ratio of neutral current $\nu - p$ elastic scattering to charged current quasielastic $n(\nu_\mu, \mu)p$ on a carbon target. In both cases one detects protons. Thus it is, in principle, a very simple experimental measurement. What is the ratio of protons of a given energy without muons to those of the same energy with a muon? Note, this is a somewhat nonstandard measurement of the charged current. Often one uses the muon to define the kinematics of the event. Here we focus on the recoiling proton and use its energy to estimate the Q^2 . Then we integrate over a large range of muon kinematics and simply ask is their a muon present or not?

This ratio of neutral to charged currents is sensitive to strange quarks since they only change the numerator and give no contribution to the denominator. Furthermore, many experimental and theoretical errors cancel in the ratio. For example, one is much less sensitive to the absolute neutrino flux. Some of the sensitivity to the axial mass M_A , which is used to parameterize the axial form factor $G_A(Q^2)$, cancels since both the numerator and denominator depend on M_A . Finally, since one detects a proton in both the numerator and denominator, final state interactions of the proton with the nucleus are common and mostly cancel in the ratio. For example, an optical potential is expected to reduce the flux by the same amount in both the numerator and denominator. Therefore, a number of nuclear structure uncertainties are reduced in the ratio.

As an example we consider a neutrino energy near 800 MeV and $Q^2 = 0.5 \text{ GeV}^2$. A five percent measurement of the neutral to charged current ratio is sensitive to Δs at the ± 0.03 level. This we believe is a reasonable goal for an elastic experiment and should provide the definitive measurement of strange quark contributions to the nucleon spin. The measurement is also sensitive to F_2^s but at a lesser level. It would be very interesting to make a measurement with antineutrinos. One can then use the neutrino and antineutrino results to separately extract G_A^s and F_2^s . Note, neutrino scattering is not very sensitive to F_1^s . The G_A^s results would be unique to neutrino scattering, while the F_2^s results could be compared to parity violating electron scattering and would provide a crucial check since neutrino scattering is much less sensitive to radiative corrections.

The Fermi Lab Intense Neutrino Scattering Experiment (FINESE) is proposed for the MINI-BOONE beam line at Fermi Lab. This would use a target of segmented scintillator and should be almost ideal for measuring the neutral to charged current ratio and Δs . More details are contained in the talk at this workshop by Rex Tayloe [14].

Alternatively, one could attempt an elastic measurement using the Main Injector beam line at Fermi Lab. See the talk by Jorge Morfin [15]. However there may be important backgrounds from neutrons produced by neutrino interactions in the dirt surrounding the detector and from inelastic events induced in the detector by high energy neutrinos. These backgrounds could compromise the elastic measurement and should be studied further.

In conclusion, neutrino-nucleon elastic scattering is the largest opacity source for mu and tau neutrinos in a core collapse supernova and this sets the time scale for neutrinos to diffuse out of the core. Elastic neutrino-proton or neutrino-nucleus scattering is a very promising way to detect supernova neutrinos. The coherent nuclear cross section is very large and the spectrum of recoiling ions provides crucial information on the energy spectrum of mu and tau neutrinos. Finally it is important to measure neutrino-nucleon elastic scattering using laboratory neutrinos in or-

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