Overview of Neutrino-Nucleus Interactions

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An overview of neutrino-nucleus interactions is presented. After a brief discussion of theory and applications of detector response three examples are discussed: i) Recent work on neutrino-deuteron reactions, ii) Probing strangeness content of the nucleon with neutrinos, and iii) The role of neutrino reactions in supernova dynamics and r-process nucleosynthesis.

§1. Introduction

Recent observations of solar and atmospheric neutrinos at the Super-Kamiokande and Sudbury Neutrino Observatories are among the most exciting experimental results obtained in the last decades. These and other neutrino observations often utilize neutrino interactions with various nuclei. Neutrino-nucleus scattering is not only a useful tool for neutrino detection, but also plays an important role in understanding the dynamics of a core-collapse supernova and the subsequent nucleosynthesis. In addition, neutrinos can be used as a probe of fundamental physics at low energies. The purpose of this talk is to present a brief overview of neutrino-nucleus interactions to highlight the rich nuclear physics program that can be carried out at facilities that can produce low-energy neutrinos.

One can divide investigation of neutrino-nucleus interactions into roughly four groups:

• Theory and Applications of Detector Response: Solar, atmospheric, accelerator, and reactor neutrinos have different energies necessitating the calculation of detector response to neutrinos at different energy ranges.
• Input into Astrophysics: This includes a study of neutrino reactions in core-collapse supernovae and also input into the r-process nucleosynthesis calculations.
• Tests of Nuclear Structure Calculations and Approximation Methods: Examples in this category are i) Comparison of indirect methods to calculate Gamow-Teller matrix elements (such as (p,n) reactions) to possible direct systematic studies and ii) Using effective field theories both to directly calculate neutrino-deuteron interactions and check for inconsistencies in the potential model calculations.
• Probing Fundamental Physics at Low Energies: This can lead to a rich physics program. One example is determination of the proton strange form factors to better understand the strangeness contribution to the proton spin.

In the following sections, after a brief discussion of theory and applications of detec-
tor response, three examples are discussed to illustrate the breadth of the phenomena that relate to neutrino-nucleus scattering: i) Recent work on neutrino-deuteron reactions and related tests of effective field theories, ii) Probing strangeness content of the nucleon with neutrinos, and iii) The role neutrino interactions in supernova dynamics and r-process nucleosynthesis.

§2. Detector response

An elementary introduction to the calculation of neutrino cross sections is given in Ref. 5), and recent results are summarized in Refs. 6) and 7). One can divide studies of detector response roughly into four categories from lowest to highest neutrino energies. For solar neutrino energies where one has mostly bound discrete final states, Shell Model and random phase approximation can be used. Here the appropriate targets include chlorine $^{37}\text{Cl}$, gallium $^{71}\text{Ga}$, iodine $^{127}\text{I}$, molybdenum $^{100}\text{Mo}$, and ytterbium $^{176}\text{Yb}$. One should point out that even when solar neutrinos are detected via their interactions with electrons in a water detector such as Super-Kamiokande, neutrino interactions with $^{18}\text{O}$, present in water in trace amounts, may be significant.

For low-energy laboratory neutrinos such as those used by the LSND, KARMEN, KamLAND, and Borexino experiments, one has both bound discrete and continuum final states and the appropriate targets are carbon $^{12}\text{C}$ and oxygen $^{16}\text{O}$.

Supernova neutrino energies are similar to those of low-energy laboratory neutrinos. One needs to calculate either capture of supernova neutrinos on terrestrial detectors or neutrino reactions in a supernova environment (For a discussion of the role on neutrinos in the dynamics of core-collapse supernovae and the r-process nucleosynthesis that can take place in such supernovae cf. Section 5). Neutrino interactions that need to be calculated to study a core-collapse supernova are depicted in Figure 1. One observes that not only Fermi and Gamow-Teller transitions, but in a number of cases also the first-forbidden transitions, need to be calculated.

Atmospheric neutrinos typically have the highest energies among the neutrino sources listed here. Neutrino capture in this case is mostly to the final states in the continuum.

Collective phenomena are very important in low-energy structure of nuclei. Since such effects are amenable to algebraic descriptions (see e.g. Ref. 52) symmetries significantly simplify calculations of some nuclear reactions. One should point out that collective effects seem not to play an important role in neutrino capture...
on nuclei; hence dynamical symmetries of nuclei do not simplify neutrino capture calculations as they do calculations of sub-barrier fusion. It is however possible for nuclear collectivity to influence other weak interaction processes in nuclei. (A discussion of nuclear fusion cross sections that are important for solar energy generation is beyond the scope of this talk. For a review see Ref. 56).

§3. Neutrino-deuteron scattering

Sudbury Neutrino Observatory is a real-time heavy-water Cerenkov detector: neutrinos are observed by measuring inelastic neutrino-deuteron scattering. The only measurement of the total cross section for charged-current breakup of deuterons by electron neutrinos has only about 35% precision. Furthermore since this measurement utilizes decays of stopped muons at the LAMPF beam-stop the neutrino spectrum resembles that of a supernova, not that of the Sun. Although the current theoretical accuracy (~ 5%) is sufficient to interpret the Sudbury Neutrino Observatory results, it is important to know neutrino-deuteron cross-sections better to fully exploit the current and future experimental results. The calculation of this cross section requires at least three pieces of input: i) A one-body piece that needs to be convoluted with the deuteron and two-proton wavefunctions (or two-neutron wavefunction for the electron antineutrino breakup); ii) A two-body piece which includes meson-exchange terms; iii) Radiative corrections. Recent calculations that incorporate modern nucleon-nucleon potentials, but treat meson-exchange currents with different methods differ by about 5%. The calculation of this cross section can be elegantly done using the tools of effective field theories. Using the power-counting scheme of Refs. it was found that in next-to-leading order theoretical uncertainties were dominated by an unknown axial two-body counter-term which eventually needs to be experimentally fixed. Next-to-next-to-leading order calculations indicate that such an expansion indeed converges at neutrino energies of interest. There is general agreement about the validity and consistency of these results and the related results for proton-proton fusion. Recoil corrections can also be important as they may effect angular distributions. Finally, a careful analysis of the radiative corrections indicate that they are of the order of a few percent.

§4. Strangeness in nuclei

Neutrino elastic scattering can be used to probe strange quark content of the nucleon and its contribution to the proton spin. The nucleon axial current

\[ \langle N|Z\bar{A}_{\mu}|N \rangle \sim \frac{1}{2} \langle N|\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d - \bar{s}\gamma_\mu\gamma_5 s|N \rangle \]

has isovector (up and down quarks) and isoscalar (strange quark) contributions as indicated. The ratio of the proton-to-neutron knockout reactions, which is dependent on the isoscalar form factor at \( Q^2 = 0 \) (i.e. \( \Delta s \)), can be used to study the strangeness
contribution\textsuperscript{76}:
\[
\frac{\sigma(\nu + A \rightarrow p + X)}{\sigma(\nu + A \rightarrow n + X')} \sim 1 + \frac{16}{5} \Delta s.
\]

Extraction of $\Delta s$ from such ratios significantly reduces nuclear-model dependences\textsuperscript{77}.

A second possibility is to look directly for isoscalar excitations, e.g.
\[
\nu + ^{12}C \rightarrow ^{12}C^* (12.7 \text{ MeV}, 1^+ T = 0) + \nu.
\]

Isospin mixing in nuclei certainly complicates such an analysis, but it may be possible to separate isoscalar and isovector contributions in certain nuclei\textsuperscript{78}. Another possibility to determine proton strange form factors is neutrino-proton elastic scattering\textsuperscript{79}. A recent summary of the studies of strange quark contributions to nucleon structure is given in Ref. \textsuperscript{80} and the role of neutrinos is discussed in Ref. \textsuperscript{81}.

\section{Neutrino Interactions in Supernovae}

Understanding neutrino transport in a supernova is an essential part of understanding supernova dynamics. In a core-collapse driven supernova, the inner core collapses subsonically, but the outer part of the core supersonically. At some point during the collapse, when the nuclear equation of state stiffens, the inner part of the core bounces, but the outer core continues falling in. The proto-neutron star, shrinking under its own gravity, loses energy by emitting neutrinos, which only interact weakly and can leak out on a relatively long diffusion time scale. Most neutrinos emitted from the core are produced by a neutral current process, and so the luminosities are approximately the same for all flavors. The energy spectra are approximately Fermi-Dirac with a zero chemical potential characterized by a neutrinosphere temperature. The $\nu_\tau, \overline{\nu}_\tau, \nu_\mu, \overline{\nu}_\mu$ interact with matter only via neutral current interactions. These decouple at relatively small radius and end up with somewhat high temperatures, about 8 MeV. The $\overline{\nu}_e$'s decouple at a larger radius because of the additional charged current interactions with the protons, and consequently have a somewhat lower temperature, about 5 MeV. Finally, since they undergo charged current interactions with more abundant neutrons, $\nu_e$'s decouple at the largest radius and end up with the lowest temperature, about 3.5 to 4 MeV. Although numerical values of these temperatures depend on specific models, this temperature hierarchy is model-independent.

R-process nucleosynthesis requires a neutron-rich environment, i.e., the ratio of electrons to baryons, $Y_e$, should be less than one half. Time-scale arguments based on meteoritic data suggests that one possible site for r-process nucleosynthesis is the neutron-rich material associated with core-collapse supernovae\textsuperscript{82,83}. In one model for neutron-rich material ejection following the core-collapse, the material is heated with neutrinos to form a “neutrino-driven wind”\textsuperscript{84,85}. In outflow models freeze-out from nuclear statistical equilibrium leads to the r-process nucleosynthesis. The outcome of the freeze-out process in turn is determined by the neutron-to-seed ratio. The neutron to seed ratio is controlled by three quantities: i) The expansion rate; ii) The neutron-to-proton ratio (or equivalently the electron fraction, $Y_e$); iii)
The entropy per baryon. Of these three the neutron-to-proton ratio is completely determined by the neutrino-nucleon and neutrino-nucleus interactions.

Electron fraction in the nucleosynthesis region is given approximately by

$$Y_e \simeq \frac{1}{1 + \lambda_{\nu_e,p}/\lambda_{\nu_e,n}} \simeq \frac{1}{1 + T_{\nu_e}/T_{\nu_e}},$$

where $\lambda_{\nu_e,n}$, etc. are the capture rates and various neutrino temperatures are indicated by $T$. Hence if $T_{\nu_e} > T_{\nu_e}$, then the medium is neutron-rich. As we discussed above, without matter-enhanced neutrino oscillations, the neutrino temperatures satisfy the inequality $T_{\nu_e} > T_{\nu_e} > T_{\nu_e}$. But matter effects via the MSW mechanism, by heating $\nu_e$ and cooling $\nu_e$, can reverse the direction of inequality, making the medium proton-rich instead. Hence the existence of neutrino mass and mixings puts severe constraints on heavy-element nucleosynthesis in supernova. These constraints are investigated in Refs. 86) and 88). One should also point out that in stochastic media (i.e. media with large density fluctuations) neutrino flavors would depolarize 89), 90). Although recent solar neutrino experiments rule out such effects for the Sun 91), they may be important in supernova.

There are two kinds of neutrino reactions that can destroy r-process: i) neutrino neutral current spallation of alpha particles 93); ii) formation of too many alpha particles, known as the “alpha effect” 94), 95). The alpha effect comes at the epoch of alpha-particle formation: protons produced by $\nu_e$ capture on neutrons will in turn capture more neutrons to bind into alpha particles, reducing the number of free neutrons available to the r-process and pushing $Y_e$ towards 0.5. Reducing the $\nu_e$ flux will resolve this problem, but we can only do so at a relatively large radius so that effective neutrino heating already can have occurred. One way to achieve this is transforming active electron neutrinos into sterile neutrinos 96)–101). For the case of active-sterile mixing with fixed values of neutrino parameters and matter density, for $Y_e > 1/3$ only electron neutrinos, and for $Y_e < 1/3$ only electron antineutrinos can undergo an MSW resonance 96). If both electron neutrino and antineutrino fluxes go through a region of neutrons and protons in equilibrium (i.e. the reactions $\nu_e + n \rightarrow p + e^-$ and $\bar{\nu}_e + p \rightarrow n + e^+$ are in steady state equilibrium with the $\nu_e$ and $\bar{\nu}_e$ fluxes), then no matter what the initial $Y_e$ is one may expect that the system will evolve to a fixed point with $Y_e = 1/3$ ensuring a neutron-rich medium 100). Realistic calculations of the supernova wind models do not bear out this assessment as shown below; although the electron antineutrinos are converted into sterile species, they are regenerated before the electron fraction in the wind freezes out.

Neutrino driven wind models, where the outflow is homologous (i.e. fluid velocity is proportional to the distance) are characterized by two parameters: entropy per baryon and the expansion timescale, $\tau$ (i.e. $\tau = r_0 e^{t/\tau}$). In Refs. 96) and 101) we solved the neutrino evolution equations in matter. In addition we tracked the thermodynamic and nuclear statistical equilibrium evolution of a mass element and updated the numbers of neutrons and protons at each time step directly from the weak capture rates. This coupling of the neutrino evolution and self-consistent determination of the abundances is essential to accurately determine the number of
neutrons available for the r-process. The results are illustrated in Figures 2 and 3 for expansion timescales of $\tau = 0.3$ and $\tau = 0.9$ seconds respectively. One observes that there is a wide range of neutrino parameters which neutralizes the alpha effect and increases the neutron-to-seed ratio to produce favorable conditions for r-process nucleosynthesis.

§6. Conclusions

Various topics covered in this talk were chosen to illustrate the utility of a comprehensive low-energy nuclear physics program which could investigate neutrino interactions at energies appropriate for nuclear and particle astrophysics as well as nuclear structure. Such a program was originally proposed by the ORLaND collaboration at Oak Ridge National Laboratory\cite{102,103}. The Spallation Neutron Source, currently under construction at this Laboratory, will produce neutrinos from the decay of stopped pions created during spallation and from the decay of the daughter muons. The pulsed nature of such neutrinos also proves to be useful in eliminating unwanted backgrounds. The short-term prospects for such a program seem to be unclear. However, one expects that a neutrino physics program either at Oak Ridge or at other spallation neutron facilities being built around the world will eventually be a reality, since such a program would offer many experimental advantages at relatively low cost\cite{104}.

Recent observations of heavy-element abundances in ultra metal-poor halo stars provide a deeper insight into the location of the site for r-process nucleosynthesis. The abundances of the heavier ($Z > 56$) stable neutron-capture elements in such stars match well the scaled solar system r-process abundances. This concordance breaks down for the lighter neutron-capture elements, supporting previous
suggestions\textsuperscript{82,83} that different r-process production sites are responsible for lighter and heavier neutron-capture elements. Indeed, neutron-star mergers were also proposed as a site for r-process nucleosynthesis\textsuperscript{106}.

Figures 2 and 3 indicate that as the expansion timescale gets shorter, the optimal parameter space moves to larger values of $\Delta m^2$. However, at very short dynamic expansion timescales the alpha effect can be very small obviating active-sterile conversion. Indeed recent calculations indicate that the expansion time scale can be shorter in some cases\textsuperscript{107}. A recent comprehensive overview of element synthesis in stars is given in Ref. 108).

In calculating the contours of Figs. 2 and 3 the neutrino mixing parameter space was freely searched with no reference to the accelerator neutrino experiments. Nevertheless it is rather interesting to observe that the optimal parameter space seems to be very similar to that which was hinted at by the LSND experiment\textsuperscript{109}. The MiniBooNE experiment currently under construction at Fermilab\textsuperscript{110} will either provide confirming evidence or prove LSND wrong and set more stringent limits on the neutrino parameters.

Similarities between the Big Bang during nucleosynthesis and the neutrino-driven high-entropy ejecta in a core-collapse supernova were emphasized in the literature\textsuperscript{111}. Indeed they are isospin mirrors of each other; the role played by the protons in the Big Bang nucleosynthesis is played by the neutrons in the supernova nucleosynthesis. In both cases the neutron-to-proton ratio is controlled by the neutrino interactions. The regions of the neutrino parameter space that affects nucleosynthesis in these environments are shown in Fig. 4 (Ref. 112). Consequently one can argue that experiments such as LSND, KARMEN, ORLaND and MiniBooNE that probe this region of the neutrino parameter space are relevant to understanding both the Big Bang and supernova nucleosynthesis (see, e.g. Ref. 113). Future experiments such as MiniBooNE or ORLaND (or similar detectors), no matter what their outcomes are, will probe this remarkable interplay between element production in the cosmos and the fundamental properties of neutrinos.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{neutrino_parameter_space.png}
\caption{Regions of neutrino parameter space sensitive to supernovae (left-leaning shading) and the early universe (right-leaning shading) nucleosynthesis.}
\end{figure}
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