Very Low-Energy Neutrino Interactions

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Abstract. Neutrino-nucleus reaction cross sections are now evaluated rather accurately by shell-model (SM) or SM+RPA calculations based on recent advances in nuclear structure studies. Due to these achievements, reliable constraints on supernova neutrino temperatures as well as neutrino oscillation parameters become possible. Supernova neutrino tempeatures are constrained from abundances of elements obtained by using new ν-nucleus reaction cross sections. A possibility of constructing supernova neutrino spectrum from beta-beam measurements is pointed out. Neutrino mass hierarchy and mixing angle θ_{13} can be determined from abundance ratio of ^{7}Li/^{11}B, which is sensitive to the MSW matter oscillation effects in supernova explosions. Inverted mass hierarchy is shown to be statistically more favored based on a recent analysis of presolar grains. Effects of neutrino-neutrino interactions are also shown to play important roles in r-process nucleosynthesis. Importance and possibilities of direct measurements of ν-induced cross sections on ^{40}Ar and ^{208}Pb are discussed for future supernova neutrino detections. Recent calculations of the cross sections for ν-^{40}Ar are presented. The need for new theoretical evaluations of the cross sections for ν-^{208}Pb is pointed out. Challenges to experiments on coherent elastic scattering are presented.

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INTRODUCTION

Subjects treated and discussions made in the “very low energy neutrino interactions” session are summarized by giving answers to the following questions: (1) how important are ν-processes in nucleosynthsis? (2) how ν-oscillations affect the nucleosynthsis? (3) how accurately do we know ν-nucleus cross sections?

HOW IMPORTANT ARE ν-PROCESSES IN NUCLEOSYNTHESIS

Rare elements such as ^{7}Li, ^{11}B, ^{138}La and ^{180}Ta are produced by ν-processes in supernova explosions[1]. Now, more accurate evaluations of the production yields by ν-processes are required. Abundances of ^{7}Li and ^{11}B are obtained with new neutrino-nucleus cross sections and astrophysical galactic chemical evolutions (GCE) of light elements. Supernova neutrino (SNν) temperatures for ν_μ and ν_τ are constrained to be rather low, T_{ν_μ,ν_τ} =6 MeV. Roles of isomers in ^{180}Ta are studied to solve the over-production problem of ^{180}Ta. Abundances of ^{180}Ta, ^{138}La and r-process elements give constraints on the SNν temperatures for ν_e and $\bar{\nu}_e$; T_{ν_e} =3.2 MeV and $T_{\bar{\nu}_e}$ =4 MeV[2].

As for the shape of the SNν spectrum, there is no available experimental information though we use Fermi-Dirac distribution with or without a chemical potential or polynomial-type distributions. Construction of SNν spectrum directly from beta-beam measurements is discussed[3]. The use of beta-beams is shown to be quite promising.

HOW ν-OSCILLATIONS AFFECT THE NUCLEOSYNTHESIS?

The MSW matter oscillation effects in He-C layer enhance productions of ^{7}Li and ^{11}B in supernova explosions. The abundance ratio of ^{7}Li/^{11}B depends sensitively on the neutrino mass hierarchy and the mixing angle θ_{13}. Both the mass hierarchy and θ_{13} can be determined from the abundance ratio. Inverted mass hierarchy is shown to be favored with 74% probability from the studies of pre-solar grains in Murchison meteorite with Bayesian analysis[2].

Effects of ν-ν interactions on nucleosynthesis is discussed. A new type of ν oscillation from both ν-ν interactions and MSW effects can affect r-process nucleosynthesis above a black-hole accretion disk[4].

Study of the effects of ν-ν interaction on nucleosynthesis, which has just started recently, is important as it is connected with the problem of the specification of the r-process sites. In recent studies, neutron star mergers and MHD (magneto-hydrodynamic) jet supernova explosions are plausable candidates for the r-process site besides the ν-driven wind supernova explosions as the requirement of $Y_e < 0.5$ (Y_e is lepton-to-baryon ratio in matter) is not necessarily satisfied in ν-driven supernova explosions.

HOW ACCURATELY DO WE KNOW ν-NUCLEUS CROSS SECTIONS?

Direct measurements of neutrino-nucleus reaction cross sections are available only for a limited targets; carbon and iron. Present shell-model (SM) calculations using new SM Hamiltonians with proper tensor force, or hybrid model of SM+RPA, can reproduce experimental neutrino-nucleus reaction cross sections in ^{12}C and ^{56}Fe at DAR energies[5]. The Gamow-Teller (GT) strength and e-capture rates in ^{56}Ni can be also reproduced by SM calculations.

^{40}Ar and ^{208}Pb are important targets for supernova neutrino detections. Direct measurements of the cross sections for these nuclei are possible by spallation neutron source (SNS) and LArTPC[6], and HALO[7]. It is very important to carry out the measurements for future supernova neutrino detection and study of ν oscillations.

Cross sections for ^{40}Ar (ν, e^-) ^{40}K are evaluated by SM+RPA[5]. In the SM calculation, the experimental GT strength in ^{40}Ar is found to be well reproduced. Calculated cross sections are close to those by RPA[8], while the GT contributions are enhanced for the SM case.

Although several calculated cross sections for ν-^{208}Pb are available, more accurate theoretical evaluation of the cross section is necessary. Inclusion of spreading in the GT strength due to coupling to 2p-2h states is important.

Coherent elastic scattering from isoscalar targets is a challenging experiment, where careful removal of backgrounds and detection of recoil nucelus at keV energy region are necessary[9, 10]. If total flux and energy spectrum of reactor $\bar{\nu}_e$ are fixed, we can discuss existence or non-existence of sterile neutrinos.

Instead of direct measurements, indirect approach with the use of (p, p') reactions are also planned. Study of γ-ray emission from giant resonances in ^{12}C and ^{16}O are plannned by using (p, p') reactions in relation to the γ-ray emission in ^{12}C, ^{16}O (ν, ν')[11]. This measurement will provide us important information on γ-ray production from neutral-current ν-^{12}C, -^{16}O interactions.

Finally, we discuss if we can obtain information on strange quark content of nucleon from ν-nucleus reactions. Cross sections can be sensitive to the strange axial form factor, G_A^s [3]. As scatteing cross sections for proton and neutron tend to cancel, separate measurement of (ν, ν'p) and (ν, ν'n) is favored at quasi-elastic region. In case of pure isoscalar transitions such as ^{12}C (ν, ν') ^{12}C (1^+, T=0), we should note that isospin mixing effects can be important and the magnitude of the cross section is quite small.

SUMMARY

Now, experimental ν-induced reaction cross sections for ^{12}C and ^{56}Fe at DAR energies can be well reproduced by SM (SM+RPA) calculations with the use of new SM Hamiltonians. The GT strengths in ^{56}Ni and ^{40}Ar are also well described by SM calculations. Direct measurements as well as further theoretical investigations of ν-nucleus cross sections on ^{40}Ar and ^{208}Pb are highly recommended. Beta-beam and coherent scattering experiments are also worth challenges for better understanding of neutrino-nucleus interactions and neutrino properties.

We hope that we get a desicive determination of the neutrino mass hierarchy from long base-line accelerator experiments in near future. We are very much interested if the same conclusion for the mass hierarchy, that is, inverted mass hierarchy, is obtained. We also expect that studies of neutrino oscillations induced by the MSW effects and ν-ν interactions make further progress with fruitful astrophysical applications.

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