Astronomical Method to Determine the Neutrino Mass Hierarchy [1]

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Neutrino-nucleus reaction processes play important roles in the synthesis of rare elements such as ^{7}Li, ^{11}B, ^{138}La and ^{180}Ta in the explosive environments realized in supernovae. We have constructed new shell-model Hamiltonians by taking account of the proper tensor components in the interactions so that they can explain the new shell evolutions and new magic numbers in drip-line nuclei. The new Hamiltonians, SFO [2] and GXPF1J [3] are found to be quite successful in describing the spin responses in nuclei such as Gamow-Teller transition strengths in ^{12}C, ^{14}C, ^{56}Fe and ^{56}Ni.

As the neutrino-nucleus reactions are induced dominantly by spin-dependent transitions, we can now evaluate neutrino-nucleus reaction cross sections such as on ^{12}C and ^{56}Fe accurately with the use of new shell-model Hamiltonians [4,5]. Note that the experimental neutrino-induced cross sections are available only for these two nuclei. As the case for ^{12}C was reported in the Annual Report of NAOJ in 2012 [6], we show here the case for ^{56}Fe (ν, e$^-$) ^{56}Co induced by DAR neutrinos. Calculated value obtained by using GXPF1J is $\sigma = 259 \times 10^{-42}$ cm^2. Averaged value for several calculations is $\sigma_{th} = (258 \pm 57) \times 10^{-42}$ cm^2 [7], which is in good agreement with the experimental value from KARMEN Collaborations: $\sigma_{exp} = (256 \pm 108 \pm 43) \times 10^{-42}$ cm^2 [8].

New neutrino-nucleus reaction cross sections updated with the use of the new Hamiltonians are applied to evaluate more precise theoretical estimates of nucleosynthesis of ^{7}Li, ^{11}B and ^{55}Mn including the neutrino processes in the supernova explosions [4,5]. The production yields of ^{7}Li and ^{11}B are found to be enhanced by 13~14 % for SFO-WBP compared to those for Woosley's (HW92) [9], where WBP [10] is used for the evaluation of neutrino-induced reactions on ^{4}He.

Effects of ν-oscillations on the production yields of ^{7}Li and ^{11}B are investigated. Charged-current reactions become also important in case of oscillations. A new method to determine the neutrino mass hierarchy and the mixing angle θ_{13} from the abundance ratio of ^{7}Li/^{11}B is proposed. In the case of a normal hierarchy, the ratio is shown to be enhanced by the oscillation effects for $\sin^2 2\theta_{13} \geq 0.002$ due to the existence of the high-density resonance (see Fig. 1). The dependence of the ratio on the interactions are rather modest as shown in Fig. 2. Since the recent reactor and accelerator experiments give $\sin^2 2\theta_{13} \sim 0.1$, the neutrino mass hierarchy can be determined from the strong, robust dependence of the abundance ratio ^{7}Li/^{11}Bi on the oscillation parameters. Note that the mass hierarchies can not be distinguished only with vacuum oscillations unless the CP phase is finite.

According to a recent work based on the deduction of the ratio ^{7}Li/^{11}B from pre-solar grains of a meteorite [11], the inverse mass hierarchy is statistically more favored [12].

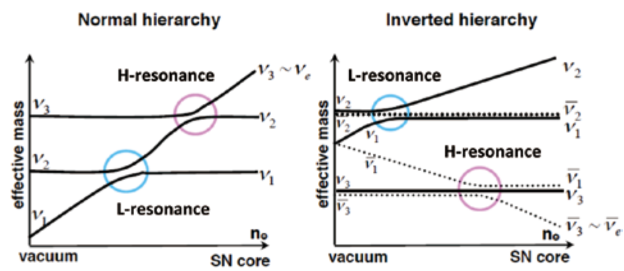

Figure 1: MSW effects in normal (left panel) and inverted (right panel) hierarchies. High-density resonance denoted as H-resonance occurs for ν_e ($\bar{\nu}_e$) in case of a normal (inverted) hierarchy, while low-density resonance denoted as L-resonance occurs for ν_e in both hierarchies.

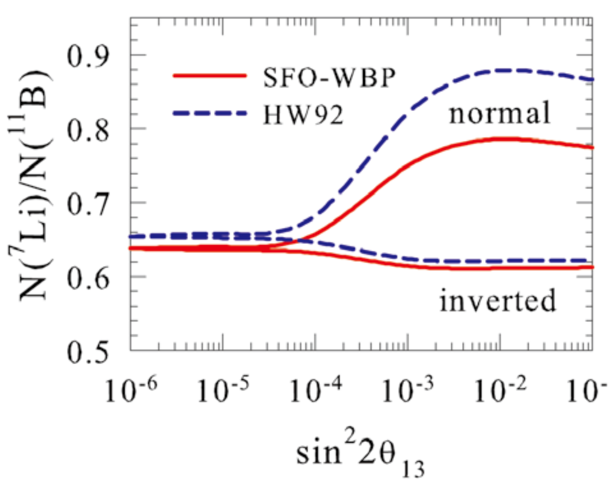

Figure 2: Comparison of the dependence of the abundance ratio ^{7}Li/^{11}B on the mixing angle θ_{13} for both neutrino mass hierarchies between SFO-WBP and HW92 cases. The same set of neutrino temperatures, T_{ν_e} =3.2 MeV, $T_{\bar{\nu}_e}$ =5.0 MeV and $T_{\nu_{\mu,\tau}} = T_{\bar{\nu}_{\mu,\tau}}$ = 6 MeV, and total neutrino energy $E_\nu = 3 \times 10^{53}$ erg are taken for the both cases.

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