Nuclear weak interactions, supernova nucleosynthesis and neutrino oscillation

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Abstract. We study the nuclear weak response in light-to-heavy mass nuclei and calculate neutrino-nucleus cross sections. We apply these cross sections to the explosive nucleosynthesis in core-collapse supernovae and find that several isotopes of rare elements ^{7}Li, ^{11}B, ^{138}La, ^{180}Ta and several others are predominantly produced by the neutrino-process nucleosynthesis. We discuss how to determine the suitable neutrino spectra of three different flavors and their anti-particles in order to explain the observed solar system abundances of these isotopes, combined with Galactic chemical evolution of the light nuclei and the heavy r-process elements. Light-mass nuclei like ^{7}Li and ^{11}B, which are produced in outer He-layer, are strongly affected by the neutrino flavor oscillation due to the MSW (Mikheyev-Smirnov-Wolfenstein) effect, while heavy-mass nuclei like ^{138}La, ^{180}Ta and r-process elements, which are produced in the inner O-Ne-Mg layer or the atmosphere of proto-neutron star, are likely to be free from the MSW effect. Using such a different nature of the neutrino-process nucleosynthesis, we study the neutrino oscillation effects on their abundances, and propose a new novel method to determine the unknown neutrino oscillation parameters, θ_{13} and mass hierarchy, simultaneously. There is recent evidence that some SiC X grains from the Murchison meteorite may contain supernova-produced neutrino-process ^{11}B and ^{7}Li encapsulated in the grains. Combining the recent experimental constraints on θ_{13}, we show that although the uncertainties are still large, our method hints at a marginal preference for an inverted neutrino mass hierarchy for the first time.

1. Introduction

Neutrino interactions with atomic nuclei play the critical roles in various scales of astronomical and cosmological phenomena. Still unknown mass and oscillation properties of neutrinos take the important keys to resolve many fundamental questions in particle physics and astrophysics such as why baryon- and lepton-symmetries are broken in the Universe, why we need unified theory beyond the standard model of elementary particles, why the core-collapse supernovae explode, etc. We discuss in this article how to determine the unknown neutrino oscillation parameters from the studies of element synthesis in supernovae [1, 2].

2. Core-Collapse Supernovae and Neutrino Spectra

Core-collapse supernovae emit intensive flux of three flavor neutrinos with total energy $\sim 3.0 \times 10^{53}$ ergs [3]. This total energy is almost equal to the gravitational binding energy of a 1.4 $M_{\odot}$ neutron star.

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2.1. Supernova Model

In our supernova model [4] the neutrino energy spectra are assumed to obey Fermi-Dirac distributions with zero-chemical potentials [5], and the explosion energy is set to be $\sim 0.3\%$ of total neutrino energy as assumed in the literatures. Nucleosynthesis yields generally depend on supernova models with different zero-age main-sequence masses, metallicities, and explosion energies. Since the neutrino-induced nucleosynthesis is a very weak process, one can adopt a post-processing method in that we calculate only the explosive nucleosynthesis in well studied supernova model for SN1987A, and then the contribution from the other supernova models scale to those calculated by Woosley and his collaborators [6, 7].

Neutrino temperatures depend on the dynamics of core-collapse and explosion. We here confine ourselves to the core-collapse supernovae which form the neutron star as a remnant. Although the black-hole associated explosion [8, 9] is another source of neutrinos, it is known to have a minor contribution due to the Salpeter initial mass function of stellar formation.

The neutrino spectra for $\nu_{\rm e}$ and $\bar{\nu}_{\rm e}$ are determined by the microscopic physics of high-density nuclear matter which has saturation properties at neutron-rich environment, leading to a neutrino temperature more or less independent of the initial supernova conditions. Although ν_e and $\bar{\nu}_{\rm e}$ interact with supernova matter with different proton and neutron number abundances through both charged- and neutral-current interactions, $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ interact only through the neutral-current interaction. This results in a hierarchy of different neutrino temperatures $T_{\nu_{\rm e}}<T_{\bar{\nu}_{\rm e}}<T_{\rm x}$ for different mean-free paths and diffusion coefficients, where x stands for μ or τ.

2.2. Galactic Chemical Evolution and Neutrino Temperature for $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$

The supernova ν-process is known to produce ^{7}Li and ^{11}B in amounts comparable to those produced in the Galactic cosmic-ray spallation process and the stellar nucleosynthesis in small-to-intermediate mass stars [11]. The neutrino temperature for $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ brings about the production of ^{11}B from supernovae appropriate for the observed Galactic chemical evolution of the light elements. The temperature of $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ is thus estimated to be $T_{\nu_{\mu,\tau}} = 6.0 \pm 1.0$ MeV [5]. This temperature is also severely constrained from the measured isotopic ratio $(^{11}\mathrm{B}/^{10}\mathrm{B})_{\rm sun} = 4.5 \pm 0.1$ in the solar system abundance. This ratio clearly indicates the fact that more than 50% of ^{11}B arises from the supernova ν-process because ^{10}B is almost purely created in Galactic cosmic-ray spallation which results in $(^{11}\mathrm{B}/^{10}\mathrm{B})_{\rm GCR} \approx 2.0$.

2.3. Nucleosynthesis and Neutrino Temperature for $\nu_{\rm e}$ and $\bar{\nu}_{\rm e}$

We use nucleosynthesis of ^{180}Ta in O-Ne-Mg layer to estimate the temperatures $\nu_{\rm e}$ and $\bar{\nu}_{\rm e}$. It is currently believed that two isotopes ^{138}La and ^{180}Ta among the heavy elements may be predominantly synthesized by the ν-process [12]. Although the calculated result can reproduce the solar abundance of ^{138}La with charged current reactions for $\nu_{\rm e}$ temperature of ≈ 4 MeV, it overproduces the abundance of ^{180}Ta. Here we investigate the possibility that this overestimate originates from the unique feature that the naturally occurring abundance of ^{180}Ta is actually a meta-stable 9^- isomer with half-life of $\geq 10^{15}$ yr, while the true ground state is a 1^+ unstable state which β-decays with a half-life of only 8.15 hr (see Figure 1).

In the ν process, low-spin excited states in ^{180}Ta are strongly populated from ^{180}Hf by Gamow-Teller transitions and subsequently decay preferentially to the 1^+ ground state. However, in a high temperature photon bath, the meta-stable isomer is excited from the ground state by (γ,γ') reactions through highly excited states. Therefore, the final isomeric branching ratio should be evaluated by a time-dependent calculation. Our supernova nucleosynthesis calculation by including these complicated photon processes based on the measured nine linking transitions [13] shows that the isomeric residual population ratio turns out to be ≈ 0.39 [14]. We stress that the isomer ratio is almost independent of the astrophysical parameters of supernovae such as the peak temperature, the temperature time constant, the supernova neutrino energy spectrum, and

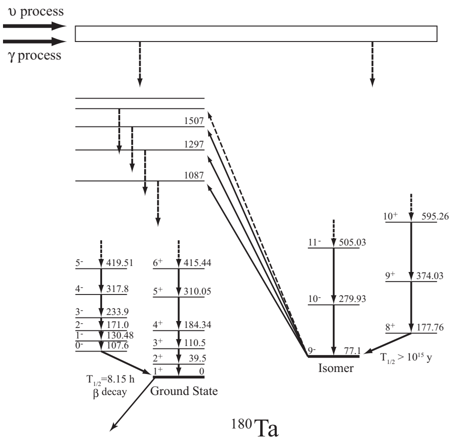

Figure 1. Partial nuclear level scheme of ^{180}Ta [14]. The ground state decays via β-decay with a half-life of 8.15 h, while the isomer is a meta-stable state. The measured [13] excitation energies of states are indicated.

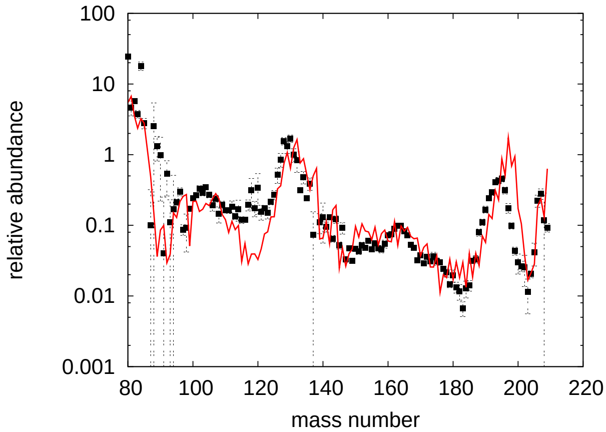

Figure 2. Abundance pattern (solid line) of the r-process nucleosynthesis [16] compared with the solar system r-process abundance (points).

the explosion energy. We finally obtain the concordant result between the observed solar system abundances of ^{138}La and ^{180}Ta and the theoretical predictions for $T_{\nu_e} \approx T_{\bar{\nu}_e} = 4.0$ MeV [14].

2.4. R-Process Nucleosynthesis for Breaking Degenberacy $T_{\nu_e} < T_{\bar{\nu}_e}$

We here finally try to resolve a weak degeneracy between T_{ν_e} and $T_{\bar{\nu}_e}$ by imposing a neutron-rich condition $0.2<Y_e<0.5$ for successful r-process heavy element synthesis. Since the r-process is presumed to occur deep inside the iron-core near the atmosphere of proto-neutron star, the environment is still very neutron-rich. The mean-free path or equivalently the diffusion coefficient for ν_e is shorter than that of $\bar{\nu}_e$ due to the different frequencies of charged-current interactions between $\nu_e + n \rightarrow p + e^-$ and $\bar{\nu}_e + p \rightarrow n + e^+$. Therefore, the neutrino-sphere for $\bar{\nu}_e$ is deeper than that for ν_e, hence resulting in $T_{\nu_e} < T_{\bar{\nu}_e}$. We find that only when we set $T_{\nu_e} = 3.2$ MeV and $T_{\bar{\nu}_e} = 4.0$ MeV, the calculated abundance pattern of r-process nucleosynthesis can well explain the observed solar-system r-process abundances [15, 16], as displayed in Figure 2.

3. Supernova Nucleosynthesis and Neutrino Oscillation

Neutrinos are emitted during ~10 s in the supernova explosion. Both neutral and charged current interactions on abundant nuclei, ^{4}He and ^{12}C, spall them into free nucleons and light nuclei. Subsequently the explosive nucleosynthesis similar to the hot Big-Bang nucleosynthesis occurs at high-temperatures and densities when the shock arrives. These neutrino-induced reactions, called the ν-processes, affect the abundances of the light elements ^{6,7}Li, ^{9}Be and ^{10,11}B [10].

Figure 3 shows the major nucleosynthesis paths to produce ^{7}Li and ^{11}B during supernova explosions. The reactions, $^4\mathrm{He}(\nu,\nu'p)^3\mathrm{H}$ and $^4\mathrm{He}(\nu,\nu'n)^3\mathrm{He}$ are important for the production of ^{7}Li through $^3\mathrm{H}(\alpha,\gamma)^7\mathrm{Li}$ and $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}(e^-,\nu_e)^7\mathrm{Li}$ processes. If the ν-^{4}He reaction cross sections are enhanced due to the neutrino oscillations as to be discussed later, not only the abundance of ^{7}Li but also that of ^{11}B increase through the radiative alpha-capture reactions $^7\mathrm{Li}(\alpha,\gamma)^{11}\mathrm{B}$ and $^7\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}(e^+\nu_e)^{11}\mathrm{B}$. The neutral current reactions, $^{12}\mathrm{C}(\nu,\nu'p)^{11}\mathrm{B}$ and $^{12}\mathrm{C}(\nu,\nu'n)^{11}\mathrm{C}$, also are important for the production of ^{11}B. Details are discussed in [1, 2, 5].

3.1. Weak Interaction Cross Sections

As for the ν-induced reaction cross sections, there are only LSND experimental data for ν-^{12}C [18]. We should therefore totally rely on the theoretical estimate of neutrino-nucleus cross sections. We calculate neutrino-nucleus cross sections for ^{4}He, ^{12}C, ^{138}Ba, ^{180}Hf and many other nuclei in order to study the ν-induced nucleosynthesis of LiBeB isotopes, ^{138}La, ^{180}Ta and r-process elements. For this purpose, we use nuclear shell model [19] and quasi-particle random phase approximation (QRPA) [20]. Nuclear shell model is one of the most reliable models to describe the Gamow-Teller (GT) and spin-dipole transitions at relatively low excitation energies, while QRPA is suitable at relatively high excitation energies. Therefore, we need both models to calculate not only the GT but also the spin-dipole and higher-multipole transition probabilities for the supernova neutrinos energy up to 100 MeV. See refs. [19, 20] for details of calculations and applications of the cross sections to several astrophysical weak nuclear processes.

3.2. Neutrino Mixing Parameters

Neutrino-flavor matter oscillations affect the nuclear reactions induced by charged current interactions, ν_e-A and $\bar{\nu}_e$-A, while the neutral current interactions do not change. Flavor oscillations are described by three mixing angles θ_{12}, θ_{23}, and θ_{13} plus a CP-violating phase δ_{CP}. Solar, atmospheric, and reactor neutrino oscillation measurements [21, 22, 23, 24, 25, 26] have provided information on the neutrino mass differences, i.e $\Delta m_{12}^2 \equiv |m_1^2 - m_2^2| = 7.9 \times 10^{-5}$ eV [25] and $\Delta m_{13}^2 \approx |\Delta m_{23}^2| \approx 2.4 \times 10^{-3}$ eV^2 [26, 22]. However, these cannot determine the mass hierarchy, i.e. whether $\Delta m_{23}^2 > 0$ (normal) or $\Delta m_{23}^2 < 0$ (inverted) is the correct order.

Mixing angles θ_{12} and θ_{23} were also determined precisely. θ_{13} has become available only recently. The three best current measurements are $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$ [27], $\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat.}) \pm 0.019(\text{syst.})$ [28], and $\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat.}) \pm 0.030(\text{syst.})$ [29]. These results are consistent with the previously reported upper limit $\sin^2 2\theta_{13} < 0.12(0.20)$ from the MINOS collaboration [26] for the normal (inverted) hierarchy, and with $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$ at the 90% C.L. from the T2K collaboration [30]. However, the data do not yet determine the mass hierarchy.

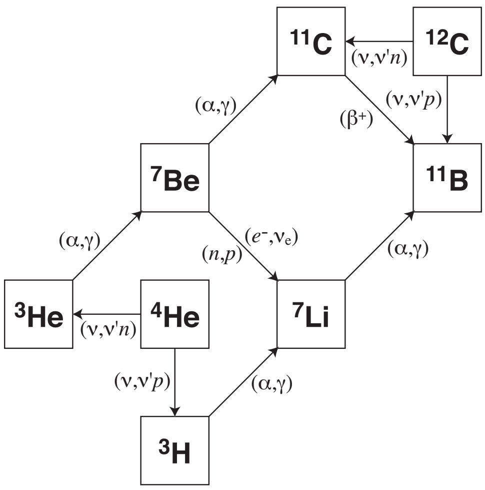

Figure 3. Nucleosynthesis path of light elements ^{7}Li and ^{11}B during supernova explosions [5].

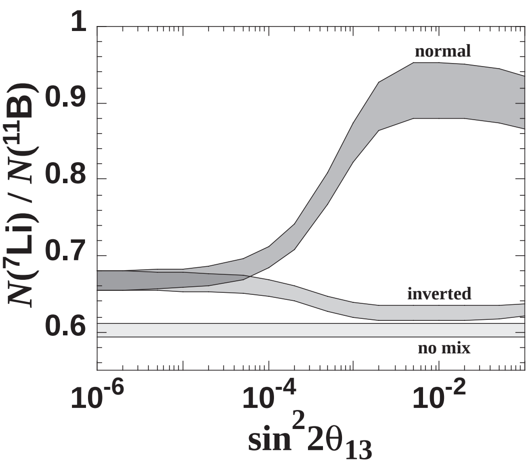

Figure 4. The shaded ranges include the uncertainties of neutrino energy spectra deduced from the calculations using three sets of neutrino temperatures and total neutrino energies [1].

3.3. New Constraint on Neutrino Mass-Hierarchy

Since supernova neutrino temperatures for $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ are the same, energy spectra of these neutrinos are degenerate to one another. In this case any observables which arise from the neutrino oscillation do not depend on the CP-violating phase δ_{CP} [31, 32]. Therefore, the supernova nucleosynthesis is only sensitive to the mixing angle θ_{13} and the mass hierarchy.

Figure 4 shows the predicted number-abundance ratio of ^{7}Li/^{11}B as a function of mixing angle θ_{13} for both mass hierarchies [1, 2, 5] . The uncertainty due to neutrino spectra is included as shaded regions. We should note that although uncertainties in the ν-process cross sections still remain, we find that they are largely canceled out when we take the ^{7}Li/^{11}B ratio. This is because ^{7}Li and ^{11}B are mainly produced through the ν-process from ^{4}He and the dependence of their yields on the ν-process reaction rates is similar to each other. Therefore, the ratio is almost independent of the Hamiltonians used in the calculations of the ν-process cross sections [1, 2].

The ^{7}Li/^{11}B ratio in the case of adiabatic 13-mixing resonance and normal hierarchy is remarkably larger than that without neutrino oscillations, even with the spectral uncertainties included. Thus, the enhancement of observed ^{7}Li/^{11}B ratio may constrain the lowest value of θ_{13} and eliminate the possibility of inverted hierarchy. Several long-baseline experiments in particle physics have determined $\sin^2 2\theta_{13} \approx 10^{-1}$. Our proposed nucleosynthetic method as displayed in Figure 4 would provide an independent confirmation [1, 2, 5].

Fujiya et al. [33] have recently discovered SiC X grains from the Murchison meteorite which contains most likely supernova-produced ν-process ^{11}B and ^{7}Li. We apply their meteoritic constraint by combining with the recent experimentally determined θ_{13} value to our predicted ^{7}Li/^{11}B ratio, as illustrated in Figure 4. We examined the possible implications of these new results based upon a Bayesian analysis of the uncertainties in the measured meteoritic material and the associated supernova nucleosynthesis models [34], and obtained that all these data are marginally more consistent with the inverted neutrino mass hierarchy [35].

4. Summary and Discussions

We studied the ν-process nucleosynthesis in core-collapse supernovae. We first found that average neutrino temperatures suitable for explaining the observed solar system abundances, meteoritic isotope ratios, and Galactic chemical evolution of the light-to-heavy mass elements, turn out to be $T_{\nu_e} = 3.2$ MeV, $T_{\bar{\nu}_e} = 4.0$ MeV, and $T_{\nu_{\mu,\tau}} = T_{\bar{\nu}_{\mu,\tau}} = 6.0$ MeV, respectively. Some of these isotopes like ^{7}Li, and ^{11}B are predominantly produced by the charged current interactions in the He-layer, and are affected strongly by the neutrino flavor oscillation due to the matter effects (MSW-effects). With the use of this specific feature, we proposed a new method to determine the unknown neutrino mass hierarchy along with the mixing angle θ_{13}. Recent experimental constraints on θ_{13} and the first detection of ^{11}B and ^{7}Li encapsulated in the SiC X grains from the Murchison meteorite lead to marginal preference for an inverted neutrino mass hierarchy in our proposed method.

A recent high-resolution spectroscopic observation of supernova remnant has succeeded in the determination of lithium isotopic abundances [36]. Observational efforts [37, 38, 39] to obtain Li and B abundances in stars, which have been formed in regions directly affected by prior generations of massive stars and subsequent supernovae, also are underway. These would detect the signature of the supernova ν-process.

Supernovae are the unique source in nature that provides three flavors of energetic neutrinos. The neutrino interactions with abundant nuclei produce rare isotopes such as ^{7}Li, ^{11}B, ^{23}Na, ^{40}Ar, ^{50}V, rare Mn-Fe-Co-Ni isotopes, ^{92}Nb, ^{98}Tc, ^{138}La, ^{180}Ta, and many others. For the studies of supernova ν-process, however, one needs to know the weak interactions between energetic neutrinos and these nuclei. At the moment, we still do not have efficient neutrino-beam whose intensity is high enough to measure the neutrino-nucleus reaction cross sections in the laboratory experiments. It is therefore highly desirable to study the photo-induced [40] and charge-exchange reactions [41] in order to estimate the nuclear weak matrix elements. High precision theoretical models [19, 20] to calculate these weak matrix elements are also desirable.

The combination of supernova nucleosynthesis and nuclear physics studies may ultimately provide precise constraints on still poorly known neutrino mass hierarchy.

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