Nuclear de-excitation associated with neutrino-carbon interactions

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Abstract. Neutrino interactions in low energy regions below 30 MeV, where the experimental searches for supernova relic neutrino are conducted, have a large uncertainty due to complicated nuclear effects such as the Pauli blocking effect and de-excitation of a residual nucleus. Understanding the effect of nuclear de-excitation is especially critical since neutrons measured by liquid scintillator detectors can be emitted via de-excitation. We build a systematic method to predict nuclear de-excitation associated with neutrino-carbon interaction using TALYS and Geant4. This prediction is combined with the results of neutrino event generators, and we find a large increase in neutron multiplicity.

1. Introduction

The experimental searches for supernova relic neutrino are conducted below 30 MeV, where atmospheric neutrino interactions are the dominant background. Neutrino interactions in this low-energy region have a large uncertainty due to complicated nuclear effects, for example, a momentum distribution of nucleons in the nucleus, Pauli blocking and de-excitation of a residual nucleus. Sophisticated neutrino event generators GENIE [1], NEUT [2], and NuWro [3] provide several models to predict the momentum distribution, and the Pauli blocking effect. However, they usually do not treat the de-excitation. De-excitation can release many different types of particles. Understanding the effects of nuclear de-excitation is very important, especially for liquid scintillator detectors. This is because liquid scintillator detectors are sensitive to the energy deposit of the particles emitted by the de-excitation and also to the neutron multiplicity.

A systematic study to predict de-excitation is needed, taking into account the next generation of large liquid scintillator detectors. We build a prediction method of the de-excitation using TALYS and Geant4. In the following, the method and impact on neutron multiplicity are described.

2. Prediction method

To combine the results with those of the neutrino event generator, an event-by-event simulation is preferred. We achieve this requirement by combining two software TALYS [4] and Geant4 [5]. TALYS which is an open-source software package to simulate nuclear reactions is used to calculate branching ratios of γ, proton, neutron, and α emissions from the excited state of the residual nucleus. Geant4 is a widely-used simulator, and especially G4RadioactiveDecay is a smart tool to trace decay chain event by event. The information about branching ratios that is extracted from TALYS is input into Geant4, and it simulated the decay chain. In addition to branching ratios, information about the spectroscopic factor, paring effect, and excitation energy are necessary. The details are as follows.

2.1. Spectroscopic factor

We prepare a probability of removing a nucleon from each shell level to determine the shell level of the emitted nucleons via neutrino-nucleus interactions. As for the single nucleon disappearance, 0.296 for the s-hole state, 0.704 for the p-hole state [6] are adopted. As for others, we assume all nucleons have the same probabilities.

2.2. Paring effect

In the simple shell model picture, there are four protons (neutrons) in the $p_{3/2}$ shell and two in the $s_{1/2}$ shell. However, in a more sophisticated model, the $p_{1/2}$ shell which is about 4 MeV above $p_{3/2}$ is also partially filled with a pair of protons (neutrons) in 40% due to pairing effects [7]. This means that the residual ^{11}C (^{11}B) nucleus is not always left in the ground state even if a proton (neutron) disappears from the $p_{3/2}$ shell, In a case of there is a partial occupation of $p_{1/2}$ and proton (neutron) disappearance from $p_{3/2}$, the residual ^{11}C (^{11}B) nucleus goes to the first excited state with $J^{\pi} = 1/2^{-}$ and then emit γ-ray going to the ground state. The energy of the γ-ray is 2.0 MeV for ^{11}C and 2.1 MeV for ^{11}B since there is only one excited state that has $J^{\pi} = 1/2^{-}$ below 10 MeV.

2.3. Branching ratios

The branching ratios are extracted from TALYS except for the case of the p-hole state that is mentioned above. The de-excitation via γ-ray, proton, neutron, and α emission which are dominant channels are considered. Nuclei that have $Z \geq 3$ and $A \geq 3$ are taken into account. Figure 1 shows branching ratios of ^{11}C*. This corresponds to single neutron disappearance from $s_{1/2}$ and has $J^{\pi} = 1/2^{+}$. Proton emission is dominant, accounting for about 90% around 20 MeV, which is the general excitation energy region of the s-hole state.

To make accurate predictions for multi-decay, it is necessary to accurately calculate the branching ratios and populations of the residual nuclei after the first-step decay. This information is also calculated by TALYS, and it is seen that the population of the residual nuclei after the first-step decay depends on the excitation energy of the initial residual nucleus.

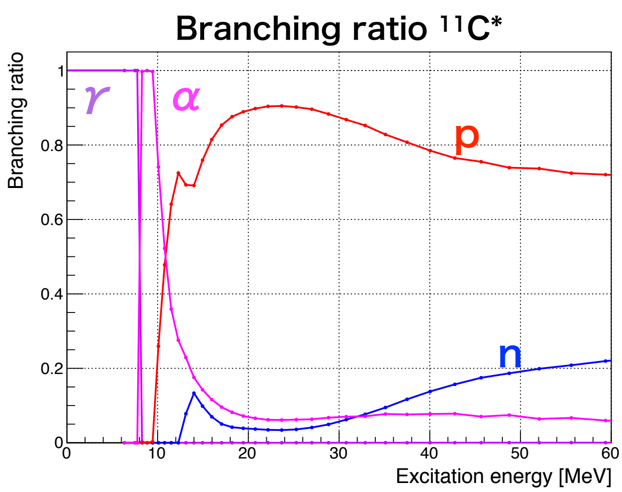

Figure 1. Branching ratios of $J^{\pi} = 1/2^{+}$ ^{11}C*. The violet line is for γ-ray, the magenta line is for α, the red line is for proton, and the blue line is for neutron.

2.4. Excitation energy
Since excitation energy has a finite width, we need to prepare a model for the distribution of the excitation energy. We adopted a Lorentzian mean of 23 MeV and width (FWHM) of 14 MeV [7] for $s_{1/2}$-hole and exactly zero for p-hole state neglecting pairing effect. In the case of multi-nucleon disappearance such as ^{10}C, we simply calculate the sum of the excitation energy of each hole. The excitation energy is randomly determined following these distributions in our simulation.

The mean and width of excitation energy are not precisely known. To estimate the corresponding systematic error, we changed these values within 23 ± 1 MeV for the mean and 14^{+10}_{-2} MeV for the width. The effect is smaller than model-dependent uncertainty that will be mentioned in Section 3.

3. Result and application
3.1. Results of branching ratio for $s_{1/2}$-hole state
Table 1 shows the results of the branching ratio for de-excitation of ^{11}C* $s_{1/2}$-hole state. The proton emission is the dominant decay channel accounting for 90%. Most of the emitted particles via de-excitation are below the neutron separation energy of ^{12}C. Thus, particle emission via nuclear de-excitation rarely affects neutron production via the secondary interaction in a detector.

Our results were compared with another estimation predicted by SMOKER [7]. We found a large deviation that is 54.3% in total, and it is assigned as a model-dependent systematic uncertainty of our prediction. As for the systematic uncertainty coming from excitation energy that is mentioned in Section 2.4, it is 14.8% which is negligible compared with the model-dependent uncertainty.

Decay mode	Branching ratio [%]
^{11}C(n)	1.7
^{11}C(n,γ)	0.5
^{11}C(n,n)	0.0
^{11}C(n,p)	3.5
^{11}C(n,α)	0.2
^{11}C(p)	1.8
^{11}C(p,γ)	19.1
^{11}C(p,n)	14.6
^{11}C(p,p)	20.0
^{11}C(p,α)	26.2

Decay mode	Branching ratio [%]
^{11}C(γ...)	1.6
^{11}C(α)	3.8
^{11}C(α,γ)	2.2
^{11}C(α,n)	0.5
^{11}C(α,p)	2.2
^{11}C(α,α)	2.3

Table 1. Branching ratio for de-excitation of ^{11}C* $s_{1/2}$-hole state. The first column shows decay mode for one-step or two-step.

3.2. Application to the neutrino-carbon interaction
Finally, we applied our prediction to the neutrino-^{12}C interaction and checked the impact on neutron multiplicity. We simulated Neutral Current Quasi-Elastic (NCQE) interactions using NuWro that is one of the sophisticated neutrino event generators. After the nuclear species of a residual nucleus is determined by NuWro, the particles emitted via de-excitation are predicted following our method. Figure 2 shows a neutron multiplicity distribution of NCQE interactions with 1 GeV monochromatic neutrino energy. Mean neutron multiplicity is 0.772 for NuWro and 1.018 for NuWro with de-excitation prediction. The neutron multiplicity largely increases due

to the nuclear de-excitation. This enhancement is very important especially in measurements of neutron via neutrino-nucleus interaction by large liquid scintillator detectors.

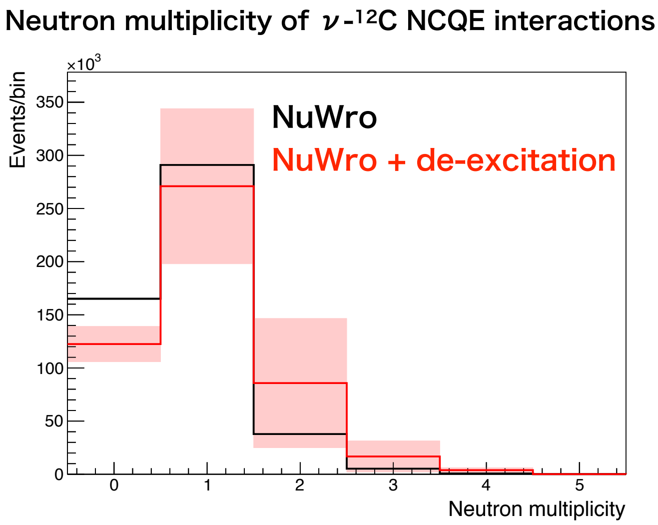

Figure 2. Neutron multiplicity of NCQE interactions. Neutrino energy is 1 GeV in monochrome. The black line represents the results of NuWro. The red line represents the results of NuWro combining our de-excitation prediction, and the red shaded region represents the systematic uncertainty coming from the model (TALYS) and excitation energy.

4. Summary

We show an event-by-event simulation of nuclear de-excitation for neutrino-carbon interactions using TALYS and Geant4. We found a non-negligible enhancement in neutron multiplicity that can be measured by a large liquid scintillator.

Acknowledgments

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