17th International Conference on Topics in Astroparticle and Underground Physics
26th Aug. - 3rd Sep. 2021, online

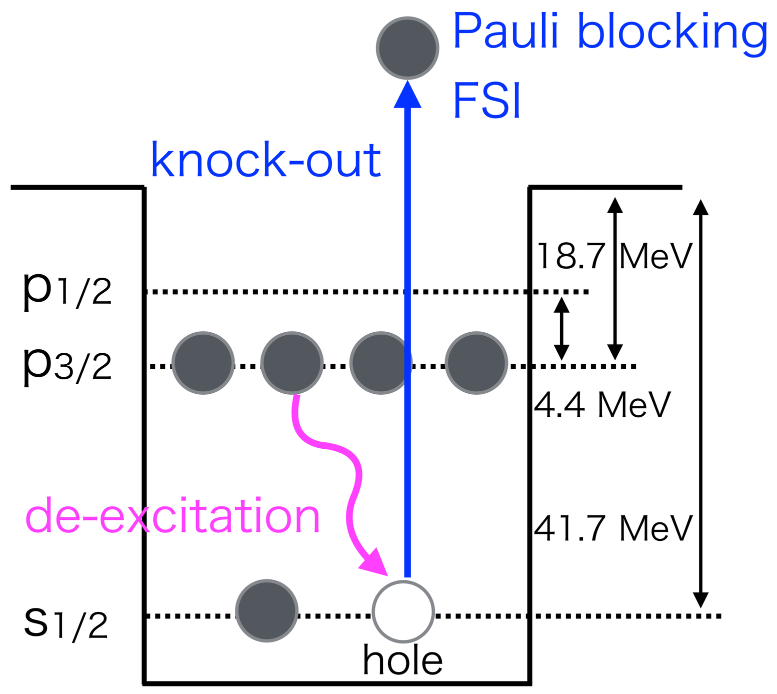
Nuclear de-excitation associated with neutrino-carbon interactions

Seisho Abe
for the KamLAND Collaboration
RCNS, Tohoku University
seisho@awa.tohoku.ac.jp

1, Neutrino astrophysics and interactions

Abbreviations
Br Branching ratio(s)
Ex Excitation energy

- The searches for supernova relic neutrino are conducted below 30 MeV where atmospheric neutrino events are the dominant background.
- **Particle emissions via nuclear de-excitation associated with neutrino-nucleus interactions have large impact in the low energy region**
  - Affects energy spectra and multiplicity especially for liquid scintillator detectors such as KamLAND
- However, neutrino event generators usually do not treat the excitation
- **We carried out a systematic study to predict the de-excitation event by event using TALYS [1] and Geant4 [2]**

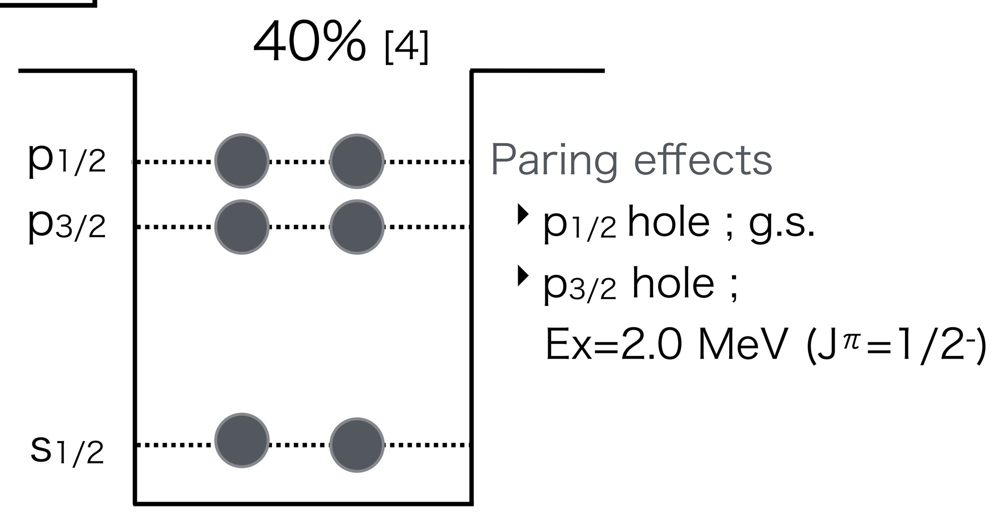


^{12}C, single n disappearance

Let us focus on ^{12}C target

2, Prediction method

- Residual nucleus with Z≥3 && N≥3 are considered
- Branching ratio (Br) for g, a, p and n are considered
- Types of residual nuclei will be determined by the ν event generators

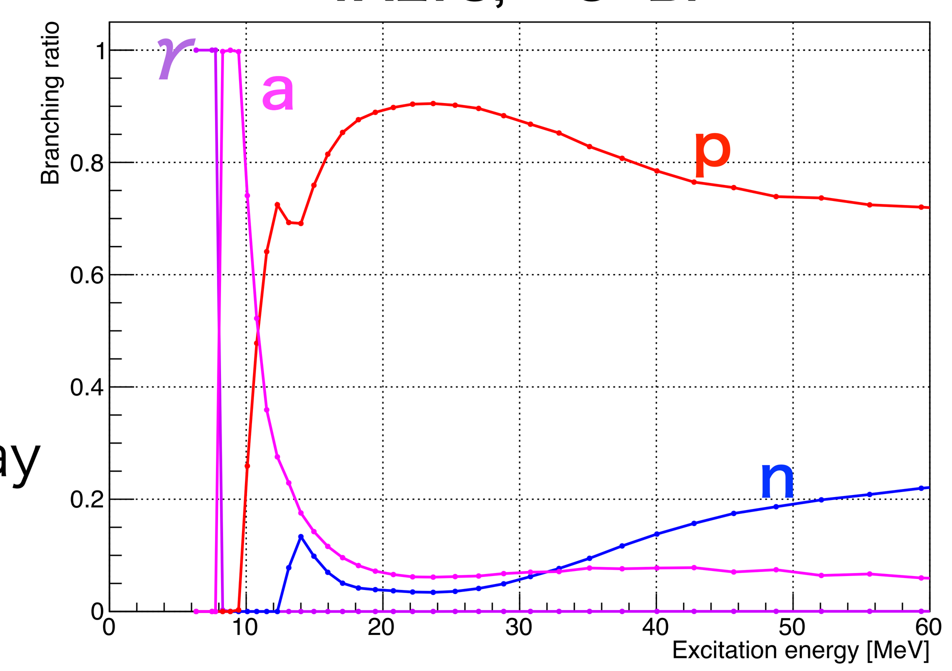


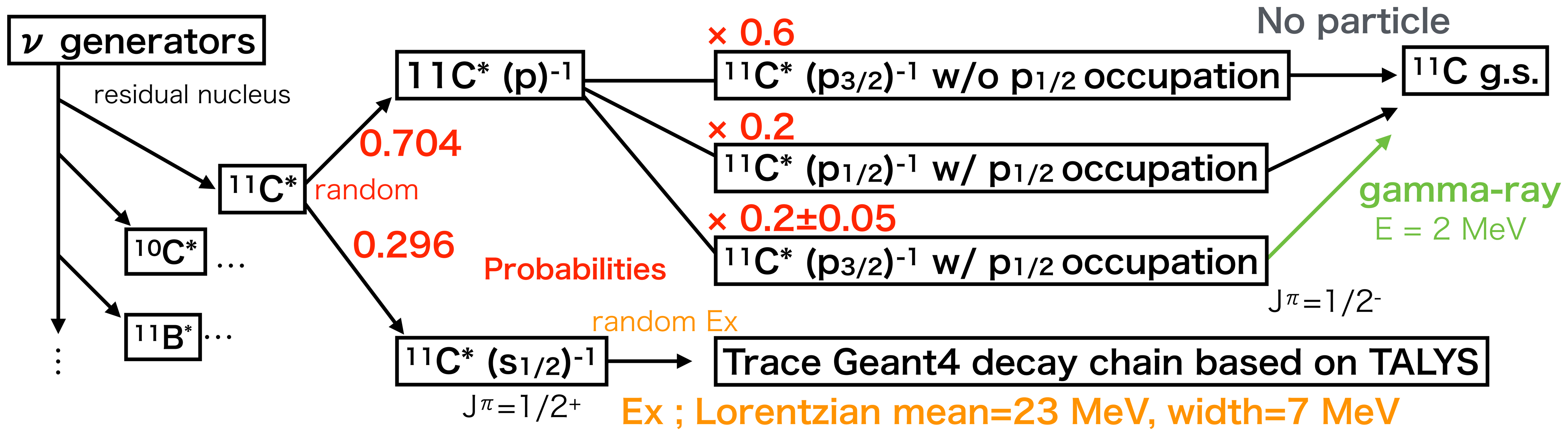
^{12}C, partial occupation of $p_{1/2}$

2.1, Single neutron disappearance from ^{12}C (^{11}C*)

- Case1) Disappearance from p shell
  - With a probability of 0.704 [3]
  - 20±5% ; Emit 2.0 MeV γ-ray and goes to the g.s. [4]
  - 80% : goes to the g.s. w/o particle emission
- Case2) Disappearance from $s_{1/2}$ shell ($J^{\pi}=1/2^+$)
  - With a probability of 0.296 [3]
  - Br and Q values are extracted from TALYS [1]
  - Trace the decay chain using Geant4 event by event
    - Br data of TALYS are inputed into G4RadioactiveDecay
  - Excitation energy (Ex) ; Lorentzian with mean=23 MeV, width=7 MeV [4]
    - Randomly determined according to this function

TALYS, ^{11}C* Br

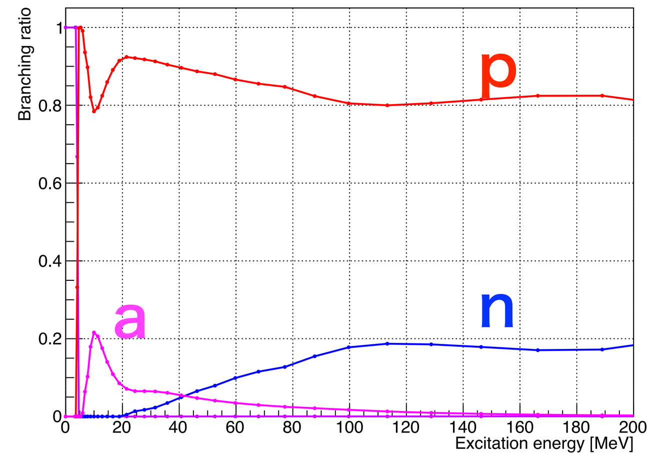




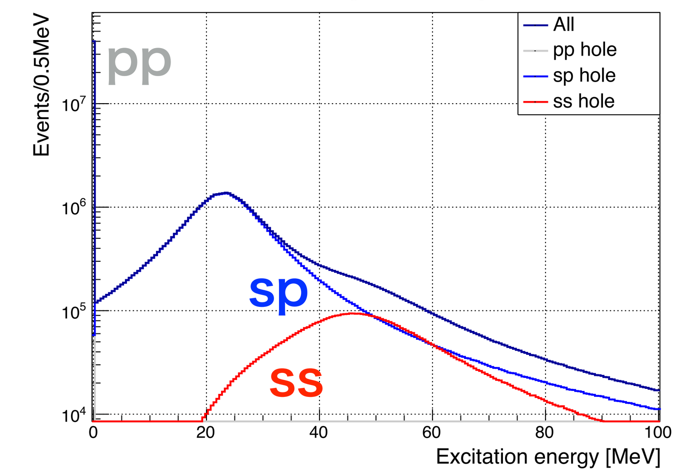
2.2, Multi-nucleon disappearance

- Ex is calculated as the sum of each hole
  - p shell hole ; 0 MeV
  - s shell hole ; Lorentzian with mean = 23 MeV, width = 7 MeV
- Assume all nucleons in any shell have the same probability

γ TALYS, ^{10}C* Br



Ex for ^{10}C*



3, Results and application

3.1, Br and energy spectra

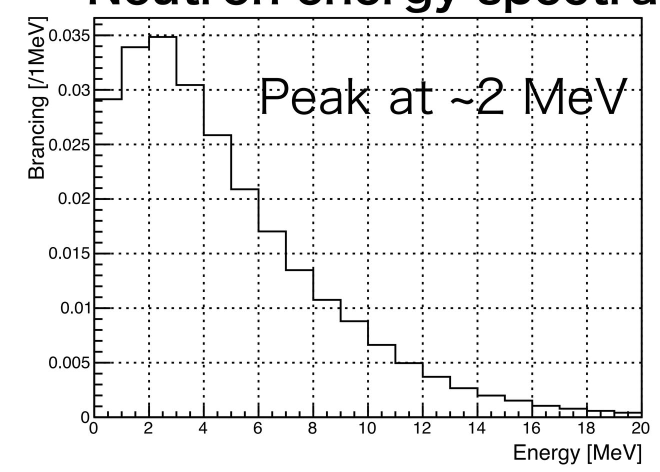
- ^{11}C*
  - ~20% involve neutrons
  - Most of the particles are below 10 MeV
    - Tend to be high for multi-nucleon disappearance
- Br for protons have higher than that of neutrons
  - This trend is the other way around for proton disappearance

^{11}C*, $s_{1/2}$ hole

Mode	Br [%]
(n)	1.70
(n,g)	0.46
(n,n)	0.03
(n,p)	3.48
(n,a)	0.20
(p)	1.79
(p,g)	19.05
(p,n)	14.55
(p,p)	20.04
(p,a)	26.15

Mode	Br [%]
(a)	3.77
(a,g)	2.24
(a,n)	0.51
(a,p)	2.17
(a,a)	2.25

Neutron energy spectra

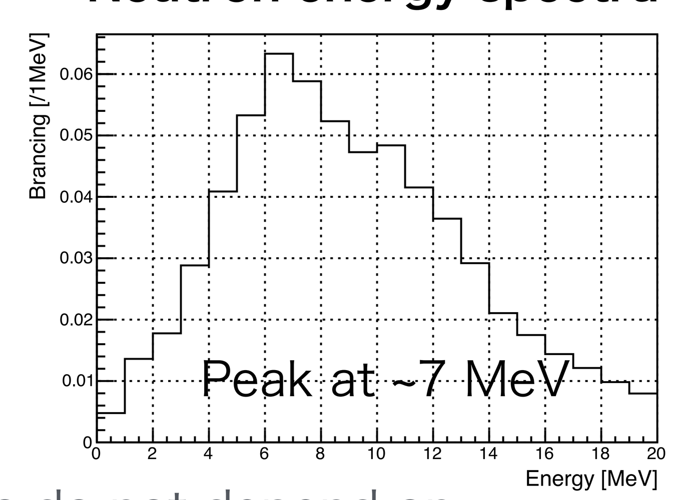


^{10}C*, $s_{1/2}$ 2 hole

Mode	Br [%]
(n)	6.2
(n,g)	0.0
(n,n)	0.0
(n,p)	6.0
(n,a)	0.0
(p)	0.0
(p,g)	0.0
(p,n)	0.0
(p,p)	27.3
(p,a)	36.4

Mode	Br [%]
(a)	8.7
(a,g)	0.0
(a,n)	0.0
(a,p)	14.1
(a,a)	1.3

Neutron energy spectra



These results do not depend on the ν event generators

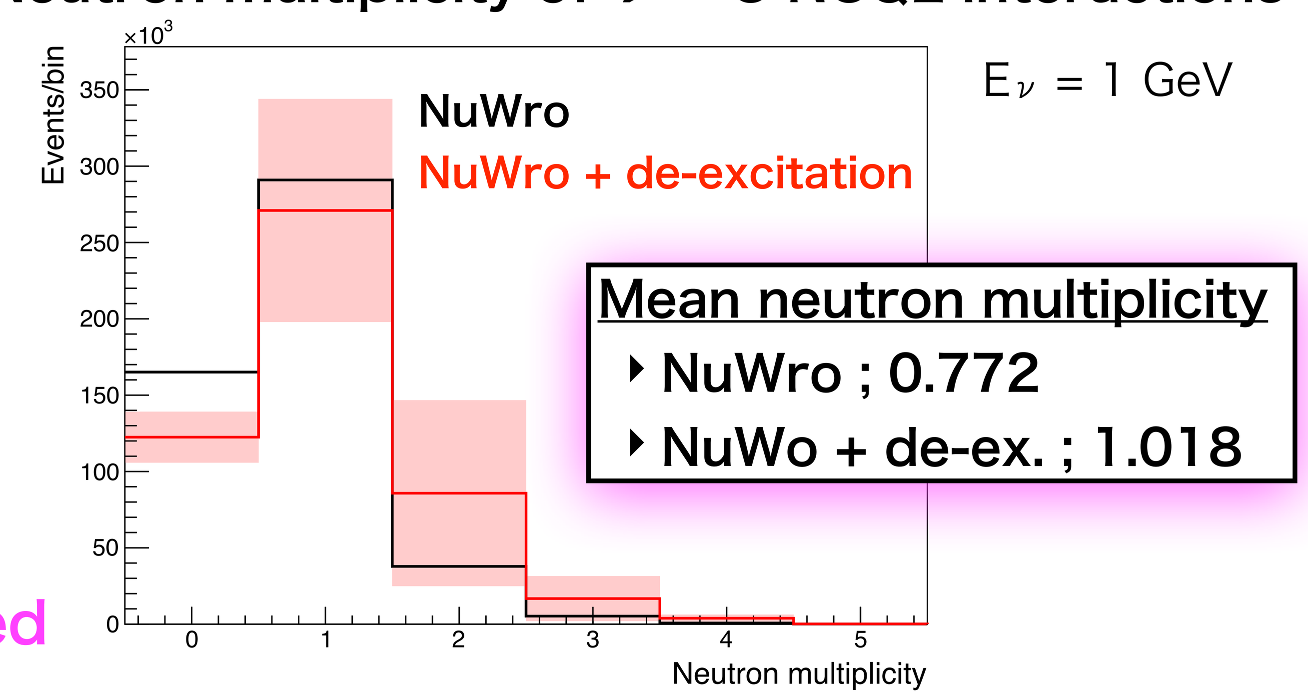
3.2, Systematic error on the Br

- Model dependent uncertainty
  - Compare with another estimation based on SMOKER [4] for each mode
  - 54.3% for ^{11}C*. 118.1% for ^{10}C*
- Ex uncertainty
  - By changing Ex distribution with mean=23±1 MeV and width=7^{+5}_{-1} MeV
  - ~15% for any nuclei
- The total systematic error
  - 56.3% for ^{11}C*. 118.9% for ^{10}C*

3.3, Application to the ν-^{12}C interaction

- Apply the results on a output of neutrino event generator NuWro [5]
  - Types of residual nuclei is from NuWro
- **Neutron multiplicity that can be measured with KamLAND increases significantly**

Neutron multiplicity of ν-^{12}C NCQE interactions



These predictions are now applied to the analysis of atmospheric and J-PARC ν analysis at KamLAND

Reference
[1] A. J. Koning, et al., https://doi.org/10.1051/ndata:07767
[2] S. Agostinelli et al., https://doi.org/10.1016/S0168-9002(03)01368-8
[3] L. Lapikas et al., https://doi.org/10.1103/PhysRevC.61.064325
[4] Y. Kamyshkov et al., https://doi.org/10.1103/PhysRevD.67.076007
[5] T. Golan et. al., https://doi.org/10.1016/j.nuclphysbps.2012.09.136