De-excitation tool for neutrino experiments: GEMINI++4ν

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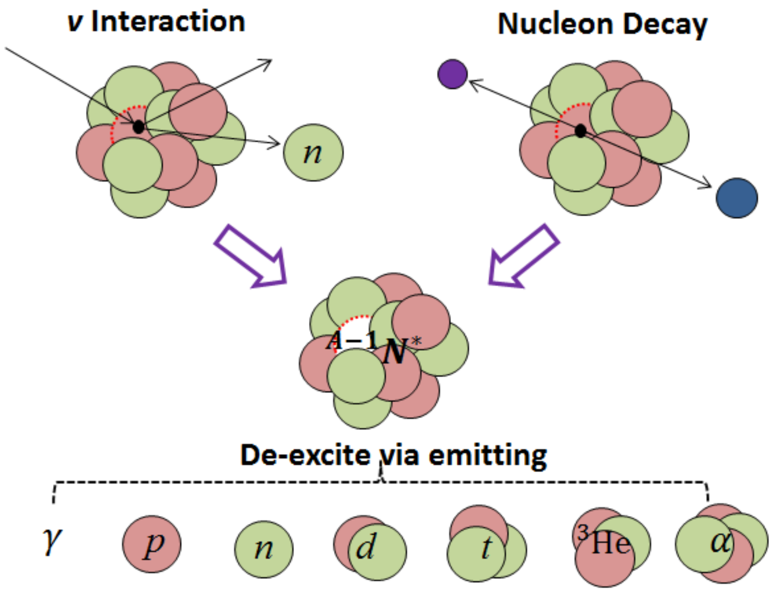
Outline

1. *Motivation*
2. *De-excitations from TALYS*
3. *De-excitations from GEMINI++*
4. *GEMINI++4ν*
5. *Summary*

*TALYS: H. Hu, **W.L. Guo**, et al., Phys. Lett. B 831 (2022) 137*
*GEMINI++/4ν: Y.J. Niu, **W.L. Guo**, M. He, J. Su, arXiv: 2408.14955*

(1) Motivation

Nuclear de-excitations in ν experiments are playing an increasingly significant role associated with



- **Liquid scintillator**
  - ➢ neutrons
  - ➢ unstable isotopes
- **Water Cherenkov**
  - ➢ monoenergetic γ
  - ➢ neutrons
- **Liquid Argon TPC**
  - ➢ Emitted particles

$\uparrow \frac{\text{Signal}}{\text{BKG}}$

However, no universally adopted and quantitatively accurate models to describe de-excitation cascade!

Statistical model codes

Statistical model codes were widely used to predict de-excitations related to some topics

1. **TALYS** → $p \to \bar{\nu} K^+$, DSNB, Strange axial coupling constant
2. **ABLA** → Energy resolution of accelerator neutrinos
3. **SMOKER** → Neutron invisible decays
4. **CASCADE** → Experimental data of $^{11}\mathrm{B}^*$ and $^{15}\mathrm{N}^*$ de-excitations

See arXiv:2408.14955 for relevant references

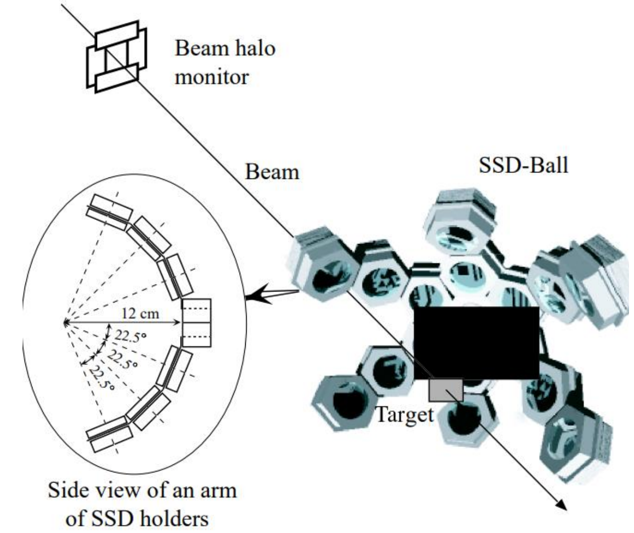
Common features of theses codes:

- Input Nucleus(N/A), Excited energy, Spin, Parity
- Apply nuclear model to calculate partial decay width for evaporation of particle i
- De-excitations are dealt with as a sequential binary decays

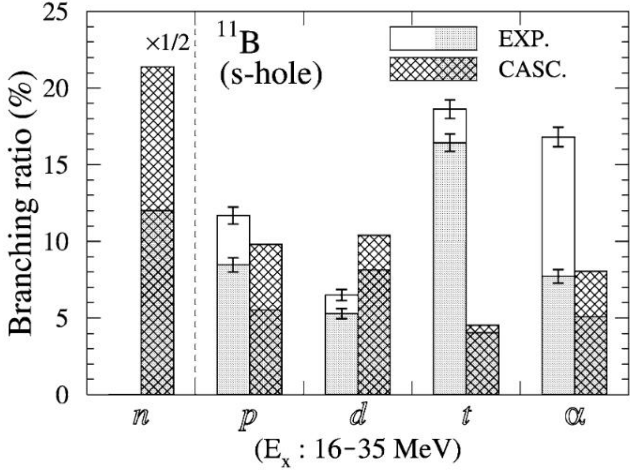
In order to assess performances of de-excitation codes, it is necessary to compare their predictions with measurements for interested nuclei.

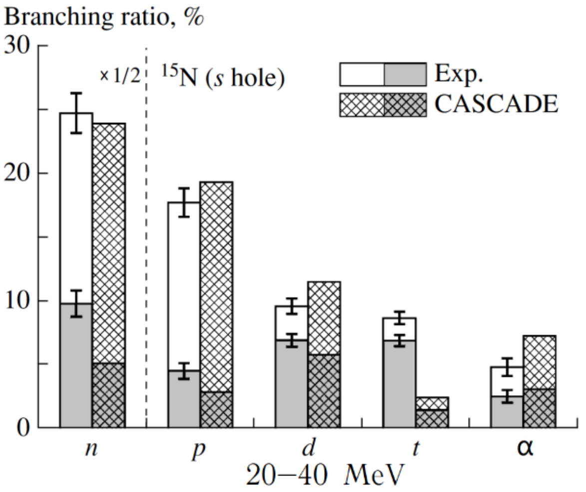
$^{11}\mathrm{B}^*$ and $^{15}\mathrm{N}^*$ experimental data are the best for us to validate these codes!

Experiment 1 from Yosoi et al.



No neutron result!

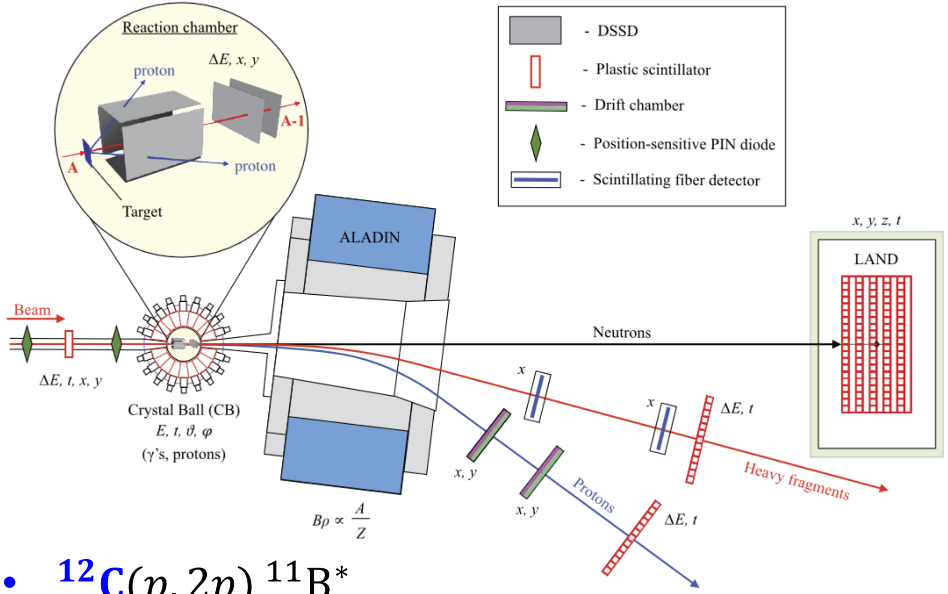




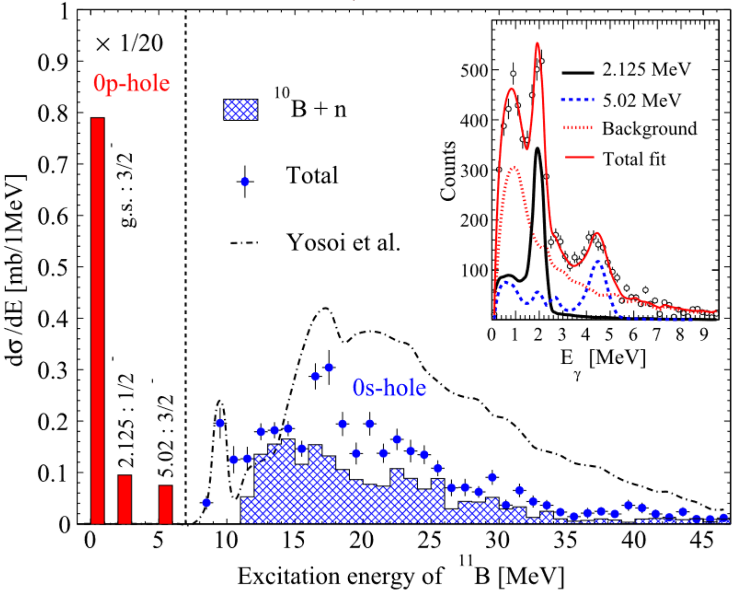
M. Yosoi et al., Phys. Lett. B 551 (2003); Phys. Atom. Nucl. 67, (2004) 1810

- Quasi-free (*p*, 2p) reaction, targets are carbon ($^{12}C \rightarrow {}^{11}B^*$) and ice ($^{16}O \rightarrow {}^{15}N^*$)
- Different thresholds: 3.1, 4.0, 4.6 and 4.5 MeV for *p, d, t* and *α*
- Results shown above, darker color for ‘2-body’ decay and lighter for ‘3-body’ decay

Experiment 2 from Panin et al.



V. Panin, et al., Phys. Lett. B 753 (2016) 204



- ${}^{12}\mathrm{C}(p,2p)\,{}^{11}\mathrm{B}^*$
- Good energy resolution, no threshold for particle identification, even **residual nuclei**
- Only three **two-body decay** channels of ${}^{11}\mathrm{B}^*$ were analyzed: ${}^{10}\mathrm{B}+\mathrm{n}$, ${}^{9}\mathrm{Be}+\mathrm{d}$ and ${}^{7}\mathrm{Li}+\alpha$

➡ **Two relative ratios:** $\frac{n+{}^{10}\mathrm{B}}{\mathrm{Total}}$, $\frac{(d+{}^{9}\mathrm{Be})+(\alpha+{}^{7}\mathrm{Li})}{\mathrm{Total}}$

(2) De-excitations from TALYS

TALYS is a nuclear reaction program, and is extensively used for both basic and applied science

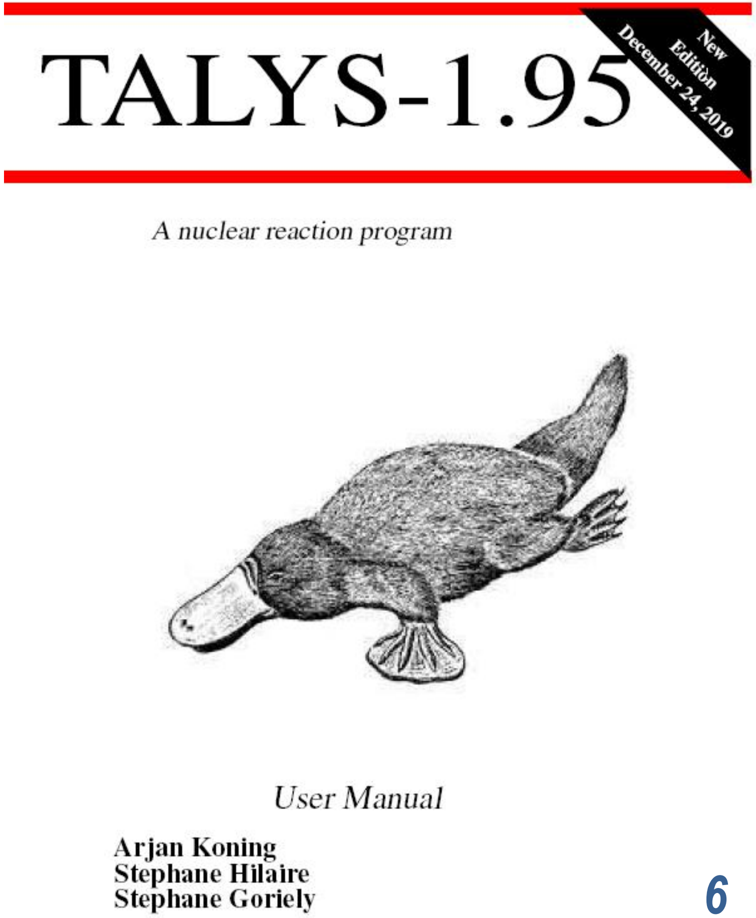
https://nds.iaea.org/talys/

A.J. Koning, D. Rochman, Nucl. Data Sheets 113 (2012) 2841

Code	TALYS
Input	Nucleus, Excited energy table (spin, parity)
Formulism of width Γ_i	Hauser-Feshbach (HF)
Output	Statistical branching ratios and energy spectra
Convenience	Not event-by-event, Inconvenience

TALYS+Geant4 → NucDeEx → Event by event

See next talk or S. Abe, Phys. Rev. D 109 (2024) 036009



the TALYS workflow

Inputting

```
USER INPUT FILE

# --------- basic
projectile 0
element b
mass 11
energy  Ex_10MeV
```

E_x spectrum:

152	1	0
153	3	0
154	5	0
155	7	0
156	9	0
157	11	0
158	13	0
159	15	0
160	17	1846
161	19	1795
162	21	1858
163	23	1776
164	25	1619
165	27	1449
166	29	1166
167	31	1036
168	33	920
169	35	755
170	37	608
171	39	594
172	41	484
173	43	481
174	45	422
175	47	381
176	49	373
177	51	321
178	53	274
179	55	259

B11* Population

bin	Ex	Popul.	J= 0.5	J= 1.5
0	0.000	0.000E+00	0.000E+00	0.000E+00
1	2.125	0.000E+00	0.000E+00	0.000E+00
2	4.445	0.000E+00	0.000E+00	0.000E+00
3	5.020	0.000E+00	0.000E+00	0.000E+00
4	6.742	0.000E+00	0.000E+00	0.000E+00
5	6.792	0.000E+00	0.000E+00	0.000E+00
6	7.286	0.000E+00	0.000E+00	0.000E+00
7	7.978	0.000E+00	0.000E+00	0.000E+00
8	8.560	0.000E+00	0.000E+00	0.000E+00
9	8.920	0.000E+00	0.000E+00	0.000E+00
10	9.184	0.000E+00	0.000E+00	0.000E+00
11	9.272	0.000E+00	0.000E+00	0.000E+00
12	9.820	0.000E+00	0.000E+00	0.000E+00
13	9.873	0.000E+00	0.000E+00	0.000E+00
14	10.262	0.000E+00	0.000E+00	0.000E+00
15	10.330	0.000E+00	0.000E+00	0.000E+00
16	10.602	0.000E+00	0.000E+00	0.000E+00
17	10.960	0.000E+00	0.000E+00	0.000E+00
18	11.272	0.000E+00	0.000E+00	0.000E+00
19	11.450	0.000E+00	0.000E+00	0.000E+00
20	11.600	0.000E+00	0.000E+00	0.000E+00
21	11.893	0.000E+00	0.000E+00	0.000E+00
22	12.040	0.000E+00	0.000E+00	0.000E+00
23	12.554	0.000E+00	0.000E+00	0.000E+00
24	12.917	0.000E+00	0.000E+00	0.000E+00
25	13.137	0.000E+00	0.000E+00	0.000E+00
26	13.160	0.000E+00	0.000E+00	0.000E+00
27	14.040	0.000E+00	0.000E+00	0.000E+00
28	14.340	0.000E+00	0.000E+00	0.000E+00
29	14.563	0.000E+00	0.000E+00	0.000E+00
30	15.290	0.000E+00	0.000E+00	0.000E+00
31	15.877	4.490E+02	4.490E+02	0.000E+00
32	17.096	1.168E+03	1.168E+03	0.000E+00
33	18.409	1.230E+03	1.230E+03	0.000E+00
34	19.822	1.336E+03	1.336E+03	0.000E+00
35	21.344	1.461E+03	1.461E+03	0.000E+00
36	22.983	1.511E+03	1.511E+03	0.000E+00
37	24.747	1.494E+03	1.494E+03	0.000E+00
38	26.647	1.455E+03	1.455E+03	0.000E+00
39	28.693	1.285E+03	1.285E+03	0.000E+00
40	30.896	1.194E+03	1.194E+03	0.000E+00

Multiple emissions

Emission particle	Residual nuclei
γ	$^{11}B^*$
n	$^{10}B^*$
p	$^{10}Be^*$
d	$^{9}Be^*$
t	$^{8}Be^*$
h (He3)	$^{8}Li^*$
α	$^{7}Li^*$

Fractions depend on nuclear model and E_x,Spin,Parity of B11

Continue multiple emissions of secondary residual nuclei ;…until all nuclides are in ground state.

Not event by event

6a. Total exclusive cross sections

n	p	d	t	h	a	cross section	reaction
0	0	0	0	0	0	2.07032E+03	(g,g)
1	0	0	0	0	0	1.69535E+03	(g,n)
0	1	0	0	0	0	5.83451E+02	(g,p)
0	0	1	0	0	0	7.79416E+02	(g,d)
0	0	0	1	0	0	3.75780E+02	(g,t)
0	0	0	0	1	0	1.90771E+01	(g,h)
0	0	0	0	0	1	4.54468E+02	(g,a)
2	0	0	0	0	0	9.14239E+02	(g,2n)
1	1	0	0	0	0	1.99535E+03	(g,np)
1	0	1	0	0	0	2.26783E+03	(g,nd)
0	1	1	0	0	0	7.42452E+01	(g,pd)
0	0	2	0	0	0	1.01104E+02	(g,2d)
1	0	0	1	0	0	6.97048E+01	(g,nt)
0	1	0	1	0	0	4.35866E+01	(g,pt)
0	0	1	1	0	0	6.09453E+01	(g,dt)
1	0	0	0	1	0	8.92146E+01	(g,nh)
1	0	0	0	0	1	1.85022E+03	(g,na)
0	1	0	0	0	1	2.60059E+01	(g,pa)
0	0	1	0	0	1	2.27855E+02	(g,da)
0	0	0	1	0	1	1.67928E+01	(g,ta)
3	0	0	0	0	0	[illegible]	(g,3n)
2	1	0	0	0	0	[illegible]	(g,2np)
1	2	0	0	0	0	1.64648E+02	(g,n2p)
2	0	1	0	0	0	1.59934E+02	(g,2nd)
1	1	1	0	0	0	3.95761E+02	(g,npd)
1	0	2	0	0	0	2.43055E+02	(g,n2d)
0	1	2	0	0	0	1.02633E+01	(g,p2d)
2	0	0	1	0	0	1.06419E+01	(g,2nt)
1	1	0	1	0	0	2.15312E+02	(g,npt)
0	1	1	1	0	0	3.05659E+01	(g,pdt)
2	0	0	0	1	0	1.18952E+02	(g,2nh)
1	1	0	0	1	0	1.95448E+01	(g,nph)
2	0	0	0	0	1	4.91123E+01	(g,2na)
1	1	0	0	0	1	5.22685E+02	(g,npa)
3	1	0	0	0	0	3.32887E+01	(g,3np)
2	2	0	0	0	0	1.46930E+02	(g,2n2p)
3	0	1	0	0	0	1.16789E+01	(g,3nd)
2	1	1	0	0	0	1.34623E+02	(g,2npd)
1	2	1	0	0	0	2.73945E+01	(g,n2pd)
2	0	2	0	0	0	1.57760E+01	(g,2n2d)
1	1	2	0	0	0	3.95762E+01	(g,np2d)
1	2	0	1	0	0	6.33796E+01	(g,n2pt)
1	1	1	1	0	0	1.45623E+01	(g,npdt)
1	2	0	0	0	1	1.87126E+01	(g,n2pa)

Absorption cross section : 4926.31348

Sum over exclusive channel cross sections: 17612.78516
(n,gn) + (n,gp) +...(n,ga) cross sections: 0.00000
Total : 17612.78516
Initial population cross section : 22643.18750

For illustrations!

Branching ratios

Change discrete level number of nuclides

In TALYS, all discrete states of all nuclides only emit γ, finally decay into their ground state

Discrete states

Continuous states

Emitted flux per excitation energy bin of Z= 4 N= 6 (10Be):

bin	Ex	gamma	neutron	proton	deuteron	triton	helium-3	alpha	Total
0	0.000	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
1	3.368	4.27753E+02	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	4.27753E+02
2	5.958	5.99935E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	5.99935E+01
3	5.960	1.01168E+02	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	1.01168E+02
4	6.179	1.77084E+02	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	1.77084E+02
5	6.263	6.35393E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	6.35393E+01
6	7.371	5.62423E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	5.62423E+00
7	7.542	3.40607E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	3.40607E+01
8	9.270	3.15495E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	3.15495E+00
9	9.560	1.80959E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	1.80959E+01
10	10.150	2.35273E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	2.35273E+00
11	10.591	3.47120E-04	3.17376E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	3.58777E+00	3.53257E+01
12	11.510	4.39747E-04	3.52765E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	5.88183E+00	4.11587E+01
13	12.509	5.78110E-04	4.03321E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	6.45328E+00	4.67860E+01
14	13.595	9.19605E-04	4.66271E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	6.44623E+00	5.30742E+01
15	14.775	1.56067E-03	5.44424E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	8.37811E+00	6.28221E+01
16	16.058	2.77599E-03	6.05345E+01	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	8.54838E+00	6.90857E+01
17	17.452	5.81825E-03	7.05929E+01	0.00000E+00	0.00000E+00	1.36527E-01	0.00000E+00	7.87023E+00	7.86055E+01
18	18.967	9.47813E-03	7.62352E+01	0.00000E+00	0.00000E+00	5.76376E+00	0.00000E+00	6.36011E+00	8.83686E+01

Lead to a wrong result, for example

$$^{11}\mathrm{B}^* \rightarrow p + {}^{10}\mathrm{Be}^* \;\Rightarrow\; {}^{11}\mathrm{B}^* \rightarrow p + {}^{10}\mathrm{Be} + \gamma$$

If Be10* is in 7th discrete state

Be10 in NNDC

E(level) (keV)	J^π(level)	$T_{1/2}$(level)	E(γ) (keV)	I(γ)	M(γ)	Final Levels	
0.0	0+	1.51×10^{+6} y 4 % β⁻ = 100					
3368.03 3	2+	125 fs 12 % IT = 100	3367.415 30	100	E2	0.0	0+
5958.39 5	2+	< 55 fs % IT = 100	2589.999 60 5955.9 5	>90 <10	M1 E2	3368.03 0.0	2+ 0+
5959.9 6	1−	% IT = 100	2591.5 6 5958.0 6	17 8 83 8	E1 E1	3368.03 0.0	2+ 0+
6179.3 7	0+	0.8 ps +3−2 % IT ≈ 100	219.4 3 2811 7 6178	24 2 76 2	E1 E2 E0	5959.9 3368.03 0.0	1− 2+ 0+
6263.3 50	2−	% IT = 100	303.4 50 2894.9 50 6261.2 50	≤1 99 1 1 1	 E1 M2	5959.9 3368.03 0.0	1− 2+ 0+
7371 1	3−	15.7 keV 5 % IT > 0 % n > 0	1412 4002	15 11 85 8	E1 E1	5958.39 3368.03	2+ 2+
7542 1	2+	6.3 keV 8 % α = 3.5 12 % n > 0					
9270	(4−)	150 keV 20 % n > 0					
9560 20	2+	141 keV 10 % α = 0.16 4 % n > 0					
10150 20	3−	296 keV 15 % α > 0					

$$^{11}\mathrm{B}^* \rightarrow p + n + {}^{9}\mathrm{Be}^*$$

$$^{11}\mathrm{B}^* \rightarrow p + \alpha + {}^{6}\mathrm{He}^*$$

To accurately give B11* de-excitation results:

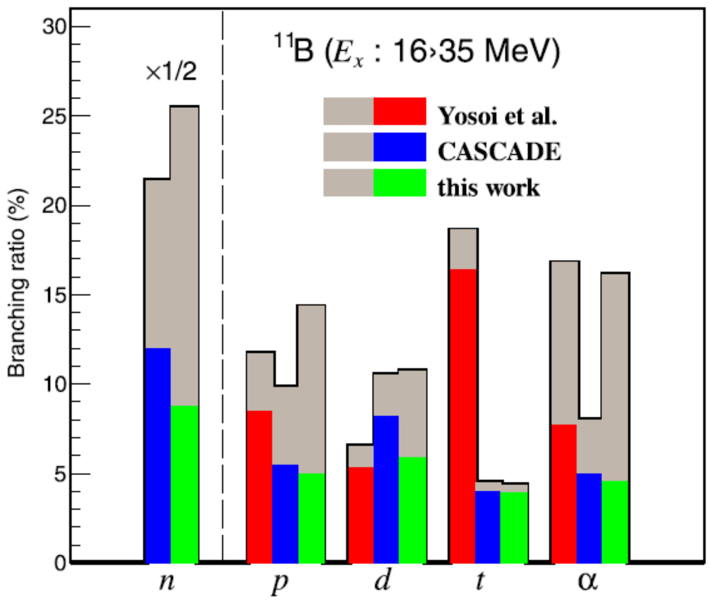
1. Should know population of every discrete state **OK**
2. Should know decay BRs of every discrete state **X**

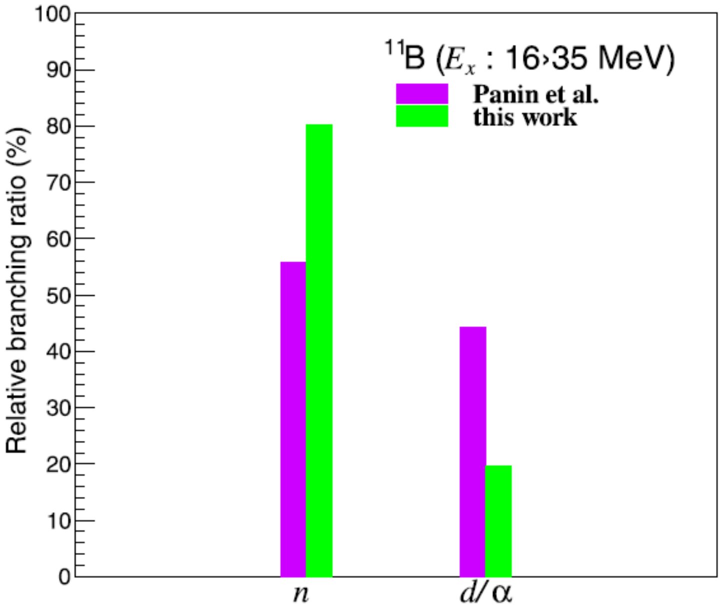
To reduce uncertainty, we change discrete level number:

Nuclide	^{10}B	^{9}B	^{8}B	^{10}Be	^{9}Be	^{8}Be	^{7}Be	^{9}Li	^{8}Li	^{7}Li	^{6}Li	others
Default	10	10	4	10	5	5	8	7	5	9	10	10
New	5	5	3	5	5	5	5	3	3	3	3	1

TALYS predictions

H. Hu, **W.L. Guo**, et al., Phys. Lett. B 831 (2022) 137

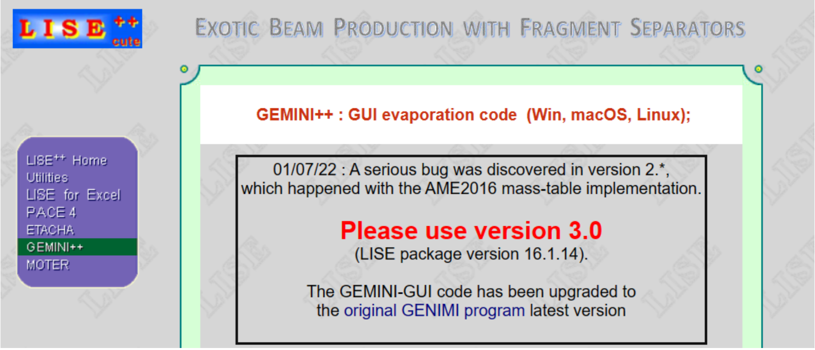




TALYS can partially account for experiment data, bad for t mode!

(3) De-excitations from GEMINI++/GEMINI++4ν

GEMINI++: a Monte Carlo code, is an improved C++ version based on GEMINI



R. J. Charity, PRC 82 (2010), 014610; PRC 82 (2010) 044610
https://lise.frib.msu.edu/gemini.html

Code	TALYS	GEMINI++
Input	Nucleus, Excited energy table (spin, parity)	Nucleus, Excited energy, Spin
Formulism of width Γ_i	Hauser-Feshbach (HF)	HF or Weisskopf-Ewing (WE)
Output	Statistical branching ratios and energy spectra	Complete de-excitation cascade
Convenience	Not event-by-event, Inconvenience	***Event-by-event, Convenience***

This code has been extensively used in nuclear physics and got cheerful achievements

GEMINI++, like other codes, is designed for handling complex fragment formation in heavy-ion fusion reactions, light nuclei?

For $^{11}B^*$ and $^{15}N^*$, the Weisskopf-Ewing formalism is used in GEMINI++

$$\Gamma_i^{WE} = \frac{2S_i+1}{2\pi\rho^0(E_x)}\int\sum_{l=0}^{\infty}(2l+1)T_l(\varepsilon)\rho(U)d\varepsilon,$$

Γ_i^{WE}: the partial decay width for evaporation of particle *i*
S_i, l : the spin and orbital angular momenta
$T_l(\varepsilon)$: the transmission coefficient, ε: the kinetic energy of *i*
U : $E_x - B_i - E_{rot} - \varepsilon$
ρ^0, ρ: the SI level densities of the parent and daughter nuclei

Back-shifted term E_1:

$$\rho(U) \propto \frac{\exp[2\sqrt{a(U-E_1)}]}{a^{1/4}(U-E_1)^{5/4}},$$

Pairing/Shell corrections
= modify excited energy

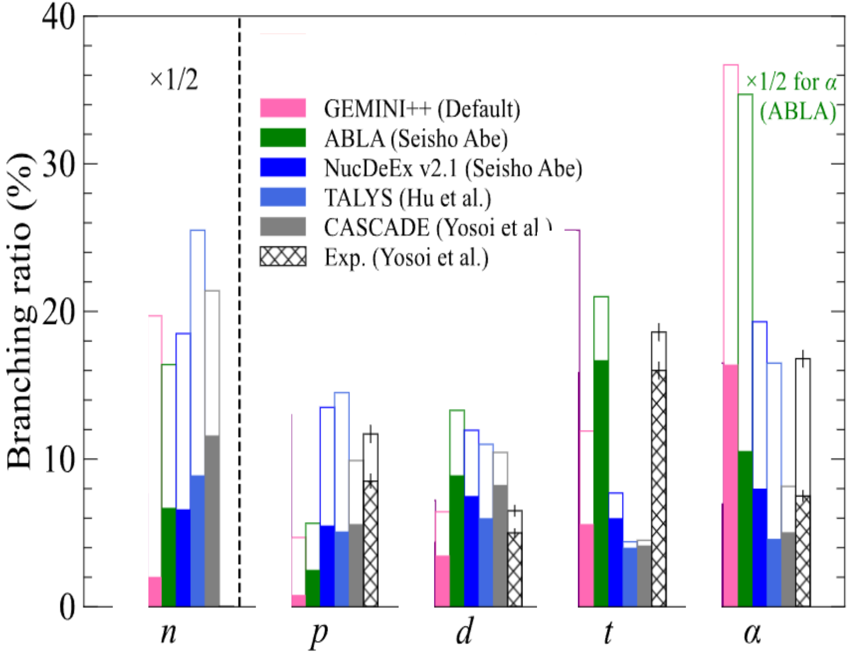
Suppression factors F_s:

$$\Gamma_i = \Gamma_i^{WE} \times F_s$$

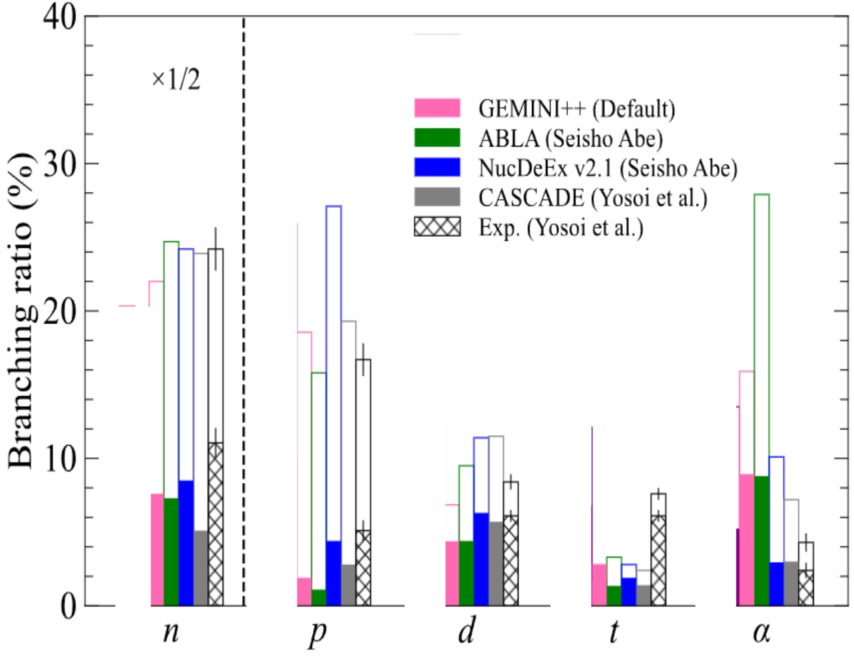
Adjust its predictions
Final results based on Γ_i

GEMINI++ predictions

$^{11}B^*$



$^{15}N^*$



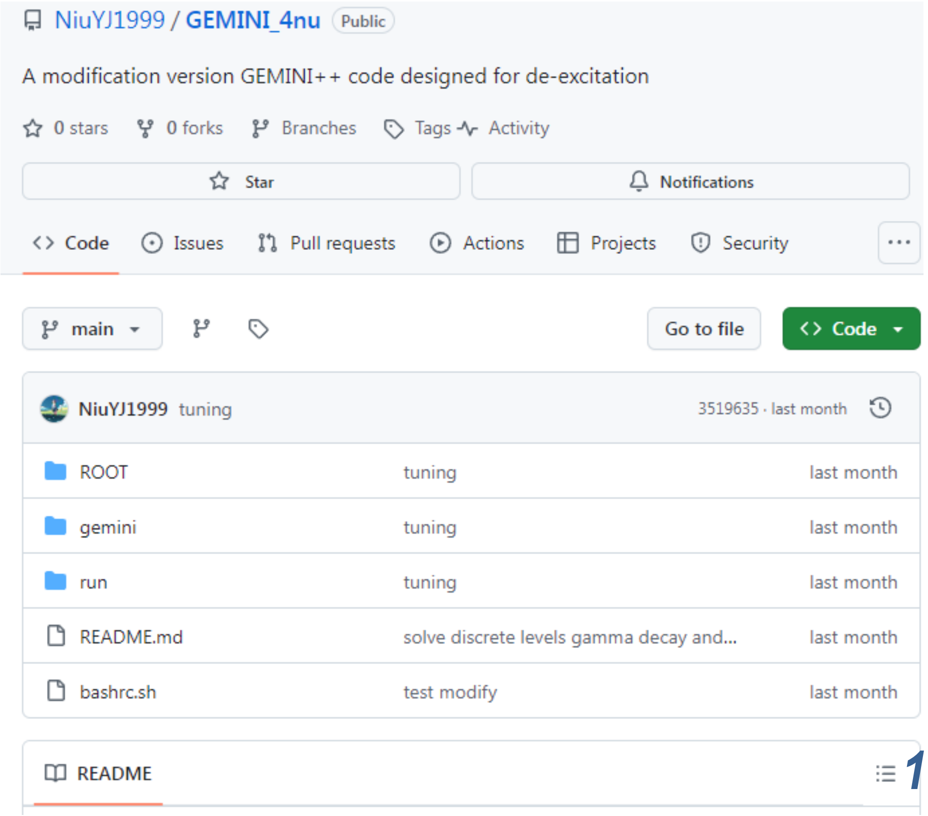
GEMINI++ can't describe de-excitations of both $^{11}B^*$ and $^{15}N^*$ well

(4) GEMINI++4ν

GINIMI++4ν is developed for neutrino experiments to handle de-excitations of residual nuclei associated with ν interaction and nucleon decay based on GEMINI++ code

Open source:

https://github.com/NiuYJ1999/GEMINI_4nu



Making three reasonable modifications:

- ✓ Remove back-shifted term
- ✓ Add discrete states
- ✓ Remove/adjust suppression factors

Modification 1: Remove back-shifted term

The back-shifted term E_1 is equivalent to reducing E_x of the compound nucleus

- Suppress emissions of massive particles compared with γ emission
- Massive particles will require a higher E_x to begin their evaporation

Threshold values:

We simulate 5000 events for every interval of 0.1 MeV in the range of 0 MeV ≤ Ex ≤ 50 MeV.

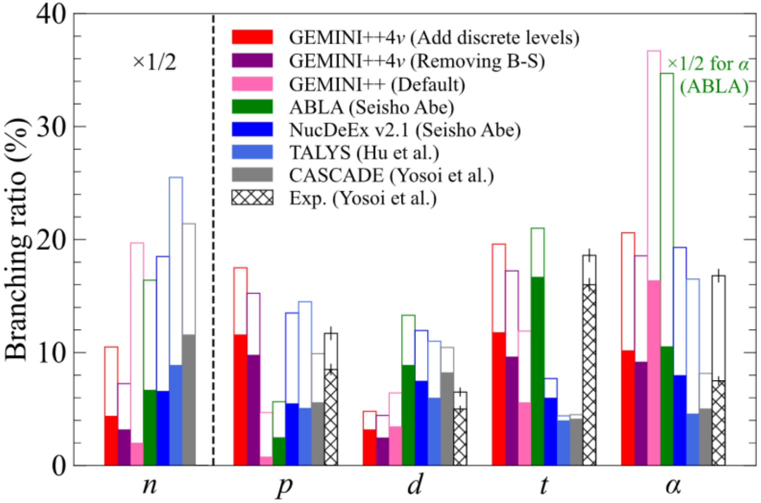
Modes	Theory	GEMINI++	GEMINI++4ν
$n + {}^{10}B$	11.5	12.2	12.2
$p + {}^{10}Be$	11.2	17.1	12.2
$d + {}^{9}Be$	15.8	16.6	16.6
$t + {}^{8}Be$	11.2	20.5	12.1
$\alpha + {}^{7}Li$	8.7	10.1	10.1

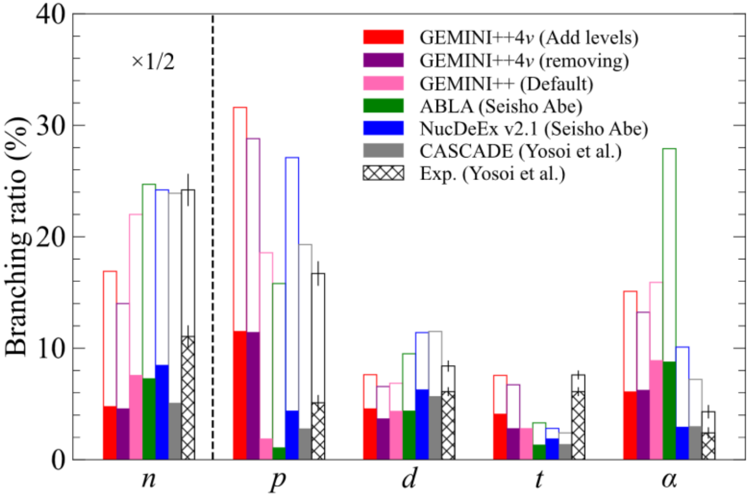
the back-shifted term E_1 is not used properly for the case of light nuclei

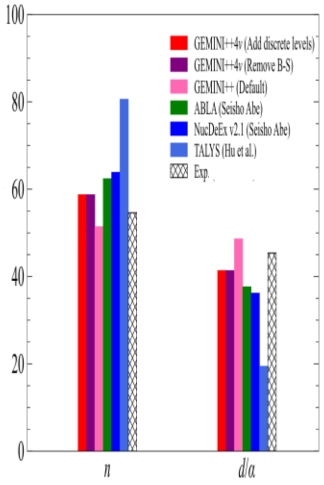
No available E_1 → **Remove E_1**

Impact of Modification 1 on de-excitations

$^{11}B^*$ **Yosoi Experiment** $^{15}N^*$ **Panin Exp.**







Only Removing back-shifted term:

- Increase *p* and *t* BRs versus GEMINI++
- $^{11}B^*$: basically agree with Exps 1 and 2
- $^{15}N^*$: become worse for *n* and *p* BRs

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Modification 2: Add discrete states

GEMINI++ only considers continuous levels

Daughter nuclei of de-excitations are usually left in discrete levels when its E_x is low

Add discrete states :

Due to the unclear boundary between discrete and continuum states, we only consider the discrete levels:

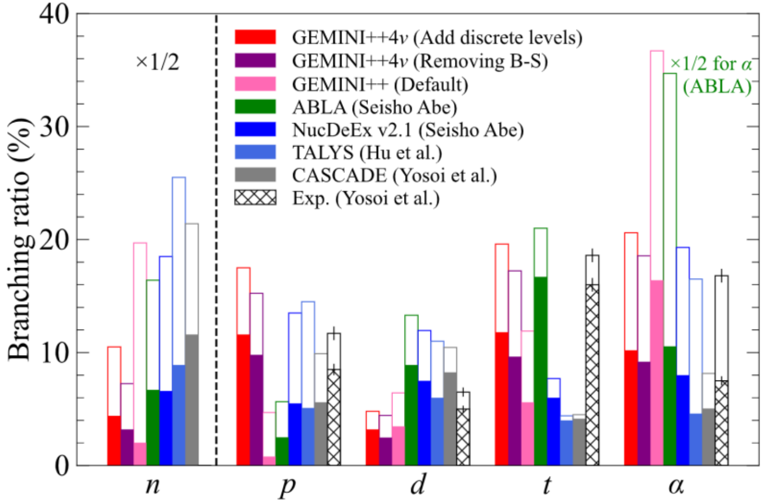
- ✓ $E_x < 6$ **MeV**
- ✓ **Decay known**

Implement: modify outputs

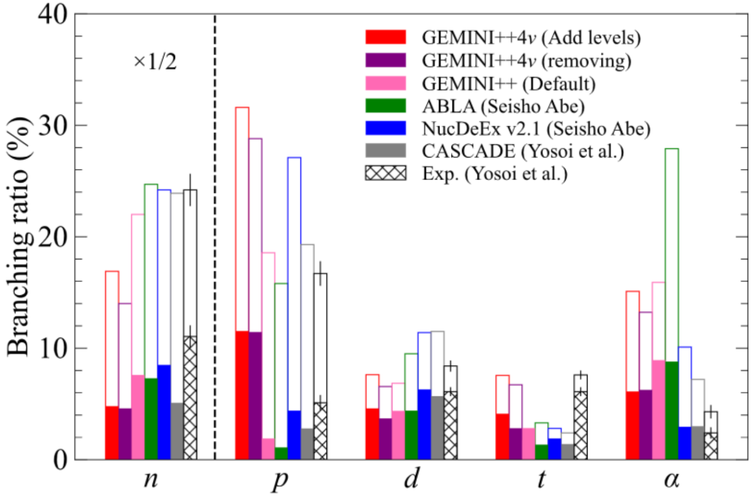
- If the excited energy of parent nucleus in the last binary decay is higher than the highest discrete level considered obviously, this GEMINI++ event will be kept;
- If it is lower than all of the discrete levels, this state will be set as the ground state and the kinematics of the previous decay will be recalculated;
- If it lies between two discrete levels, we shall reset this state to the lower level and recalculate the kinematics of the previous decay.

Impact of Modifications 1 and 2 on de-excitations

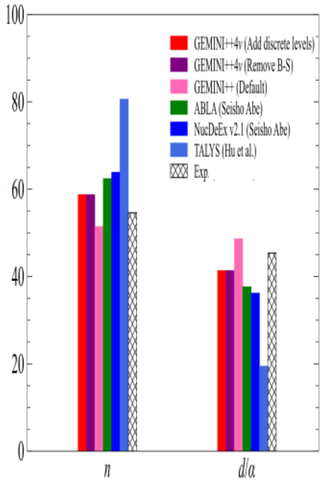
$^{11}B^*$ **Yosoi Experiment**



$^{15}N^*$



Panin Exp.



Both Removing BS and Add discrete states:

- Increase all BRs of Exp. 1 versus Modification 1
- $^{11}B^*$: basically agree with Exps 1 and 2
- $^{15}N^*$: become worse for *p* and *alpha*

Including discrete levels can increase the kinetic energy of the finally emitted particles → over thresholds

Modification 3: Suppression factors

Default F_s settings originate from the de-excitations of heavy nuclei

Settings	n	p	d	t	^{3}He	α
Default	1.0	1.0	0.5	0.5	0.5	1.0
$F_s = 1.0$	1.0	1.0	1.0	1.0	1.0	1.0
$F_s = 0.5$	1.0	0.5	0.5	0.5	0.5	0.5

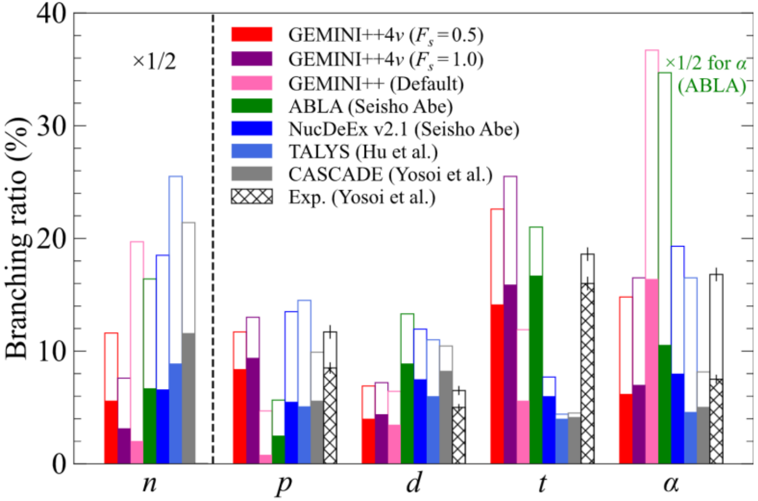
Are default settings reasonable for light nuclei?

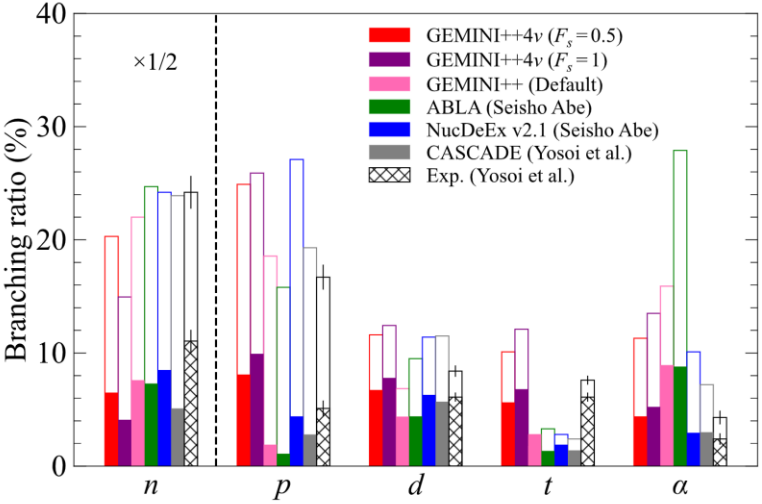
- Don't use suppression factor to adjust results, namely $F_s = 1.0$ for all particles
- $F_s = 0.5$ for all charged particles. Compared with default, only two changes

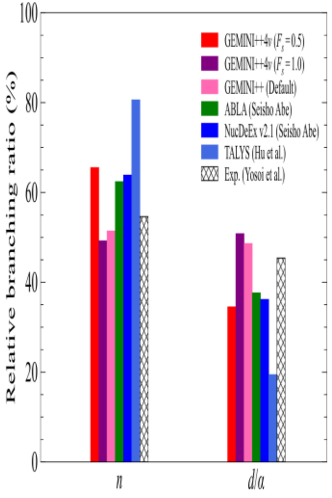
GEMINI++4v predictions

Including all 3 modifications, present both $F_s = 1.0$ and $F_s = 0.5$ results:

$^{11}\mathrm{B}^*$ **Yosoi Experiment** $^{15}\mathrm{N}^*$ **Panin Exp.**







GEMINI++4v with $F_s = 1.0$:

- Good agreement with $^{11}\mathrm{B}^*$ data
- Can't account for $^{15}\mathrm{N}^*$ data well

GEMINI++4v with $F_s = 0.5$: **Recommend!**

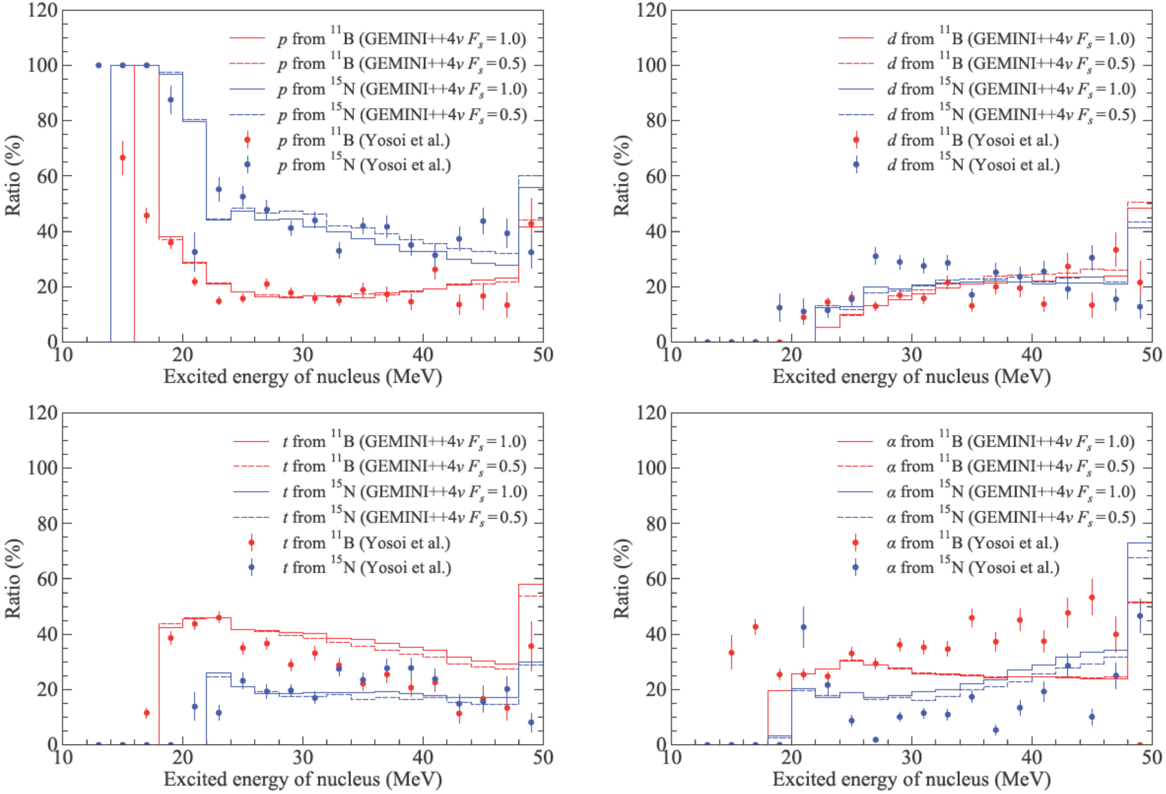
- Good agreement with $^{11}\mathrm{B}^*$ data
- Partially account for $^{15}\mathrm{N}^*$ data, include *n*

This is the first time that a code can basically reproduce both $^{11}\mathrm{B}^*$ and $^{15}\mathrm{N}^*$ data

Accidental coincidence check

Fixed energy ranges of $16 \le Ex \le 35$ MeV for $^{11}B^*$ and $20 \le Ex \le 40$ MeV for $^{15}N^*$

➡ **Compare the ratio of each type of charged particle emission among four types for every energy bin**



- $F_s = 1.0$ and $F_s = 0.5$ differences are relatively small
- Predicted shapes are basically consistent with data except α
- Discrepancy maybe come from $^{11}B^* \rightarrow t + \alpha + \alpha$

Not coincidental!

Summary

- De-excitations are playing an increasingly significant role in ν experiments
- De-excitation codes were widely used, should be compared with experimental data
- TALYS can partially account for experimental data, not event-by-event
- GEMINI++4ν give the best predictions for both $^{11}\mathrm{B}^*$ and $^{15}\mathrm{N}^*$ de-excitations, event-by-event

Thanks for your attention!