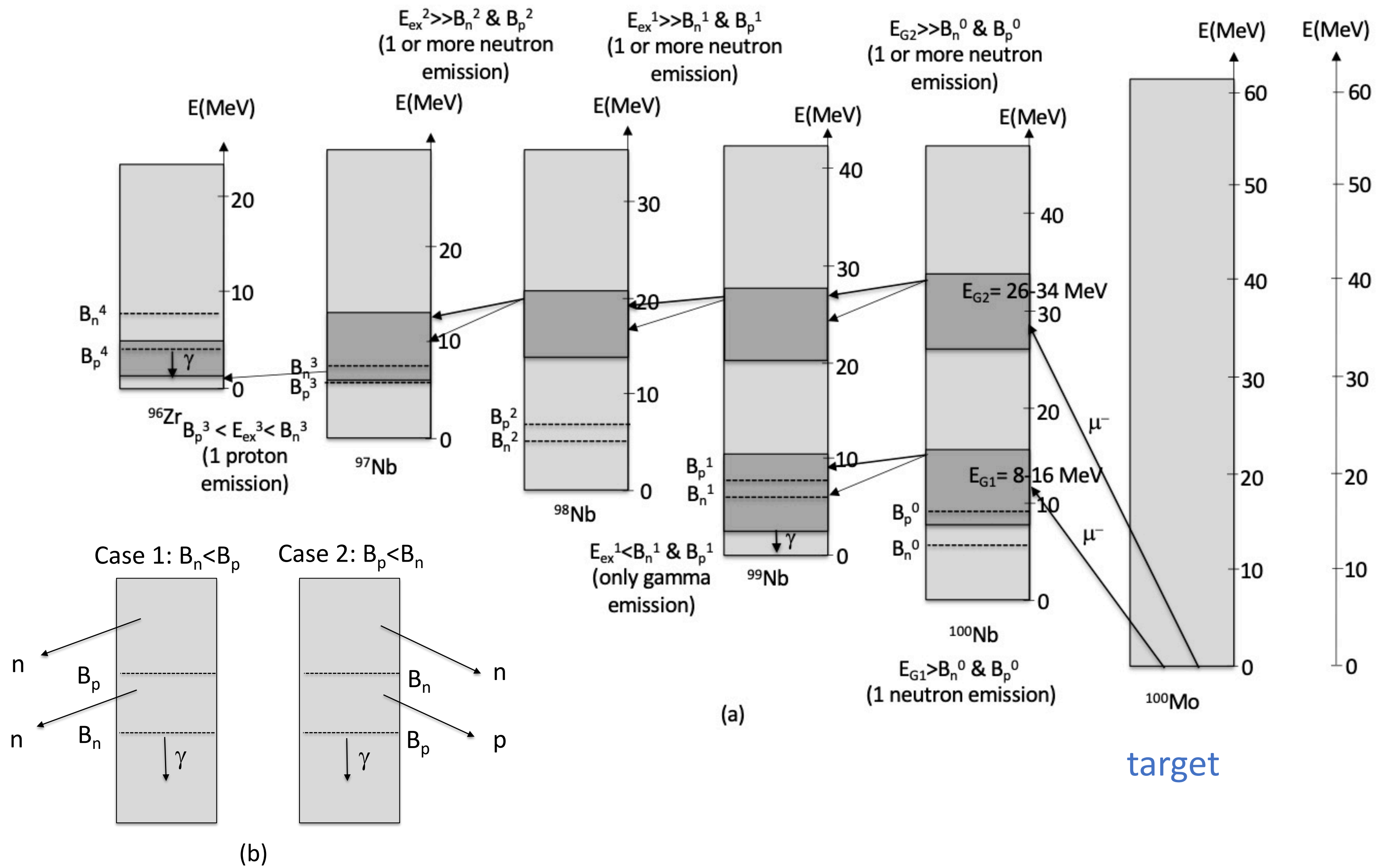
Proton-Neutron Emission Model for Neutrino Nuclear Response

IZYAN HAZWANI BINTI HASHIM
Universiti Teknologi Malaysia
OMC4DBD Collaboration meeting
19-20/04/2021

OUTLINE

1) Layout of proton-neutron emission model (PNEM)
2) Theory and assumption in PNEM
3) Flowchart of cascade calculation in PNEM
4) PNEM calculation for previous experiment at PSI Oct-Nov 2019
5) Simulation for ^{136}Ba and ^{nat}Ba PSI Oct-Nov 2021 experiment

Layout of proton-neutron emission model (PNEM)



target

Theory and assumption in PNEM

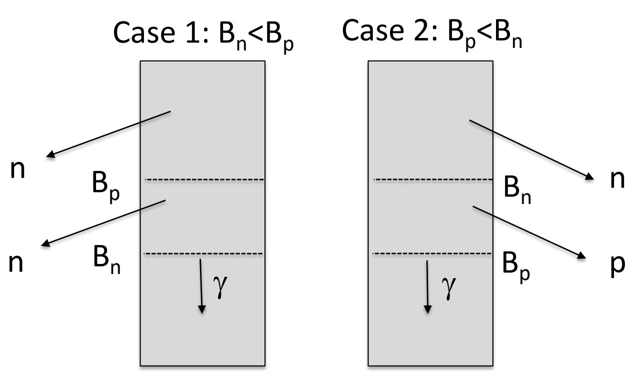
Nuclear Reaction

- The projectile (muon) and target(nuclei) composite system is equilibrated to form a compound system in thermal equilibrium.
- If the projectile energy is high enough, some nucleons and/or nucleon clusters can be emitted in the course of the cascade process before thermal equilibrium is reached pre-equilibrium (PEQ) stage and follows by equilibrium (EQ) stage.

Maximum excitation after muon capture

- The maximum excitation energy in PNEM is decide by the Q-value of muon capture on target.
- The energy increment for PNEM (ΔE) is set until as low as 0.1 MeV bin but it will take longer simulation time.

Probability of neutron, proton and gamma emission



- neutron emission: proton emission = 3:1
- set by the neutron and proton separation energy (B_n and B_p)
- when E < B_n and B_p , then gamma emission take place.

$$B_n = [(M[i, j-1] + M_n) - M[i,j]]$$

$$B_p = [\left(M[i-1, j-1] + M_p\right) - M[i,j]]$$

Theory and assumption in PNEM

Neutron emission and distribution

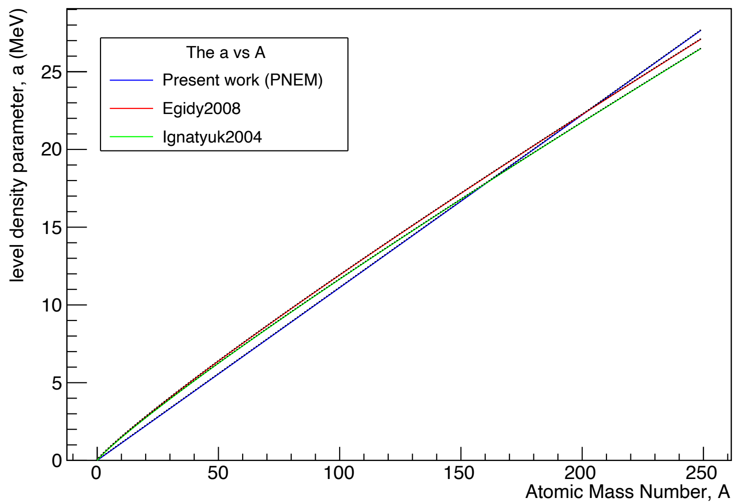
- For the first neutron emission, the PEQ and EQ neutron emission are considered.
- For the second and more neutron emission only EQ mode is considered.
- The ratio of EQ/PEQ neutron emission is set to 25% ratio.

$$S(E_n) = E_n \exp\left(-\frac{E_n}{T_{EQ}}\right) + x\, E_n \exp\left(-\frac{E_n}{T_{PEQ}}\right)$$

Proton emission and distribution

- Only one proton emission is possible.
- After emission, the nuclei will be in ground state.
- Proton emission is allowed when proton binding energy is lower than neutron binding energy.

Level density parameter (a)



- The relationship for level density parameter (a) versus atomic mass number (A).

$$a = \frac{A}{9}\ MeV^{-1}$$

- statistical error of about 10%.

Theory and assumption in PNEM

Output from PNEM

1) Radioactive Isotope (RI) population yield

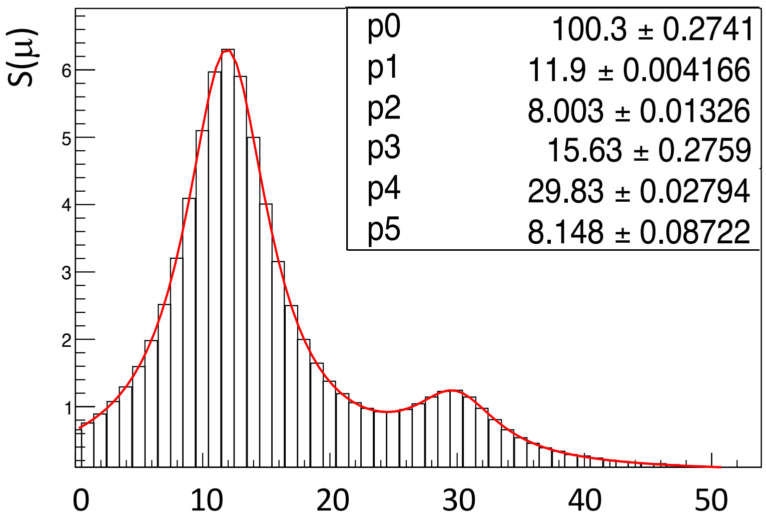
- The RI population yield is obtained from the integration of the excitation energy at each nuclei.

$$S(Y) = \int_{min}^{max} E_{ex}^{i} dx$$

where

$$S(E_{ex}^{i}) = S(E_{ex}^{i-1}) - S(E_n) - B_n$$

2) Muon capture strength distribution



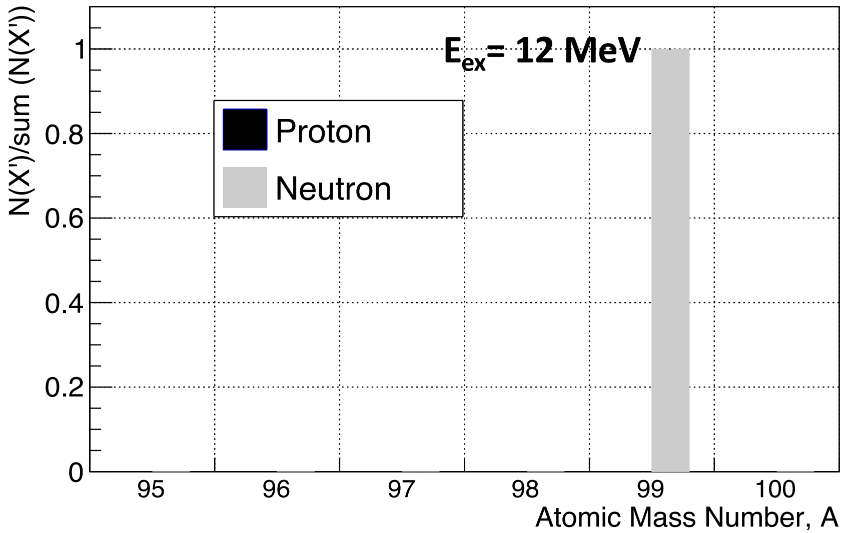
Excitation Energy, E^{0}_{ex} (MeV)

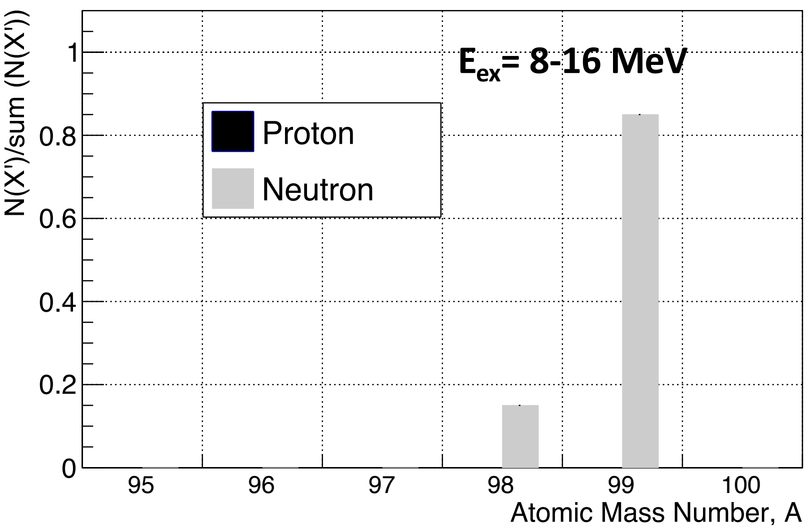
$$B_i(\mu, E_i) = \frac{B_i(\mu)}{(E - E_{G1})^2 - (\Gamma_i /2)^2}$$

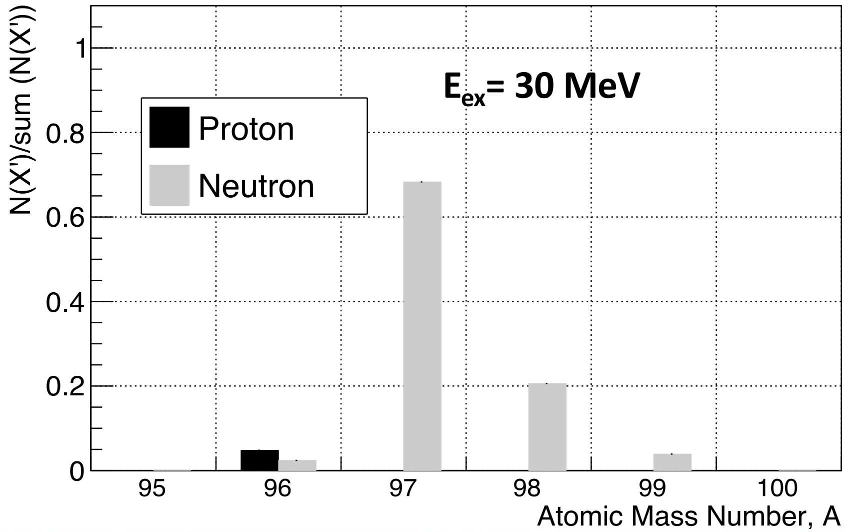
$$S(\mu) = \sum_{i=1,2} B_i(\mu, E_i)$$

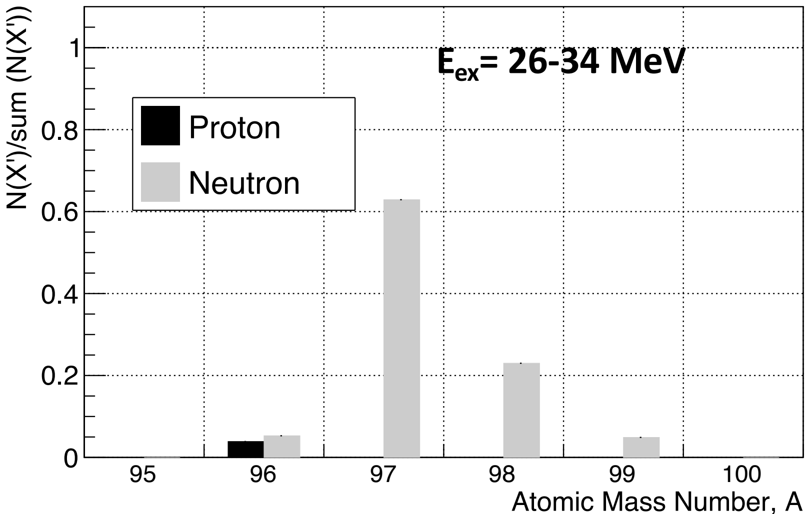
Theory and assumption in PNEM

Excitation energy range versus RI population









Flowchart of cascade calculation in PNEM

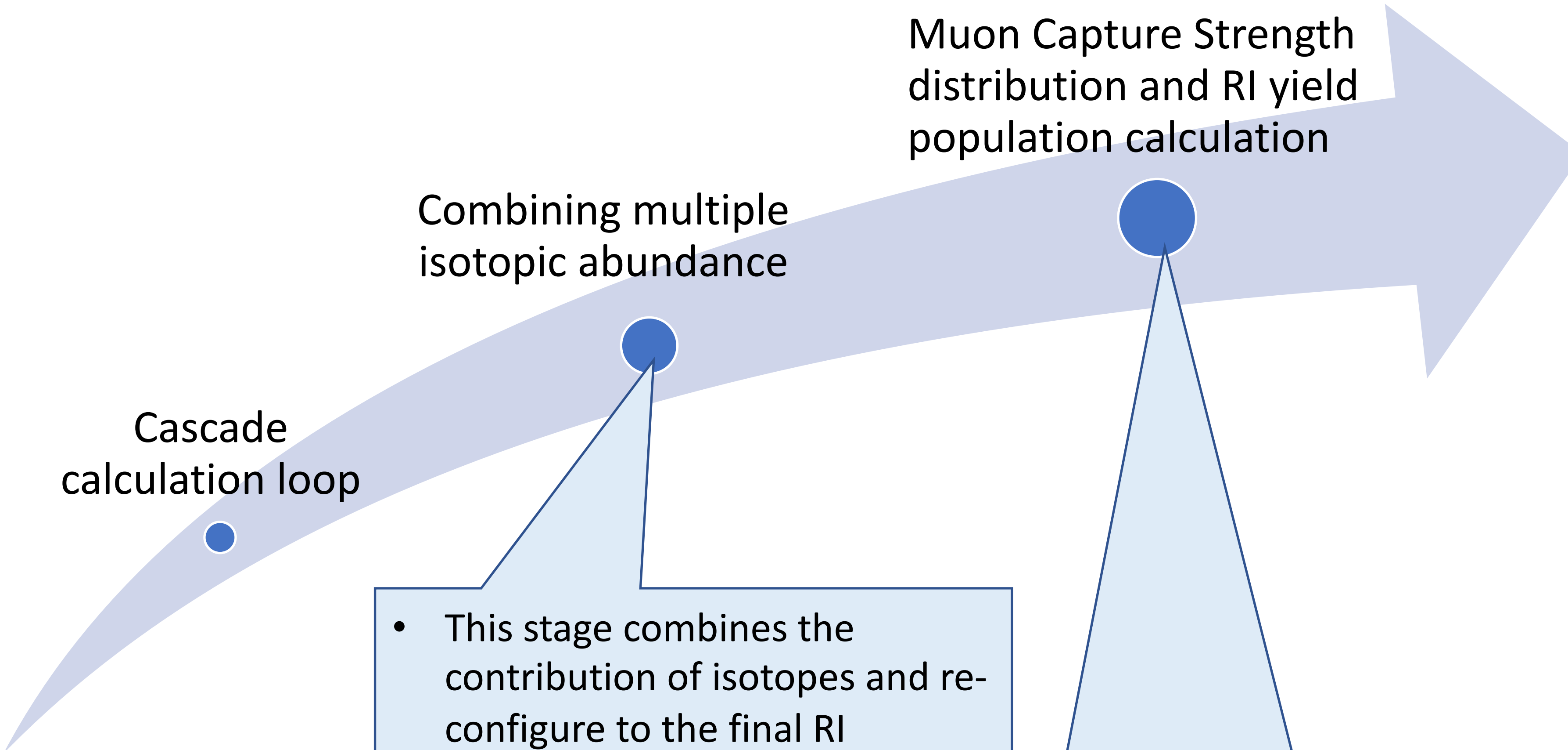
Cascade calculation loop

Combining multiple isotopic abundance

Muon Capture Strength distribution and RI yield population calculation

- Continuous cascade process until input energy reaches 0.
- Increasing number of trials and reducing the energy bin size will resulting longer calculation time.
- Automatically choose the emission mode based on the value of excitation energy.
- Need to run several times if the target have many isotopic components
    - If ${}^{Nat}Mo$ with 8 isotopes, then the calculation need to be done 8 times.

Flowchart of cascade calculation in PNEM



- This stage combines the contribution of isotopes and re-configure to the final RI population yield based on isotopic contribution.

- This stage combines the contribution of excitation energy fractions and re-configure to the final RI population yield.

Comparison with other OMC experimental data

Table 1

RIs produced by OMC on ^{100}Mo (Enrichment 96.5% ^{100}Mo, 2.5% ^{98}Mo, 1.0% ^{97}Mo) and 0.5% ^{96}Mo). Columns 1 and 2 show the reactions and the RIs. Columns 3 and 4 gives the experimental results and the calculations.

Reaction	Final N	Experimental	This model
$^{100}Mo(\mu,0n)$	^{100}Nb	8 [19]	12 ± 4
$^{100}Mo(\mu,1n)$	^{99}Nb	51 [19]	58 ± 7
$^{100}Mo(\mu,2n)$	^{98}Nb	16 [19]	15 ± 1
$^{100}Mo(\mu,3n)$	^{97}Nb	13 [19]	9 ± 4
$^{100}Mo(\mu,4n)$	^{96}Nb	6 [19]	4 ± 2
$^{100}Mo(\mu,5n)$	^{95}Nb	3 [19]	2 ± 1
$^{100}Mo(\mu,1p)$	^{99m}Tc	0 [19]	0
$^{100}Mo(\mu,1n1p)$	^{98}Tc	0 [19]	0
$^{100}Mo(\mu,2n1p)$	^{97}Tc	0 [19]	0
$^{100}Mo(\mu,3n1p)$	^{96}Tc	0 [19]	0
	Total, $\Sigma(\%)$	97	100

Table 4

RIs produced by OMC on ^{127}I. Columns 1 and 2 show the reactions and the RIs. Columns 3 and 4 gives the experimental results and the calculations.

Reaction	Final N	Experimental	This model
$^{127}I(\mu,0n)$	^{127}Te	7 ± 3 [13]	7.0 ± 3
$^{127}I(\mu,1n)$	^{126}Te	44 ± 3 [13]	54.6 ± 7
$^{127}I(\mu,2n)$	^{125}Te	15 ± 3 [13]	21.4 ± 5
$^{127}I(\mu,3n)$	^{124}Te	15 ± 2 [13]	10.7 ± 3
$^{127}I(\mu,4n)$	^{123}Te	8 ± 5 [13]	2.7 ± 1
$^{127}I(\mu,5n)$	^{122}Te	1.5 ± 10 [13]	1.2 ± 10
$^{127}I(\mu,1p)$	^{126}Sb	0 [13]	0
$^{127}I(\mu,1n1p)$	^{125}Sb	0 [13]	1.7 ± 5
$^{127}I(\mu,2n1p)$	^{124}Sb	0 [13]	0
$^{127}I(\mu,3n1p)$	^{123}Sb	0 [13]	0.45 ± 5
$^{127}I(\mu,4n1p)$	^{122}Sb	0 [13]	0
$^{127}I(\mu,5n1p)$	^{121}Sb	0 [13]	0.12 ± 5
	Total, $\Sigma(\%)$	97.3	99.9

Table 5

RIs produced by OMC on ^{209}Bi. Columns 1 and 2 show the reactions and the RIs. Columns 3 and 4 gives the experimental results and the calculations.

Reaction	Final N	Experimental	This model
$^{209}Bi(\mu,0n)$	^{209}Pb	3 ± 1 [13]	7 ± 3
$^{209}Bi(\mu,1n)$	^{208}Pb	46 ± 4 [13]	54.6 ± 7
$^{209}Bi(\mu,2n)$	^{207}Pb	30 ± 3 [13]	21.4 ± 5
$^{209}Bi(\mu,3n)$	^{206}Pb	10 ± 3 [13]	10.7 ± 3
$^{209}Bi(\mu,4n)$	^{205}Pb	5 ± 1 [13]	2.7 ± 2
$^{209}Bi(\mu,5n)$	^{204}Pb	1 ± 1 [13]	1.2 ± 1
$^{209}Bi(\mu,1p)$	^{208}Tl	0 [13]	0
$^{209}Bi(\mu,1n1p)$	^{207}Tl	0 [13]	0
$^{209}Bi(\mu,2n1p)$	^{206}Tl	0 [13]	0
$^{209}Bi(\mu,3n1p)$	^{205}Tl	0 [13]	0.98 ± 5
$^{209}Bi(\mu,4n1p)$	^{204}Tl	0 [13]	0.13 ± 5
$^{209}Bi(\mu,5n1p)$	^{203}Tl	0 [13]	0.25 ± 6
	Total, $\Sigma(\%)$	95.2	98.9

Shows similar pattern obtain by experiment and this model.

- 1 neutron has the highest probability
- No experimental evidence on gamma rays associated with the proton emission.
- Prediction by PNEM shows 1-3% proton emission can be observed for these isotopes.

Comparison from previous PSI 2019 measurement

Only (μ,0n) reaction is observed for all three isotopes

- contribute to only about 6-13% of the whole reaction.
- Might be caused by the statistical loss during target transfer to RCL Lab shown by peaks which decay within few minutes are observed in the beginning of offline measurement

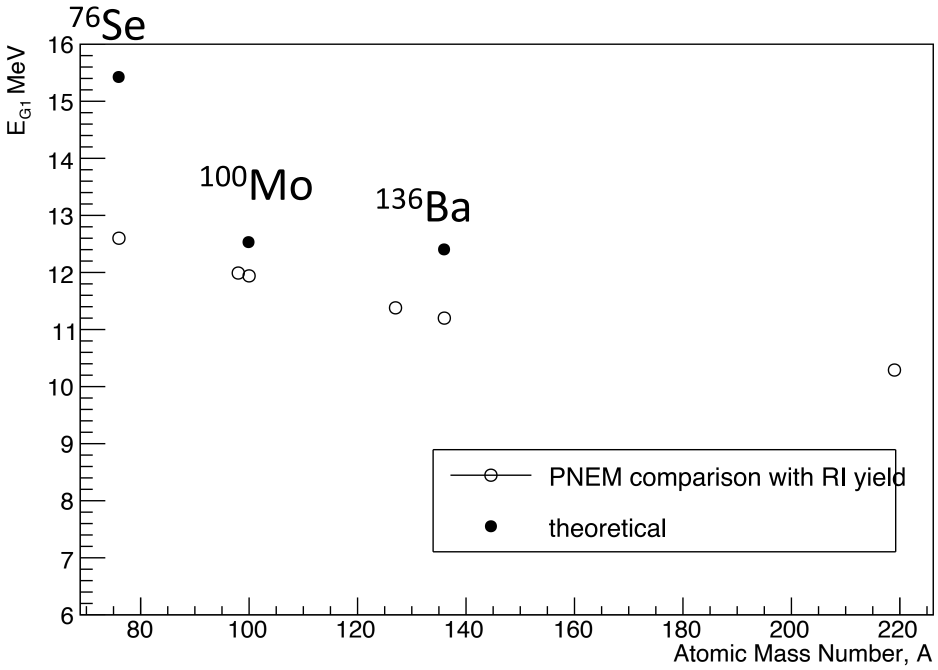
Isotope		PSI exp	PNEM
	event	N(X)	Percentage (%)
^{24}Mg	(μ,0n)	**2.89E+11**	0.06
	(μ,1n)		0.66
	(μ,2n1p)		0.25
	(μ,3n1p)		0.04
	(μ,4n1p)		0.01
	(μ,5n)		<0.01

Isotope		PSI exp	PNEM
	event	N(X)	Percentage (%)
^{82}Kr	(μ,0n)	**5.39E+07**	0.13
	(μ,1n)		0.6
	(μ,2n1p)		0.2
	(μ,3n1p)		0.09
	(μ,4n1p)		0.06
	(μ,5n)		<0.01

Isotope		PSI exp	PNEM
	event	N(X)	Percentage (%)
^{130}Xe	(μ,0n)	**1.54E+07**	0.12
	(μ,1n)		0.55
	(μ,2n1p)		0.23
	(μ,3n1p)		0.1
	(μ,4n1p)		0.04
	(μ,5n)		0.01

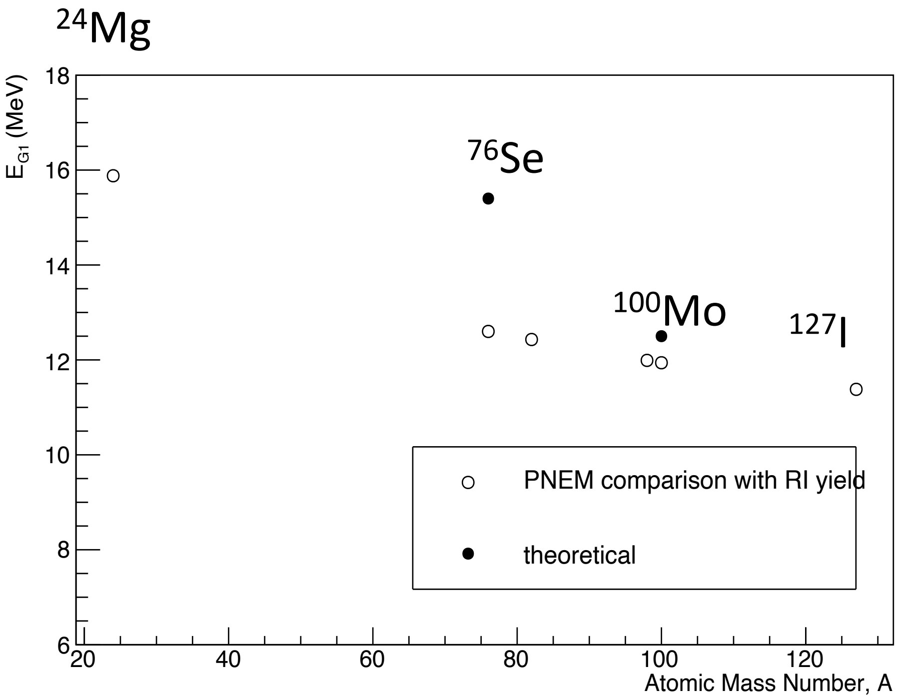
Recalculation of PNEM is on-going using the updated enrichment received from Daniya.

Relationship of EG1 and EG2 with A



- So far, all published theoretical calculation shows no evidence of the second giant resonance (GR) peak.
- More calculation and comparison with RI experimental is on-going.

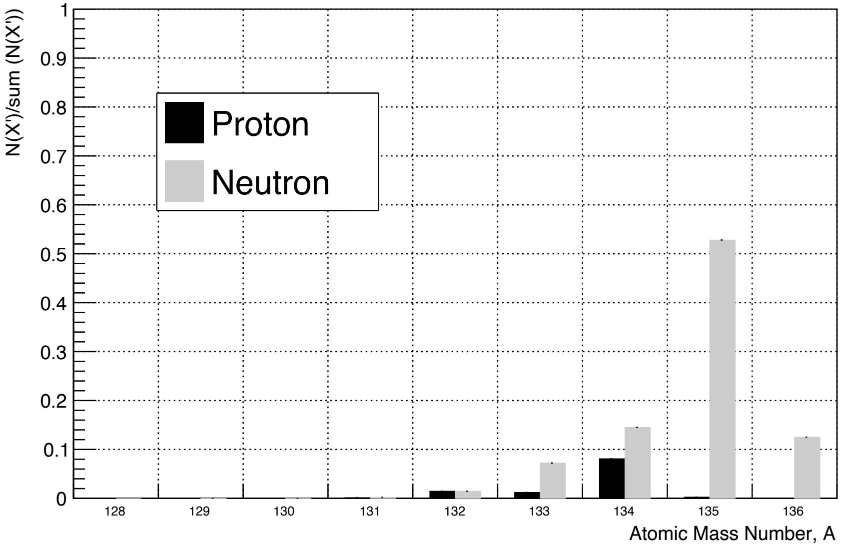
- Expected GR peak for 24Mg, 82Kr and 130Xe if use same approach.
- However, the current offline data is not convincing for comparison and referring to theoretical comparison (kortelainen2004) show the GR peak for light nuclei is in 4-6 MeV.



Prediction for 2021 campaign

^{136}Ba

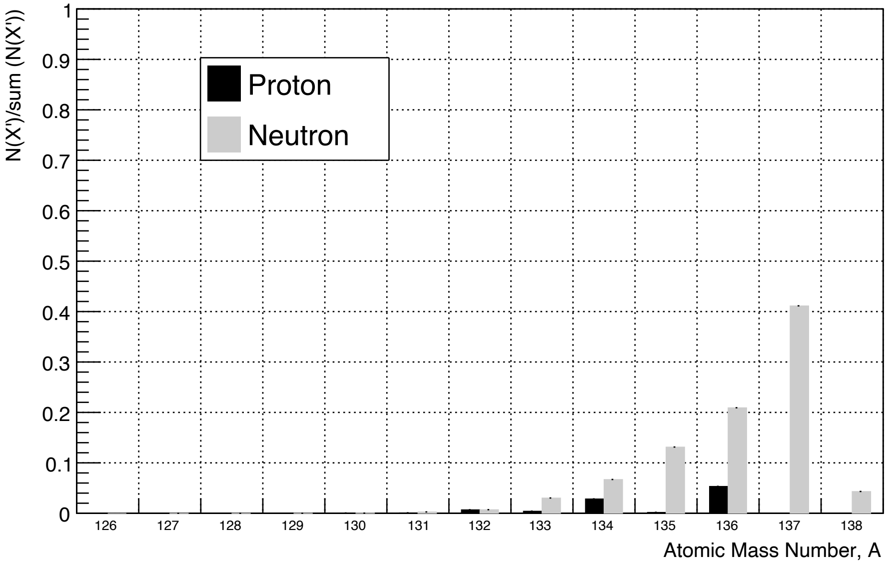
Enrichment: ^{136}Ba (95.27%), ^{135}Ba (3.73%), ^{134}Ba(1.0%)



Highest population at A=135 is coming from ^{136}Ba(μ,1n) reaction.

^{Nat}Ba

Enrichment: ^{132}Ba(0.1%) , ^{134}Ba(2.42%), ^{135}Ba(6.59%), ^{136}Ba(7.85%), ^{137}Ba(11.23%), ^{138}Ba(71.70%)



Highest population at A=137 is coming from ^{138}Ba(μ,1n) reaction.

Expected gamma rays will be discussed in Faiznur's Talk.

Conclusion and Remarks

From PNEM, highest probability of 1 neutron emission is expected.
In previous 2019 campaign:

- only gamma associate with the 0 neutron emission for all ^{24}Mg, ^{82}Kr and ^{130}Xe.
- some gamma are unobservable due to stable and semi stable (half-life : few years)
- some gamma loss after beam stopped (half-life: second- minutes)

For PSI 2021 campaign, also many gamma are unobservable due to stable and semi stable. Our only hope is to find evidence of proton emission which halflife in few hours