Neutron detection simulations in low energy nuclear physics
- GEANT4+SCINFUL -

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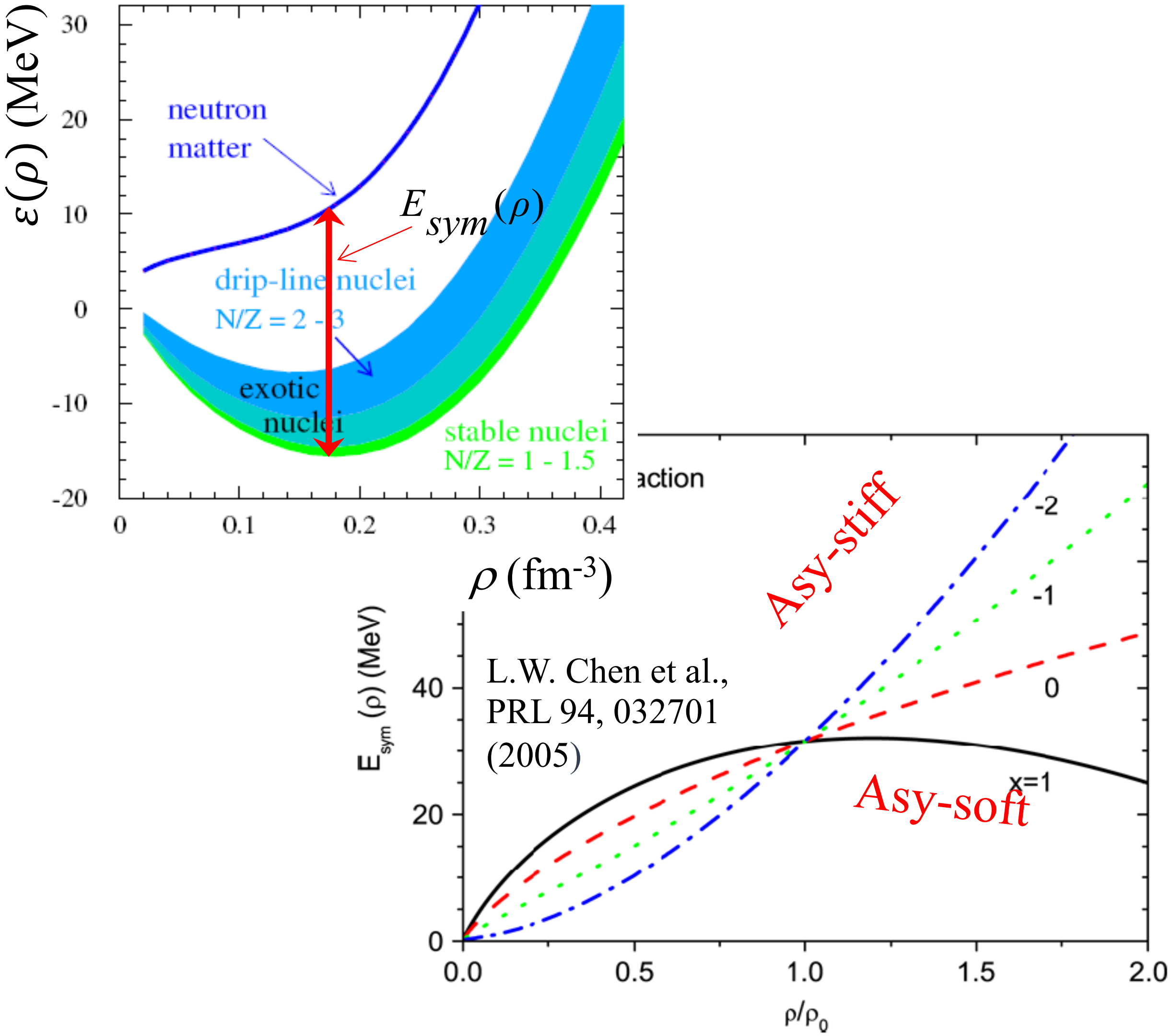
Equation of States and Symmetry Energy

- Equation of state :
  - $\varepsilon(\rho,\delta) = \varepsilon(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + \mathcal{O}(\delta^4)$
  - where $\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$, isospin asymmetry
- Symmetry energy, $E_{sym}(\rho)$, is energy difference between the pure neutron matter and isospin symmetric matter.
- Example: Binding energy of nuclear matter
  - $B(A,Z) = a_{vol}A - a_{sur}A^{2/3} - a_{Coul}\frac{Z(Z-1)}{A^{1/3}} - a_{sym}\frac{(N-Z)^2}{A} \pm \delta_{pair}$
  - $\varepsilon(\rho,\delta)A = Zm_p + Nm_n - B(A,Z)$

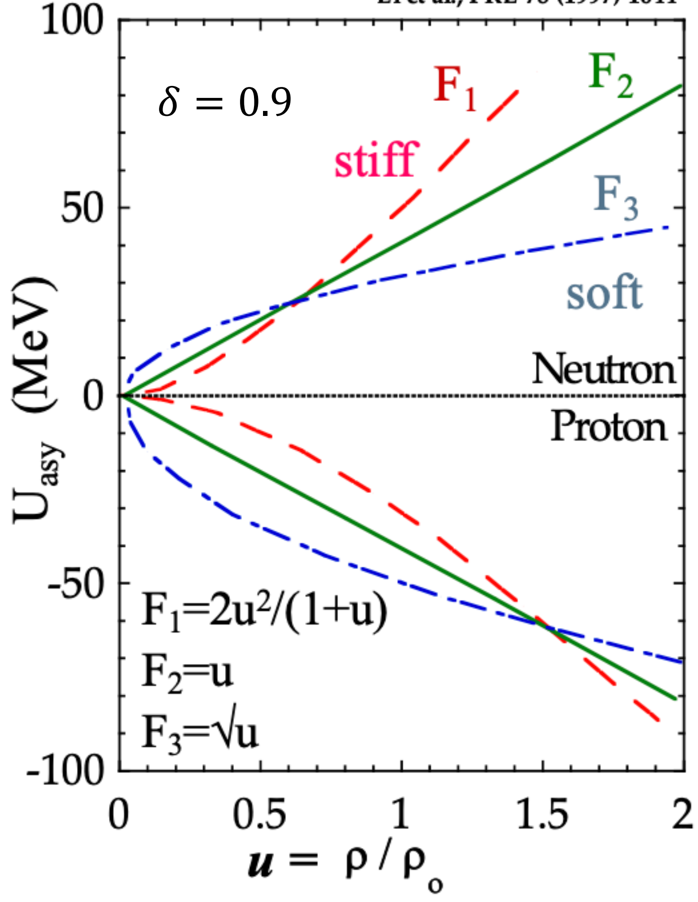


Equation of States and Symmetry Energy

$$\varepsilon(\rho,\delta) = \varepsilon(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + \mathcal{O}(\delta^4)$$

- Symmetry potential for neutron (proton) having repulsive (attractive) behavior with different forms of F_n.
- The opposite sign of the potential will affect differently the reaction dynamics of neutrons and protons.
- One of observables in heavy ion collision experiment to extract Symmetry energy is neutron to proton yield ratio.

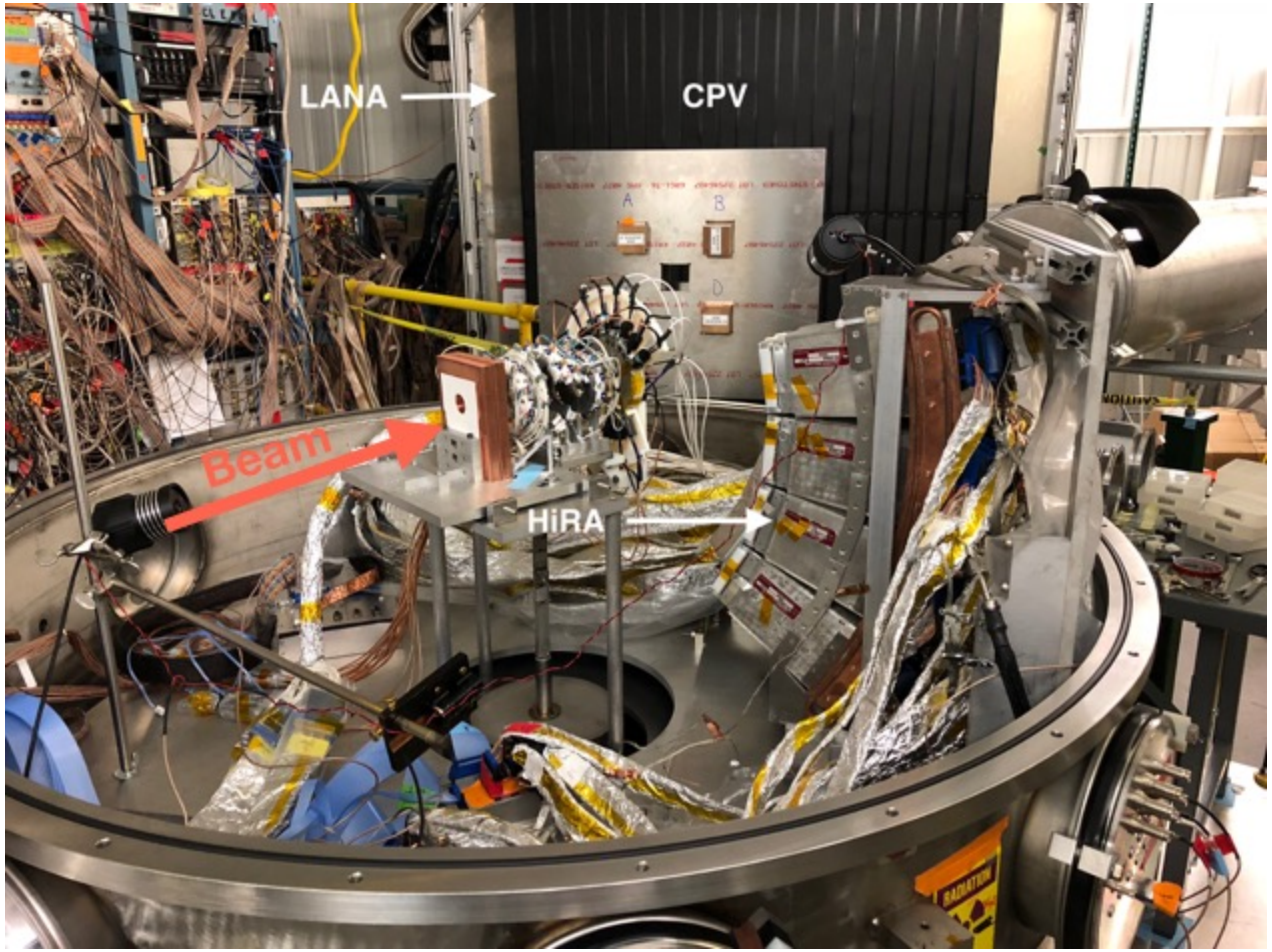
Li et al., PRL 78 (1997) 1644



Experimental overview

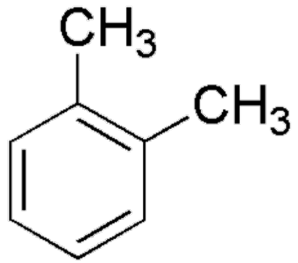
E14030 & E15190

- Feb 8 ~ Mar 25 @ NSCL for the study of EOS
- ^{40,48}Ca beam (56, 140 AMeV) and ^{58,64}Ni, ^{112,124}Sn target were used
- HiRA(High Resolution Array)
  - Charged particle detection
  - Well established detector (~100% eff)
- v+LANA(Large Area Neutron Array)
  - Veto wall to reject charged particle (New)
  - Liquid organic scintillator / NE213
  - 25 bars / 200 x 7.62 x 6.35 cm^3
  - Detection efficiency not yet determined



Neutron detectors

Principle of Neutron Detector



NE213 (Xylene)

- Neutron doesn't produce any light by itself. Light is produced from charged particles as a result of scattering of n from other nucleus.
- Organic scintillators consist mainly ^{1}H and ^{12}C.
- Main component of light is from elastic scattering of n from ^{1}H.
- Inelastic scattering of n from ^{12}C also produces charged ions (p, d, t, ^{3}He, ^{4}He) which produce light.
- Neutron detection efficiency is much lower than 100%. It is also not well established.
- Extracting neutron detection efficiency from simulation is the main focus of this talk.

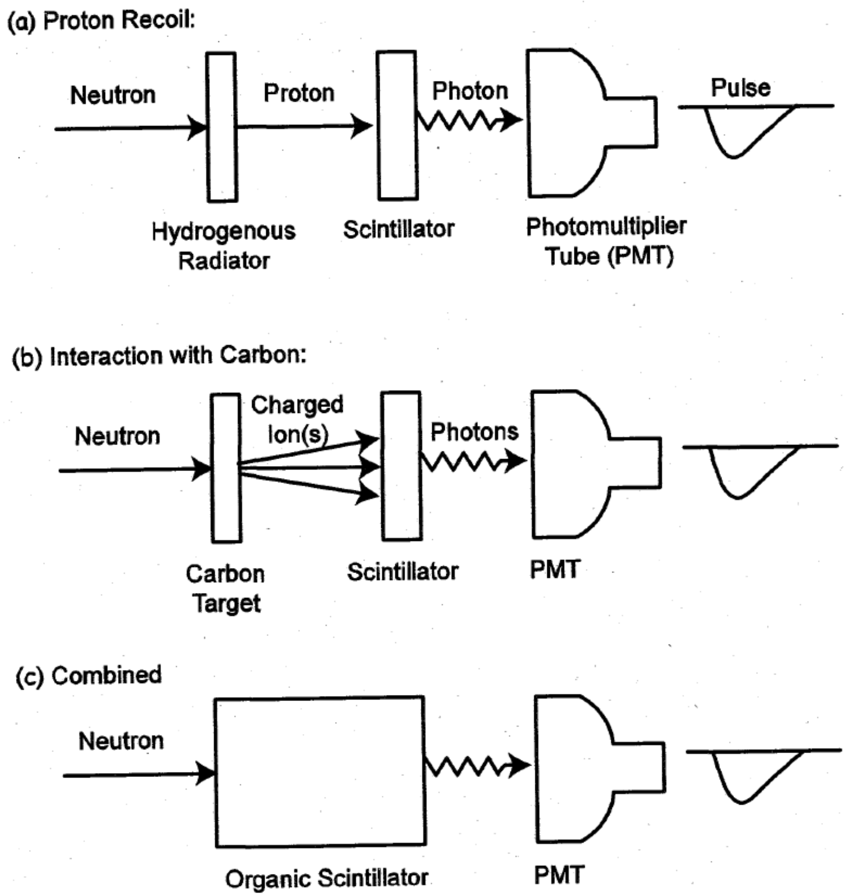


Figure 1. Schematic illustration of neutron detection. This figure is cited from Ref. 1

Neutron Simulations Codes

Neutron simulation lists

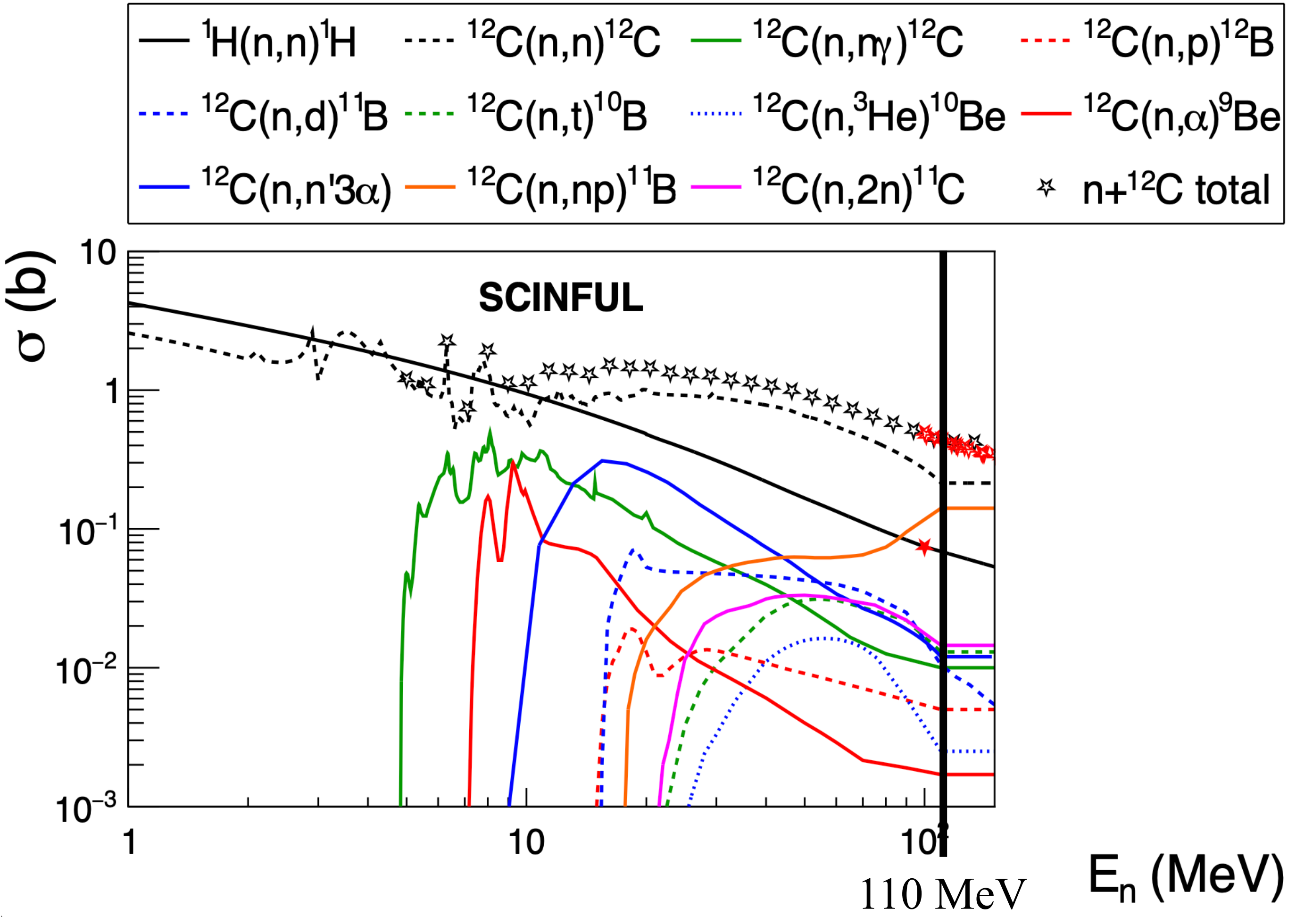
	SCINFUL	SCINFUL-QMD	PHITS (SCINFUL mode)	GEANT4 (SCINFUL mode)	MENATE_R
Elastic ^{1}H Elastic ^{12}C	Implemented	Implemented	Implemented	Implemented	Implemented
Inelastic ^{12}C	9 channels	9 channels	9 channels	9 channels	6 channels
Energy Validity	En < 110 MeV En < 80 MeV	En < 3 GeV En < 800 MeV	En < 3 GeV	En < 3 GeV	En < 150 MeV
Geometry	Cylinder fixed	Cylinder fixed	Flexible One PMT	Flexible Two or more PMTs.	Flexible Two or more PMTs.
Physics models	SCINFUL	SCINFUL JQMD	SCINFUL JQMD, INCL	SCINFUL JQMD, cascade models	MENATE_R

SCINFUL-QMD

Cross-section from n-induced reactions

- SCINFUL (up to 80 MeV / extended 150 MeV)
  - Total 11 initial channels + sequential decays
  - Elastic scattering
    - n + ^{1}H / n + ^{12}C
  - Inelastic scattering of n+^{12}C (9 channels)
  - Reaction cross-section (XS) up to 110 MeV.
    - Treats constant XS up to 150 MeV.
  - Possible sequential decays from the initial reaction channel

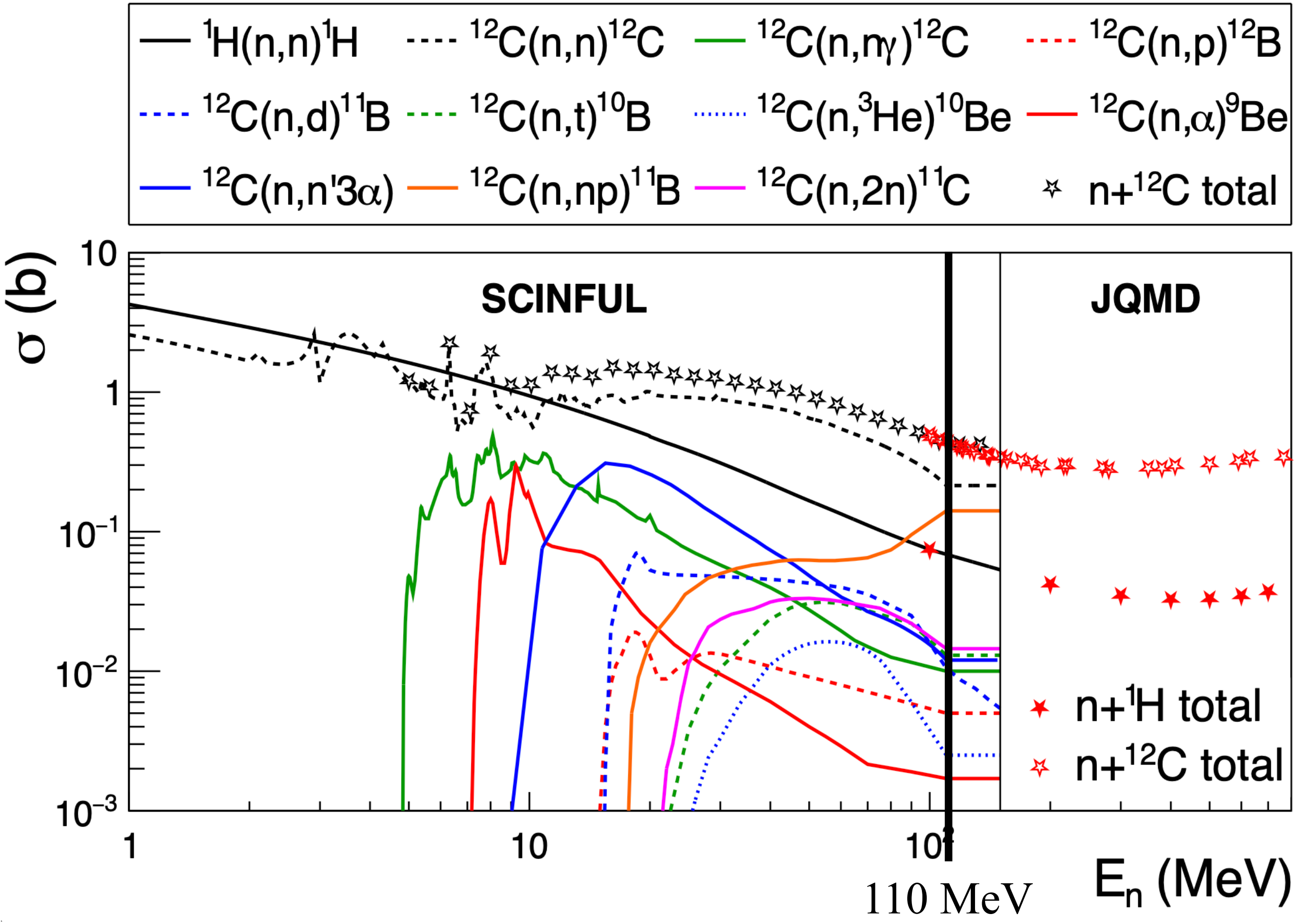
- n+^{12}C -> d+n'+^{10}B (example)
  - I. n+^{12}C -> ^{13}C (Compound)
  - II. ^{13}C -> d+$^{11}B^*$ (Excited / $^{12}C(n,X)$ channel)
  - III. $^{11}B^*$ -> n+^{10}B (Ground state) OR n+$^{10}B^*$
  - IV. $^{10}B^*$ -> γ+^{10}B (If possible) OR further decay



SCINFUL-QMD

Cross-section from n-induced reactions

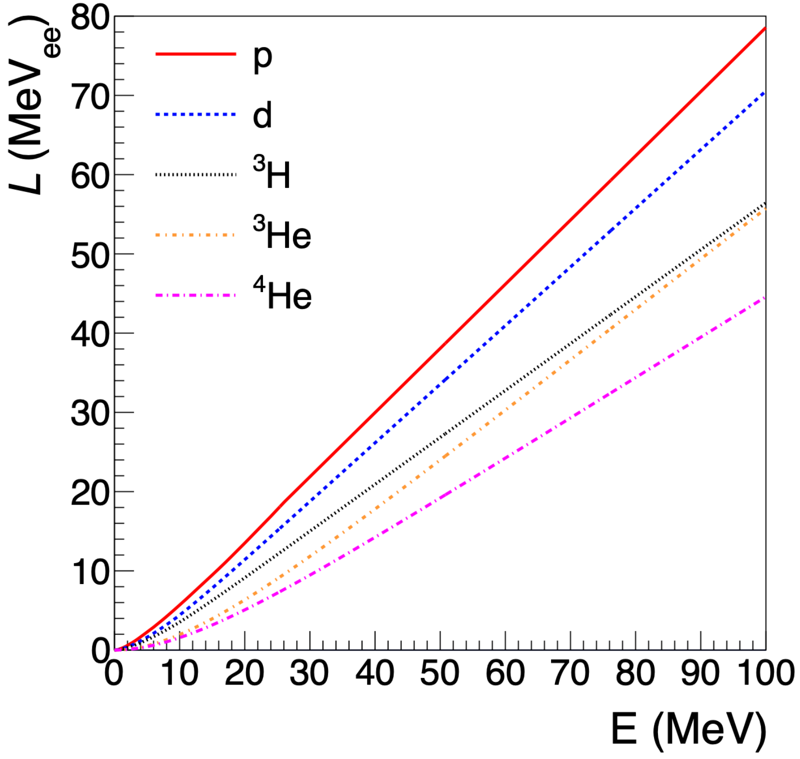
- JQMD (En > 150 MeV)
  - One of the Quantum Molecular Dynamics (QMD) developed by Japan Atomic Energy Research Institute (JAERI).
  - n + ^{1}H / n + ^{12}C
  - Reaction probability from 2 total cross-section.
  - QMD reaction stops at 100 fm/c.
  - After 100 fm/c, highly excited nucleus will decay to light ions (p, d, t, ^{3}He, ^{4}He) by Statistical Decay Model (SDM).

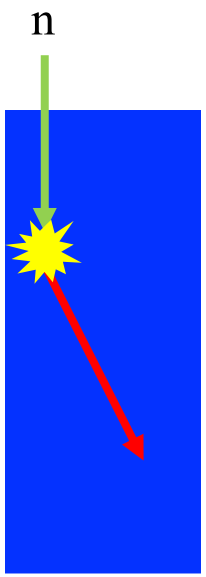


Light output function

Light output in NE213

- Charged particles traveling in the detector make different light outputs (MeV_{ee}) depending on the particle type.
- Light outputs for different particles can be described as a function of kinetic energy by the empirical formula described in SCINFUL-QMD.
  - Parameters fitted from experimental data.
  - The empirical formula is used in SCINFUL-QMD above the minimum energy for each particles. ($E_k > E_{min}$)
  - Below the minimal energy, SCINFUL-QMD converts kinetic energy to light output from the database by Verbinski data. ($E_k < E_{min}$)





$$L = a_1 E - a_2\{1.0 - \exp(-a_3 E)\},$$

Table 2. Coefficients in Equation (1) for proton, deuteron, triton, ^{3}He ion, and alpha particle with the minimum energy used in the equation.

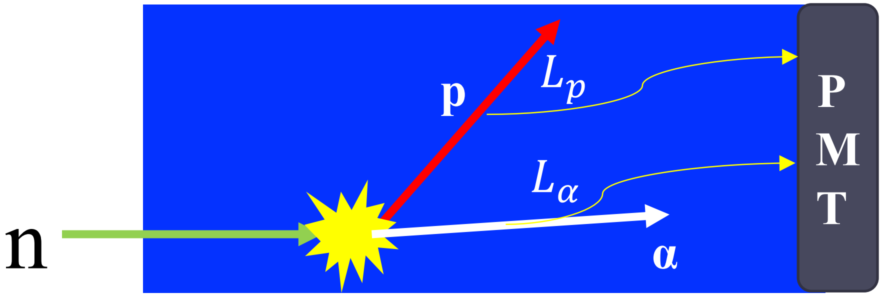
Particle	Coefficient a_1	Coefficient a_2	Coefficient a_3	Minimum energy (MeV)
Proton	0.81	2.43	0.29	25
Deuteron	0.74	3.45	0.20	10
Triton	0.72	7.19	0.07	10
^{3}He ion	0.54	3.97	0.20	5
Alpha particle	0.51	6.42	0.08	5

PHITS SCINFUL mode

doi : 10.1080/00223131.2021.2019622

Response function

Neutron response function of organic scintillator



neutron

Neutron incident (En > thresholds)

↓

Neutron reaction (SCINFUL or QMD)

↓

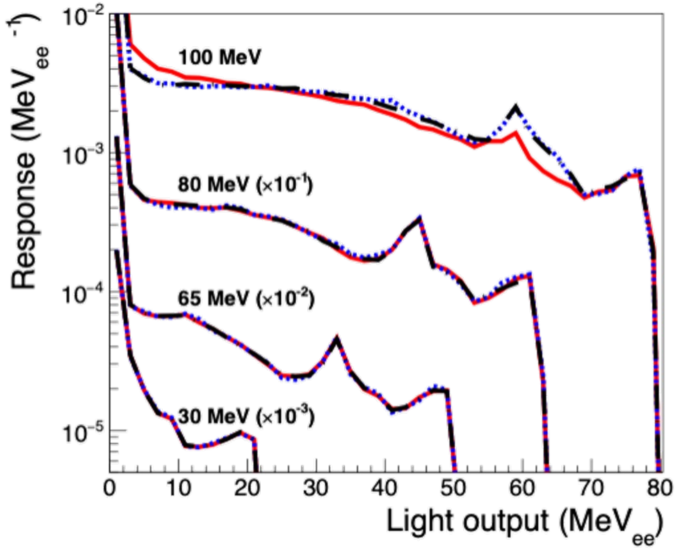
Are charged particles produced?

↓

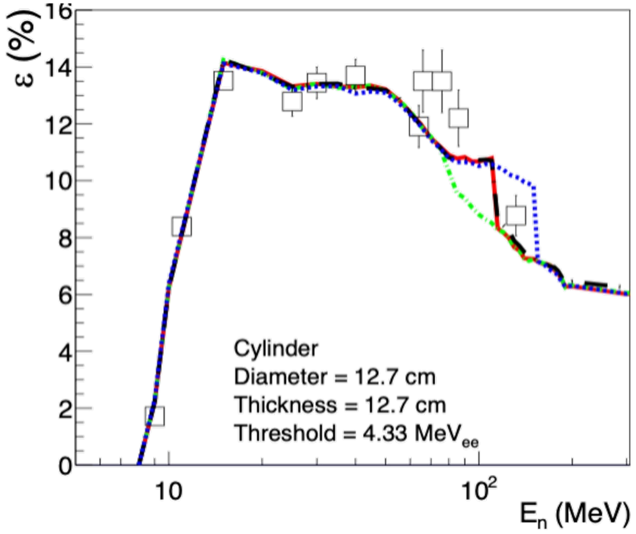
Convert to light from i th ion. (Total L = Total $L + L_i$)

↓

Construct response function and determine efficiency



Light output distribution of neutron En normalized by # of incident neutrons

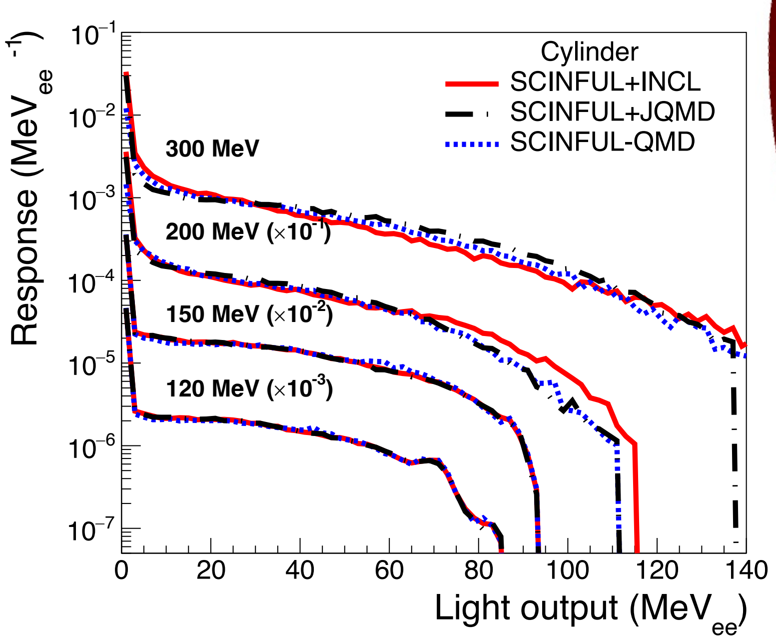


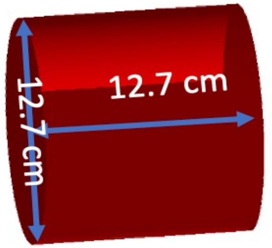
$$\varepsilon = \int_{L_{thr}}^{\infty} Response(L)\, dL$$

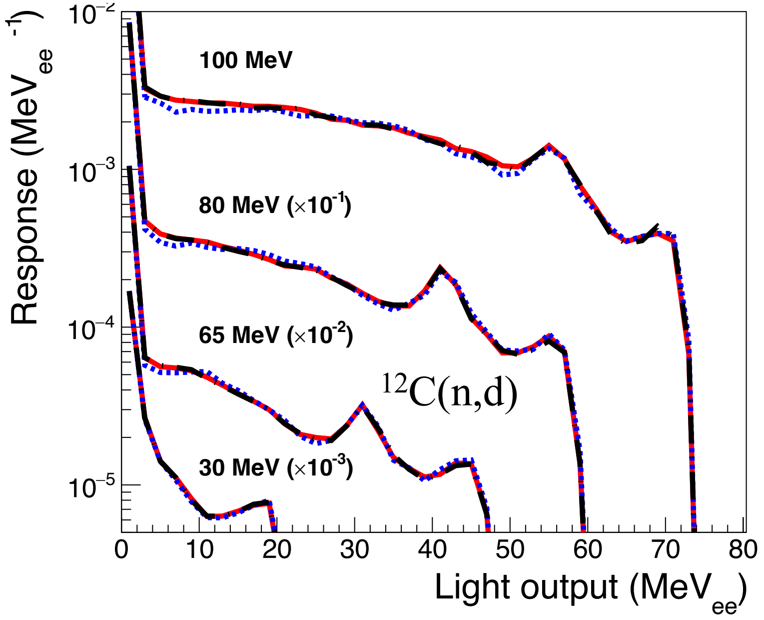
Response function

Cylindrical detector (SCINFUL-QMD)

- Response function is the light output distributions for the average neutron.
  - Light output distribution normalized by # of incident neutrons
  - Response functions for the same cylindrical geometry (Diameter : 12.7 cm & Thickness : 12.7 cm) using SCINFUL-GEANT4 are compared to each other.
- GEANT4 has another model, the Liège Intranuclear Casecade, INCL.
  - The results from INCL++ are also compared. (En > 150 MeV)
  - ~10^2 times faster than QMD.

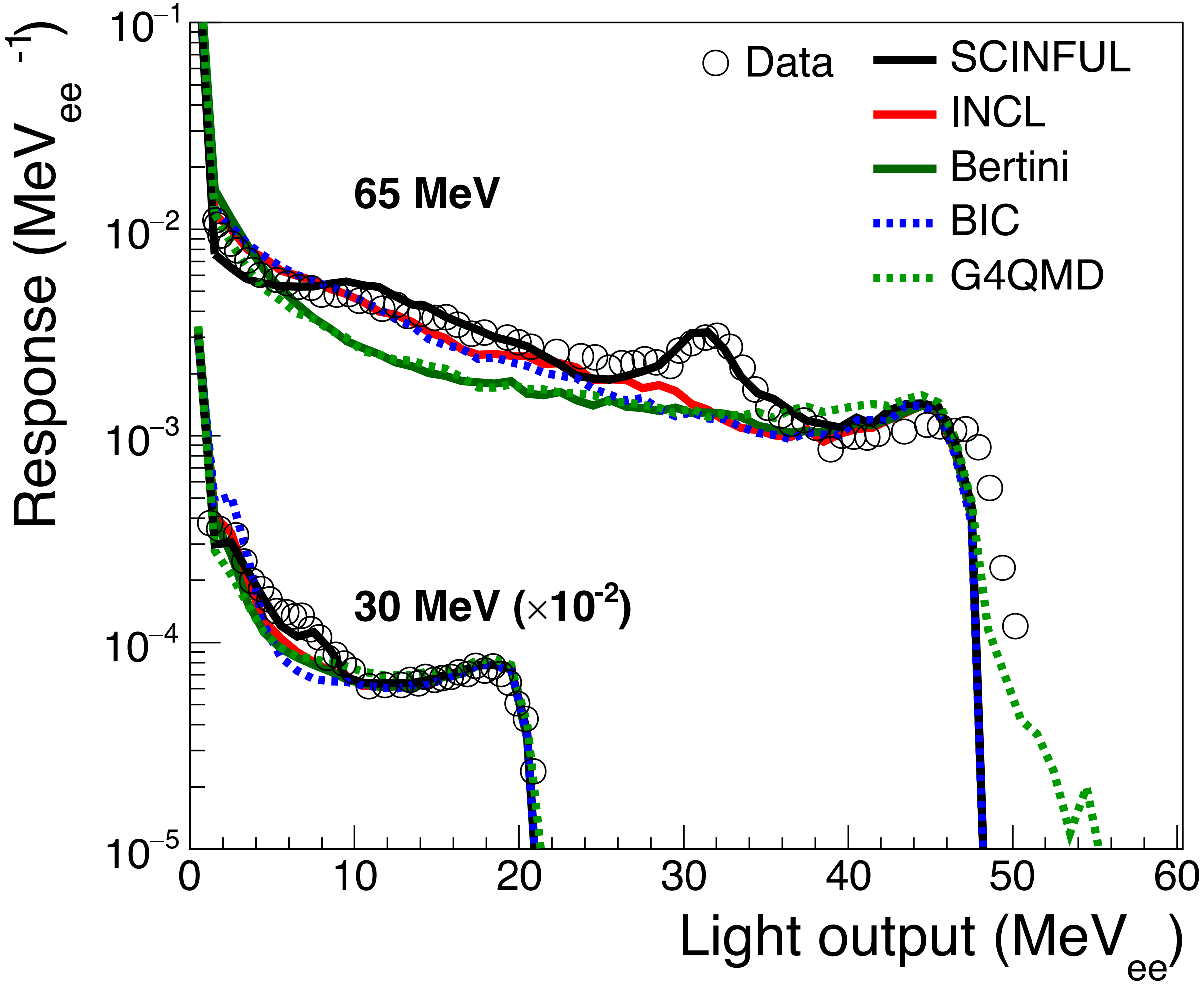


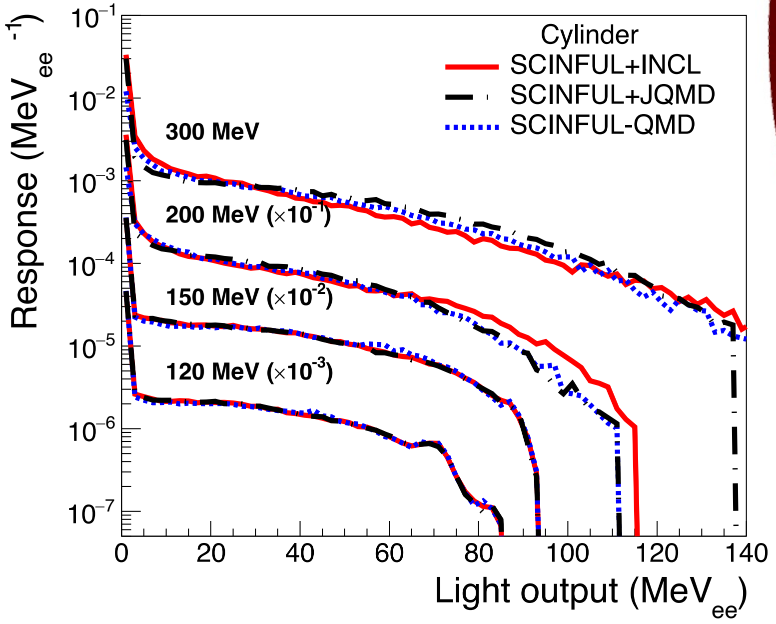


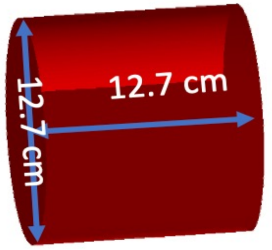


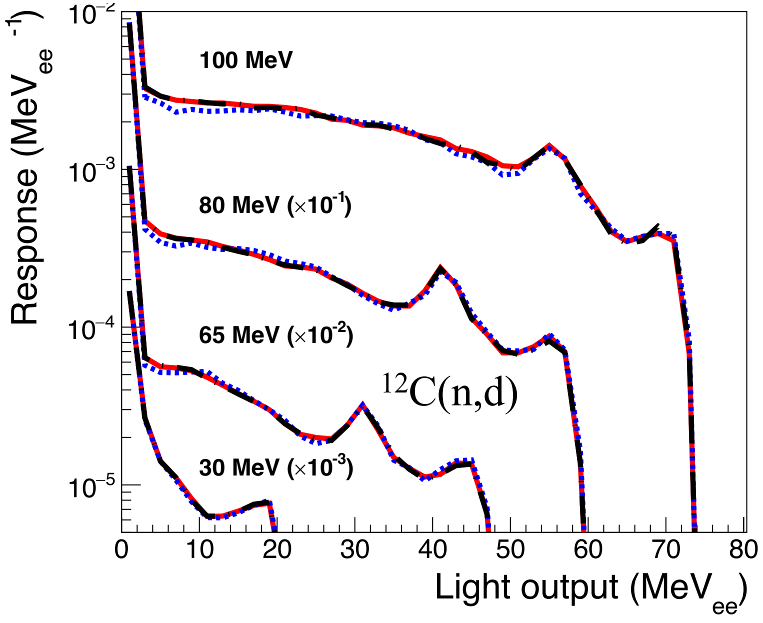
Response function

Cylindrical detector (SCINFUL-QMD)







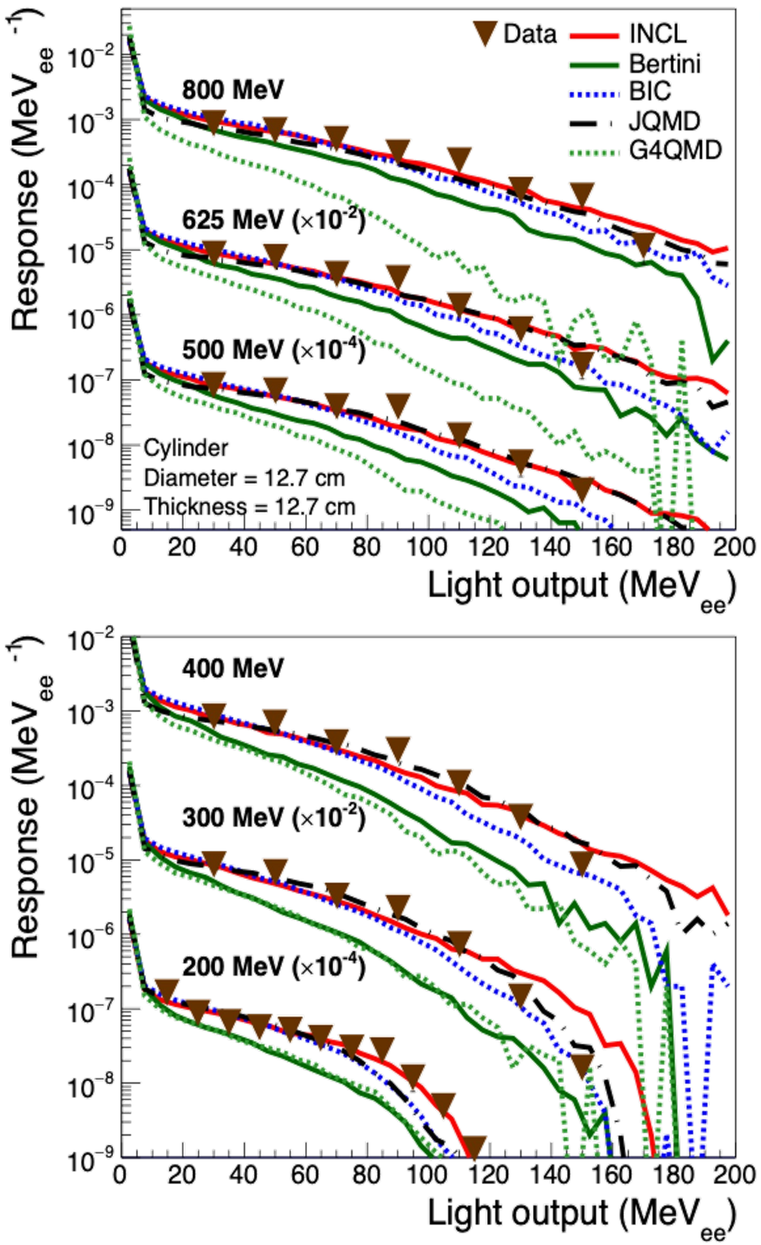


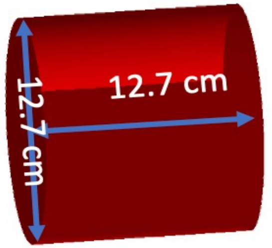
Response function

Cylindrical detector / Compare to experimental data

- Comparison between experimental data and simulation using different physics model options in GEANT4 for the cylindrical detector.
  - Diameter : 12.7 cm
  - Thickness : 12.7 cm

- The experimental data taken from
  - doi.org/10.1080/18811248.2006.9711153
- SCINFUL-GEANT4 results
  - INCL seems much closer to JQMD and better agreement at En = 200 MeV.
  - Poor agreements for Bertini, BIC, G4QMD.
  - INCL (Bertini and BIC) : ~10^2 times faster than QMD

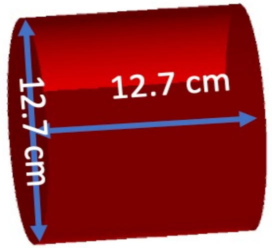


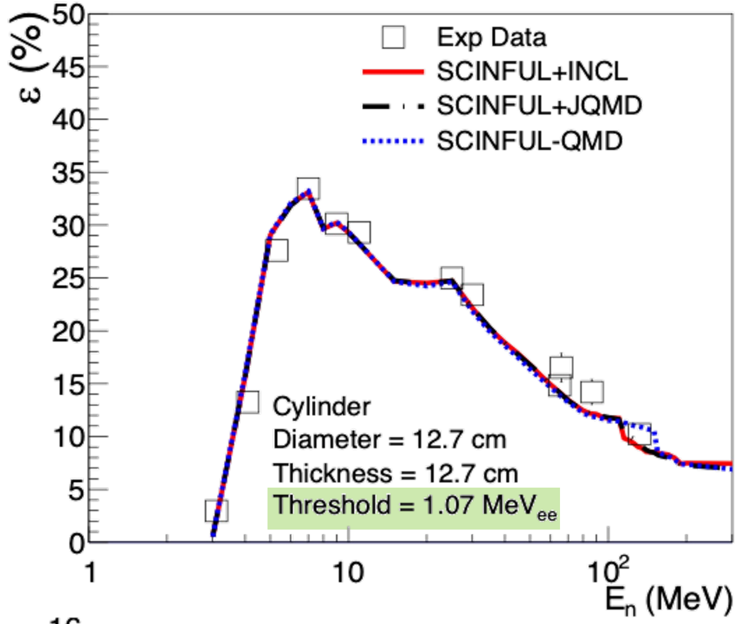


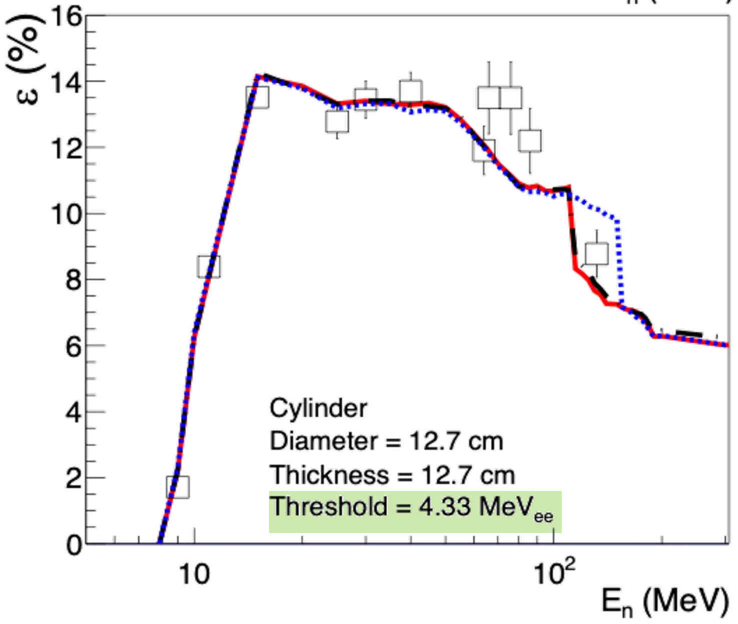
Detection efficiency

Cylindrical detector / Compare to experimental data

- The detection efficiency comparison between experimental data and SCINFUL-GEANT4 for the cylindrical detector.
  - Diameter : 12.7 cm
  - Thickness : 12.7 cm
  - Threshold : 1.07 (top), 4.33 MeV_{ee} (bottom)
- A jump at 150 MeV of SCINFUL-QMD → switching model from SCINFUL to JQMD at 150 MeV.
- The experimental data taken from
  - doi.org/10.1080/00223131.2021.2019622

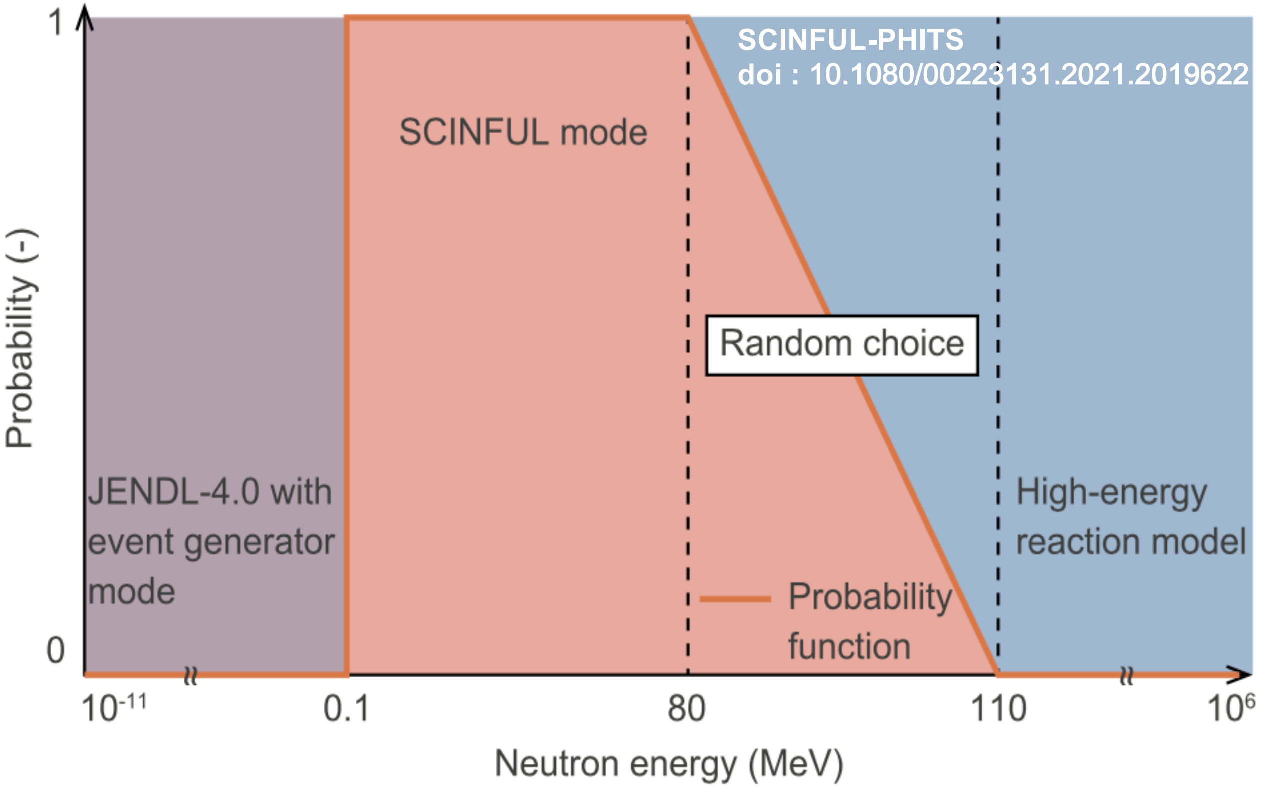






SCINFUL-QMD

Cross-section



- Inelastic scattering of n+^{12}C (9 channels)
- Total 11 initial channels + sequential decays
- Cross-section up to 110 MeV.

n+^{12}C -> p+n'+^{11}B (example)

I. n+^{12}C -> ^{13}C (Compound)
II. ^{13}C -> p+^{12}B* (Excited / ^{12}C(n,X) channel)
III. ^{12}B* -> n+^{11}B (Ground state) OR n+11B*
IV. ^{11}B* -> γ+^{11}B (If possible)

En > 150 MeV (JQMD)

- n + ^{1}H / n + ^{12}C
- Total 2 channels + SDM (Statistical Decay Model)

SCINFUL-GEANT4 : mixture of models between 80 – 110 MeV

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Detection efficiency

Cylindrical detector / Compare to experimental data

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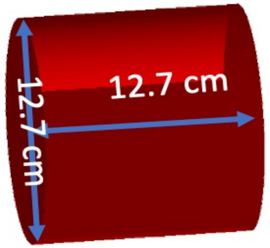
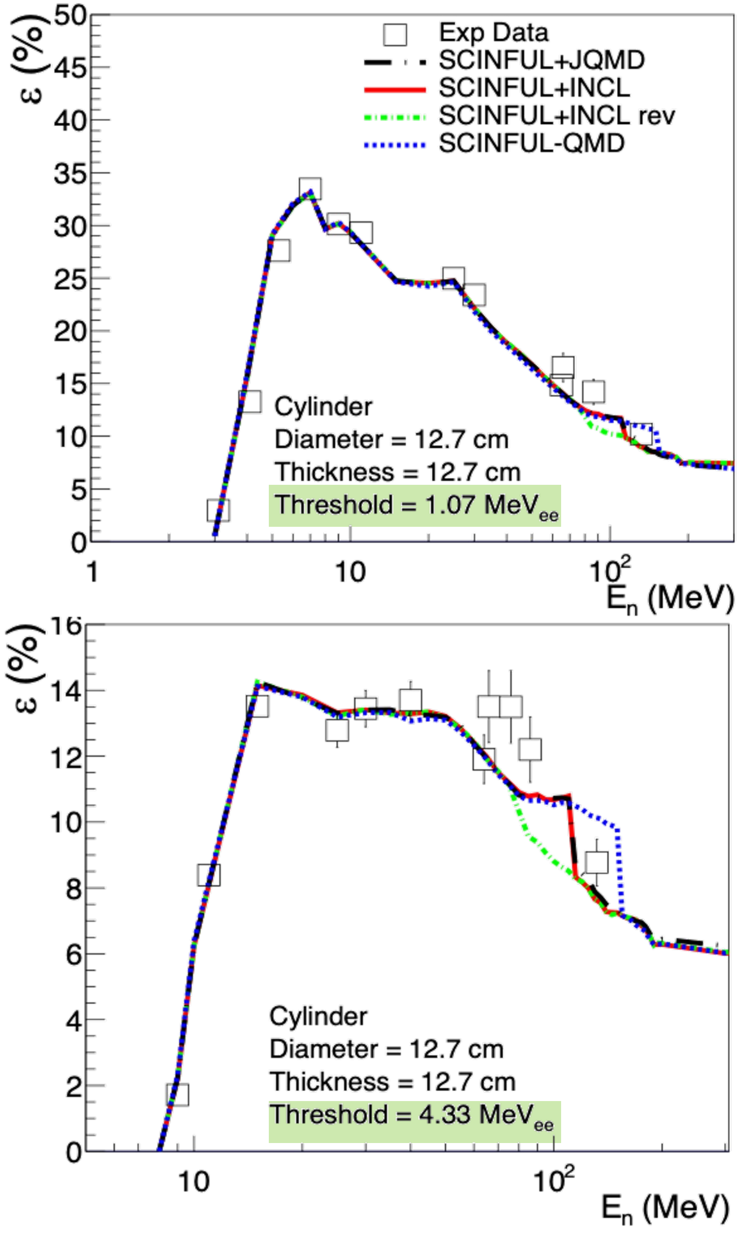
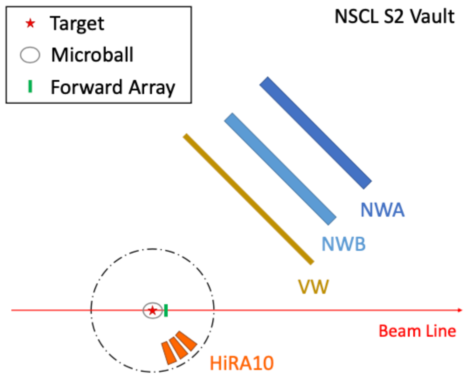
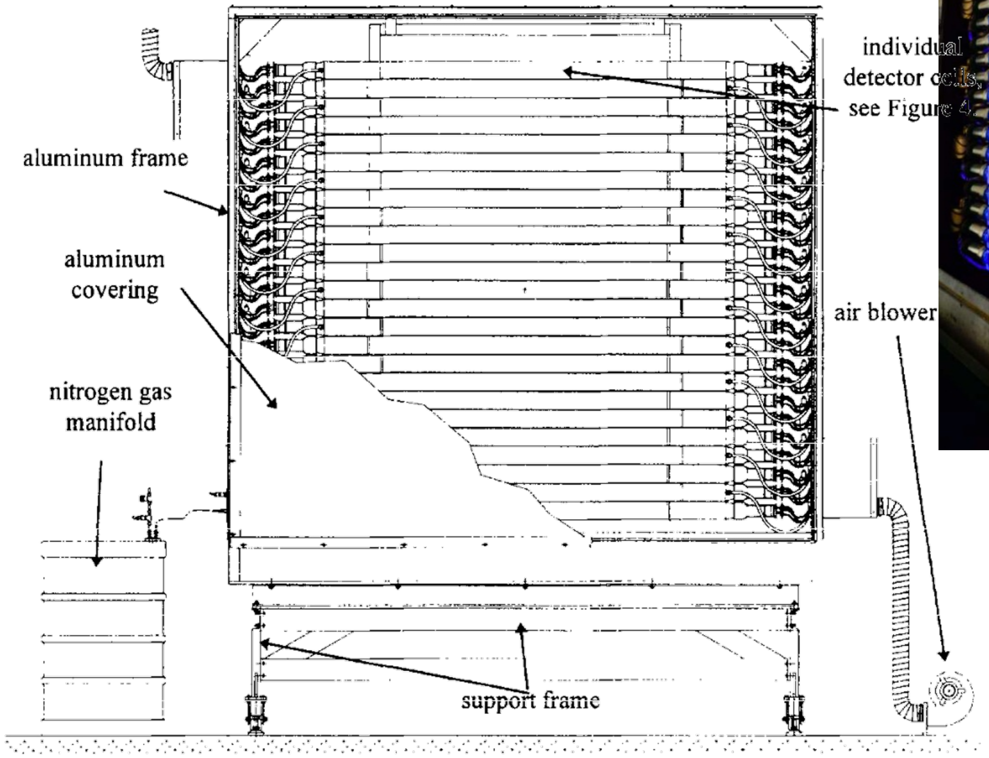




Large Area Neutron Array

- Large Area Neutron Array (LANA)
    - 2 walls / NWB (front), NWA (back)
    - NE213 liquid organic scintillator
    - 200 x 7.62 x 6.35 cm^3
    - 3 mm thick Pyrex container
    - 2 PMTs at the end of bar

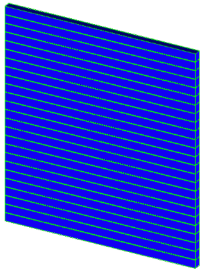


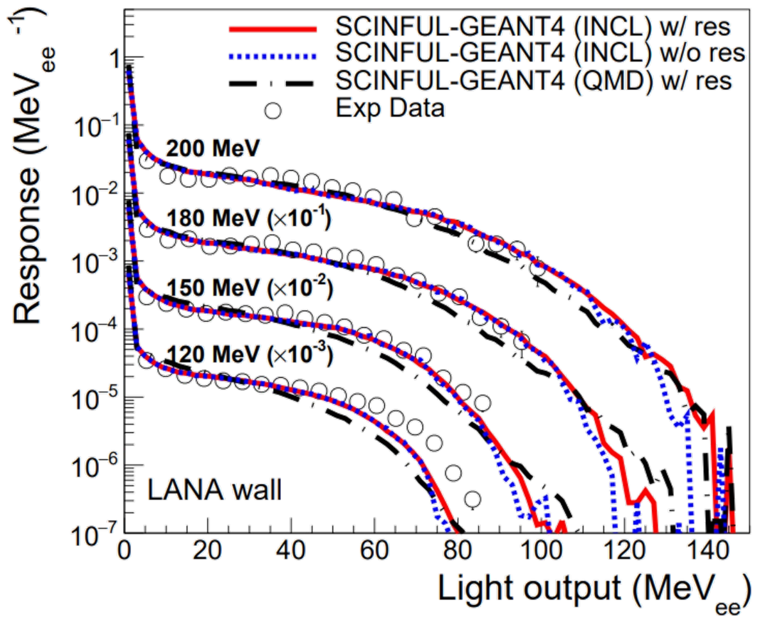


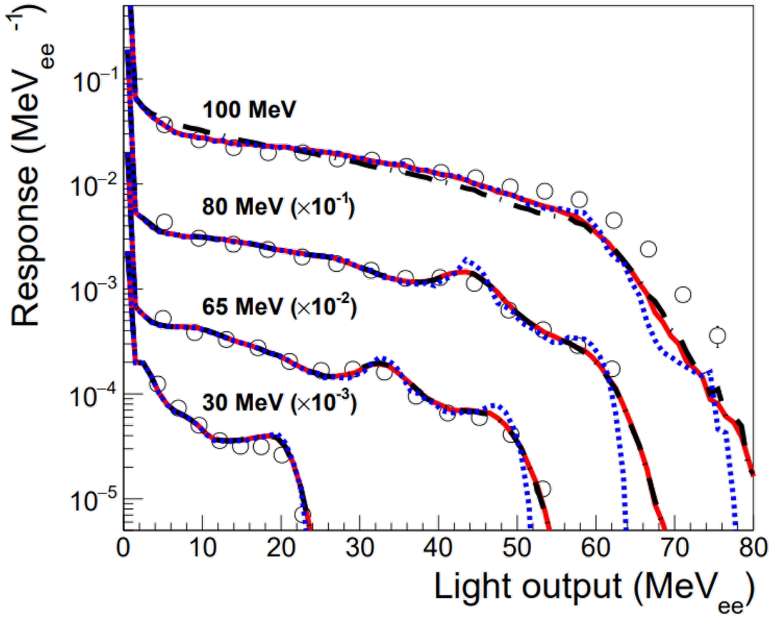
Response function

Large Area Neutron Array (LANA) / Compare to experimental data

- The comparison for the response functions from experimental data and the simulations for LANA detector configurations.
  - No experimental efficiency determinations only the shape of the response functions.
  - Normalized by integration from 3 MeVee to infinity.
  - The results from SCINFUL-GEANT4 has been folded by resolution formula,
    - $\frac{dL}{L} = \sqrt{A^2 + \frac{B^2}{L} + \frac{C^2}{L^2}}$ FWHM
    - A = 0.17, B = 0.15, C = 0.02
    - Mainly affect the high energy tails.





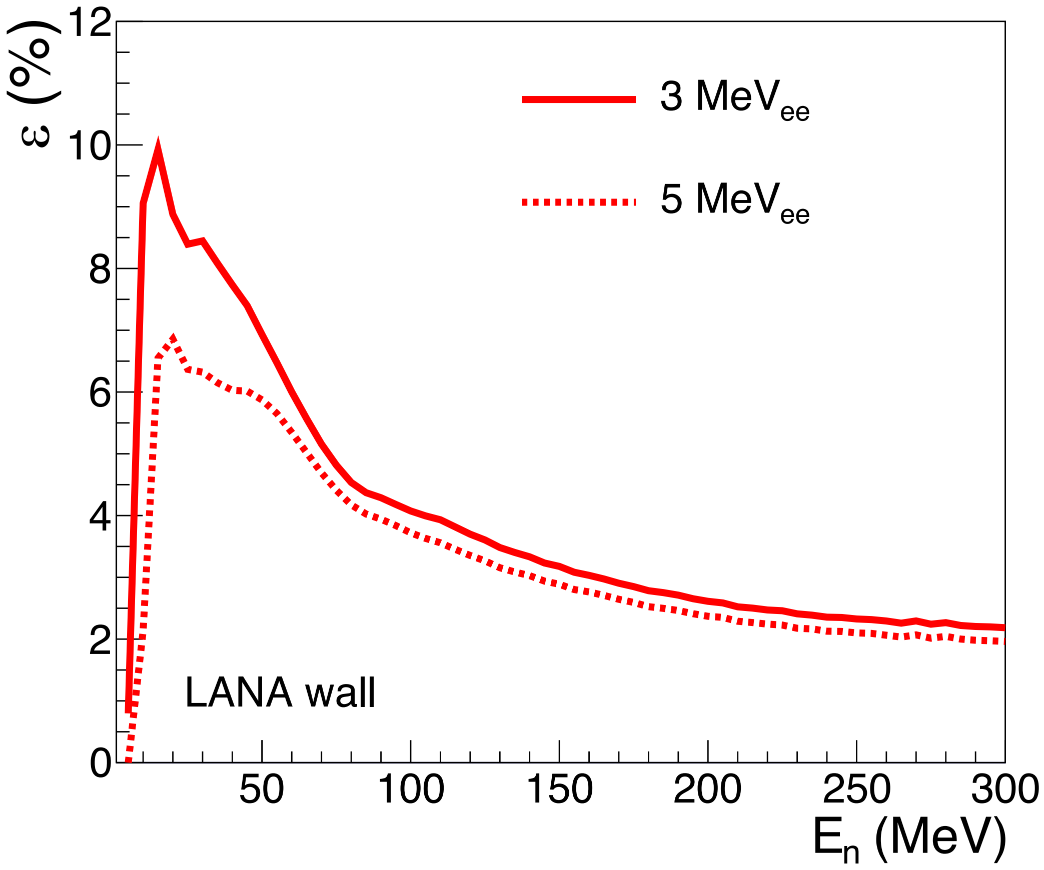


Detection efficiency

LANA

- Detection efficiency of LANA calculated by SCINFUL-GEANT4
  - SCINFUL / En < 110 MeV
  - INCL / En > 80 MeV

- Absence of data points because of uncertainty for the number of incident neutrons i.e. no efficiency data.

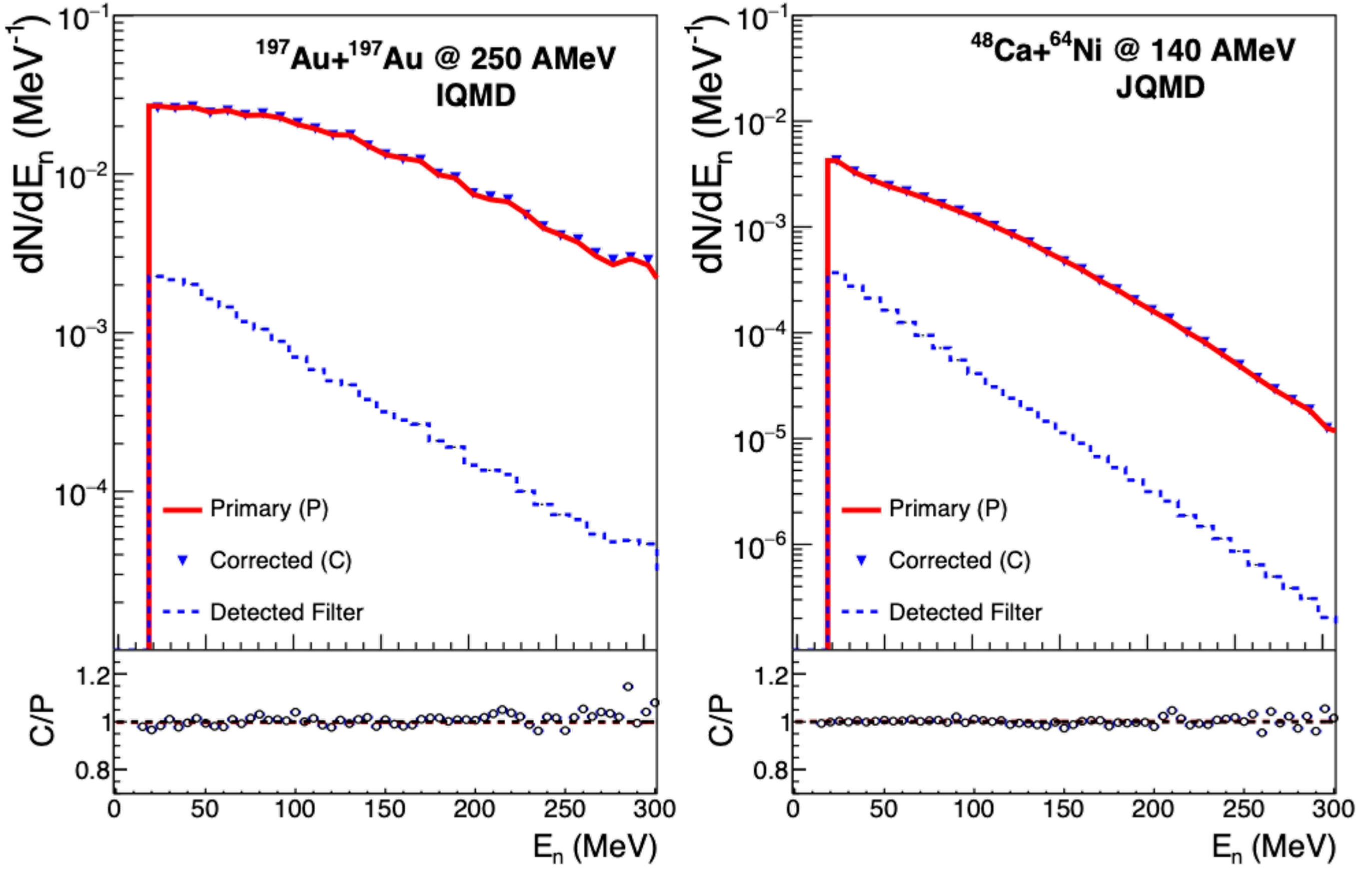


Event Generator mode

Two event generators: IQMD and JQMD

- To validate SCINFUL-GEANT4, two event generators are poerformed in GEANT4.
  - ^{197}Au + ^{197}Au @ 250 AMeV / IQMD
    - High neutron multiplicity
  - ^{48}Ca + ^{64}Ni @ 140 AMeV / JQMD
    - Experiment system

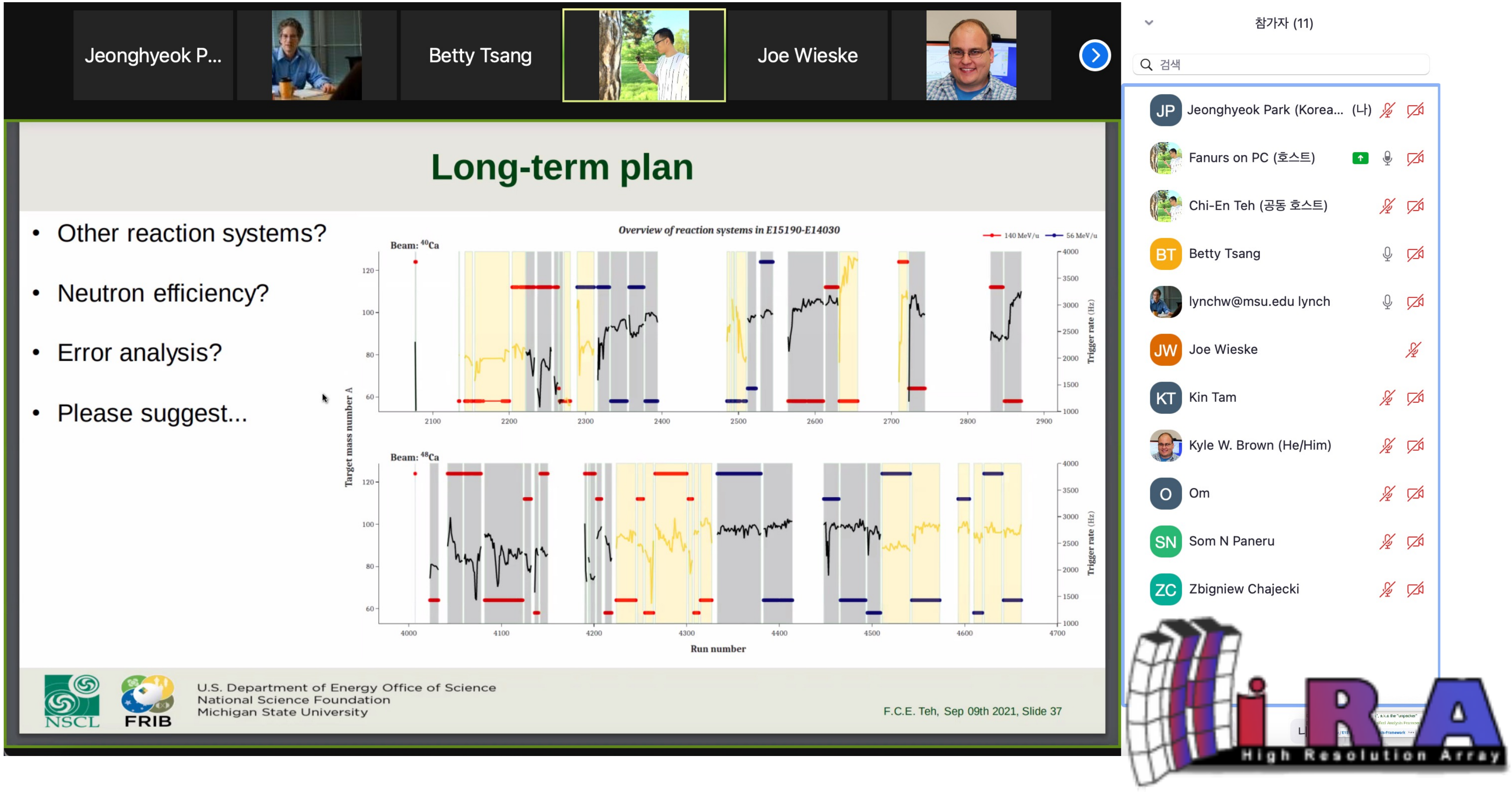
  - Primary : neutrons from event generators in LANA coverage
  - Detected : neutrons interacted with LANA
  - Corrected : Detected / efficiency



Summary

- A new simulation code, SCINFUL-GEANT4, has been developed to simulate neutron detection efficiency. We adopt:
  - Cross-section of SCINFUL / JQMD
  - Physics model of SCINFUL / JQMD
- GEANT4 can offer other cascade models, BIC, Bertini, INCL for the high energy of neutron reaction.
  - ~100 times faster than JQMD.
  - INCL model is the best option among the cascade models.
- SCINFUL-GEANT4 was compared to SCINFUL-QMD and experimental data.
  - Perfect agreements with SCINFUL model (En < 80 MeV).
  - Good agreements with INCL model (En > 100 MeV).
- Estimated neutron detection efficiency of LANA.
  - 10 % ~ 20 MeV / 2 % ~ 300 MeV.
- Physics Event Generator was performed to validate the simulation.
- Future: Apply neutron detection efficiency of LANA to neutron spectra → n/p ratios → symmetry energy constraints

Acknowledgement

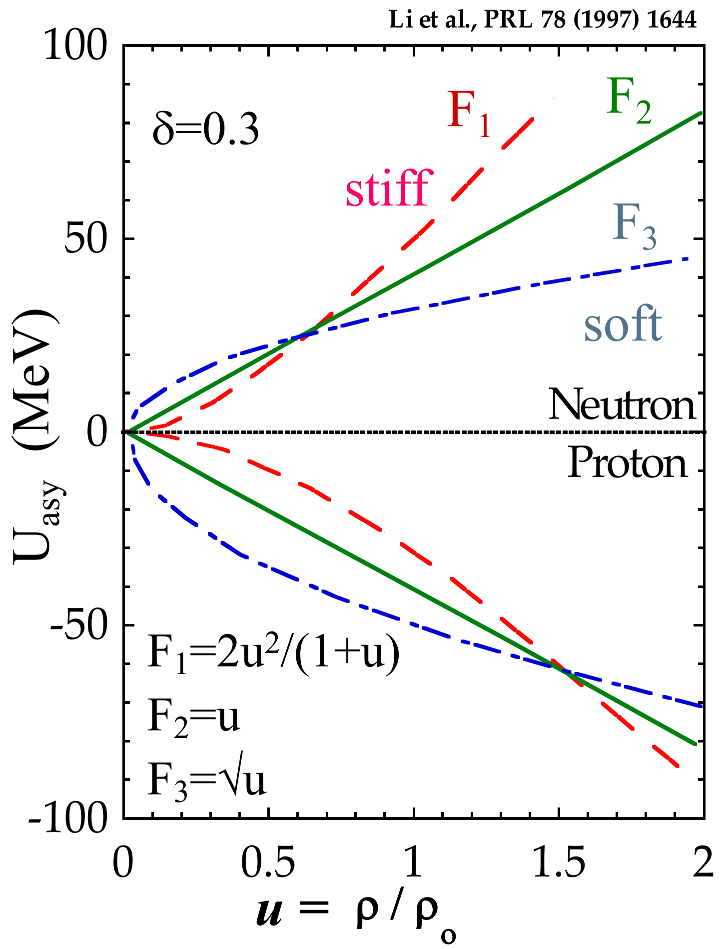


backups?

Probing the symmetry energy by nuclear collisions

$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)\ ;\ \ \delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$

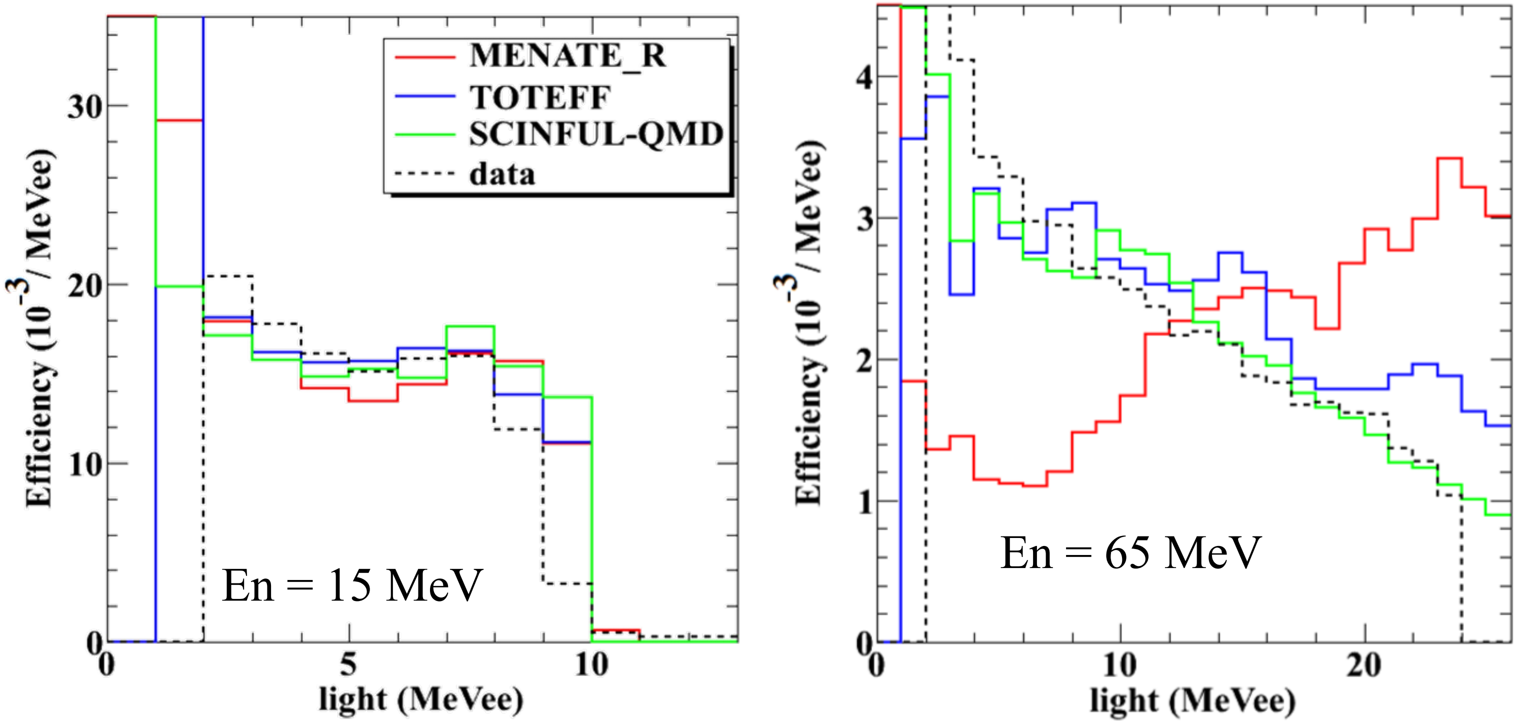
- To maximize sensitivity, reduc e systematic errors:
  - Vary isospin of detected particle
  - Vary isospin asymmetry δ=(N-Z)/A of reaction.
- Low densities ($\rho<\rho_0$):
  - Neutron/proton spectra and flow s
  - Isospin diffusion
- High densities ($\rho\approx2\rho_0$) :
  - Neutron/proton spectra and flow s
  - π^+ vs. π^- production



Neutron Simulation (SCINFUL-GEANT4)

Why SCINFUL?

- MENATE_R
  - Based on GEANT4
  - Advanced with geometry
- TOTEFF
  - Based on FORTRAN code
  - Negative efficiency above 100 MeV of neutron
- SCINFUL-QMD
  - Based on FORTRAN code
  - Limitation with geometry (cyl)
- SCINFUL-GEANT4
  - Incorporated SCINFUL-QMD
  - Flexible to change geometry

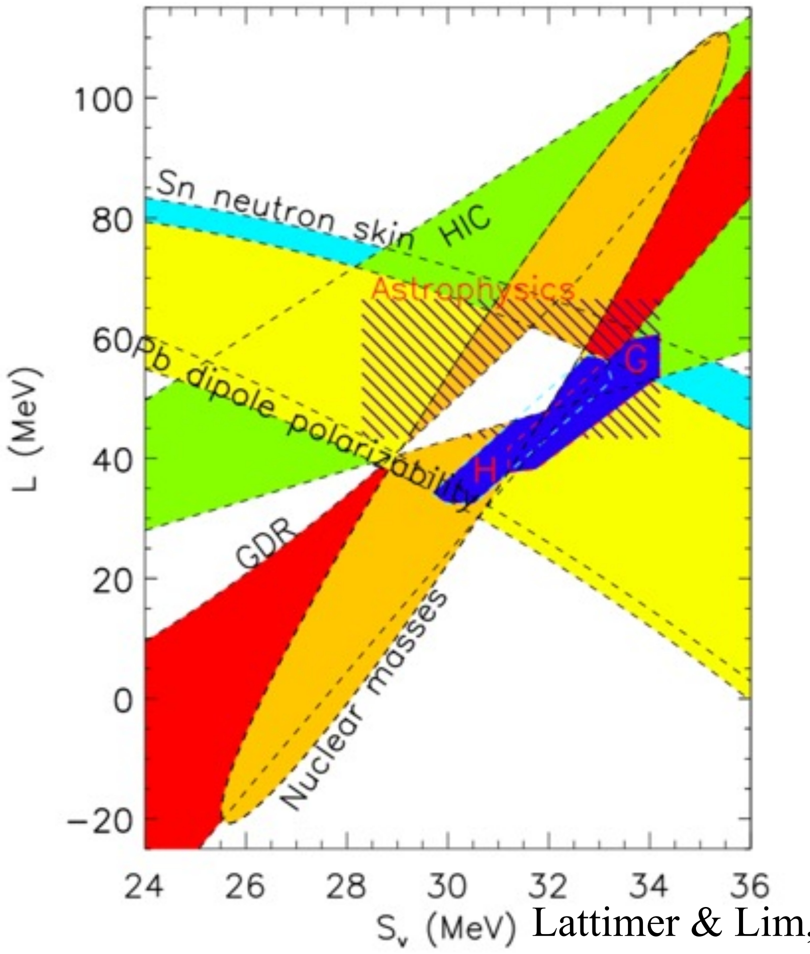


Light response function for different energy of neutron

D. Coupland thesis

Equation of States and Symmetry Energy

- Expansion of symmetry energy around the saturation density $\rho_0 \approx 0.16\ fm^{-3}$
  - $E_{sym}(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$
  - $L = \frac{3}{\rho_0} P_{sym} = 3\rho_0 \frac{\partial E_{sym}(\rho)}{\partial \rho}\Big|_{\rho=\rho_0}$ (slope)
  - $K_{sym} = 9{\rho_0}^2 \frac{\partial^2 E_{sym}(\rho)}{\partial \rho^2}\Big|_{\rho=\rho_0}$ (curvature)
- Constraints on symmetry energy slope parameter L and its magnitude S_0 from several experiments.
  - S_0 : 28 ~ 32 MeV
  - L : 40 ~ 60 MeV

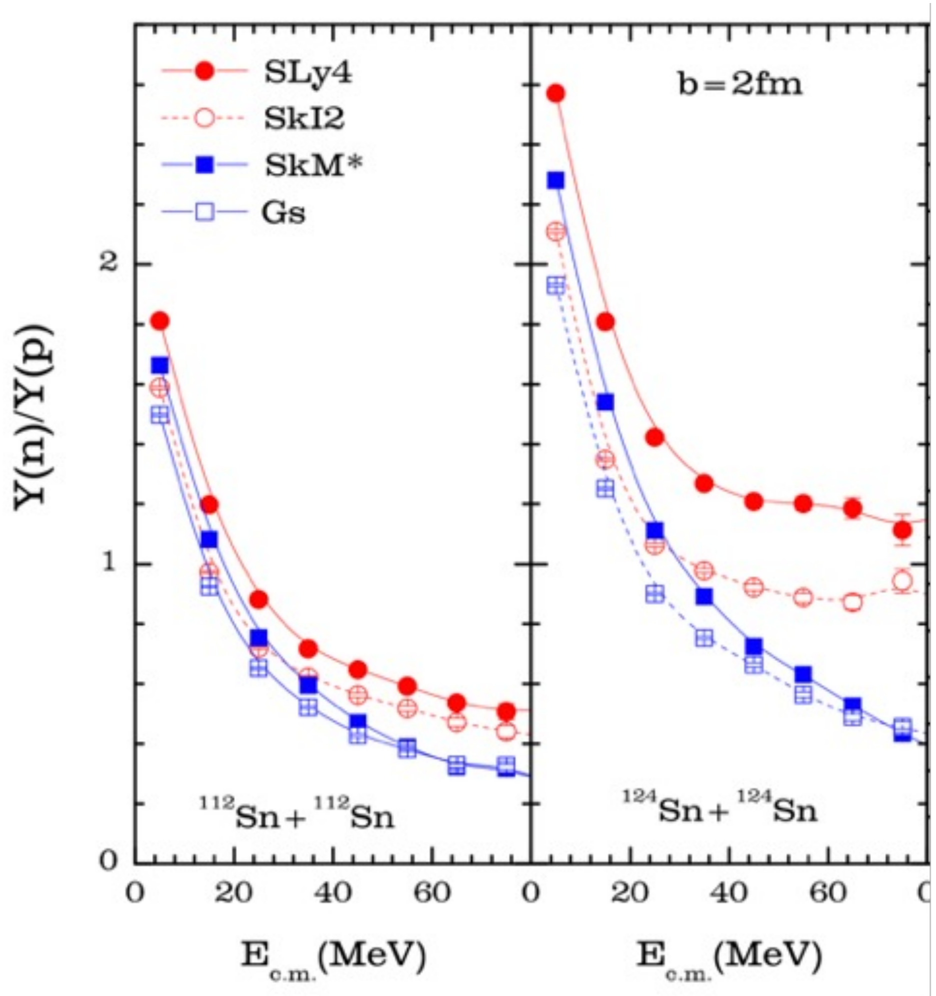


Lattimer & Lim, ApJ 771, 51 (2013)

Effective mass splitting

- In neutron-rich matter, many theories predict that the neutron and proton effective masses become different.
  - $m_n^* < m_p^*$ at SLy4
  - $m_n^* > m_p^*$ at SkM*
- Effective mass splitting strongly influences to the ratio of neutron over proton and other probes of the density dependence of symmetry energy.

Name	S_0 (MeV)	L (MeV)	m_n^*/m_n	m_p^*/m_p
SkM*	30	46	0.82	0.76
SLy4	32	46	0.68	0.71
Gs	31	93	0.81	0.76
SkI2	33	104	0.66	0.70



Y. Zhang, M. B. Tsang, Z.Li, and H. Liu / Phys. Lett. B 732, 186 (2014)

Neutron Simulations Codes

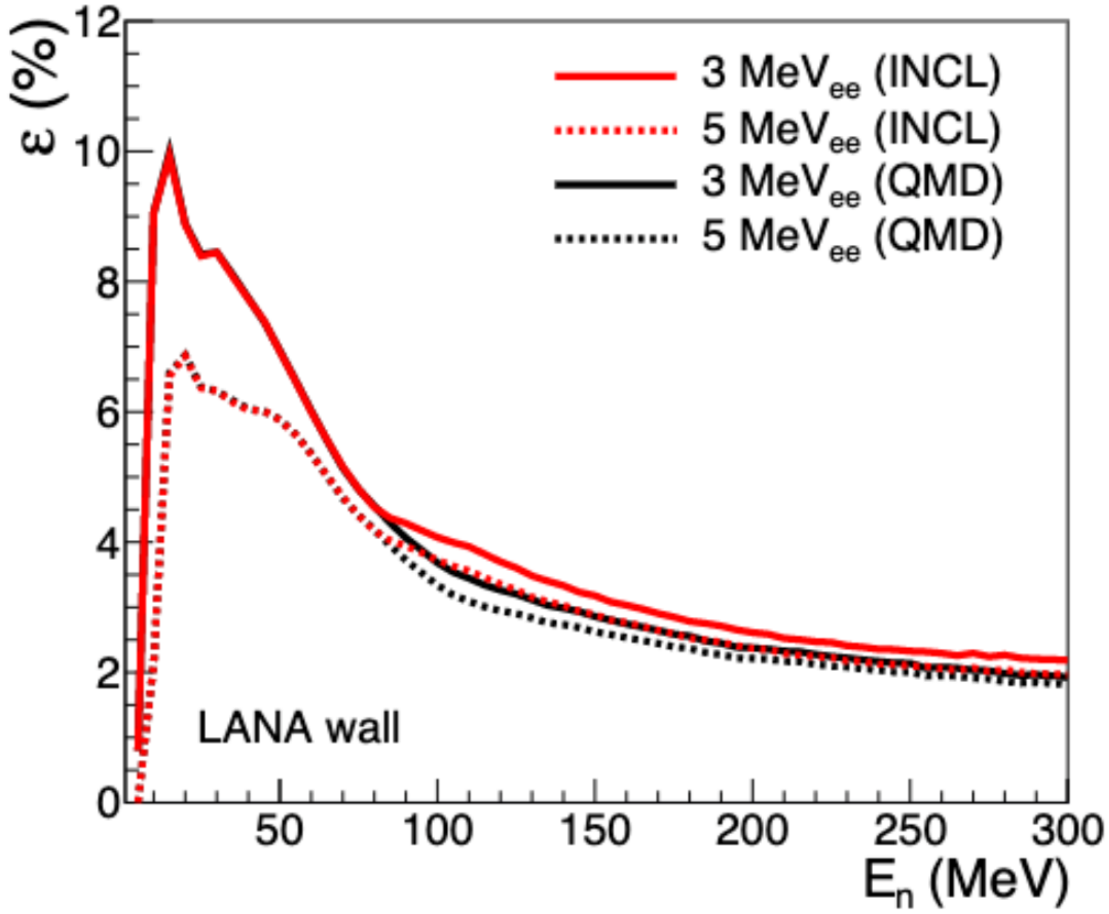
Neutron simulation lists

	SCINFUL	SCINFUL-QMD	PHITS (SCINFUL mode)	SCINFUL-GEANT4	MENATE_R
Elastic ^{1}H Elastic ^{12}C	O	O	O	O	O
Inelastic ^{12}C	9 channels	9 channels	9 channels	9 channels	6 channels
Energy Valid	En < 80 MeV	En < 3 GeV En < 800 MeV	En < 3 GeV	En < 3 GeV	En < 150 MeV
Geometry	Cylinder fixed	Cylinder fixed	Flexible One PMT	Flexible Two or more PMTs.	Flexible Two or more PMTs.
Physics models	SCINFUL	SCINFUL JQMD	SCINFUL JQMD, INCL	SCINFUL JQMD, INCL++, BIC	MENATE_R
Transition from low to high n energy	N/A	En = 150 (MeV)	80 < En < 110 (MeV)	80 < En < 110 (MeV)	N/A

Detection efficiency

LANA

- Detection efficiency of LANA calculated by SCINFUL-GEANT4
  - SCINFUL / En < 110 MeV
  - INCL / En > 80 MeV



- Absence of data points because of uncertainty for the number of incident neutrons i.e. no efficiency data.