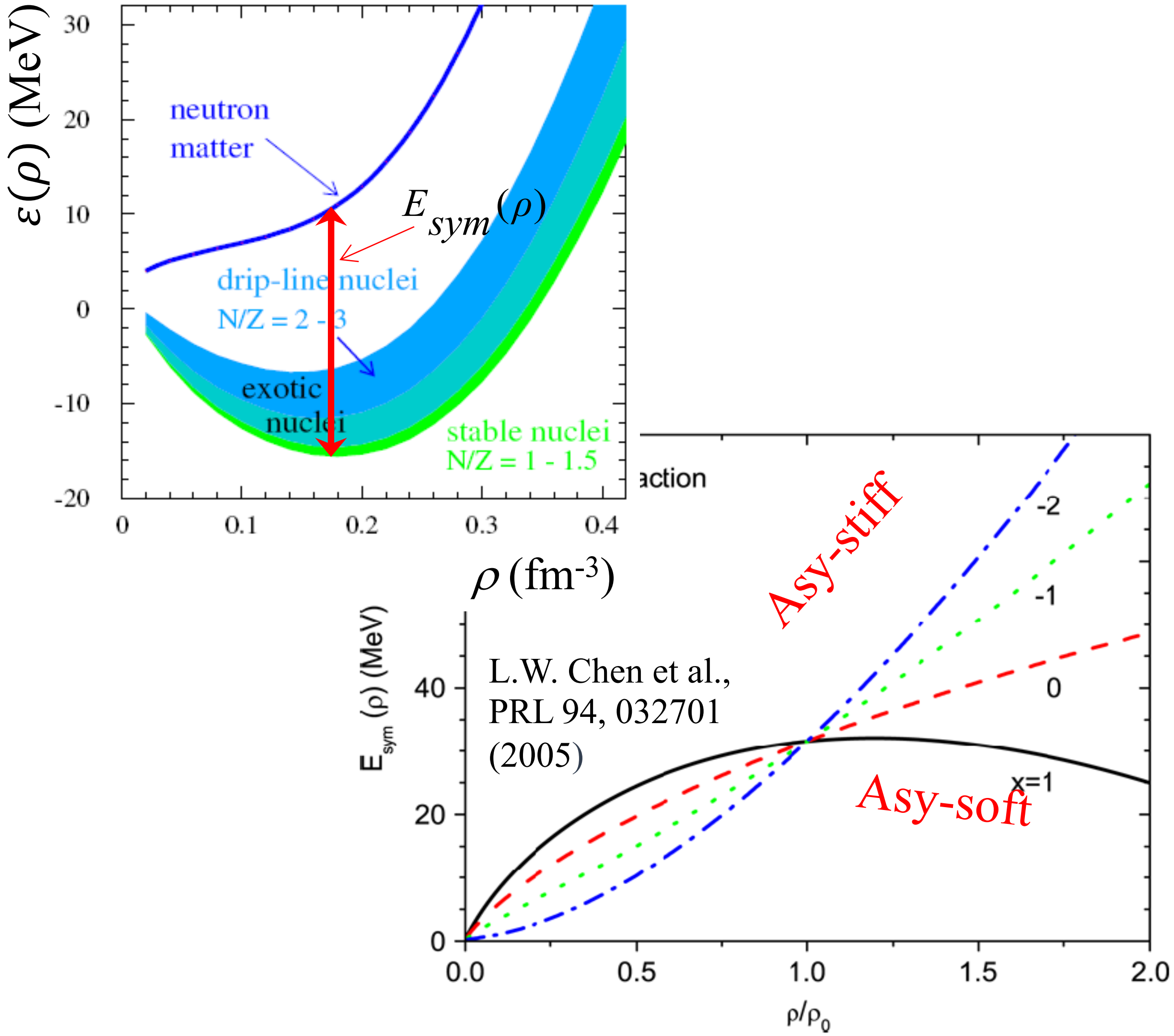
Overview of E14030 & E15190 at NSCL and Simulation

Jeonghyeok Park

Contents

Equation of States and Symmetry Energy

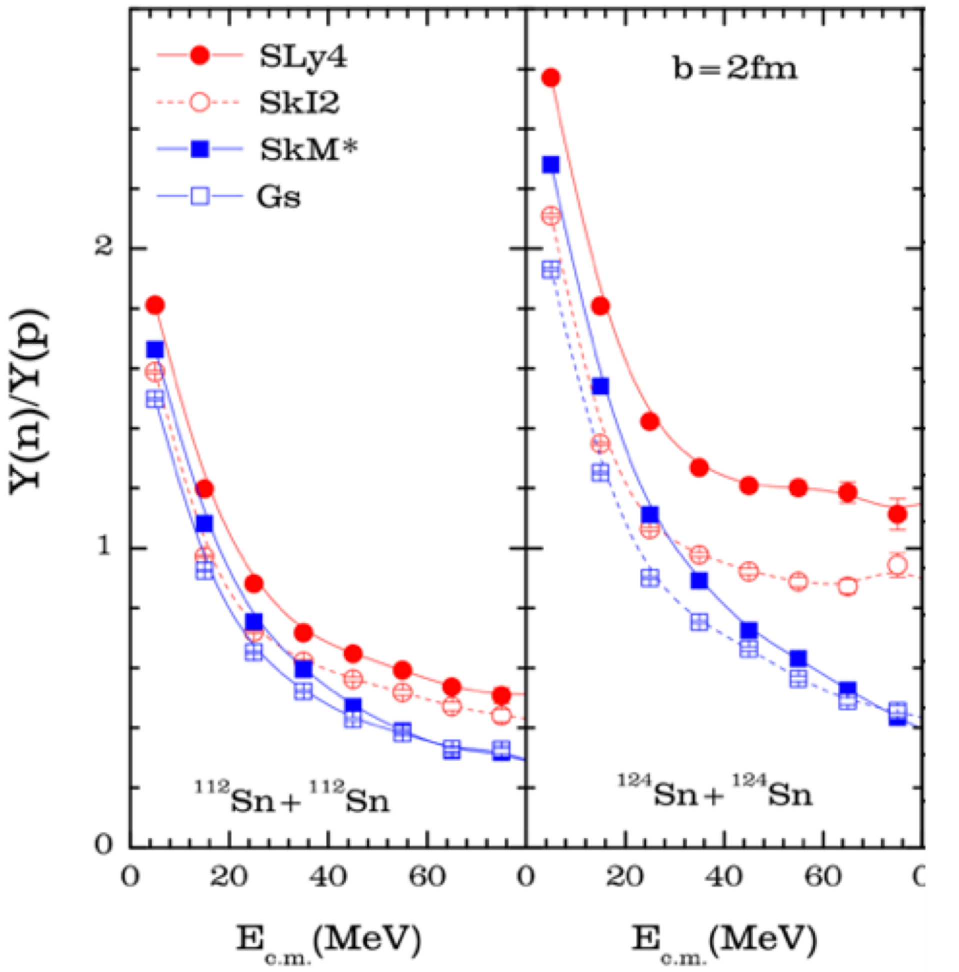
- Binding energy of nuclear matter :
  - $B(A,Z) = a_{vol}A - a_{sur}A^{2/3} - a_{Coul}\frac{Z(Z-1)}{A^{1/3}} - a_{sym}\frac{(N-Z)^2}{A} \pm \delta_{pair}$
- Equation of state :
  - $\varepsilon(\rho,\delta)A = Zm_p + Nm_n - B(A,Z)$
  - $\varepsilon(\rho,\delta) = \varepsilon(\rho,\delta=0) + E_{sym}(\rho)\delta^2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



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.

Skyrme	S0 (MeV)	L (MeV)	m_n^*/m_n	m_p^*/m_p
SLy4	32	46	0.68	0.71
SkM*	30	46	0.82	0.76

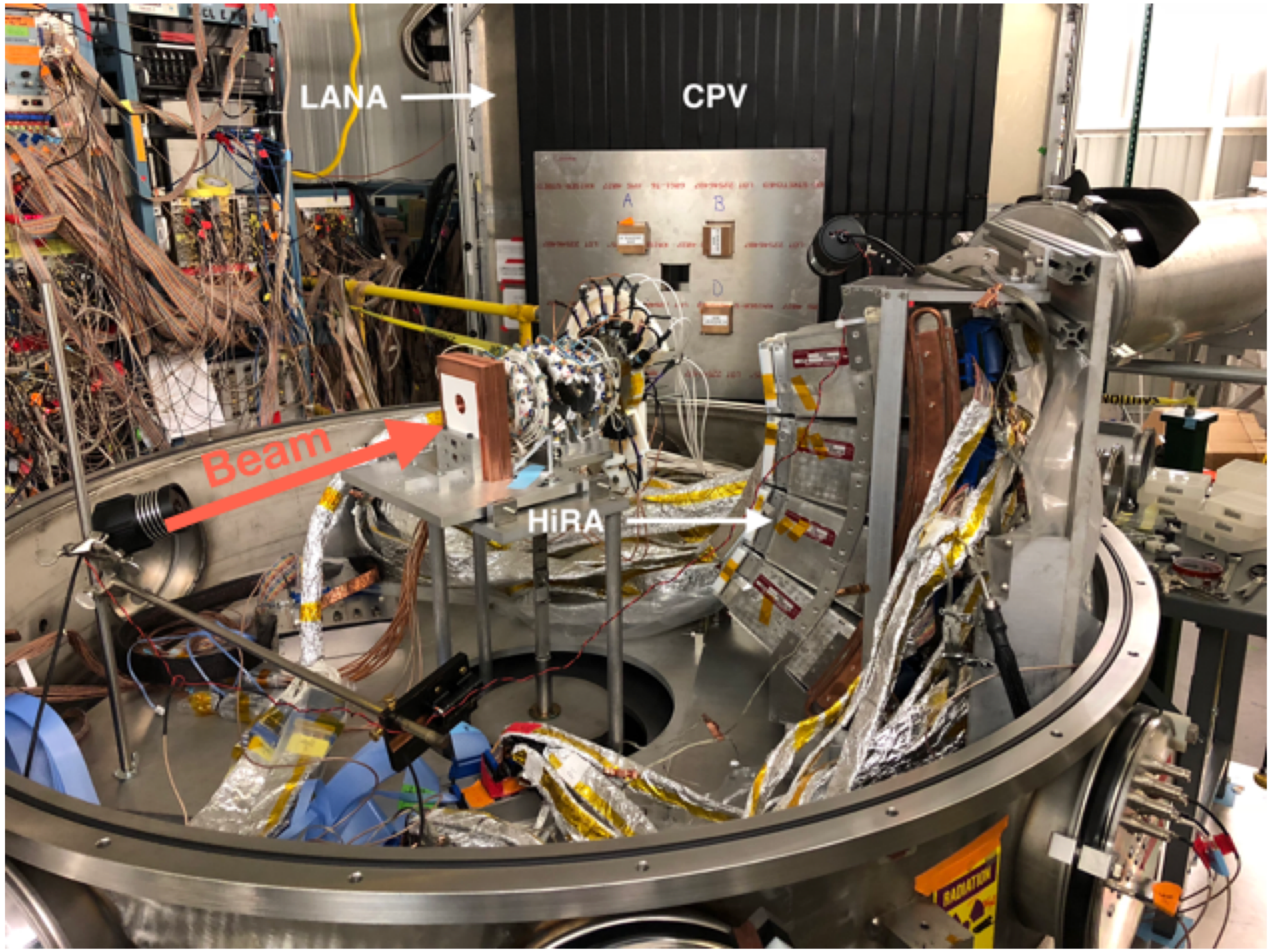


Y. Zhang, M. B. Tsang, Z.Li, and H. Liu / Phys. Lett. B 732, 186 (2014)

Experimental overview

E14030 & E15190 : Probing the effective mass dependence of the symmetry energy & Probing the momentum dependence of the isovector mean field potential

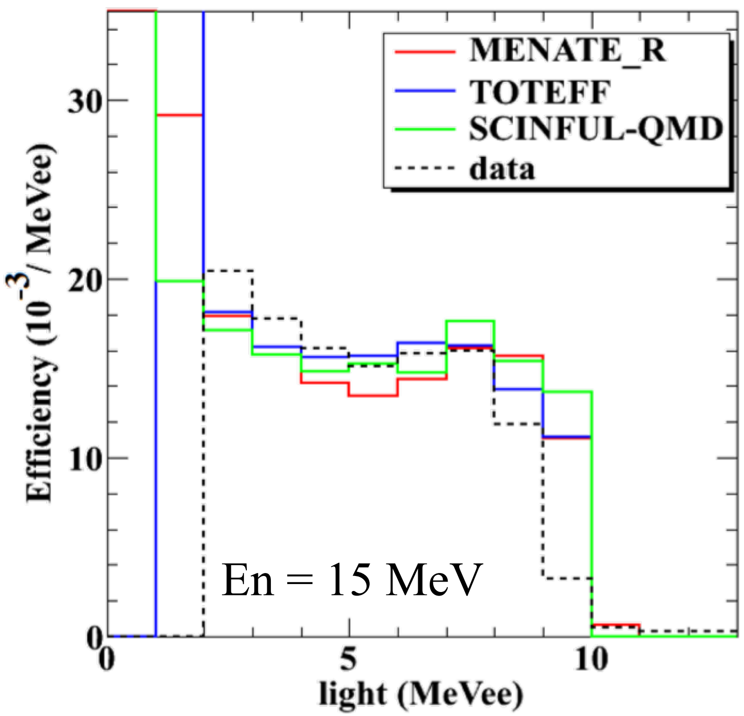
- Feb 8 ~ Mar 25 @ NSCL
- ^{40,48}Ca beam(56, 140 AMeV) and ^{58,64}Ni, ^{112,124}Sn target were used
- HiRA(High Resolution Array)
  - Charged particle detection
- CPV(Charged Particle Veto)
  - Veto charged particles incident to neutron detector
- LANA(Large Area Neutron Array)
  - Neutron detection
  - NE213
  - Connected with FADC(Korea)

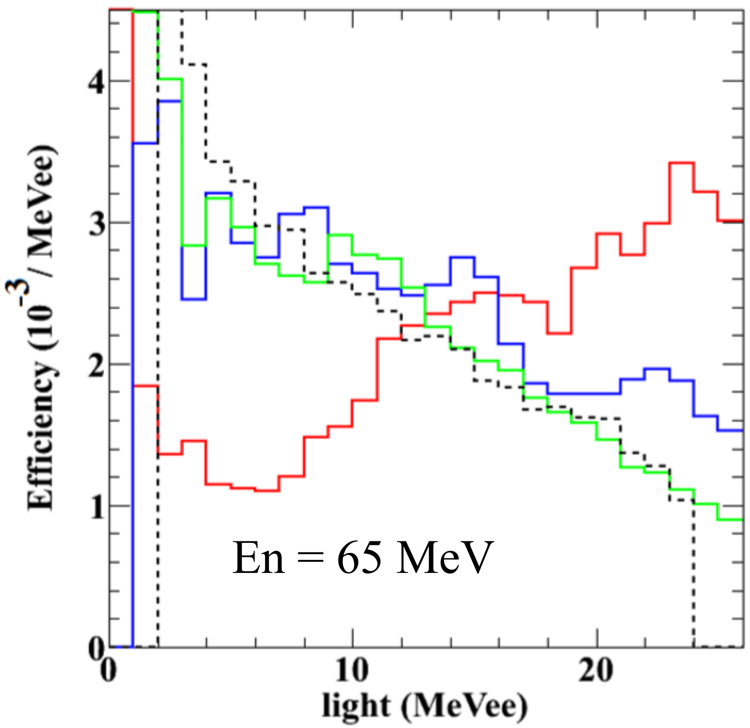


Neutron Simulation

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
  - Switch to QMD model above 150 MeV

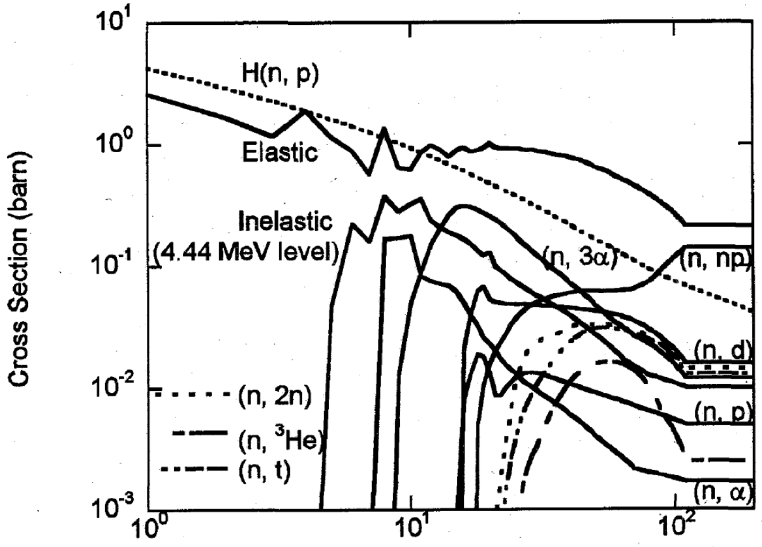




Neutron Simulation

Principle of Neutron Detector

- Produced light inside of neutron detector mainly comes from elastic scattering with hydrogen.
- Not only from hydrogen, charged ions(proton, deuteron, triton, alpha) from inelastic scattering with carbon produce the light.
- Organic scintillator is combined one.



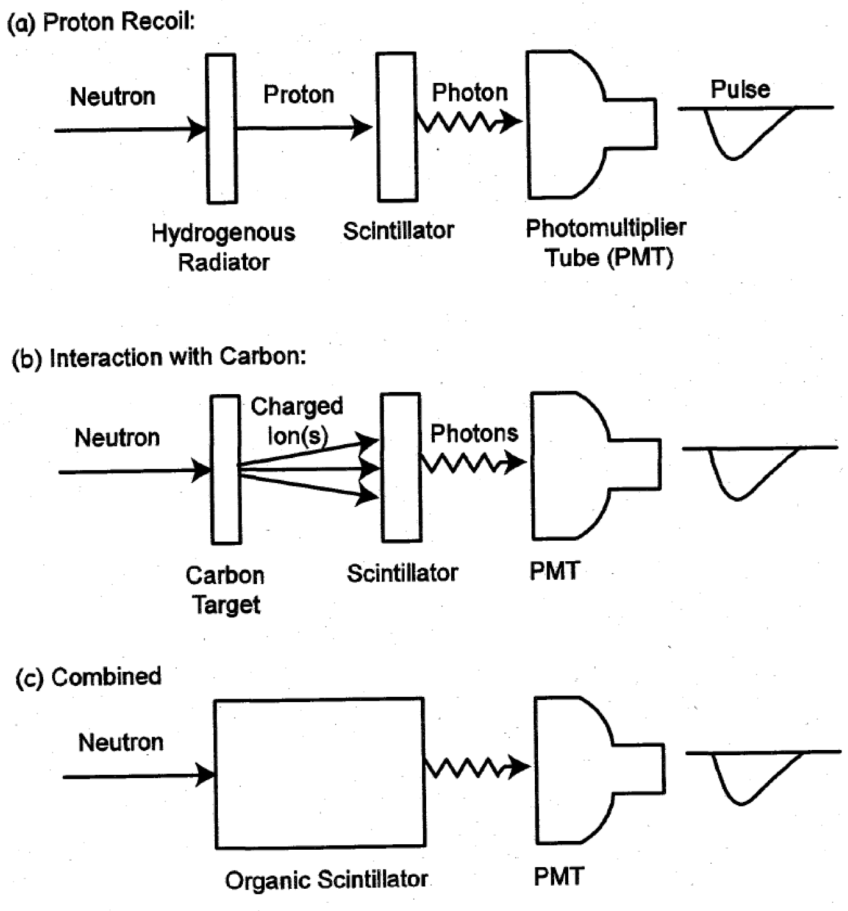


Figure 1. Schematic illustration of neutron detection. This figure is cited from Ref. 1

Neutron Simulation

Neutron Simulation Strategies

- Incorporate SCINFUL light output function
  - Light output for each particle is different.
- Incorporate SCINFUL cross-section
  - Up to 150 MeV of neutron
- Incorporate sequential decays
- Incorporate SCINFUL angular distribution

- Progress :
  - Incorporate SCINFUL light output function of p, d, t, ^{3}He and α. – done
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  - Incorporate sequential decays from excited nucleus. – In progress

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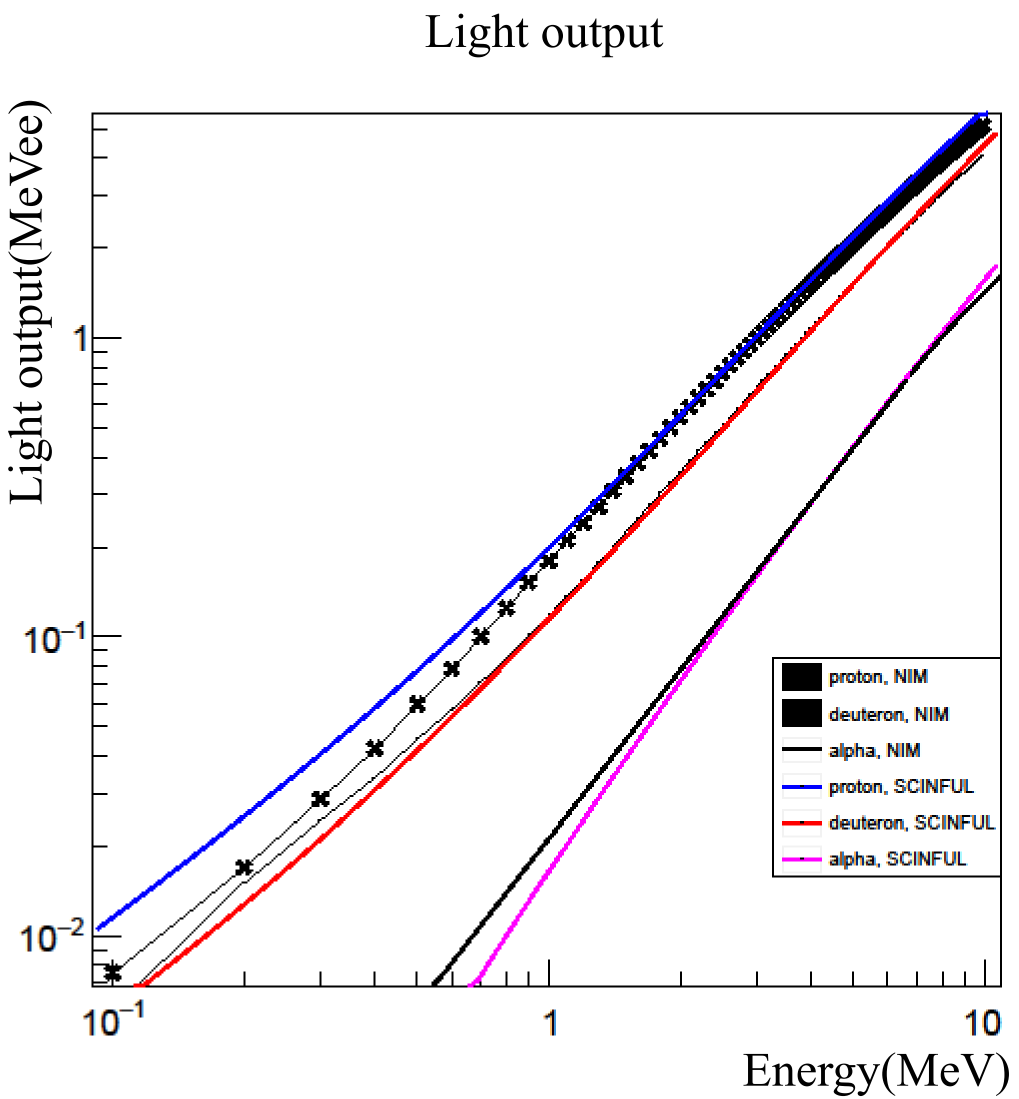
Neutron Simulation

Light output function of NE213

- The light output for each particle is different.
- Light output from SCINFUL : colored lines.
  - Satoh et al., Radiation Protection Dosimetry (2007), Vol. 126, No. 1–4, pp. 555–558
  - doi:10.1093/rpd/ncm112
- Light output from NIM article : black lines
  - NIM A (2017) 868 73-81
  - doi : 10.1016/j.nima.2017.06.021



Neutron Simulation

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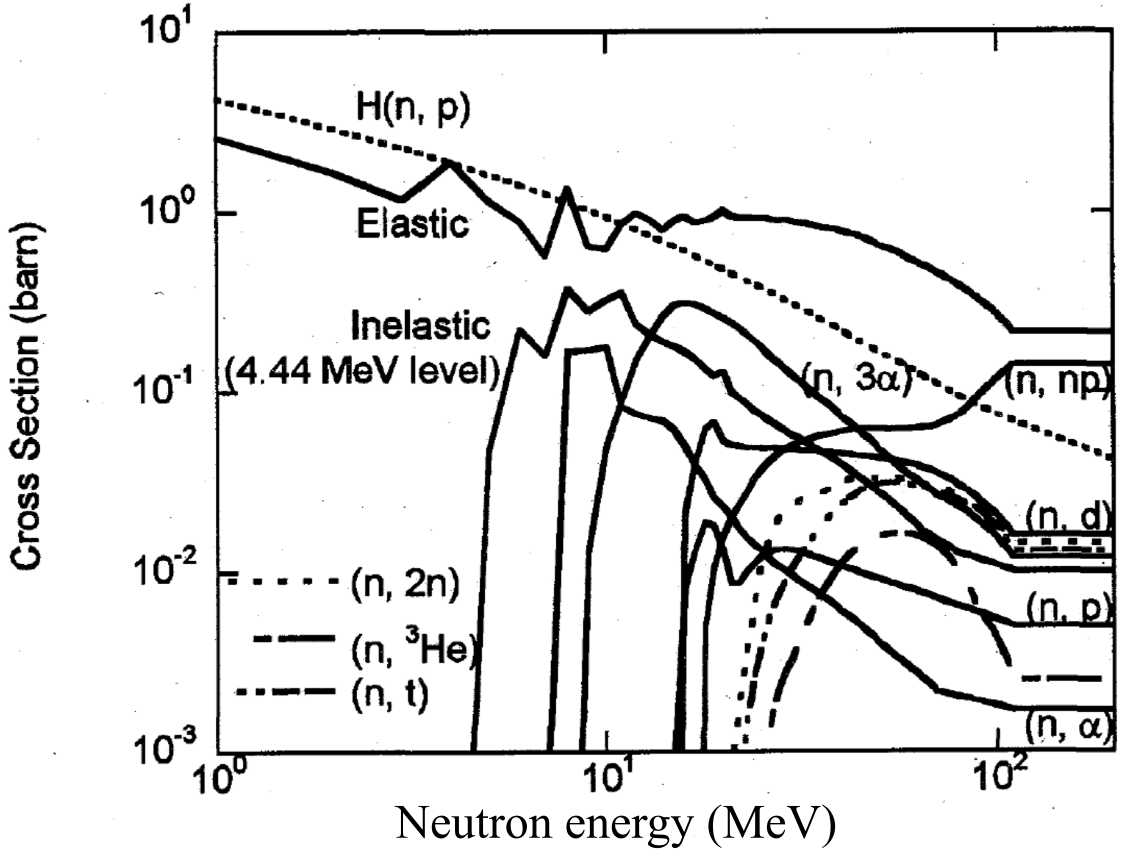
Neutron Simulation

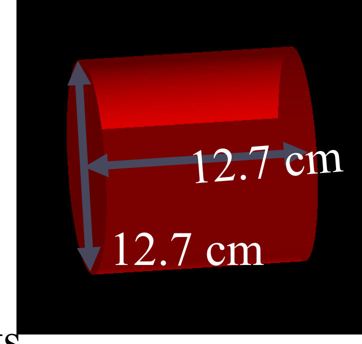
Channel List

- 11 channels are included in SCINFUL.
  - H(n,p)
  - ^{12}C(n,n)
  - ^{12}C(n,n')^{12}C* ~ 4.44 MeV
  - ^{12}C(n,2n)^{11}C
  - ^{12}C(n,p)^{12}B
  - ^{12}C(n,np)^{11}B
  - ^{12}C(n,d)^{11}B
  - ^{12}C(n,t)^{10}B
  - ^{12}C(n,^{3}He)^{10}Be
  - ^{12}C(n,α)^{9}Be
  - ^{12}C(n,n3α)
- Sequential decays are not included in GEANT4.



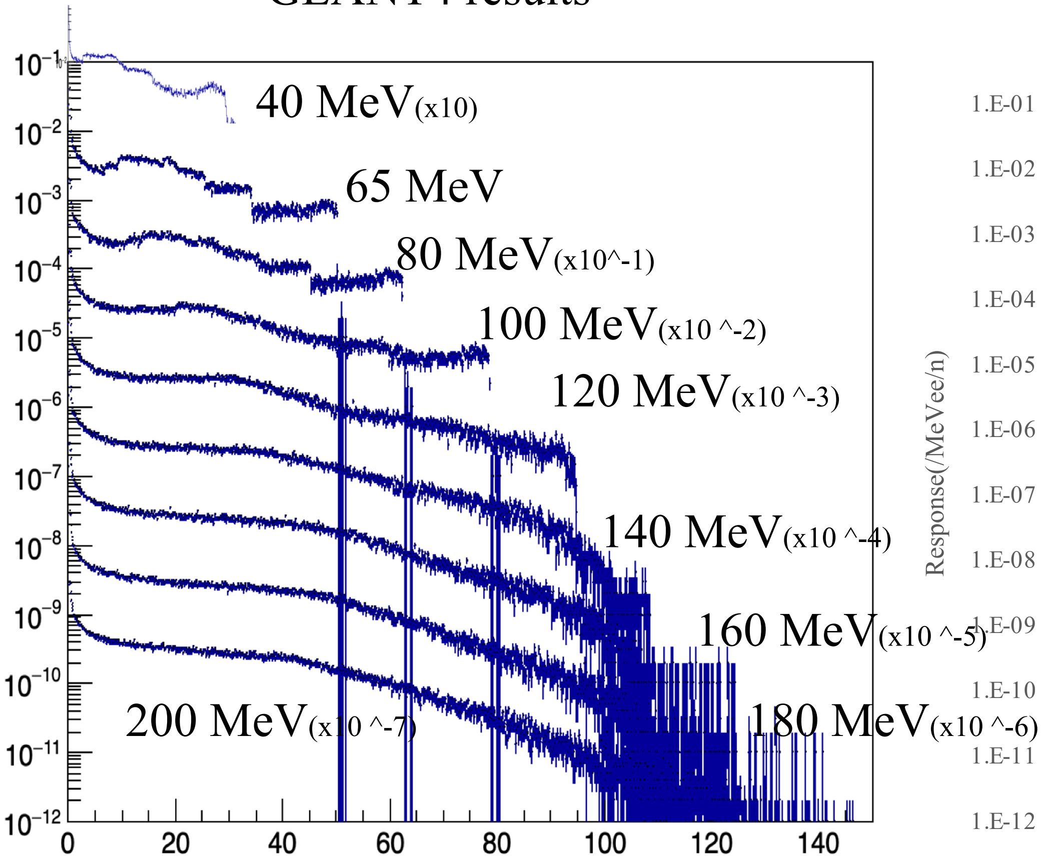
Neutron Simulation

Light response

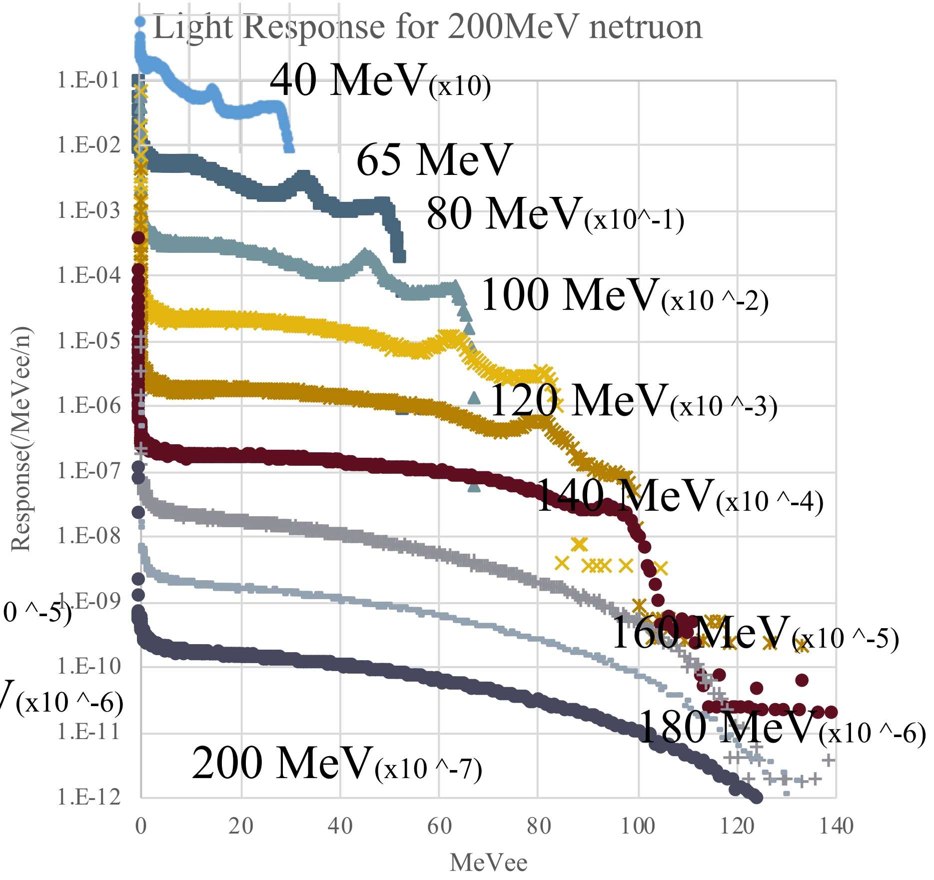


- Comparison between GEANT4 and SCINFUL.
- Since SCINFUL can only produce cylinder fix the geometry as cylinder in GEANT4.
- Only cross-section has been applied.

GEANT4 results



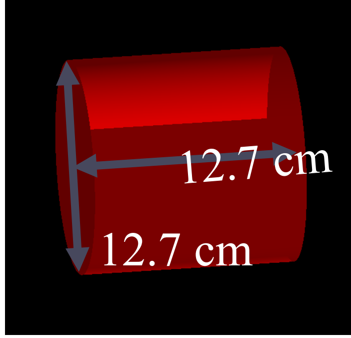
SCINFUL results



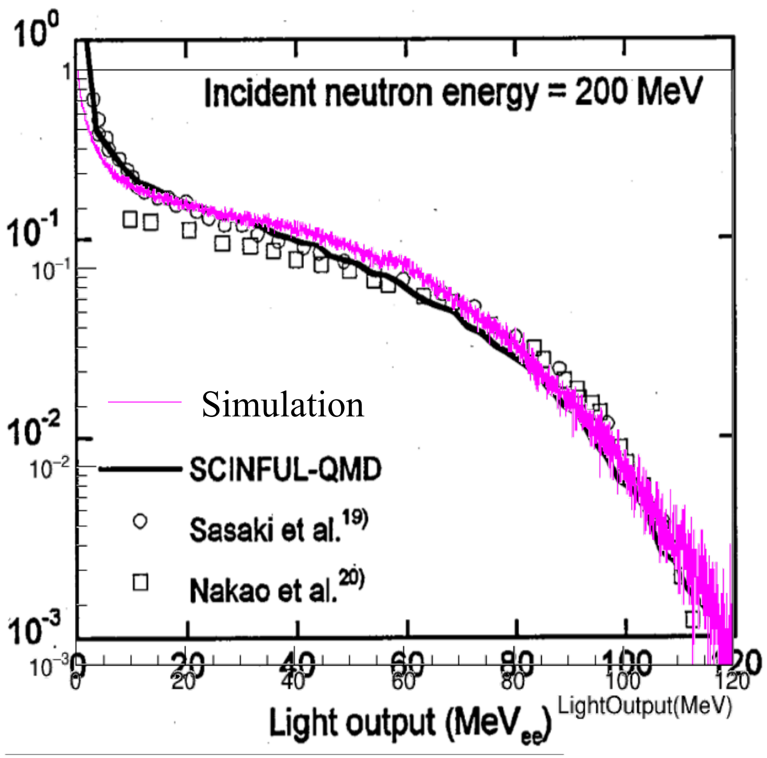
Neutron Simulation

Light response

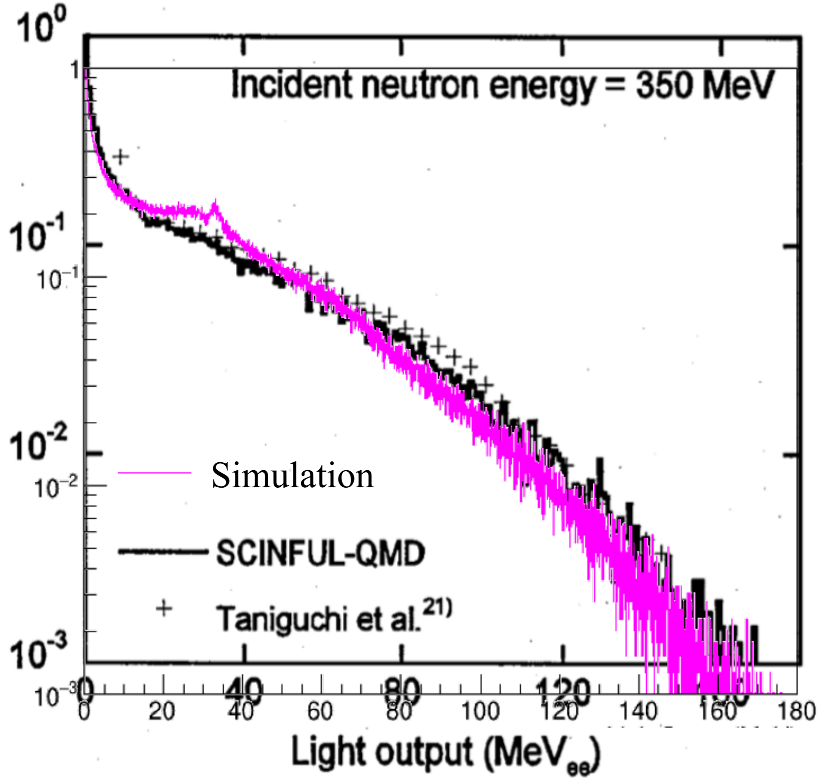
- At the high energy of neutron results from GEANT4 have good agreements with SCINFUL.
- QGSP_BIC physics list is adopted for the high energy neutron.



200 MeV

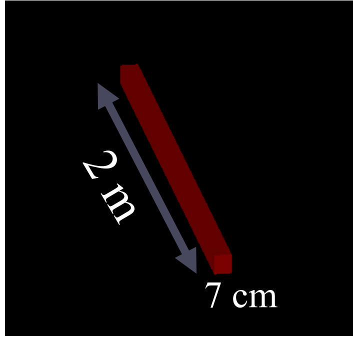


350 MeV

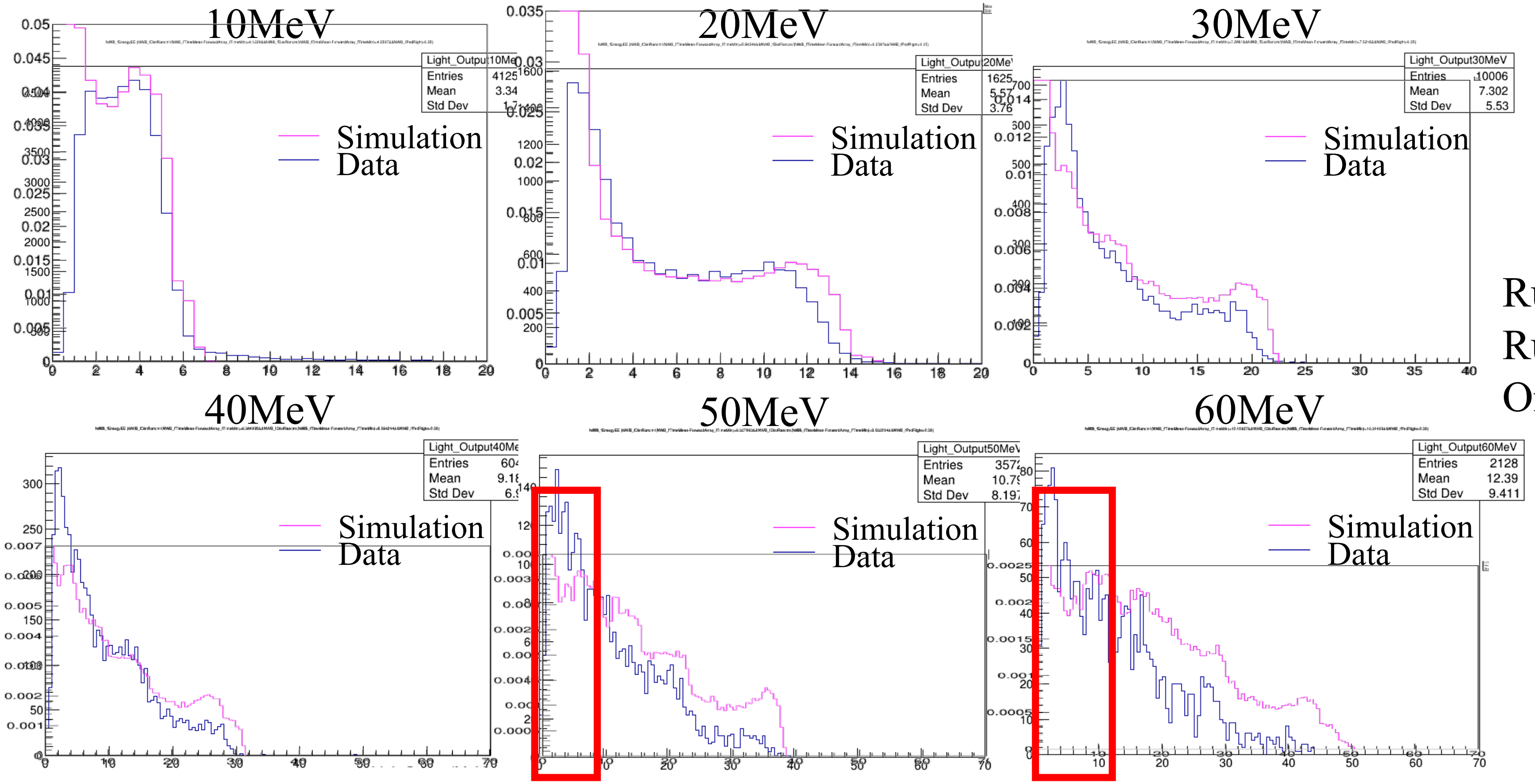


Neutron Simulation

Compare with Experiment data



- From 50 MeV of neutron, simulation and data has no agreements.
- Sequential decays are not incorporated.



Run4621-4640
Run4336-4380
Only Neutron

Neutron Simulation

Neutron Simulation Strategies

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  - Up to 150 MeV of neutron
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- Progress :
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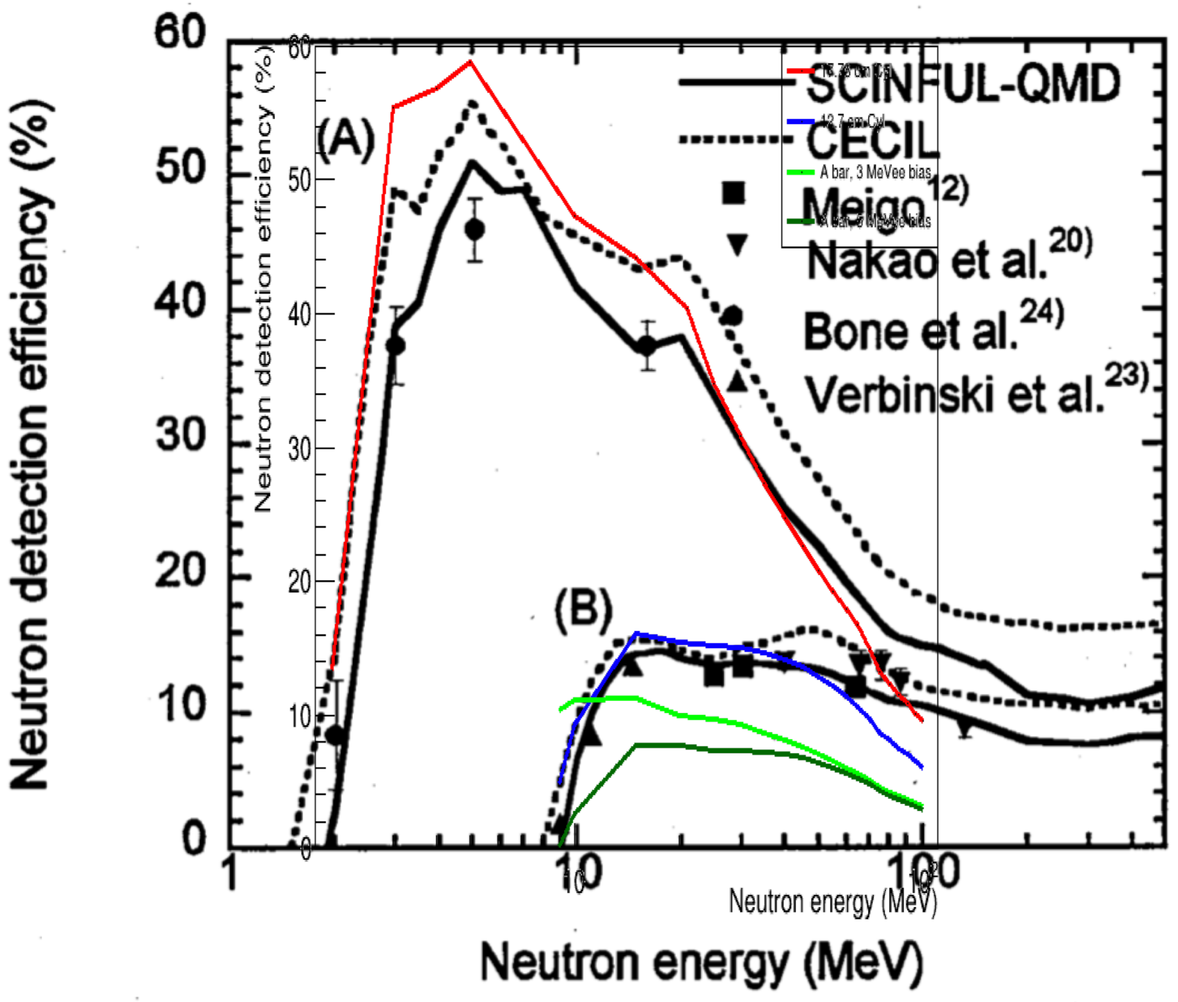
  - Incorporate SCINFUL cross-section – done
  - Incorporate SCINFUL angular distribution – done
  - Incorporate sequential decays from excited nucleus. – In progress

Neutron Simulation

Neutron Detector Efficiency

- Neutron detection efficiency
  - Cylinder, 17.78 cm thickness, 0.45 MeVee biased
  - Cylinder, 12.7 cm thickness, 4.33 MeVee biased
  - Bar, 7 cm thickness, 3 MeVee biased
  - Bar, 7 cm thickness, 5 MeVee biased



Neutron Simulation

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- Because of the export control for SCINFUL, simulation work has been stopped now.
- Neutron simulation with GEANT4 and SCINFUL will be developed after getting permission from NEA(Nuclear Energy Agency).

Summary

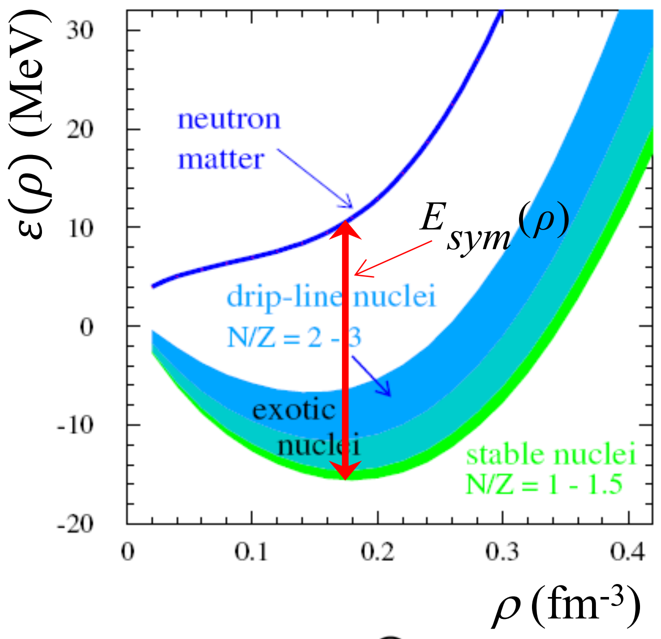
- An experiment(E14030 & 15190) for probing effective mass dependence of symmetry energy was conducted at NSCL in 2018.
- In order to estimate the efficiency of the NE213 organic scintillator, GEANT4 was used with SCINFUL data.
- GEANT4 simulates well at the high energy of the neutron.
- Neutron simulation is still under development.
- Neutron simulation will be developed after getting permission from NEA.

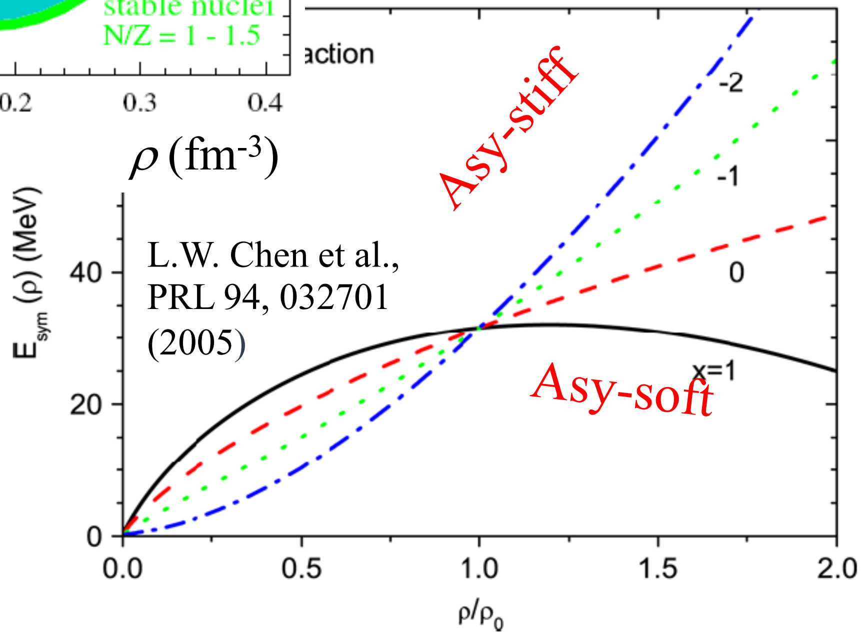
Neutron Simulation

Neutron Detector Efficiency

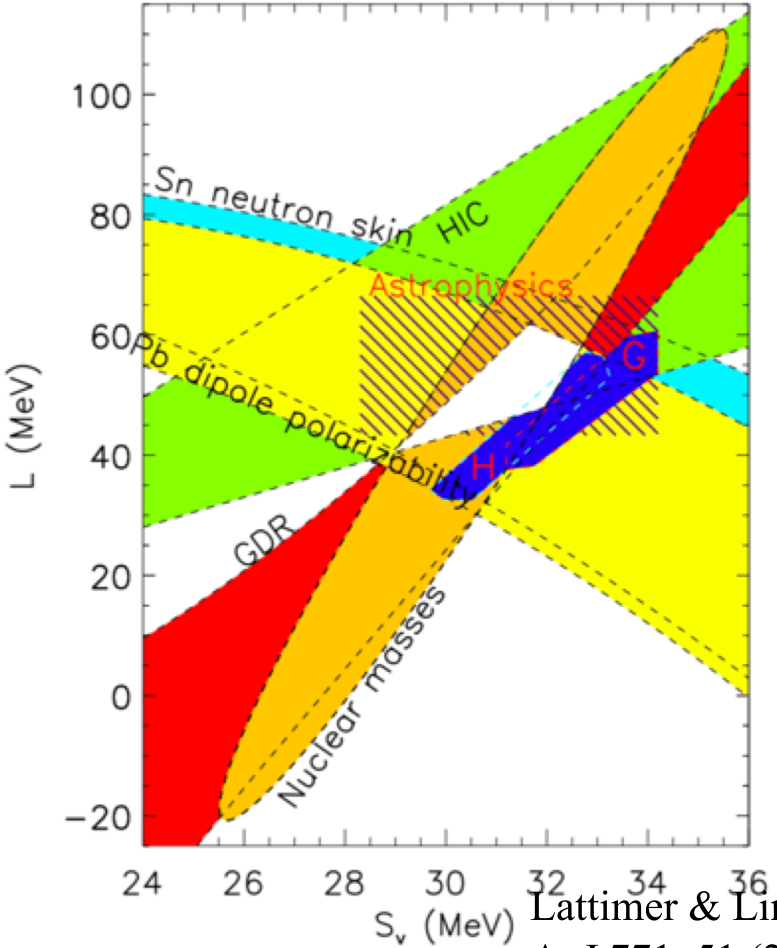
Back up : Equation of States and Symmetry Energy

- Binding energy of nuclear matter :
  - $B(A,Z) = a_{vol}A - a_{sur}A^{2/3} - a_{Coul}\frac{Z(Z-1)}{A^{1/3}} - a_{sym}\frac{(N-Z)^2}{A} \pm \delta_{pair}$
- Equation of state :
  - $\varepsilon(\rho,\delta)A = Zm_p + Nm_n - B(A,Z)$
  - $\varepsilon(\rho,\delta) = \varepsilon(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + \mathcal{O}(\delta^4)$
- Symmetry energy is energy difference between the pure neutron matter and isospin symmetric matter.
  - $E_{sym}(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$
  - $L = \frac{3}{\rho_0}P_{sym} = 3\rho_0 \left.\frac{\partial E_{sym}(\rho)}{\partial\rho}\right|_{\rho=\rho_0}$ (slope)
  - $K_{sym} = 9{\rho_0}^2 \left.\frac{\partial^2 E_{sym}(\rho)}{\partial\rho^2}\right|_{\rho=\rho_0}$ (curvature)



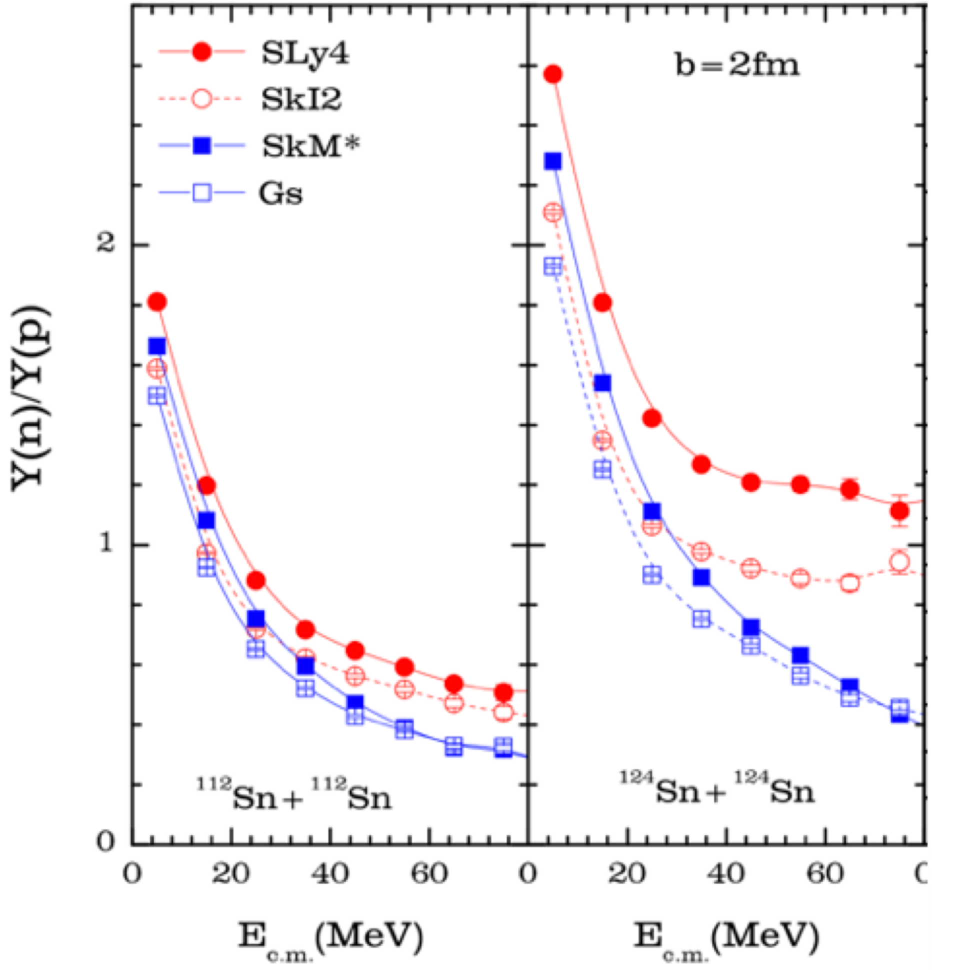


Back up : $S_0 - L$



Lattimer & Lim, ApJ 771, 51 (2013)

S_0 : 28 ~ 32 MeV
L : 40 ~ 60 MeV



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

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

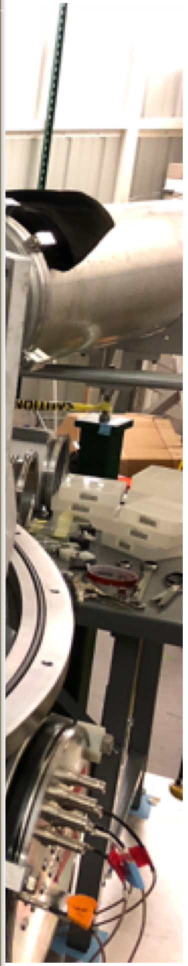
Experimental overview

E14030 & E15190 : Probing the effective mass dependence of the symmetry energy & Probing the momentum dependence of the isovector mean field potential

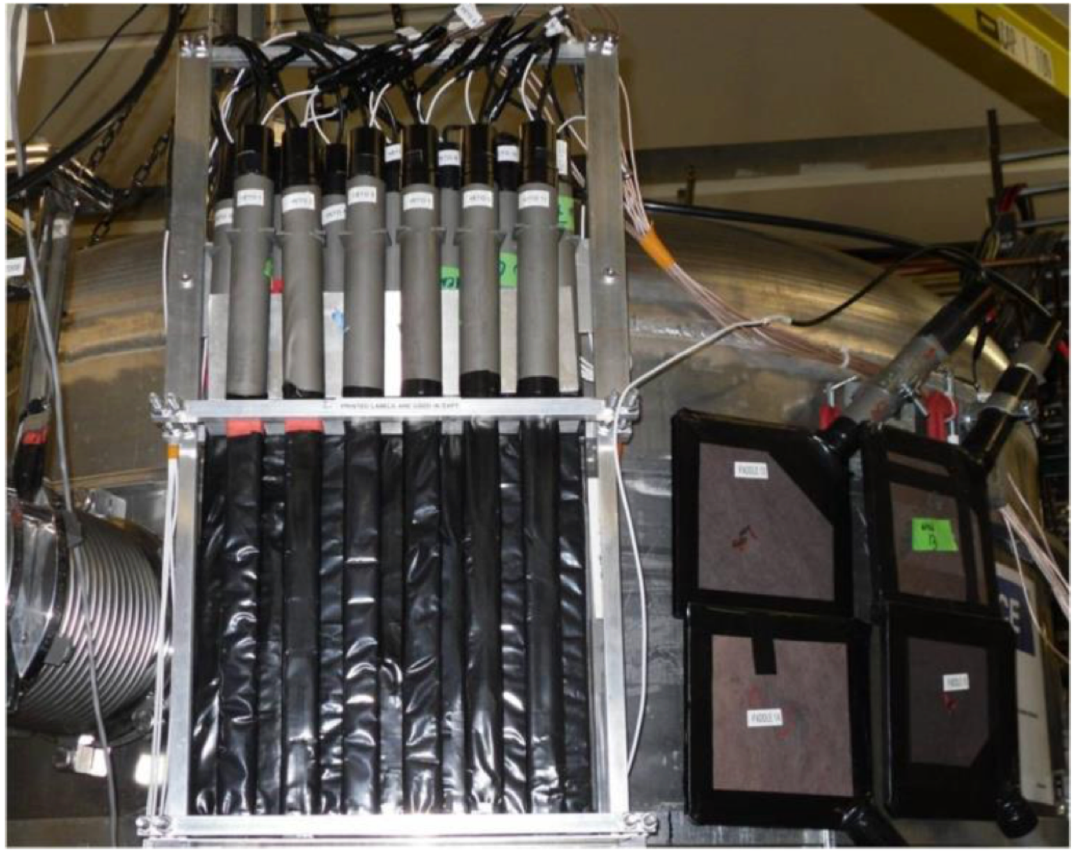
- Feb 8 ~ Mar 25 @ NSCL
- ^{40,48}Ca beam(56, 140 AMeV) and ^{58,64}Ni, ^{112,124}Sn target were used
- HiRA(High Resolution Array)
  - Charged particle detection
- CPV(Charged Particle Veto)
  - Veto charged particles incident to neutron detector
- LANA(Large Area Neutron Array)
  - Neutron detection
  - NE213
  - Connected with FADC(Korea)

Beam	Target	Shadow bars	Avg trigger rate	Total time [HH:MM:SS]
Ca40@56 MeV/u	^{112}Sn	OUT	2107	12:39:56
		IN	2413	18:28:50
		TOTAL	2289/ 256M	31:08:46
Ca40@56 MeV/u	^{124}Sn	OUT	0	0
		IN	2841	08:40:31
		TOTAL	2841/ 88M	08:40:31
Ca40@56 MeV/u	^{58}Ni	OUT	2558	16:26:05
		IN	2694	21:05:26
		TOTAL	2635/ 355M	37:31:31
Ca40@56 MeV/u	^{64}Ni	OUT	0	0
		IN	2751	08:05:27
		TOTAL	2751/ 80M	08:05:27
Ca40@140 MeV/u	^{112}Sn	OUT	2168	08:25:27
		IN	2016	43:53:08
		TOTAL	2041/ 384M	52:18:35
Ca40@140 MeV/u	^{124}Sn	OUT	3057	07:56:28
		IN	198	10:52:46
		TOTAL	1404/ 95M	18:49:14
Ca40@140 MeV/u	^{58}Ni	OUT	3651	12:26:46
		IN	2931	32:24:36
		TOTAL	3131/ 505M	44:51:22
Ca40@140 MeV/u	^{64}Ni	OUT	0	0
		IN	2915	11:28:46
		TOTAL	2915/ 120M	11:28:46

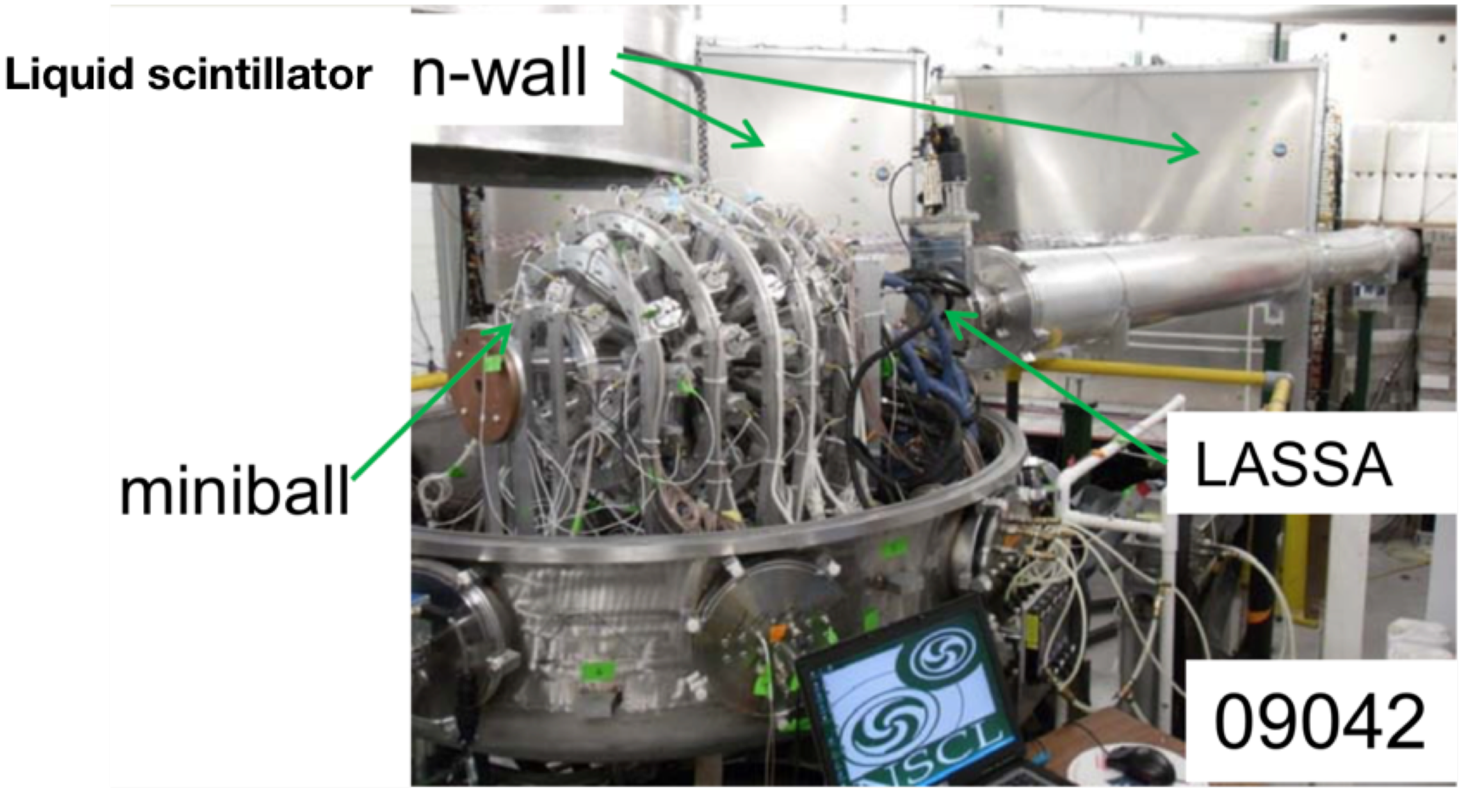
Beam	Target	Shadow bars	Avg trigger rate	Total time [HH:MM:SS]
Ca48@56 MeV/u	^{112}Sn	OUT	2812	06:39:33
		IN	2756	08:00:24
		TOTAL	2781/ 146M	14:39:57
Ca48@56 MeV/u	^{124}Sn	OUT	2558	26:06:27
		IN	2756	23:52:39
		TOTAL	2653/ 477M	49:59:06
Ca48@56 MeV/u	^{58}Ni	OUT	2619	05:41:13
		IN	2691	08:00:10
		TOTAL	2661/ 131M	13:41:23
Ca48@56 MeV/u	^{64}Ni	OUT	2762	25:40:37
		IN	2824	29:27:25
		TOTAL	2795/ 554M	55:08:02
Ca48@140 MeV/u	^{112}Sn	OUT	2332	06:07:25
		IN	2435	07:05:39
		TOTAL	2387/ 113M	13:13:04
Ca48@140 MeV/u	^{124}Sn	OUT	2590	18:33:19
		IN	2229	27:50:59
		TOTAL	2373/ 396M	46:24:18
Ca48@140 MeV/u	^{58}Ni	OUT	2353	07:34:11
		IN	2334	06:54:51
		TOTAL	2344/ 122M	14:29:02
Ca48@140 MeV/u	^{64}Ni	OUT	2705	18:26:12
		IN	2273	27:55:13
		TOTAL	2444/ 408M	46:21:25



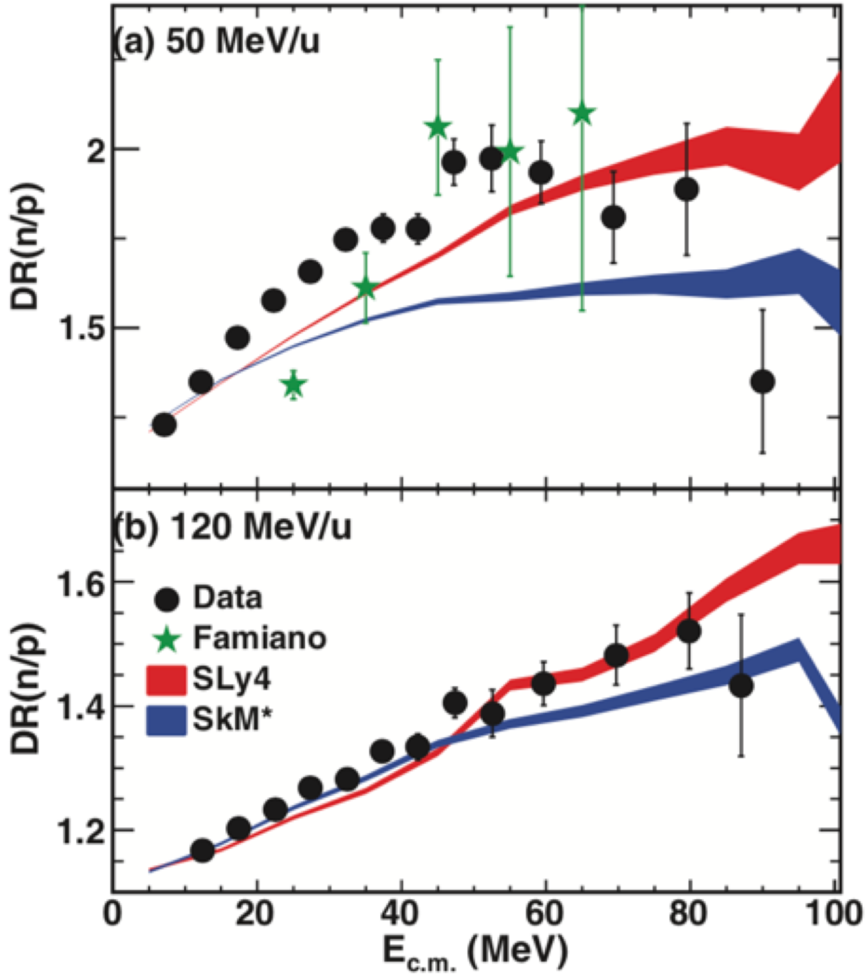
Back up : Charged Particle Veto

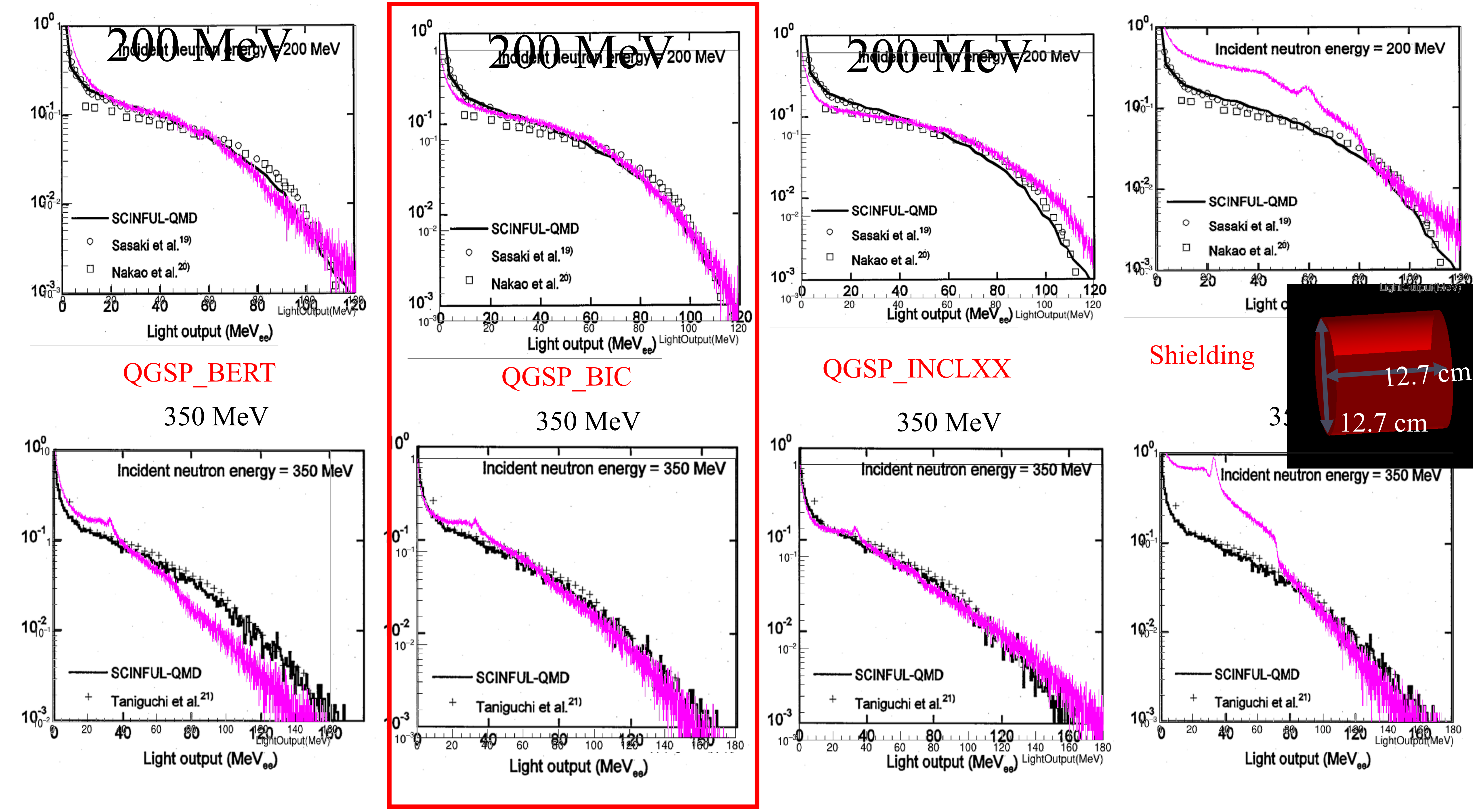


Back up : Previous experiment result



$^{112}Sn+^{112}Sn$ and $^{124}Sn+^{124}Sn$ collisions at the beam energy of 50MeV and 120MeV.





200 MeV
Incident neutron energy = 200 MeV
SCINFUL-QMD
Sasaki et al.[19]
Nakao et al.[20]
Light output (MeV$_{ee}$)
LightOutput(MeV)
QGSP_BERT
QGSP_BIC
QGSP_INCLXX
Shielding
12.7 cm
12.7 cm
350 MeV
Incident neutron energy = 350 MeV
SCINFUL-QMD
Taniguchi et al.[21]
Light output (MeV$_{ee}$)
LightOutput(MeV)