Status of neutron detector simulation

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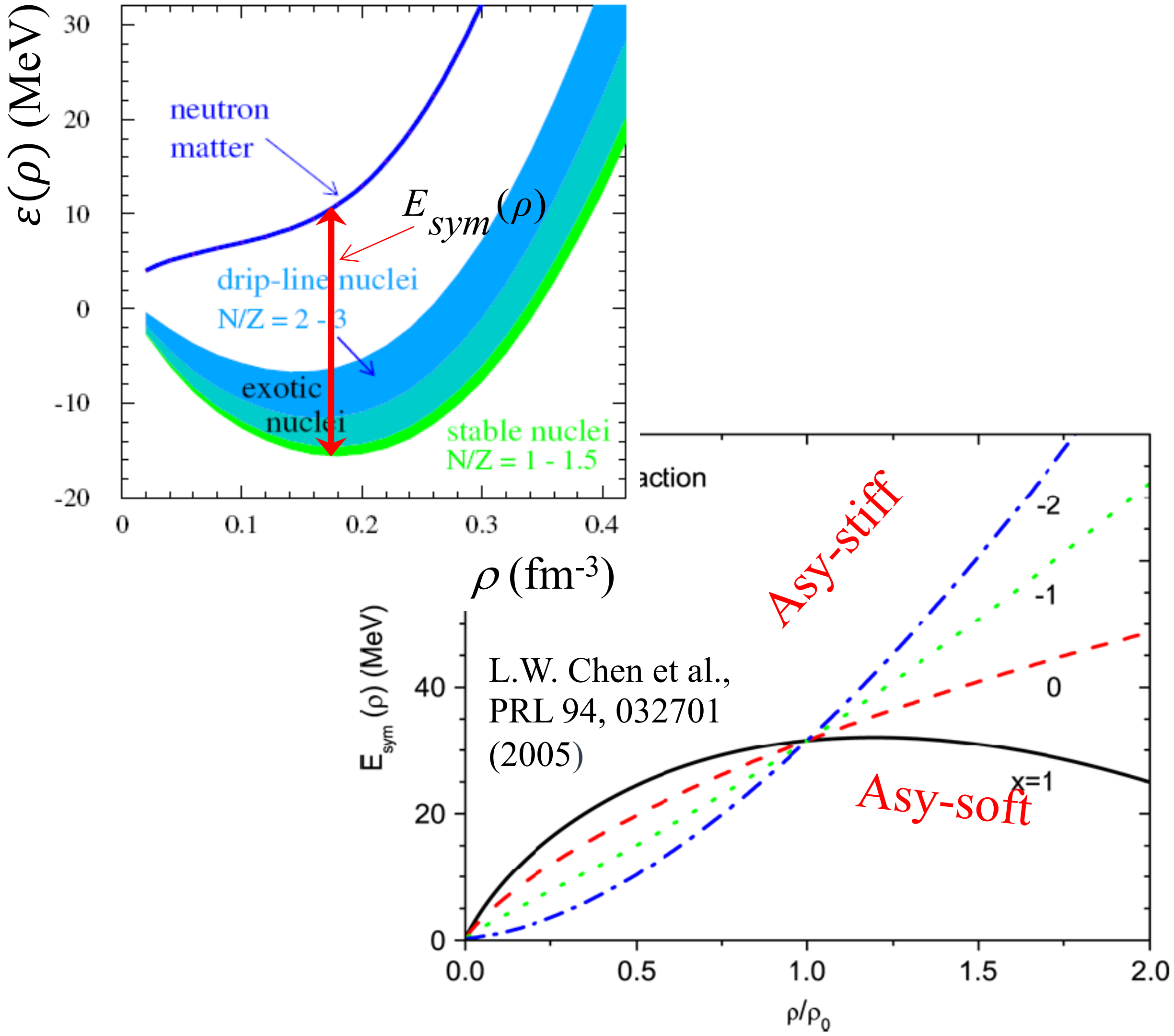
Contents

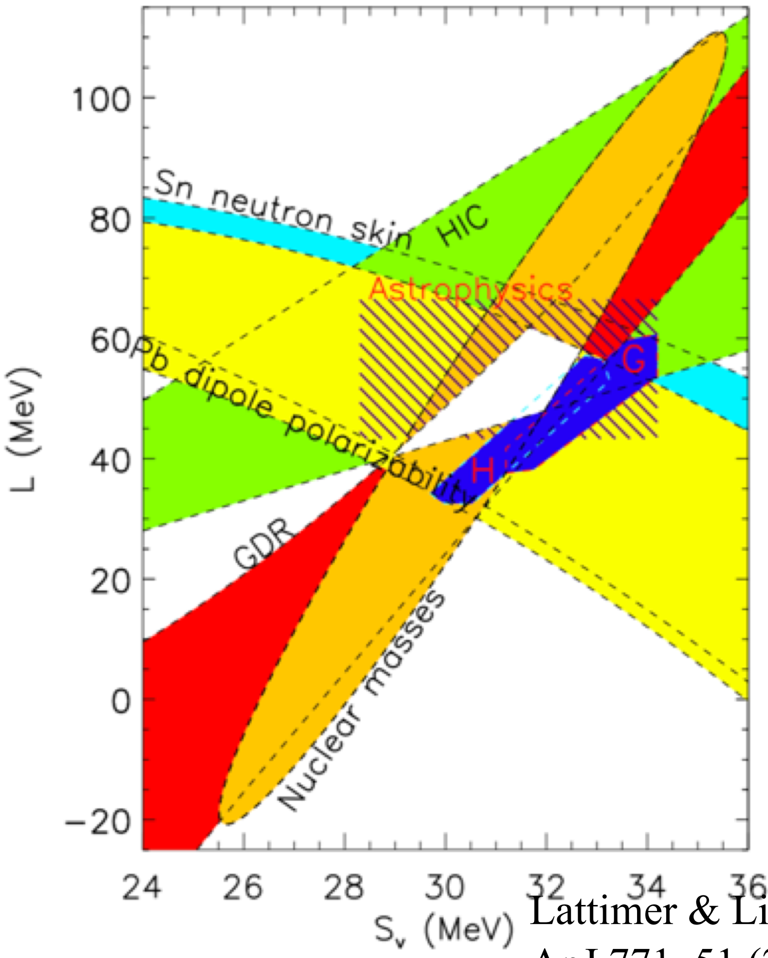
Equation of States and Symmetry Energy

- 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.



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

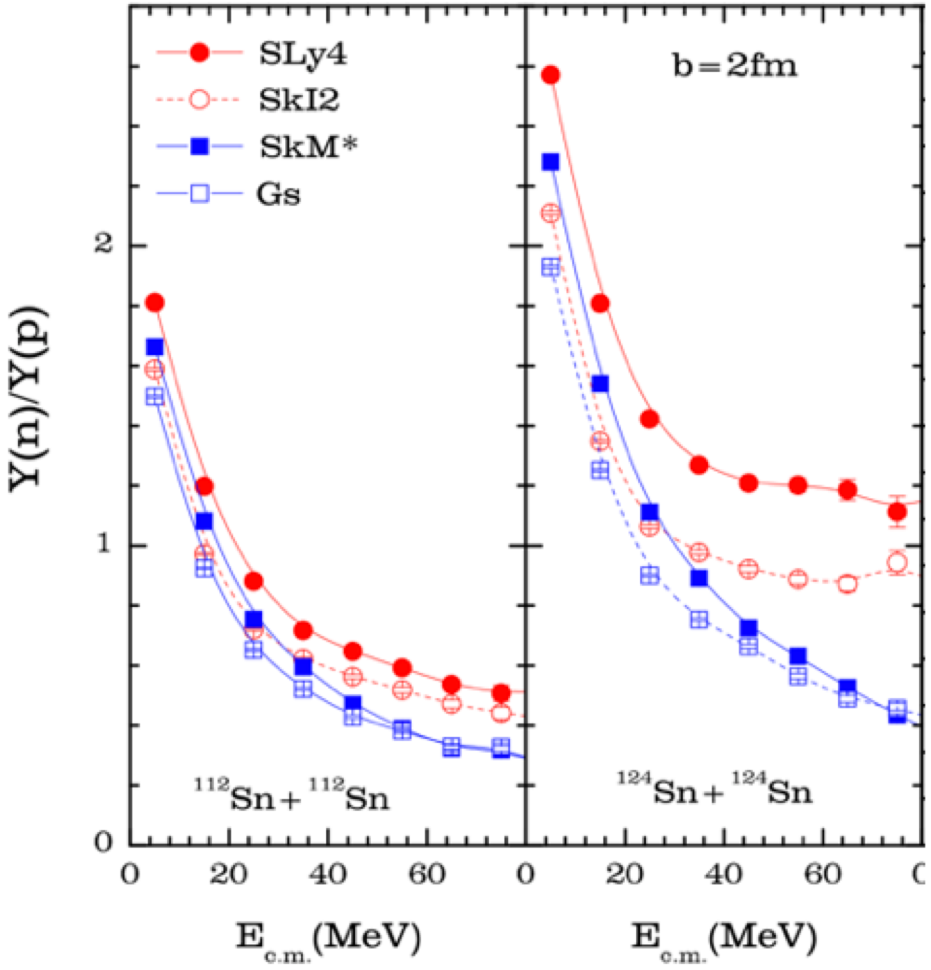


Lattimer & Lim, ApJ 771, 51 (2013)

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

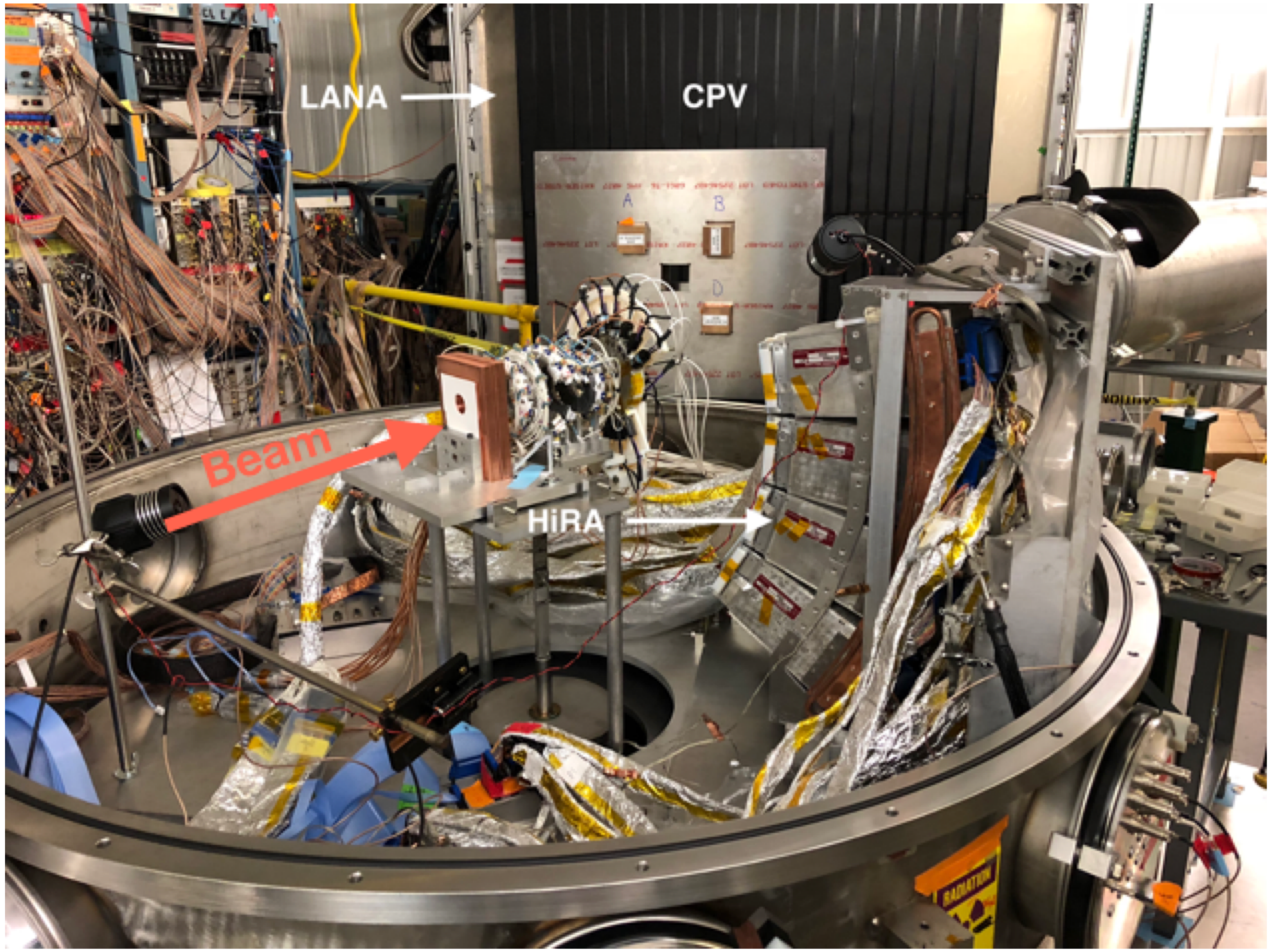


Y. Zhang, M. B. Tsang, Z.Li, and H. Liu / Phys. Lett. B 732, 186 (2014)

Experimental overview

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

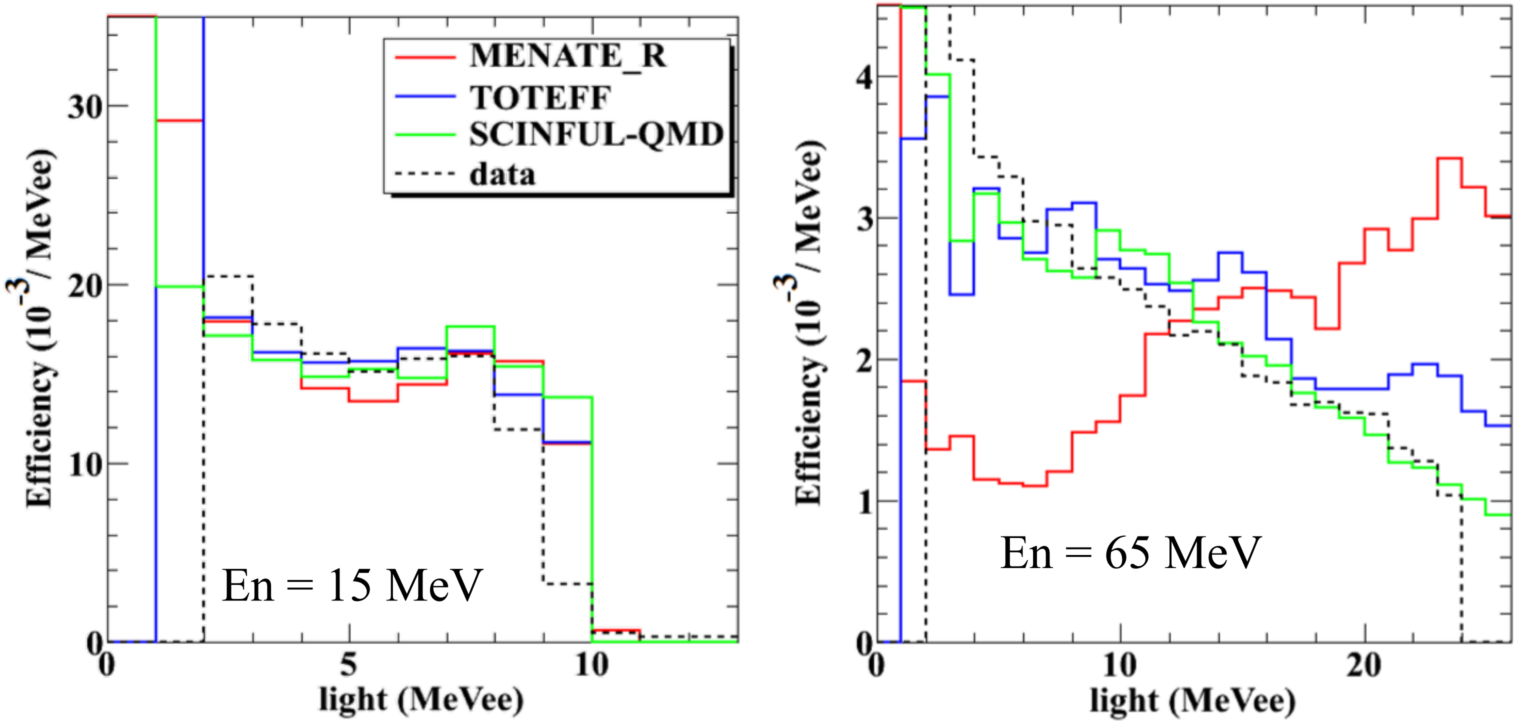
- Feb 8 ~ Mar 25 @ NSCL
- ^{40,48}Ca beam(56, 140 AMeV) and ^{58,64}Ni, ^{112,124}Sn target were used
- HiRA(High Resolution Array)
  - Charged particle detection
- CPV(Charged Particle Veto)
  - Veto charged particles incident to neutron detector
- LANA(Large Area Neutron Array)
  - Neutron detection
  - NE213, 2 m Bar type
  - Connected with FADC constructed for LAMPS



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
- With using GEANT4 and SCINFUL, neutron simulation is being developed.

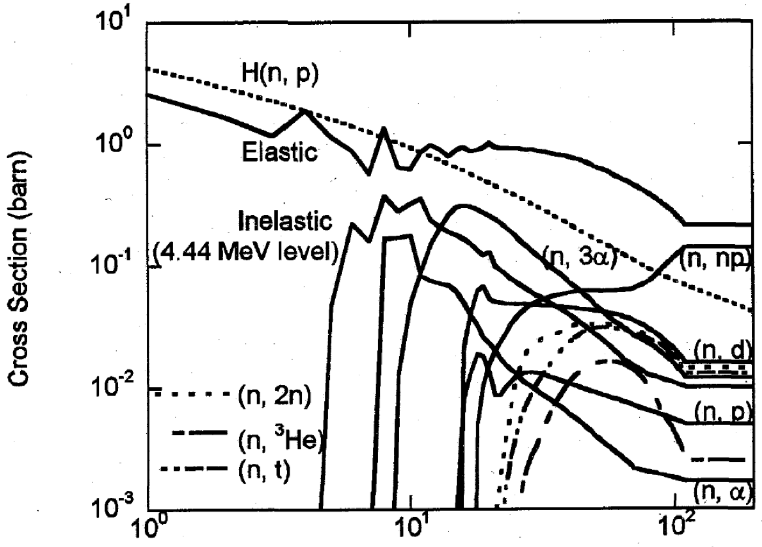


Light response function for different energy of neutron

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.



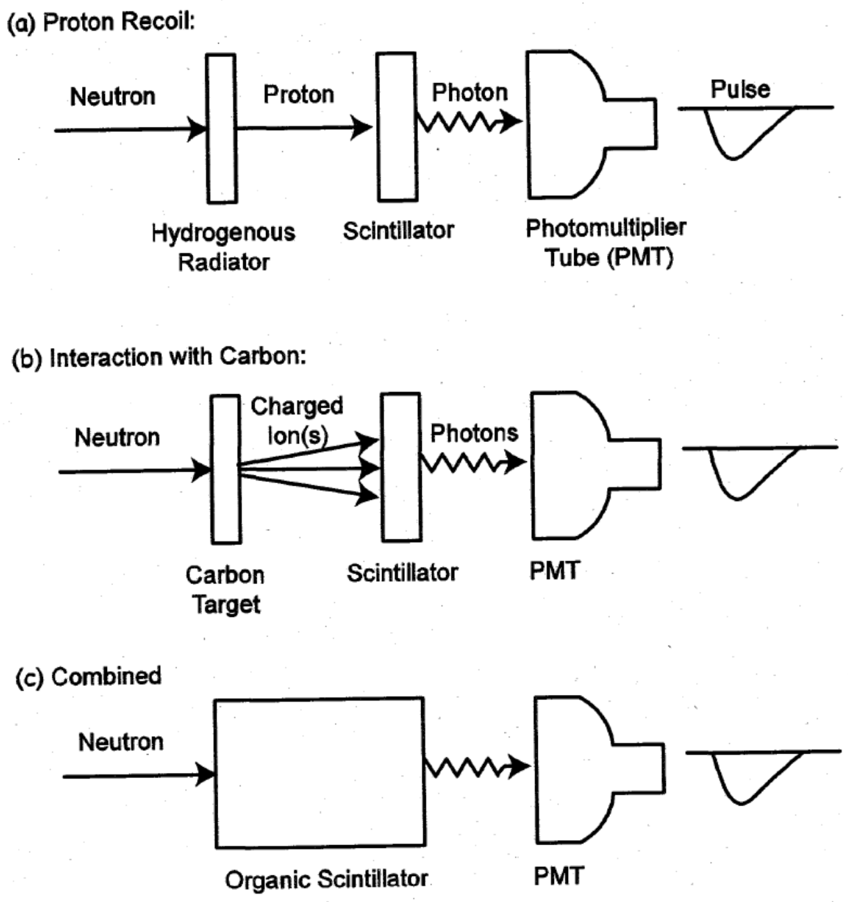


Figure 1. Schematic illustration of neutron detection. This figure is cited from Ref. 1

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

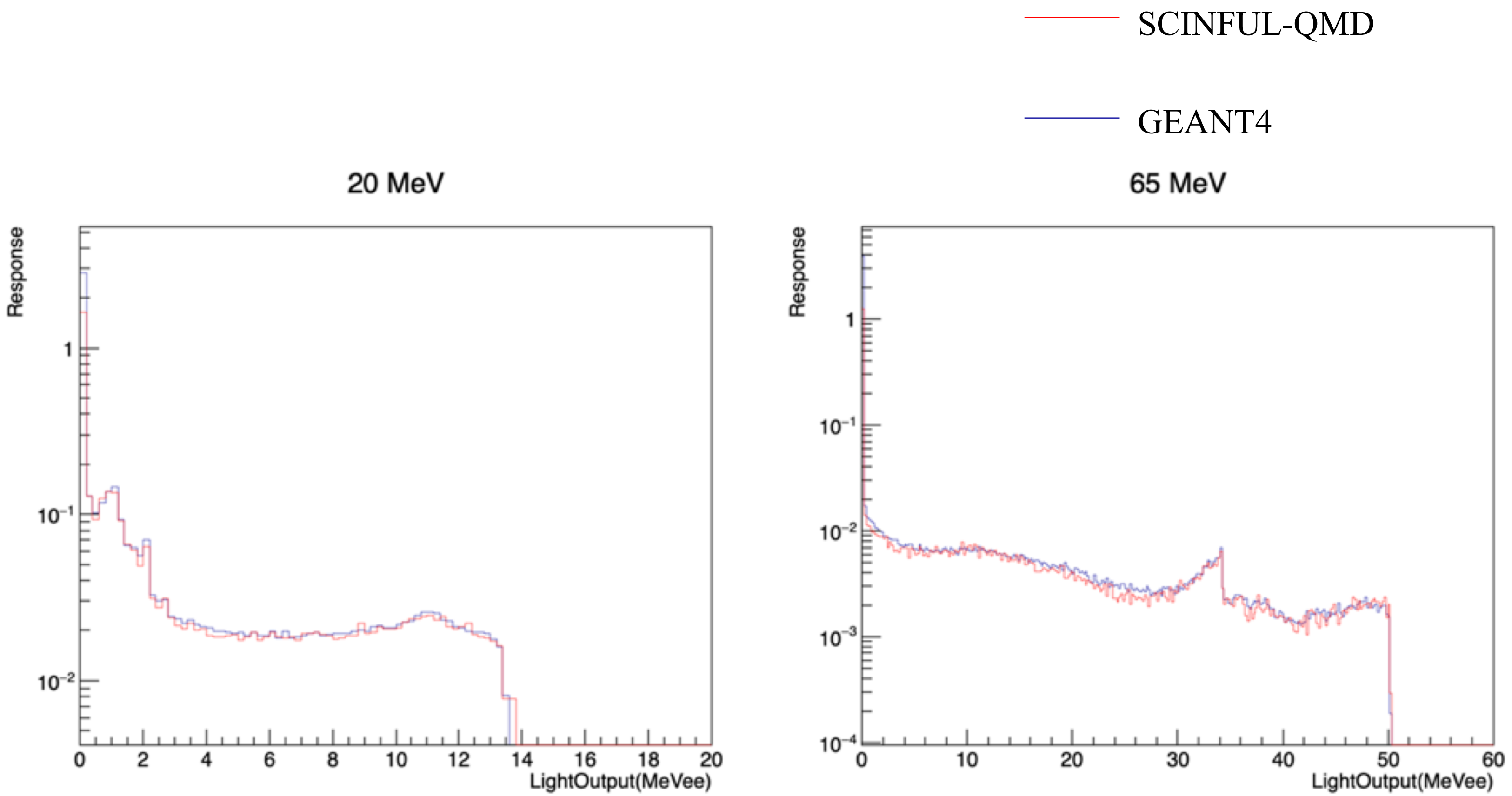
- Progress :
  - Incorporate SCINFUL light output function of p, d, t, ^{3}He and α. – done
  - Incorporate SCINFUL cross-section – done
  - Incorporate SCINFUL angular distribution – done
  - Incorporate sequential decays from excited nucleus. – In progress

- Because of the export control for SCINFUL, simulation work stopped.
- Neutron simulation with GEANT4 and SCINFUL has been started developing after got permission from NEA(Nuclear Energy Agency).
- All model for low energy of neutron has been implemented in new simulation.

Neutron Simulation

Light Response

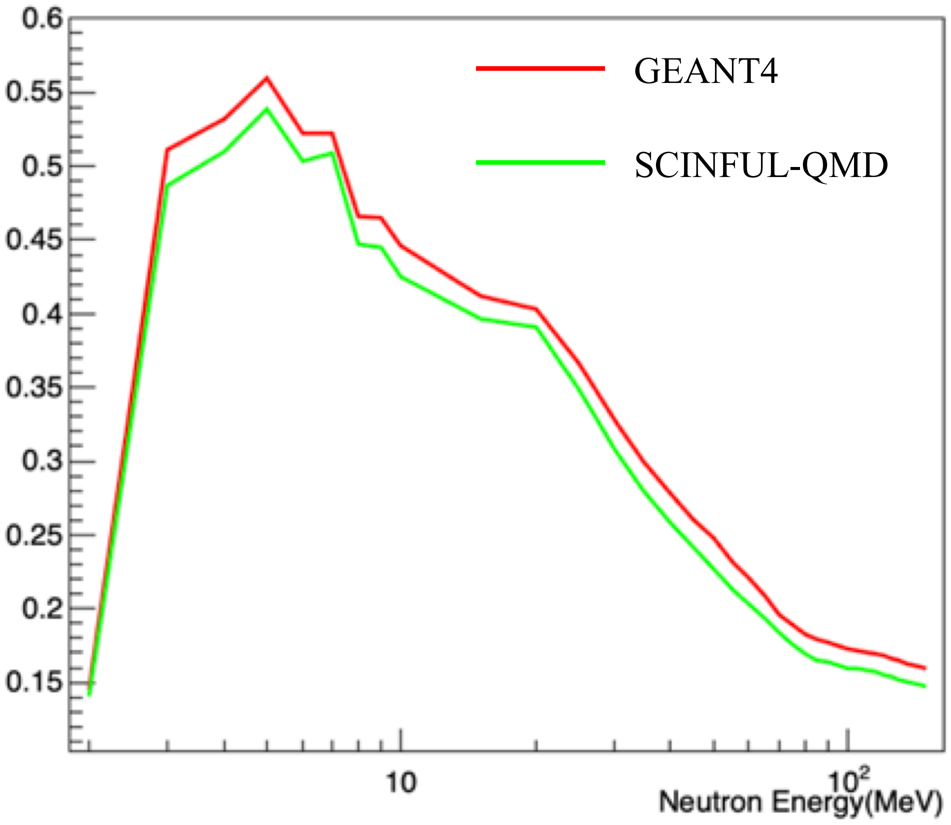
- Light response comparison for low energy of neutron.
- After implementing SCINFUL model, GEANT4 results have good agreement with SCINFUL results.
- GEANT4 has little different detector configuration with respect to SCINFUL.



Neutron Simulation

Neutron Detector Efficiency

- Neutron detector efficiency plot for low energy of neutron.
- Because of the different detector configuration(different atomic density), GEANT4 has higher efficiency.
- SCINFUL-QMD uses QMD model above 150 MeV of neutron.
- Implementing QMD model is needed for the higher energy of neutron.



Efficiency as a function of neutron energy

Neutron Simulation

QMD Model Implementation

- GEANT4 already has QMD model, JQMD(JAERI QMD, Japan Atomic Energy Research Institute), which is the same model in SCINFUL-QMD.
- The error occurs when trying to use G4QMD model with nucleon projectile or target.
- The bug has been fixed in the current beta version of GEANT4.

```
subroutine jqmd00

      JJJ     QQQQQ     MMM      MMM  DDDDDDD
      JJJ   QQQQQQQQQ   MMMM    MMMM  DDDDDDDD
      JJJ  QQQ     QQQ  MMMMM MMMMM  DDD    DDD
      JJJ  QQQ     QQQ  MMM MMM MMM  DDD     DDD
      JJJ  QQQ     QQQ  MMM  M  MMM  DDD     DDD
      JJJ  QQQ     QQQ  MMM     MMM  DDD     DDD
      JJJ  QQQ QQQ QQQ  MMM     MMM  DDD     DDD
JJJ   JJJ   QQQQQQQQQ   MMM     MMM  DDD    DDD
 JJJJJJJ      QQQQQQ    MMM     MMM  DDDDDDDD
   JJJJ          QQQ    MMM     MMM  DDDDDDD

       Jaeri Quantum Molecular Dynamics
           for Nuclear Reactions

      parameter ( Version = 1.00 )

                 made by

     Japan Atomic Energy Research Institute

      parameter ( Last Revised = 1998 12 03 )
```

```
15-Nov-2007 Tatsumi Koi    (hadr-qmd-V09-00-01)
- First implmentation of QMD reaction model
  based on JQMD (Niita et al., JAERI-Data/Code 99-042)
  Use Collision library of Geant4

  History (this file)
        GNUMakefile
  include/G4QMDGroundStateNucleus.hh
  include/G4QMDNucleus.hh
  include/G4QMDParticipant.hh
  include/G4QMDSystem.hh
  include/G4QMDCollision.hh
  include/G4QMDMeanField.hh
  include/G4QMDParameters.hh
  include/G4QMDReaction.hh
  src/G4QMDCollision.cc
  src/G4QMDGroundStateNucleus.cc
  src/G4QMDMeanField.cc
  src/G4QMDNucleus.cc
  src/G4QMDParameters.cc
  src/G4QMDParticipant.cc
  src/G4QMDReaction.cc
  src/G4QMDSystem.cc
```

Koi, T. & Asai, Makoto & Wright, D & Niita, Koji & Nara, Yasushi & Amako, K & Sasaki, T. (2003). Interfacing the JQMD and JAM Nuclear Reaction Codes to Geant4. 10.2172/813352.

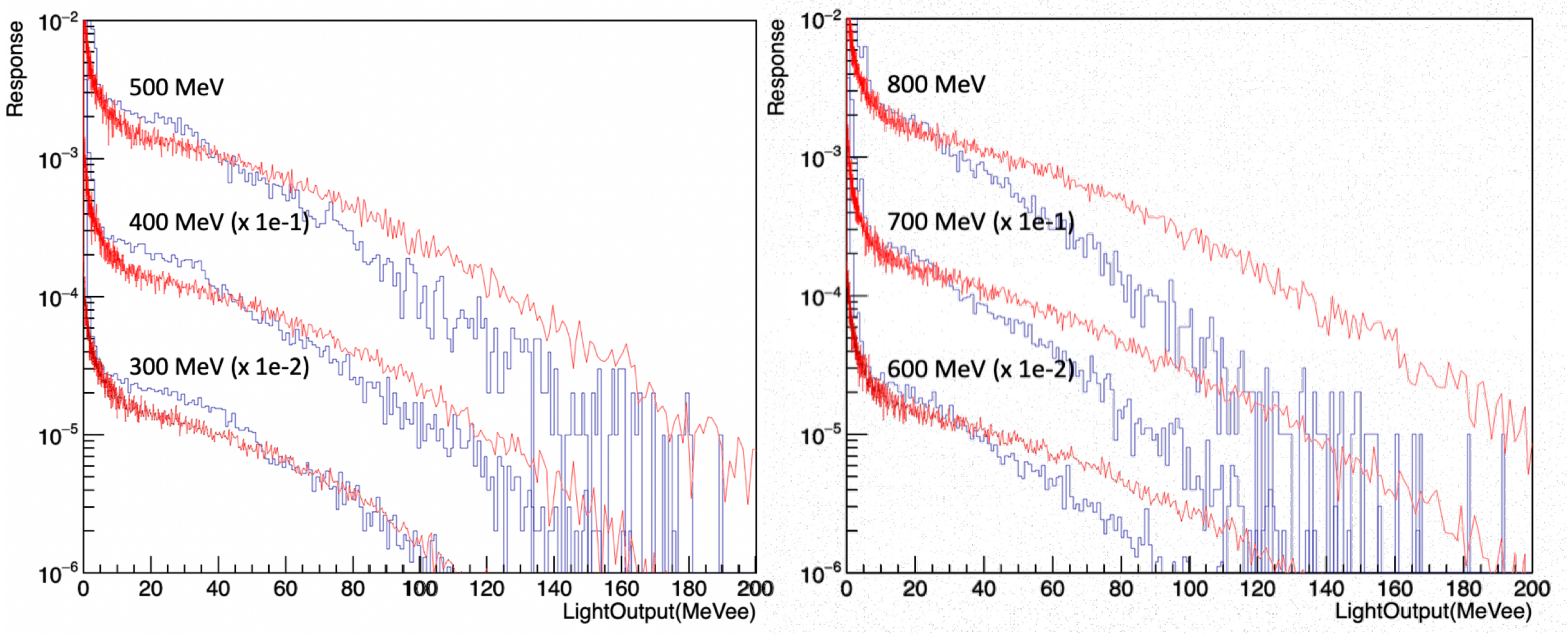
Neutron Simulation

QMD Model Implementation

SCINFUL-QMD

GEANT4

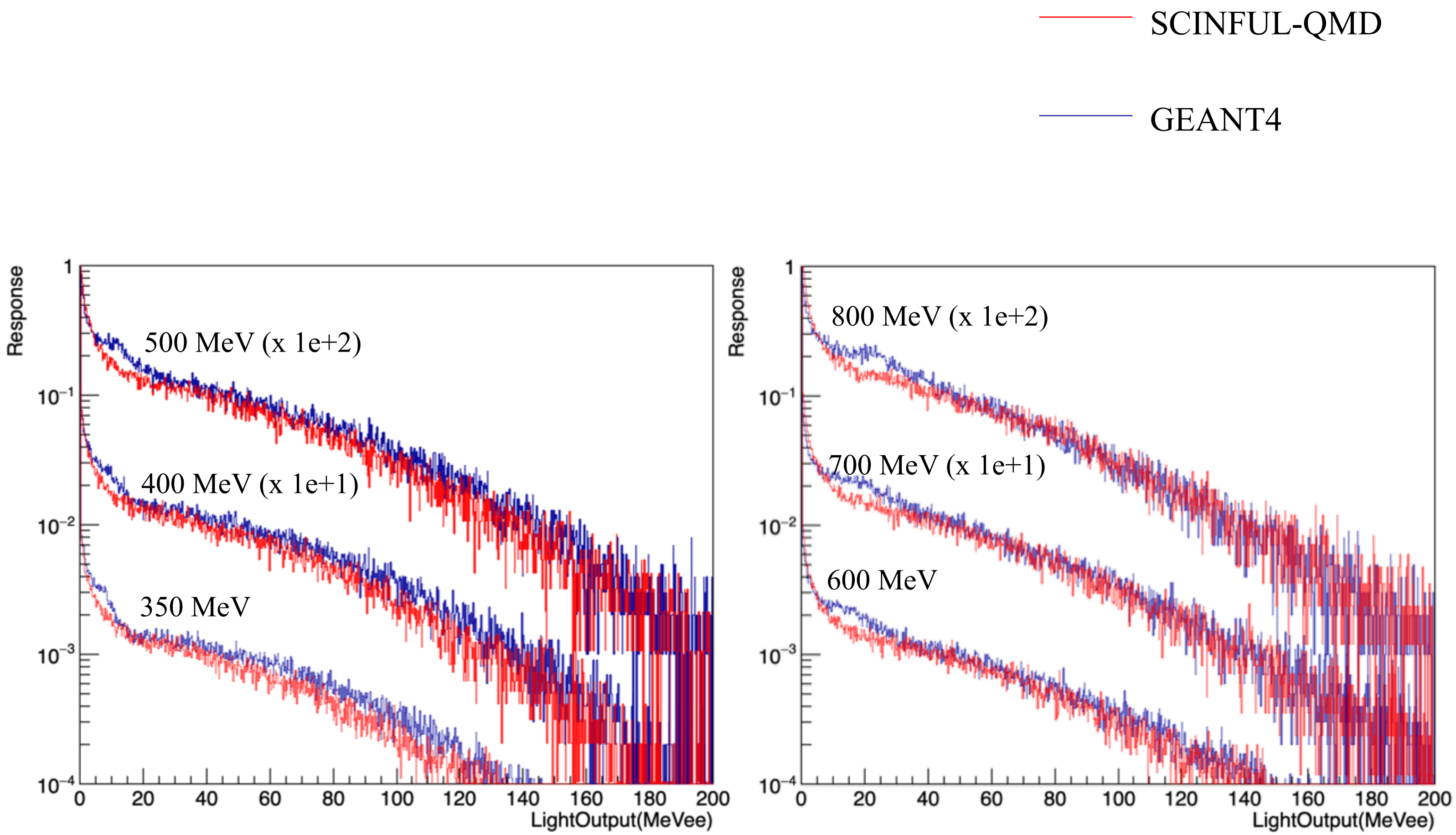
- Light response comparison for high energy of neutron.
- Basic GEANT4 library cannot reproduce SCINFUL results.
- The reason for the big discrepancy is because of miss implementation for inelastic collision channels in G4QMD model.



Neutron Simulation

QMD Model Implementation

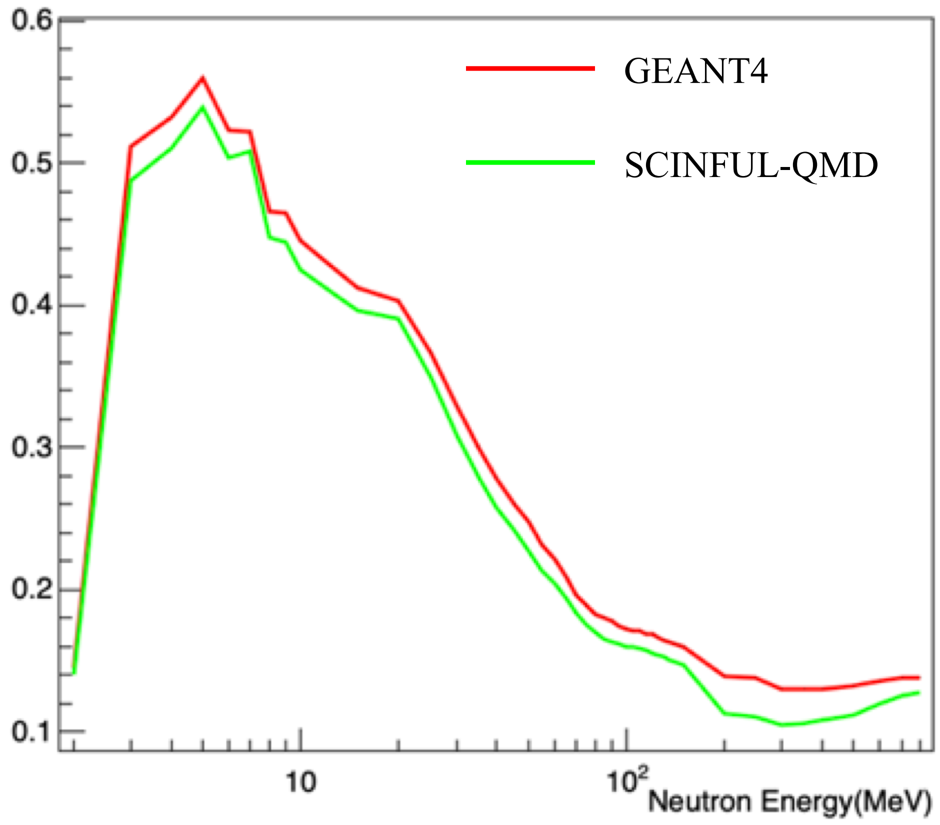
- Light response comparison for high energy of neutron after fixing inelastic collision channels.
- GEANT4 now has good agreements with SCINFUL-QMD results.
- Small discrepancy exists at low light yield.
- This discrepancy will be fixed.



Neutron Simulation

Neutron Detector Efficiency

- Neutron detector efficiency plot including high energy of neutron.
- Sudden drop at 150 MeV comes from QMD model for SCINFUL-QMD, whereas GEANT4 cannot reproduce.
- Guessing the difference of efficiency plot between two programs for high energy of neutron comes up because of the discrepancy around low light yield with QMD model.



Efficiency as a function of neutron energy

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 model.
- Neutron simulation has been developed after got the permission from NEA.
- Still has discrepancy for QMD model and the efficiency plot, but they will be fixed.

- Neutron simulation will be also used for the neutron array in LAMPS.

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
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  - Charged particle detection
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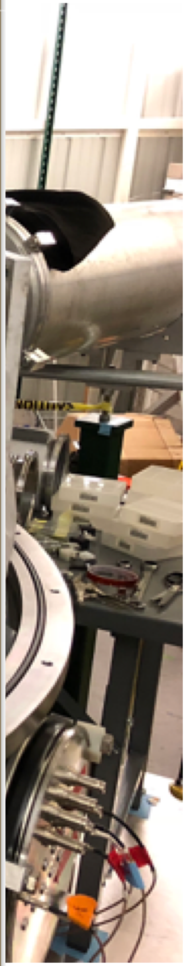
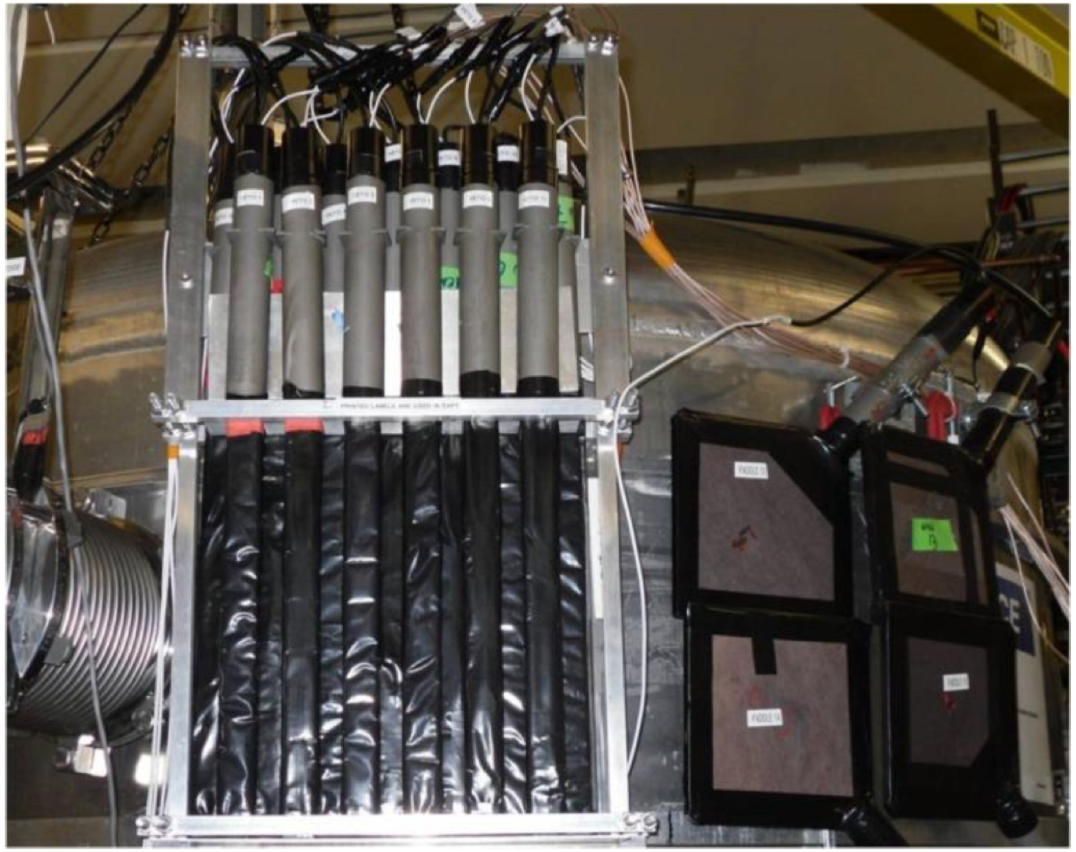
- LANA(Large Area Neutron Array)
  - Neutron detection
  - NE213
  - Connected with FADC(Korea)

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

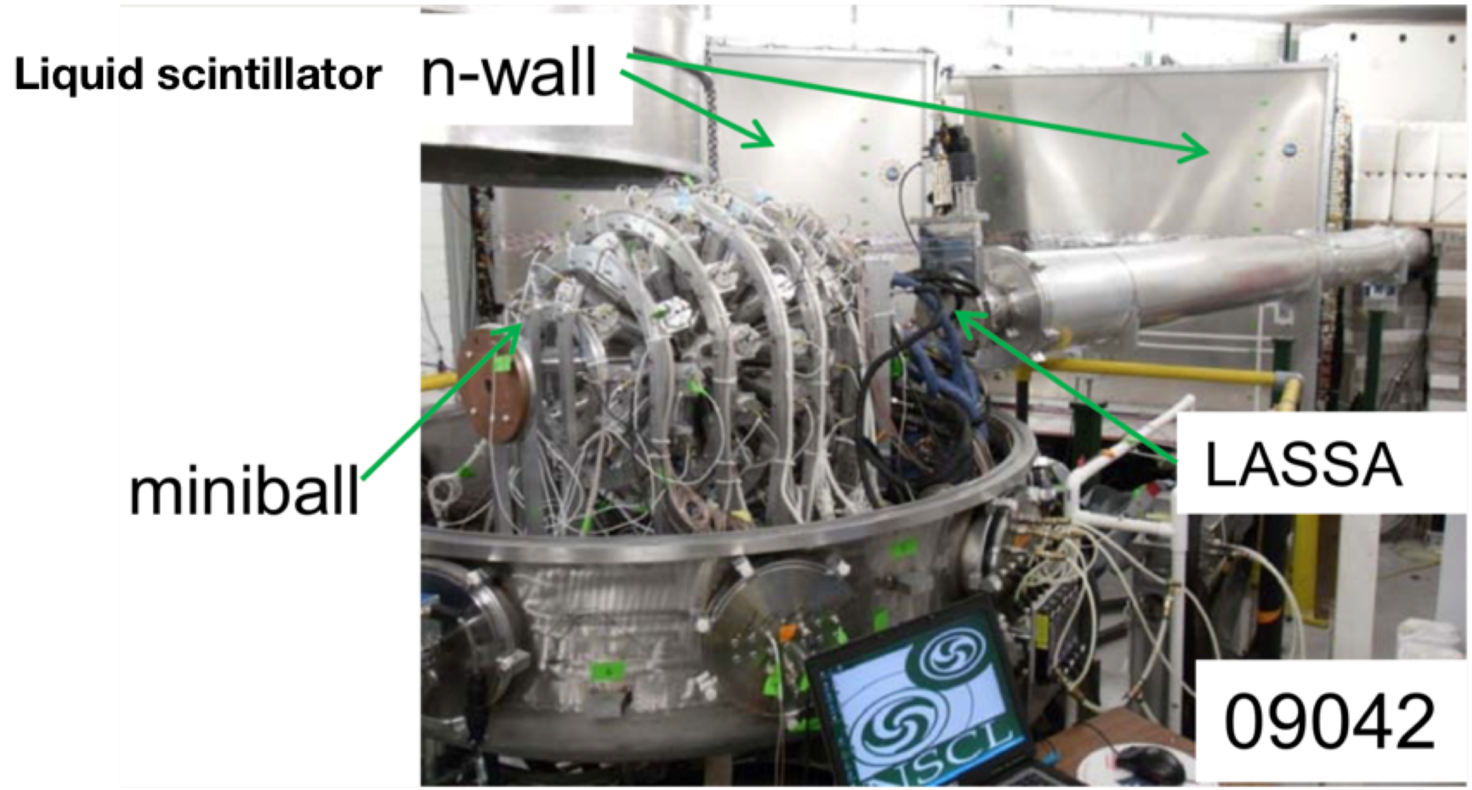
Beam	Target	Shadow bars	Avg trigger rate	Total time [HH:MM:SS]
Ca48@56 MeV/u	^{112}Sn	OUT	2812	06:39:33
		IN	2756	08:00:24
		TOTAL	2781/ 146M	14:39:57
Ca48@56 MeV/u	^{124}Sn	OUT	2558	26:06:27
		IN	2756	23:52:39
		TOTAL	2653/ 477M	49:59:06
Ca48@56 MeV/u	^{58}Ni	OUT	2619	05:41:13
		IN	2691	08:00:10
		TOTAL	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

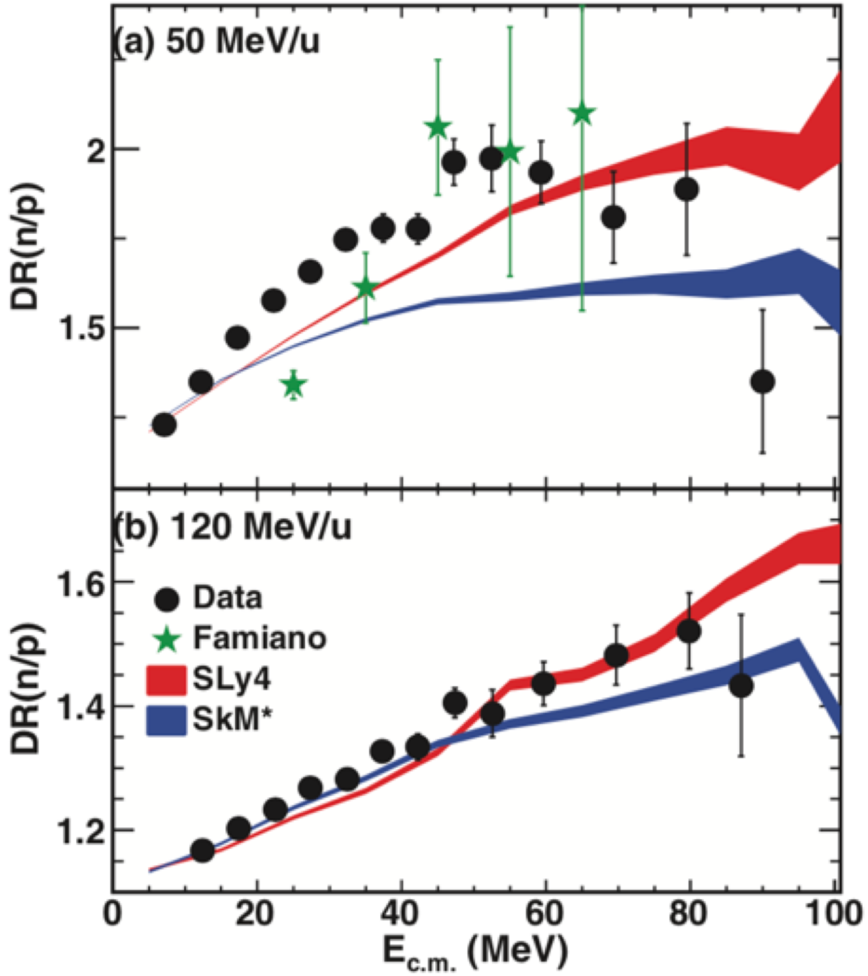


Back up : Charged Particle Veto



Back up : Previous experiment result





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