DDX measurements and theoretical analysis of $^{6,7}Li$ at 8 and 10 MeV

Guochang CHEN

China Institute of Atomic Energy
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Introduction of N-TOF Group

- 7 staffes (including 2 retired)
- Xichao Ruan (Header)

Zuying Zhou, Hongqing Tang, Xia Li, Hangxiong Huang, Qiping Zhong and me.

I. Neutron beam facility at CIAE

1) HI-13 Tandem 2×13MV (DC/Plused)

- **Pulse width: ~ 1ns;**
- **8~14 MeV: d+D, 10^9 neutrons/s;**
- **4~10 MeV: p+T, 10^8 neutrons/s;**
- **22~42 MeV: d+T, 10^7 neutrons/s;**
- **White neutron source: d-Be reaction;**
- **Deuterium and Tritium gas target;**

2) Neutron generator (DC/Plused)

2.5 MeV: d+D, 10^{10} neutrons/s;
14 MeV: d+T, 10^{11} neutrons/s;

3) Small tandem 2×1.7MV (DC)

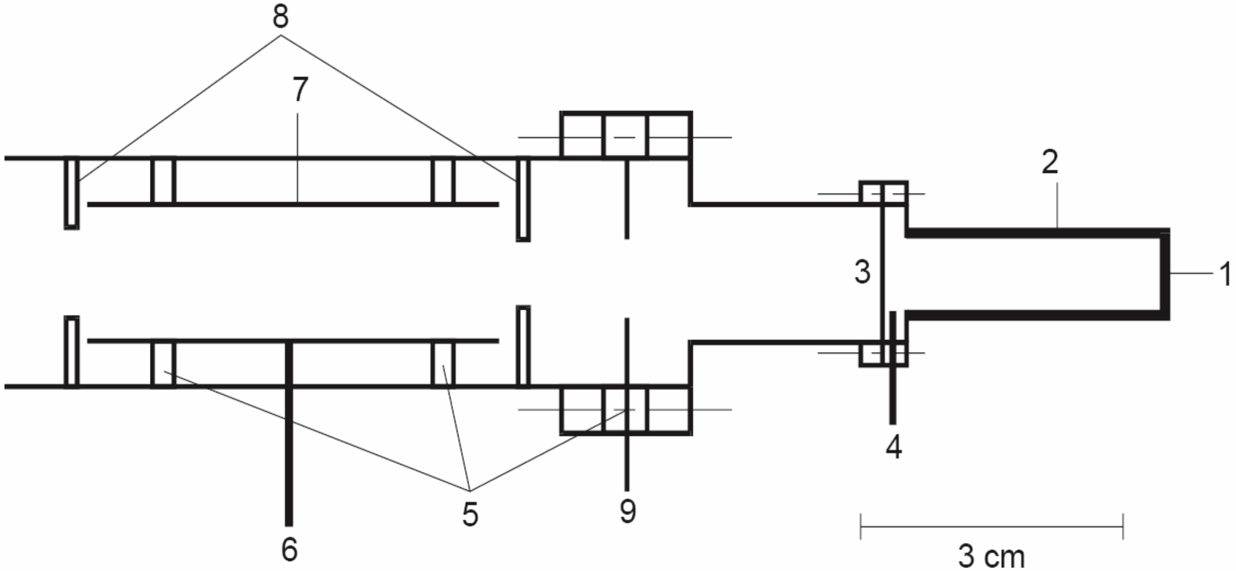
3~6 MeV: d+D, 10^{10} neutrons/s;
14~20 MeV: d+T, 10^{9} neutrons/s;
0.07~2.5 MeV: p+T, 10^{9} neutrons/s;
0.03~1.7 MeV: p+Li, 10^{10} neutrons/s;
Continuous beam, pulsed beam under development;

4) Reactor

High flux thermal neutron;

II. DDX measurement of $^{6,7}Li$

D_2 Gas Target



Length: 30 mm
Inner diameter: 10 mm
Outer diameter: 11mm
Gold backing: 0.5mm
Mo entrance foil: 10 μm
Gas pressure: 6 bar

1. gold backing; 2. platinum liner; 3. molybdenum entrance foil; 4. filling pipe; 5. insulators; 6. pickup signal; 7. pickup cylinder; 8. apertures; 9. suppressor voltage(-300V)

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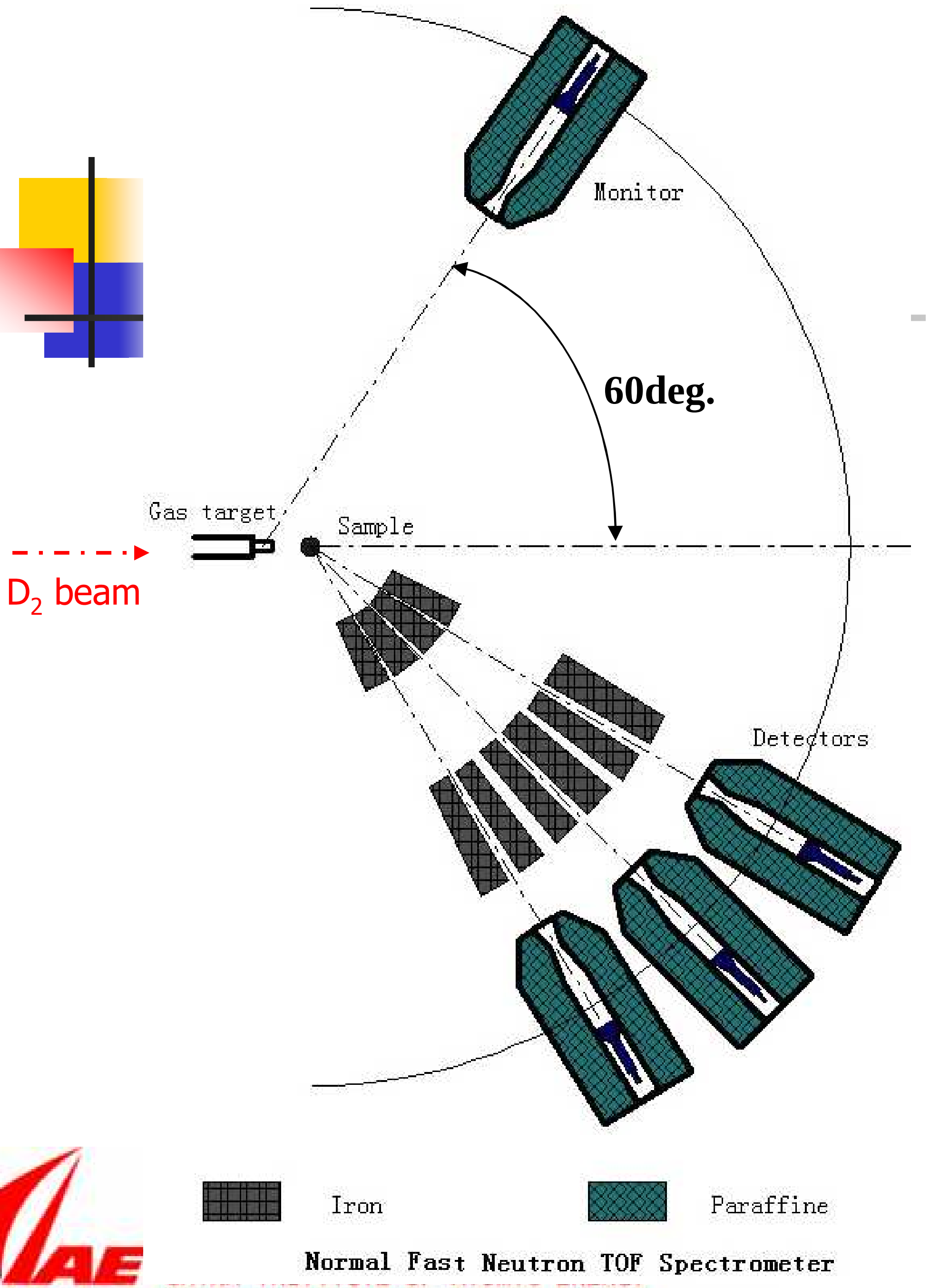


Distance:

3 main detectors are shielded and collimated;

Target ↔ Sample: 18 cm;

Sample ↔ Det. : ~ 6 m;

Angle: -30~160° ; 10° interval

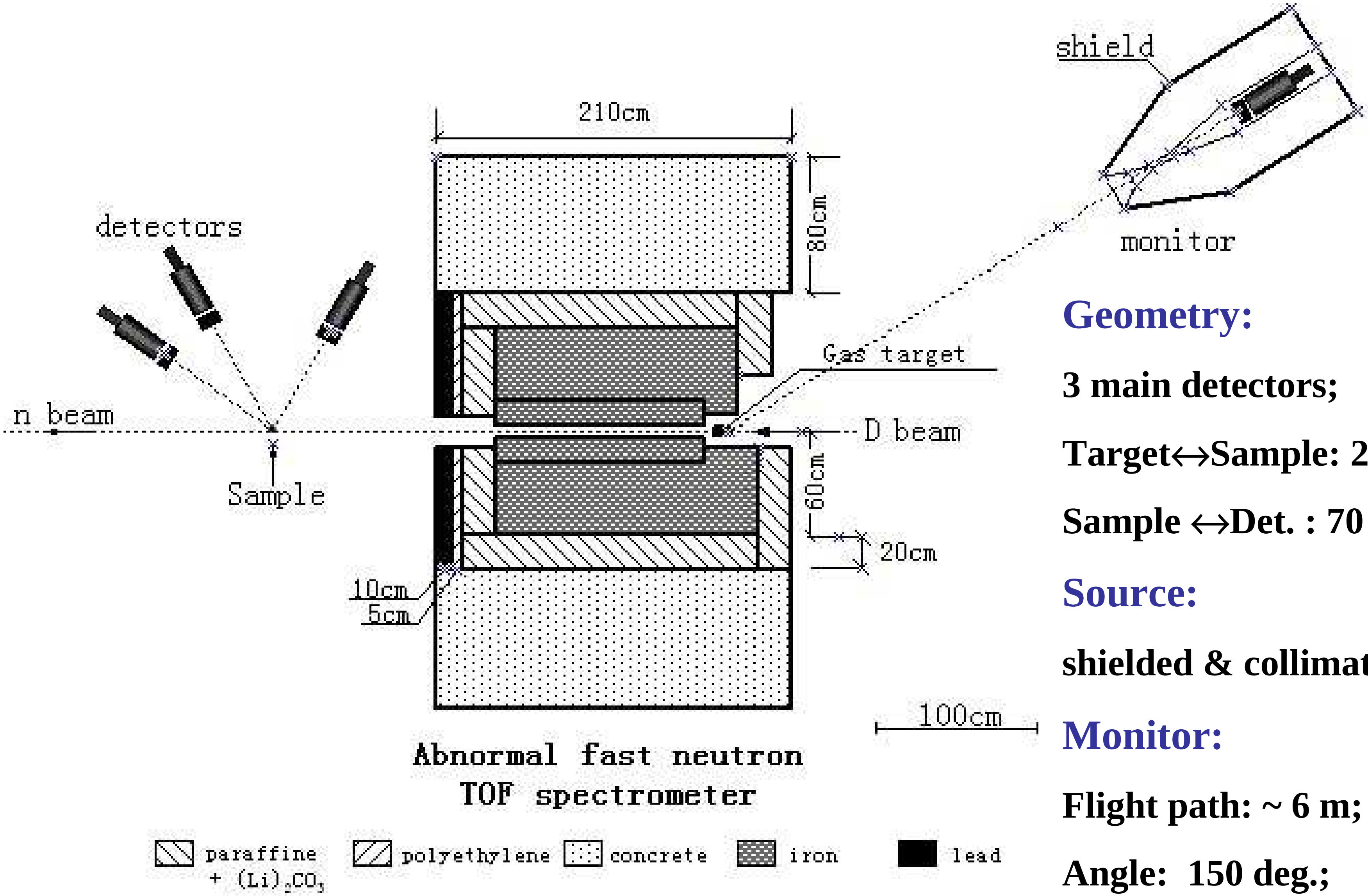
Monitor:

Stilbene scintillator/NE-213

Geometry: Φ30×30 mm; Φ25.4×25.4 mm;

Flight path: ~ 6 m;

Angle: 60 deg;



Geometry:

3 main detectors;

Target↔Sample: 220 cm;

Sample ↔Det. : 70 cm;

Source:

shielded & collimated;

Monitor:

Flight path: ~ 6 m;

Angle: 150 deg.;

Projectile

	8 MeV	10 MeV
E_d (MeV)	~ 5.80	~ 7.765
$\bar{I}_d$ (μA)	~ 0.3	~ 1.0
Pulse width (ns)	~ 1.0	~ 1.0
Rep. Freq.(MHz)	2.0	4.0

Detectors

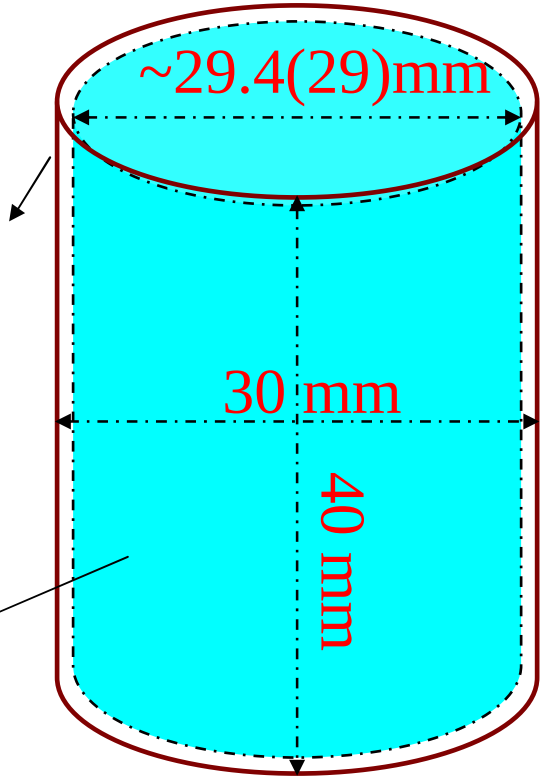
	8 MeV	10 MeV
Normal	BC-501A (160 keV) Φ17.78×10.16 cm	ST-451 (480 keV) Φ10.0×5.0 cm
Abnormal		ST-451 (160 keV)
Angle	30 ~150 deg. (12)	30 ~ 120 deg. (9)

Angle interval of each detector is 10 degree.

The scintillation liquid ST-451 is very similar to NE-213 scintillators used at PTB.

Lithium Samples

Al container is used to prevent the sample from oxidizing
^{6}Li:~ 0.3 mm
^{7}Li:~ 0.5 mm



^{6,7}Li sample

The samples are composed of highly purified and isotopically enriched lithium metal.

Sample	Geom. (mm×mm)	Wt.(Al) (g)	Wt.(tot) (g)	Atomic Percent (%)		
				^{6}Li	^{7}Li	^{27}Al
$^{6}Li^{a}$	Φ30 ×40	8.037	20.791	90.3	8.6	1.1
$^{6}Li^{b}$	Φ30 ×40	4.152	15.533	90.638	9.362	
^{7}Li	Φ30 ×40	8.174	23.272	5.0	95.0	
Al	Φ30 ×40		7.350*			
CH_2	Φ25 ×40		18.252			

Wt.(Al): weight of Al container; Wt.(tot): weight of sample+container;

***: It is an empty aluminum container; a,b: normal and abnormal;**

Data analysis (1)

- **Raw event reduction using PAW;**
- **Deadtime correction and background subtraction;**
- **Neutron energy determination:**

1) Use Li elastic and gamma peak;

2) Use Δt between elastic and the 1^{st} inelastic scattering neutron of C, flight path and angle;

Neutron energies agree with each other within uncertainty by 1) and 2) method;

Data analysis (2)

- **n-p reaction cross sections for normalization**
- **M-C simulation**

The measured TOF spectra were simulated by the code STREUER.

- **Transformation of the STREUER results in experimental condition**

including Time response function, TAC calibration and non-linearity, normalization factor etc.

Data analysis (3)

- **The data base of STREUER code was iteratively improved, and the data of Al container were included in simulation;**
- **Comparison between MC calculations and measurements;**
- **Experimental results;**

Uncertainties

- **Statistical uncertainty**

  3~7% (normal); ~ 15% (abnormal)

- **Neutron detection efficiency**

  ~ 5%; around the threshold its ~ 10%;

- **Scattering angle:** $\leq 0.5°$;
- **n-p cross section:** ~ 1%;
- **Correction of multiple scattering:** 1~3%;
- **Energy resolution:** ~ 5%(normal); ~20%(abnormal);

III. Theoretical Calculation

- **Based on Hauser-Feshbach(HF) + Exciton Model;**
- **The first particle emissions can be described by pre-equilibrium and equilibrium mechanisms;**
- **Angular momentum conservation and angular coupling effects are taken into account;**
- **Nuclear recoil effect;**

- **Two-body and three-body breakup processes**

  $^{5}He \rightarrow n+\alpha;$ $^{5}Li \rightarrow p+\alpha$

  $^{6}He^{*} \rightarrow n+n+\alpha;$

- **Direct three-body breakup process**

  $n+{}^{6}Li \rightarrow n+d+\alpha$

n+^{6}Li Reaction

$$
n+{}^{6}Li \rightarrow {}^{7}Li^{*}
\begin{cases}
\gamma + {}^{7}Li & & (n,\gamma)^{7}Li \\
n+{}^{6}Li \begin{cases} {}^{6}Li & k=gs,2 \\ p+{}^{5}He \rightarrow n+\alpha & k \geq 4 \\ d+\alpha & k=1,3,4,\ldots \\ n+{}^{5}Li \rightarrow p+\alpha & k \geq 6 \end{cases} & \begin{matrix} (n,el+n') \\ (n,2np\alpha) \\ (n,nd\alpha) \\ (n,2np\alpha) \end{matrix} \\
p+{}^{6}He \begin{cases} {}^{6}He & k=gs \\ n+n+\alpha & k=1 \\ n+{}^{5}He \rightarrow n+\alpha & k>1 \end{cases} & \begin{matrix} (n,p)^{6}He \\ (n,2np\alpha) \\ (n,2np\alpha) \end{matrix} \\
d+{}^{5}He \rightarrow n+\alpha & & (n,nd\alpha) \\
t+\alpha & & (n,t)\alpha \\
n+d+\alpha & & (n,nd\alpha)
\end{cases}
$$

Inelastic scattering

Direct three-body breakup

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n+^{6}Li Reaction channel conclusion

$$
n +^6 Li = \begin{cases} \gamma +^7 Li & Q = 7.249\ MeV \\ p +^6 He & \beta^-, T_{1/2} = 806.7\ ms, Q = -2.725\ MeV \\ d +^5 He(n+\alpha) & Q = -1.475\ MeV \\ t + \alpha & Q = 4.782\ MeV \\ 2n +^5 Li(p+\alpha) & Q = -3.700\ MeV \\ n, p +^5 He(n+\alpha) & Q = -4.594\ MeV \\ n, d + \alpha & Q = -1.475\ MeV \end{cases}
$$

→ (n, γ), (n, el), (n, inl), (n, p), (n, nd)α, (n, t)α and (n, 2np)α

n+^{7}Li Reaction

$$
n+{}^7Li \rightarrow {}^8Li^* \left\{
\begin{array}{lll}
\gamma+{}^8Li & & (n,\gamma)^8Li \\
n+{}^7Li \left\{
\begin{array}{l}
\begin{array}{lll} {}^7Li & k=gs & (n,el)^7Li \end{array} \\
\begin{array}{lll} \gamma+{}^7Li & k=1 & (n,n')^7Li \end{array} \\
n+{}^6Li \left\{
\begin{array}{lll}
{}^6Li & k=gs,2 & (n,2n)^6Li \\
p+{}^5He \rightarrow n+\alpha & k\geq 4 & (n,3np\alpha) \\
d+\alpha & k=1,3,4,\ldots & (n,2nd\alpha) \\
n+{}^5Li \rightarrow p+\alpha & k\geq 6 & (n,3np\alpha)
\end{array}\right. \\
p+{}^6He \left\{
\begin{array}{lll}
{}^6He & k=gs & (n,np) \\
n+n+\alpha & k\geq 1 & (n,3np\alpha)
\end{array}\right. \\
\begin{array}{ll} d+{}^5He \rightarrow n+\alpha & (n,nd\alpha) \end{array} \\
\begin{array}{ll} t+\alpha & (n,t)\alpha \end{array}
\end{array}\right. & & \\
p+n+{}^6He \left\{
\begin{array}{lll}
{}^6He & k=gs & (n,np) \\
n+n+\alpha & k\geq 1 & (n,3np\alpha)
\end{array}\right. & & \\
d+{}^6He \left\{
\begin{array}{lll}
{}^6He & k=gs & (n,np) \\
n+n+\alpha & k\geq 1 & (n,3np\alpha)
\end{array}\right. & & \\
t+{}^5He \rightarrow n+\alpha & &
\end{array}\right.
$$

n+^{7}Li Reaction channel conclusion

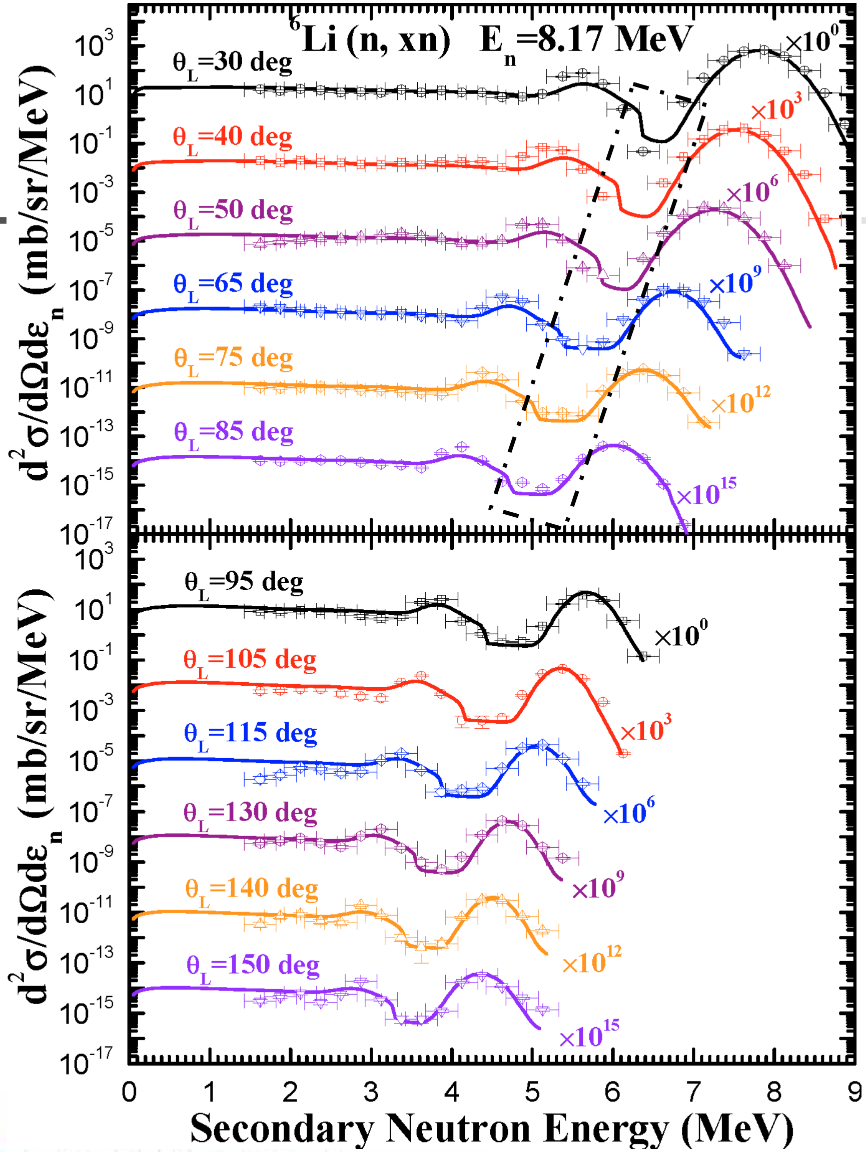
$$n +^7 Li = \begin{cases} \gamma +^8 Li & Q = 2.033\ MeV \\ n' +^7 Li^* & Q = -0.4776\ MeV \\ d +^6 He & Q = -7.750\ MeV \\ t +^5 He & Q = -3.3362\ MeV \\ 2n +^6 Li & Q = -7.249\ MeV \\ n,\ p +^6 He & Q = -9.974\ MeV \\ n,\ d +^5 He & Q = -9.618\ MeV \\ n,\ t + \alpha & Q = -2.467\ MeV \\ 2n,\ p +^5 He & Q = -11.842\ MeV \\ 2n,\ d + \alpha & Q = -8.724\ MeV \end{cases}$$

→ (n, γ), (n, el), (n, inl), (n, 2n), (n, np)$^6He_{gs}$, (n, d)$^6He_{gs}$, (n, nt)α, (n, 2nd)α and (n,3np)α

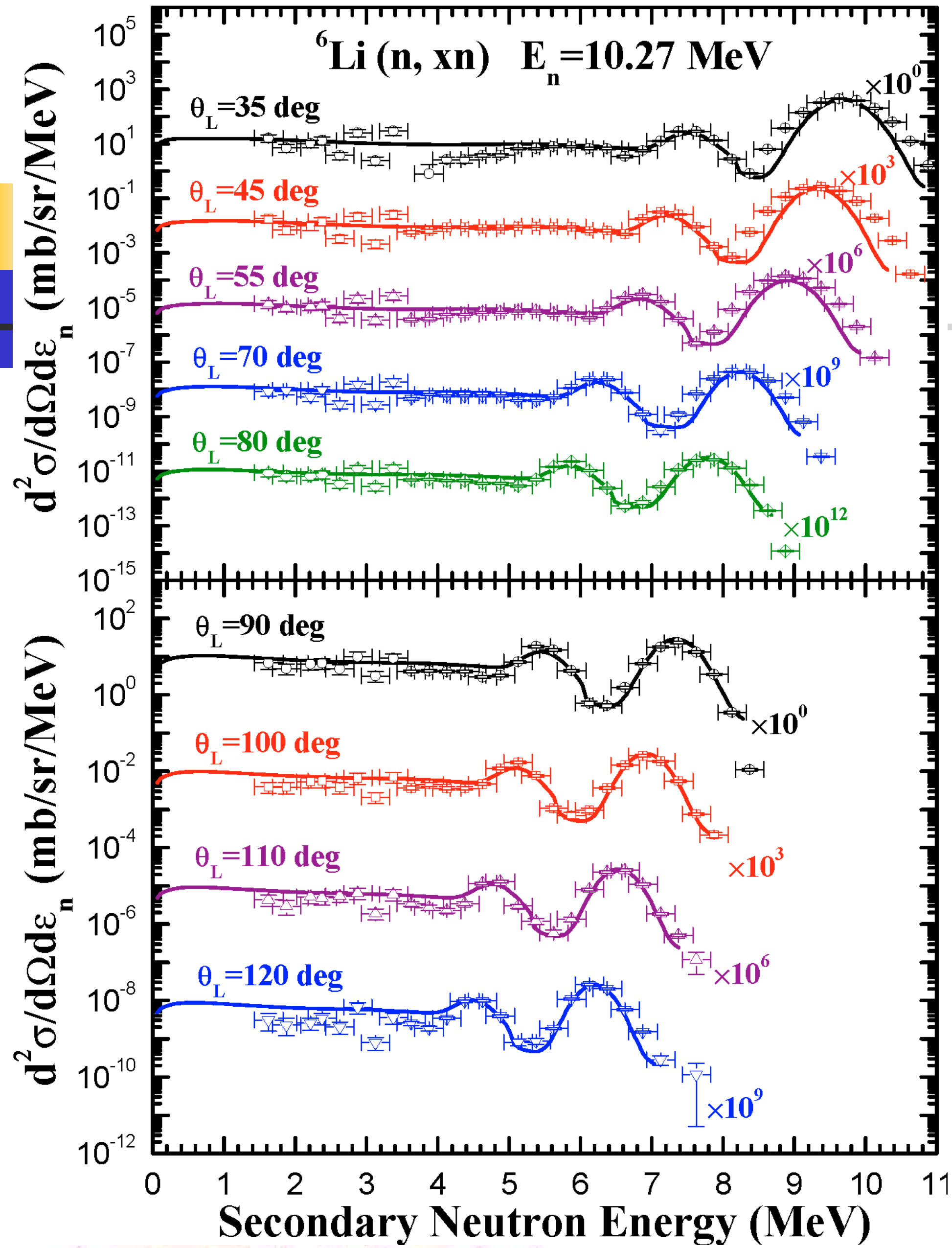
- **Based on H-F and exciton model;**
- **Lithium reaction processes analysis;**
- **LUNF code was developed by CNDC for Li model calculation up to 20 MeV;**
- **APOM94 code was applied to obtain Optical model parameters;**
- **Adopt the latest level scheme of TUNL;**

IV. Comparison between Exp. & Cal.

^{6}Li Part



- A big energy gap between ground state and the 1st level (Ex=2.186 MeV);
- Main contribution from (n, n)^{6}Li*(1st) →d+α and elastic;
- Guess: maybe there exist other new levels;



- >3.5 MeV: measured by normal spectrometer;
- ≤ 3.5MeV: by abnormal (energy bin is 50 keV);
- Not enough beam time for abnormal measurement;
- Need to set a little bigger energy bin in abnormal data analysis;

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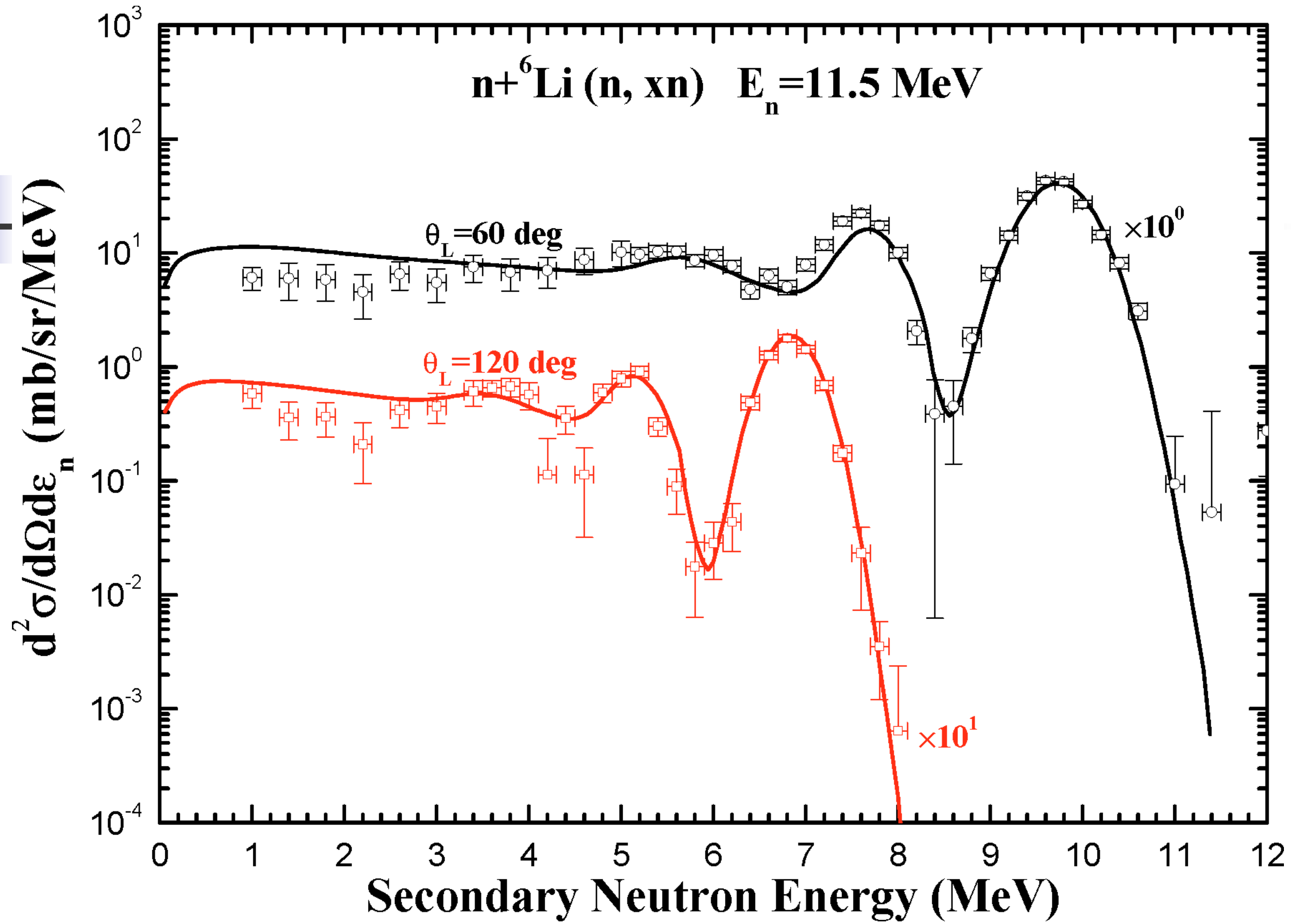

Comparison between calculated results and M.Ibaraki measurements

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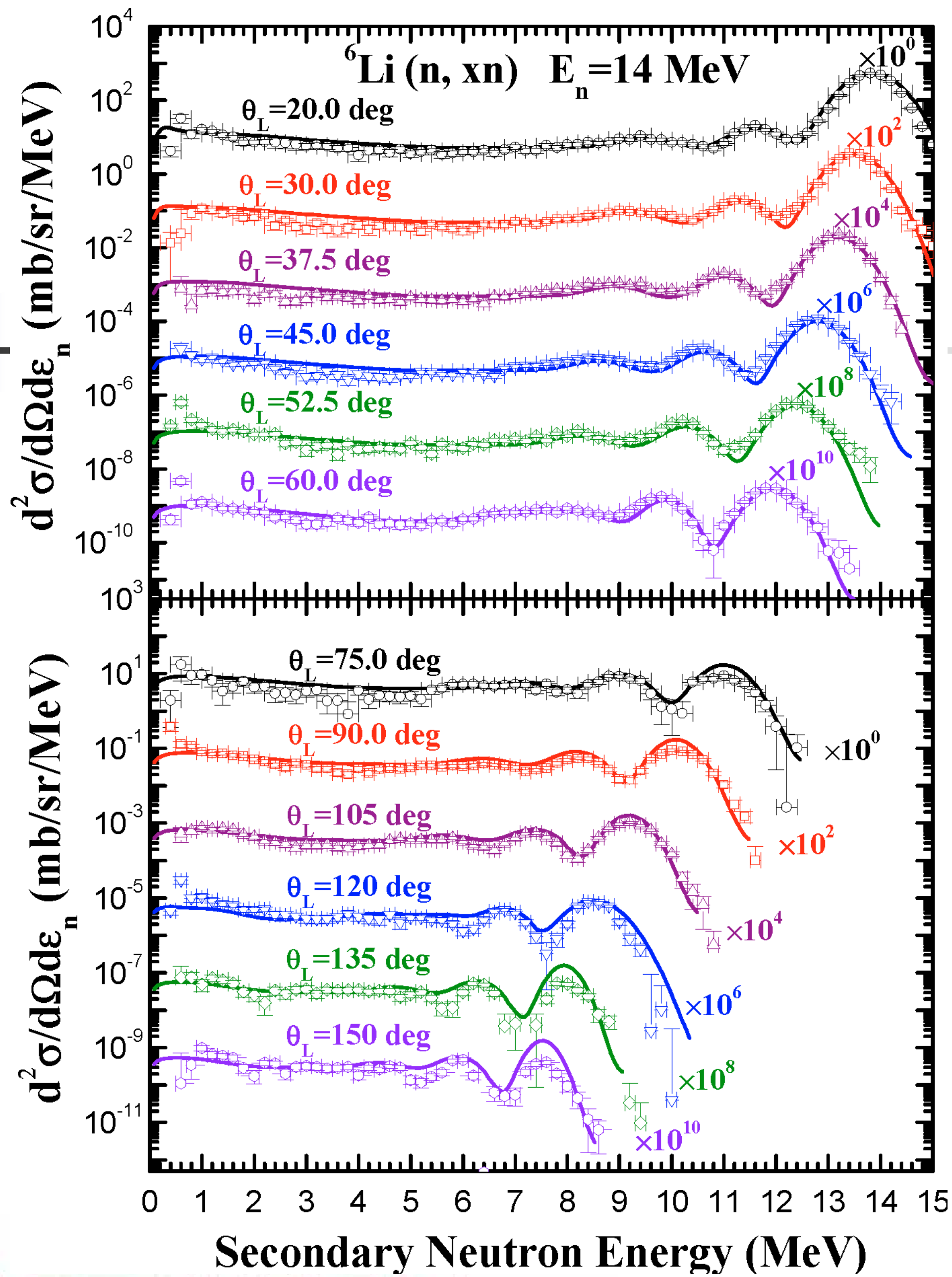

Exp. Data were taken from Tohoku University measurements

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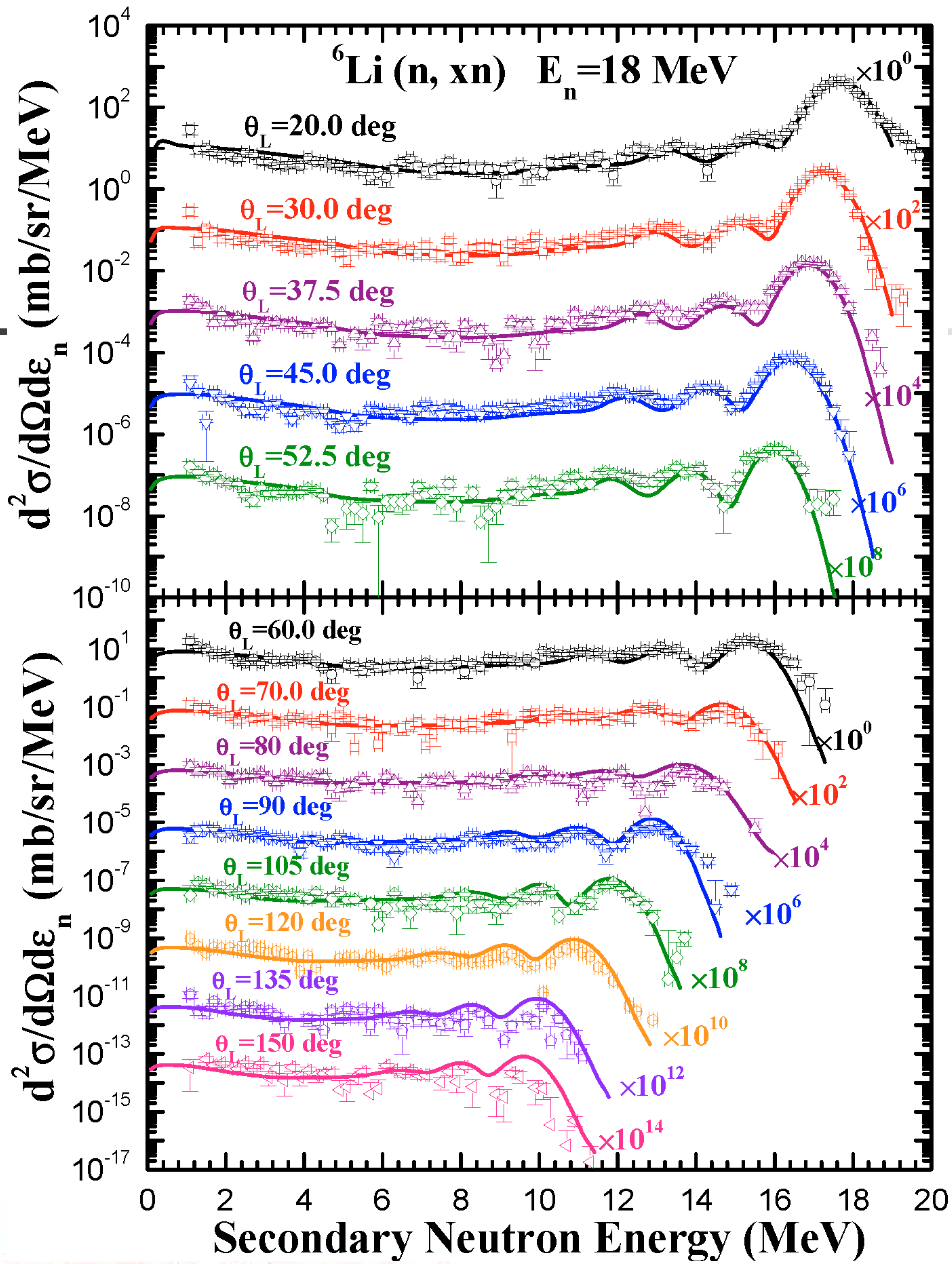
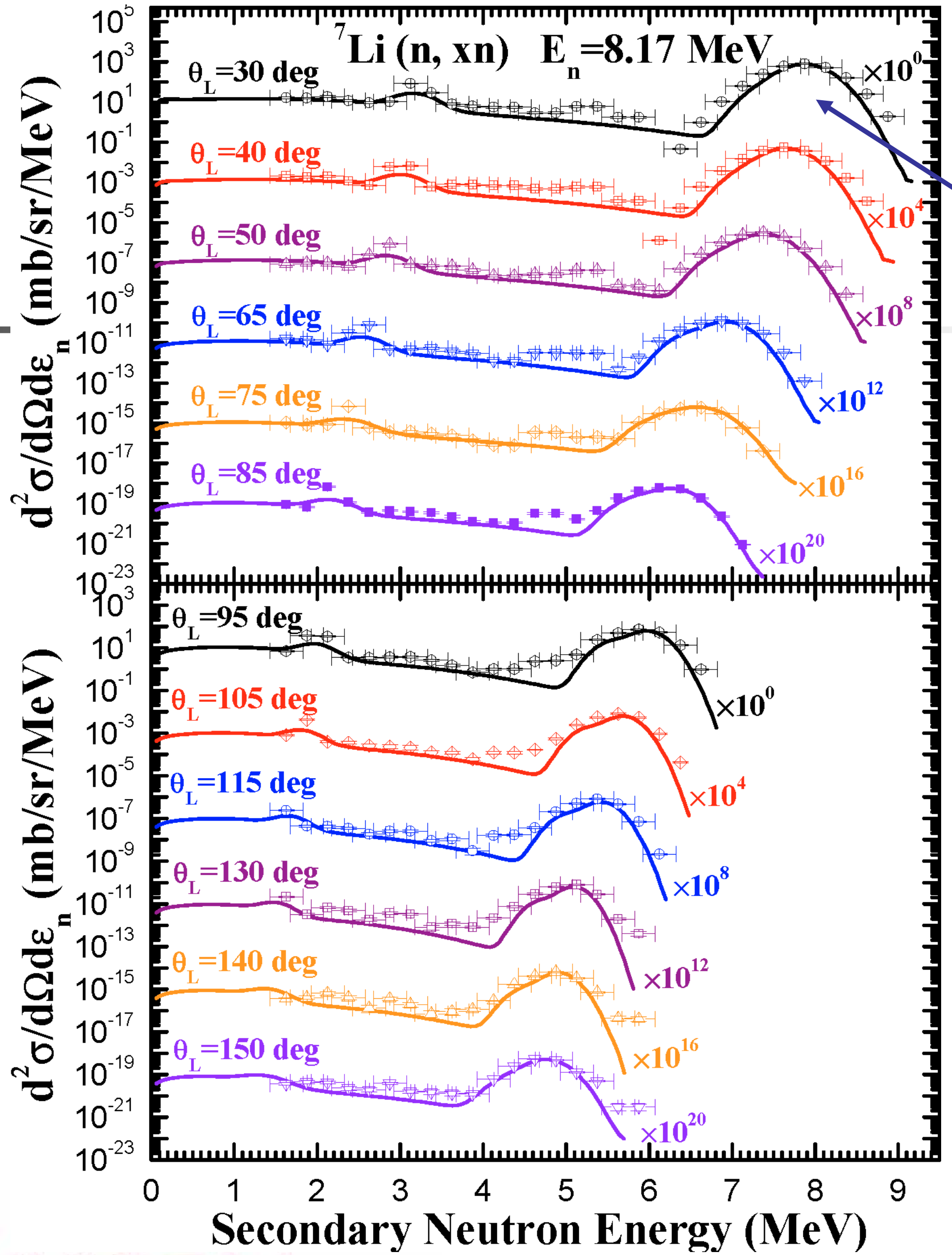


Exp. Data were taken from Tohoku University measurements

^{7}Li Part



Include elastic and 1st inelastic

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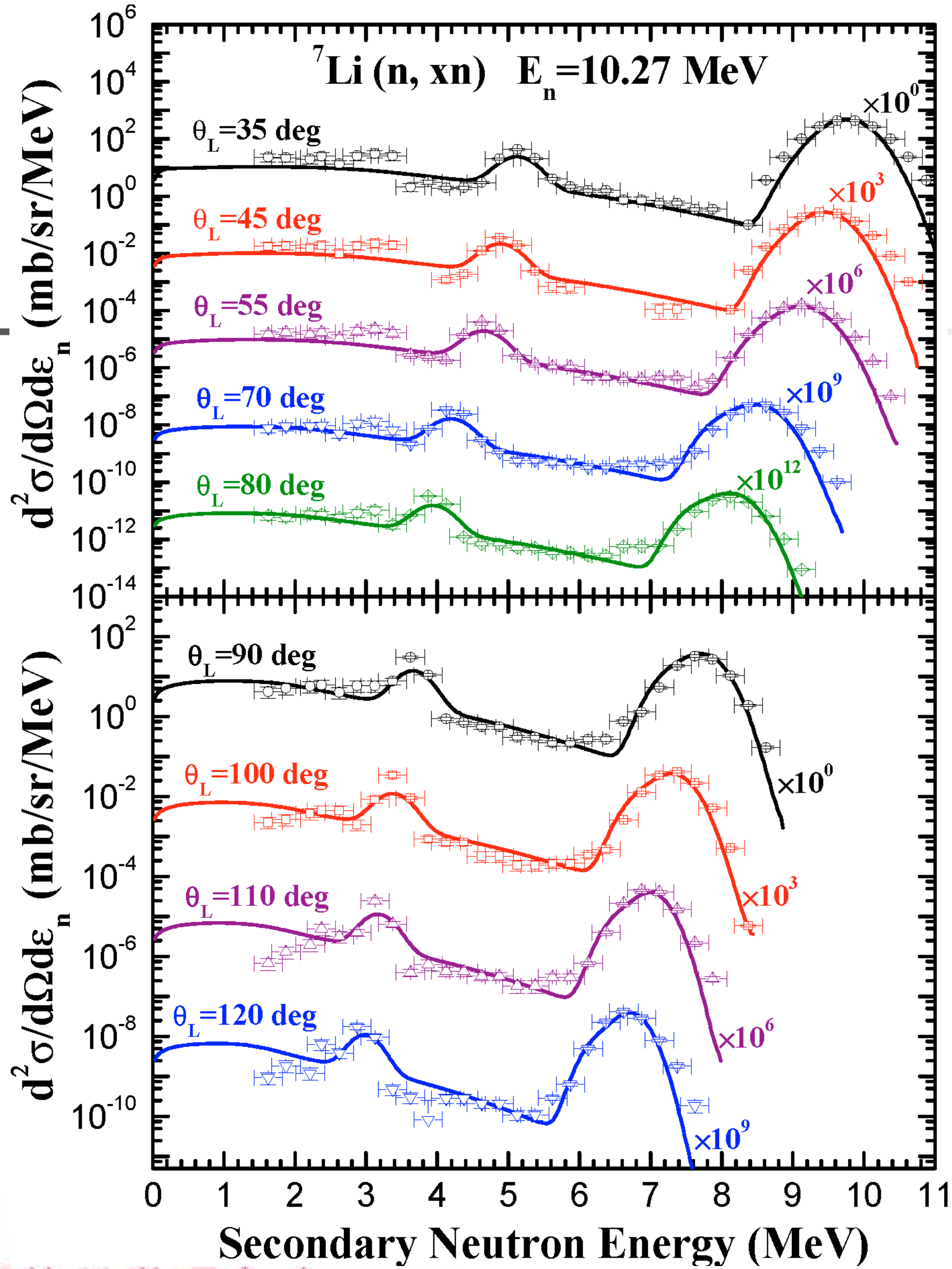

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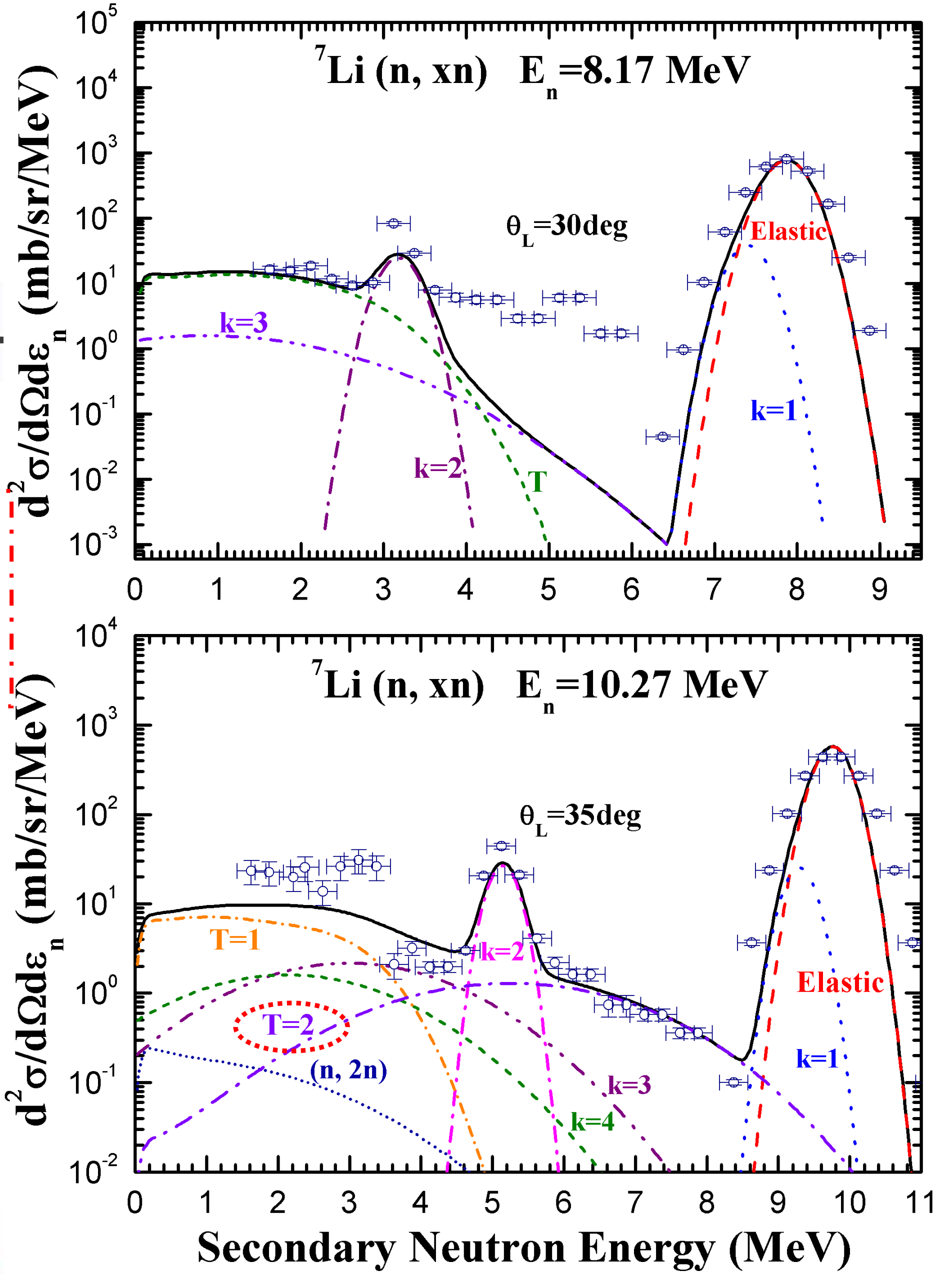

Table of Isotopes 8th edition

- $k=1\sim3$: the first emitted neutron from $^8Li^*$ to the k_{th} excited state of ^7Li;
- T: $^7Li(n, t)^5He_{gs}$

- $k=1\sim4$: the first emitted neutron from $^8Li^*$ to the k_{th} excited state of ^7Li;
- T=1, 2: $^7Li(n, t)^5He$

^5He at gs and 1st excited state (E_{th}=8.53 MeV)

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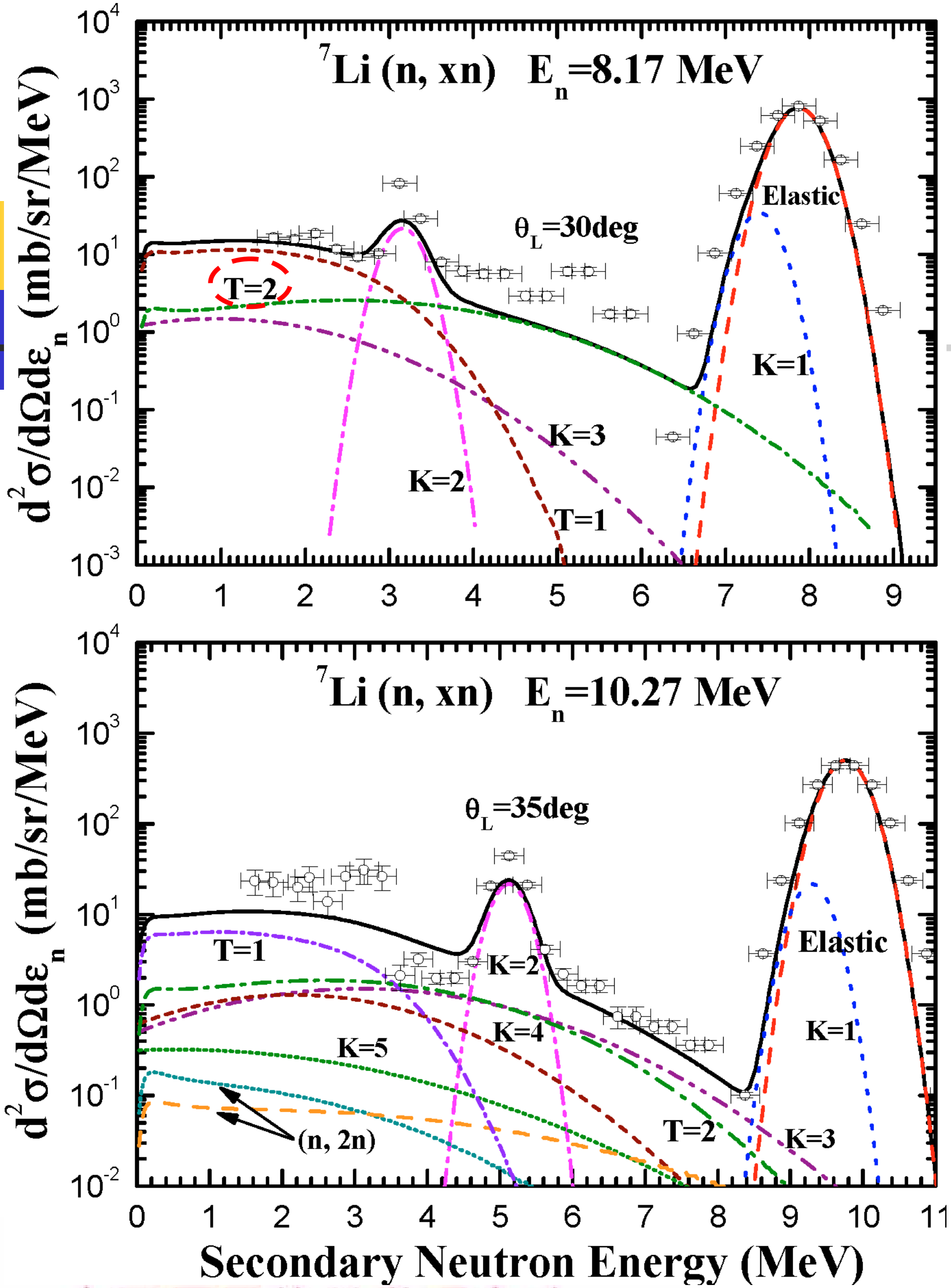
The partial neutron emission spectra



^{5}He level scheme & reaction threshold of ^{7}Li(n,t)^{5}He* in MeV:

	1st	2nd	E_{th}
8th	4 (1/2-)	16.75(3/2+)	8.53
latest	1.27(1/2-)	16.84(3/2+)	5.32

The partial neutron emission spectra

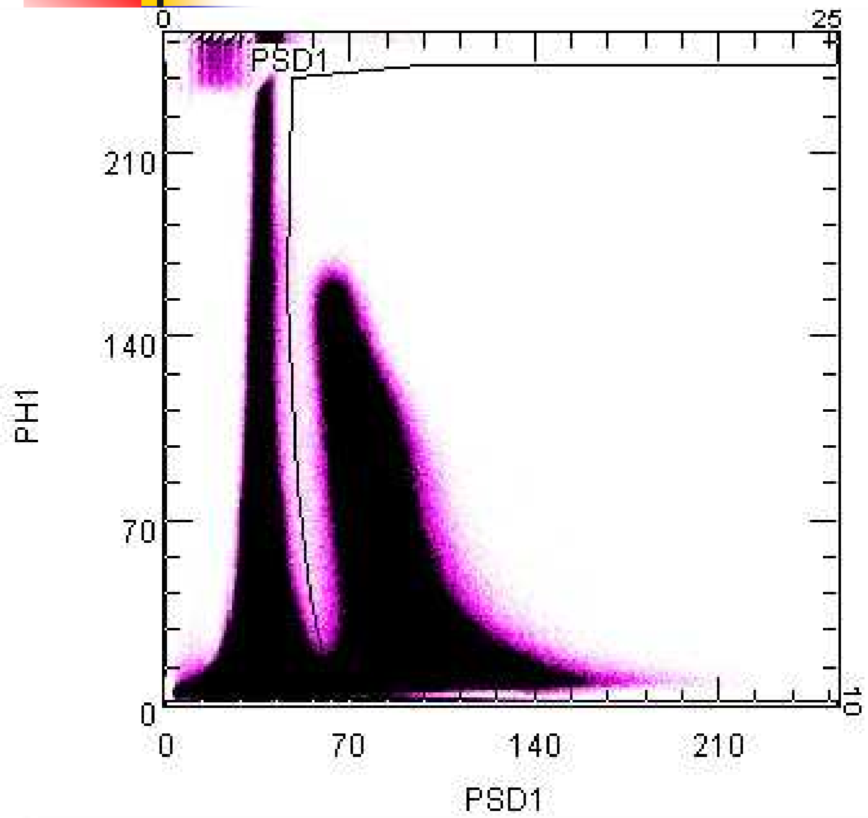
Summary

- DDX of $^{6,7}Li$ were measured at 8 and 10 MeV;
- Using LUNF code, the calculated DDX were obtained and compared with the experimental data;
- Exist some deviations between Exp. and Cal.;
- For modify LUNF code, need more reasonable experimental data at different energy regions and level scheme;

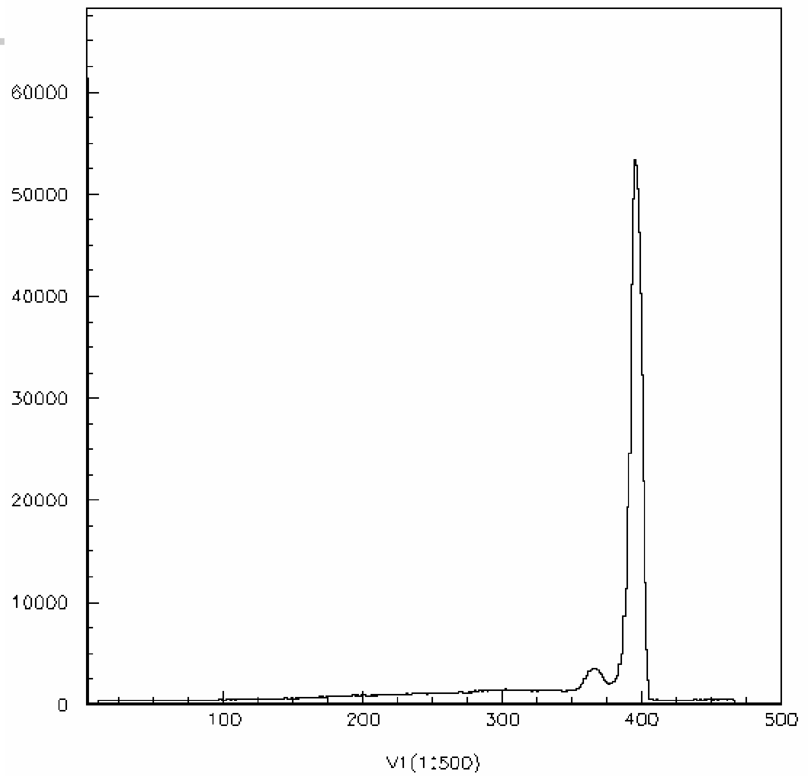
Thanks
Dank
谢谢!

PH vs. PSD

TOF



PAW



PH vs. PSD open a window to obtain TOF spectra

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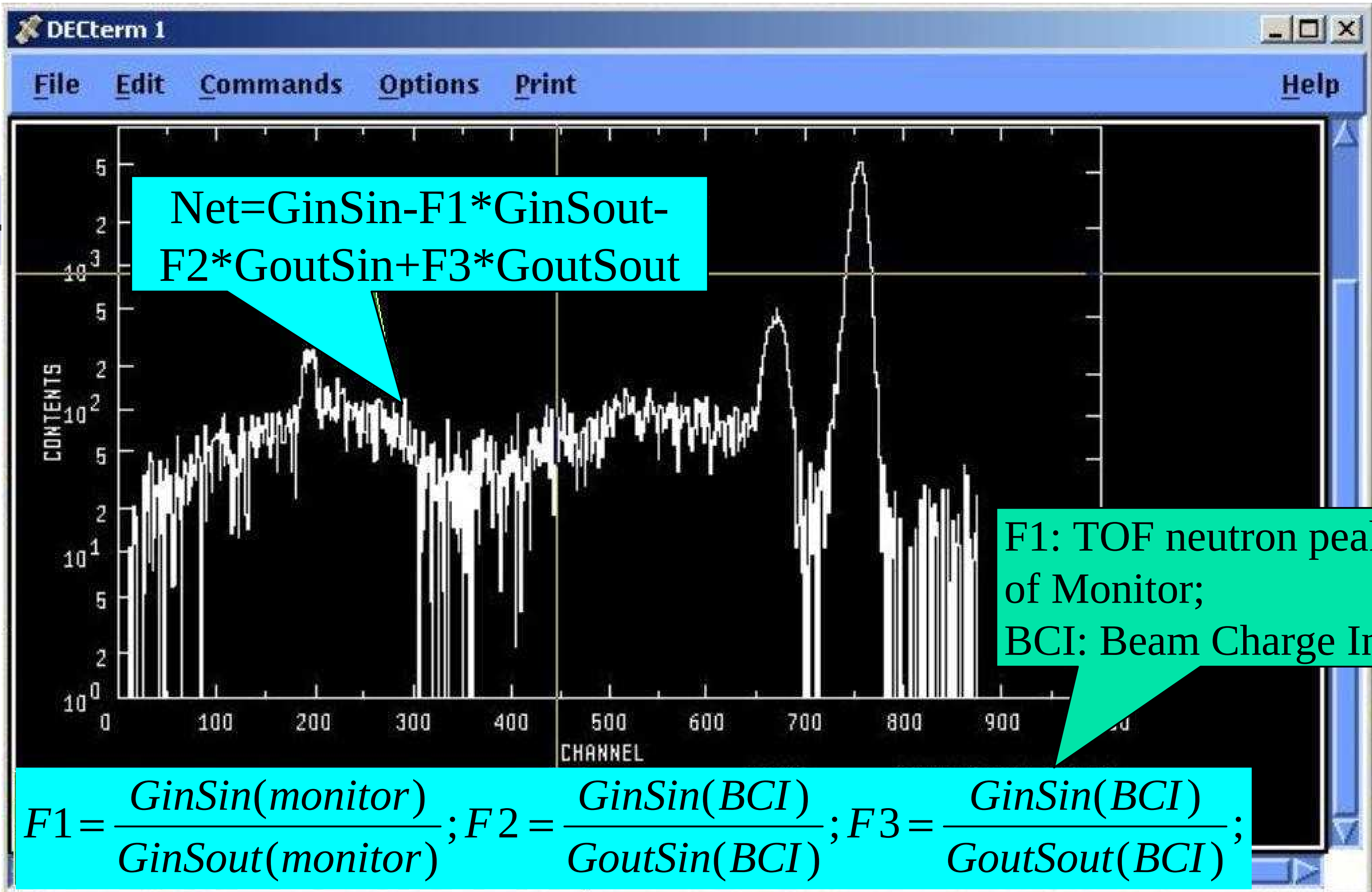
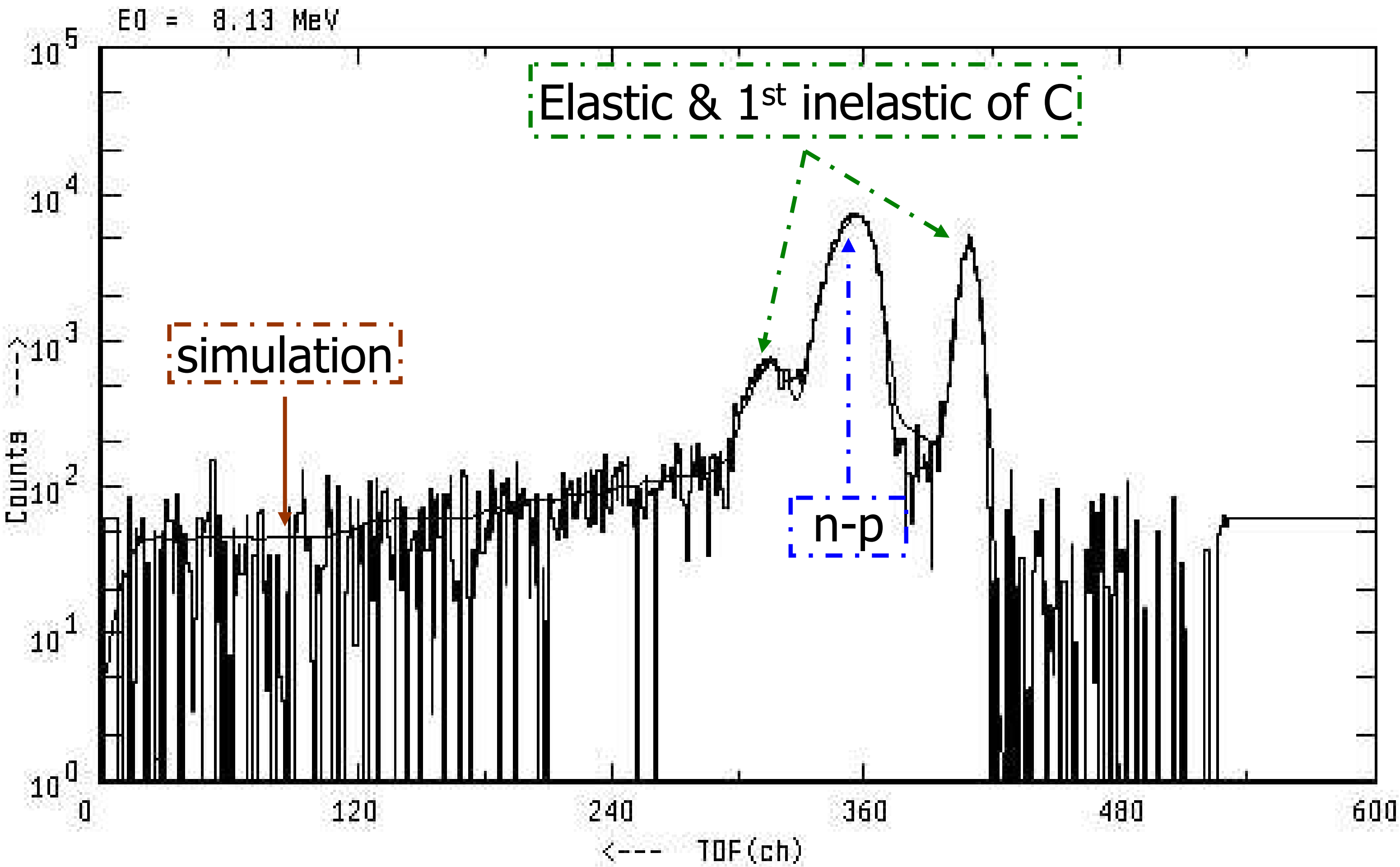
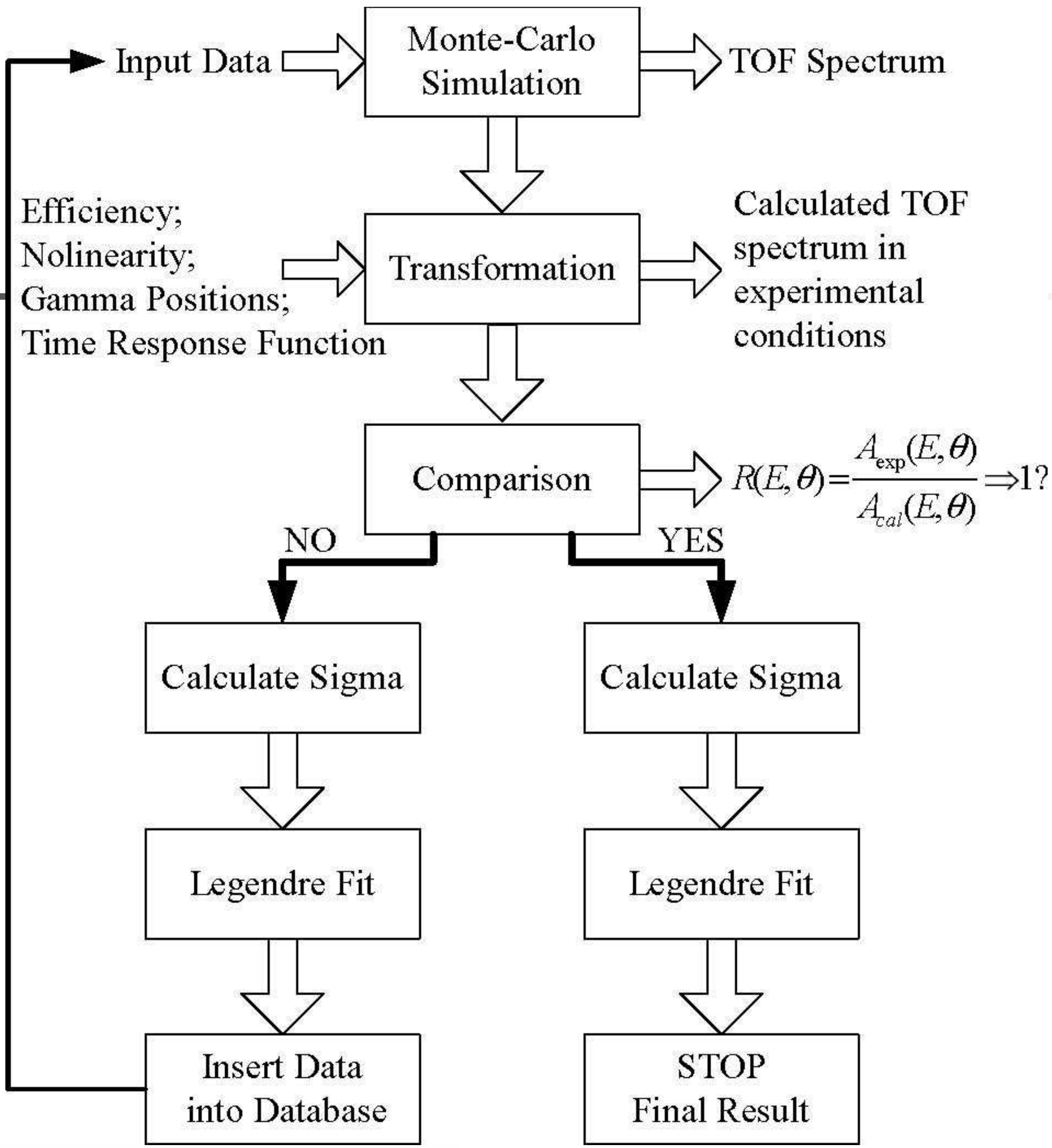
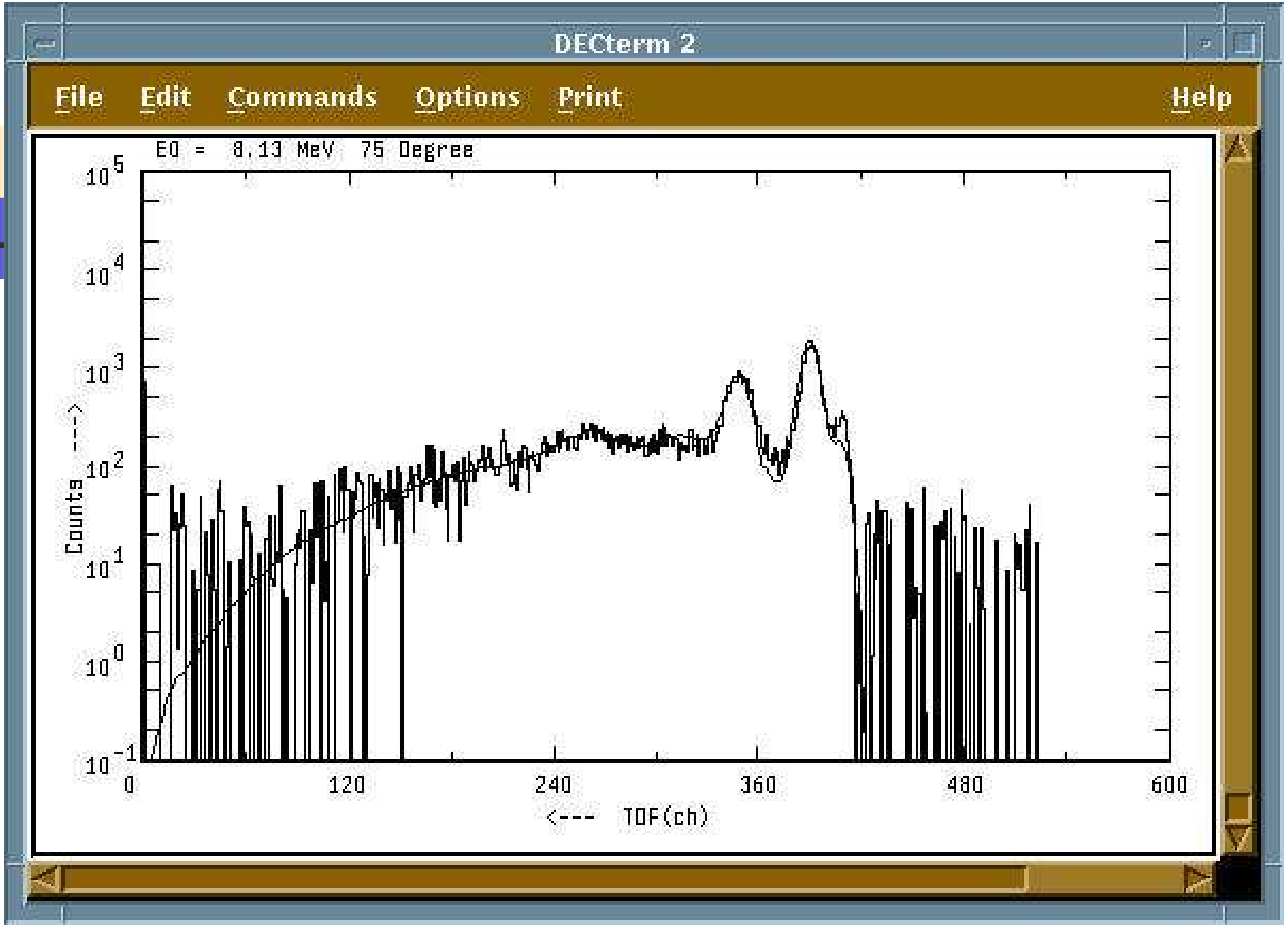


Net TOF spectrum after deadtime correction & background subtraction



TOF spectra of CH_2 sample


Input Data
Monte-Carlo Simulation
TOF Spectrum
Efficiency;
Nolinearity;
Gamma Positions;
Time Response Function
Transformation
Calculated TOF spectrum in experimental conditions
Comparison
$R(E,\theta)=\frac{A_{exp}(E,\theta)}{A_{cal}(E,\theta)}\Rightarrow 1?$
NO
YES
Calculate Sigma
Calculate Sigma
Legendre Fit
Legendre Fit
Insert Data into Database
STOP Final Result



Comparison between simulated and EXP. of ^{6}Li

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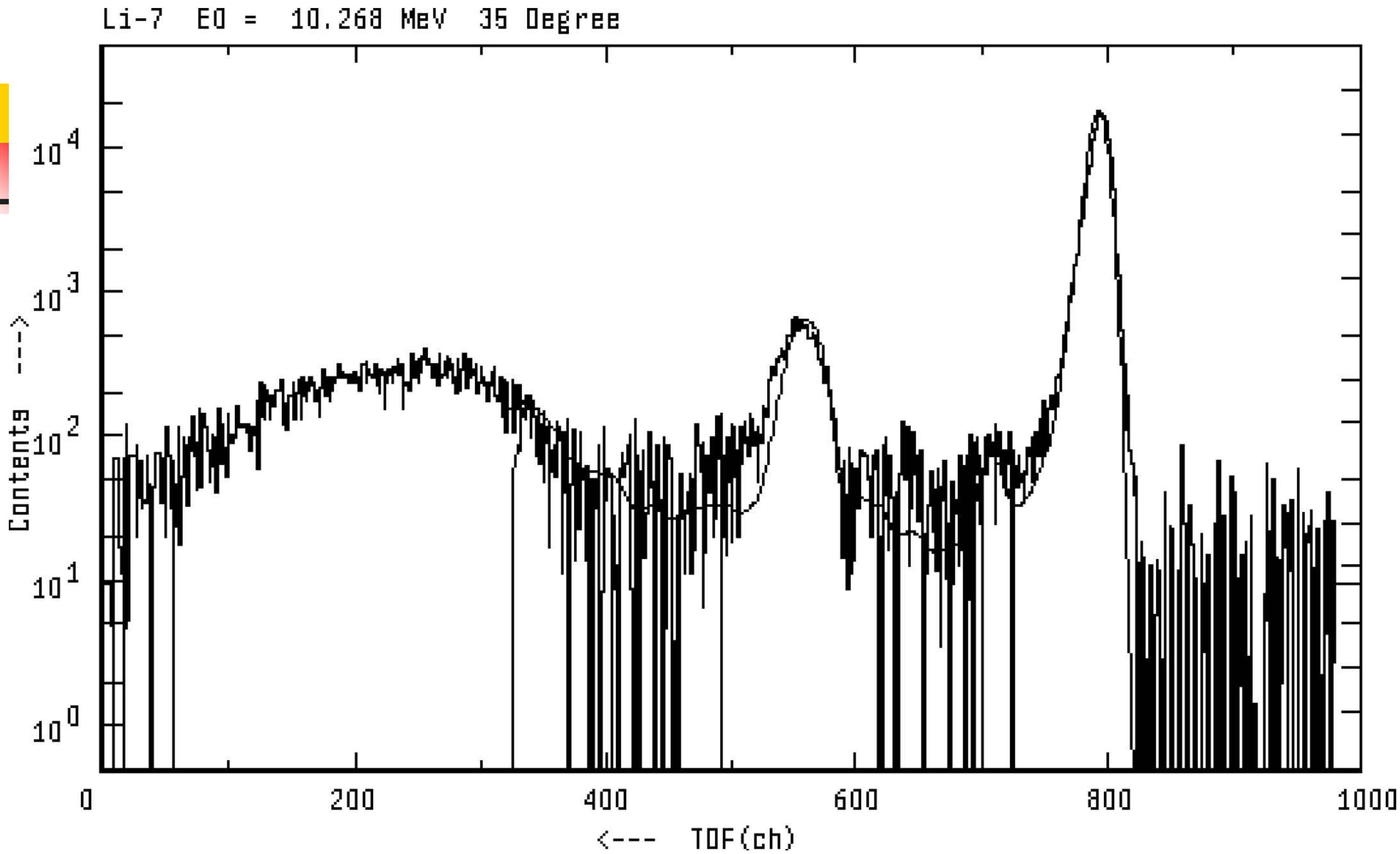
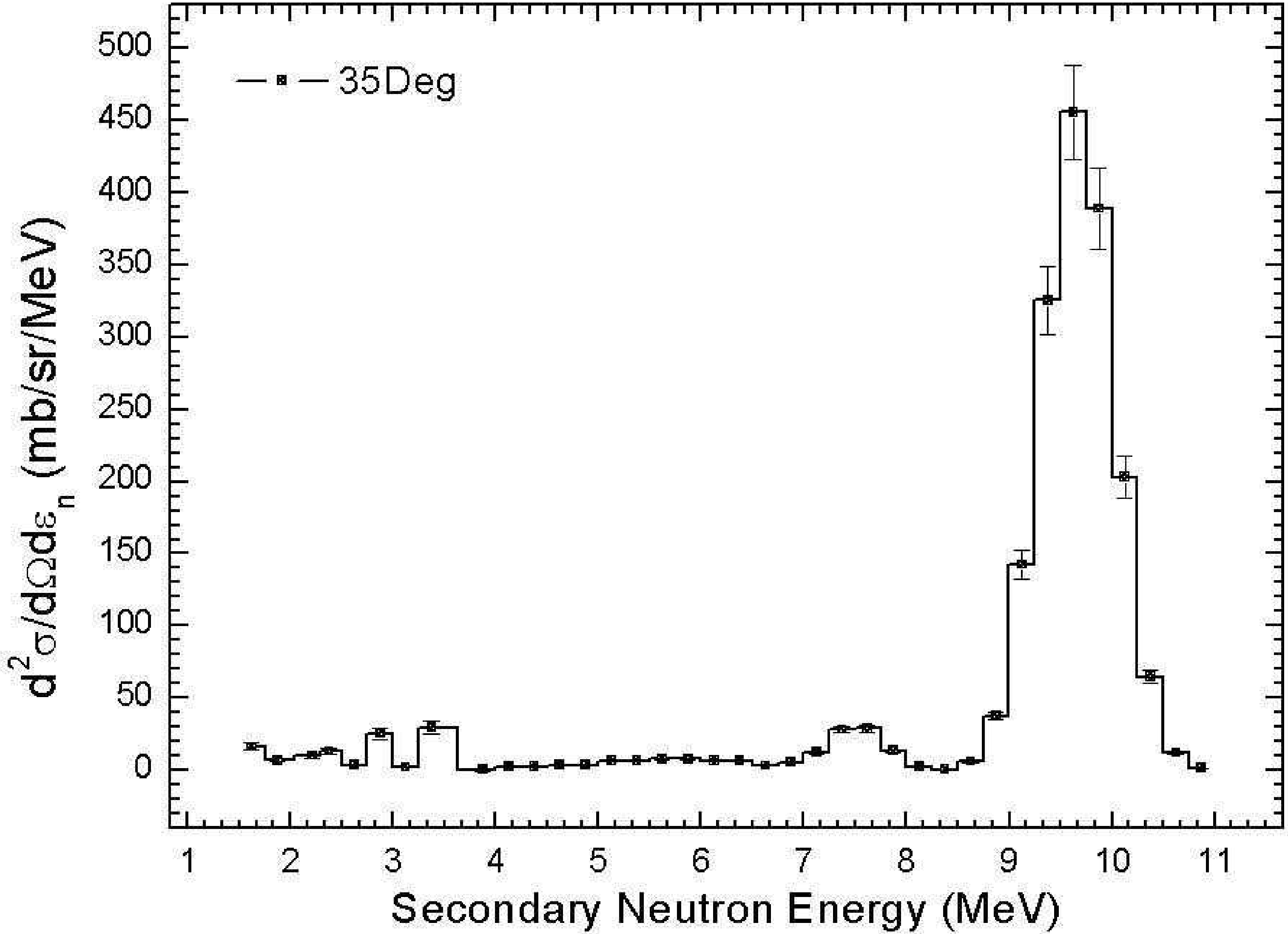
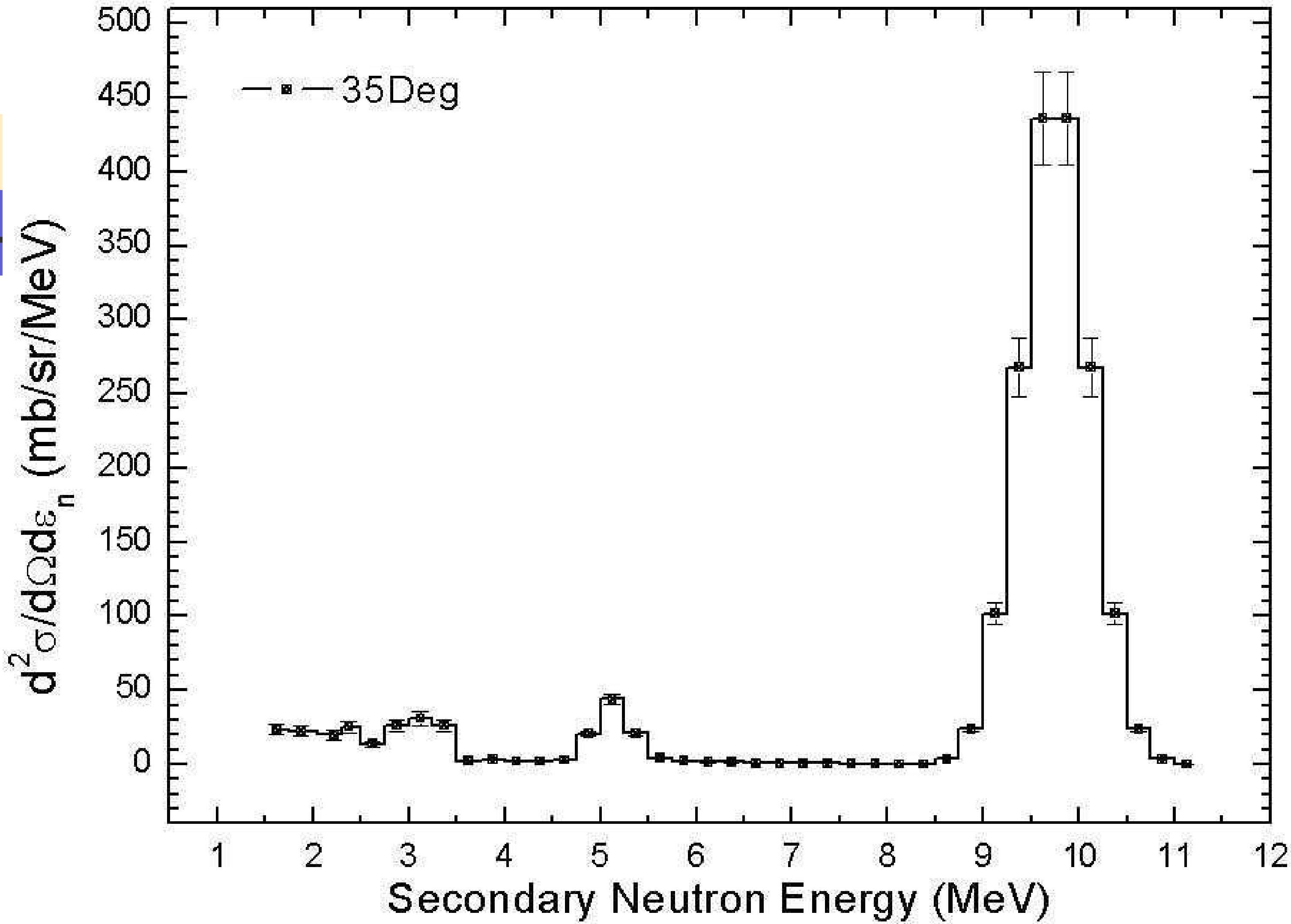


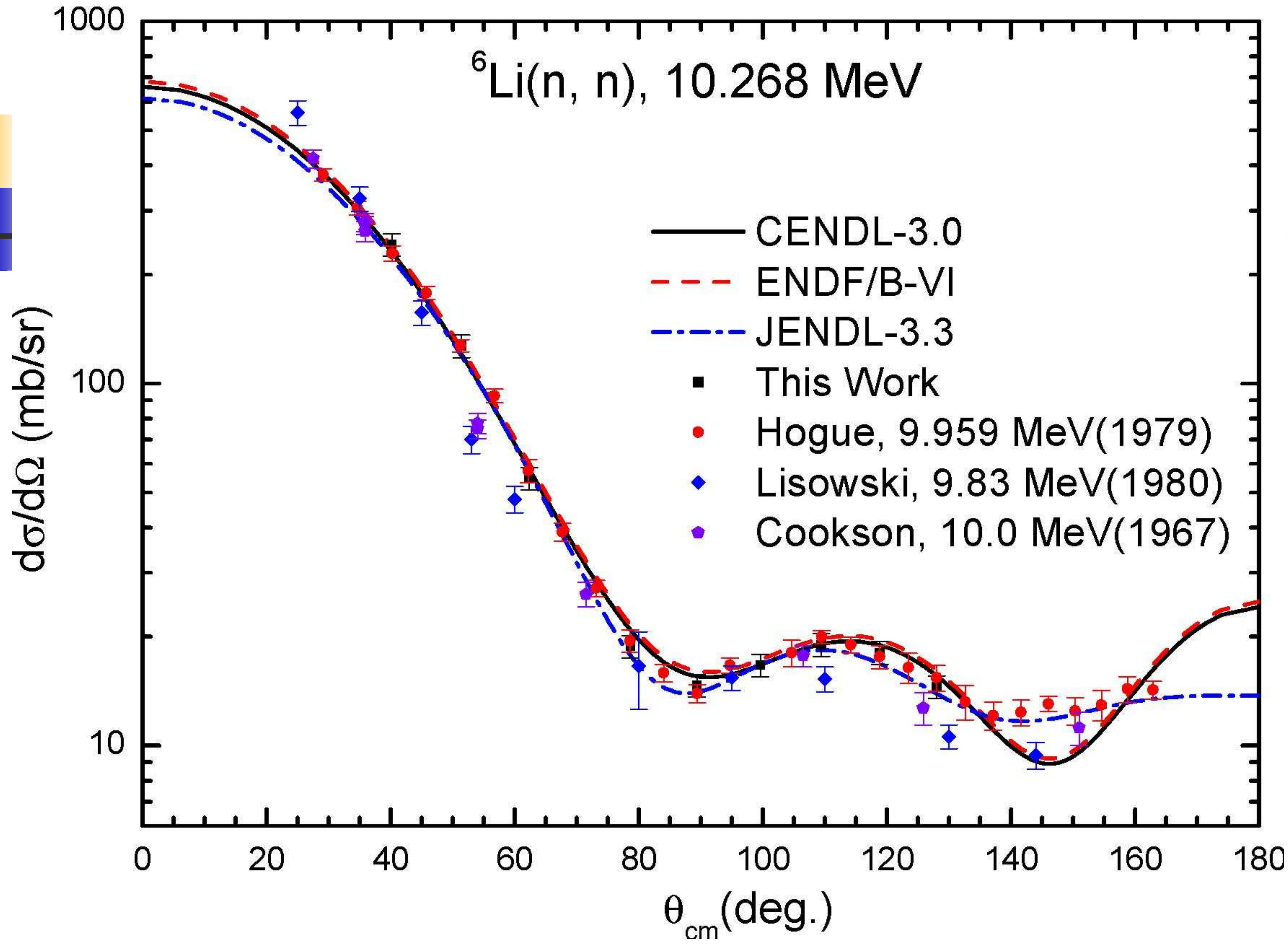
Comparison between simulated and EXP.



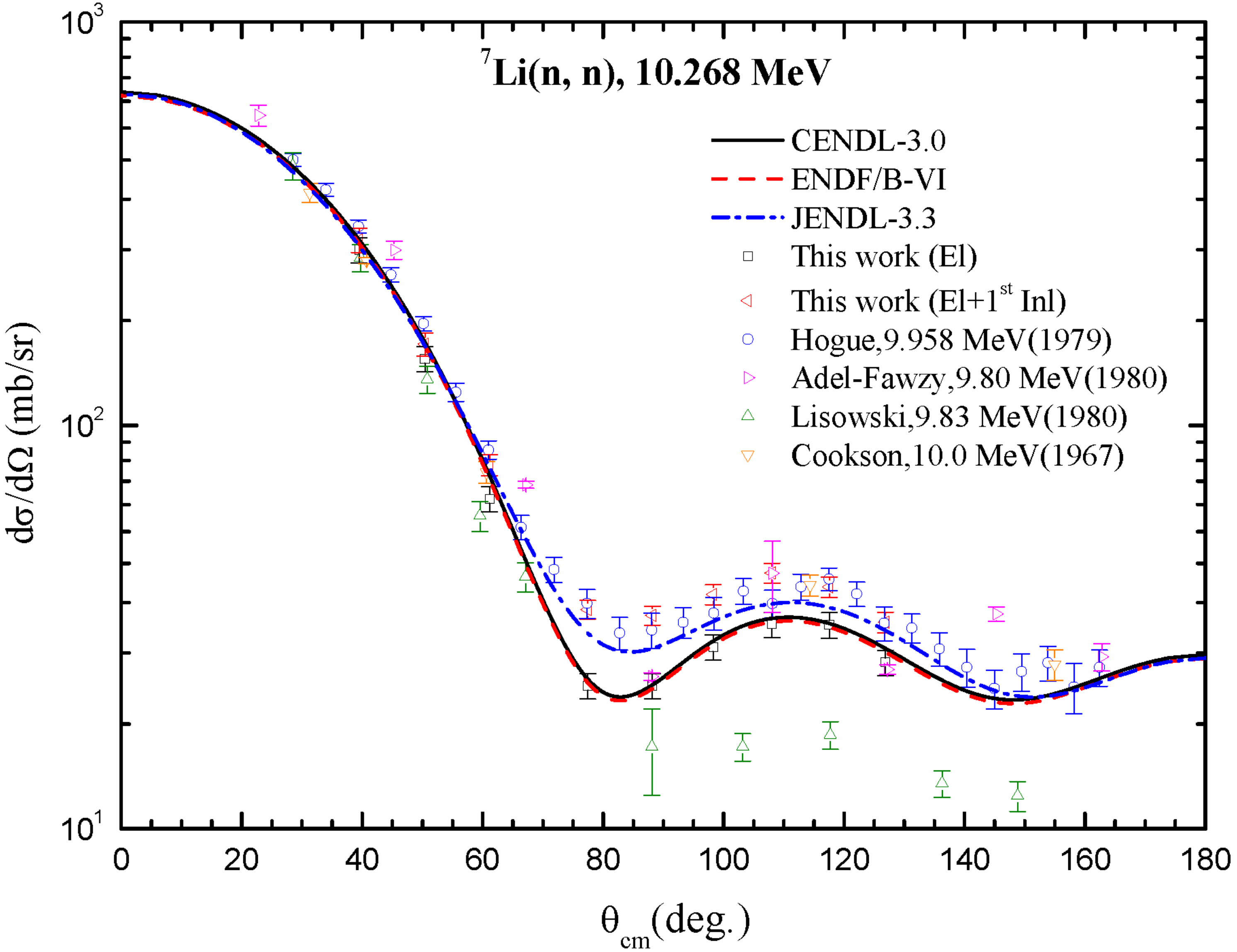
^{6}Li DDX experimental result at 10MeV



^{7}Li DDX experimental result at 10MeV



Comparison of elastic angular distribution (1)



Comparison of elastic angular distribution (2)

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