Neutron capture cross section and capture gamma-ray spectra of ^{138}Ba in the keV-neutron energy region

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Introduction

s-process nucleosynthesis

- Slow neutron capture process (s-process)
  - A ≥ 90 (Zr to Pb,Bi), Main component, in AGB stars
  - 56 ≤ A ≤ 90 (Fe to Sr, Zr), Weak component, in Massive stars
- Main component

  He shell burning in low mass AGB stars
  - $^{13}C(\alpha,n)^{16}O$, KT = 8 keV, 95%
  - $^{22}Ne(\alpha,n)^{25}Mg$, KT = 23 keV, 5%
- Neutron magic nuclides

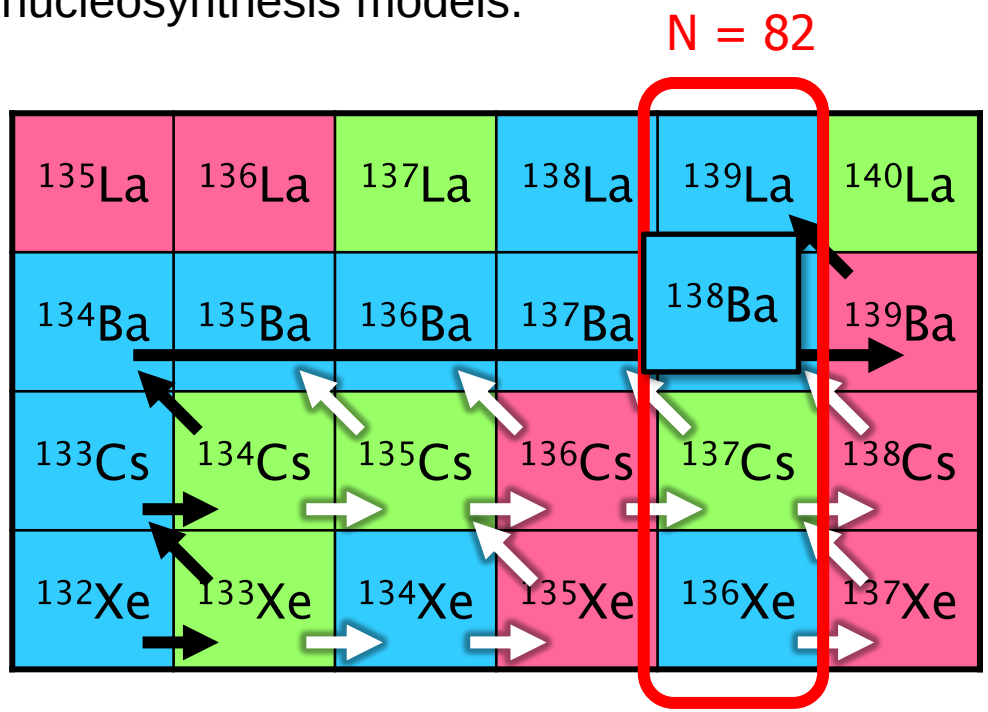
  Most of nuclides: Reaction flow is in equilibrium: σN_s = constant

  Neutron magic nuclides: not equilibrium due to small σ.

  σN_s gives important information on neutron exposure.

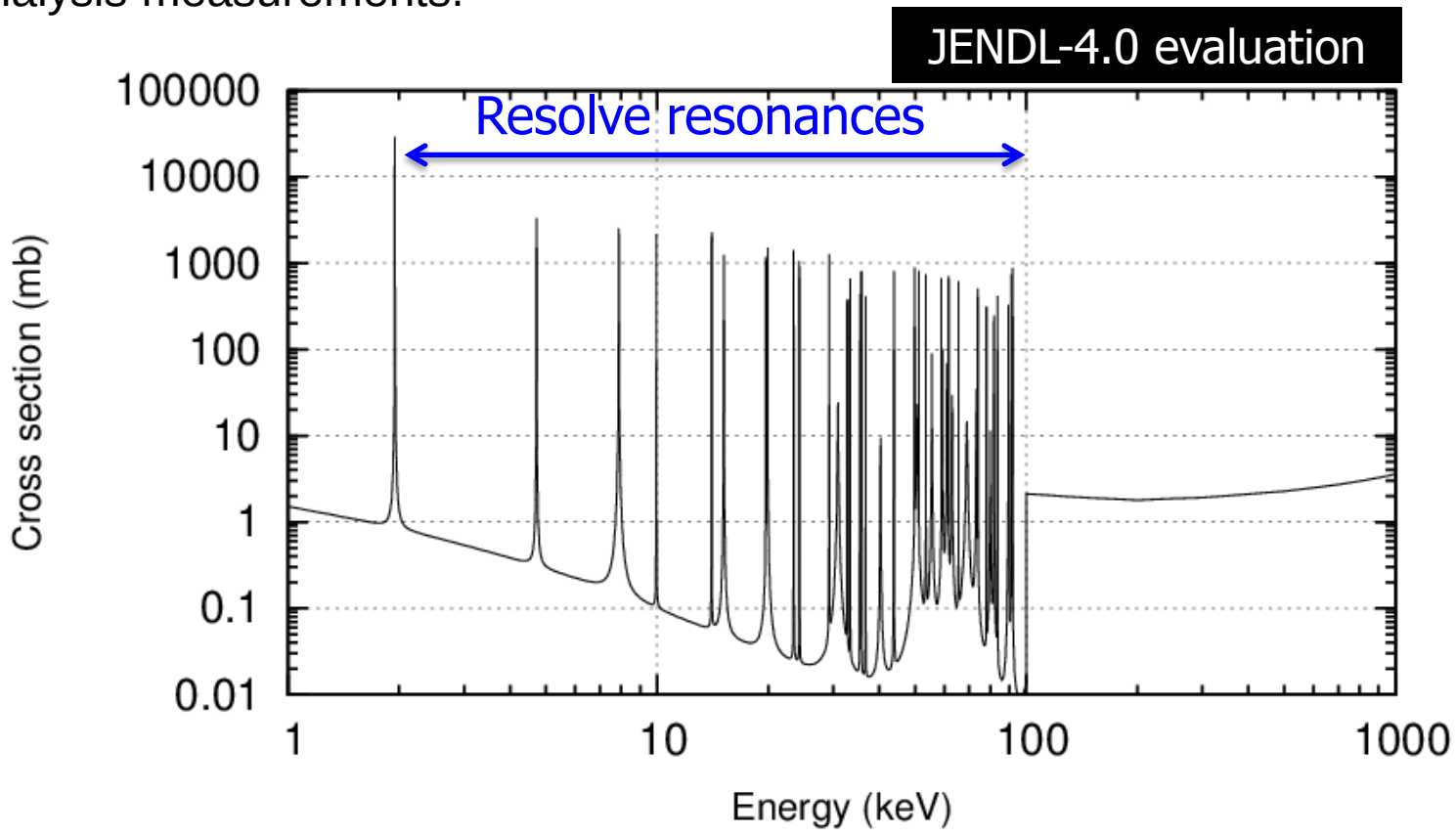
^{138}Ba in *s*-process

- Bottleneck nuclide
  - ^{138}Ba: N=82, neutron magic, small (n,γ) cross section
  - All *s*-process paths go through ^{138}Ba.
- Reliable data of the (n,γ) cross section of ^{138}Ba is very important in s-process nucleosynthesis models.



^{138}Ba(n,γ) cross section in keV region

- ^{138}Ba(*n*,γ) reaction in the keV energy region is dominated by resolved resonances.
- Evaluated cross sections of ^{138}Ba in keV region are based on resonance analysis measurements.



Previous measurements in keV region

- Resonance parameters

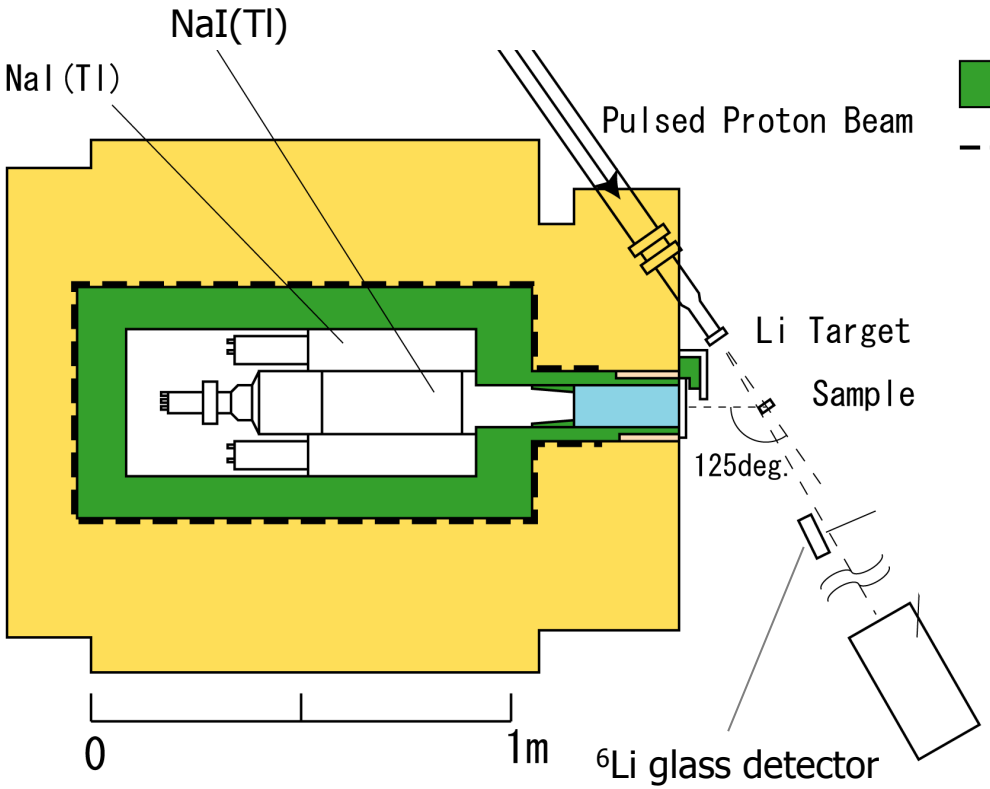
	Year	Facility	Type	Energy
Beer et al.	1997	Geel	Capture	0.65 – 200 keV
Brusegan et al.	1994	Geel	Transmission	0.65 – 195 keV
Mizumoto et al.	1988	JAEA	Transmission	0.65 – 63 keV
Musgrove et al.	1978	Oak Ridge	Capture	4.7 – 91 keV
Bilpuch et al.	1961	Duke	Transmission	31.7 – 192 keV

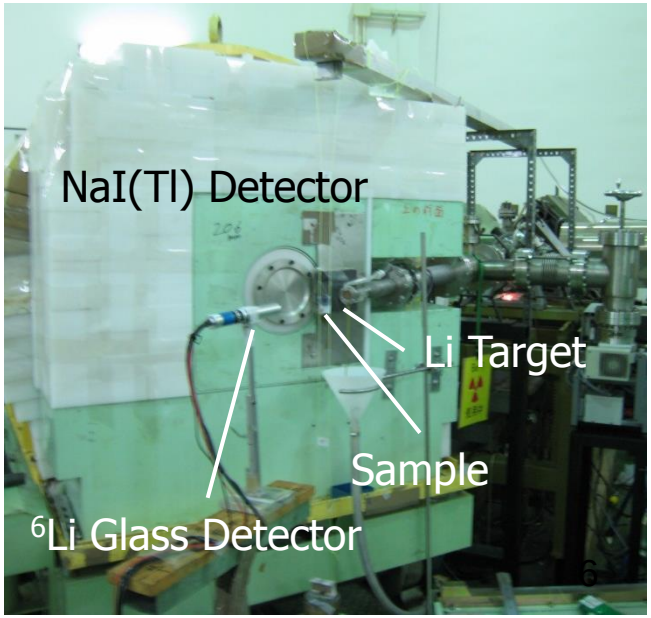
- Average cross section

	Year	Facility	
Heil et al	2005	Karlsruhe	KT = 5 keV Maxwellian
Beer et al.	1980	Karlsruhe	KT = 23 keV Maxwellian

Neutron Facility at Tokyo Tech

- 3-MV Pelletron accelerator
- Neutron source : $^{7}Li(p,n)^{7}Be$ reaction
- Pulsed beam : 1.5 ns width ×4 MHz repetition, flight path L = 12 cm
- Detector: Anti-Compton NaI(Tl) spectrometer (crystal size: 6” diam. ×12” long)





Present measurement

- **The present method has less energy resolution but more sensitive to smaller cross section than resonance analysis.**
- **Resonance analysis cannot measure a contribution of the direct capture process.**
- **The gamma-ray spectra can be measured.**

	Present	Beer (1997)	Musgrove (1978)
Source	Van de Graaf ^{7}Li(p,n)^{7}Be reaction	Electron LINAC (γ,n) reaction	Electron LINAC (γ,n) reaction
Energy	15 – 80 keV	0.65 – 200 keV	0.65 – 91 keV
Flight length	12 cm	28.4 m, 58.6 m	40 m
Time resolution	3 ns	1 ns	2 ns
Energy resolution	12% @ 30 keV	0.02% @ 30 keV	0.02% @ 30 keV
Detector	NaI(Tl)	C_6D_6	C_6F_6
Quantity	Average cross section	Resonance area	Resonance area
γ-ray spectrum	O	×	×

Sample

Ba-138 sample

Chemical form	$BaCO_3$
Physical form	Powder
Chemical purity	99.995 %
Net weight (Ba-138)	29.84 g
Diameter	56.2 mm
Thickness	12.7 mm

Heated at 150° C for 6.5 h.

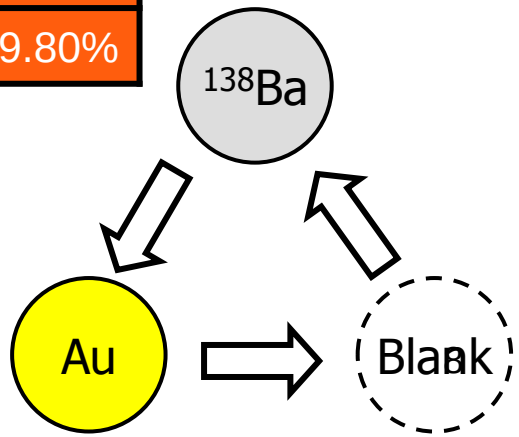
Encased in a graphite container

Isotopic composition

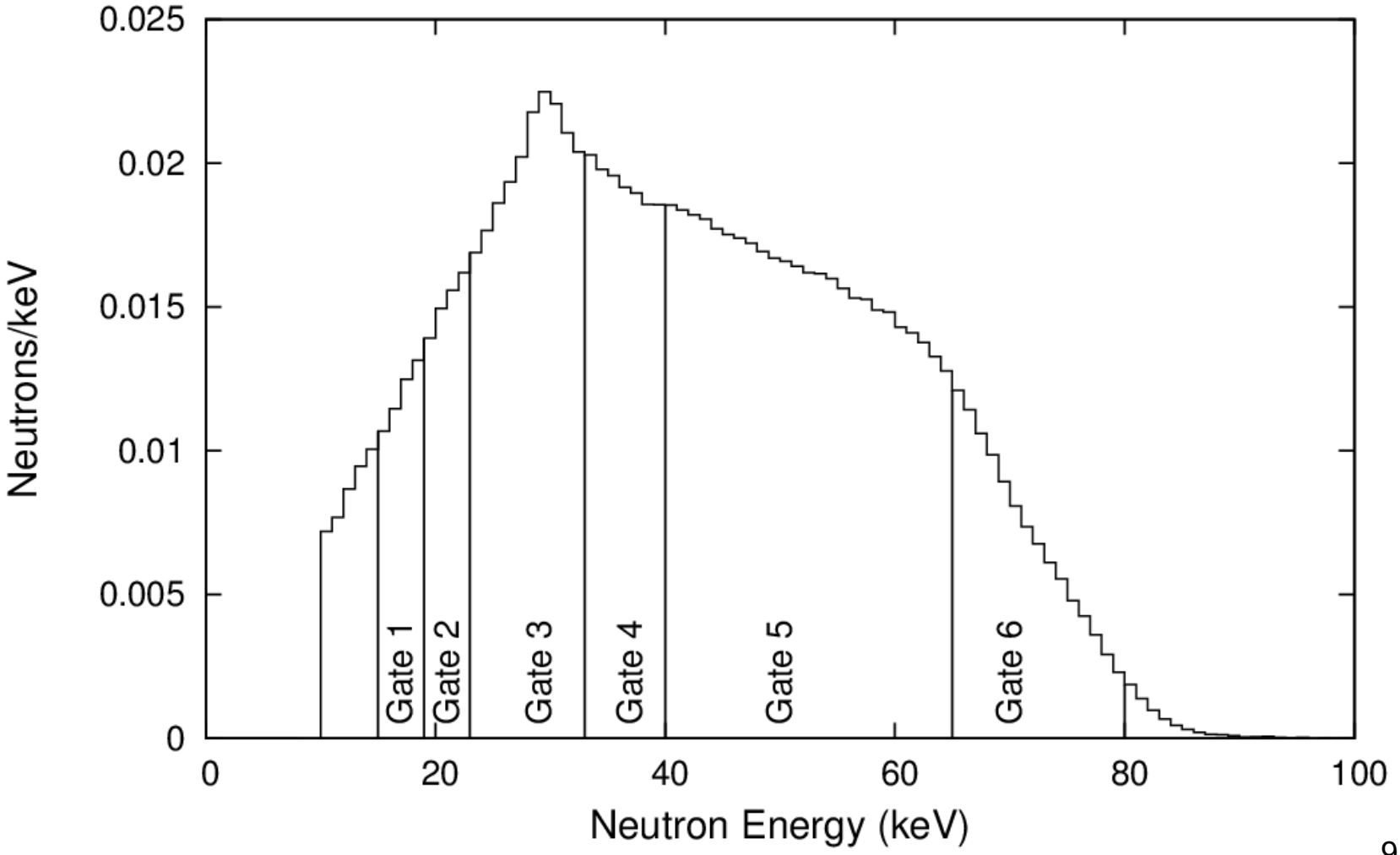
Ba-130	Ba-132	Ba-134	Ba-135	Ba-136	Ba-137	Ba-138
<0.01%	<0.01%	<0.01%	0.02%	0.02%	<0.16%	99.80%

Measurement time

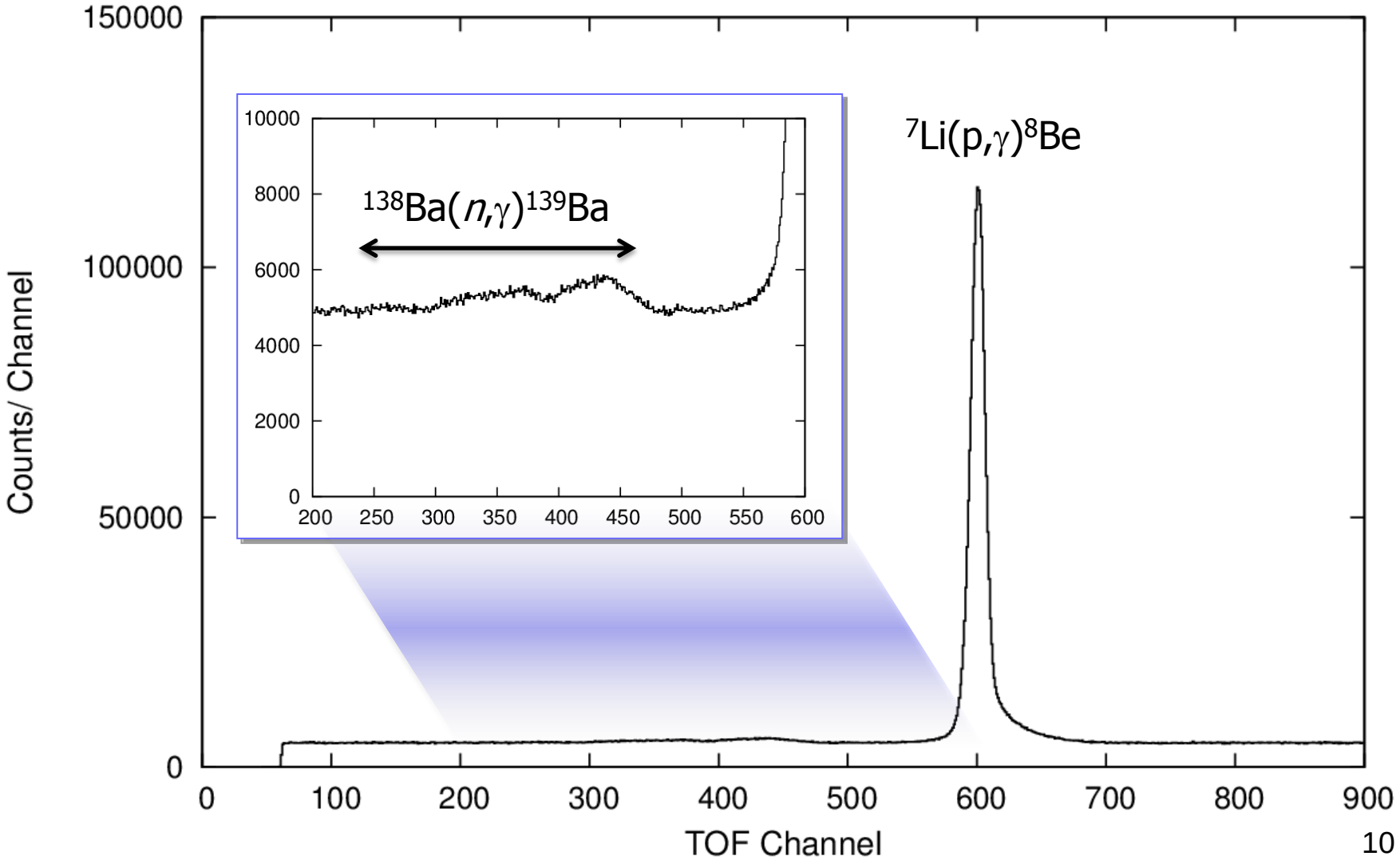
Ba-138	Au	Blank
63 h	2 h	6 h



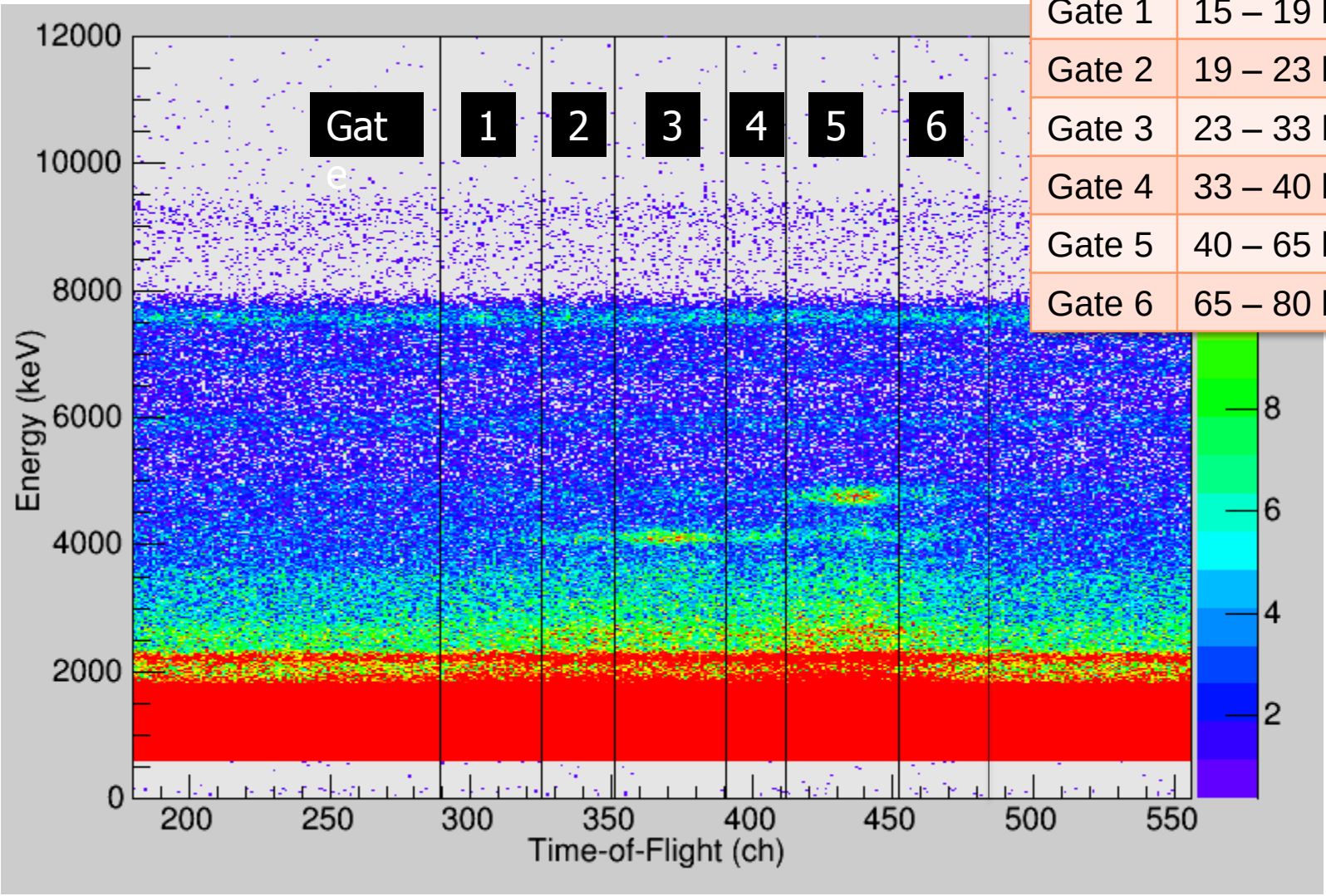
Incident Neutron Spectrum



Gamma-Ray TOF Spectrum

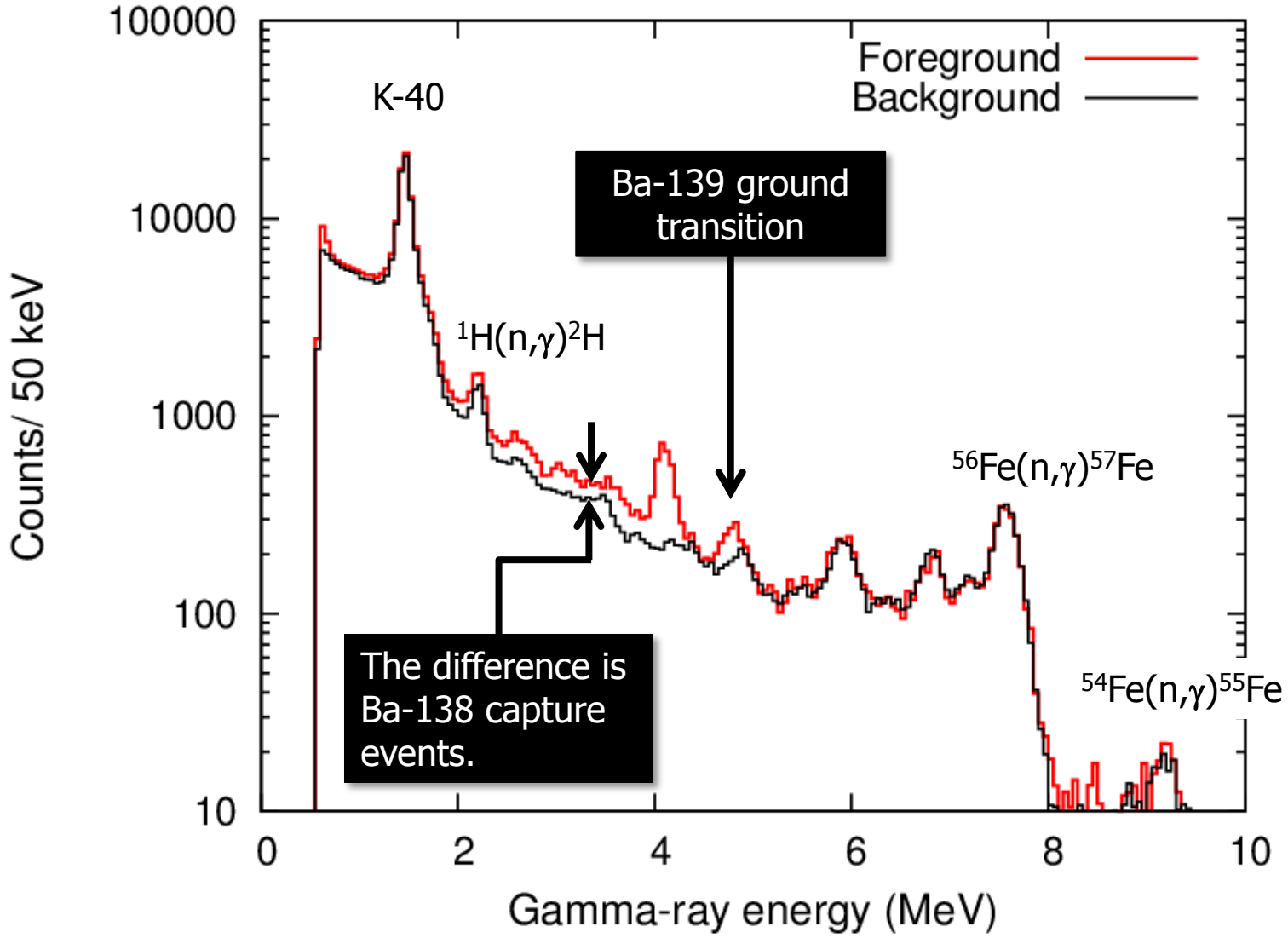


2D spectrum of TOF vs. PH

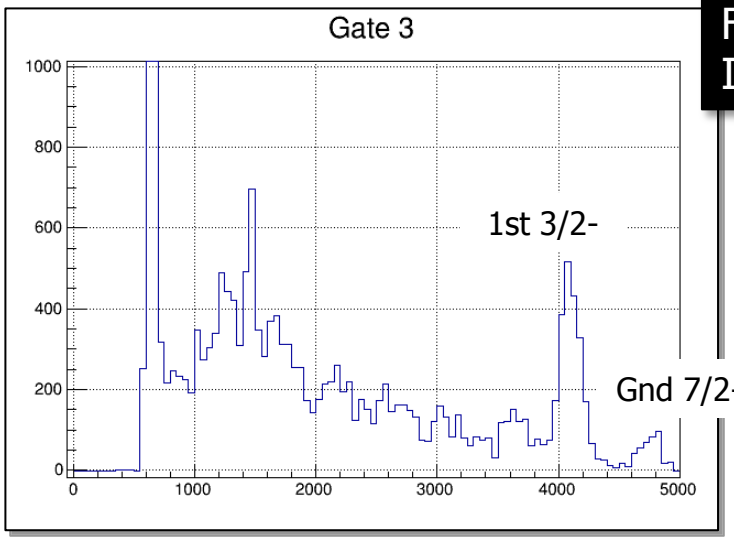


Gate 1	15 – 19 keV
Gate 2	19 – 23 keV
Gate 3	23 – 33 keV
Gate 4	33 – 40 keV
Gate 5	40 – 65 keV
Gate 6	65 – 80 keV

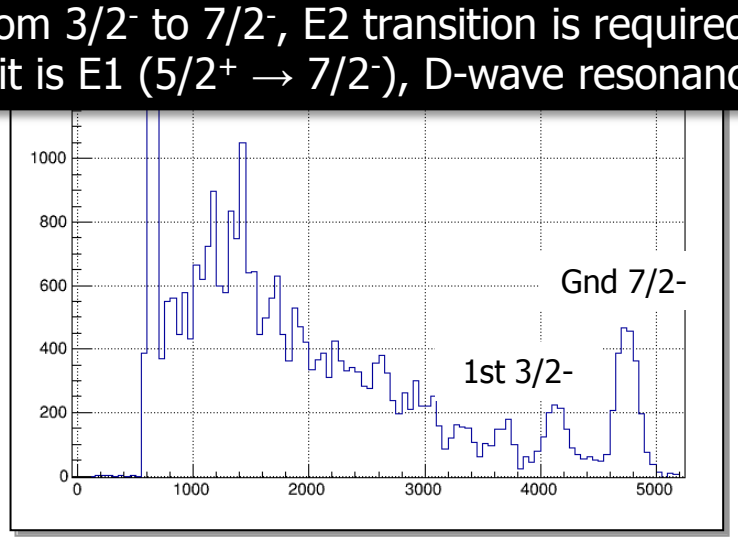
Background subtraction (23 - 33 keV)



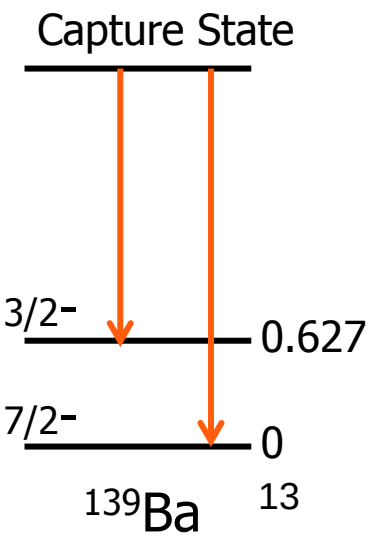
Net pulse-height spectra



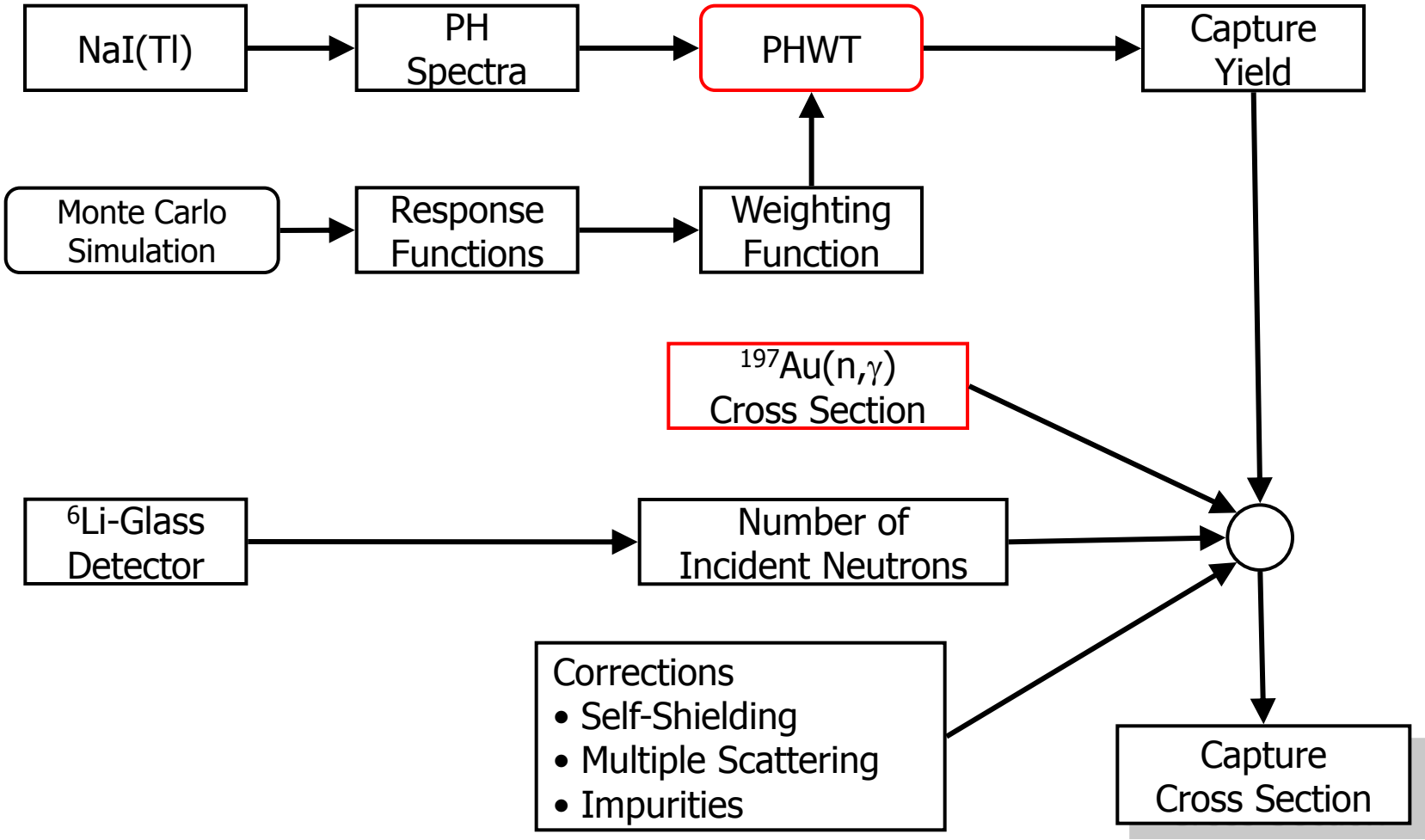
From $3/2^-$ to $7/2^-$, E2 transition is required.
If it is E1 ($5/2^+ \rightarrow 7/2^-$), D-wave resonances exist.



Gate	E_n (keV)	ENDF/B-VII.1			JENDL-4.0			Mughabghab (2006)			
	L	0	1		0	1		0	1		?
	J	$1/2^+$	$1/2^-$	$3/2^-$	$1/2^+$	$1/2^-$	$3/2^-$	$1/2^+$	$1/2^-$	$3/2^-$	?
1	15 - 19	0	0	0	0	1	0	0	0	0	0
2	19 - 23	0	0	0	0	1	1	0	0	0	2
3	23 - 33	1	1	1	1	2	3	1	1	1	6
4	33 - 40	0	0	0	0	2	2	0	0	0	1
5	40 - 65	2	1	5	6	0	6	2	1	5	9
6	65 - 80	1	1	1	3	0	3	1	1	1	6

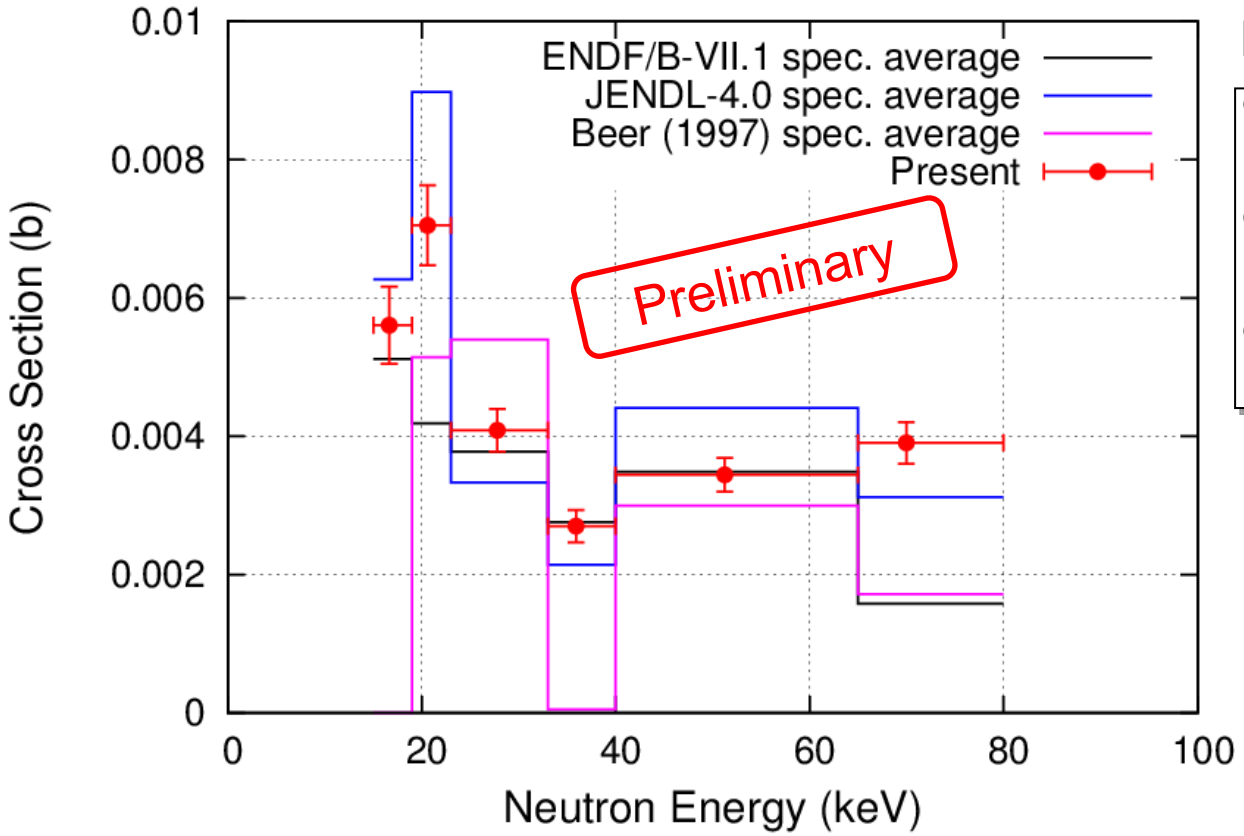


Analysis for capture cross section

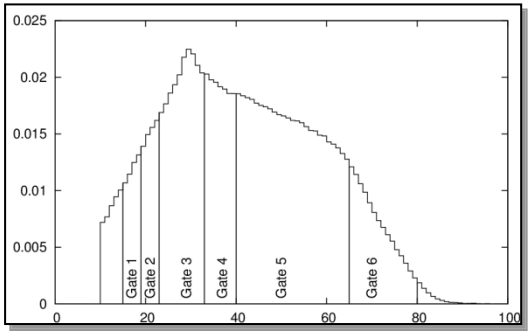


Comparison

- Spectrum averaged cross sections were calculated for ENDF/B-VII.1, JENDL-4.0.
- The Beer's experiments give only capture kernels. Average cross sections were calculated from resonance capture areas.

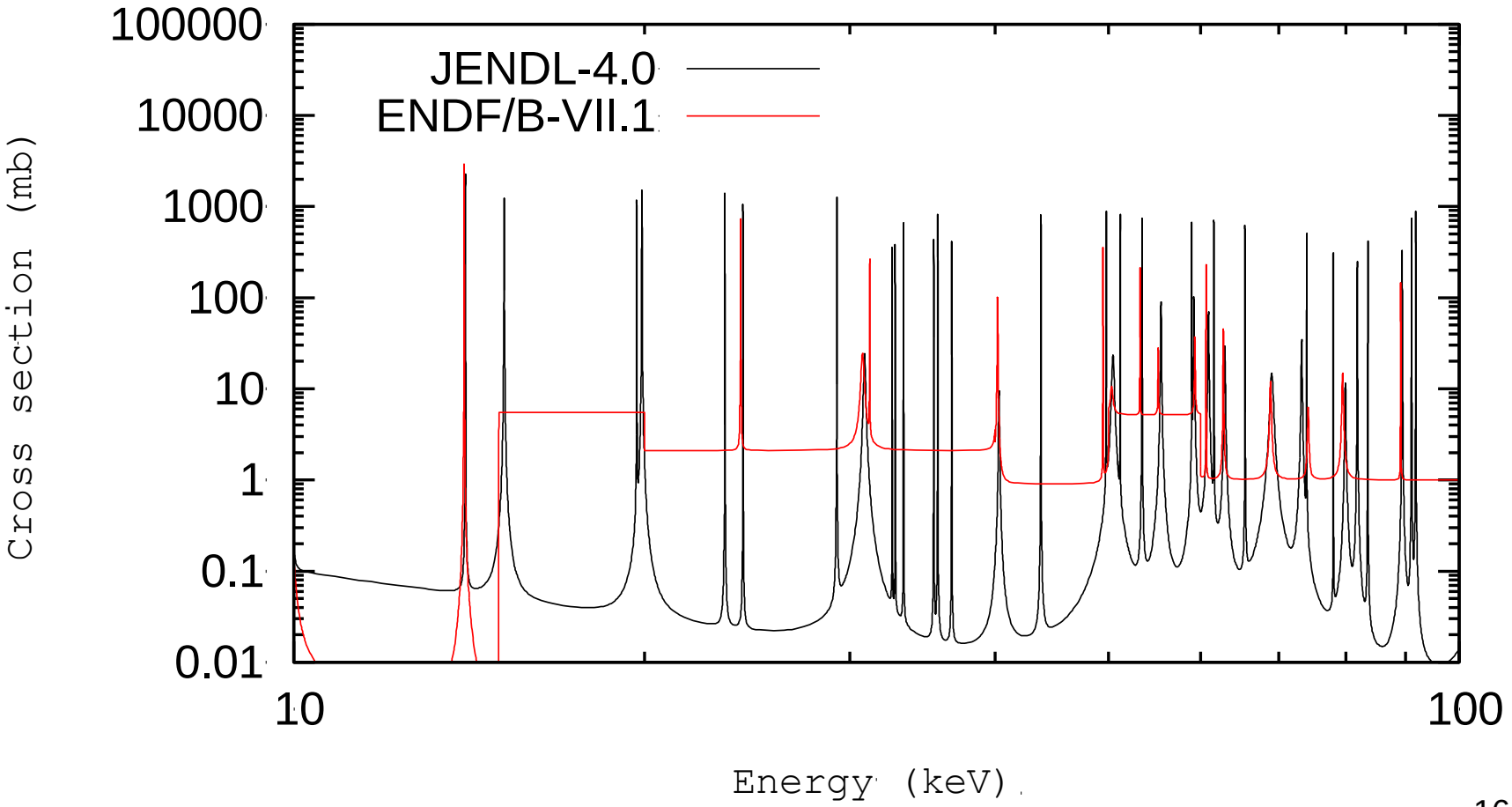


Neutron spectrum



Evaluation cross sections

Instead of adopting resonance parameters, ENDF/B-VII.1 used background cross sections to reproduce the previous activation measurements.



Summary

- The capture cross section of ^{138}Ba was determined by TOF method in the energy region of 15 – 80 keV. The cross section supports the ENDF/B-VII.1 evaluation.
- The shape of the capture gamma-ray spectrum depends on the incident neutron energy. It suggests that D-wave resonances exist in some energy regions.

Future

- Measurement at a higher energy (550 keV)
- Theoretical analysis
- Estimation of Maxwellian averaged cross sections using the present experimental results

Thank you for your attention