Thermal neutron capture in Gd isotopes

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1. Introduction

- Goals : DiceBox model calculations
  - Input : EGAF-RIPL3 data on levels,
    deexcitation & primary gammas,
    partial gamma cross sections $\sigma_{i\gamma f}$
    Model level densities, PSFs, Icc's
  - Output: Level populations, errors (from all)
    Level populations, errors
    (from quasi-continuum)
  - Capture cross section :

$$\sigma_{\gamma 0} = \sum \sigma_{\gamma}^{exp}(gs) + \sum \sigma_{\gamma}^{sim}(gs)$$

1. Introduction

❑ DiceBox Physics

- Compound nucleus decay : Extreme Statistical Model

  see F. Becvar, NIM in Phys. Res. A 417 (1998) 434-449 →↓

Partial radiative width (***i*** → *f*)

$$\Gamma_{i\gamma f} = \sum_{X,L} y_{XL}^2 \frac{f^{(XL)}(E_\gamma, \xi) E_\gamma^{2L+1}}{\rho(E_i, J_i, \pi_i)}$$

Total radiative width (of level-***i***)

$$\Gamma_{i\gamma} = \sum_f \Gamma_{i\gamma f}$$

Branching Intensity (from the given level-***i***)

$$I_{i\gamma f} = \Gamma_{i\gamma f} / \Gamma_{i\gamma}$$

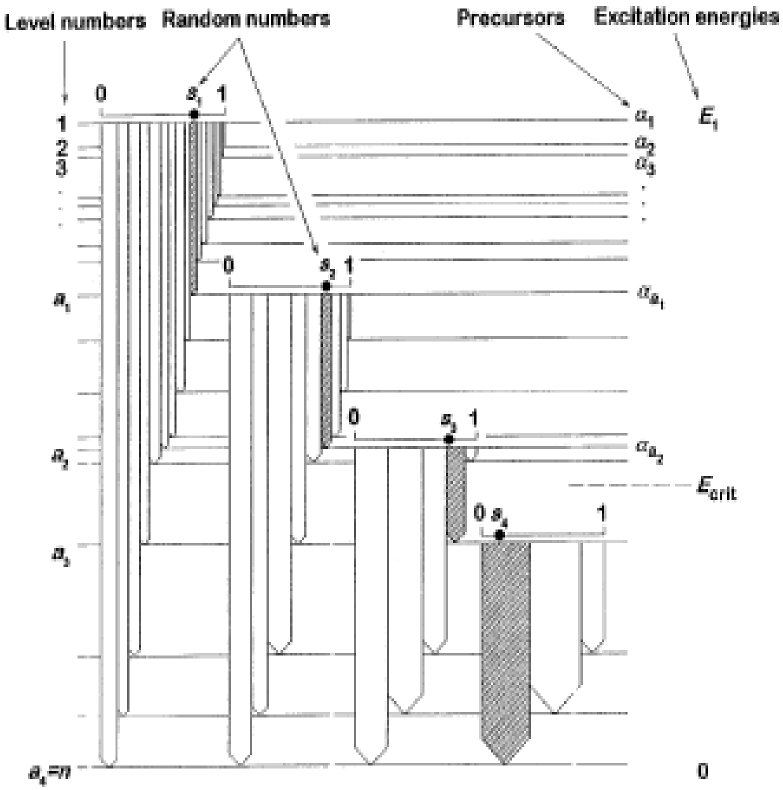


Fig. 1. Schematic description of random cascading.

❑ Auxiliary Software

- Depopulation intensity (for each discrete levels below E_{cut})

  INPUT : EGAF data file & DiceBox input data (from RIPL etc.)

  Output : Abs. gamma intensities (& errors) per capture

  Primary gamma intensities (& errors) written into DiceBox input file

- x-y Plot of Population and Depopulation intensities

  Population intensities (y) from DiceBox simulation (models)

  Depopulation intensities (x) from EGAF file (capture-γ experimental dataset)

  Quality-of-fit = reduced chi-square (χ^2/ν)

$$\equiv \quad \chi^2/\nu = \frac{1}{\nu}\sum_{i=1}^{\nu}\frac{(x_i - y_i)^2}{(\delta x_i)^2 + (\delta y_i)^2}$$

If all $x_i = y_i$, chi-square is zero !!

2. DiceBox Runs

❑ Method & policy of simulations

- M. Krticka et al. Phys. Rev. C77 (2008) on Pd isotopes
- Level Density Models

  1) CTF (Constant Temperature Formula)

  2) BSFG (Back-Shifted Fermi Gas)

  3) Composite (Gilbert-Cameron)

  Comparison with exp. data :

  No. of discete low-energy levels,

  Ave. resonance spacing around neutron separation energy (B_n) = D_0
- E1 Photon Strength Function Models

  1) BA (Brink-Axel)

  2) GLO (Generalized Lorentzian)

  3) EGLO (Enhanced GLO)

  4) KMF (Kadmensky-Markushev-Furman)

  5) GFL (Generalized Fermi Liquid)

  6) MLO (Modified Lorentzian or Plujko model)

  Comparison with exp. data : total radiation width $\langle \Gamma_{c\gamma} \rangle$ of capturing state

2. DiceBox Runs

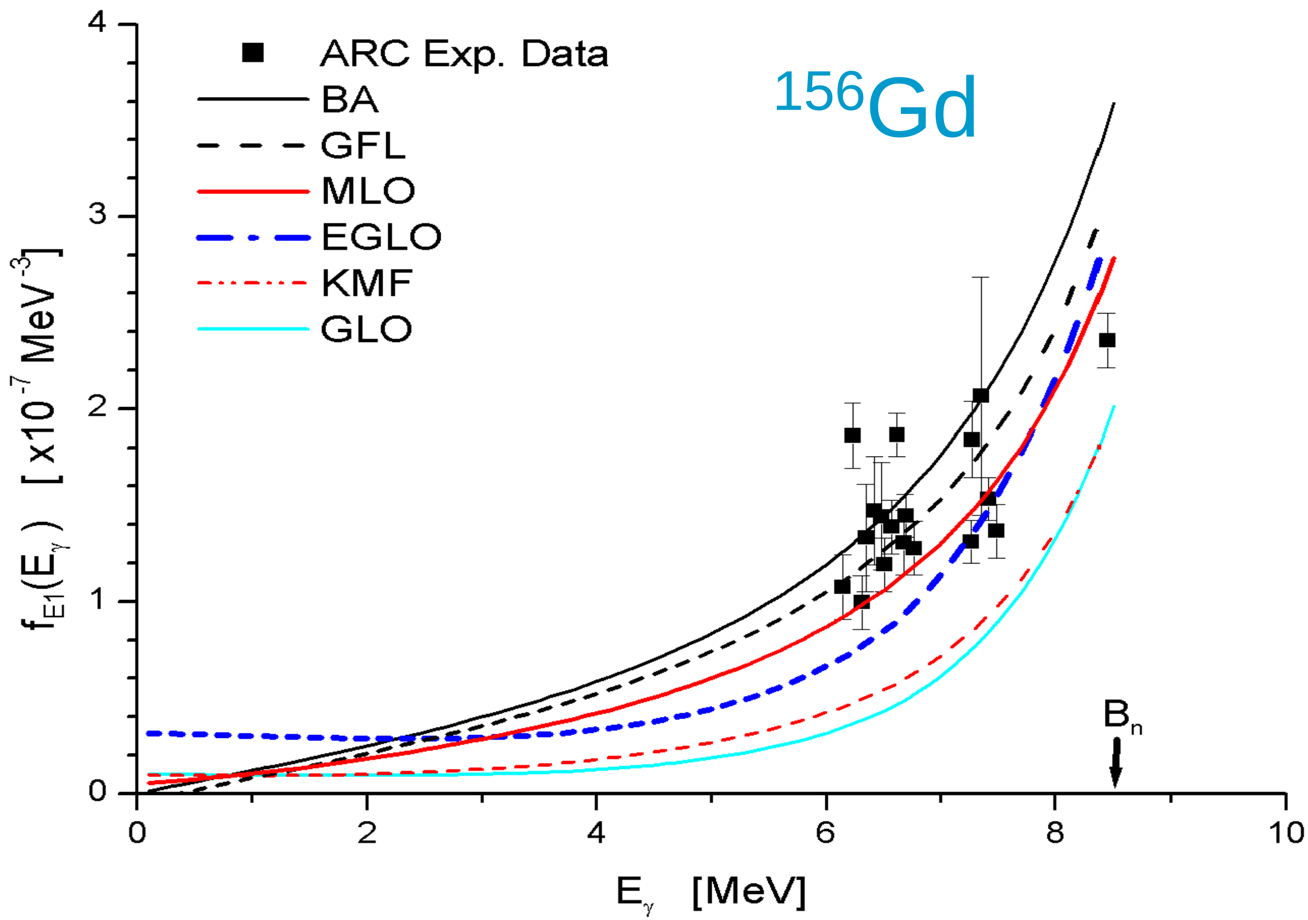
❑ Results on D_0 and $\langle \Gamma_{c\gamma} \rangle$

- Table 1

Isotope	E1	M1	Level Density	D_0 [eV] LD Model	D_0 [eV] Experiment	Γ_γ^{tot} [meV] Simulation	Γ_γ^{tot} [meV] Experiment
^{156}Gd	BA	SP	CTF	0.77	1.8(2)	67.4(9)	110(3)
	BA	SF	CTF			57.1(9)	
	BA	SF+SC	CTF			58.0(9)	
	KMF	SF+SC	CTF			28.7(3)	
	GLO	SF+SC	CTF			25.9(3)	
	EGLO	SF+SC	CTF			60.1(6)	
	GFL	SF+SC	CTF			50.5(8)	
			BSFG	1.6		von Egidy	RIPL-II
	BA	SP	BSFG			217(2)	299(3)
	BA	SF	BSFG			193(2)	275(4)
	BA	SF+SC	BSFG			196(2)	275(4)
	KMF	SF+SC	BSFG			89(1)	127(1)
	GLO	SF+SC	BSFG			76(4)	111(1)
	EGLO	SF+SC	BSFG			163(1)	237(2)
	GFL	SF+SC	BSFG			175(2)	244(3)
	GFL(m)	SF+SC	BSFG				244(3)
	MLO(12)	SF+SC	BSFG			150(2)	211(3)
	MLO(13)	SF+SC	BSFG				212(3)
	MLO(14)	SF+SC	BSFG				256(3)
	BA	SP	COMP	1.6		132	
	BA	SF+SC	COMP			116	
	GFL	SF+SC	COMP			101	
	EGLO	SF+SC	COMP			112	
	MLO(12)	SF+SC	COMP			89.4	
	KMF	SF+SC	COMP			56.2	
	GLO	SF+SC	COMP			49.7	

❑ E1 PSF Models and Exp. Data

- Fig. 2

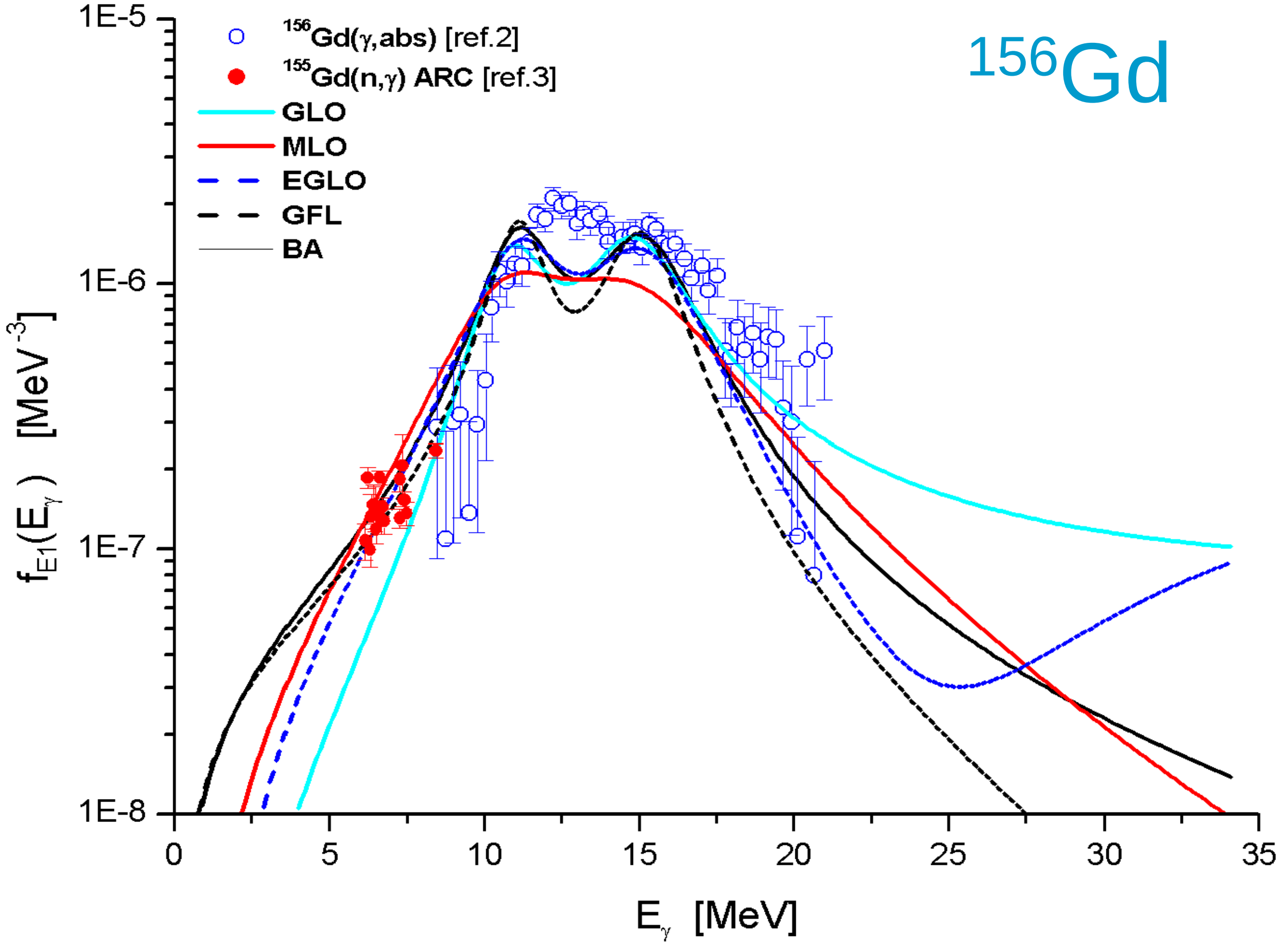


The model PSF shapes are compared with an experimental PSF dataset of average resonance capture (ARC) measurement in the reference (Mughabghab and Dunford, Phys. Lett. **B487**, 155, 2000). B_n is the binding energy of neutron in ^{156}Gd, 8.536 MeV.

2. DiceBox Runs

❑ E1 PSF Models and Exp. Photon abs. Data

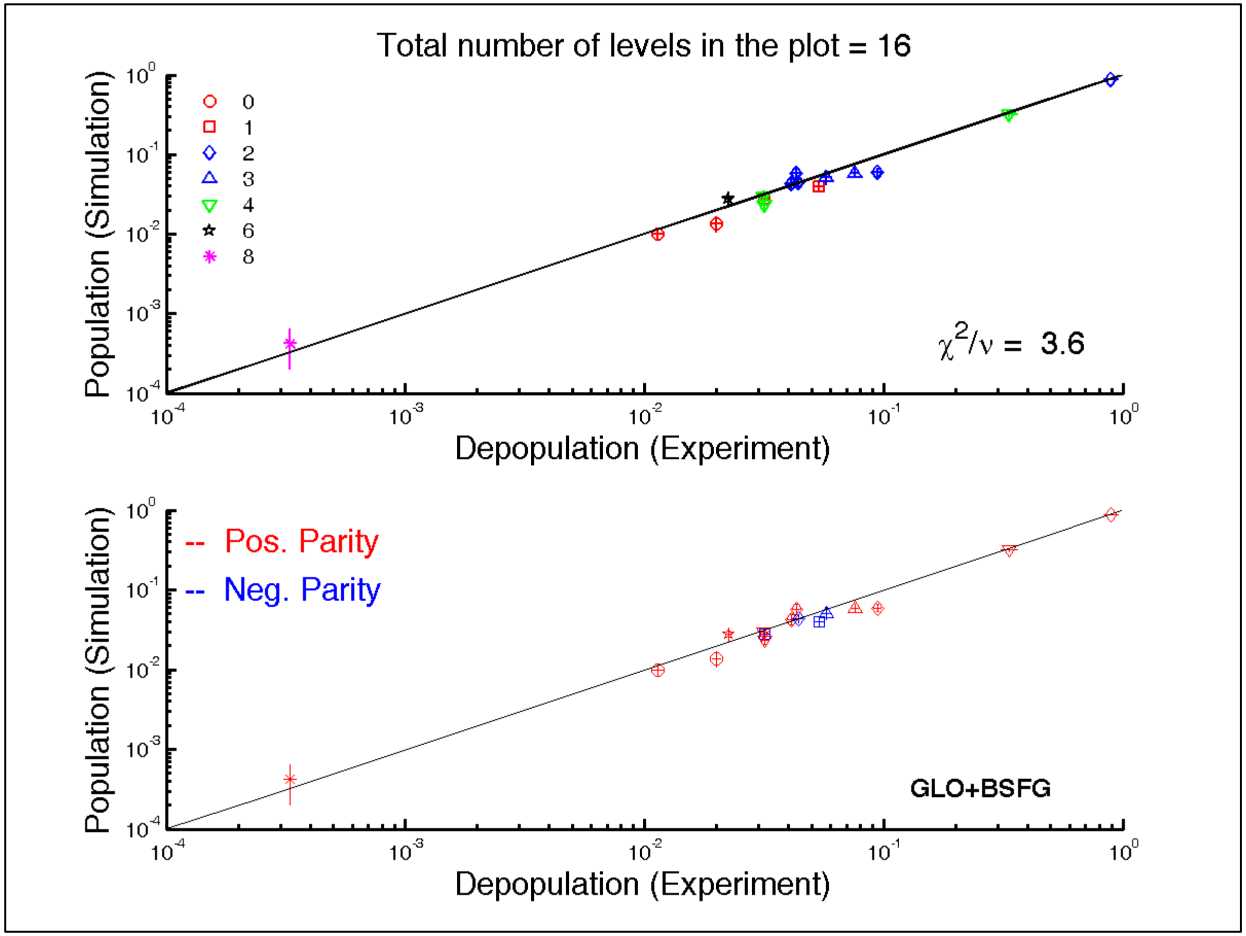
- Fig. 3 : High energy photon absorption data



3. Model Results

❑ Population-Depopulation Balance Plot (x-y)

- x : Depopulation intensity (EGAF & Budapest measurements)
- y : Population intensity (DiceBox simulations)



^{156}Gd Best Fit

- D_0 :
  1.7 (Model)
  1.8(2) (Exp)
- $\langle \Gamma_{c\gamma} \rangle$:
  109(1) (Model)
  110(3) (Exp)

4. Capture Cross Section

❑ Thermal neutron capture cross section (σ_0) : ^{155}Gd(n,γ)

$$\sigma_0 = \sum_{i=1}^{n} \sigma_{i\gamma f}^{\exp}(1+\alpha_i) + \sum_{j}^{continuum} \sigma_{j\gamma f}^{\text{sim}}(1+\alpha_j) \;, \quad f \equiv \text{g.s.}$$

First sum : n = 6 (discrete levels), partial σ_γ's from EGAF,
Icc corrections essential → 61,600(3,800) b

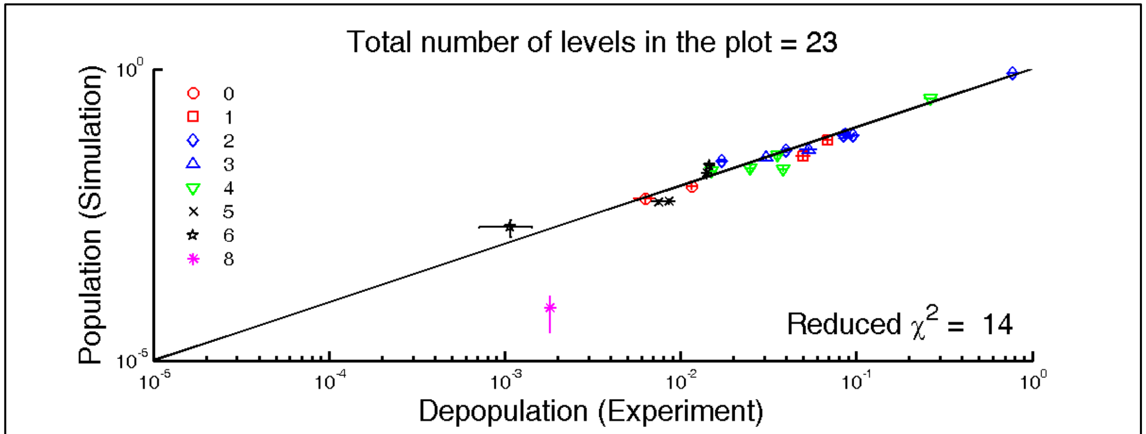
Second sum : Direct population of g.s. from continuum (DiceBox output)
4.7 – 6.5 % of total population of g.s.

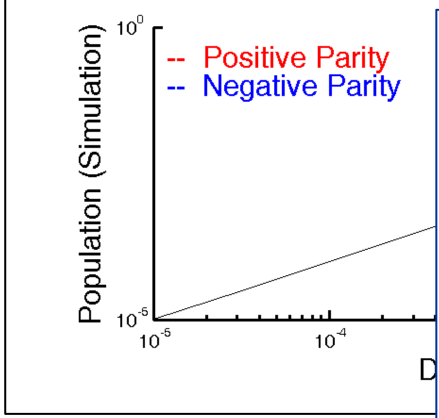
Table 5. Reference values are listed for thermal neutron capture cross section of ^{155}Gd.

First author (reference) NSR code	σ_0 (uncertainty) [b]	Comments
Lapp (PR71, 745) 1947La		$\sigma_0(^{157}Gd)/\sigma_0(^{155}Gd) = 3.5$
Inghram (PR79, 271) 1950In01	41,400	
Walker (PC) 1956Wa	25,000	Pile, mass spectroscopy
Pattenden (58Geneva) 1958Pa	66,000 (2,000)	Transmission
Tattersall (JNE12, 32) 1960Ta29	49,800 (600)	Pile oscillator, $\sigma(B) = 767$ b
Groshev(IZV26, 1119) 1962Gr33	61,000 (5,000)	
Sun (JRNC256, 541, 2003)	59,100 (4,600)	Prompt k_0 method
Firestone (EGAF)	58,400 (5,000)	
Firestone (EGAF adopted)	65,000 (2,000)	
Mughabghab (Atlas) 2006MuZx	60,900 (500)	Evaluation
Leinweber (NSE261,154,2006)	60,200	Resonance parameters and NJOY
This work	**65,200 (4,100)**	**EGAF+calculation**

→ Both sum :
σ_0 = 65,200 (4,100) b

5. Other Isotopes





- ^{158}Gd : $^{157}Gd(n,\gamma)$

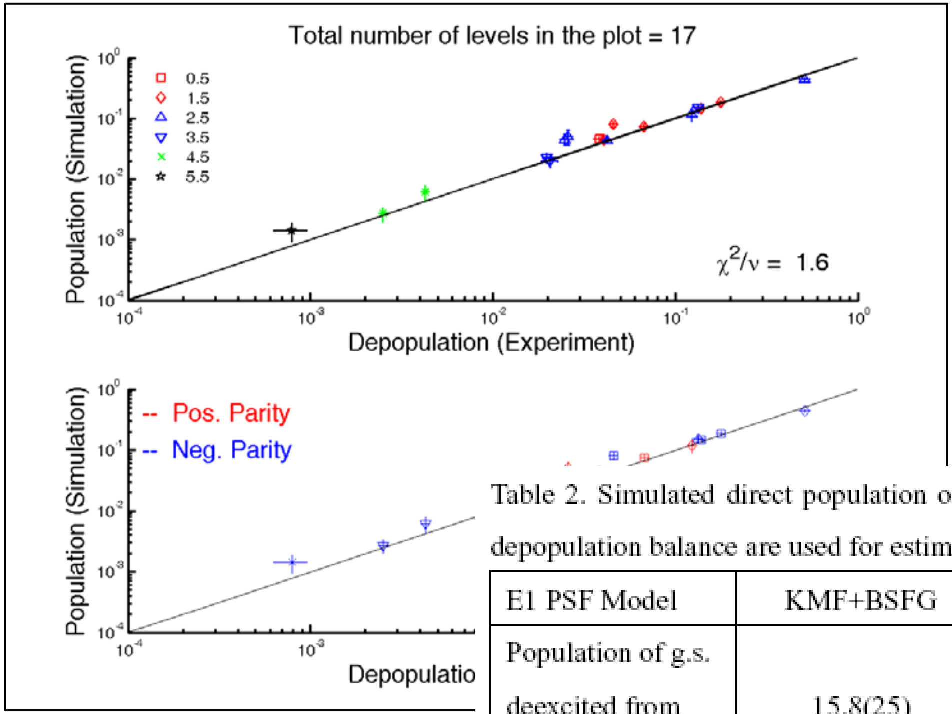
Quality of fit similar to the case of ^{156}Gd

Highest spin state (8^+) : large deviation

Table 3. Reference values are listed for thermal neutron radiative capture cross section of ^{157}Gd.

First author (reference) NSR code	$\sigma_{\gamma 0}$ (uncertainty) [b]	Comments
Lapp (PR71, 745) 1947La	3.5	$\sigma_0(^{157}Gd)/\sigma_0(^{155}Gd)$
Pattenden (58Geneva) 1958Pa	264,000 (4,500)	Transmission
Tattersall (JNE12, 32) 1960Ta29	213,000 (2,000)	Pile oscillator, σ(B) = 767(4) b
Groshev (IZV26, 1119) 1962Gr33	240,000 (12,000)	
Sun (JRNC256, 541, 2003)	232,000 (14,000)	Prompt k_0 method
Firestone (EGAF)	209,900 (5,000)	
Firestone (EGAF adopted)	232,000 (13,000)	Unweighted average of all values
Mughabghab (Atlas) 2006MuZx	254,000 (815)	Evaluation
Leinweber (NSE261,154,2006)	226,000	Resonance parameters and NJOY
This work	**216,000 (5,000)**	Combine EGAF and calculation

5. Other Isotopes



❑ ^{153}Gd : ^{152}Gd(n,γ)

Quality of fit → best

Two states' spin changed

One state's parity changed

Renormalization

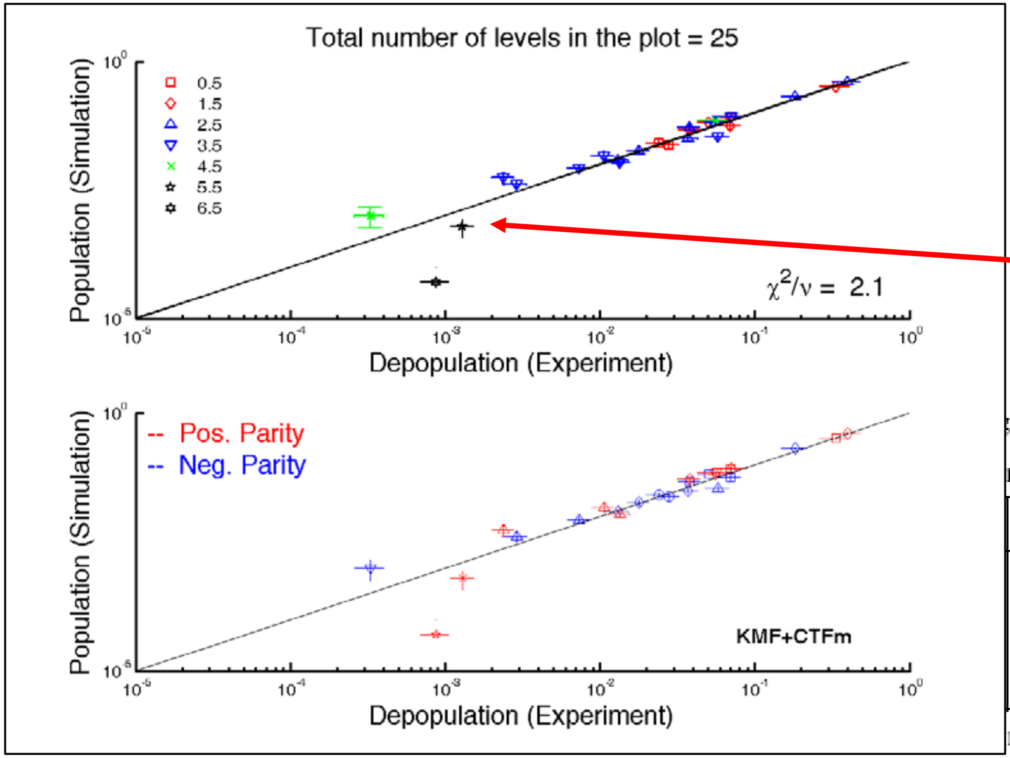
Table 2. Simulated direct population of g.s. deexcited from continuum. The best fits to the population-depopulation balance are used for estimating the portion of g.s. side feeding.

E1 PSF Model	KMF+BSFG	GLO+BSFG	KMF+CTF	EGLO+CTF
Population of g.s. deexcited from continuum [%]	15.8(25)	13.5(21)	13.1(17)	15.5(24)

Table 3. Reference values are listed for thermal neutron radiative capture cross section of ^{153}Gd.

First author (reference) NSR code	$\sigma_{\gamma 0}$ (uncertainty) [b]	Comments
Steinnes (JIN34, 2699) 1972St25	1,100 (100)	$\sigma_0(^{198}Au) = 98.8$ b
Leinweber (ANS-Vancouver) 2006LeZV	1,050	
Matsue (JRNC262, 49) 2004Ma76	839 (26)	
De Corte (ADNDT85, 47) 2003De34	755 (7)	
Firestone (EGAF adopted)	745 (10)	
Mughabghab (Atlas) 2006MuZx	735 (20)	Evaluation
This work	**690 (30)**	Combine EGAF and calculation

5. Other Isotopes



- ^{155}Gd : ^{154}Gd(n,γ)

High spin states' deviation

Isomeric cross section :
(121.05 KeV, 11/2$^-$, $T_{1/2}$ = 32 ms)
0.13(6) b

.s. deexcited from continuum. The best fits to the population-
ng the portion of g.s. side feeding.

MLO+BSFG	GFL+CTF	BA+CTF
11.4(14)	12.3(14)	12.5(15)

r thermal neutron radiative capture cross section of ^{154}Gd.

First author (reference) NSR code	$\sigma_{\gamma 0}$ (uncertainty) [b]	Comments
Walker (PC) 1956Wa	250 (120)	Pile, mass spectroscopy
Grishanin (AE19,459,1965) 1965Gr	100 (5)	
Grishanin (AE19,459,1965) 1965Gr	125 (32)	
Leinweber (ANS-Vancouver) 2006LeZV	86	
Firestone (EGAF adopted)	100 (15)	
Mughabghab (Atlas) 2006MuZx	85 (12)	Evaluation
This work	**96 (7)**	Combine EGAF and calculation

6. Summary

DiceBox result

Useful for obtaining the side-feeding intensity
Useful for deciding capture cross section for thermal neutron
Quasi-continuum emission spectrum & other pysical quantities can be predicted

Gd cross sections in review

- ^{155}Gd(n,γ) : Bigger than ENSDF value, 60900(500) b, by 7%
- ^{157}Gd(n,γ) : Smaller than ENSDF value, 254000(815) b, by 15%
- ^{152}Gd(n,γ) : Smaller than ENSDF value, 735(20) b, by 6%
- ^{154}Gd(n,γ) : Consistent with ENSDF value, 85(12) b

High spin states & isomeric states

- More study required
- Better level density?

Possible improvements ?

- Automatic search for best fit

Thanks !!!