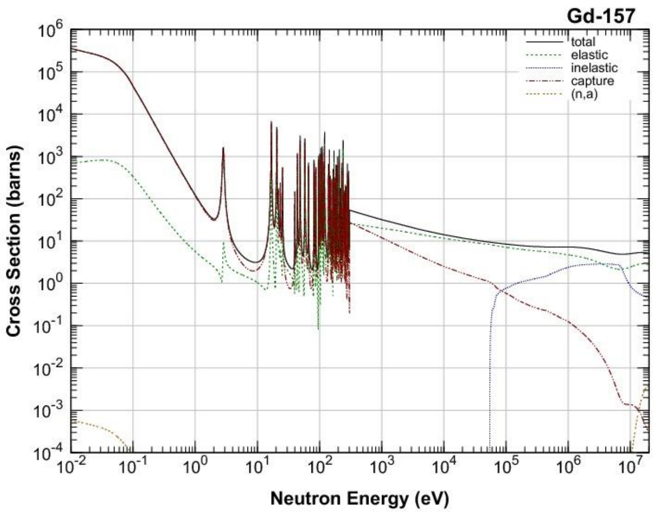
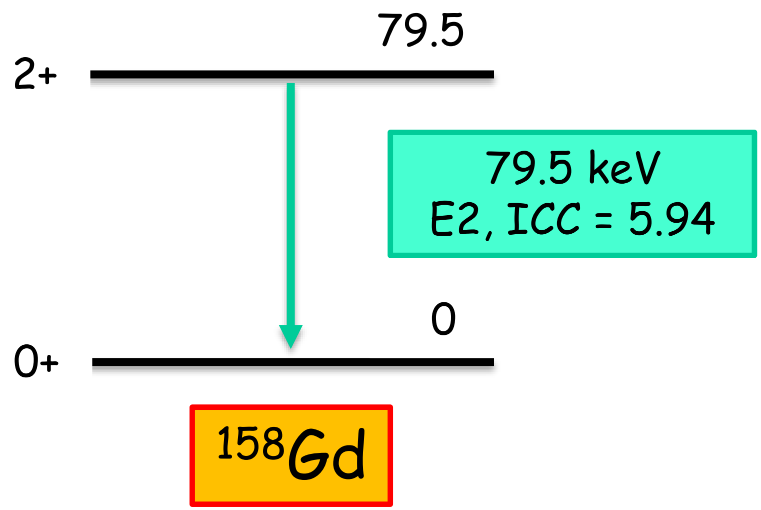
Electron and Photon Spectra of Gd following Neutron Capture

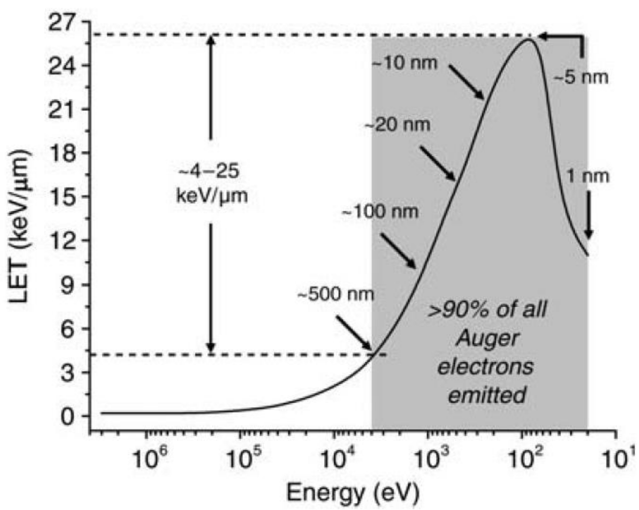
Boon Quan Lee

Motivation of GdNCT



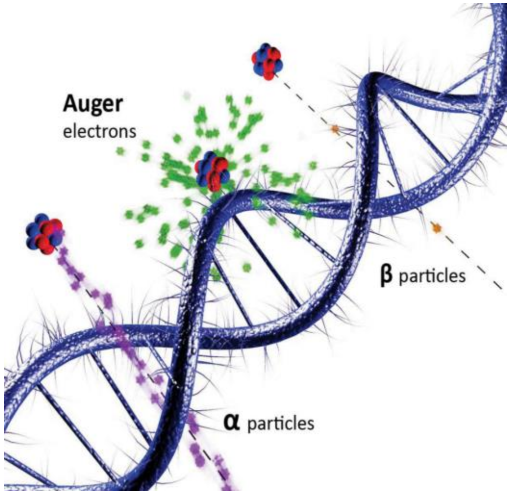
http://wwwndc.jaea.go.jp/





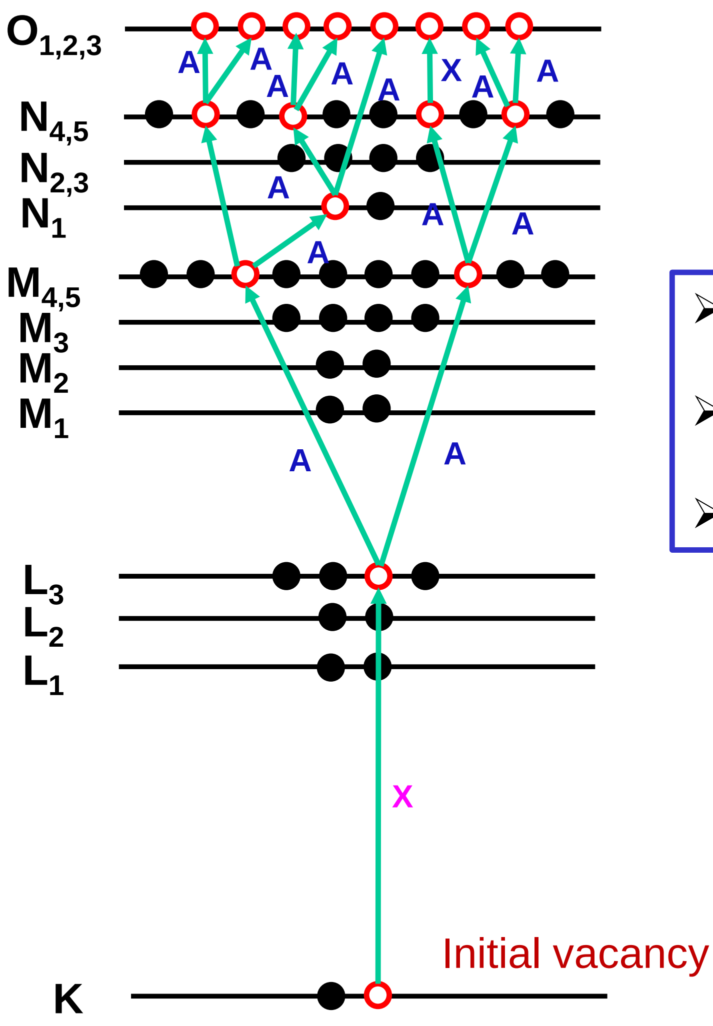
Amin I. Kassis

Radiation Protection Dosimetry (2010), pp. 1–7



(Courtesy of Thomas Tunningley, ANU).

Emission of low-energy Auger electrons



- Relaxation time $<10^{-12}$ s
- A conversion process can produce multiple electrons
- Majority are low in energy (< 5 keV)

Auger cascade in Xe

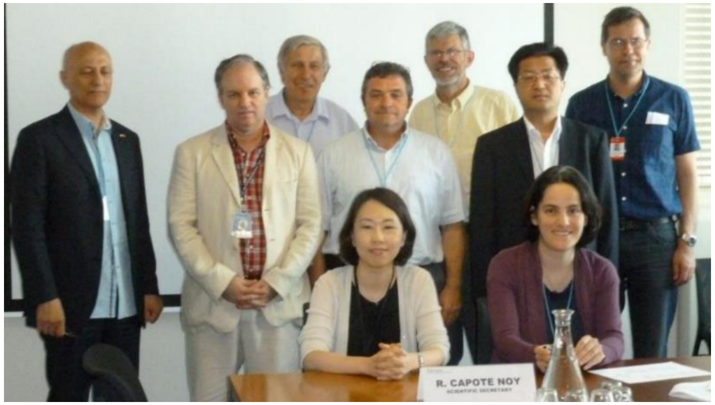
From M.O. Krause, J. Phys. Colloques, 32 (1971) C4-67

Discrepancies in Auger yields

	RADAR	DDEP	Eckerman (MIRD)	Howell (AAPM)	Nikjoo	Stepanek	Pomplun
^{99m}Tc	0.12	0.13	4.41	4.0			3.4
^{111}In	1.14	1.16	7.43	14.7		6.05	5.63
^{123}I	1.06	1.08	13.7	14.9			7.3
^{124}I	0.71		9.17		8.2		
^{125}I	1.77	1.78	23.0	24.9	20.2	14.5	12.2
^{140}Nd	0.798		9.71				
^{165}Er	0.685		7.26				
Vacancy propagation	DET K & L Shells	DET K & L Shells	DET neutral	MC neutral	MC neutral	MC isolated	MC isolated

IAEA Coordinated Research Project

Title: Auger Electron Emission from Nuclear Decay: Data Needs for Medical Applications



2013 IAEA Consultants' Meeting

AIMS: Realistic model to evaluate full energy spectrum from nuclear decay

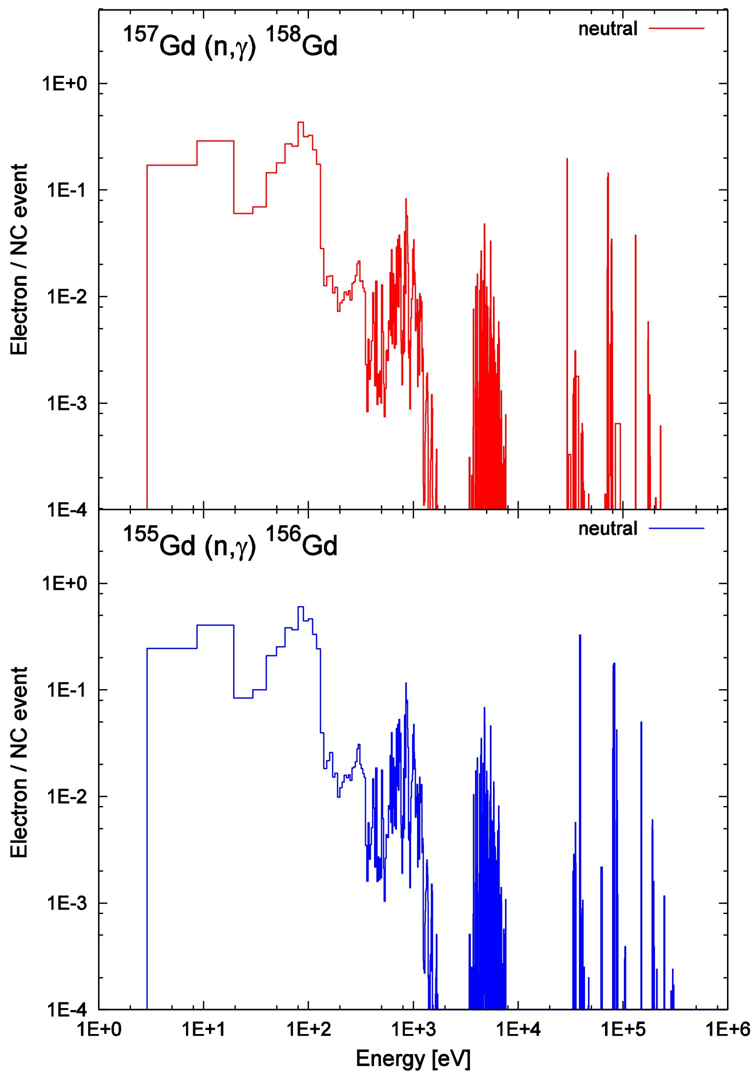
- ❑ Use of accurate conversion coefficients and electron capture rates needed for the initial vacancy distribution
- ❑ Full Monte Carlo treatment of Auger cascade
- ❑ DF calculations of transition energies to account for existence of multiple vacancies

Comparison of theoretical Auger yields

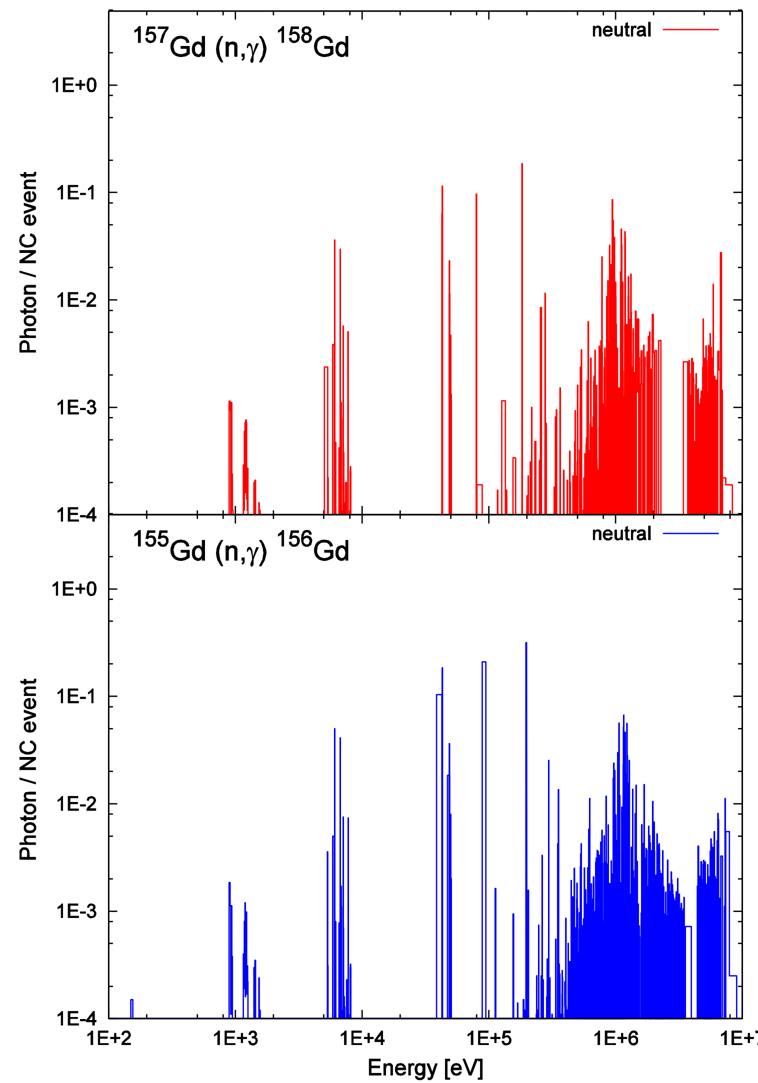
	RADAR	DDEP	Eckerman (MIRD)	Howell (AAPM)	Stepanek	Pomplun	Nikjoo	ANU	ANU
^{71}Ge	1.65							3.98	4.88
^{99m}Tc	0.12	0.13	4.41	4.0		3.4		3.52	4.39
^{111}In	1.14	1.16	7.43	14.7	6.05	5.63		5.84	7.17
^{123}I	1.06	1.08	13.7	14.9		7.3		7.38	12.3
^{124}I	0.71		9.17				8.2	5.04	8.38
^{125}I	1.77	1.78	23.0	24.9	14.5	12.2	20.2	11.9	20
^{140}Nd	0.80		9.71					7.82	9.01
^{140}Pr			5.16					3.82	4.54
^{155}Tb	1.25							12.6	13.2
^{161}Tb	0.57							9.45	9.72
^{165}Er	0.69		7.26					6.68	7.10
$^{155}Gd(n,\gamma)$								6.07	6.55
$^{157}Gd(n,\gamma)$					9.71		4.93	4.33	4.65
Vacancy propagation	DET K & L Shells	DET K & L Shells	DET neutral	MC neutral	MC isolated	MC isolated	MC neutral	MC isolated	MC neutral

Energy Spectra of Gd(n,γ)

Electron

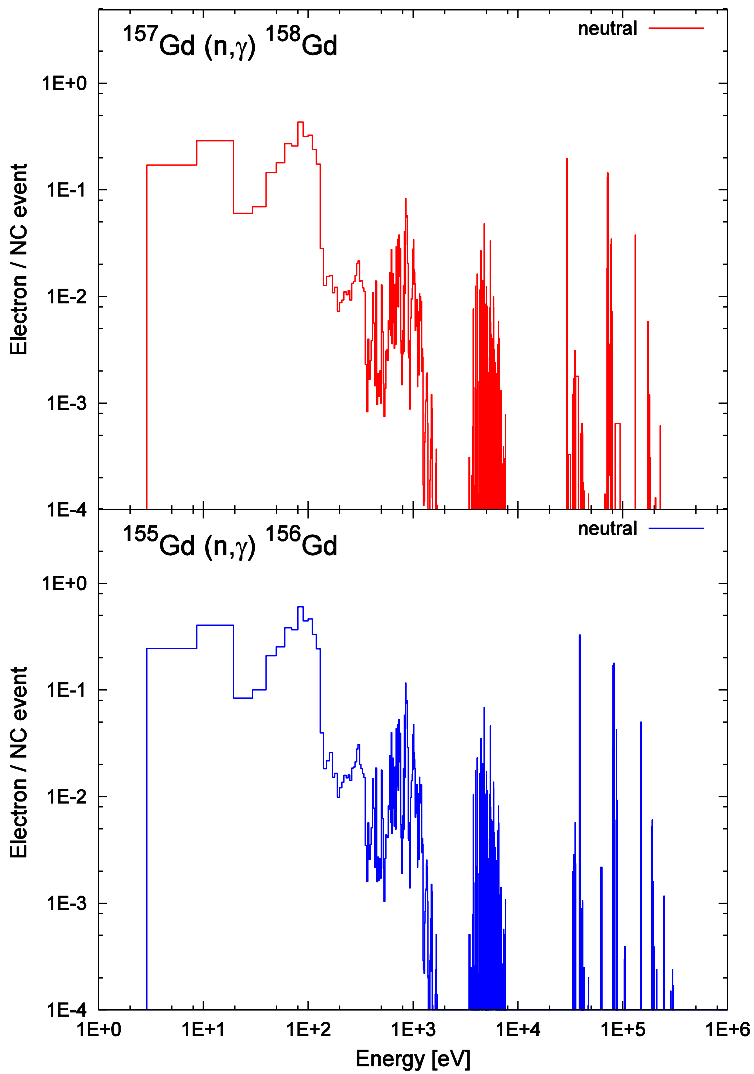


Photon



Average energy spectra of Gd(n,γ)

Electron



	^{155}Gd(n,γ) ^{156}Gd	^{157}Gd(n,γ) ^{158}Gd
No. X-ray	0.50	0.32
X-ray energy	16.7	10.4
No. IC	0.89	0.64
IC energy	67.7	44.0
No. Auger	6.55	4.65
Auger energy	5.53	3.83
No. LE e- (<50 keV)*	7.37	5.26
LE e- energy*	71.1	47.7

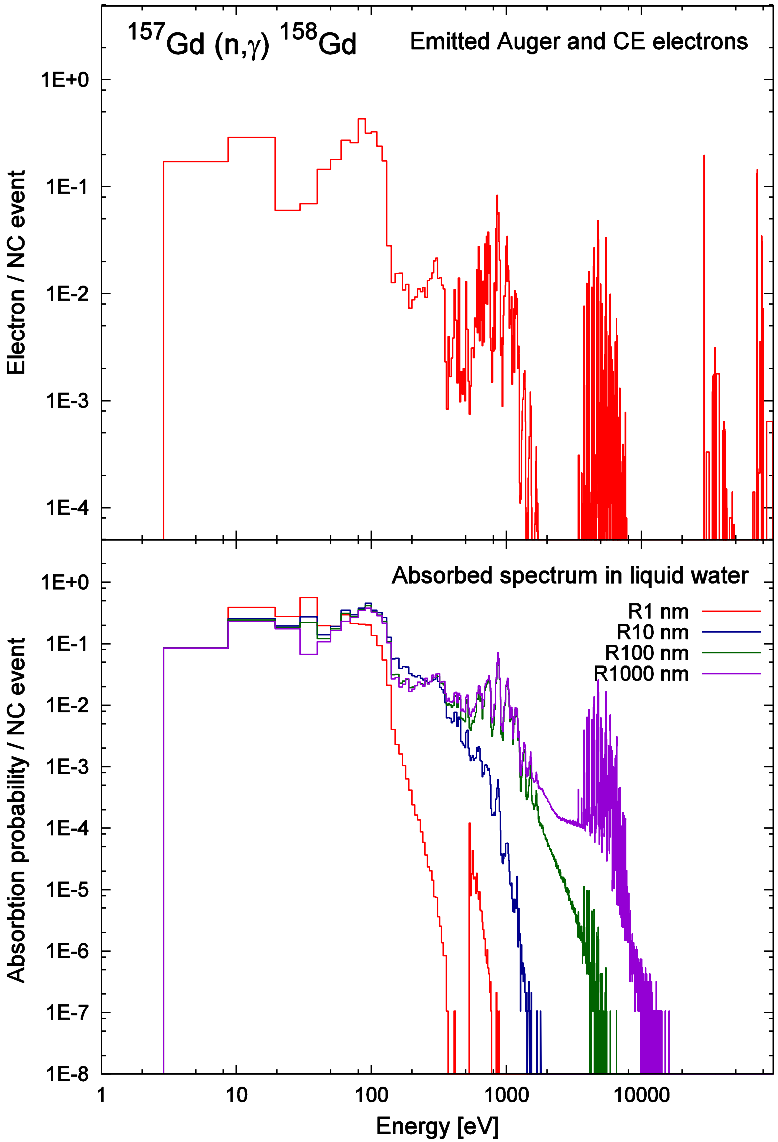
energy in keV.
per neutron capture.
* max projected range (NIST) = 43 μm

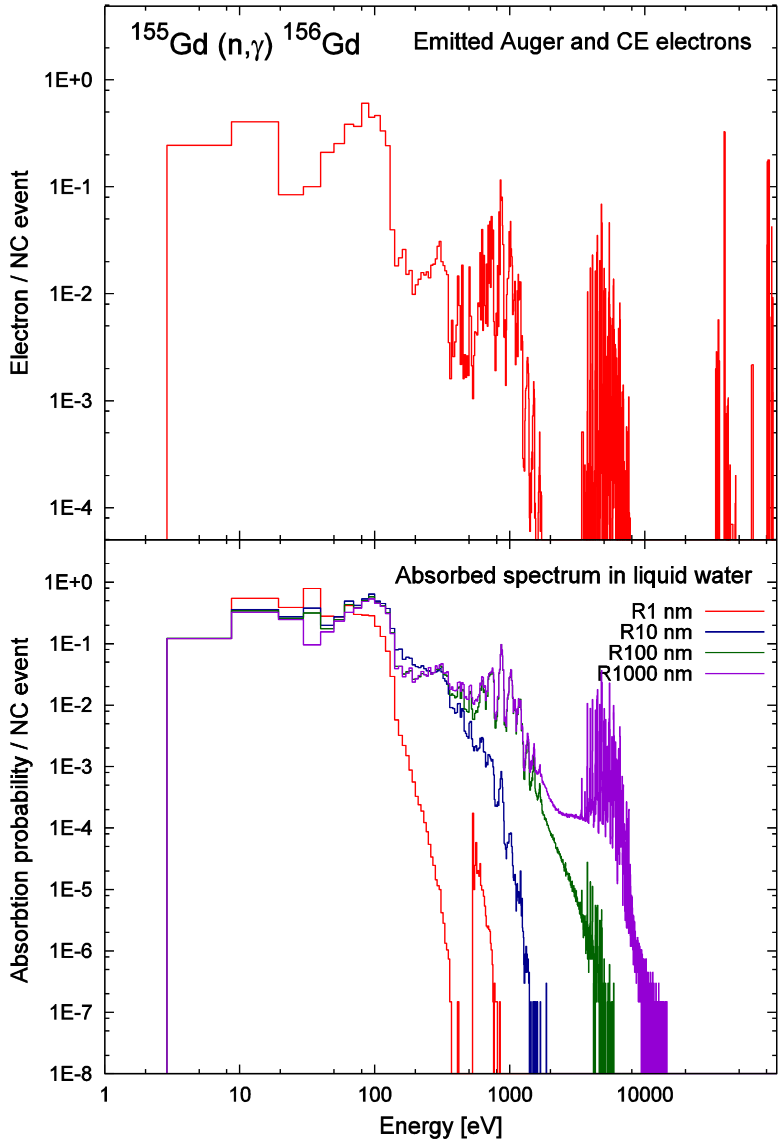
Average energy deposition in water by short-range radiations (simulation)

Radius (nm)	$^{155}Gd(n,\gamma)^{156}Gd$	$^{155}Gd(n,\gamma)^{156}Gd$	$^{157}Gd(n,\gamma)^{158}Gd$	$^{157}Gd(n,\gamma)^{158}Gd$ - A	$^{10}B(n,\alpha)^{7}Li$ - B	Ratio of B to A
1	0.17	0.23	0.12	0.16	0.59	3.7
10	0.55	0.68	0.39	0.49	5.23	10.7
100	1.67	1.88	1.19	1.34	51.7	38.6
1000	4.81	5.05	3.47	3.63	498	137
5000	7.09	7.35	5.38	5.55	1923	346
10000	10.5	10.8	8.79	8.96	2339	261
Vacancy Propagation	Isolated	Neutral	Isolated	Neutral		

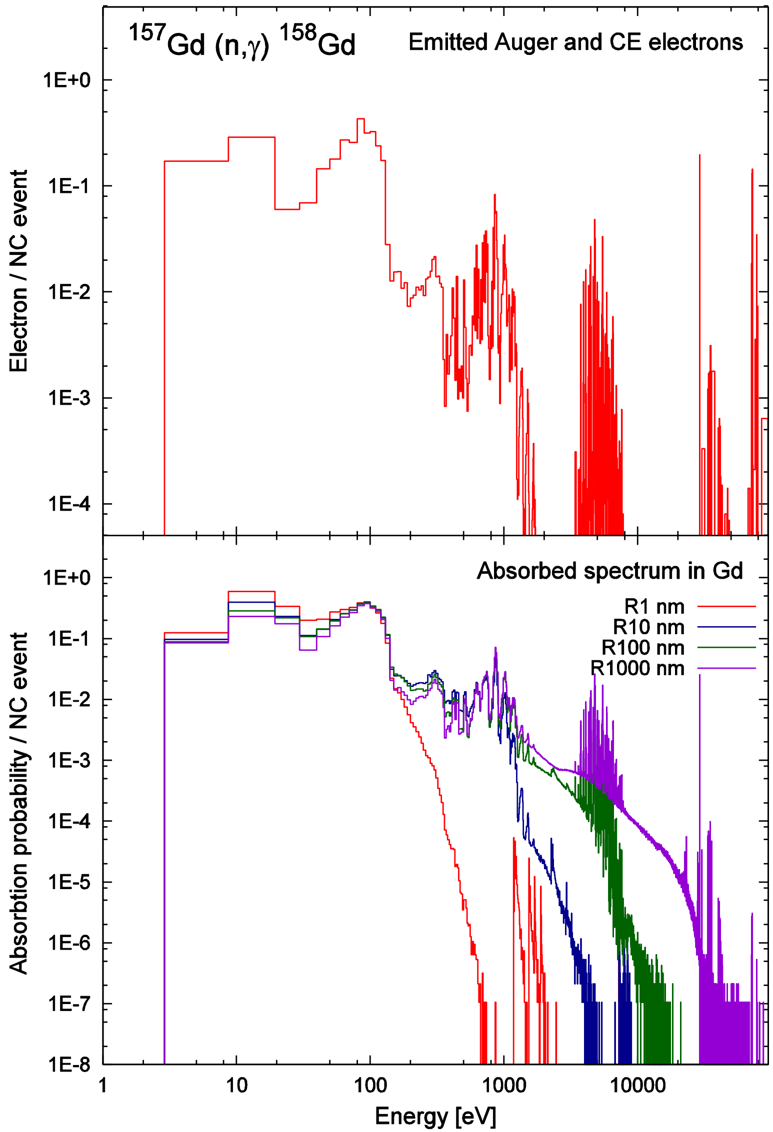
energy in keV.
per neutron capture.

Energy deposition in water by conversion and Auger electrons (simulation)





Self-absorption in Gd

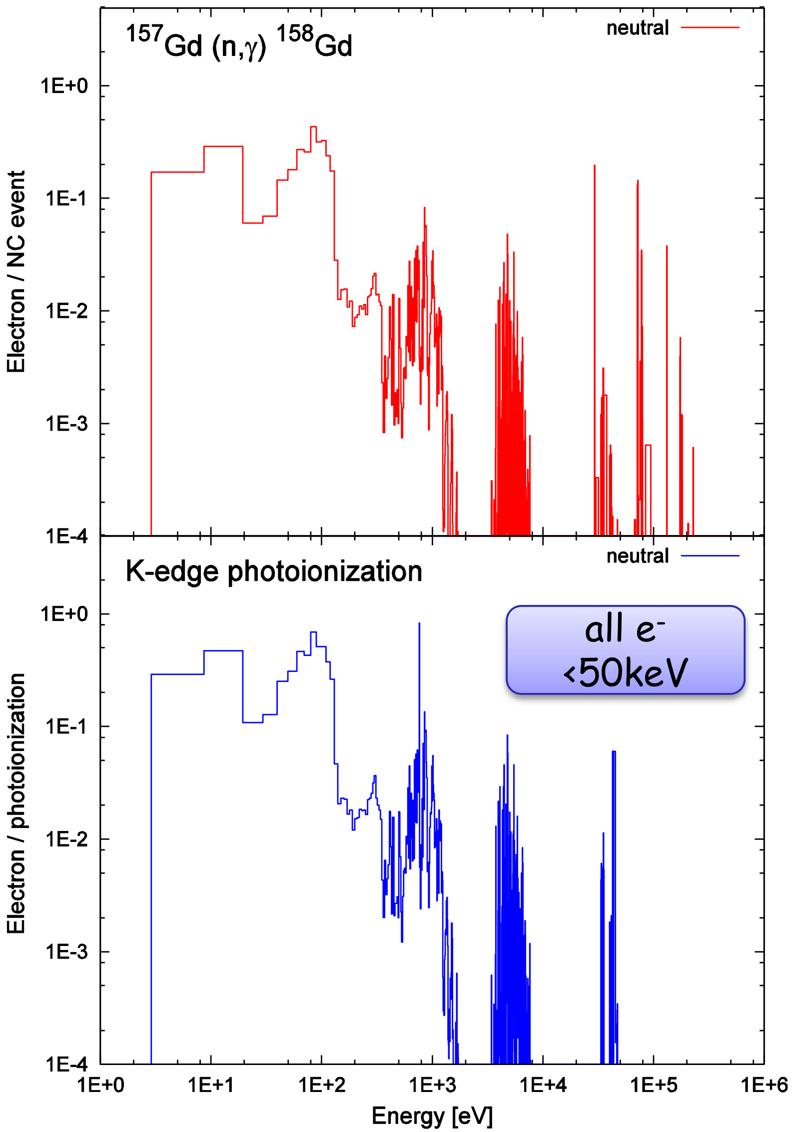


Radius (nm)	$^{155}Gd(n,\gamma)^{156}Gd$	$^{157}Gd(n,\gamma)^{158}Gd$
1	0.39 (3.6%)	0.28 (3.1%)
5	0.91 (8.4%)	0.64 (7.2%)
10	1.44 (13.4%)	1.02 (11.4%)
50	2.45 (22.7%)	1.74 (19.4%)
100	3.89 (36.1%)	2.76 (30.8%)
1000	8.79 (81.6%)	6.24 (69.6%)

energy in keV.
per neutron capture.

*Percentage relative to energy absorption in water of 10 μm radius.

Average spectrum following K-edge photoionization of Gd



	$^{157}Gd(n,\gamma)^{158}Gd$	K-edge Gd
No. X-ray	0.32	0.97
X-ray energy	10.4	35.3
No. Auger	4.65	7.67
Auger energy	3.83	7.44
No. Photo e^-	-	1.0
Photo e^- energy	-	2.79

Radius(nm)	$^{157}Gd(n,\gamma)$ ^{158}Gd	K-edge Gd
1	0.16	0.27
10	0.49	0.94
100	1.34	2.80
1000	3.63	6.25
5000	5.58	7.10
10000	8.96	8.33

energy in keV.
per neutron capture or photoionization.

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Summary & Outlook

- Full energy spectra of Gd following NC - based on the latest nuclear data from ENSDF
- Local energy deposition (homogeneous) has been simulated and compared to $^{10}B(n,\alpha)^{7}Li$ – generally BNC is higher per NC event in different volumes of liquid water
- Self-absorption by Gd particles can be significant – need nanoparticles
- K-edge photoionization generates more Auger electrons than GdNC per event
- Database of Auger spectra is in development – connected to ENSDF

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