JAEA NDC

Covariance Evaluation of Self-Shielding Factor and Its Temperature Gradient for Uncertainty Evaluation of Doppler Reactivity

ERRORF collaboration

Collaboration

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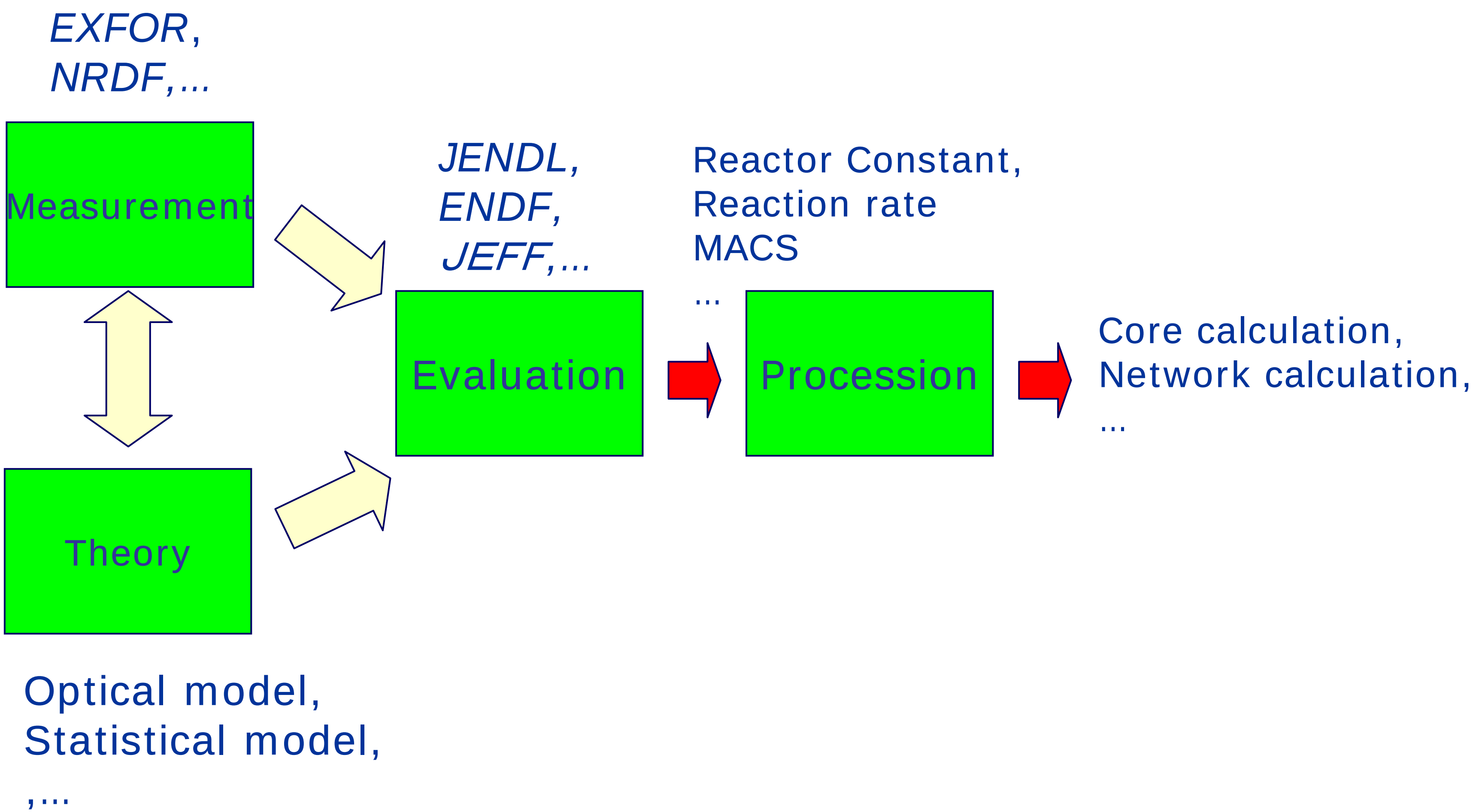
Contents

- Doppler reactivity
- Covariance evaluation of α-value
- Uncertainty in Doppler reactivity using covariances from ERRORF

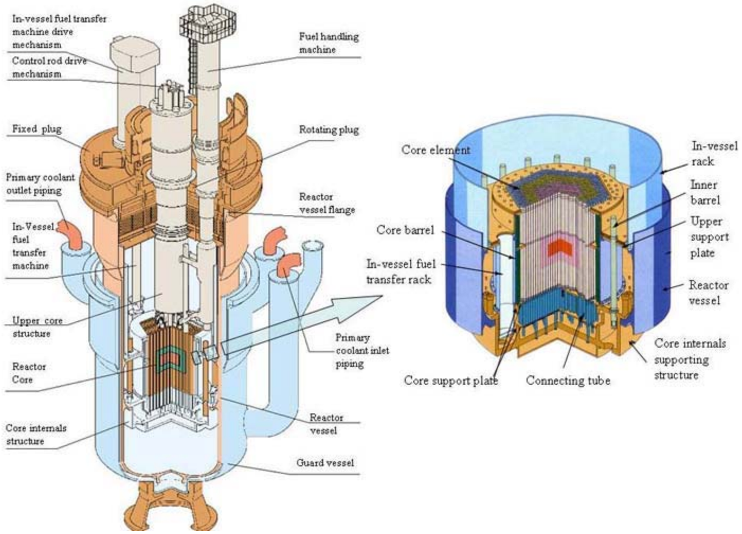
Flow of nuclear data

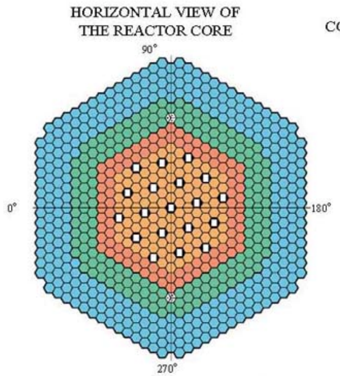


Doppler Reactivity and Nuclear Data

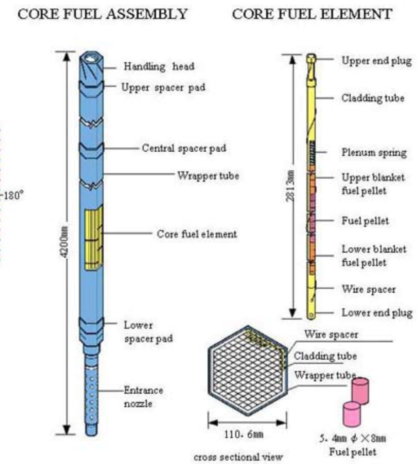
Fast breeder reactor calculation

- **Complicated inhomogeneous structure (pellet, cladding tube, wrapper tube etc.)**





Core elements		Symbol	Number
Core fuel assembly	Inner core		108
	Outer core		90
Blanket fuel assembly			172
Control rod			19
Neutron source			2
Neutron shield assembly			316
Surveillance assembly			8

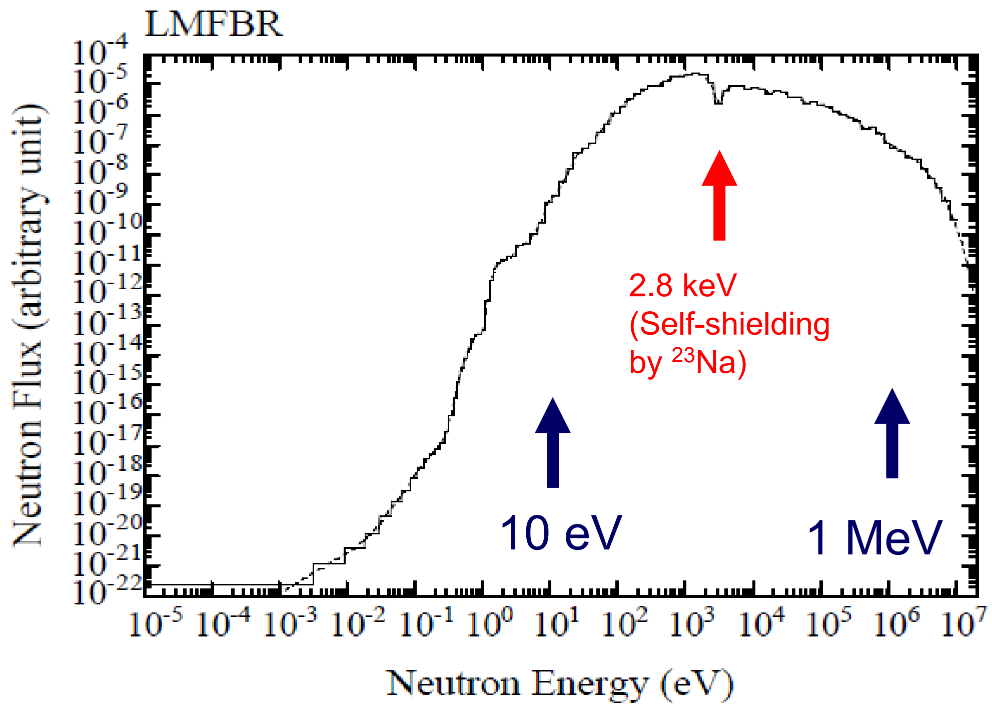


Uncertainty in prediction:

group structure, burning chain, 3D effect…

Fast breeder reactor and nuclear data

- **Energy spectrum of fast breeder reactor**



Nuclear data in wide neutron energy (10^2 eV ~ 10^6 eV) also could be a source of uncertainty in prediction

Reactor core parameters

- Criticality (k_{eff}) (+/- 3%, 1σ)
- Sodium void reactivity worth (+/- 20%, 2σ)
- Doppler reactivity worth (+/- 14%, 2σ)
- …

Doppler reactivity is an important safety parameter in self-regulation characteristics of reactors.

Criticality and reactivity worth (Definition)

- **Criticality (k_{eff}):**

ratio of

# of incoming neutron per unit time (e.g. fission neutron)

to

# of expended neutron per unit time (e.g. fission, capture)

$$k_{\text{eff}} \cong \frac{\int dE\, \nu(E)\, \sigma_{\text{fission}}(E)\, \phi(E)}{\int dE \left[\sigma_{\text{capture}}(E) + \sigma_{\text{fission}}(E)\right] \phi(E)}$$

k_{eff} =1 (critical), <1 (subcritical), >1 (supercritical)

Criticality and reactivity worth (Definition)

- **Reactivity worth (ρ) - change of reactivity:**

$$\rho = \Delta p = \frac{1}{k_{\mathrm{eff}}(1)} - \frac{1}{k_{\mathrm{eff}}(2)}$$

for Temperature change 1→2

Example:

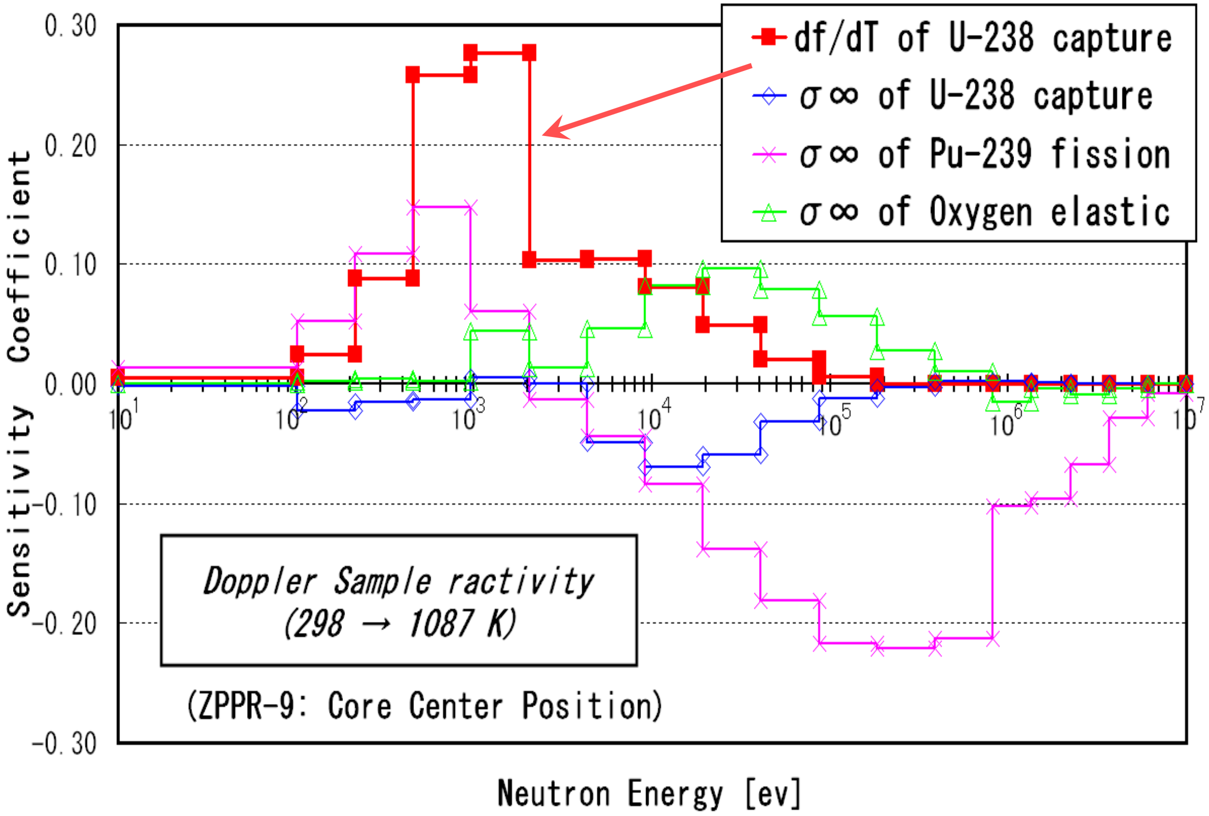
$$\rho = \Delta p = \frac{1}{k_{\mathrm{eff}}(T_{\mathrm{low}})} - \frac{1}{k_{\mathrm{eff}}(T_{\mathrm{high}})}$$

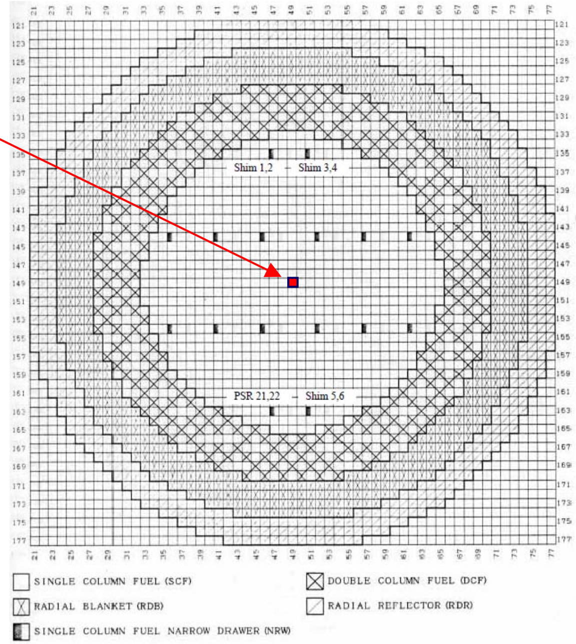
for Temperature change $T_{low} \rightarrow T_{high}$

Doppler reactivity worth

Sensitivity for a Sample Doppler Reactivity (ZPPR-9)

(* Sample material: Natural uranium dioxide, app. 1 kg)





(by M.Ishikawa)

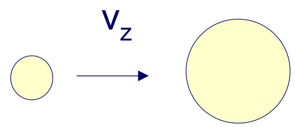
Covariance Evaluation of α-value for Doppler Reactivity Uncertainty

N. Otuka, A. Zukeran, H. Takano, G. Chiba, M. Ishikawa,
J.Nucl.Sci.Technol.Vol.45 No.3 (in press)

Temperature dependence of cross section

- **Doppler broadening (single-level Breit-Wigner)**

$$\sigma_\gamma(E,T)=\sigma_0\left(\frac{\Gamma_\gamma}{\Gamma}\right)\sqrt{\frac{E_0}{E}}\sqrt{\frac{m}{2\pi kT}}\int_{-\infty}^{\infty}\frac{\exp\left(-\frac{E_c}{kT}\right)}{1+\left(\frac{2(E_C-E_0)}{\Gamma_{\text{tot}}}\right)}dv_z$$

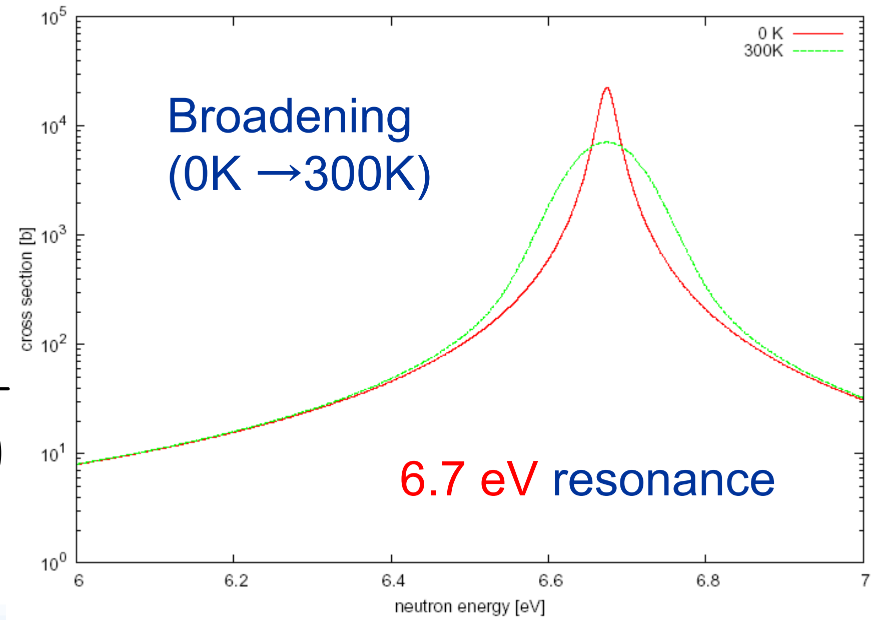


Change in self-shielding effect f:

$$f^g(T,\sigma_b)=\frac{\sigma_{\text{eff}}{}^g(T,\sigma_b)}{\sigma_{\text{eff}}{}^g(T_0,\sigma_b=\infty)}$$

, where $\sigma_{\text{eff}}=\frac{\int dE\sigma(E,T)\phi(E,T,\sigma_b)}{\int dE\phi(E,T,\sigma_b)}$

JENDL-3.3 $^{238}U(n,\gamma)\ ^{239}U$cross section



Example: $^{238}U(n,\gamma)\ ^{239}U$ @ 800 deg-K

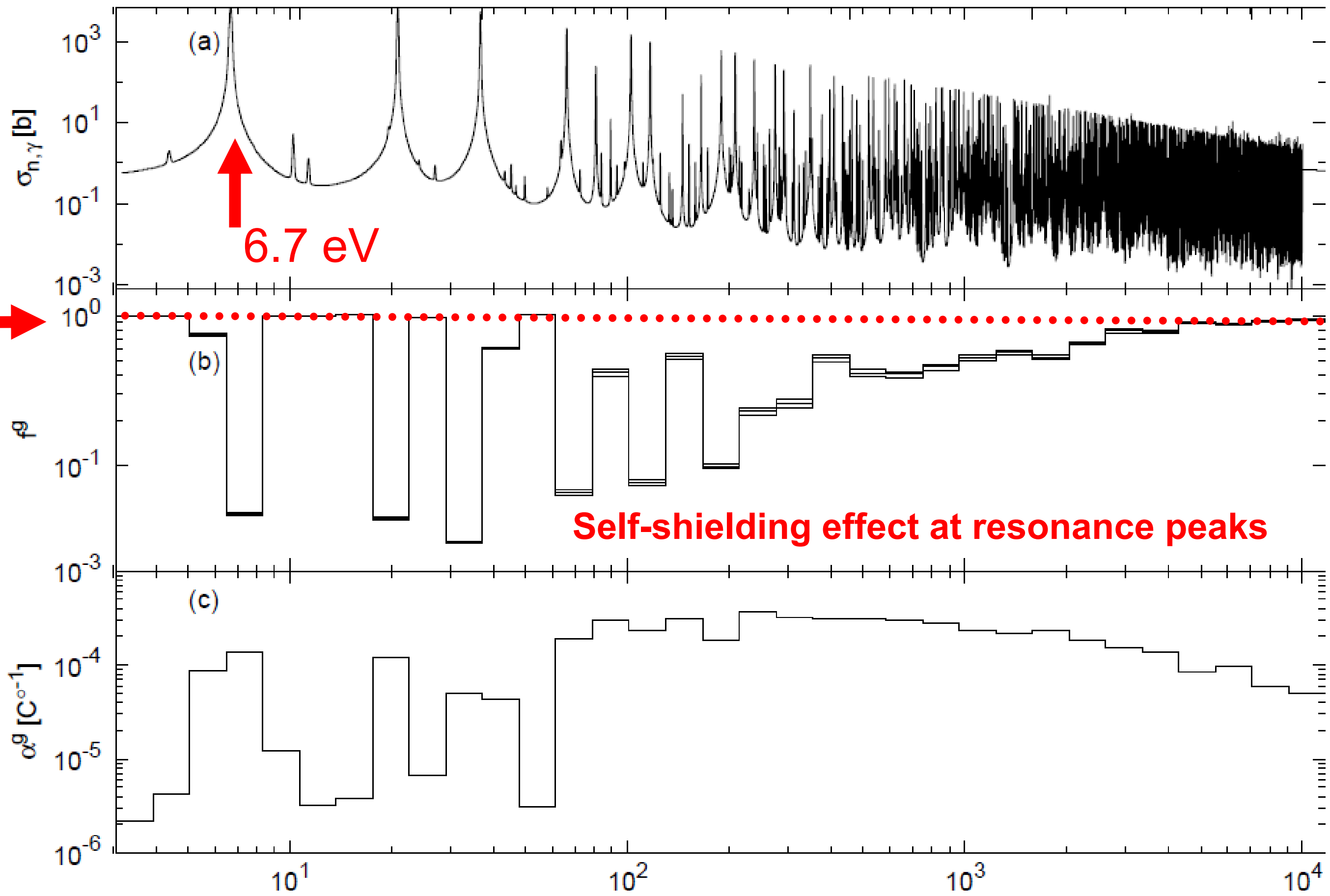
Cross section

f=1 (no self-sheilding)

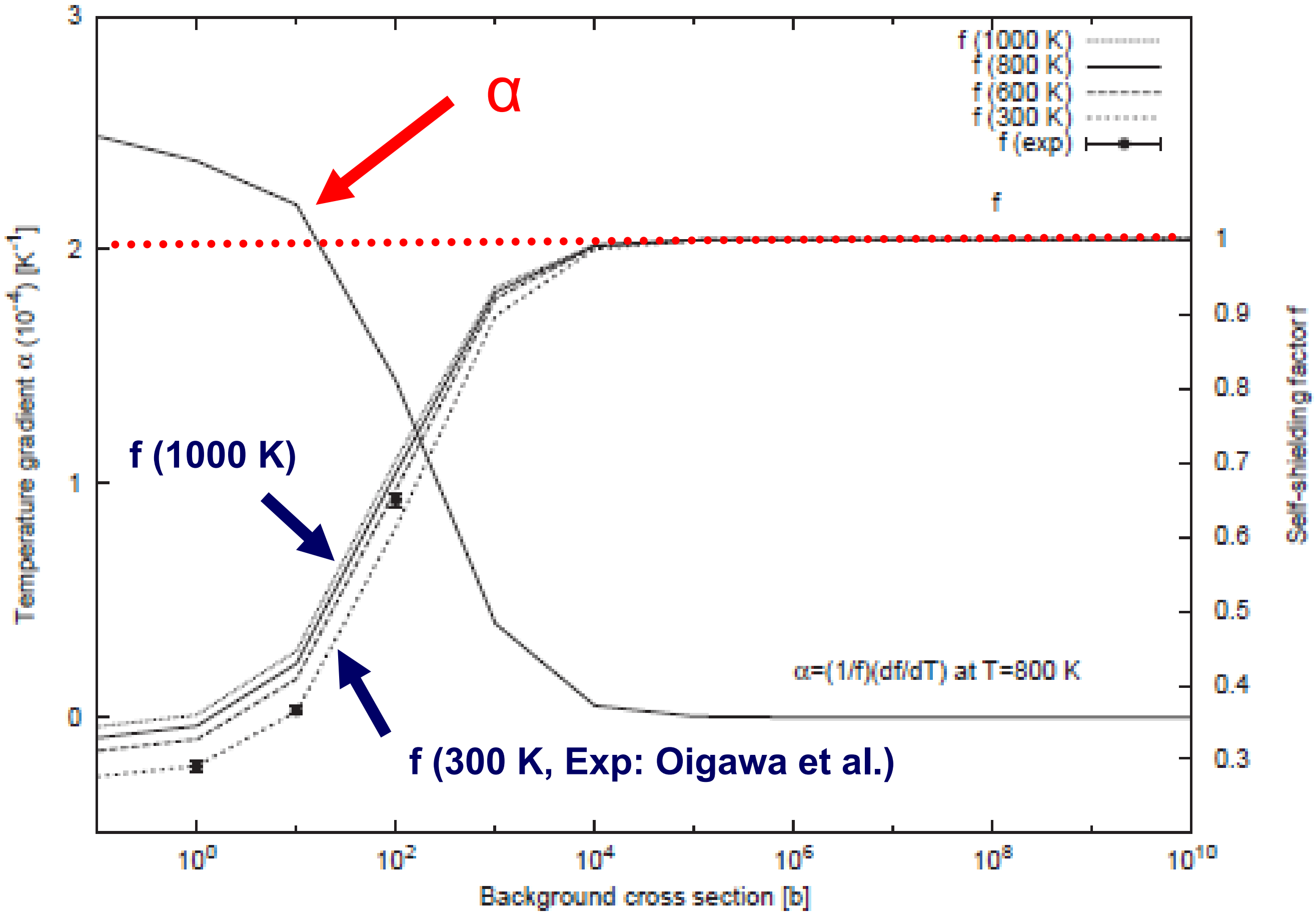
Self-shielding factor (f-factor)

Temperature gradient of f-factor (α-value):

$\alpha = (1/f)(\partial f/\partial T)$



Example of f and α (^{238}U capture, ~1 keV)



Error of reactivity worth and nuclear data

- **Doppler reactivity worth: $\rho = \rho\,(\sigma_{eff}(T_0),\ f(T),\ \alpha(T), \ldots)$**

  Error propagation

  from temperature gradient α to Doppler reactivity worth ρ

$$\frac{\Delta\rho}{\rho} = S_{\alpha}\frac{\Delta\alpha}{\alpha}$$

S_{α} can be calculated from sensitivity of criticality at high temperature $S_{keff}(T_{high})$:

$$S_{\alpha} = \left(\frac{\sigma_{eff}(T_{high}) - \sigma_{eff}(T_{low})}{\sigma_{eff}(T_{high})}\right) \times \frac{1}{\rho} \times \frac{S_{keff}(T_{high})}{k_{eff}(T_{high})}$$

, where

$$\frac{\Delta k_{eff}(T_{high})}{k_{eff}(T_{high})} = S_{keff}(T_{high})\frac{\Delta\sigma_{eff}(T_{high})}{\sigma_{eff}(T_{high})}$$

$\Delta\alpha(T)$: from uncertainty in nuclear data (Our work!)

Uncertainty in temperature gradient

- **Error propagation from nuclear data to temperature gradient α**

$$\left(\frac{\Delta\alpha^g}{\alpha^g}\right)^2 = \sum_{i,j} S^g{}_i S^g{}_j \rho_{ij} \frac{\Delta x_i}{x_i}\frac{\Delta x_j}{x_j} \rightarrow \frac{\Delta\alpha^g}{\alpha^g} \cong \sum_{i,j} S^g{}_i \frac{\Delta x_i}{x_i}$$

$\rho_{ij}\Delta x_i \Delta x_j$: covariance of resonance parameter (E_r, Γ_n, Γ_γ, Γ_f)

… evaluated in JENDL (^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu,…)

$$S^g{}_i = \frac{x_i}{\alpha^g}\frac{\partial\alpha^g}{\partial x_i}$$

S_i: Sensitivity coefficient of x_i to α

Covariance of resonance parameter (U, Np, Pu)

Nuclide	Library
^{233}U	JENDL-3.3, JEFF-3.1
^{235}U	JENDL-3.3
^{238}U	JENDL-3.3
^{237}Np	JENDL-3.3
^{238}Pu	JENDL-3.3
^{239}Pu	JENDL-3.3
^{240}Pu	JENDL-3.3, ENDF-B/VI
^{241}Pu	JENDL-3.3
^{242}Pu	JENDL-3.3, ENDF-B/VI

Flow of calculation to obtain Δα (*ERRORF*)

recent sigma   *njoy*

E_1, Γ_1, $E_2, \Gamma_{2,\ldots}$ → $\sigma(T_{low})$, $\sigma(T_{high})$ → $f(T_{low})$, $f(T_{high})$ → $\alpha = (1/f)(\Delta f/\Delta T)$

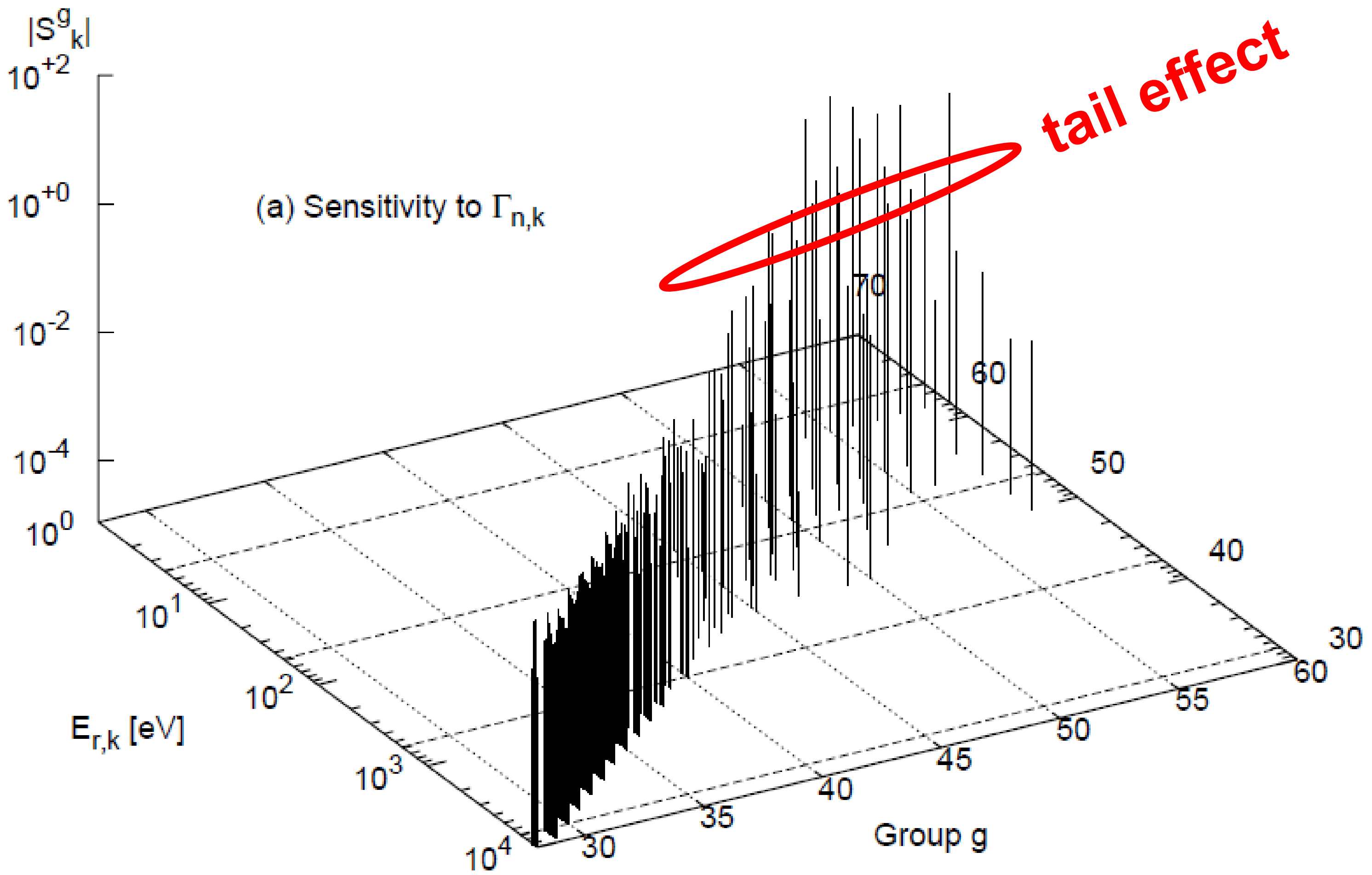
$E_1, \Gamma_1 + \delta\Gamma_1$, $E_2, \Gamma_2, \ldots$ → → $\alpha + \Delta\alpha_1$ → $S_i = (x_i/\alpha)(\Delta\alpha/\Delta x_i)$

… repeat for all resonances (561 s-wave levels for ^{238}U)

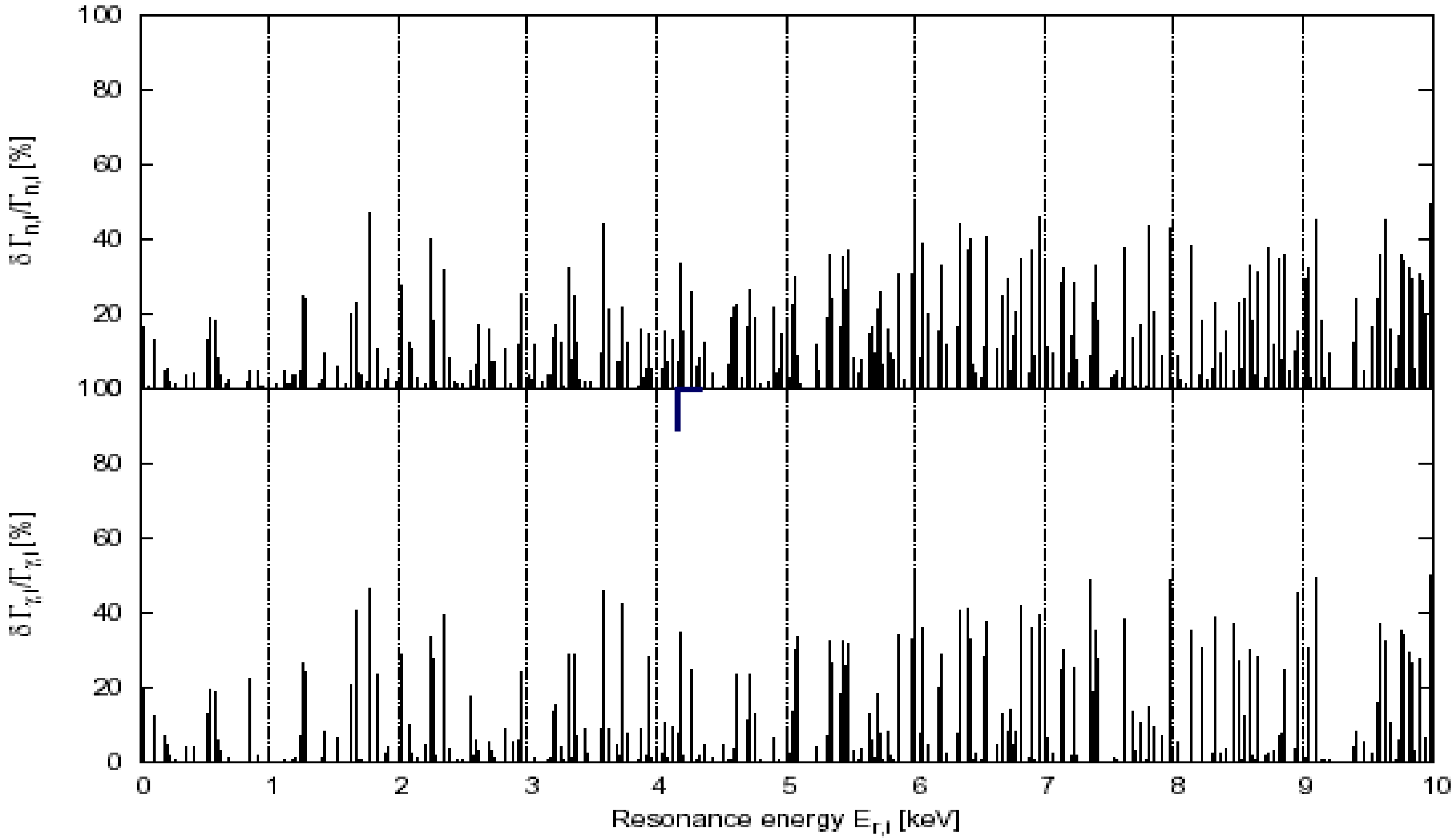
→
$$\left(\frac{\Delta\alpha}{\alpha}\right)^2 = \sum_{i,j} S_i S_j \rho_{ij} \frac{\Delta x_i}{x_i} \frac{\Delta x_j}{x_j}$$

($\rho_{ij}\, \Delta x_i\, \Delta x_j$ are from covariance in JENDL)

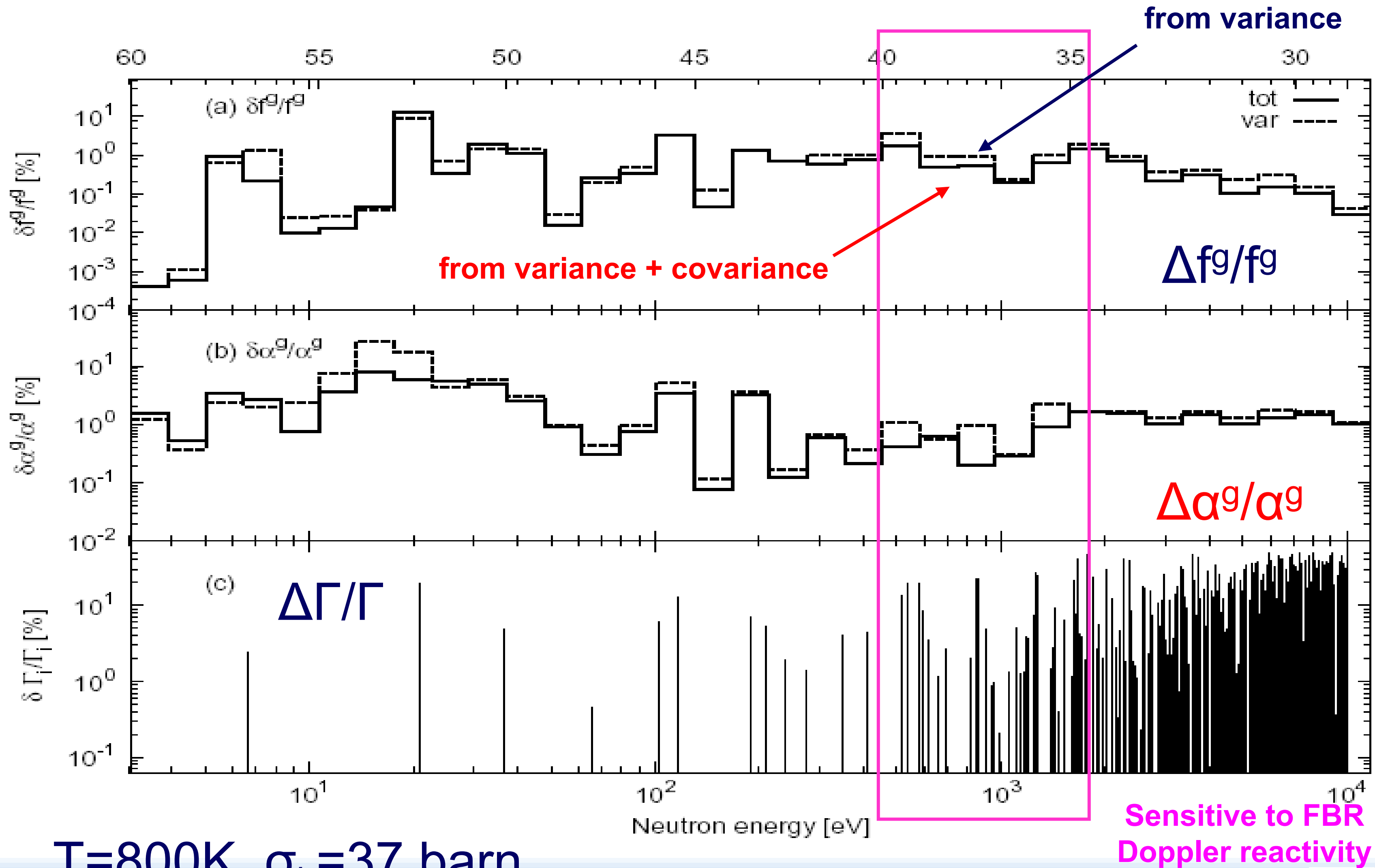
Sensitivity $S^{g}_{i} = (\Gamma_n / \alpha)\,(\Delta\alpha / \Delta\Gamma_n)$



$\Delta\Gamma_n$ and $\Delta\Gamma_\gamma$ of ^{238}U in JENDL-3.3



Δα^g/α^g (in JFS 60 group structures)



T=800K, σ_b=37 barn

$\Delta\alpha^g/\alpha^g$ (in JFS 60 group structures)

Gr	E_{max} [eV]	f	$\delta f^g/f^g$ [%] tot	$\delta f^g/f^g$ [%] var	α [10^{-4}/K]	$\delta\alpha^g/\alpha^g$ [%] tot	$\delta\alpha^g/\alpha^g$ [%] var
...	...	Unresolved resonance region					
27	1.5034E+04						
28	1.1709E+04	0.9444	0.0289	0.0437	0.3813	1.0054	1.0776
29	9.1188E+03	0.9258	0.1017	0.1490	0.4481	1.4260	1.6756
30	7.1017E+03	0.8792	0.1488	0.3142	0.7400	1.2854	1.7108
31	5.5308E+03	0.8913	0.1080	0.2258	0.6509	1.0125	1.3370
32	4.3074E+03	0.7721	0.3064	0.4182	1.1065	1.4537	1.6364
33	3.3546E+03	0.7877	0.2242	0.3687	1.2258	1.0435	1.3294
34	2.6126E+03	0.6534	0.6841	0.9353	1.4786	1.5242	1.6700
35	2.0347E+03	0.5290	1.3905	1.9059	1.8930	1.6642	1.6645
36	1.5846E+03	0.5724	0.6365	1.0292	1.7635	0.9159	2.2293
37	1.2341E+03	0.5227	0.1913	0.2321	1.9270	0.2856	0.2994
38	9.6112E+02	0.4546	0.5194	0.9475	2.3185	0.1997	0.9847
39	7.4852E+02	0.4065	0.5080	0.8958	2.4933	0.6442	0.5627
40	5.8295E+02	0.4154	1.7276	3.7449	2.5972	0.4129	1.0545
41	4.5400E+02	0.5179	0.7790	1.0278	2.5550	0.2084	0.3675

$\Delta\alpha^g/\alpha^g$

var+cov var

Sensitive to FBR Doppler reactivity

T=800K, σ_b=37 barn

Covariance of α (in JFS 60 group structures)

$$A = SVS^t$$

A: covariance of α
S: sensitivity
V: covariance of (*E*, Γ)

Gr	28	29	30	31	32	33	34	35	36	37	38	39	40	41
28	10C	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	100	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	100	1	0	0	0	0	0	0	0	0	0	0
31	0	0	1	100	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	100	-13	0	0	0	0	0	0	0	0
33	0	0	0	0	-13	100	1	0	0	0	0	0	0	0
34	0	0	0	0	0	1	10C	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	100	-1	0	0	0	0	0
36	0	0	0	0	0	0	0	-1	100	-3	0	0	0	0
37	0	0	0	0	0	0	0	0	-3	10C	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	10C	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	10C	-92	0
40	0	0	0	0	0	0	0	0	0	0	0	-92	10C	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	10C
42	0	0	0	0	0	0	0	0	0	0	0	0	1	12
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	1	1
45	0	0	0	0	0	0	0	0	0	0	0	1	0	-3
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	1	0	-3
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	1
53	0	0	0	0	0	0	0	0	0	0	0	0	0	0
54	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	0	0	0	0	0	0	0	0	0	0	0	0	0	0
56	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57	0	0	0	0	0	0	0	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0	0	0	0	0	0	0	0
59	0	0	0	0	0	0	0	0	0	0	0	0	0	0
[illegible]	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Sensitive to FBR Doppler reactivity

T=800K, σ_b=37 barn

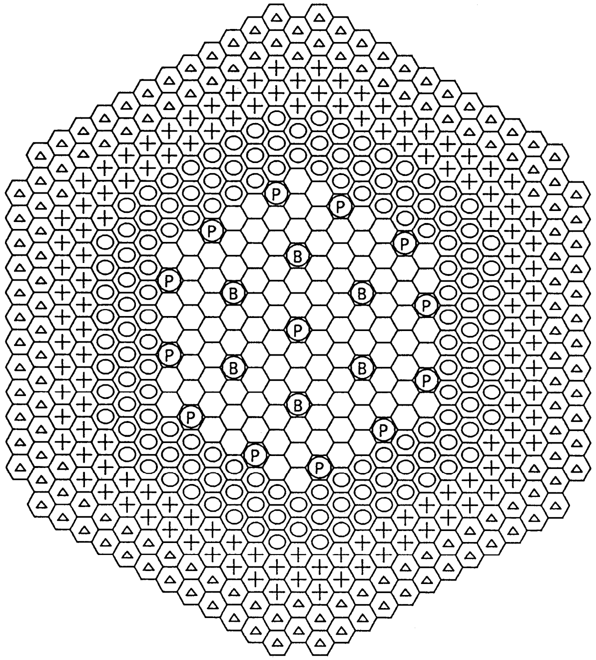
Doppler Reactivity Uncertainty Evaluation

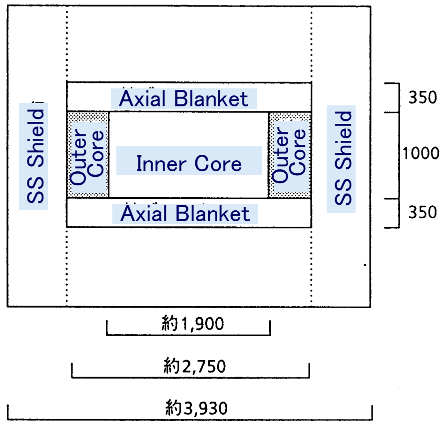
(a 600 MWe-Class Sodium-Cooled FBR)

(from Ishikawa-san)

Specification of a 600 MWe-class FBR

- Thermal power : 1,600MWt
- Operating cycle: 365 days
- Pu ratio (Inner/Outer core) : 16.5/20.5 %
- Pu composition (238/239 /240/241/242) : 3/53/25/12/7
- Burnup reactivity loss : 2.5 %dk/kk'/cycle
- Doppler Coefficient (BOEC) : -8.0E-3 Tdk/dT
- Sodium void reactivity (whole core, BOEC): 4.6 $
- Prompt neutron lifetime (BOEC) : 0.41 micro-sec
- Beta effective (BOEC) : 3.8E-3



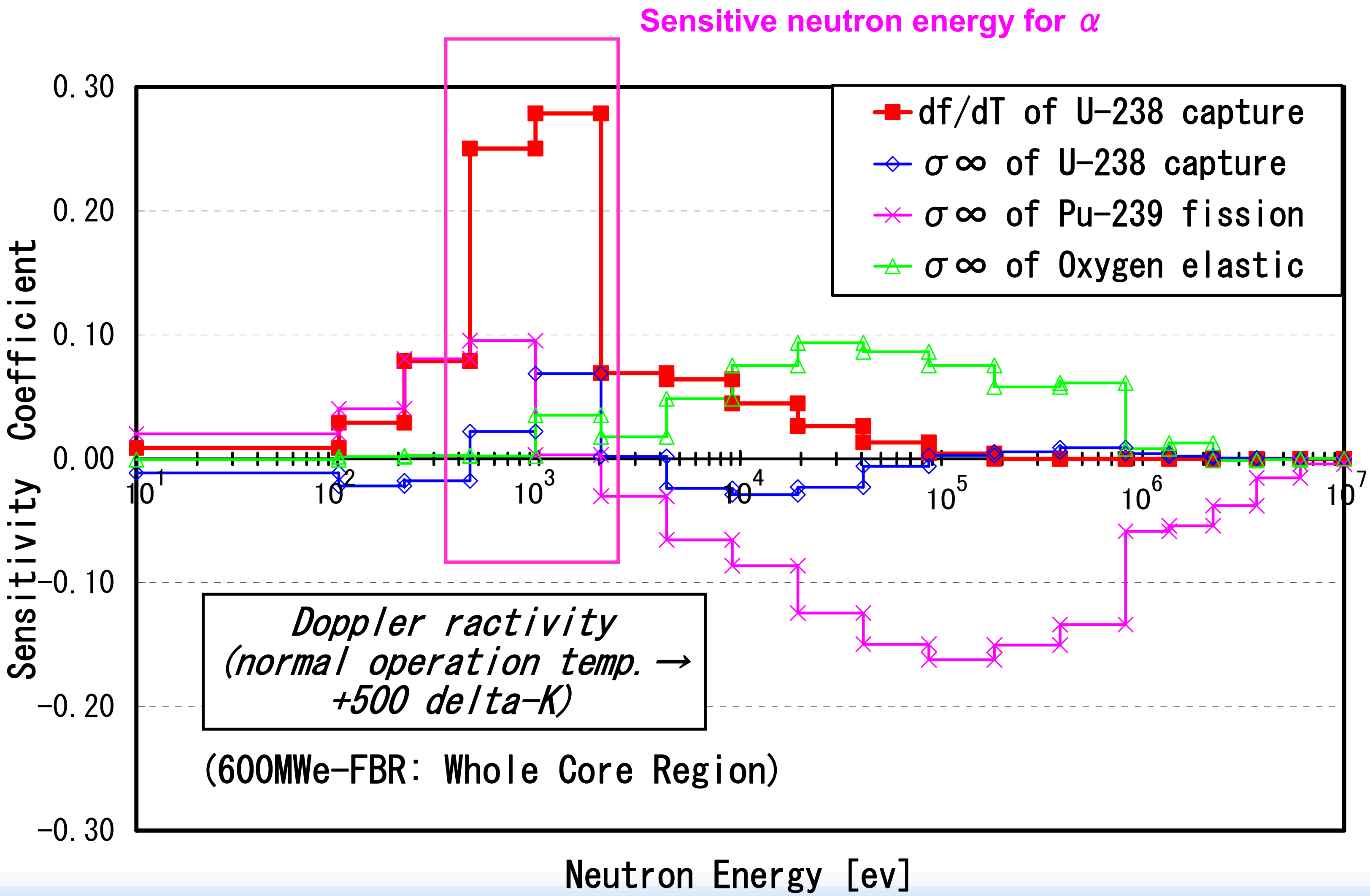


(Diameter(mm))

Inner Core	108
Outer Core	138
SS Shield	126
B4C Shield	150
Primary CR	13
Backup CR	6
Total	541

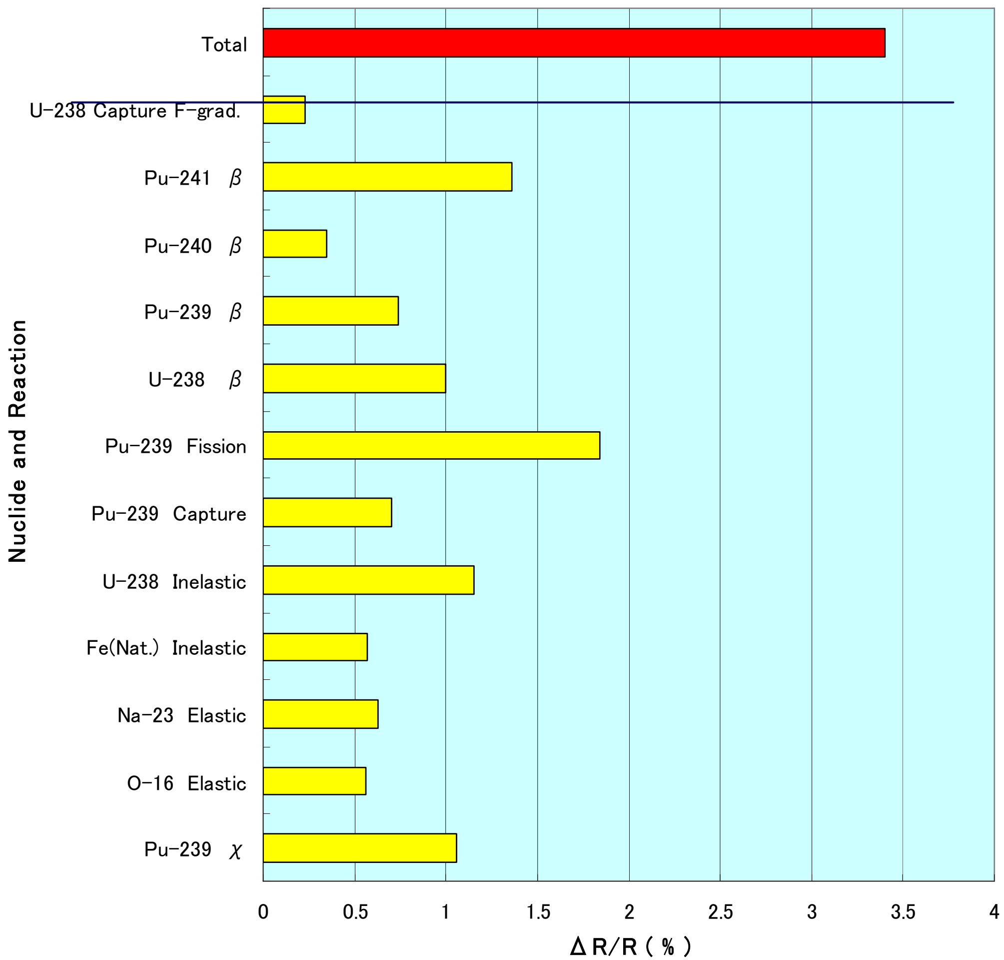
A 600MWe-class FBR Core

Sensitivity of Doppler Reactivity of a 600MWe-class FBR



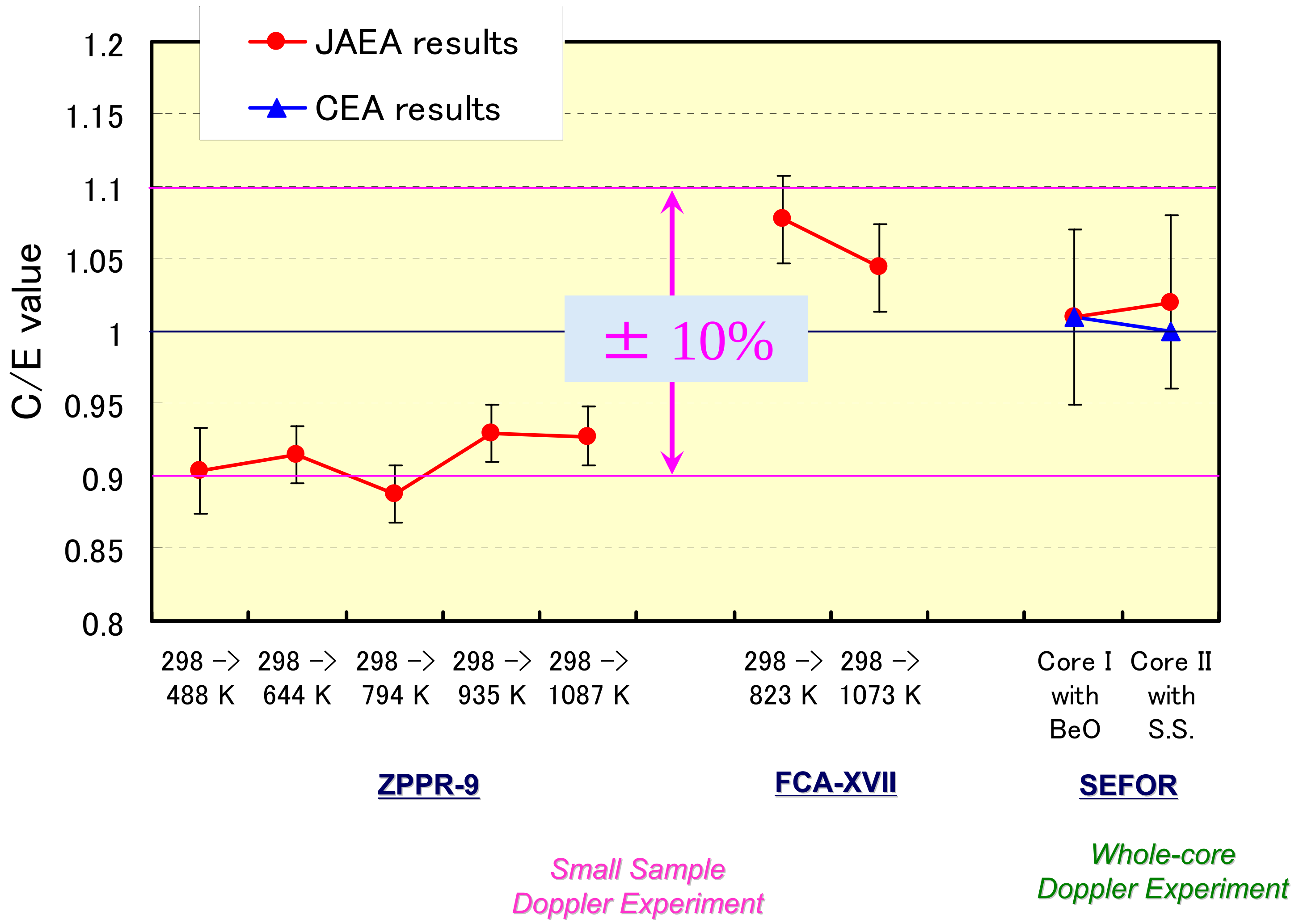
Result of uncertainty in Doppler reactivity

No.	Nuclide and Reaction	ΔR/R（％）	Contribution（％）
1	Pu-239 χ	1.06	9.7
2	C-12 Capture	0	0.0
3	O-16 Elastic	0.56	2.7
4	O-16 Inelastic	0.01	0.0
5	O-16 μ	0.02	0.0
6	Na-23 Capture	0.26	0.6
7	Na-23 Elastic	0.63	3.4
8	Na-23 Inelastic	0.07	0.0
9	Na-23 μ	0.03	0.0
10	Cr(Nat.) μ	0.01	0.0
11	Fe(Nat.) Capture	0.14	0.2
12	Fe(Nat.) Elastic	0.34	1.0
13	Fe(Nat.) Inelastic	0.57	2.8
14	Fe(Nat.) μ	0.05	0.0
15	Ni(Nat.) μ	0.01	0.0
16	U-235 Capture	0.03	0.0
17	U-235 Fission	0.05	0.0
18	U-235 ν	0.01	0.0
19	U-235 Inelastic	0.01	0.0
20	U-238 Capture	0.24	0.5
21	U-238 Fission	0.11	0.1
22	U-238 ν	0.14	0.2
23	U-238 Elastic	0.11	0.1
24	U-238 Inelastic	1.15	11.4
25	U-238 μ	0.01	0.0
26	Pu-239 Capture	0.70	4.2
27	Pu-239 Fission	1.84	29.3
28	Pu-239 ν	0.15	0.2
29	Pu-239 Inelastic	0.27	0.6
30	Pu-239 μ	0	0.0
31	Pu-240 Capture	0.13	0.1
32	Pu-240 Fission	0.22	0.4
33	Pu-240 ν	0.14	0.2
34	Pu-241 Capture	0.08	0.1
35	Pu-241 Fission	0.26	0.6
36	Pu-241 ν	0.02	0.0
37	U-235 χ	0.02	0.0
38	FP(Pu-239) Capture	0	0.0
39	U-235 β	0.04	0.0
40	U-238 β	1.00	8.7
41	Pu-239 β	0.74	4.7
42	Pu-240 β	0.35	1.1
43	Pu-241 β	1.36	16.0
44	Pu-242 β	0.23	0.5
45	U-238 Capture F-grad.	0.23	0.5
	Total	3.40	100.0



(a 600 MWe FBR, 500 delta-K)

C/E Values of Doppler Reactivity Measurement



Conclusion

Conclusion

- "ERRORF" code is now available:
  To evaluate covariance of temperature gradient of self-shielding factor (α)

- Covariance of temperature gradient was obtained for ^{238}U neutron capture in the JFS-60 group structure.

- Contribution of uncertainty of temperature gradient of self-shielding factor to a 600 MWe FBR is about 0.23% (total:3.5%)