Introduction to Nuclear Data

May 01, 2013 @KHU

이 영 욱

원자력데이터개발검증센터 **(Nuclear Data Center)**
한국 원자력연구원
yolee@kaeri.re.kr

- Nuclear Data
- Nuclear Reaction
- Reaction Model
- Evaluation Examples
- Measurements
- Uncertainties
- Nuclear Data Center @KAERI

How long is this piece of metal?

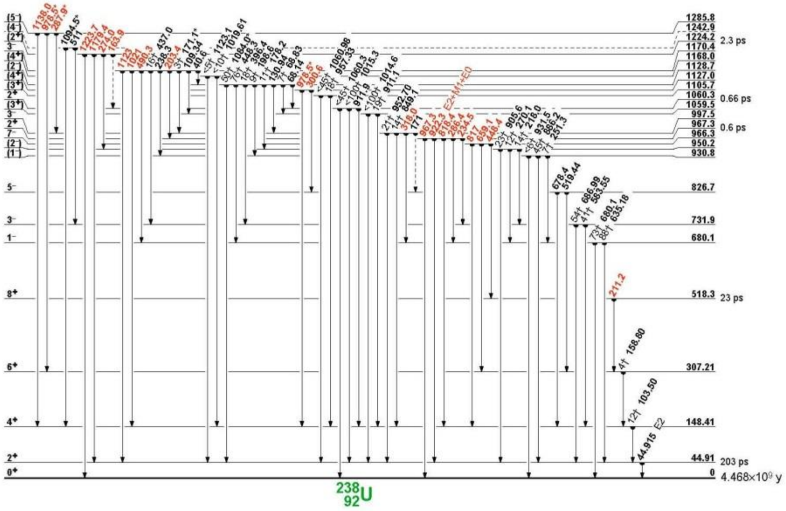
K. Manjunatha Prasad, manipal Univ.

- ✓ About 6 ~ 7 inches
- ✓ 17cm ± 2mm subject to calibration of device, observational errors, and I am 98% sure of my answer

Nuclear Data

Structure Data

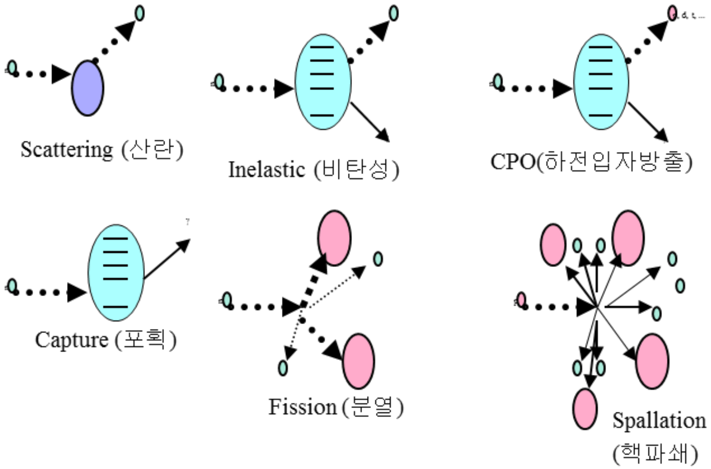
- 핵의 질량, 여기준위, 붕괴모드
- 측정가능: 약 4000여종
- 세계각국이 분담연구



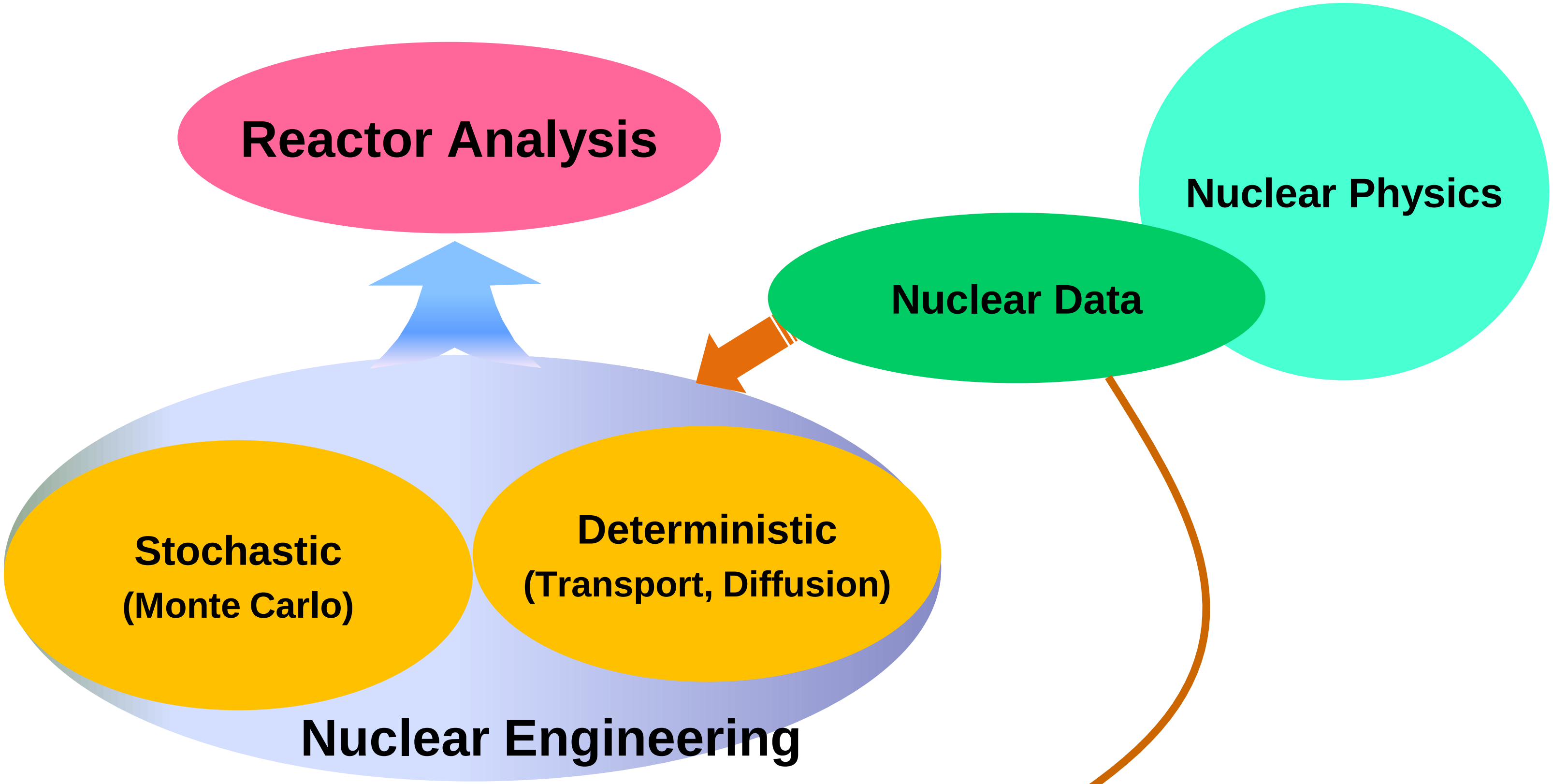
Reaction Data

- 방사선이 물질과 반응확률 (단면적)
- 방출입자의 에너지와 각분포 (DDX)

  (ENDF/B 중성자파일: 400 여개 핵종)



An Example – nuclear reactor analysis



Reactor Analysis

Nuclear Physics

Nuclear Data

Stochastic

(Monte Carlo)

Deterministic

(Transport, Diffusion)

Nuclear Engineering

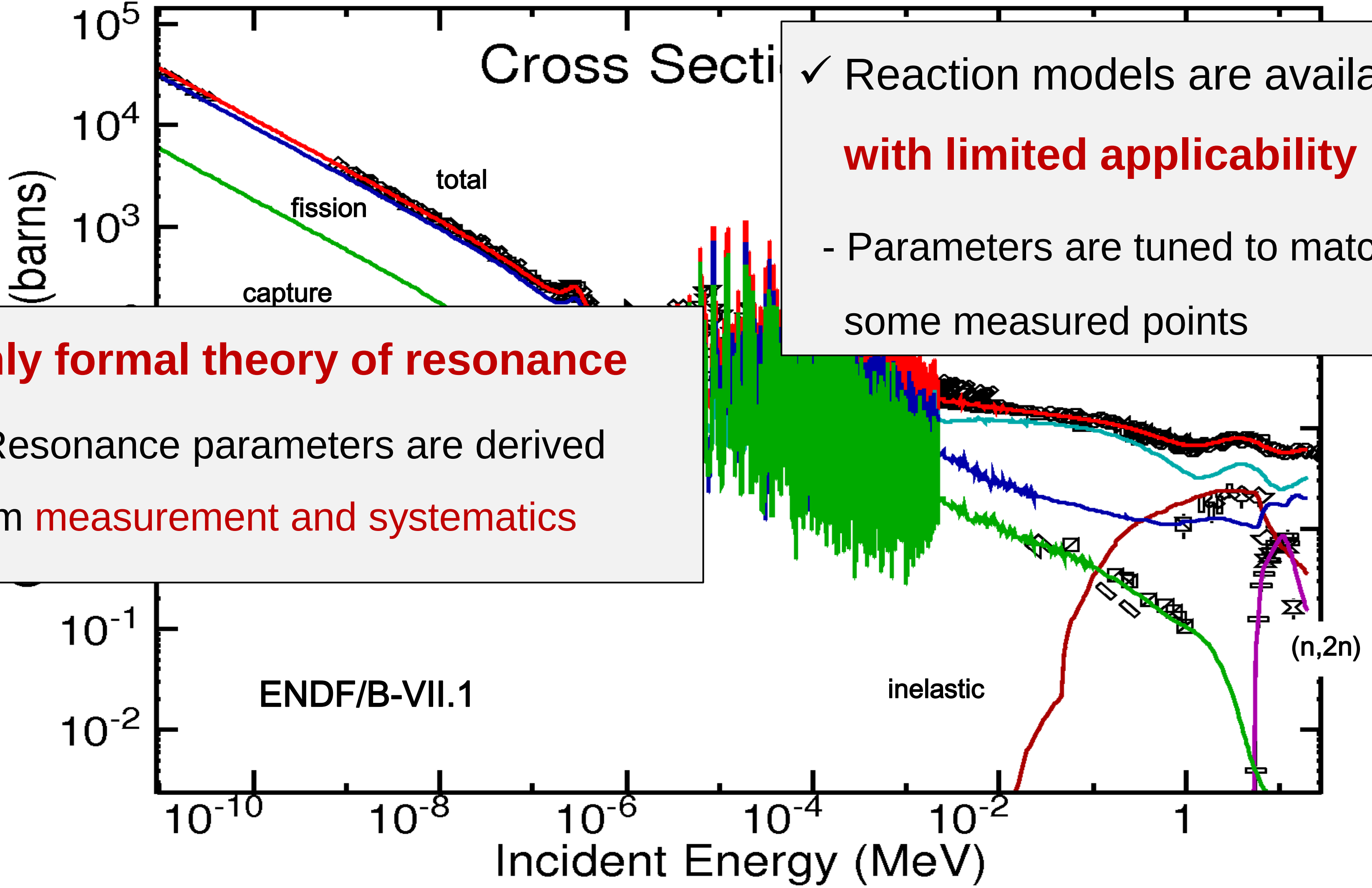
Boltzman equation for neutron transport

$$\frac{1}{v}\frac{\partial\Phi}{\partial t}+\Omega\bullet\nabla\Phi+\Sigma(\mathbf{r},E)\Phi(\mathbf{r},\Omega,E,t)=$$

$$\iint\Sigma(\mathbf{r};\Omega',E'\rightarrow\Omega,E)\Phi(\mathbf{r},\Omega',E',t)d\Omega'dE'+Q(\mathbf{r},\Omega,E,t)$$

Cross Section for Reactor Analysis

✓ Comprehensive theory of nuclear interaction **is not known yet.**



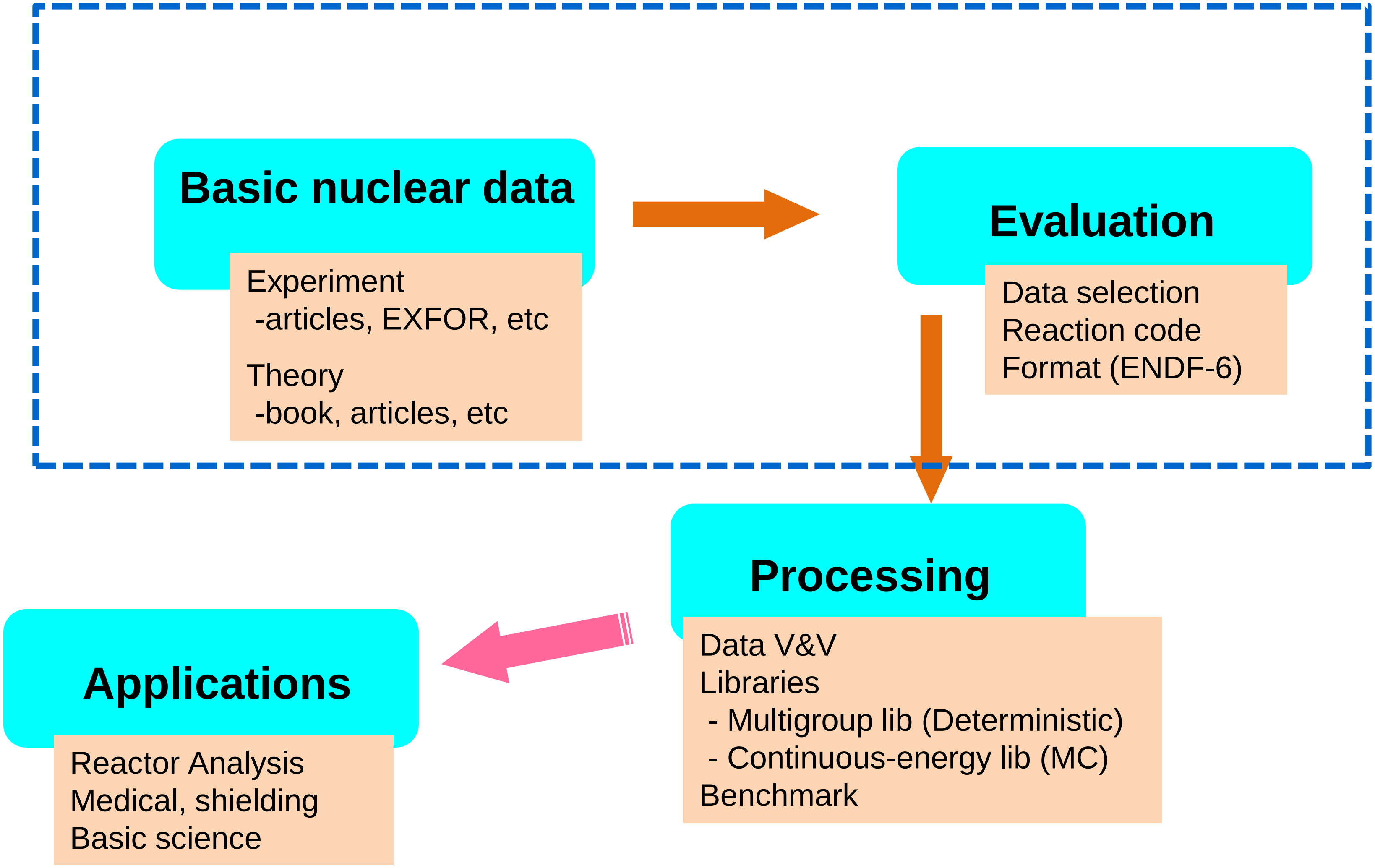
✓ Reaction models are available **with limited applicability**

- Parameters are tuned to match some measured points

✓ **Only formal theory of resonance**

- Resonance parameters are derived from measurement and systematics

Nuclear Data Activities



Basic nuclear data

Experiment
-articles, EXFOR, etc

Theory
-book, articles, etc

Evaluation

Data selection
Reaction code
Format (ENDF-6)

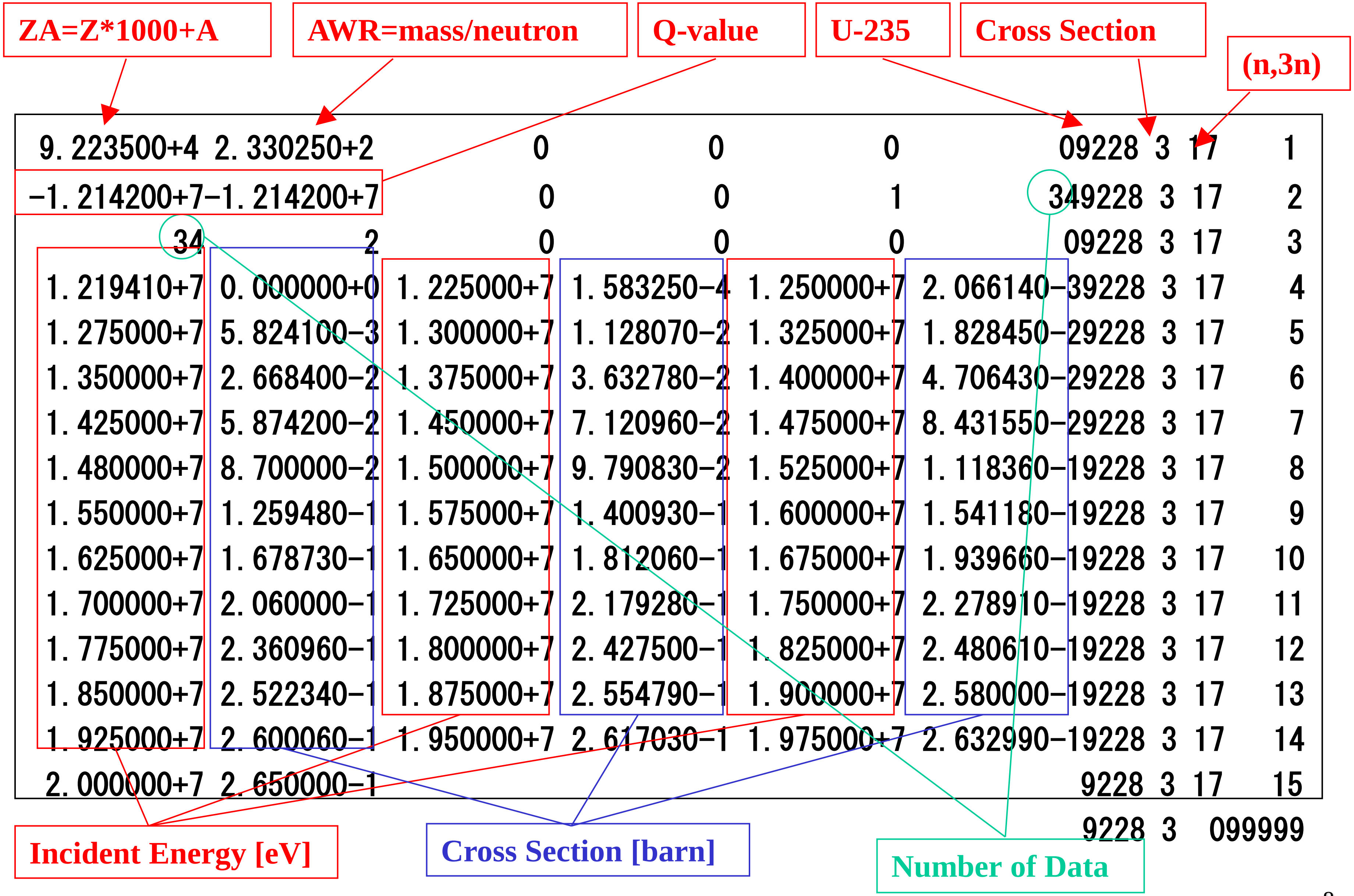
Processing

Data V&V
Libraries
- Multigroup lib (Deterministic)
- Continuous-energy lib (MC)
Benchmark

Applications

Reactor Analysis
Medical, shielding
Basic science

ENDF (Evaluated Nuclear Data File)



ZA=Z*1000+A

AWR=mass/neutron

Q-value

U-235

Cross Section

(n,3n)

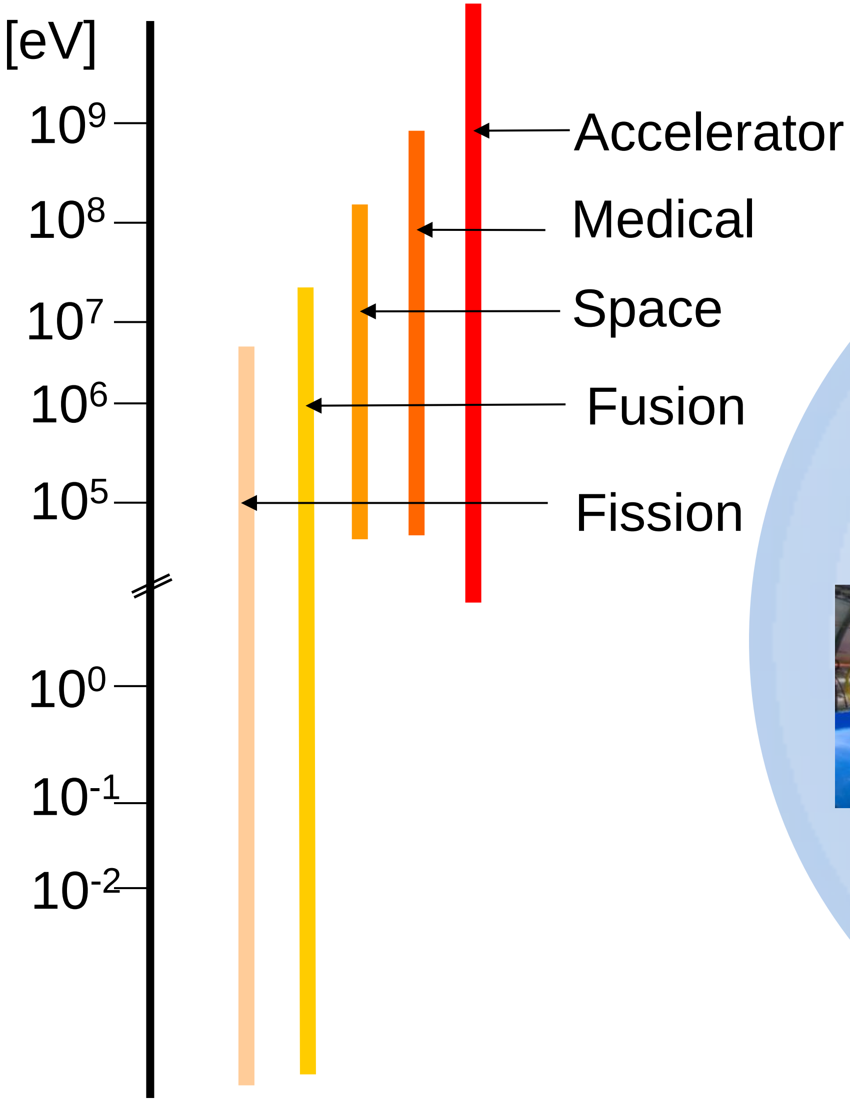
```
 9.223500+4 2.330250+2          0          0          0          09228 3 17    1
-1.214200+7-1.214200+7          0          0          1         349228 3 17    2
         34          2          0          0          0          09228 3 17    3
 1.219410+7 0.000000+0 1.225000+7 1.583250-4 1.250000+7 2.066140-39228 3 17    4
 1.275000+7 5.824100-3 1.300000+7 1.128070-2 1.325000+7 1.828450-29228 3 17    5
 1.350000+7 2.668400-2 1.375000+7 3.632780-2 1.400000+7 4.706430-29228 3 17    6
 1.425000+7 5.874200-2 1.450000+7 7.120960-2 1.475000+7 8.431550-29228 3 17    7
 1.480000+7 8.700000-2 1.500000+7 9.790830-2 1.525000+7 1.118360-19228 3 17    8
 1.550000+7 1.259480-1 1.575000+7 1.400930-1 1.600000+7 1.541180-19228 3 17    9
 1.625000+7 1.678730-1 1.650000+7 1.812060-1 1.675000+7 1.939660-19228 3 17   10
 1.700000+7 2.060000-1 1.725000+7 2.179280-1 1.750000+7 2.278910-19228 3 17   11
 1.775000+7 2.360960-1 1.800000+7 2.427500-1 1.825000+7 2.480610-19228 3 17   12
 1.850000+7 2.522340-1 1.875000+7 2.554790-1 1.900000+7 2.580000-19228 3 17   13
 1.925000+7 2.600060-1 1.950000+7 2.617030-1 1.975000+7 2.632990-19228 3 17   14
 2.000000+7 2.650000-1                                            9228 3 17   15
                                                                  9228 3  099999
```

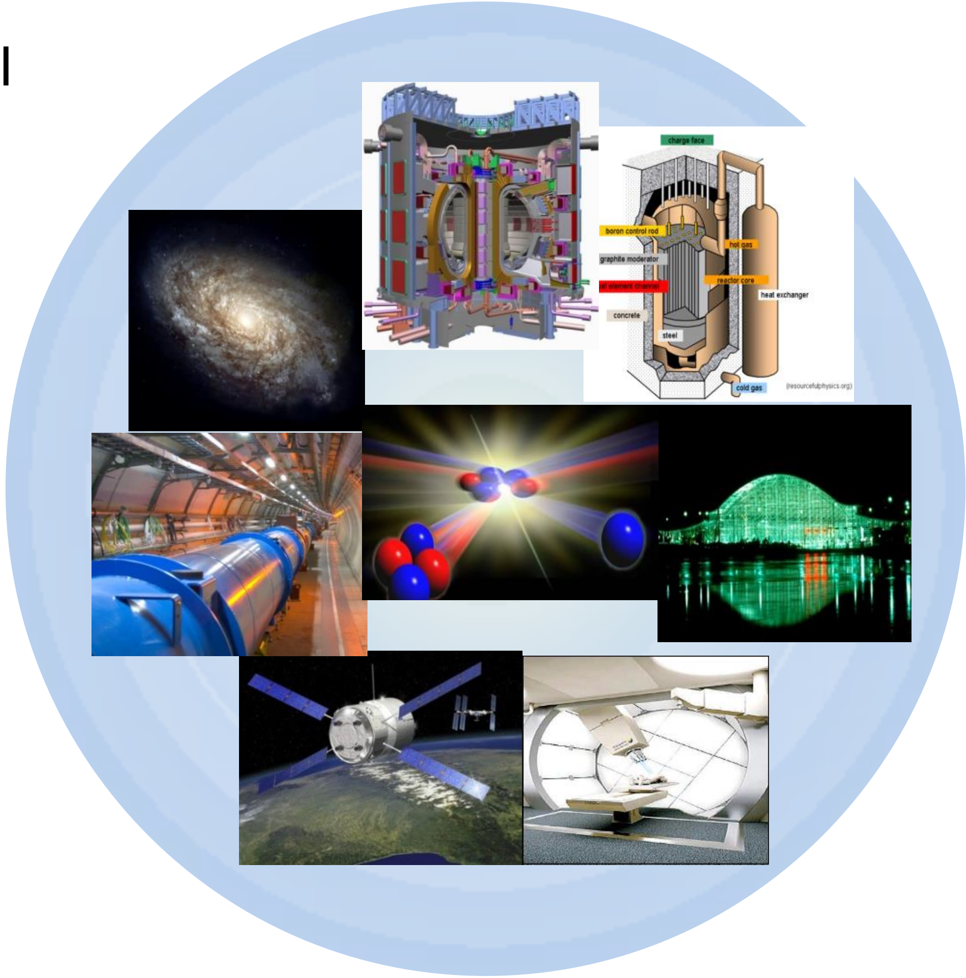
Incident Energy [eV]

Cross Section [barn]

Number of Data

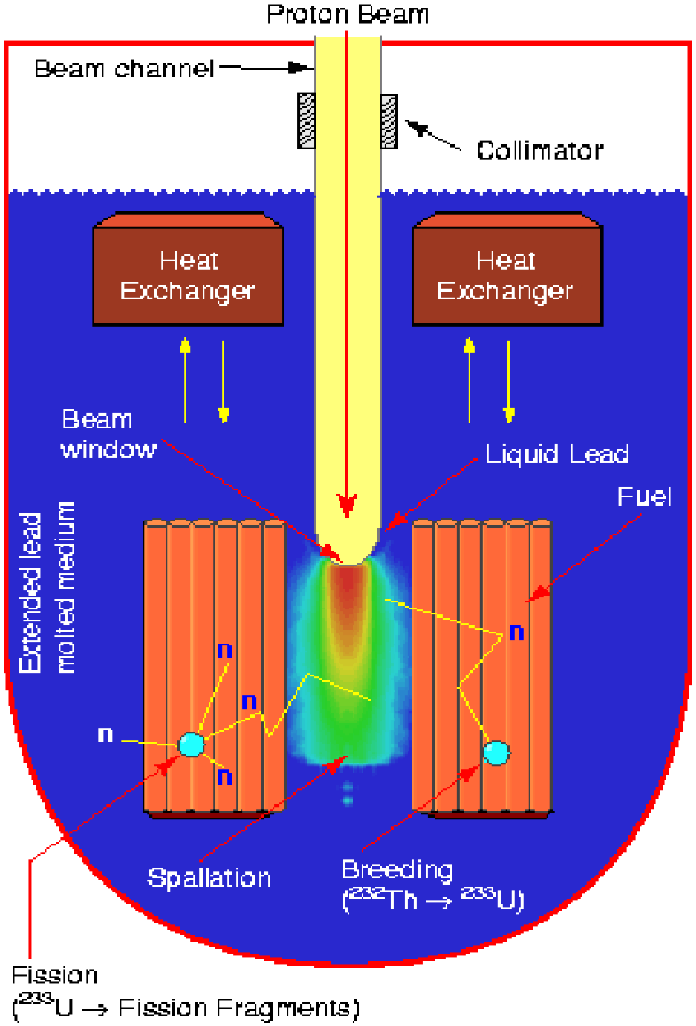
Applications





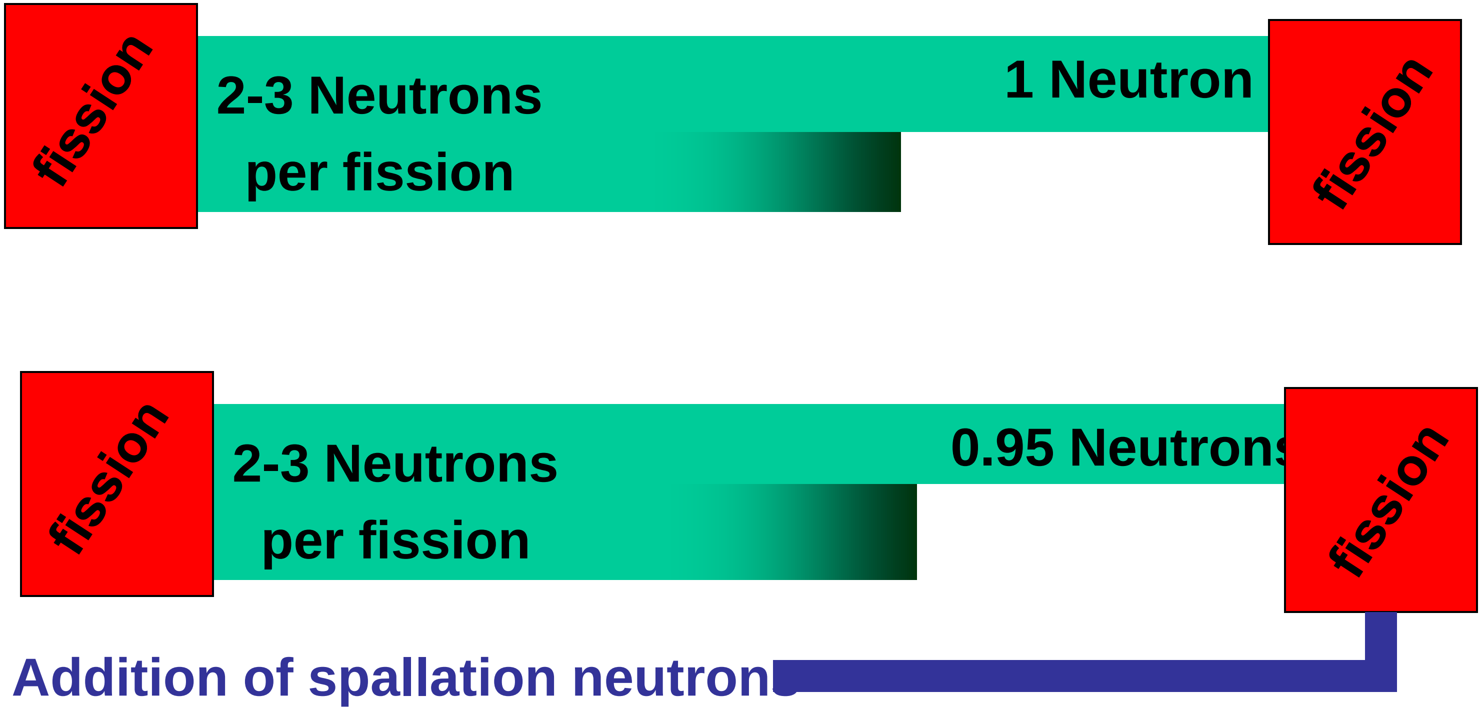
Accelerator Driven Systems

- ✓ Concept of accelerator driven systems (ADS)
- ✓ A possible facility which allows to eliminate minor Actinides; use of Th-U cycle possible.
- ✓ Proton-accelerator delivering 400-800 MeV protons provides by spallation the neutrons required for criticality.



H. Leeb, Atominstitut, Vienna University of Technology , Vienna, Austria

Concept of ADS



fission

2-3 Neutrons per fission

1 Neutron

fission

fission

2-3 Neutrons per fission

0.95 Neutrons

fission

Addition of spallation neutrons

H. Leeb, Atominstitut, Vienna University of Technology , Vienna, Austria

In stationary operation is the number of neutrons given by

$N_{tot} = (1+k+k^2+k^3+\ldots)\ N_e = N_e/(1-k)$ ==> multiplication by $1/(1-k)$

N_e number of neutrons from spallation

k effective multiplication factor, criticality of the subcritical core

Thorium-Uranium cycle

The thorium-uranium cycle

$^{232}\text{Th}\,(n,\gamma)\,^{233}\text{Pa} \rightarrow {}^{233}\text{U} + \beta$ **regeneration process**

$^{233}\text{U}\,(n,f)$ **fissile element**

parasitic reactions

$^{233}\text{U}(n,2n)^{232}\text{U}$, $^{231}\text{Pa}\,(n,\gamma)^{232}\text{Pa} \rightarrow {}^{232}\text{U} + \beta$

$^{232}\text{Th}(n,2n)^{231}\text{Th} \rightarrow \beta + {}^{231}\text{Pa}$

Advantage: almost no actinides are produced

→ long term hazard and proliferation hazard reduced.

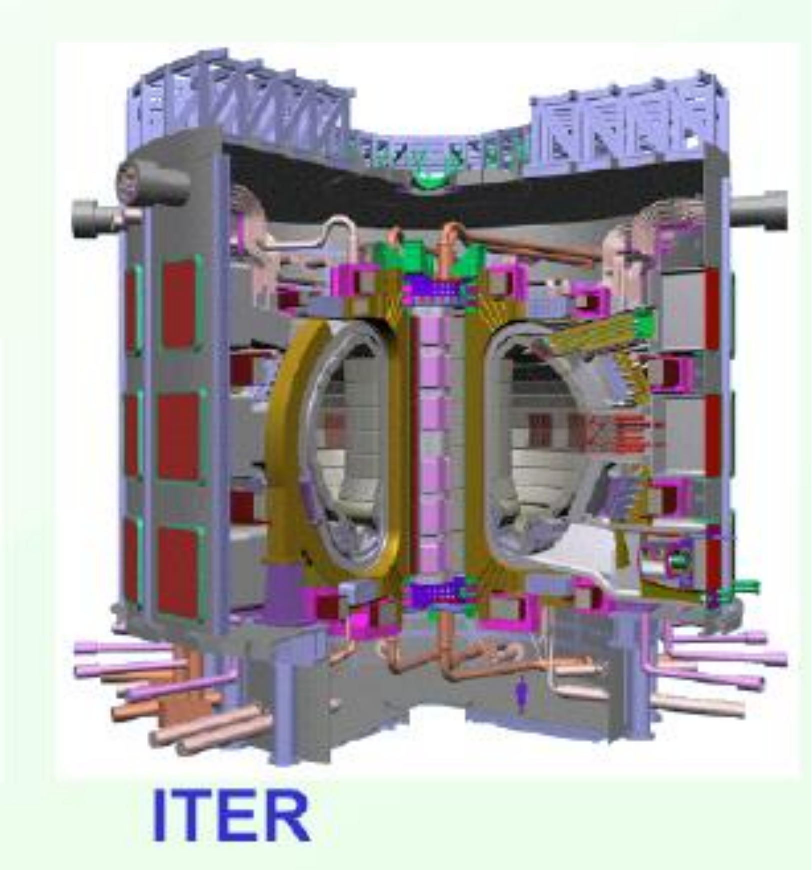
Abundance of thorium is high.

Difficulty: fast spectrum required, harder gamma-radiation

Fusion research

Strong irradiation on first wall
→Search for best materials

Material studies will be performed at future IFMIF facility with spectrum up to **60 MeV neutrons**



Medical Accelerators, Space Applications

Need for Data beyond 20 MeV

Current status

✓A wealth of neutron induced reaction data up to 20-25 MeV

✓Scarcity of experimental neutron data beyond 25 MeV

Challenges:

✓As E_{inc} increases number of open channels increases, but the data become very scarce

→Evaluations with extended energy range strongly rely on modelling

Nuclear Data Evaluation

Present status of evaluated Nuclear Data Files

- essentially a consistent set of cross sections (up to 20 MeV)
- **covariance** information is limited – reliability ?

Required developments

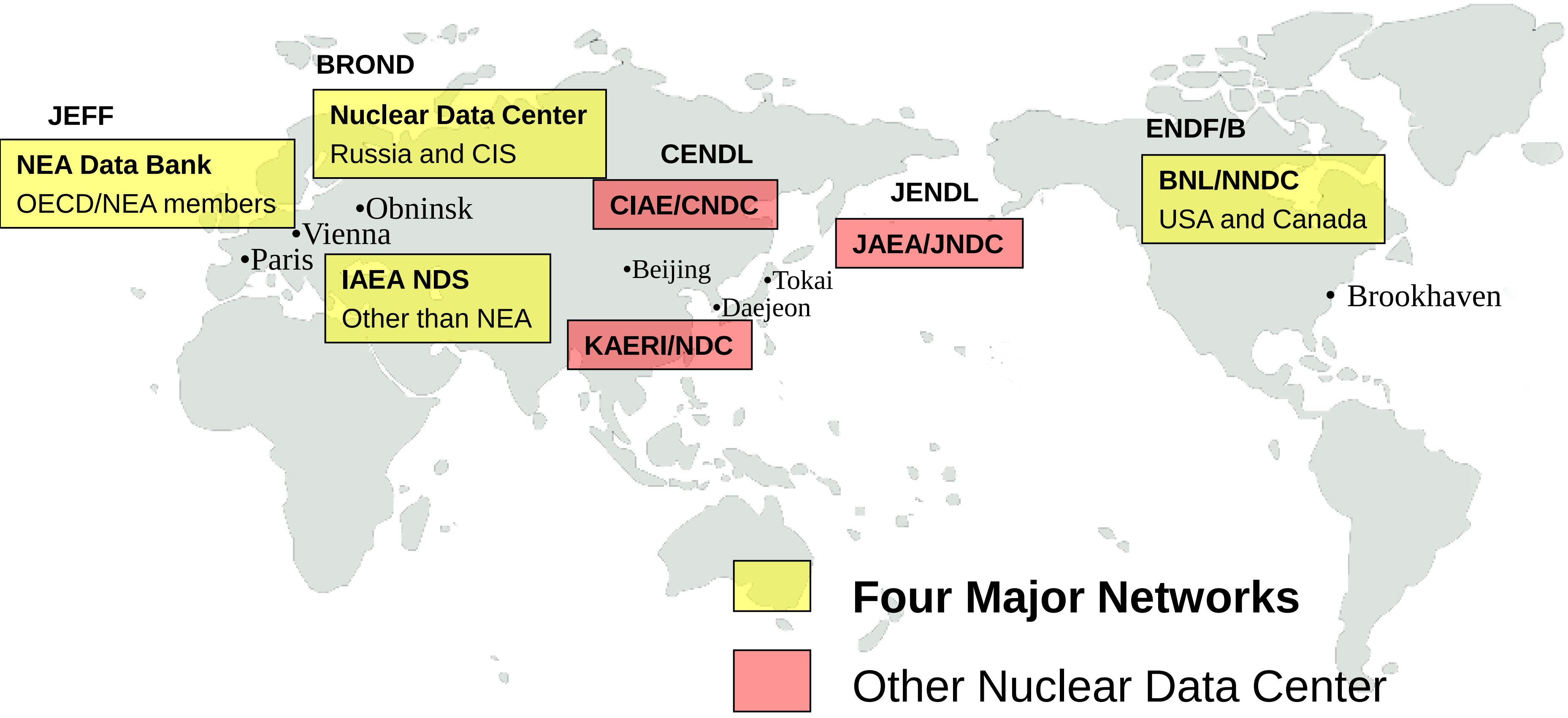
- extension of energy range requires increased use of **models**
- **uncertainty information** – request from the user community

Example: Reliable uncertainty of quantity A_{eff} is required

$$\Delta^2 A_{eff} = \sum_{\rho} \sum_{\eta} \frac{\partial A}{\partial \sigma_{\rho}} \langle \Delta\sigma_{\rho} \Delta\sigma_{\eta} \rangle \frac{\partial A}{\partial \sigma_{\eta}}$$

cross section covariances

전세계 핵데이터 네트워크 현황



JEFF

NEA Data Bank
OECD/NEA members

BROND

Nuclear Data Center
Russia and CIS

IAEA NDS
Other than NEA

CENDL

CIAE/CNDC

KAERI/NDC

JENDL

JAEA/JNDC

ENDF/B

BNL/NNDC
USA and Canada

🟨 **Four Major Networks**

🟥 Other Nuclear Data Center

- Nuclear Data
- **Nuclear Reaction**
- Reaction Model
- Evaluation Examples
- Measurements
- Uncertainties
- Nuclear Data Center @KAERI

Nuclear Reaction

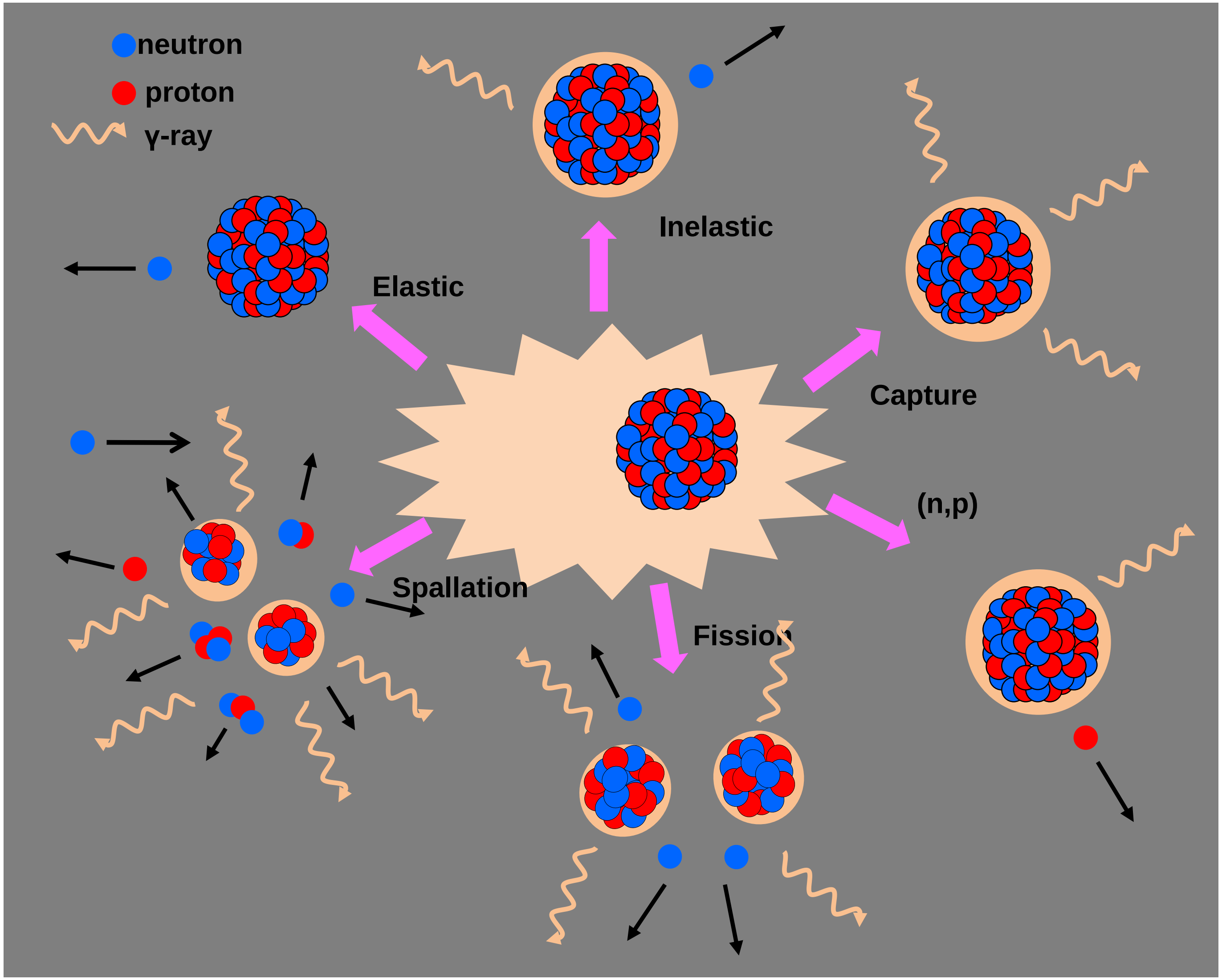
- ✓ The process in which **two nuclear particles** interact to produce products different from the initial particles

$$a + b \rightarrow c + [d + e + \dots]$$

- ✓ some or many reactions can occur in a nuclear collision

- ✓ Two very different mechanisms –
  direct (fast) one and composite nucleus one.

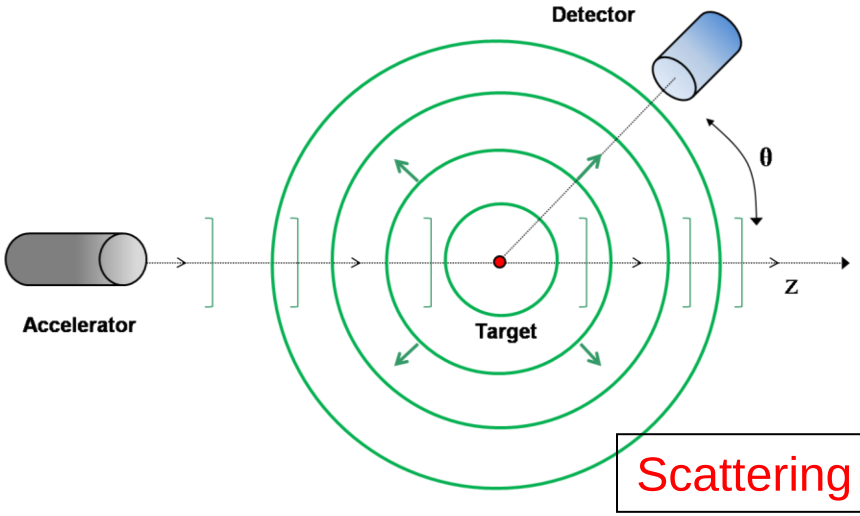
Neutron Induced Reaction



Basic Characteristics

- ✓ **Conservation Law**
  - Charge and nucleon number
    - Total number of nucleons and the sum of the charges before and after $${}^{56}_{26}\boldsymbol{Fe(p,n)}{}^{56}_{27}\boldsymbol{Co}$$
  - Energy
    - Energy, including rest mass energy, is conserved in nuclear reactions. $${}^{56}_{26}\boldsymbol{Fe(n,n')}{}^{56}_{26}\boldsymbol{Fe}^{*} \quad (\mathrm{E}_{\mathrm{1Level}} = 0.8467\ \boldsymbol{MeV})$$
  - Linear momentum($\vec{\boldsymbol{p}}$), angular momentum ($\vec{\boldsymbol{J}}$) and parity ($\boldsymbol{\pi}$)
    - thresholds, recoil
    - Parity is not conserved in weak interactions, e.g. in β decay and electron conversion.

The Quantum View of Scattering



- ✓ In the quantum theory of scattering, the scattering wave function can be the sum of a incident plane wave and a scattered outgoing spherical wave

$$\psi(\vec{r}) \approx A\left\{e^{ikz} + f(\theta)\frac{e^{ikr}}{r}\right\},$$

Scattering amplitude

where $r \to \infty \; (k = \sqrt{2\mu E}/\hbar).$

- ✓ The probability that the incident particle, traveling at speed *v*, passes through the infinitesimal area *dσ*, in time *dt*, is

$$dP = |\psi_{in}|^2 dV = |A|^2 (vdt)d\sigma.$$

- ✓ This is equal to the probability that the particle emerges into the corresponding solid angle

$$dP = |\psi_{sc}|^2 dV = \frac{|A|^2 |f|^2}{r^2}(vdt)r^2 d\Omega.$$

$$\frac{d\sigma}{d\Omega} = |f(\theta)|^2.$$

Partial Wave Expansion

- ✓ Schrödinger equation

$$\left(-\frac{\hbar^2}{2\mu}\nabla^2+V(r)\right)\Psi=E\Psi,$$

$$\text{where } \Psi(r,\theta,\phi)=R(r)Y_l^m(\theta,\phi)$$

- ➢ Separation of variables in spherical coordinate

Putting $u(r)=rR(r),$

then $R=\frac{u}{r},\frac{dR}{dr}=\frac{\left[r\frac{du}{dr}-u\right]}{r^2},\frac{d}{dr}\left(r^2\frac{dR}{dr}\right)=\frac{rd^2u}{dr^2}.$

Then, the radial Equation is

$$\frac{d^2u}{dr^2}+\left[k^2-\frac{l(l+1)}{r^2}\right]u=\frac{2\mu}{\hbar^2}Vu,$$

$$\text{where } k\left(=\frac{\sqrt{2\mu E}}{\hbar}\right) \text{ is wavenumber.}$$

Partial Wave Expansion

- The wave function can be expanded in partial waves of the orbital angular momentum,

$$\psi(r,\theta)=\sum_{l=0}^{\infty}u_l(r)P_l(\cos\theta).$$

The plane wave could be expanded as

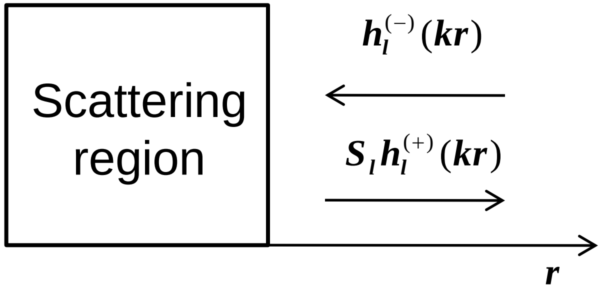
$$e^{ikz}=\sum_{l=0}^{\infty}(2l+1)i^l j_l(kr)P_l(\cos\theta),$$

with $j_l(kr)=\frac{i}{2}\left(h_l^{(-)}(kr)-h_l^{(+)}(kr)\right),$ where $h_l^{\pm}(kr)\xrightarrow[r\to\infty]{}(\mp i)^l\frac{e^{\pm ikr}}{kr}.$

In analogy with the plane wave, we write

$$\psi(r,\theta)=\sum_{l=0}^{\infty}(2l+1)i^l\psi_l(r)P_l(\cos\theta).$$

Partial Wave Expansion



The wave function $\psi_l(r)$ can be a linear combination of the same incoming/outgoing wave $h_l^{(\pm)}(kr)$,

$$\psi_l(r) = \frac{i}{2}\left(h_l^{(-)}(kr) - S_l h_l^{(+)}(kr)\right).$$

Substituting in the partial wave expansion,

$$\psi(r,\theta) = \sum_{l=0}^{\infty}(2l+1)i^l \psi_l(r) P_l(\cos\theta) = \sum_{l=0}^{\infty}(2l+1)i^l \frac{i}{2}\left(h_l^{(-)}(kr) - S_l h_l^{(+)}(kr)\right)P_l(\cos\theta)$$

$$= \sum_{l=0}^{\infty}(2l+1)i^l \left(\frac{i}{2}h_l^{(-)}(kr) - \frac{i}{2}h_l^{(+)}(kr) - \frac{i}{2}S_l h_l^{(+)}(kr) + \frac{i}{2}h_l^{(+)}(kr)\right)P_l(\cos\theta)$$

$$\to \sum_{l=0}^{\infty}(2l+1)i^l \left(j_l(kr) + \frac{S_l - 1}{2i}h_l^{(+)}(kr)\right)P_l(\cos\theta)$$

$$\to e^{ikz} + \frac{1}{2ik}\sum_{l=0}^{\infty}(2l+1)i^l (S_l - 1)P_l(\cos\theta)\frac{e^{ikr}}{r}.$$

$$\therefore\ f(\theta) = \frac{1}{2ik}\sum_{l=0}^{\infty}(2l+1)(S_l - 1)P_l(\cos\theta).$$

Integrated Cross Section

- We obtain the elastic cross section by integrating over the differential one

$$\sigma_{el} = 2\pi\int_0^{\pi} |f(\theta)|^2 \sin\theta d\theta = \frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)|S_l - 1|^2 .$$

✓ Taking into account all of the flux entering and leaving the scattering region, the absorption cross section is

$$\sigma_{abs} = -\frac{1}{v}\oint_S \vec{J}\cdot d\vec{S} = \frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)\left(1-|S_l|^2\right).$$

✓ Then, the total cross section is

$$\sigma_{tot} = \sigma_{el} + \sigma_{abs} = \frac{2\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)\left(1-\mathrm{Re}\, S_l\right).$$

✓ Transmission Coefficient

$$T_L = 1 - |S_L|^2 .$$

An Example - low-energy neutron scattering

- Only neutrons can approach close to nucleus
- At extremely low energy, s-waves (*l*=0) are dominant (En < 50 keV)
- Scattering from the hard sphere requires that the wave-function vanish at the radius of the sphere.
- Then s-wave function is

$$\psi_0(r) = \frac{i}{2kr}\left(e^{-ikr} - e^{-2ikR}e^{ikr}\right).$$

The S-matrix element is $S_0 = e^{-2ikR}.$

The elastic cross section is $\sigma_{el} = \frac{\pi}{k^2}\left|S_0 - 1\right|^2 = \frac{\pi}{k^2}\left|e^{-2ikR} - 1\right|^2.$

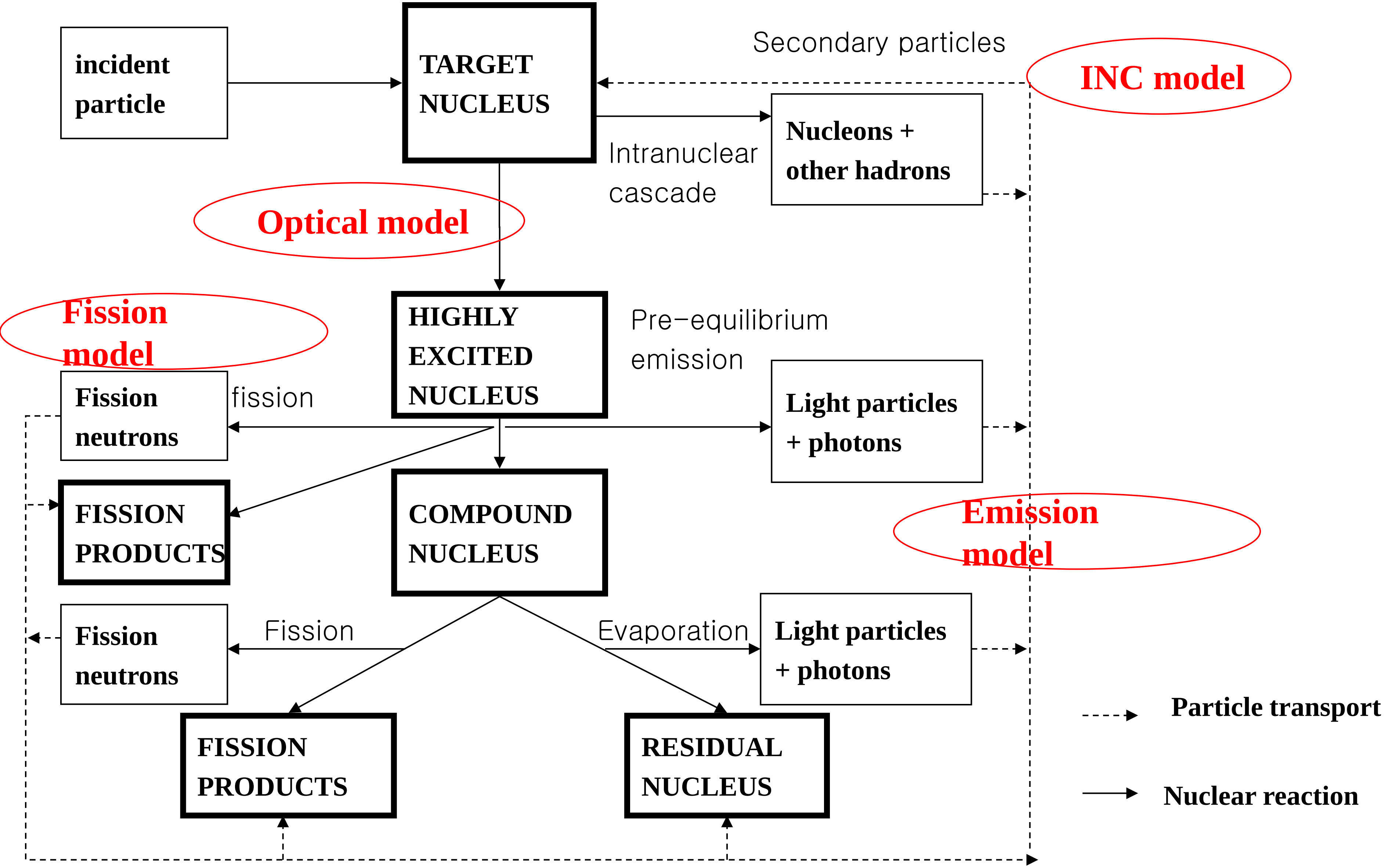
When k→0, the elastic cross section tends to a constant,

$$\sigma_{el} \xrightarrow[k\to 0]{} \boxed{4\pi R^2.}$$

This is 4 times the classical cross section.

- Nuclear Data
- Nuclear Reaction
- **Reaction Model**
- Evaluation Examples
- Measurements
- Uncertainties
- Nuclear Data Center @KAERI

General Description of Nuclear Reaction



incident particle

TARGET NUCLEUS

Secondary particles

INC model

Nucleons + other hadrons

Intranuclear cascade

Optical model

HIGHLY EXCITED NUCLEUS

Pre−equilibrium emission

Fission model

Fission neutrons

fission

Light particles + photons

FISSION PRODUCTS

COMPOUND NUCLEUS

Emission model

Fission neutrons

Fission

Evaporation

Light particles + photons

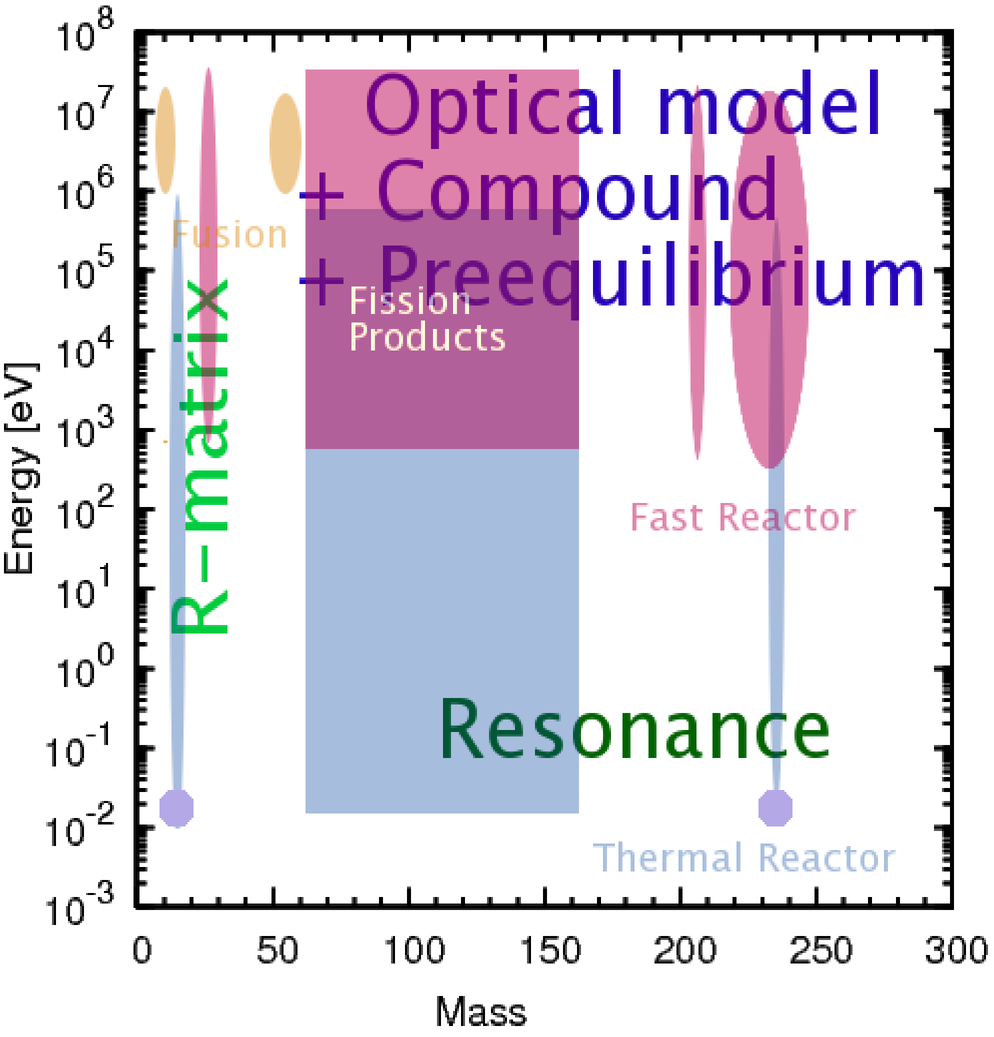
FISSION PRODUCTS

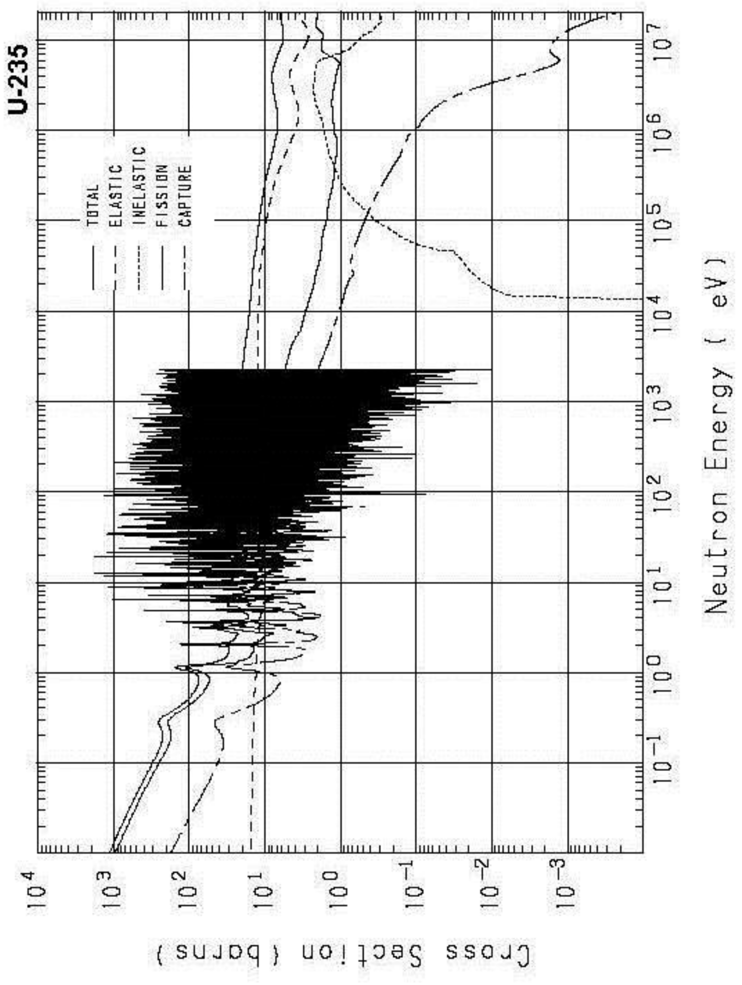
RESIDUAL NUCLEUS

Particle transport

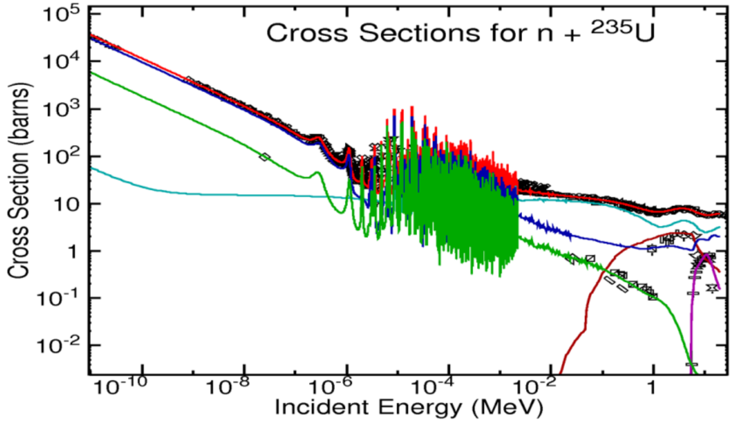
Nuclear reaction

Reaction Models vs. E_{inc} and target mass





Resonance Region



- ✓ **Resolved Resonance**
  - ➢ ENDF-6 format
    - Reich-Moore Formula (RM)
    - Multi-level Breit-Wigner Formula (MLBW)
    - Single-level Breit-Wigner Formula (SLBW)
    - Adler-Adler Formalism (AA)
  - ➢ Single-level Breit-Wigner Formula (SLBW)

Elastic scattering is obtained as

$$\sigma_{n,n}(E) = \frac{\pi}{k^2}\left\{ 4\sin^2 kR + \Gamma_{\lambda n}\frac{2(E-E_\lambda)\sin 2kR - \Gamma_\lambda(1-\cos 2kR)}{(E-E_\lambda)^2 + \frac{1}{4}\Gamma_\lambda^2} + \frac{(\Gamma_{\lambda n})^2}{(E-E_\lambda)^2 + \frac{1}{4}\Gamma_\lambda^2} \right\},$$

and (n,x) reaction

$$\sigma_{n,x}(E) = \frac{\pi}{k^2}\frac{\Gamma_{\lambda n}\Gamma_{\lambda x}}{(E-E_\lambda)^2 + \frac{1}{4}\Gamma_\lambda^2}.$$

Resonance Region

✓Unresolved Resonance

Averaging Breit-Wigner Formula

$$\overline{\sigma_{nx}} = \frac{1}{E_H - E_L}\int_{E_L}^{E_H} \sum_{\lambda} \sigma_{nx}^{(\lambda)}(E)dE \quad \Rightarrow \quad \frac{1}{D}\int_{-\infty}^{\infty} \rangle \sigma_{nx}^{(\lambda)}(E) \langle_{\lambda} dE \qquad \overline{\sigma_{nx}} = \frac{2\pi^2}{k^2}\sum_{l,J}\frac{g_J}{D_J}\left\langle \frac{\Gamma_n\Gamma_x}{\Gamma} \right\rangle_J$$

$$\overline{\sigma_{nn}} = \sum_{l}\left\{\frac{4\pi}{k^2}(2l+1)\sin^2\phi_l + \frac{2\pi^2}{k^2}\sum_{J}\frac{g_J}{D_J}\left[\left\langle \frac{\Gamma_n\Gamma_n}{\Gamma}\right\rangle_J - 2\langle \Gamma_n \rangle_J \sin^2\phi_l\right]\right\} \qquad \phi_{\mathrm{O}} = kR$$

where nuclear radius *R*,

average neutron resonance spacing is D_J

neutron width is

$$\langle \Gamma_n \rangle = \langle \gamma_n^{(0)} \rangle_{Jl} \sqrt{E} V_l(E) \quad (V_l\text{: penetration factor}),$$

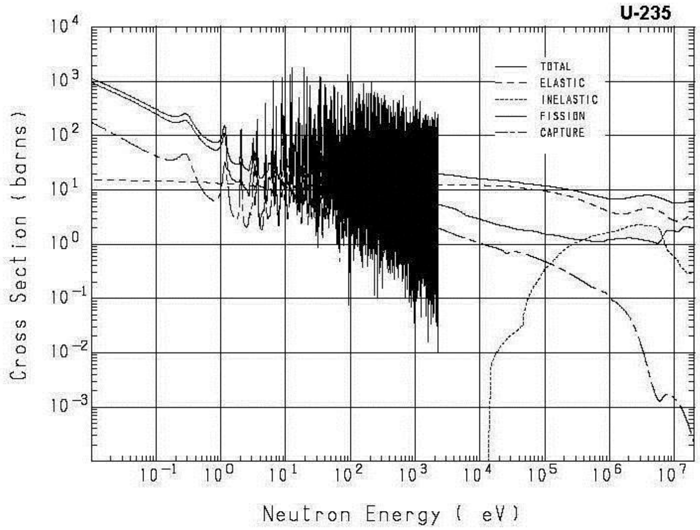
radiative and fission width are $\langle \Gamma_\gamma \rangle$ and $\langle \Gamma_f \rangle$,

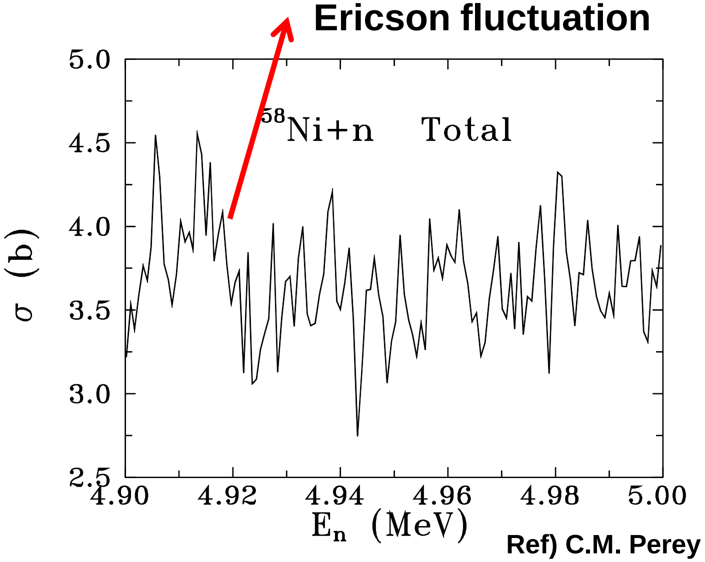
and neutron strength function is $S_J^l = \dfrac{1}{\gamma_{nJ}}\dfrac{\langle \Gamma_n^{(0)} \rangle_{Jl}}{D_J}$.

From Resonances To Fluctuations

- As the energy increases, both the resonance widths and the density of compound nucleus increase.

  → the resonances eventually overlap and can no longer be distinguished.



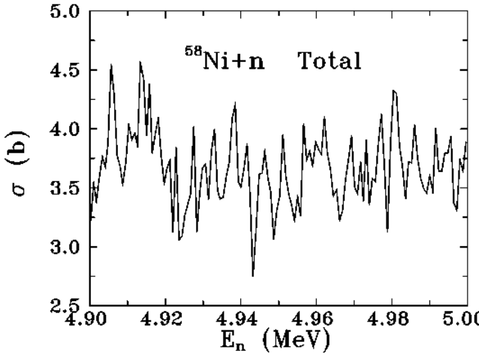


Ericson fluctuation

- Optical Model model is to describe just the prompt, direct reactions in a collision.
- Optical potential is defined as to furnish the energy-averaged scattering amplitudes.

Ref) C.M. Perey et al. ORNL-TM10841

Energy-averaged CS



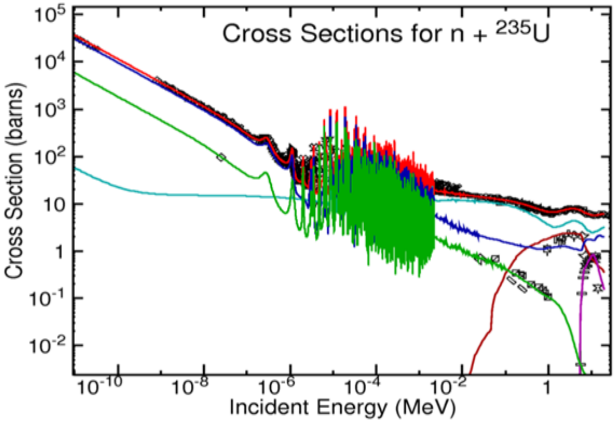
- As Energy increase, the more fluctuations will appear.
- The optical model potential furnishes the energy-averaged scattering amplitudes.
- Scattering in low incident energy (considering *l=0*)

$$\boldsymbol{S}_0 = \bar{\boldsymbol{S}}_0 + \boldsymbol{S}_0^{fl} \qquad \text{with} \left\langle \boldsymbol{S}_0^{fl} \right\rangle = 0, \;\; \text{so that} \left\langle \boldsymbol{S}_0 \right\rangle = \left\langle \bar{\boldsymbol{S}}_0 \right\rangle = \bar{\boldsymbol{S}}_0 .$$

$$\left\langle \sigma_{tot} \right\rangle = \frac{2\pi}{k^2}\left(1 - \mathrm{Re}\left\langle S_0 \right\rangle\right) = \frac{2\pi}{k^2}\left(1 - \mathrm{Re}\,\bar{S}_0\right),$$

$$\left\langle \sigma_{el} \right\rangle = \frac{\pi}{k^2}\left\langle \left|S_0 - 1\right|^2 \right\rangle = \frac{\pi}{k^2}\left|\bar{S}_0 - 1\right|^2 + \frac{\pi}{k^2}\left\langle \left|S_0^{fl}\right|^2 \right\rangle,$$

$$\left\langle \sigma_{abs} \right\rangle = \frac{\pi}{k^2}\left\langle 1 - \left|S_0\right|^2 \right\rangle = \frac{\pi}{k^2}\left(1 - \left|\bar{S}_0\right|^2\right) - \frac{\pi}{k^2}\left\langle \left|S_0^{fl}\right|^2 \right\rangle.$$

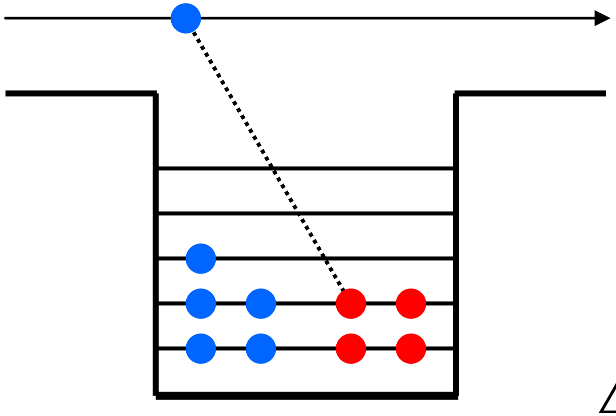


✓ In case of higher l, the same manner is applied.

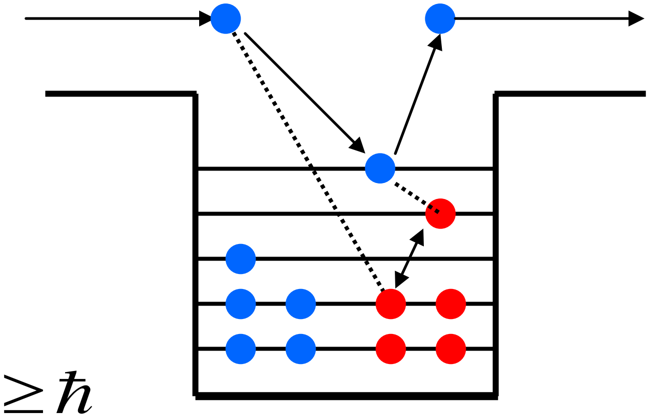
Reaction Model

- ✓ Reaction process
  - Complexity of calculation and theoretical limitation
  - Neutron-nucleus reaction occurs either directly or through the compound nucleus states.

Direct reaction



Compound reaction



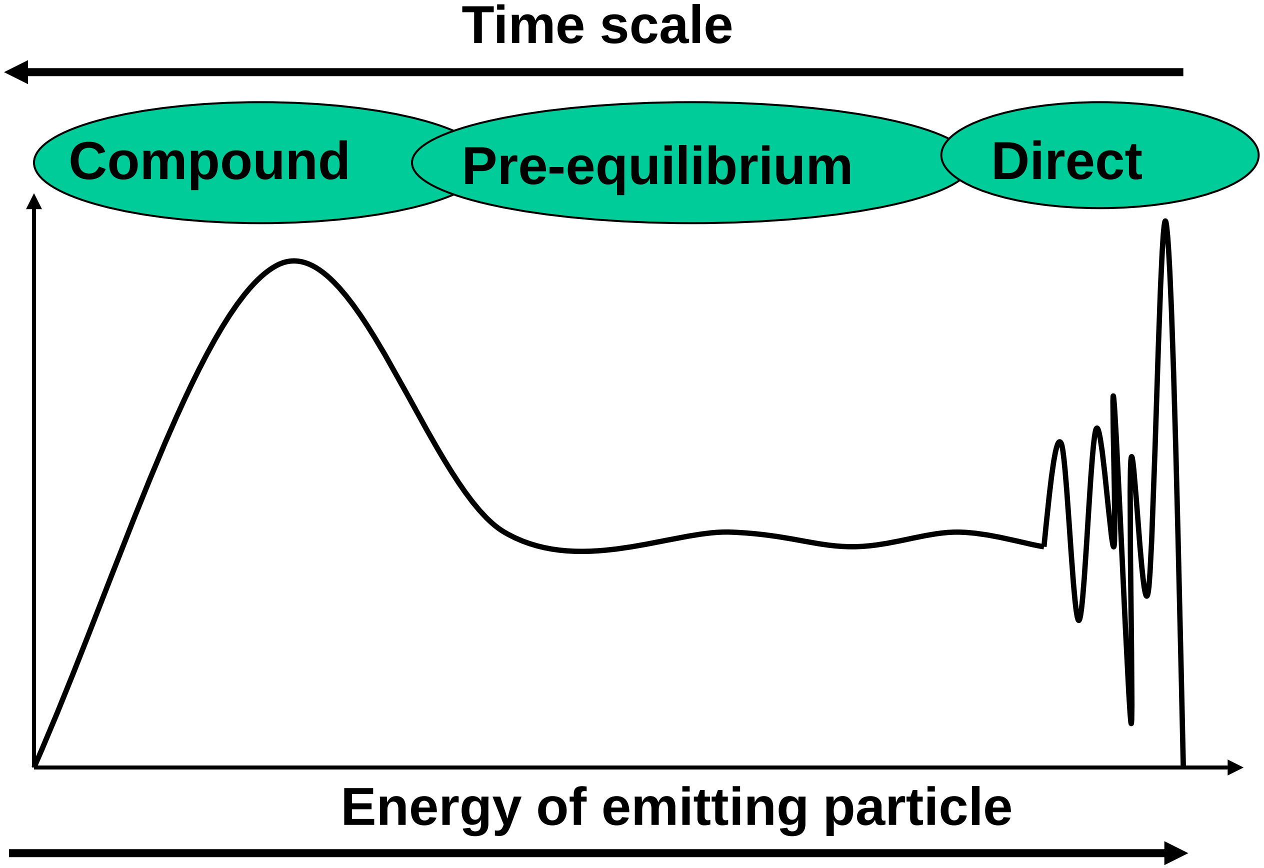
$$\Delta E \Delta t \geq \hbar$$

$\Delta t \sim 10^{-20} - 10^{-22}$ s

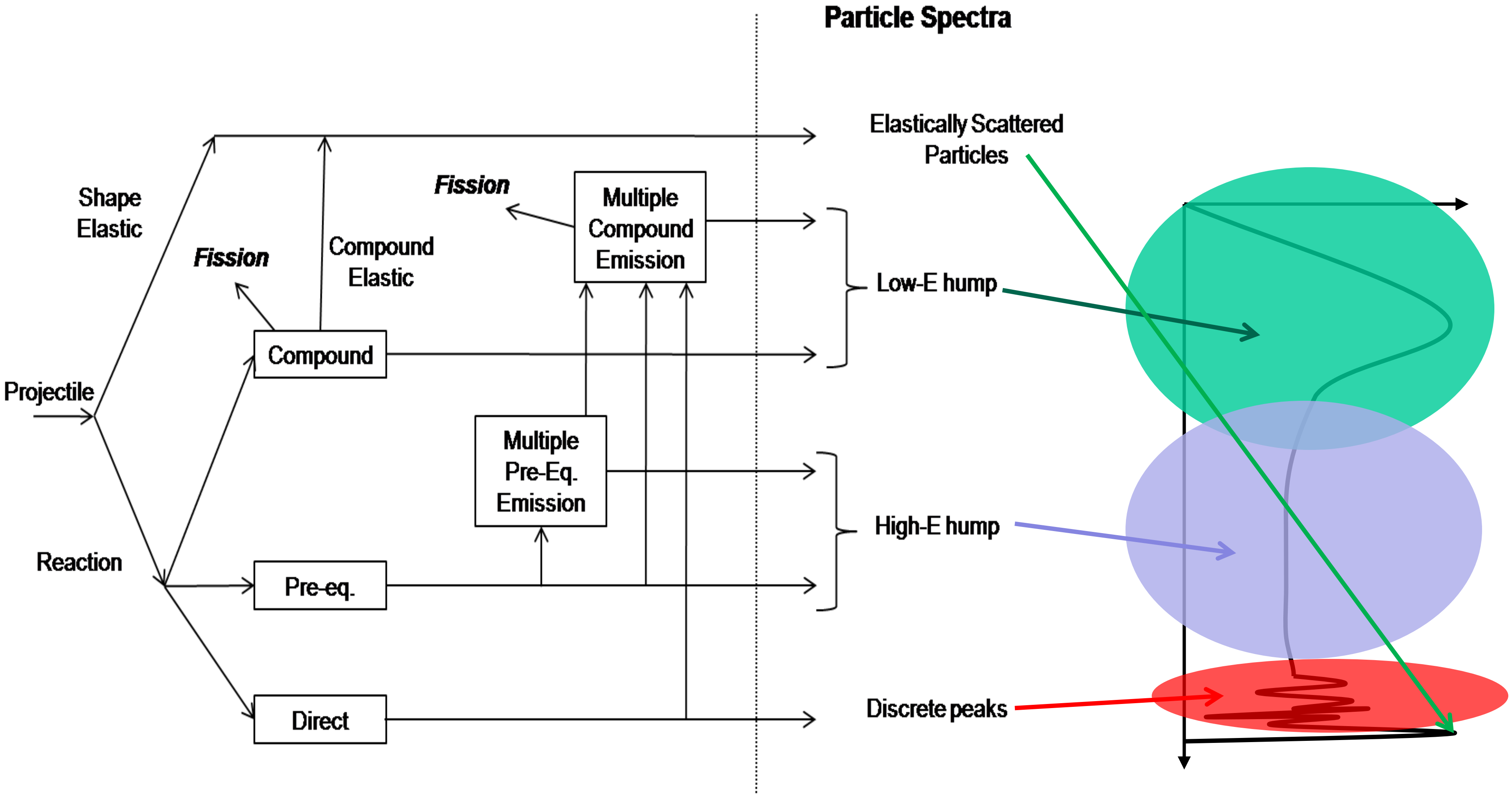
$\Delta t \sim 10^{-12} - 10^{-20}$ s

Reaction Processes

- ✓ **Classification depending on time of emission of particles**



Reaction Mechanism



Energy-averaged CS

- ✓ The Optical Model calculation gives the amount of total and shape elastic cross section (including ddx).

Putting $\sigma_{se} = \frac{\pi}{k^2}\left|\bar{S}_0 - 1\right|^2$: Shape elastic

$\sigma_{ce} = \frac{\pi}{k^2}\left\langle \left|S_0^{fl}\right|^2 \right\rangle$: Compound elastic

Then, the energy averaged elastic and absorption cross section are

$$\langle \sigma_{el} \rangle = \sigma_{se} + \sigma_{ce}$$

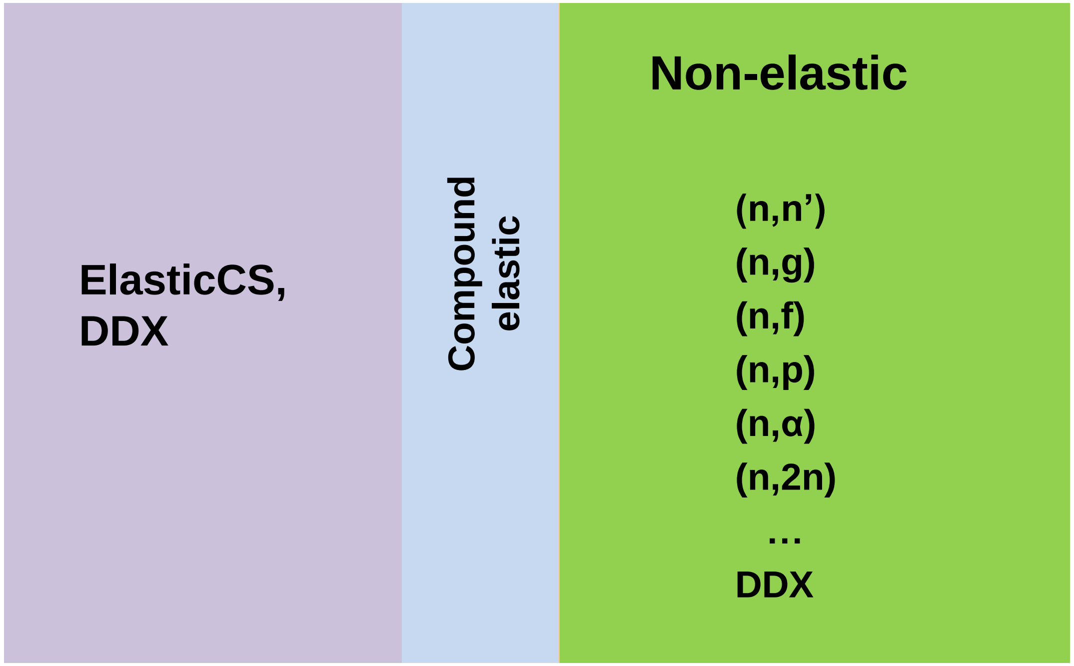
$$\langle \sigma_{\text{abs}} \rangle = \langle \sigma_{\text{tot}} \rangle - \langle \sigma_{el} \rangle \rightarrow \langle \sigma_{\text{abs}} \rangle = \langle \sigma_{\text{tot}} \rangle - \sigma_{se} - \sigma_{ce}$$

Compound formation is obtained

$$\sigma_{\text{c}} = \langle \sigma_{\text{abs}} \rangle + \sigma_{ce} = \langle \sigma_{\text{tot}} \rangle - \sigma_{se}$$

- ✓ CS derived from OM calculation σ_{tot}, σ_{se}, and σ_{c}.

Reconstruction



ElasticCS,
DDX

Compound
elastic

Non-elastic

(n,n’)
(n,g)
(n,f)
(n,p)
(n,α)
(n,2n)
…
DDX

Optical Model Potential (OMP)

- Provide the energy-averaged CS
- Also provide the transmission coefficients

  (See P.25)

- Classification of Optical model
  - Phenomenological optical model potential
    - normally used to fit and compare with experimental data.
    - well developed and widely used.
  - Microscopic potential
    - describe the projectile-target interaction in terms of nucleon-nucleon interactions
  - Phenomenological + Microscopic

Phenomenological OMP

- Phenomenological OMP for nucleon-nucleus scattering

$U_{opt}(r) = V_C(r)$	**Coulomb term**
$-(V_V + iW_V) f_{V,W}(r)$	**Complex volume**
$+(V_D - iW_D) g_{V,W}(r)$	**Complex surface**
$-2\vec{l} \cdot \vec{s}(V_{SO} + iW_{SO}) h_{V,W}(r),$	**Complex spin-orbit**

where $V_{V,D,SO}$, and $W_{V,D,SO}$ are the real and imaginary components of the volume-central (V), surface-central (D) and spin-orbit (SO) potentials.

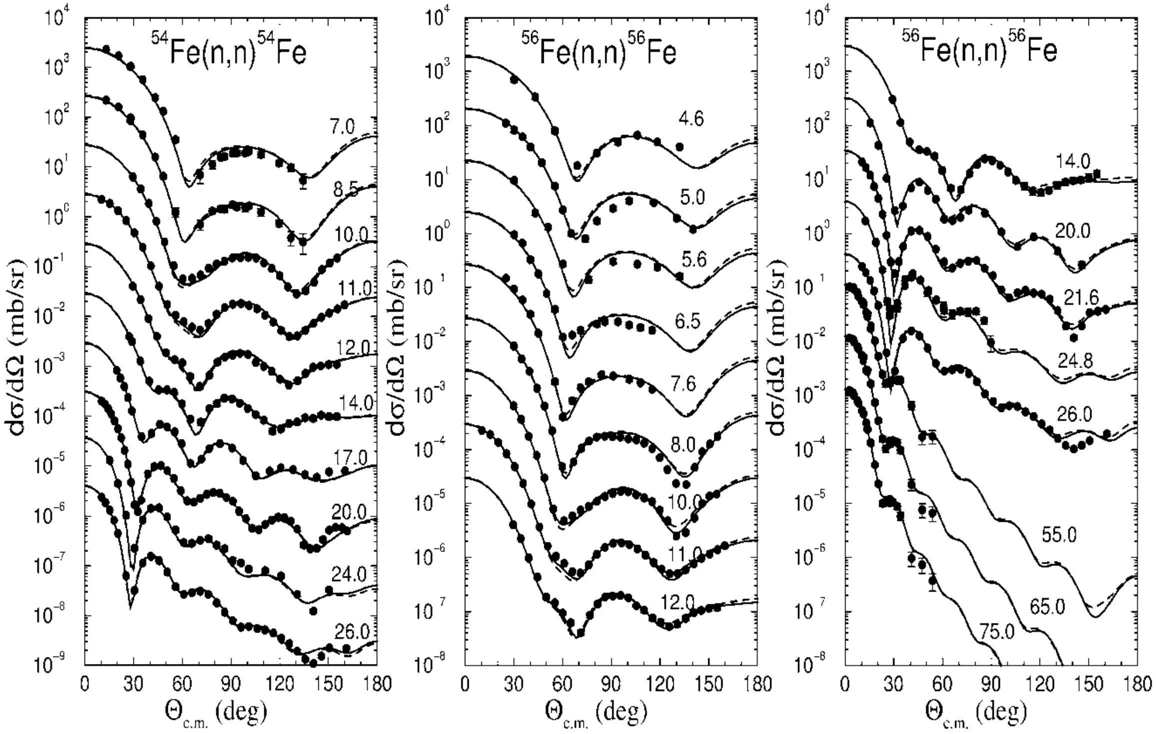
$$f_i(r) = \frac{1}{1 + \exp[(r - R_i)/a_i]}, \quad g_i(r) = \frac{d}{dr} f_i(r), \quad h_i(r) = \frac{1}{r}\frac{d}{dr} f_i(r).$$

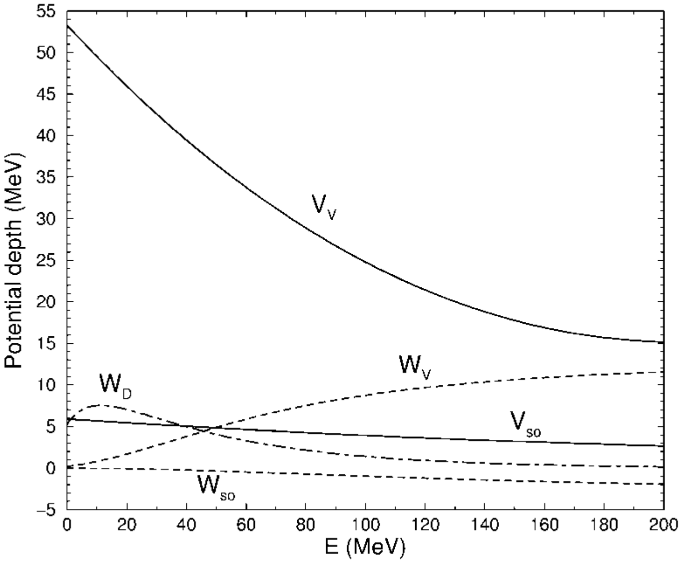
where the geometry parameters are the radius $R_i = r_i A^{1/3}$, with A begin atomic mass number, and the diffuseness parameters a_i.

OMP - spherical

“Local and global nucleon optical potentials for energies up to 200 MeV”
A.J. Koning and J.P. Delaroche, *Nucl. Phys. A713, 231 (2003)*.

Energy: $1\,\boldsymbol{keV} \le \boldsymbol{E} \le 200\boldsymbol{MeV}$ Mass: $24 \le \boldsymbol{A} \le 209$



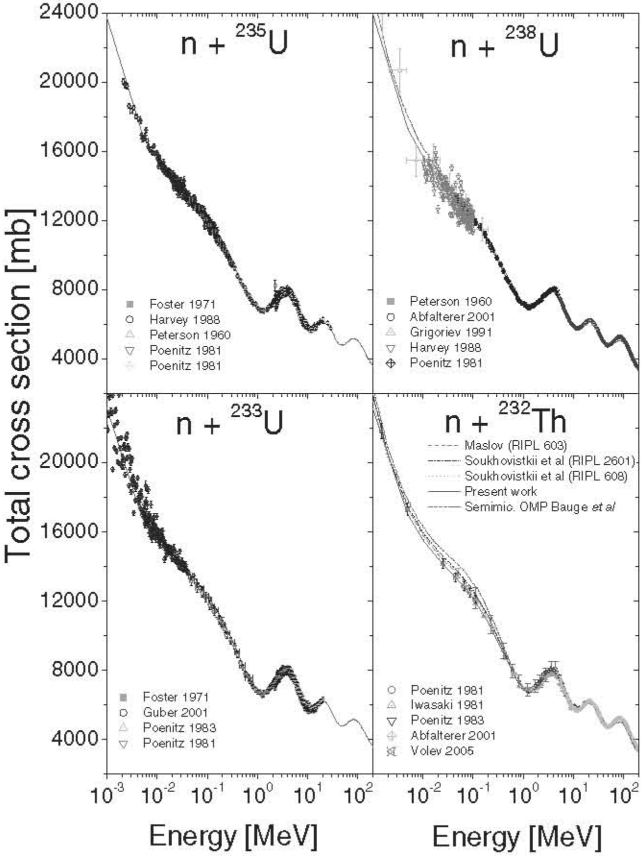


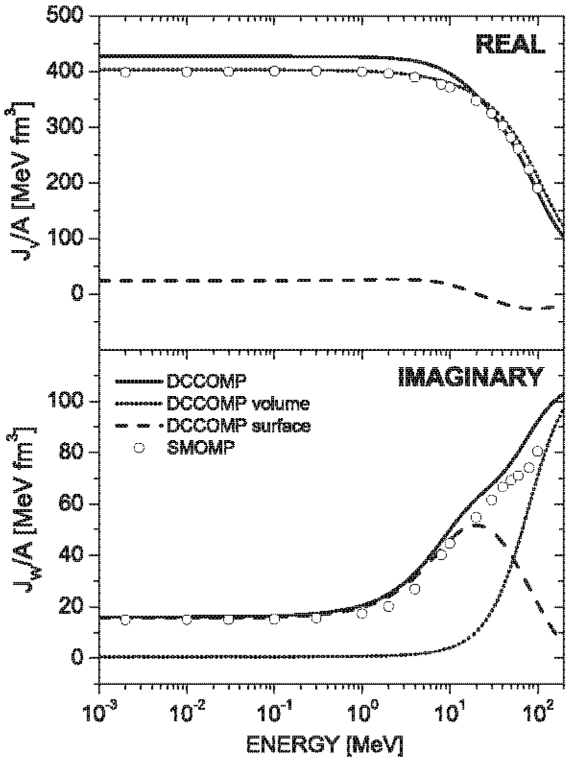
Solid lines for a local OMP and dashed lines a global one

OMP - deformed

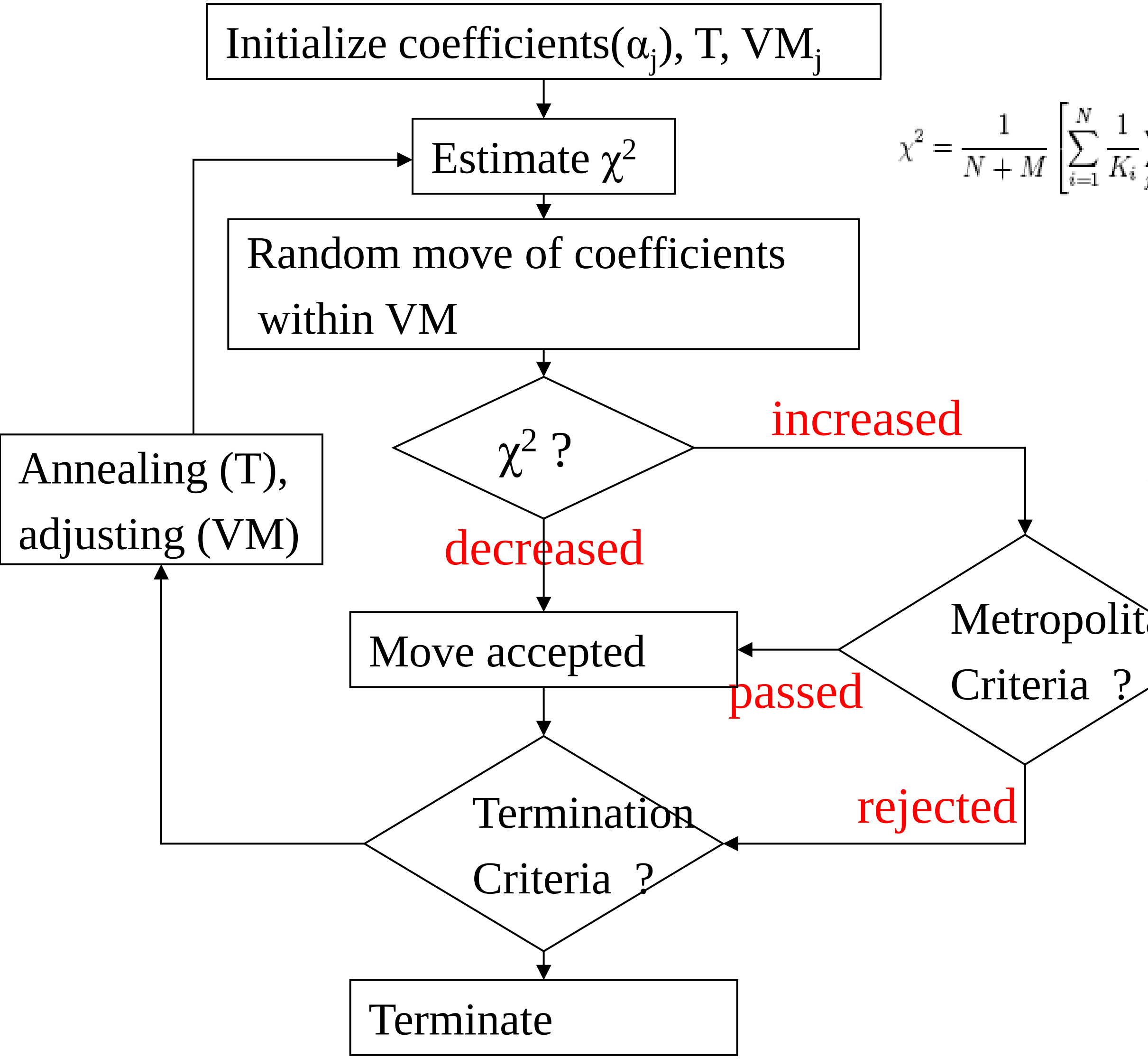
"A global Dispersive coupled-channel Optical Model Potential for Actinides"
R. Capote, S. Chiba, E.Sh. Soukhovitskii, J.M. Quesada, and E. Bauge,
J. Nucl. Sci. Technol. 45, 330(2008)

Energy: $1\boldsymbol{keV} \leq \boldsymbol{E} \leq 200\boldsymbol{MeV}$





OMP Search by SA algorithm to minimize χ^2



Initialize coefficients(α_j), T, VM_j

Estimate χ^2

Random move of coefficients within VM

χ^2 ?

increased

decreased

Metropolitan Criteria ?

passed

rejected

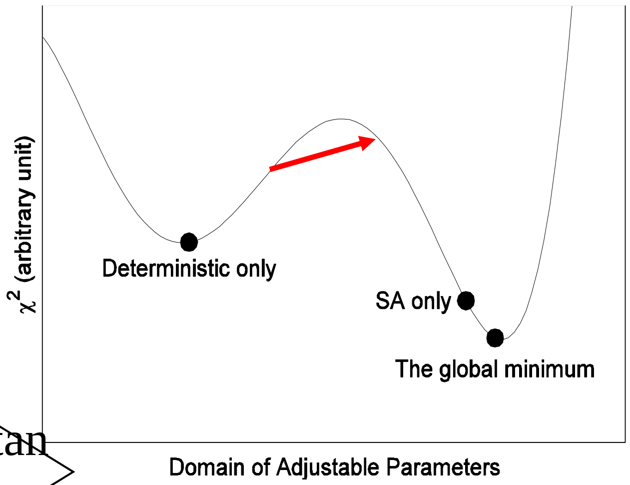
Move accepted

Termination Criteria ?

Annealing (T), adjusting (VM)

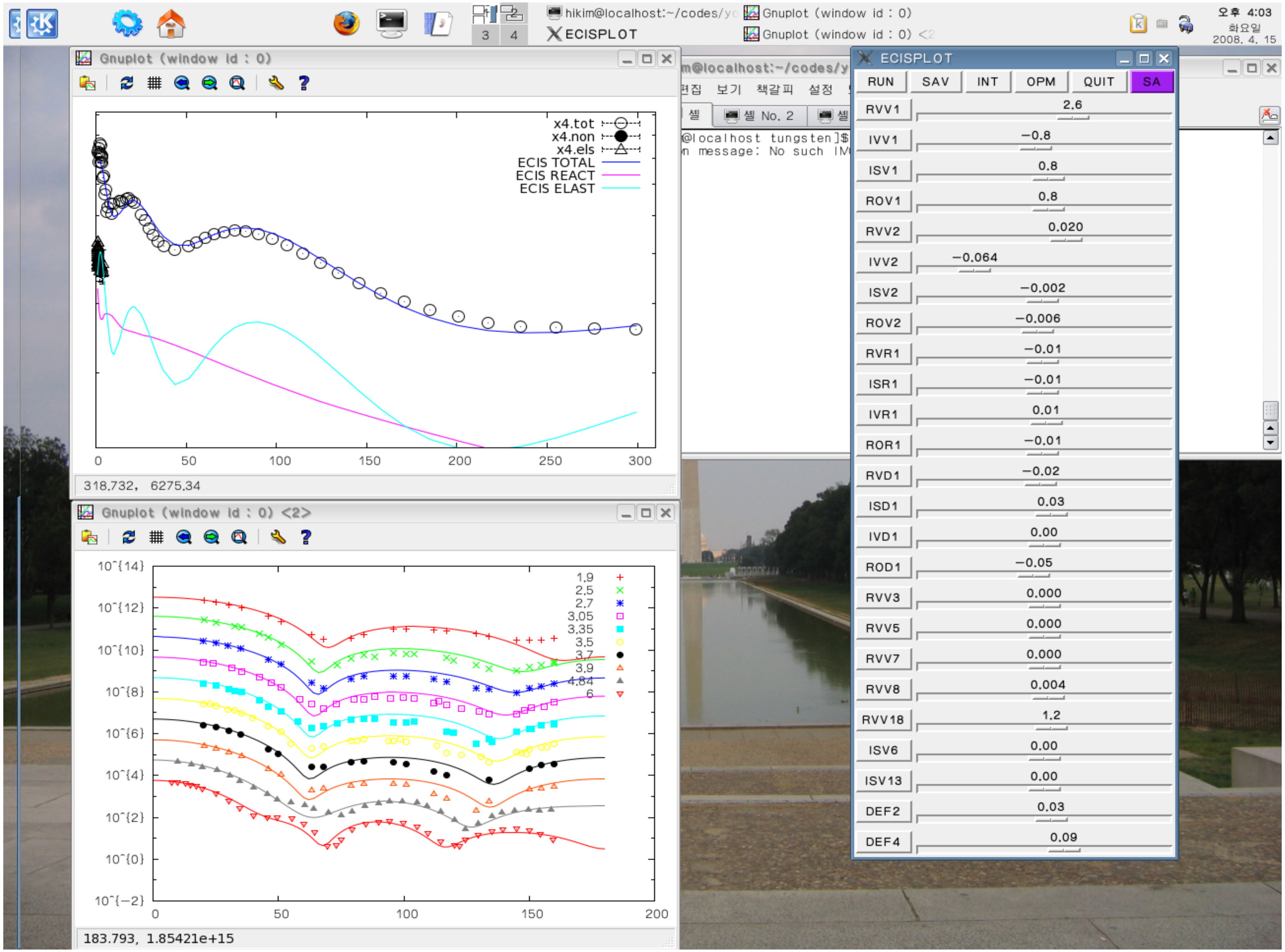
Terminate

$$\chi^2 = \frac{1}{N+M}\left[\sum_{i=1}^{N}\frac{1}{K_i}\sum_{j=1}^{K_i}\left(\frac{d\sigma_{ij}/d\Omega_{calc} - d\sigma_{ij}/d\Omega_{exp}}{\Delta\sigma_{ij}/d\Omega_{exp}}\right)^2 + \sum_{i=1}^{M}\left(\frac{\sigma_{tot_{cal_i}} - \sigma_{tot_{exp_i}}}{\Delta\sigma_{tot_{exp_i}}}\right)^2\right]$$



$$\exp\left(\frac{(\chi^2)^k - (\chi^2)^{k+1}}{T}\right) > z$$

n + Al-27 case



```
318.732, 6275.34
```

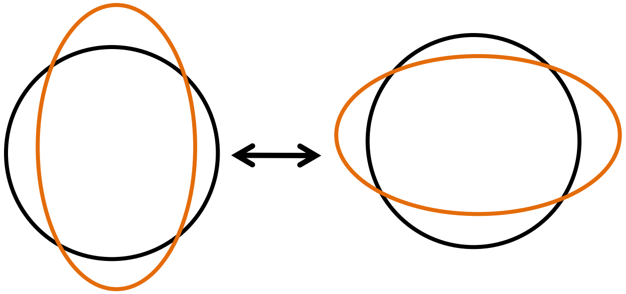
```
183.793, 1.85421e+15
```

```
@localhost tungsten]$
n message: No such IM
```

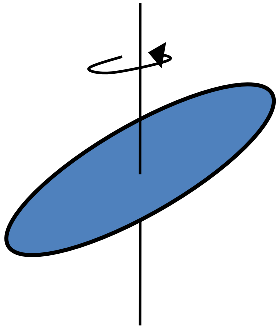
RVV1 2.6
IVV1 −0.8
ISV1 0.8
ROV1 0.8
RVV2 0.020
IVV2 −0.064
ISV2 −0.002
ROV2 −0.006
RVR1 −0.01
ISR1 −0.01
IVR1 0.01
ROR1 −0.01
RVD1 −0.02
ISD1 0.03
IVD1 0.00
ROD1 −0.05
RVV3 0.000
RVV5 0.000
RVV7 0.000
RVV8 0.004
RVV18 1.2
ISV6 0.00
ISV13 0.00
DEF2 0.03
DEF4 0.09

Direct

- Elastic scattering (Shape)
- Inelastic scattering
  - The projectile leaves the target in an excited state and its asymptotic kinetic energy is diminished.
  - To describe it, we need the basic characteristics of the ground and excited states of the target.
  - The states which are strongly excited in collisions are related to the collective movement of the target.



Vibrations



Rotations

Direct

- ✓ Strong coupling
  - ✓ Coupled Channel OMP (CCOMP)
- ✓ Weak coupling
  - ✓ Distorted Wave Born Approximation (DWBA)
    - ✓ The cross sections can be well approximated by the overlap of the interaction with the initial and final wave functions.

In the $\boldsymbol{A(\alpha,\beta)B}$ reaction, first Born approx. is

$$\frac{\boldsymbol{d\sigma_\beta}}{\boldsymbol{d\Omega}} = \frac{\boldsymbol{\mu_\alpha \mu_\beta}}{(2\pi\hbar^2)^2} \frac{\boldsymbol{k_\beta}}{\boldsymbol{k_\alpha}} |\boldsymbol{T}|^2,$$

μ_α, μ_β : reduced mass of α and β,

$\boldsymbol{k_\alpha}, \boldsymbol{k_\beta}$: wavenumber of incoming and outgoing wave

In DWBA, $\boldsymbol{\chi(k,r)} \rightarrow \exp\,(\boldsymbol{ik}\cdot\boldsymbol{r}) + \psi_{sc}$

$$\boldsymbol{T}^{DWBA} = \int \underbrace{\chi^{(-)}(\boldsymbol{k}_\beta,\boldsymbol{r})}_{\textbf{final distorted wave function}} \underset{\substack{\uparrow \\ \textbf{Form factor for interaction}}}{\boldsymbol{F}(\boldsymbol{r})} \underbrace{\chi^{(+)}(\boldsymbol{k}_\alpha,\boldsymbol{r})}_{\textbf{initial distorted wave function}} \boldsymbol{dr}$$

Compound

- The Average CS (Statistical model)

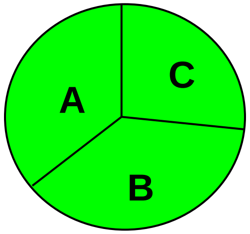
partial width for decaying into channel b

$$\sigma_{ab} = w_{ab}\,\sigma^{c}_{a}\,\frac{\Gamma^{c}_{b}}{\Gamma^{c}}$$

width fluctuation factor

CS for compound nucleus formation from channel a

total width



$$A\uparrow \rightarrow B \;\; or \; C\downarrow$$

✓ Hauser-Feshbach model

- ➢ The Bohr Hypothesis + reciprocity (time reversal invariance)
- ➢ angular momentum and parity conservation

$$\sigma_{\alpha\alpha'}dE' = \pi\lambdabar^{2}_{\alpha}\sum_{PJjl}\frac{(2J+1)T^{J}_{\alpha jl}\;\sum_{j'l'I'}T^{J}_{\alpha'j'l'}\rho^{I'}_{\alpha'}(E')dE'}{(2i+1)(2I+1)\left\{\underline{\sum_{\alpha''l''j''}T^{J}_{\alpha''l''j''}}+\sum_{\alpha''l''j''}\int T^{J}_{\alpha''l''j''}\underline{\rho^{I''}_{\alpha''}(E'')dE''}\right\}}$$

discrete levels nuclear level densities

✓ **Transmission coefficient (nucleon, fission, gamma)**

Compound

- Gamma-ray strength function
  - Describes the transmission coefficient in H-F formula when the gamma-ray emits

Strength function

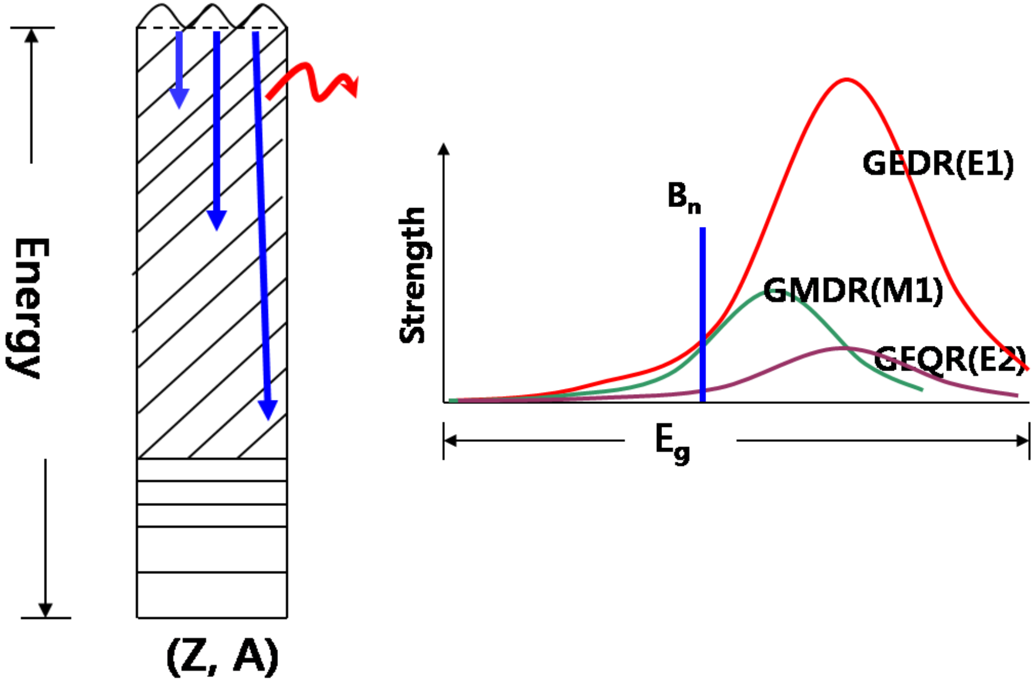
$$T_{XL}(E_\gamma) = 2\pi E_\gamma^{2L+1} \boxed{f_{XL}(E_\gamma)}$$

where

X Electromagnetic properties,

L Angular momentum,

$XL \Rightarrow E1, E2, M1, \cdots$



Compound

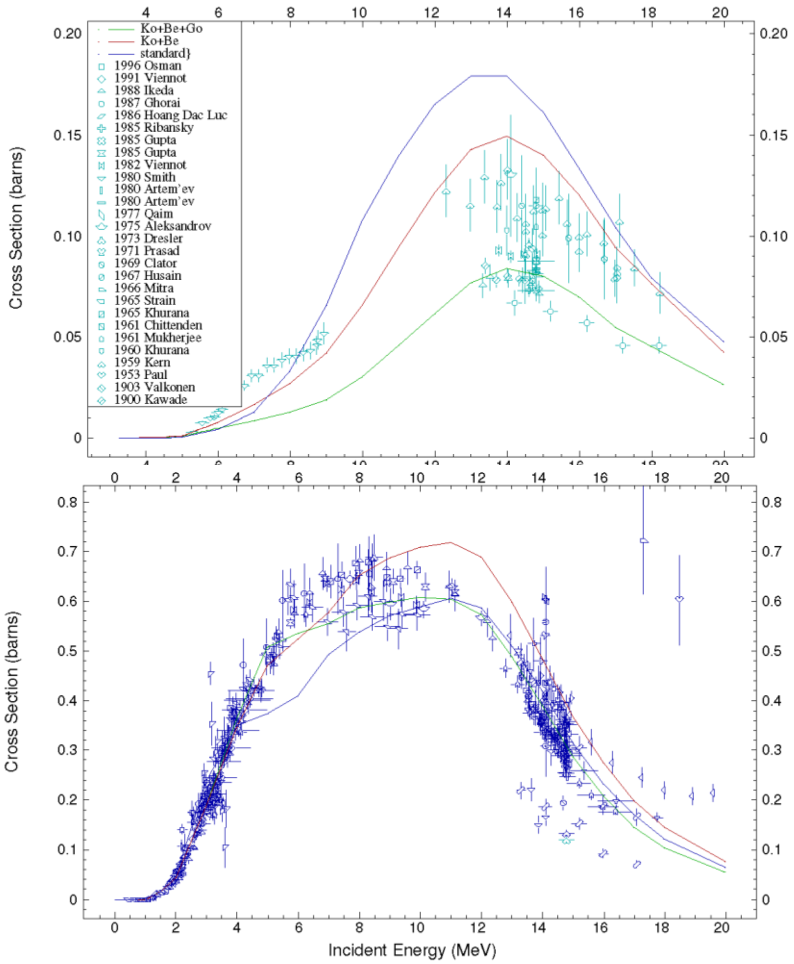
Nuclear Level Density

•Classification

- Phenomenological
  - Fermi gas model
  - Back-shifted Fermi Gas Model
  - Gilbert-Cameron model
  - Generalized superfluid model

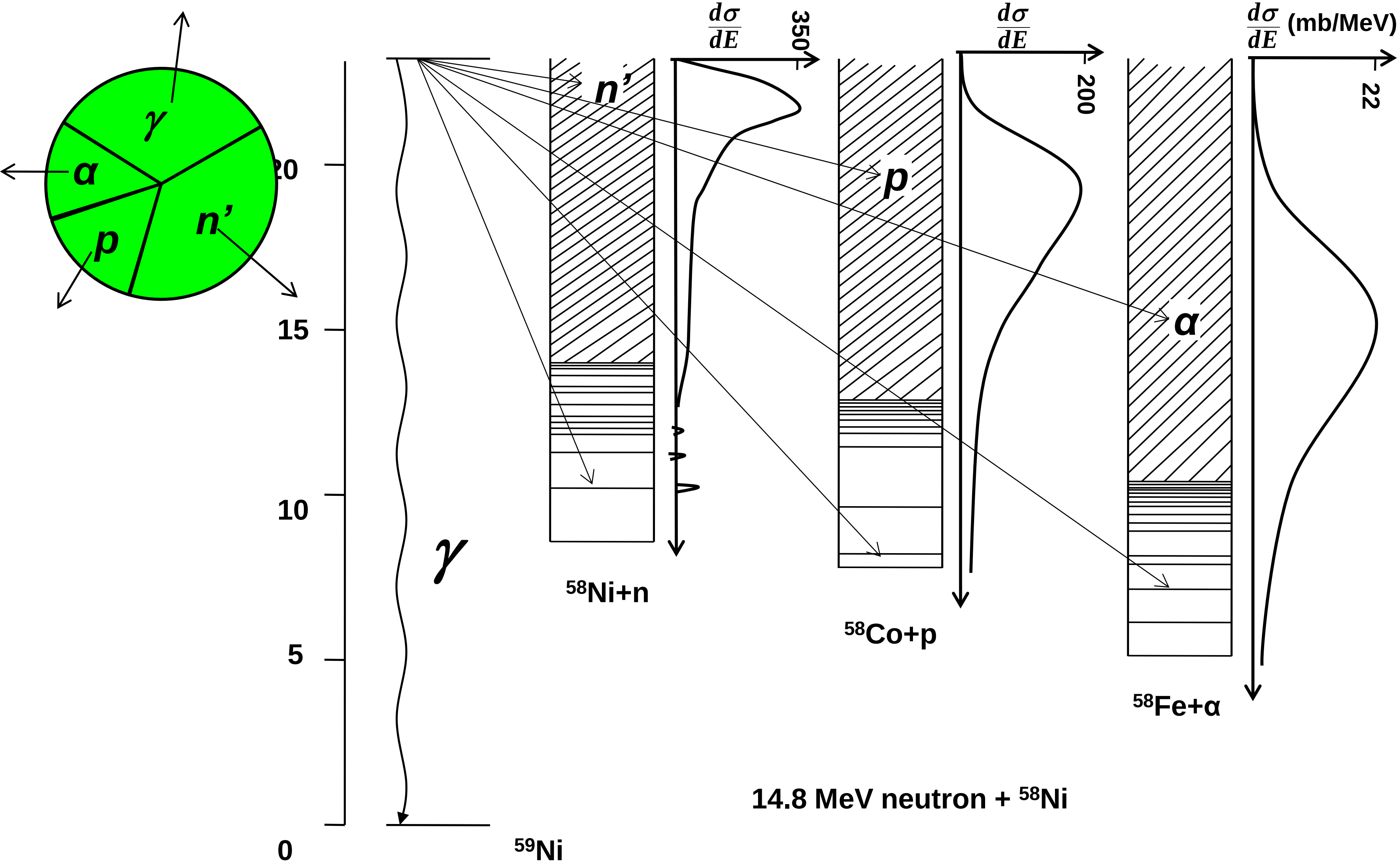
  …
- Microscopic
  - Microscopic Generalized superfluid model
  - Hartree-Fock-BCS model

  …



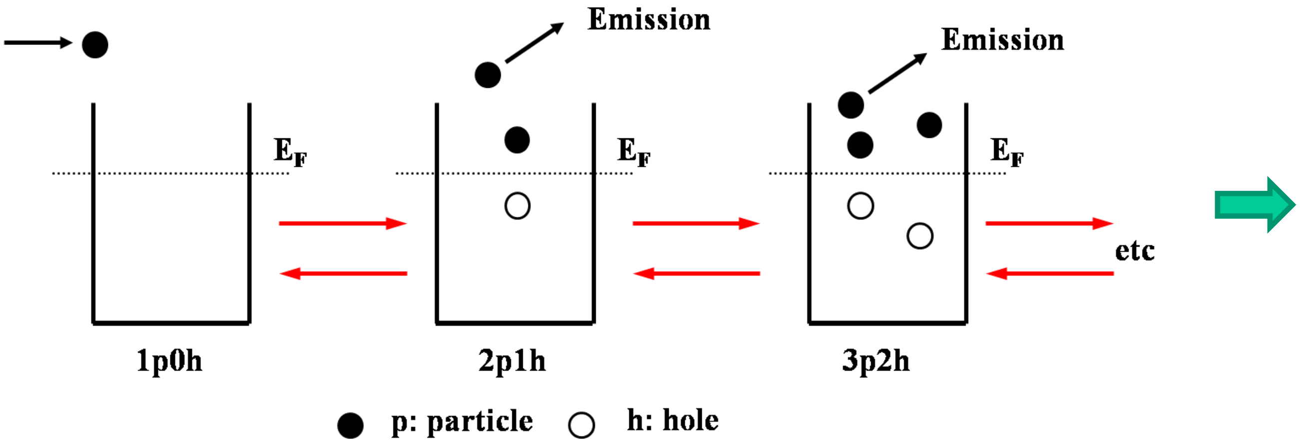
data from EMPIRE-3.1 manual

Compound - decay



14.8 MeV neutron + ^{58}Ni

Pre-equilibrium



Towards
Equilibrium

- Compound (equilibrium)
  - the nuclear reaches an equilibrium before emission occurs.
  - lost the properties of incident channel.
- Pre-equilibrium
  - retains a large fraction of the incident energy.
  - Forward peak shape

Pre-equilibrium-EXCITON

- Classification
  - Semi-classical model (EXCITON)
    - Employing a Master Equation which is a kinetic equation describing the time evolution of the probability distribution $P(n,t)$

$$\frac{dP(n,t)}{dt} = \lambda^{+}(n-2)P(n-2,t) + \lambda^{-}(n+2)P(n+2,t) \\ -[\lambda^{+}(n) + \lambda^{-}(n) + W(n)]P(n,t),$$

$P(n,t)$ - Probability that system will be in the state with n excitions during time t,

$W(n)$ - Total emission rate,

$\lambda^{+}(n), \lambda^{-}(n)$ - internal transition rates to state with $n \pm 2$.

Pre-equilibrium-MSD/MSC

- Quantum Mechanical model (MSD/MSC)
  - Multi-step Compound (MSC)
    - symmetric angular distribution for 90°
  - Multi-step Direct (MSD)
    - forward peaked angular distribution
    - Spherical or Deformed

$$\frac{d^2\sigma^{(n)}_{j\leftarrow i}(E,\Omega\leftarrow E_0,\Omega_0)}{d\Omega dE}=\frac{m}{4\pi^2\hbar^2}\sum_{t_{n-1}=\pi,\nu}\int d\Omega_{n-1}\int dE_{n-1}E_{n-1}$$

$$\times\underline{\frac{d^2\sigma^{(1)}_{j\leftarrow t_{n-1}}(E,\Omega\leftarrow E_{n-1},\Omega_{n-1})}{d\Omega dE}}\,\frac{d^2\sigma^{(n-1)}_{t_{n-1}\leftarrow i}(E_{n-1},\Omega_{n-1}\leftarrow E,\Omega_0)}{d\Omega_1 dE_1},$$

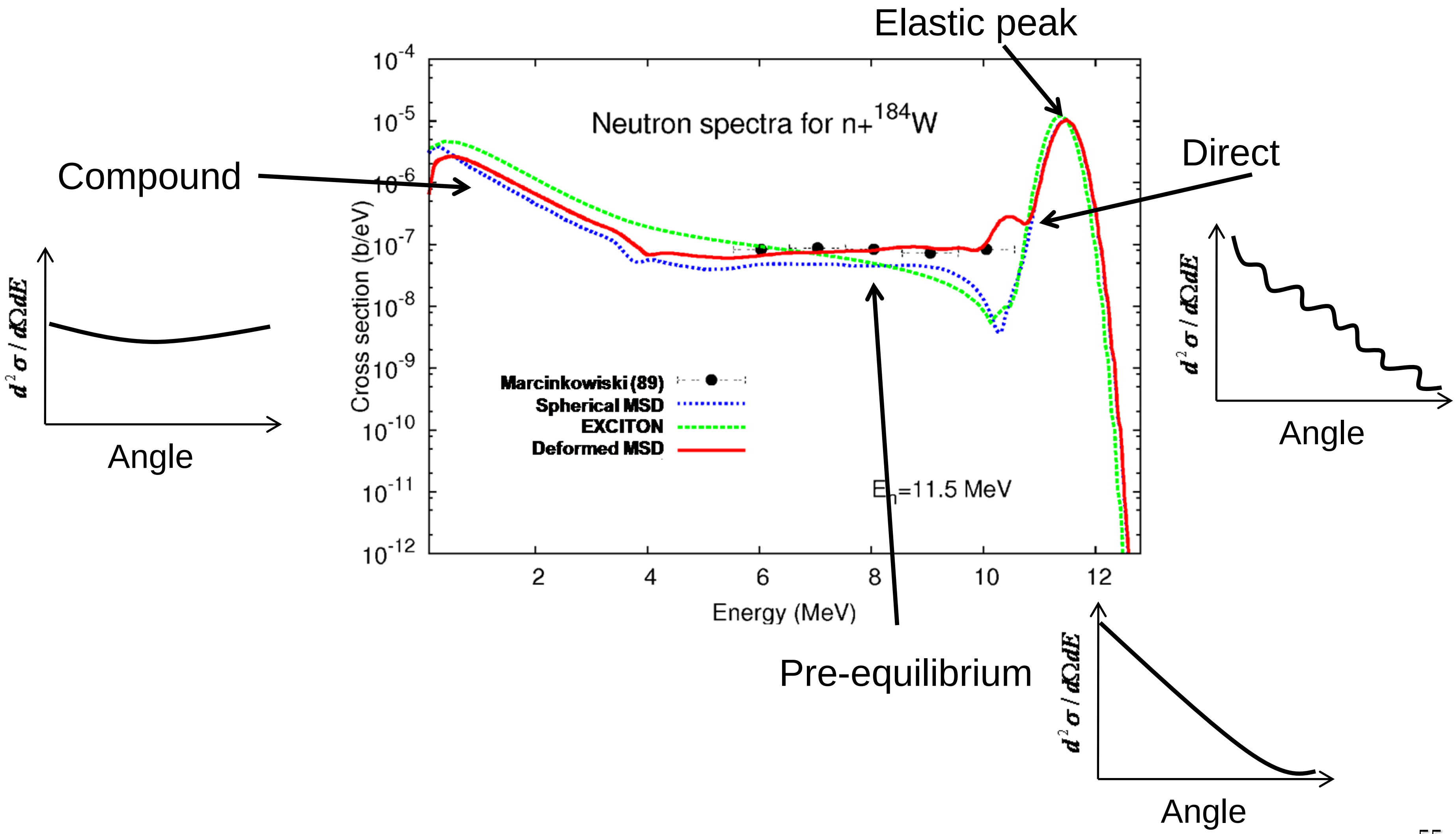
A weighted sum over squared DWBA matrix elements

$E_0,\Omega_0,E_1,\Omega_1$ are energy and solid angle of initial and Intermediate,

t_{n-1} means that the number of possible scattering terms is larger compared to the component of previous step.

- Nuclear Data
- Nuclear Reaction
- Reaction Model
- **Evaluation Examples**
- Measurements
- Uncertainties
- Nuclear Data Center @KAERI

An Example



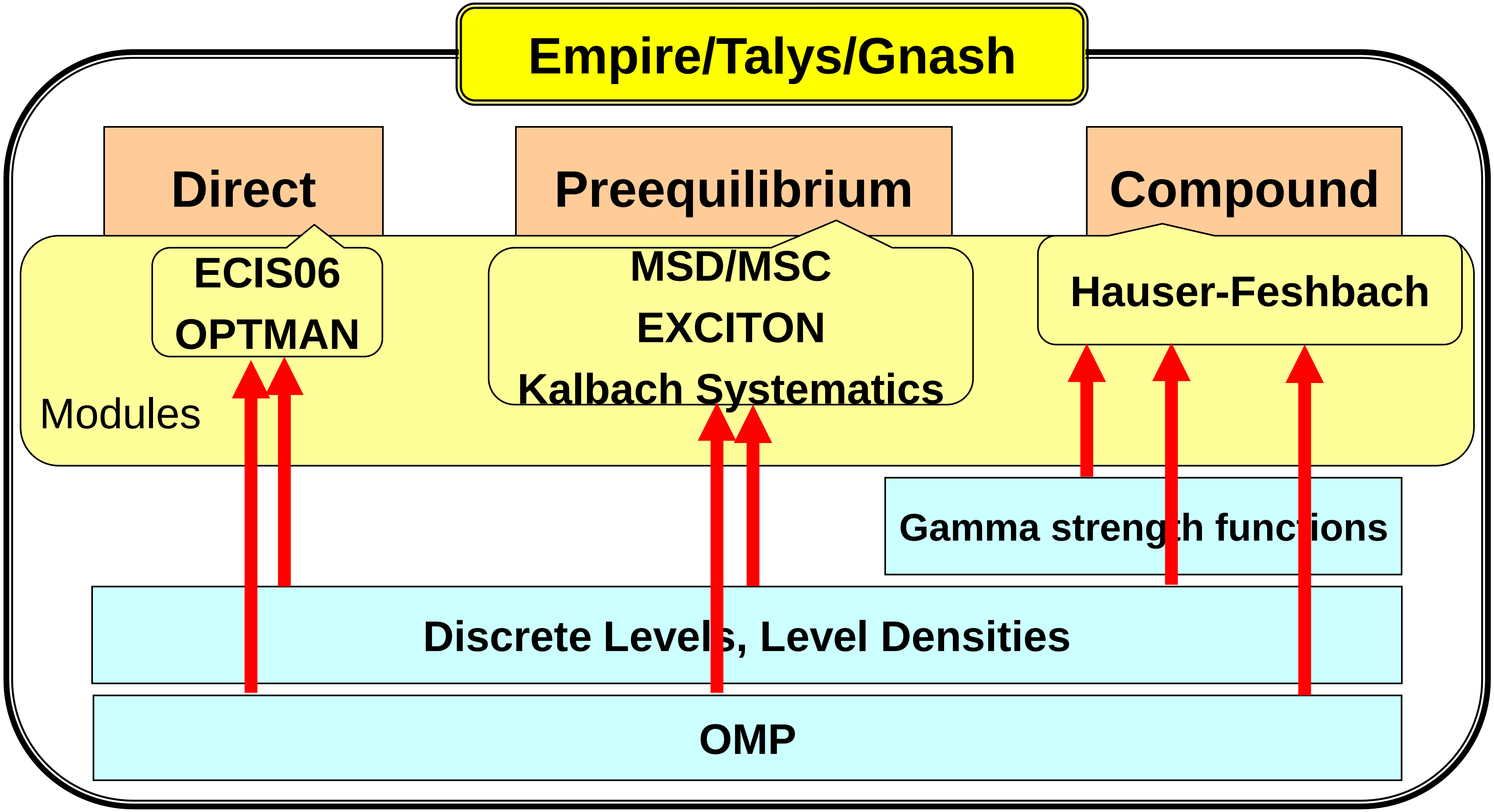
Elastic peak

Compound

Direct

Pre-equilibrium

Reaction Calculation in Fast Region



Empire/Talys/Gnash

Direct

Preequilibrium

Compound

ECIS06
OPTMAN

MSD/MSC
EXCITON
Kalbach Systematics

Hauser-Feshbach

Modules

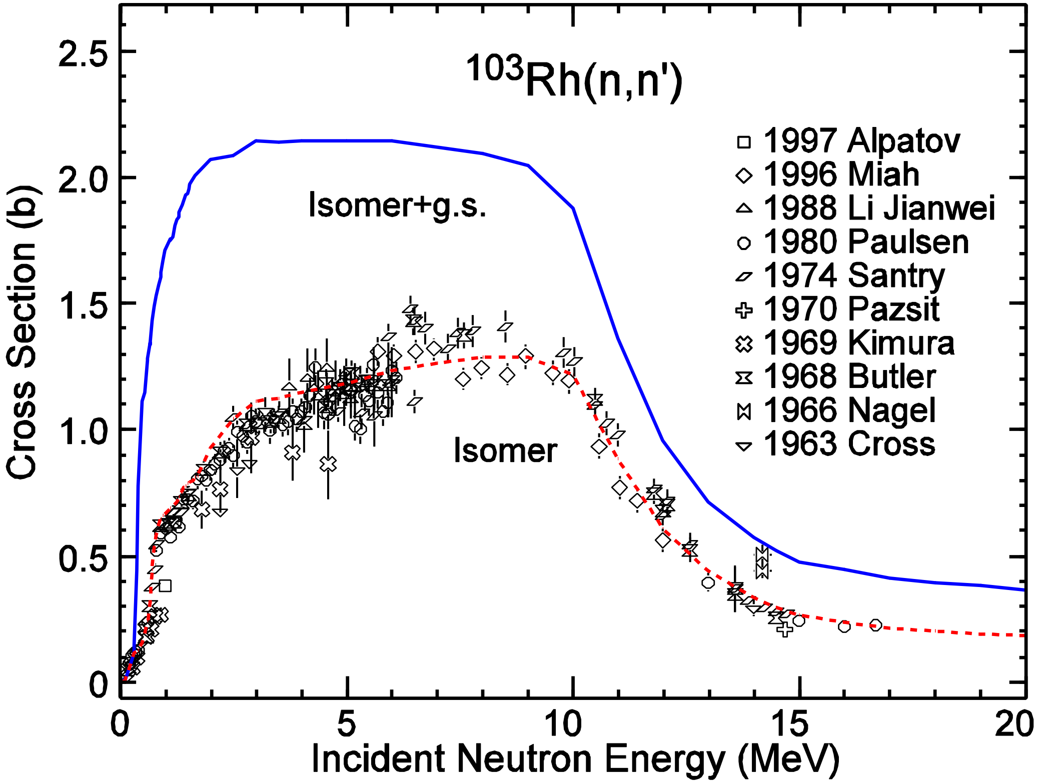
Gamma strength functions

Discrete Levels, Level Densities

OMP

Evaluation Examples - I

- ✓ No experimental data for total inelastic cross sections
- ✓ Experimental data for isomeric state with 0.0398 MeV



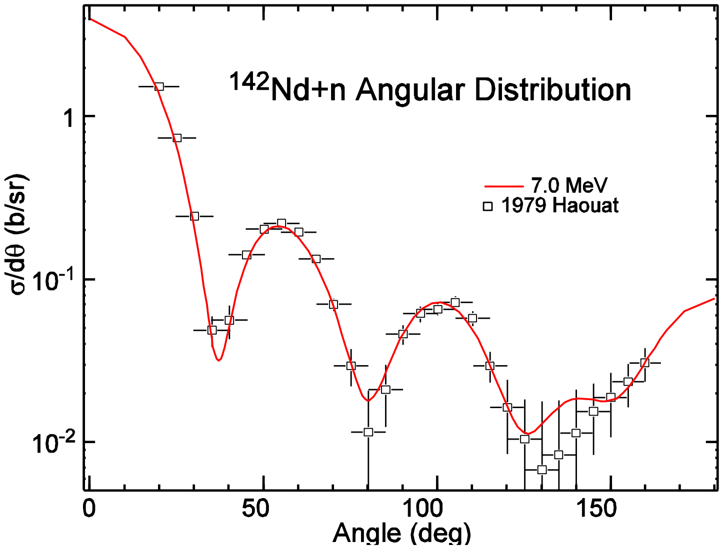
Evaluation Examples - II

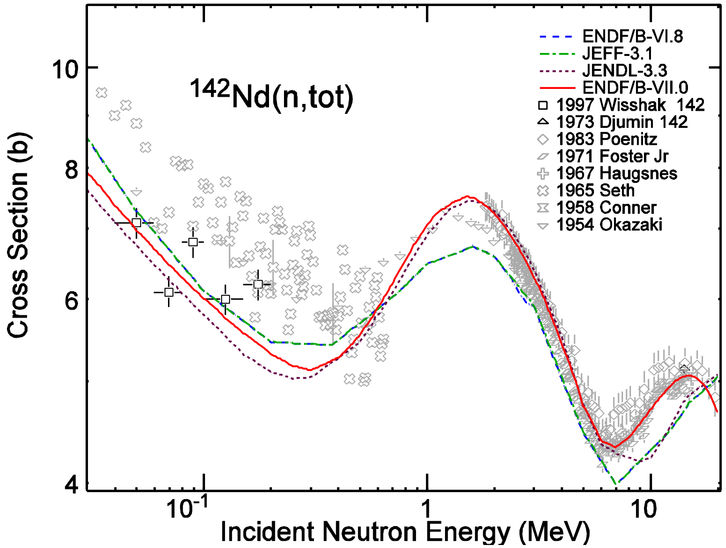
Evaluation of a full isotopic family

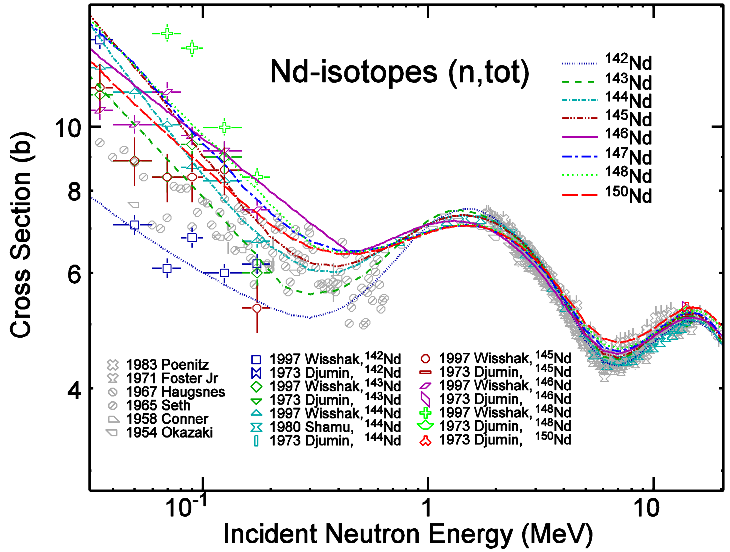
- Many nuclei have insufficient experimental data for deducing reasonable model parameters
- Neodymium
  - Elastic angular distribution and total cross section in few energy points
  - The experimental status of remaining isotopes is similar with a certain isotope (in this case, ^{142}Nd)
  - Total cross section of natural element

Evaluation Examples - II

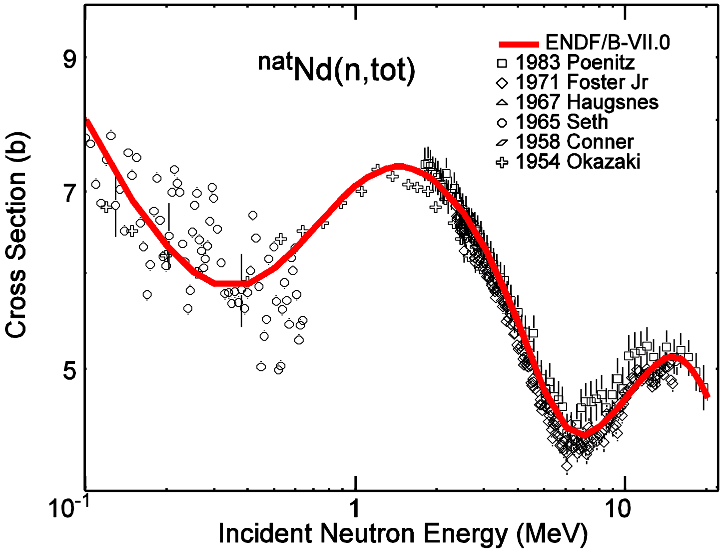
Evaluation of a full isotopic family





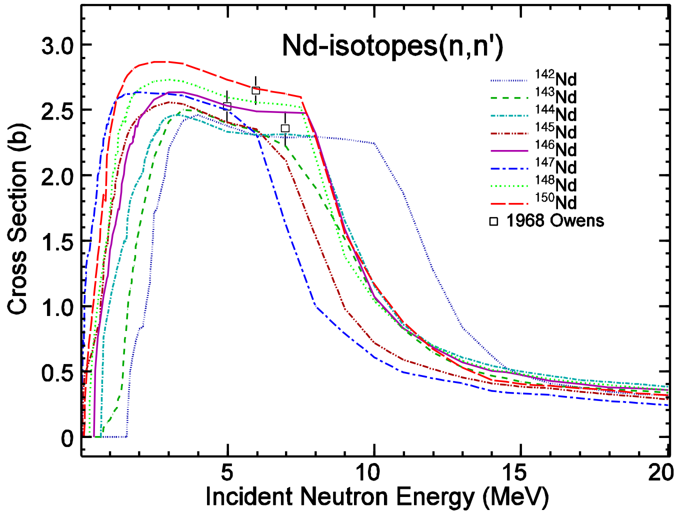


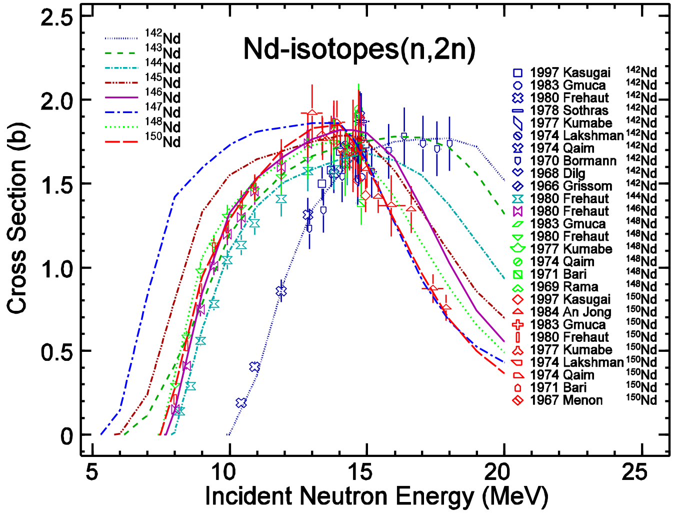
	Abundance %
^{142}Nd	27.2
^{143}Nd	12.2
^{144}Nd	23.8
^{145}Nd	8.3
^{146}Nd	17.2
^{147}Nd	0
^{148}Nd	5.7
^{150}Nd	5.6

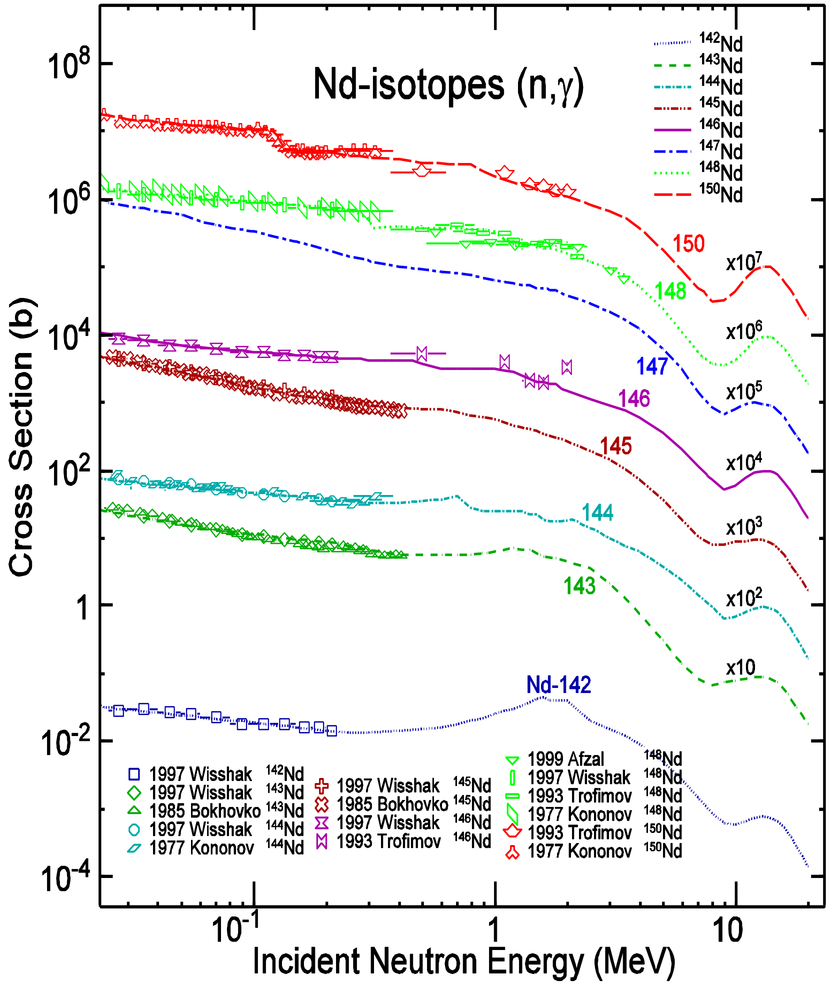


Evaluation Examples - II

Evaluation of a full isotopic family

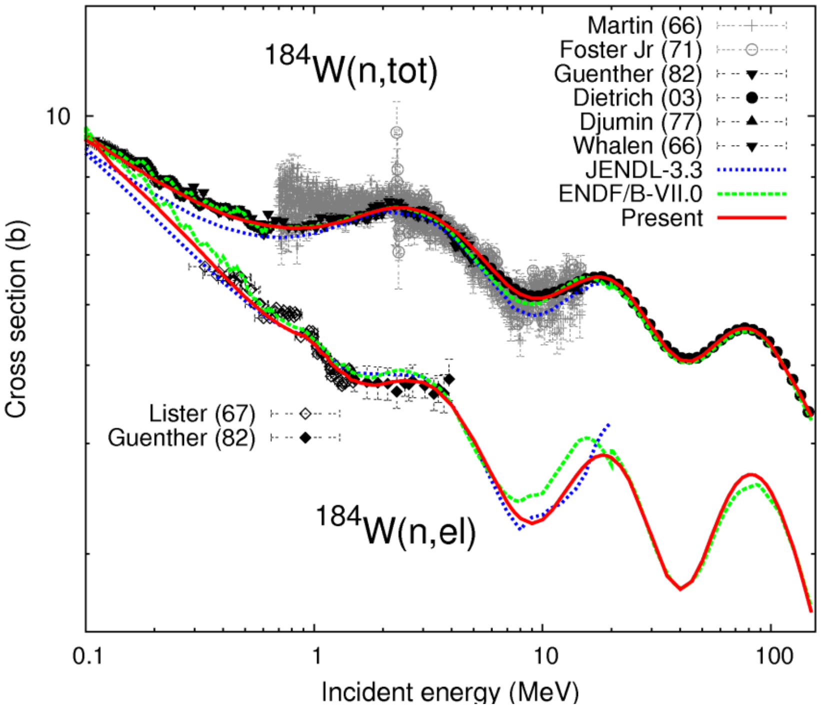


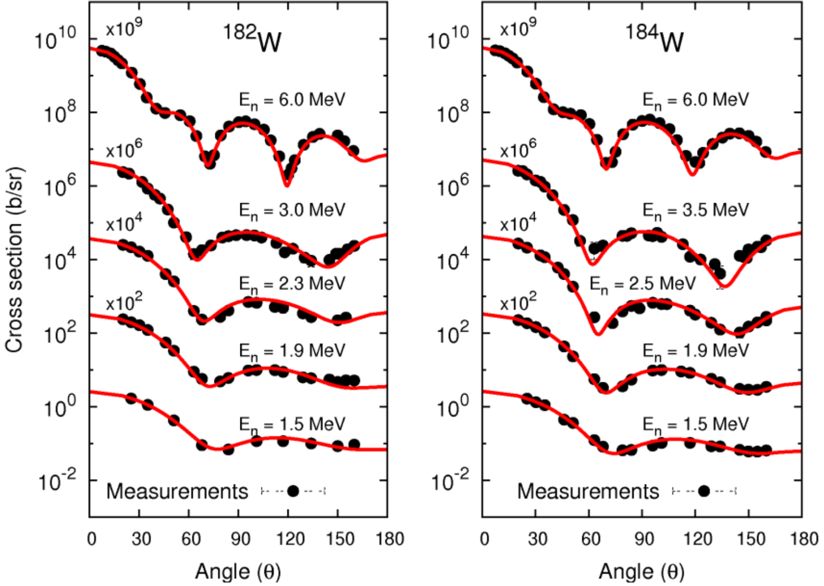


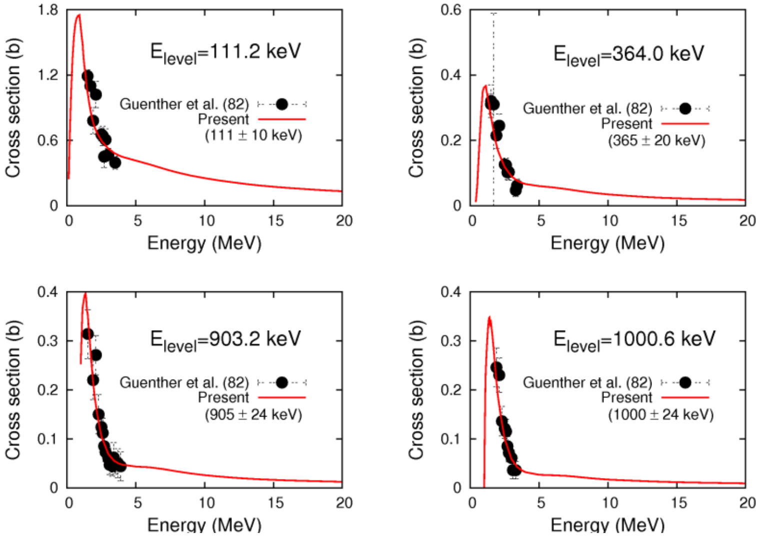


Evaluation Examples - III

up to integral experiment (benchmark)

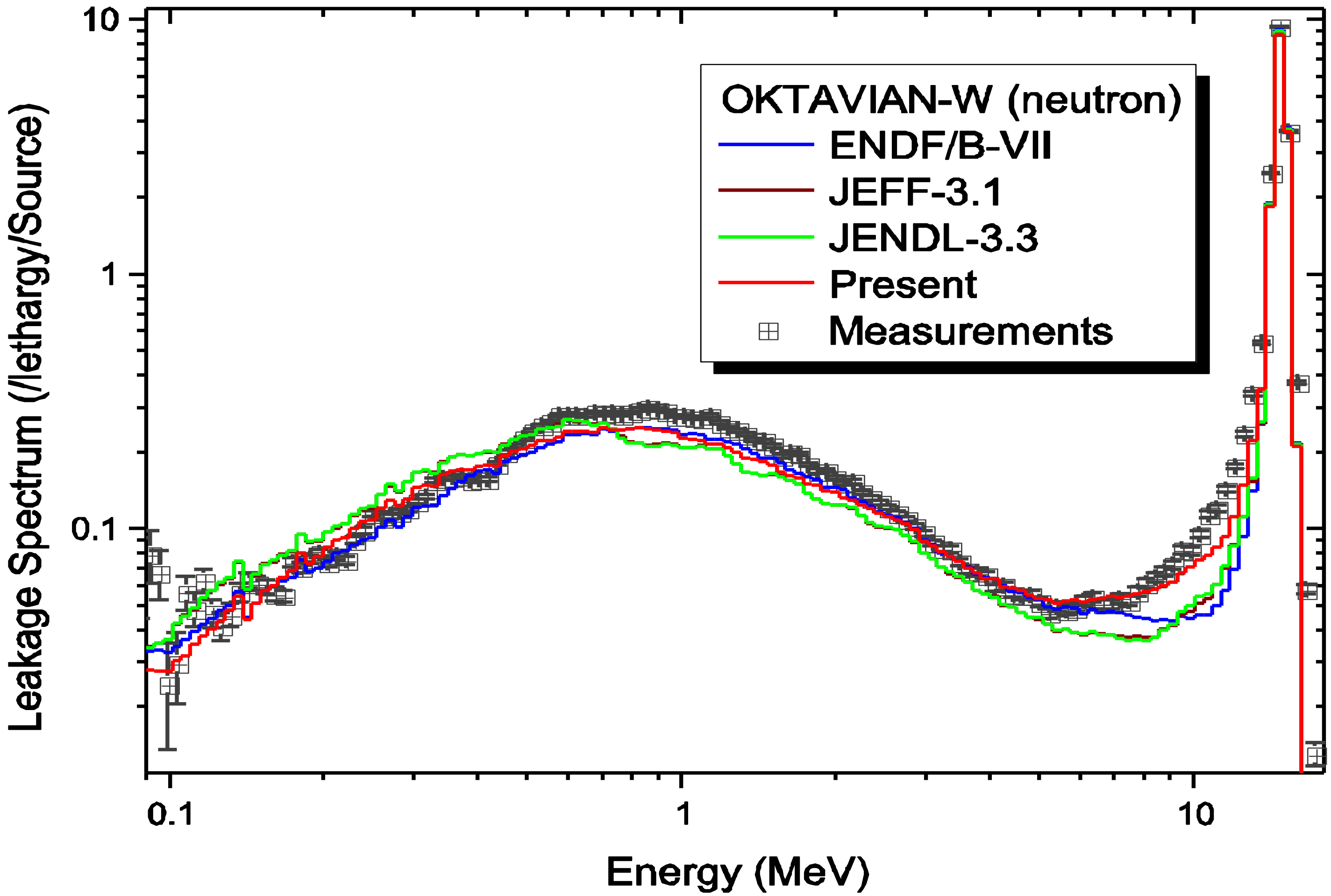






Evaluation Examples - III

up to integral experiment (benchmark)



- Nuclear Data
- Nuclear Reaction
- Reaction Model
- Evaluation Examples
- **Measurements**
- Uncertainties
- Nuclear Data Center @KAERI

✓ Neutron Sources for CS measurements

-Reactors : White spectrum (thermal CS)

-Accelerators : Mono, Quasi-mono, with pulsing

→ energy dependant CS

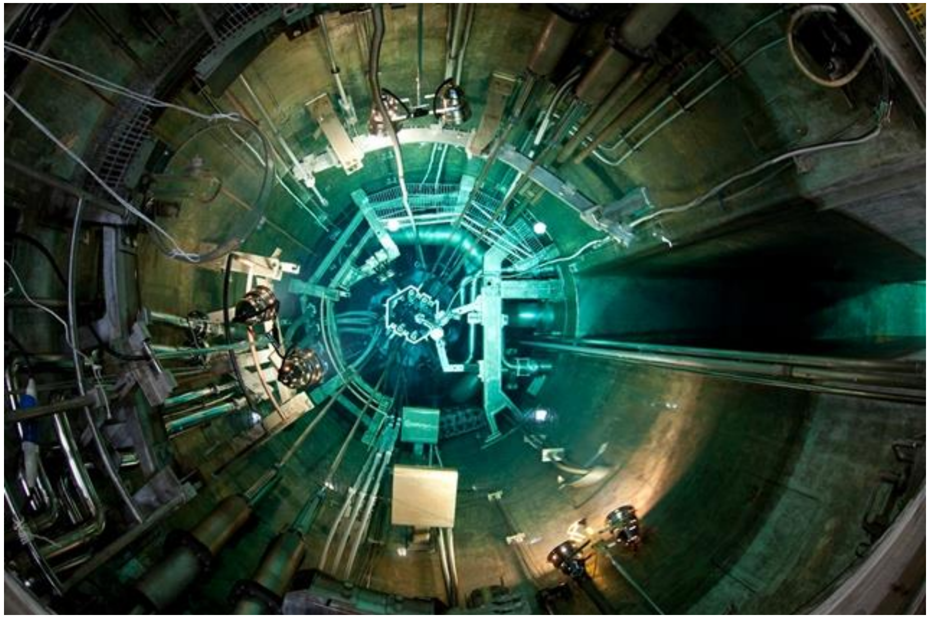


Photo-Neutron

Electron Linear Accelerators:

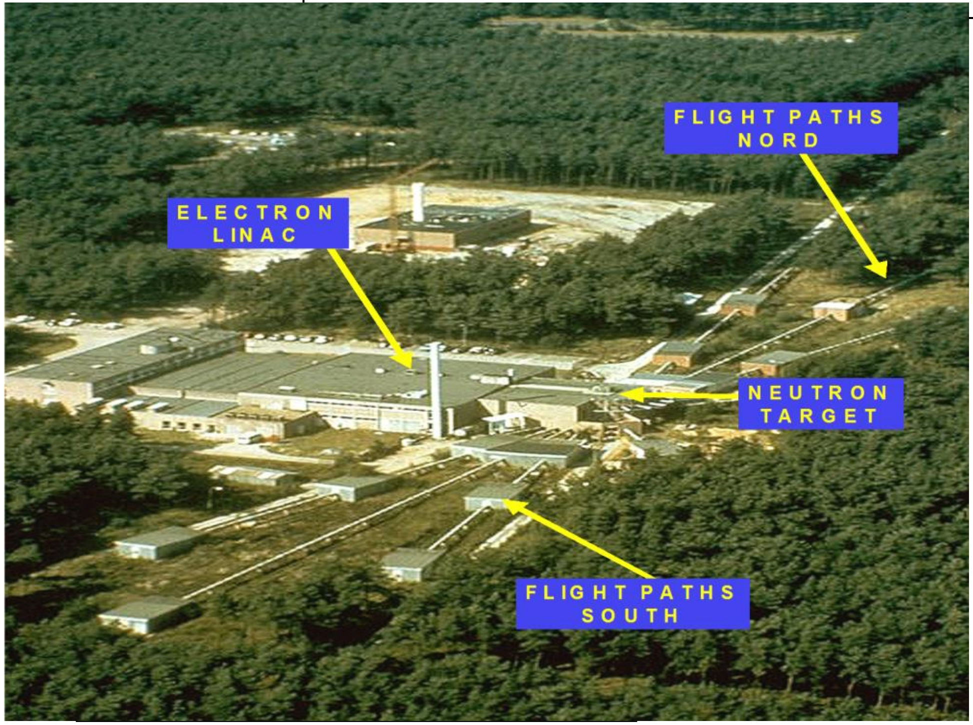
GELINA, ORELA, KUR-LINAC, PNF, etc.

Electron Beam + Ta, W, or U Target → Evaporation Neutrons

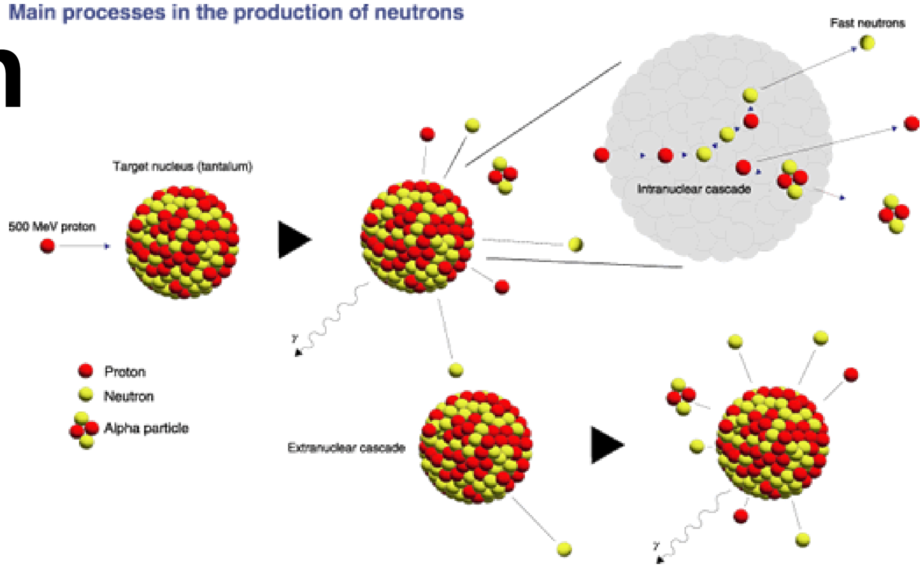
+ Moderator → En = thermal – MeV

TOF/Flight Path Length: 10 – 300 m

+ Filter (Fe, Si, etc.) → Mono Energetic



Spallation Reaction



Proton Linear Accelerator (+ Synchrotron)

Operation: WNR, n_TOF, J-PARC, SNS, CERN, etc.

Proton Beam + Pb, W, or Hg Target

→ Intra-Nuclear Cascade: En > Several 10MeV

→ Pre-Equilibrium: Several MeV < En < Several 10MeV

→ Equilibrium: Evaporation Spectrum (*kT* = 1MeV)

+ Moderator → En = thermal – GeV

TOF/Flight Path Length: 7 – a few 100 m

$D(d,n)^3He$, $^7Li(p,n)^7Be$, $T(p,n)^3He$

Van de Graaff, Cyclotron, etc.

$D(d,n)^3He$: Q = 3.3 MeV

En = 4 - 8MeV

$^7Li(p,n)^7Be$: Q = -1.646 MeV, E_{th} = 1.881 MeV

Mono-energetic (30 keV) neutrons emit only to 0 degree at E_{th}.

Several keV < En < 200MeV

$T(p,n)^3He$: Q = -0.764 MeV, E_{th} = 1.019 MeV

Mono-energetic (64 keV) neutrons emit only to 0 degree at E_{th}.

Several keV < En < Several MeV

Techniques for neutron cross section measurement

1) Activation Methods

Applicable to Radioactive Residual Nuclei

Activity Measurement after Neutron Irradiation

→ High Neutron Flux due to Short Distance between a Sample and a Neutron Source and Low Background in Activity Measurement

→ High Sensitivity

Activity Measurement by Detecting g, b, or a Rays

e.g. g- and/or b- Ray Detection of ^{198}Au
for ^{197}Au(n,g)^{198}Au (b:2.7 d) Reaction
b-Ray Detection of ^{210g}Bi and/or a-Ray Detection of ^{210}Po
for ^{209}Bi(n,g)^{210g}Bi(b:5.0 d)^{210}Po(a:138 d) Reaction
(The g-Ray Emission Probabilities of ^{210g}Bi and ^{210}Po are very small.)

Important: Correction for the Activity due to Background Neutrons
in Case of s(En) << s(Background Neutrons)

Techniques for neutron cross section measurement

2) Accelerator Mass Spectroscopy

Applicable to All Residual Nuclei

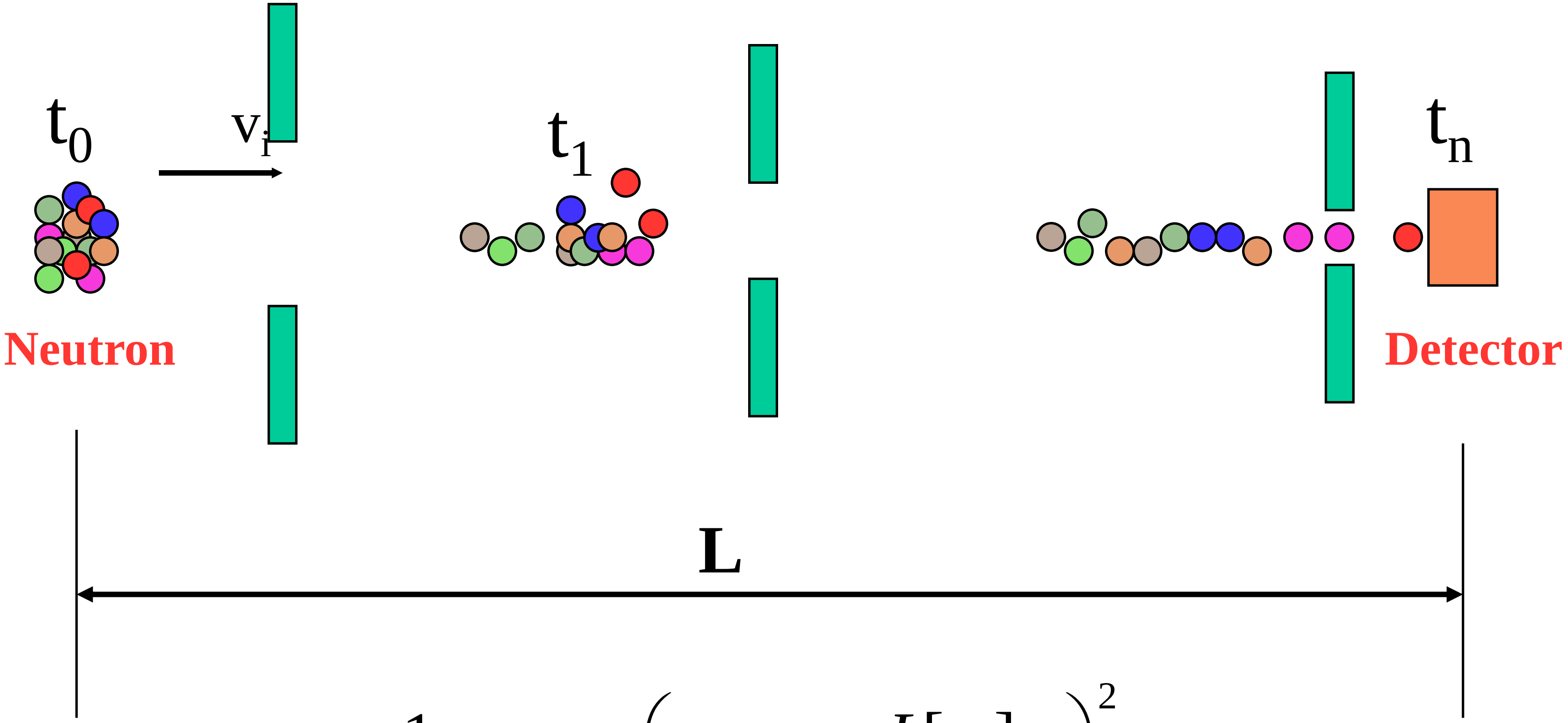
Accelerator Mass Spectroscopy (AMS) after Neutron Irradiation
→ High Neutron Flux due to Short Distance between a Sample and a Neutron Source
→ a Considerable Number of Residual Nuclei in a Sample
→ High-Resolution AMS is Applicable
to the Detection of Residual Nuclei.

Residual-Nucleus Measurement by AMS
e.g. AMS of ^{210g}Bi, ^{210m}Bi(a:3.04 My), and ^{210}Po in ^{209}Bi
for ^{209}Bi(n,g)^{210g}Bi(b:5.0 d)^{210}Po(a:138 d) Reaction
(The g-Ray Emission Probabilities of ^{210g}Bi and ^{210}Po are very Small.)

Important: Correction for the Activity due to Background Neutrons
in Case of s(En) << s(Background Neutrons)

Techniques for neutron cross section measurement

3) Neutron TOF Method



$$E_n = \frac{1}{2} m_n v^2 = \left(72.3 \bullet \frac{L[m]}{t_n[\mu \sec]}\right)^2 \qquad [eV]$$

Techniques for neutron cross section measurement

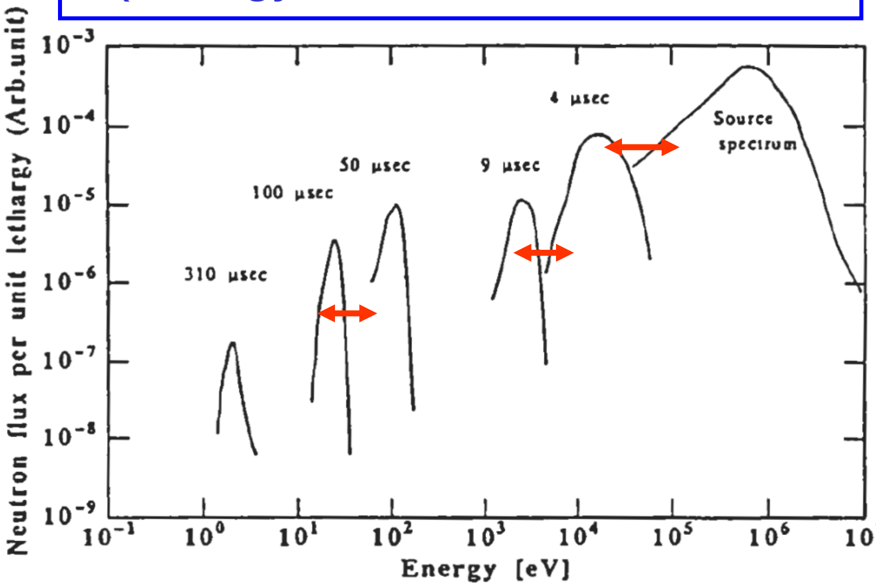
4) Lead Slowing Down Spectrometer (LSDS)

Energy vs time: $E \sim t^{-2}$

Very high intensity

~1000 x TOF

(Energy resolution 30～40%



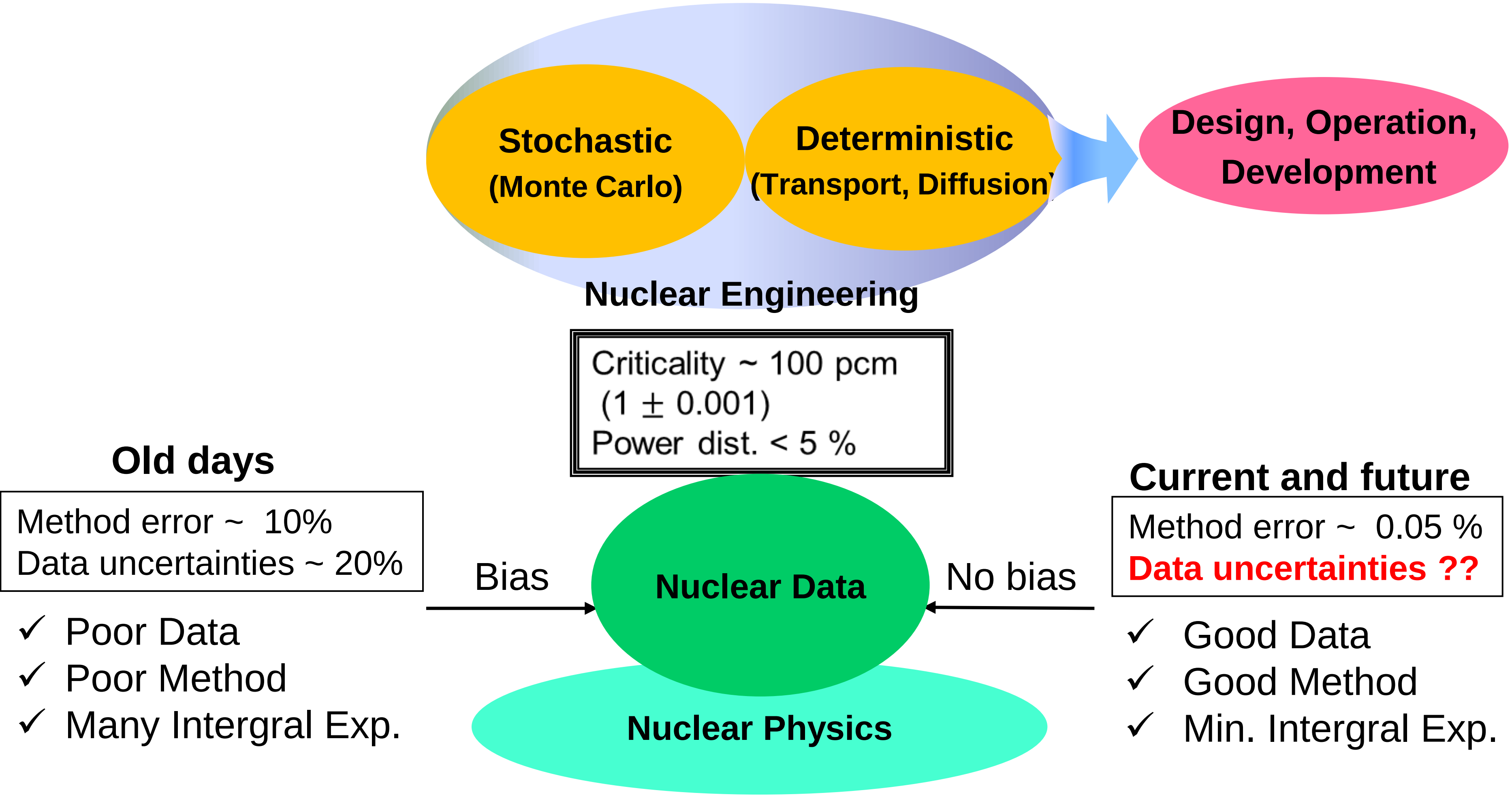
Kyoto University LSDS

LANL LSD

Experiment with ng sample !

- Nuclear Data
- Nuclear Reaction
- Reaction Model
- Evaluation Examples
- Measurements
- **Uncertainties**
- Nuclear Data Center @KAERI

Nuclear Data Uncertainties



Stochastic
(Monte Carlo)

Deterministic
(Transport, Diffusion)

Design, Operation, Development

Nuclear Engineering

Criticality ~ 100 pcm
(1 ± 0.001)
Power dist. < 5 %

Old days

Method error ~ 10%
Data uncertainties ~ 20%

- ✓ Poor Data
- ✓ Poor Method
- ✓ Many Intergral Exp.

Bias

Nuclear Data

No bias

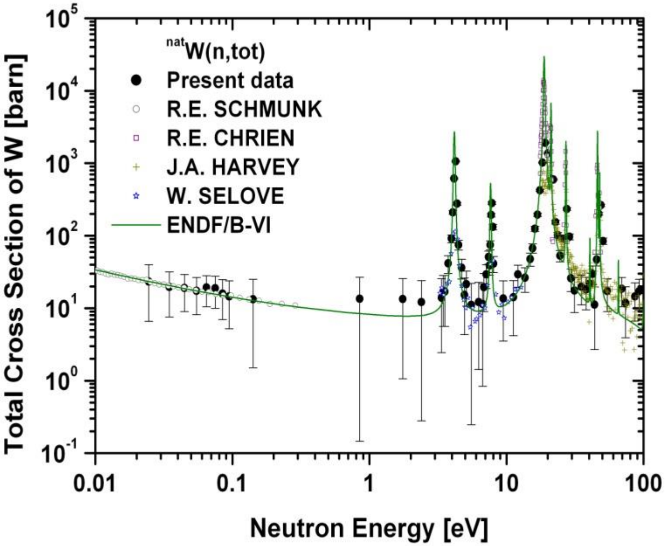
Nuclear Physics

Current and future

Method error ~ 0.05 %
Data uncertainties ??

- ✓ Good Data
- ✓ Good Method
- ✓ Min. Intergral Exp.

Parameter Estimation for variance and covariance



Non linear equation can be linearized in vicinity of solution as

$$\mathbf{y} = \mathbf{f(p)} = \mathbf{Gp} + \boldsymbol{\varepsilon}$$

where ε is random error with normal distribution of variance V_y

Generalized Least Squares method

$$\mathbf{p} = (\mathbf{G}^T \mathbf{V}_y^{-1} \mathbf{G})^{-1} \mathbf{G}^T \mathbf{V}_y^{-1} \mathbf{y}$$

$$\mathbf{V}_p = (\mathbf{G}^T \mathbf{V}_y^{-1} \mathbf{G})^{-1}$$

by multiplying G in both side

Simultaneous Estimation

Large matrix for large sets

Bayesian method (same as Kalman filter)

$$\mathbf{p} = \mathbf{p}_a + \mathbf{V}_a \mathbf{G}^T (\mathbf{G} \mathbf{V}_a \mathbf{G}^T + \mathbf{V}_y)^{-1} (\mathbf{y} - \mathbf{f(p)})$$

$$\mathbf{V}_p = \mathbf{V}_a - \mathbf{V}_a \mathbf{G}^T (\mathbf{G} \mathbf{V}_a \mathbf{G}^T + \mathbf{V}_y)^{-1} \mathbf{G} \mathbf{V}_a$$

Need a priori information p_a, V_a as well as V_y

Serial Estimation

a-priori information should be independent of current

✓ Value (e.g. cross section) can be obtained over all region of interest with suitable covariance matrix

Law of Error Propagation

Once we know covariance of cross section, we can obtain uncertainties (error) of integral quantity (e.g. reactivity) using **Sensitivity matrix** and **Law of Error Propagation**.

$$R_i = \sum_j \frac{\partial R_i}{\partial \sigma_j}\sigma_j$$

sensitivity matrix

$$V_{ii}(R) = \sum_{j,k} \frac{\partial R_i}{\partial \sigma_j} V_{jk}(\sigma) \frac{\partial R_i}{\partial \sigma_k}$$

$$\mathbf{V}_p = \mathbf{S}\mathbf{V}_{\boldsymbol{\sigma}}\mathbf{S}^{\mathrm{T}}$$

Covariance obtained from ENDF or other source
- energy dependent for each nuclide/reaction type

Sensitivity can be obtained by
- Direct variation of cross section (TMC), or
- **Generalized Perturbation method**
(with c.s. + covariances at hand)

Normalized sensitivity matrix

$$S_{i,j} = \frac{\partial R_i}{\partial \sigma_j}\frac{\sigma_j}{R_i}$$

Sensitivity Matrix

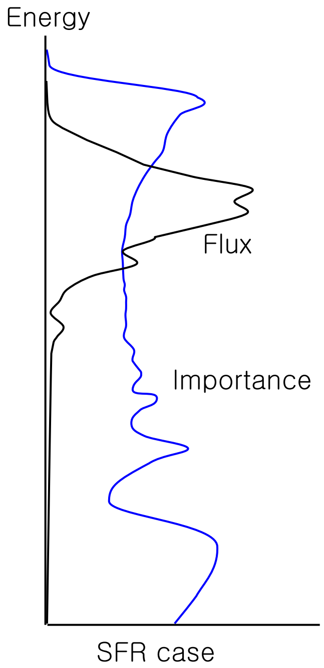
- Using Generalized Perturbation Theory

Equation of System (Neutron transport or diffusion equation)

$$A\phi = \lambda\nu\Sigma_f\phi$$

When **cross selection is slightly changed**, flux and eigen value will be changed too.

$$(A+\delta A)(\phi+\delta\phi) = (\lambda+\delta\lambda)\nu\Sigma_f(\phi+\delta\phi)$$



First order term is (ignoring second order perturbation)

$$\delta A\phi + A\delta\phi = \delta\lambda\nu\Sigma_f\phi + \lambda\nu\Sigma_f\delta\phi$$

We can elliminate flux variation by introducing adjoint flux

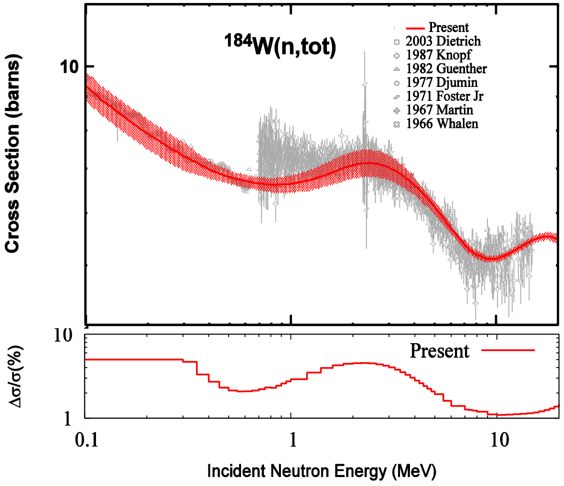
$$\langle\psi,\delta A\phi\rangle + \langle\psi,A\delta\phi\rangle = \delta\lambda\langle\psi,\nu\Sigma_f\phi\rangle + \lambda\langle\psi,\nu\Sigma_f\delta\phi\rangle$$

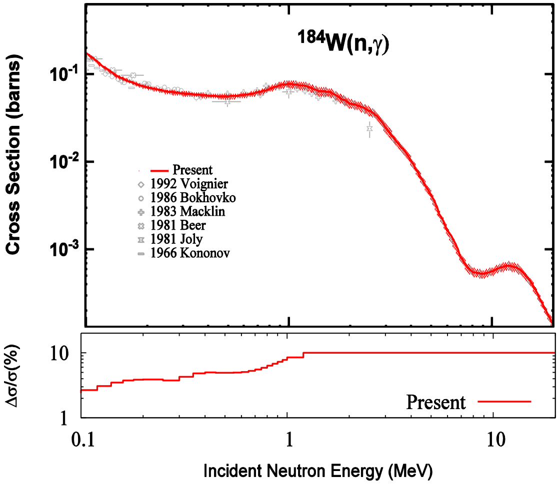
When Ψ is a solution of adjoint equation

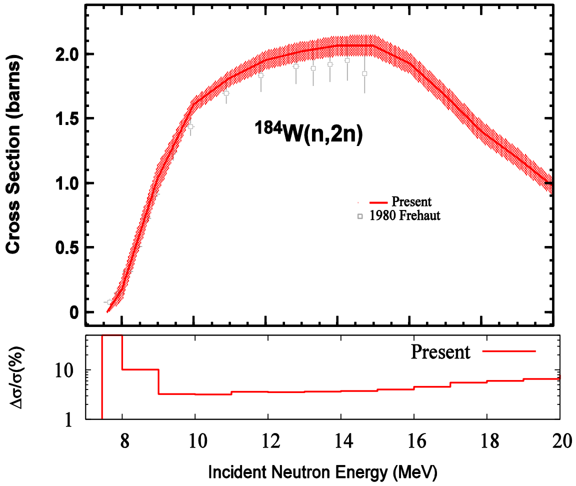
$$A^T\psi = \lambda\nu\Sigma_f^T\psi$$

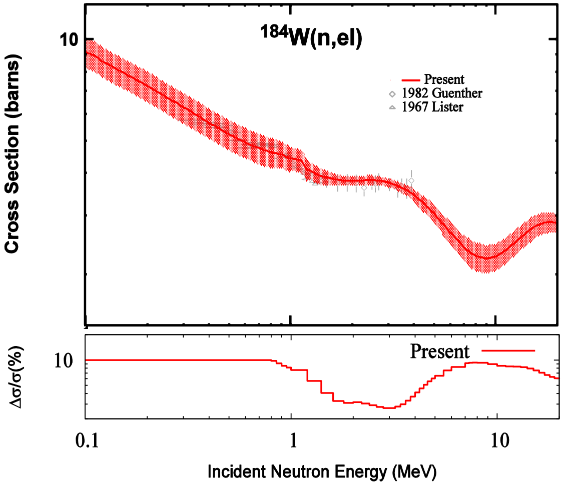
Sensitivity of eigenvalue to the cross section change is

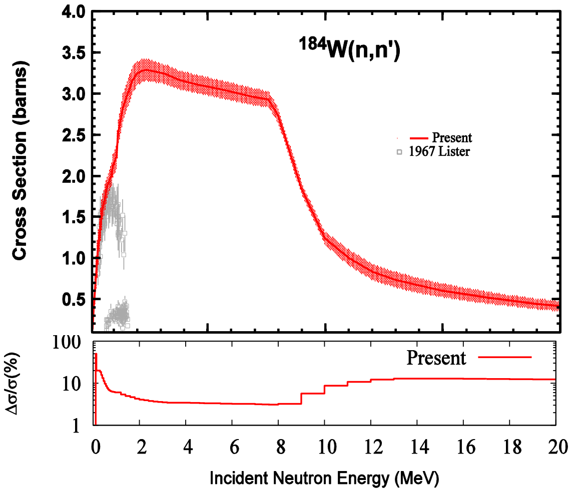
$$\delta\lambda = \langle\psi,\delta A\phi\rangle / \langle\psi,\nu\Sigma_f\phi\rangle$$

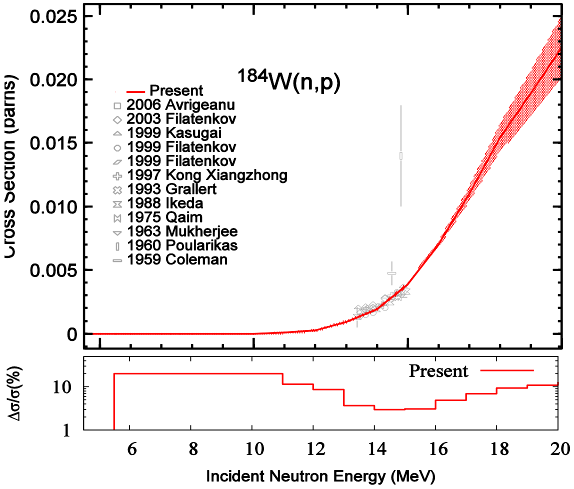

^{184}W(n,tot)
Present
2003 Dietrich
1987 Knopf
1982 Guenther
1977 Djumin
1971 Foster Jr
1967 Martin
1966 Whalen
Cross Section (barns)
10
Δσ/σ(%)
10
1
Present
0.1
1
10
Incident Neutron Energy (MeV)


^{184}W(n,γ)
Present
1992 Voignier
1986 Bokhovko
1983 Macklin
1981 Beer
1981 Joly
1966 Kononov
Cross Section (barns)
10^{-1}
10^{-2}
10^{-3}
Δσ/σ(%)
10
1
Present
0.1
1
10
Incident Neutron Energy (MeV)

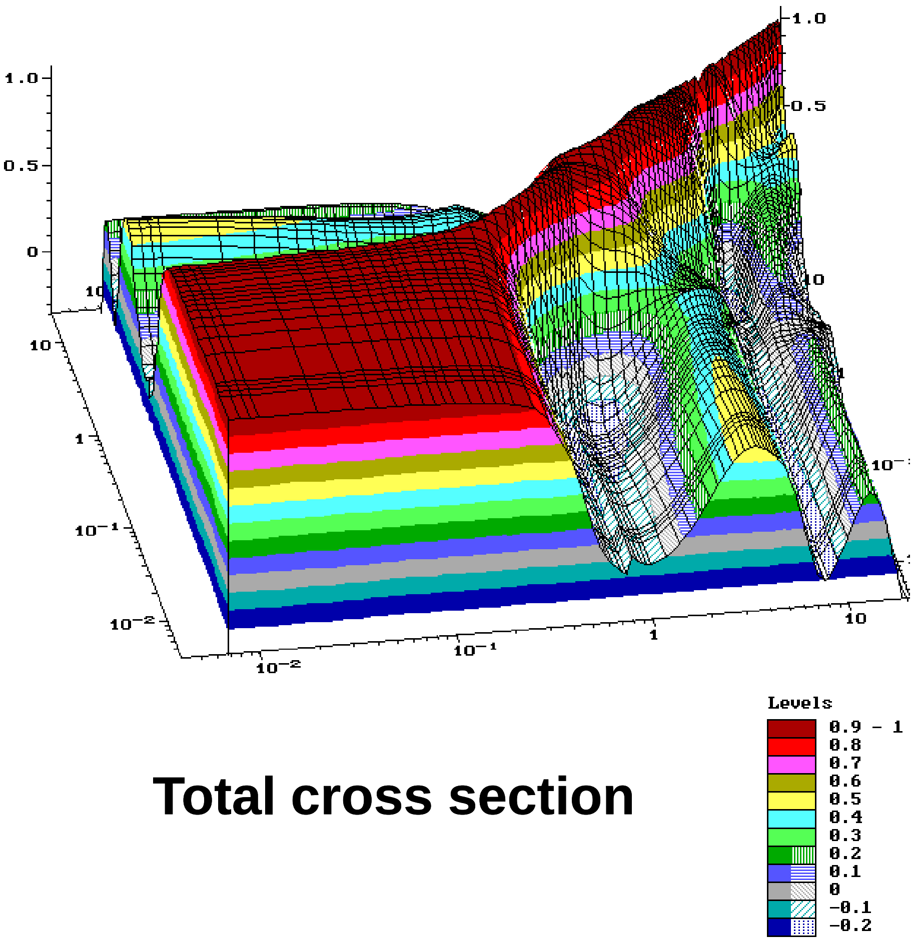

^{184}W(n,2n)
Present
1980 Frehaut
Cross Section (barns)
2.0
1.5
1.0
0.5
0
Δσ/σ(%)
10
1
Present
8
10
12
14
16
18
20
Incident Neutron Energy (MeV)


^{184}W(n,el)
Present
1982 Guenther
1967 Lister
Cross Section (barns)
10
Δσ/σ(%)
10
Present
0.1
1
10
Incident Neutron Energy (MeV)

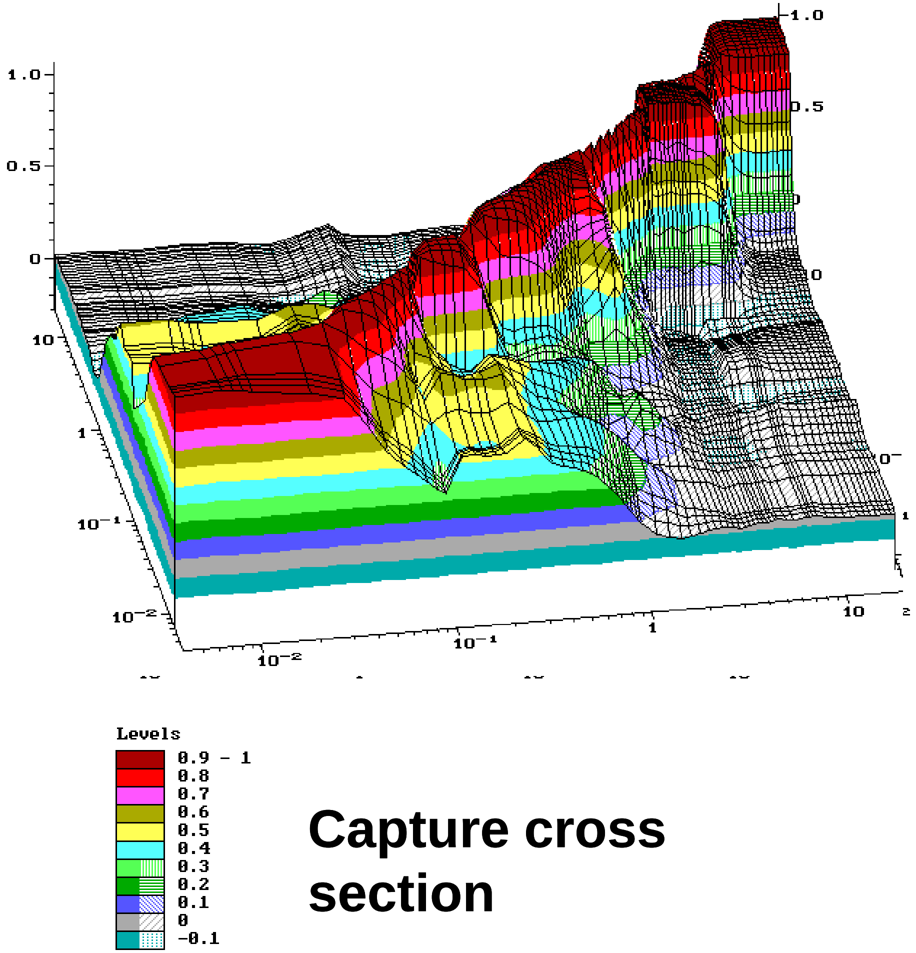

^{184}W(n,n')
Present
1967 Lister
Cross Section (barns)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
Δσ/σ(%)
100
10
1
Present
0
2
4
6
8
10
12
14
16
18
20
Incident Neutron Energy (MeV)


^{184}W(n,p)
Present
2006 Avrigeanu
2003 Filatenkov
1999 Kasugai
1999 Filatenkov
1999 Filatenkov
1997 Kong Xiangzhong
1993 Grallert
1988 Ikeda
1975 Qaim
1963 Mukherjee
1960 Poularikas
1959 Coleman
Cross Section (barns)
0.025
0.020
0.015
0.010
0.005
0
Δσ/σ(%)
10
1
Present
6
8
10
12
14
16
18
20
Incident Neutron Energy (MeV)

Correlations of ^{184}W



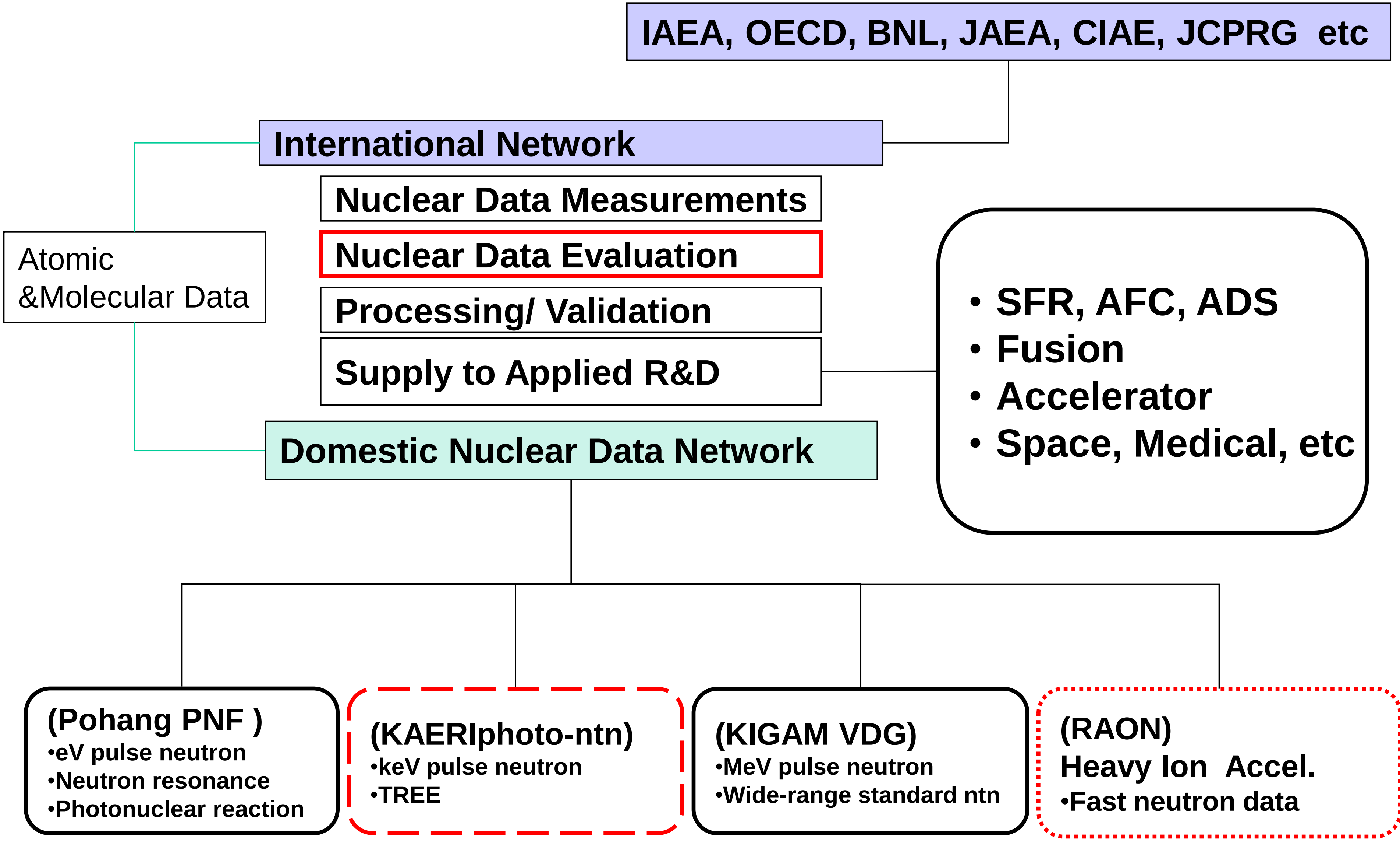
Total cross section



Capture cross section

- Nuclear Data
- Nuclear Reaction
- Reaction Model
- Evaluation Examples
- Measurements
- Uncertainties
- **Nuclear Data Center @KAERI**

Nuclear Data Network in Korea



IAEA, OECD, BNL, JAEA, CIAE, JCPRG etc

International Network

Atomic
&Molecular Data

Nuclear Data Measurements

Nuclear Data Evaluation

Processing/ Validation

Supply to Applied R&D

- **SFR, AFC, ADS**
- **Fusion**
- **Accelerator**
- **Space, Medical, etc**

Domestic Nuclear Data Network

(Pohang PNF)
•eV pulse neutron
•Neutron resonance
•Photonuclear reaction

(KAERIphoto-ntn)
•keV pulse neutron
•TREE

(KIGAM VDG)
•MeV pulse neutron
•Wide-range standard ntn

(RAON)
Heavy Ion Accel.
•Fast neutron data

International Collaboration

Cooperation with IAEA

- Fusion Evaluated Nuclear Data Library
- EXFOR Database participation

Cooperation with OECD

- Covariance data among the WEPC members
- Joining the formal JEFF member in improvement of the JEFF Library

Cooperation with ORNL

- Evaluation of Np-237, Pu-240, Cm isotopes

Cooperation with BNL

- Development of Nuclear Reaction methodology in the resonance region
- Evaluation of structure material such as zirconium

Facilities for Nuclear Data Measurements in Korea

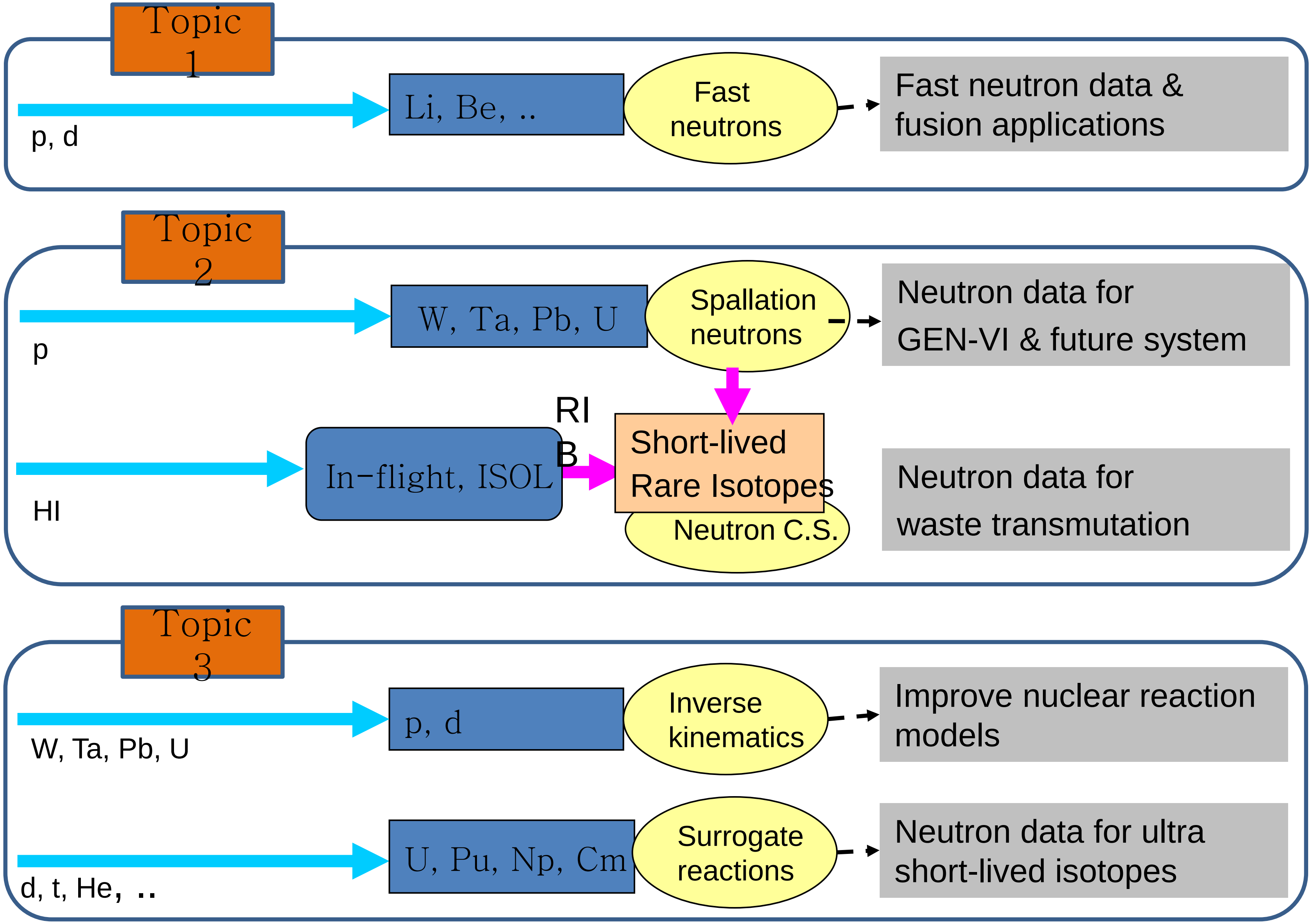
- **Existing facilities**

Facility	Characteristics	Measurements
Electron linear accelerator (PAL)	• 100 MeV, 2.5 GeV linacs • Neutron production by 100 MeV linac • γ production by 100 MeV and 2.5 GeV linacs	• Total cross section • (n,γ) by neutron activation method • Isomeric yield ratio • Photo fission
Tandem (KIGAM)	• 1.7 MV • Neutron production (p+Li, p+T, d+D)	• Total cross section
Cyclotron (KIRAMS)	• p : 20- 50 MeV / 40 μA • d : 10- 25 MeV / 20 μA • α : 20- 50 MeV / 1 μA	• Activation cross section

- **Planned facilities**

Facility	Characteristics	Status
Electron linear accelerator (KAERI)	• 17 MeV SC linac • Neutron production	• Accelerator is available • Design of TOF facility
Proton linear accelerator (KAERI)	• 100 MeV linac	• Accelerator will be available in 2013 • Design of ns pulse beam
RAON (RISP @IBS)	• SC Linac (H – U, 200 MeV/u(U)) • Cyclotron (70 MeV proton)	• Accelerator will be available in 2017 • Planning for data measurements

기초과학연구원의 중이온가속기 관련 핵데이터 연구



Topic 1

p, d

Li, Be, ..

Fast neutrons

Fast neutron data & fusion applications

Topic 2

p

W, Ta, Pb, U

Spallation neutrons

Neutron data for GEN-VI & future system

HI

In-flight, ISOL

RIB

Short-lived Rare Isotopes

Neutron C.S.

Neutron data for waste transmutation

Topic 3

W, Ta, Pb, U

p, d

Inverse kinematics

Improve nuclear reaction models

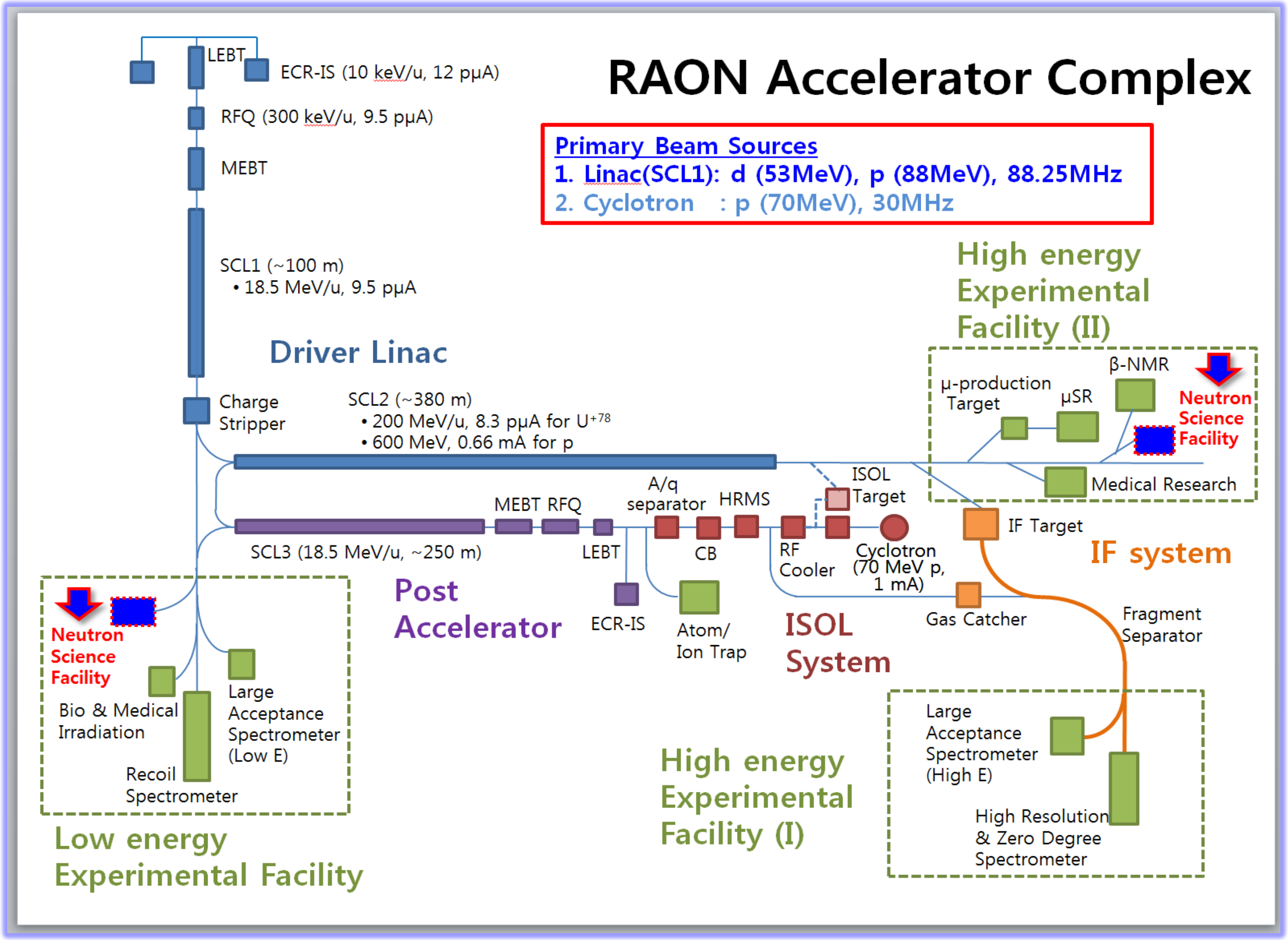
d, t, He, ..

U, Pu, Np, Cm

Surrogate reactions

Neutron data for ultra short-lived isotopes

NSF@RAON


RAON Accelerator Complex
Primary Beam Sources
1. Linac(SCL1): d (53MeV), p (88MeV), 88.25MHz
2. Cyclotron : p (70MeV), 30MHz
LEBT
ECR-IS (10 keV/u, 12 pμA)
RFQ (300 keV/u, 9.5 pμA)
MEBT
SCL1 (~100 m)
• 18.5 MeV/u, 9.5 pμA
Driver Linac
Charge Stripper
SCL2 (~380 m)
• 200 MeV/u, 8.3 pμA for U+78
• 600 MeV, 0.66 mA for p
High energy Experimental Facility (II)
μ-production Target
μSR
β-NMR
Neutron Science Facility
Medical Research
ISOL Target
MEBT RFQ
A/q separator
HRMS
SCL3 (18.5 MeV/u, ~250 m)
LEBT
CB
RF Cooler
Cyclotron (70 MeV p, 1 mA)
IF Target
IF system
Post Accelerator
ECR-IS
Atom/ Ion Trap
ISOL System
Gas Catcher
Fragment Separator
Neutron Science Facility
Bio & Medical Irradiation
Large Acceptance Spectrometer (Low E)
Recoil Spectrometer
Low energy Experimental Facility
High energy Experimental Facility (I)
Large Acceptance Spectrometer (High E)
High Resolution & Zero Degree Spectrometer

Contributions to EXFOR (IAEA)

1969~1989	1990~1999	2000~2005	2006~2011
Yonsei Univ.(1) Seoul Univ.(3) KAERI (1)	KRISS (1) Seoul Univ. (4) RIKEN (1) KIGAM (1) Kyoto Univ. (1)	Kyungpook Univ. (8) Pohang Univ. (1) Dong-A Univ. (2) Seoul Univ. (1) Pusan Univ. (1) Chung-Ang Univ. (2) KRISS (1) TRIUMF (1)	Kyungpook Univ. (30) Dong-A Univ. (5) Seoul Univ. (1) Chung-Ang Univ. (1) Sejong Univ. (1) KIGAM (2) KIRAMS (1)
Cockcroft-Walton Accel. SNU/VDG	SNU/VDG RIKEN KIGAM/VDGT Kyoto/LINAC	KIRAMS PNF KAERI/PGAA Kyoto/LINAC Tokyo/VDGT KEK RIKEN USA/VDGT	KIRAMS PNF KIGAM/VDGT KAERI/HANARO Kyoto/LINAC Tokyo/VDGT RIKEN

- KNDC has compiled and submitted the experimental data to EXFOR since 2009
- KNDC recently teamed up the measurement group to promote experimental activities.

Atomic & Molecular Data

❑ 목적

- 정밀 원자 분자 구조 및 충돌 단면적, 분광 자료 생산

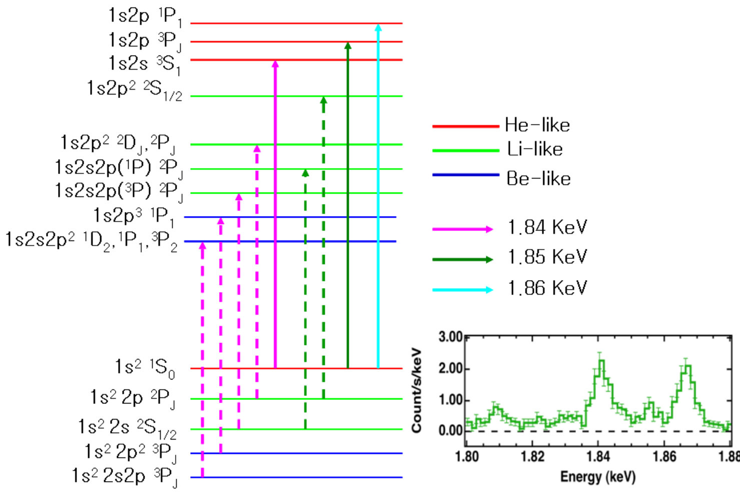
❑ 연구 내용

- MCDF(multi-configuration Dirac-Fock)로 원자의 에너지 구조, 전이 확률 및 스펙트럼 계산
- 원자 구조 및 반응 단면적 계산 코드인 FAC(Flexible Atomic Code) 원자의 충돌 단면적, 전이 확률 및 스펙트럼 계산

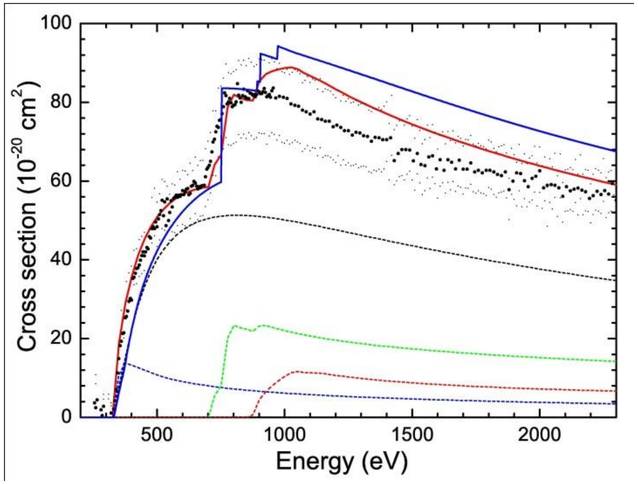
❑ 활용분야

- 핵융합 및 천체 플라즈마 스펙트럼 모델링
- 동위원소 분석용 초미세 에너지 구조 자료

원자 구조 및 분광 전이선



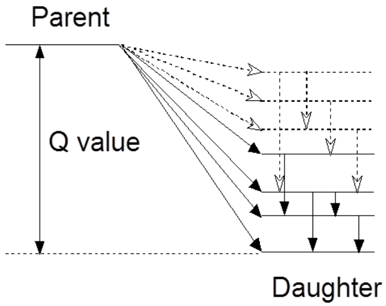
Fe^{11+} 이온의전자충돌 이온화 단면적



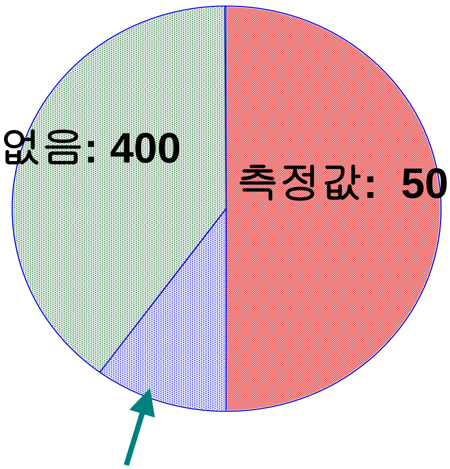
Other Business:

✓Participate in Nuclear Structure Data Network (since 2013)

Pandemonium Problem



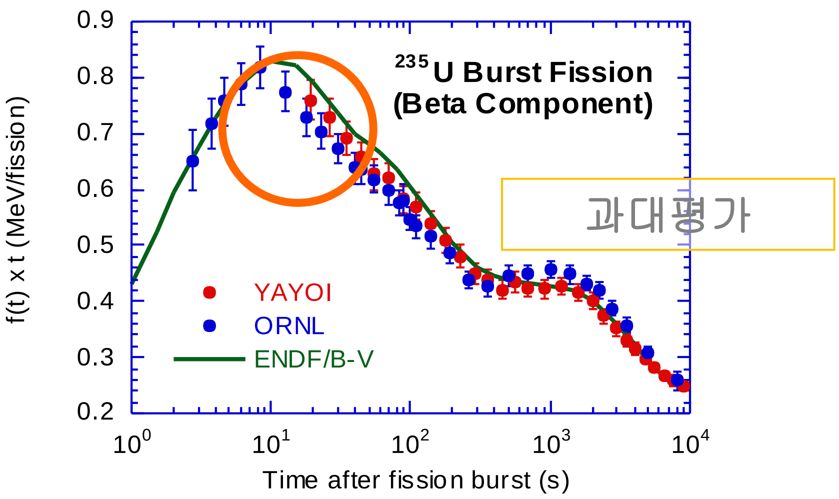
1000개의 핵분열생성물



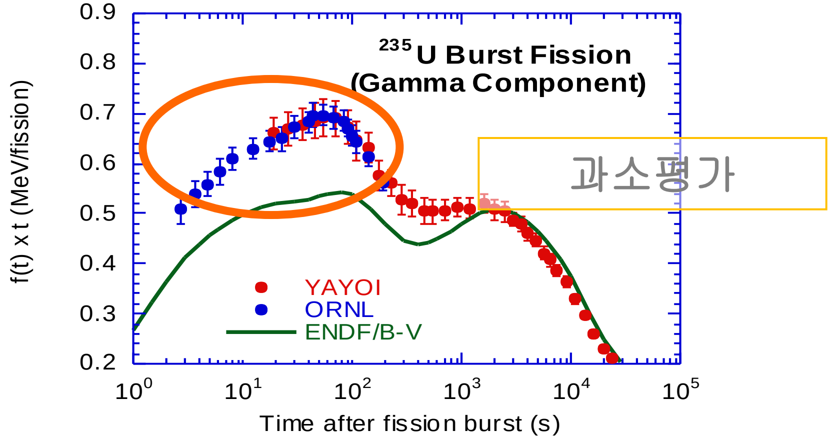
측정값 없음: 400

측정값: 500

측정값 불충분:100
Pandemonium Problem



과대평가

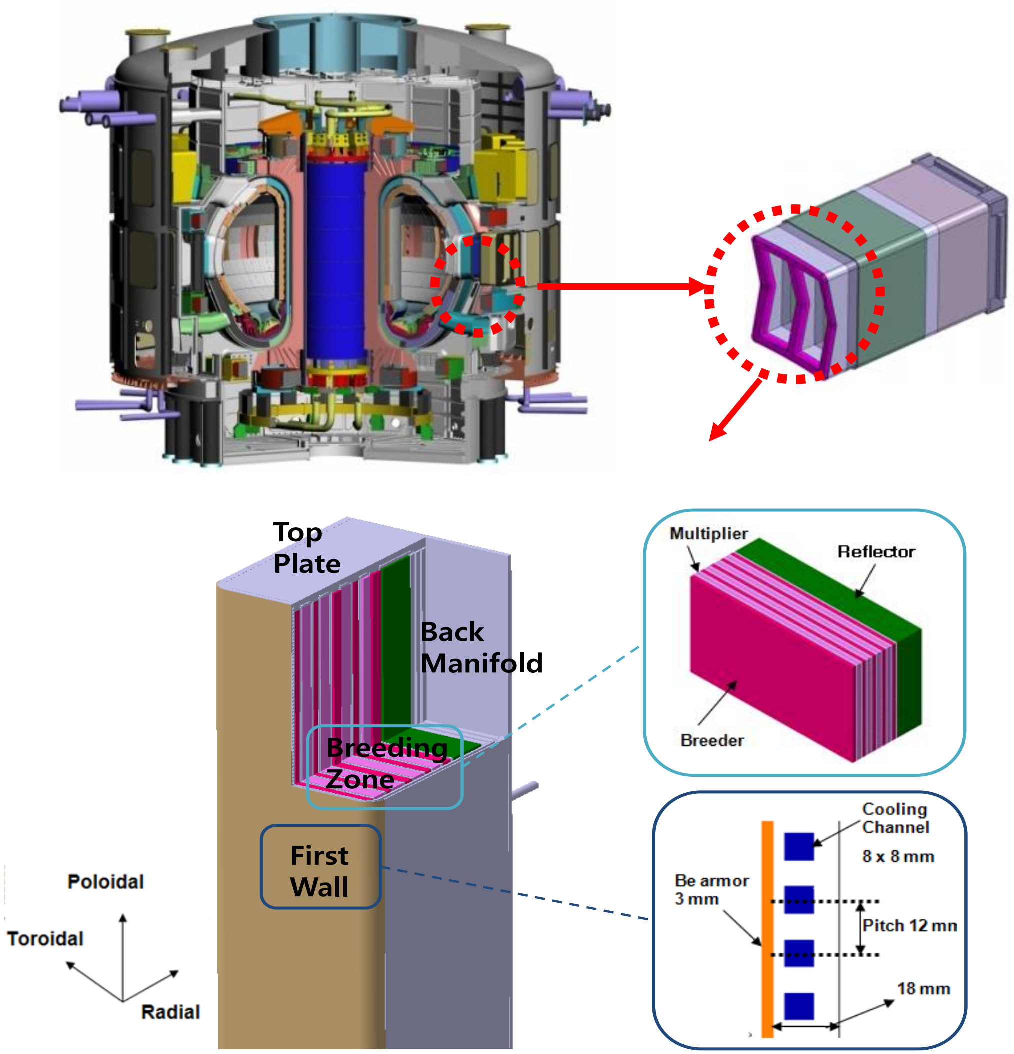


과소평가

Other Business:

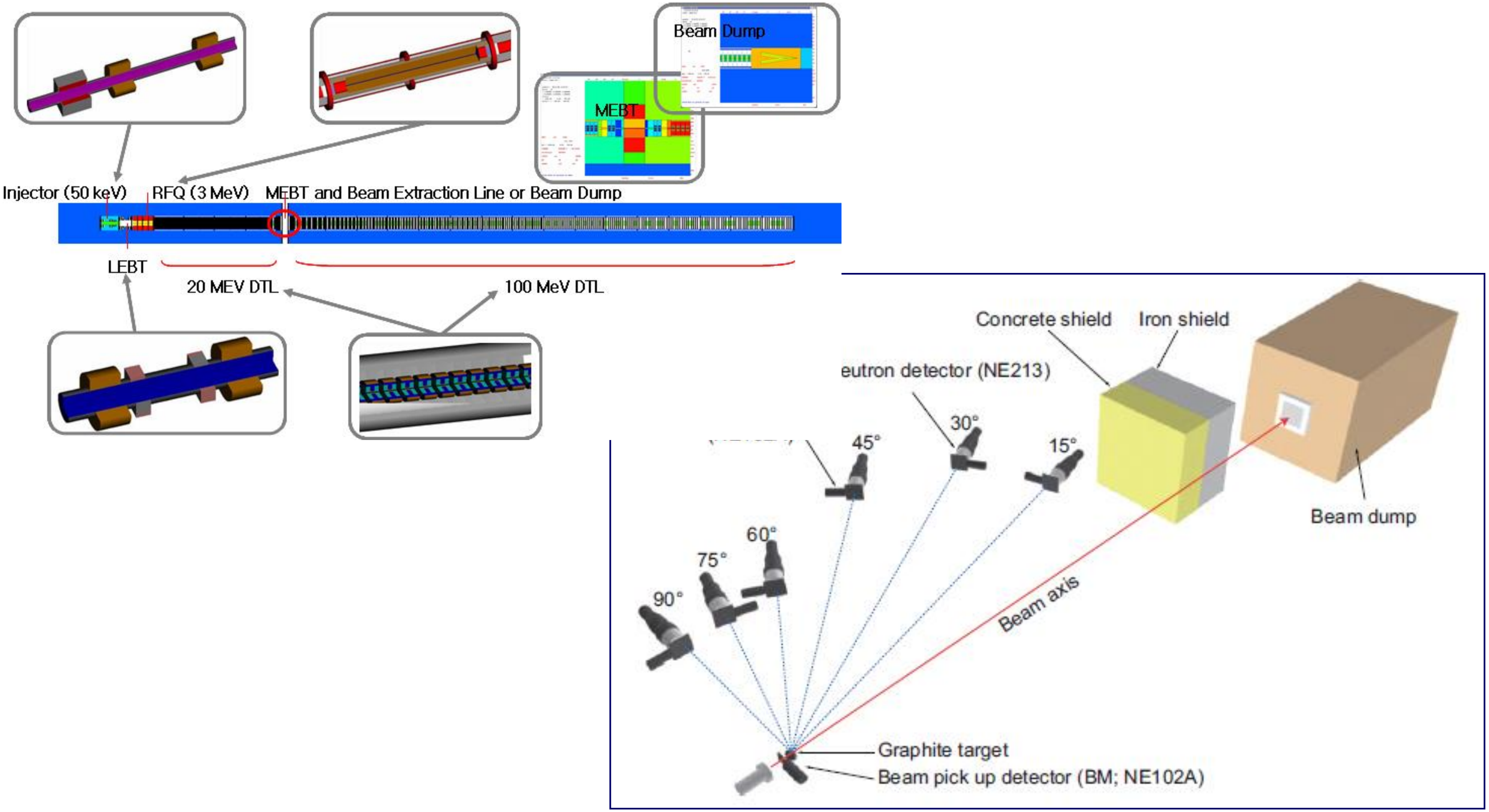
ITER TBM (Tritium Breeding Module) Neutronics Analysis

Parameter	Values
FW heat flux	Average 0.3 MW/m^2 Peak 0.5 MW/m^2
Neutron wall load	0.78 MW/m^2
Thermal Power	1.01 MW
Tritium Breeding Ratio	1.1
Structural material	RAFM (< 550 °C)
Breeder	Li_4SiO_4 pebble bed Li_2TiO_3 pebble bed (optional) < 920 °C
Multiplier	Be pebble bed < 650 °C
Reflector	Graphite pebble bed
Size	1400x510x600 (mm)
Coolant	8 MPa He 1.5 kg/s (incl. Bypass) FW (300 °C / 390 °C) Breeding Zone(390 °C/500 °C)
Purge	He with 0.1 % H_2



Other Business:

Radiological Safety Assessment of Accelarators

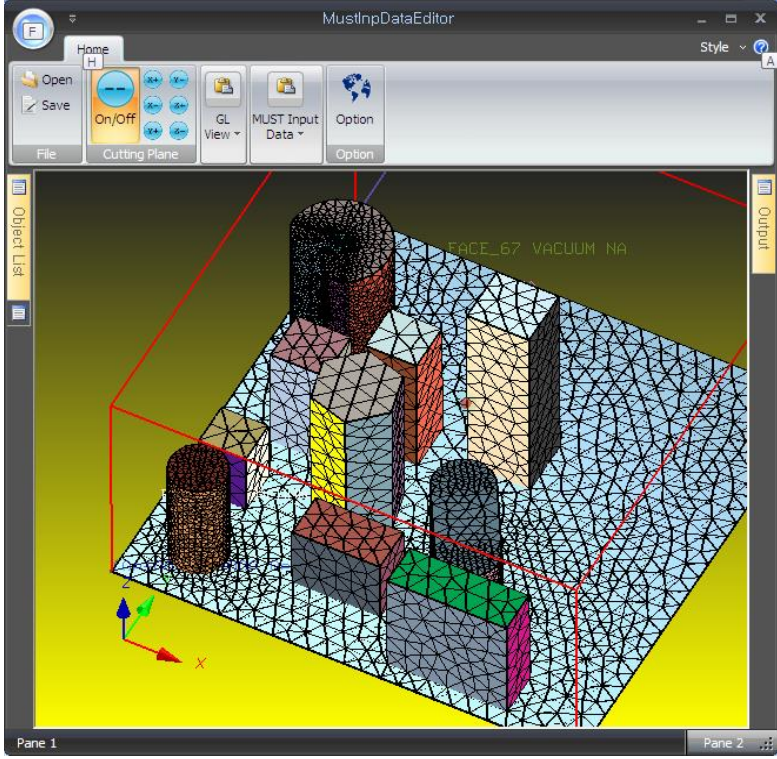


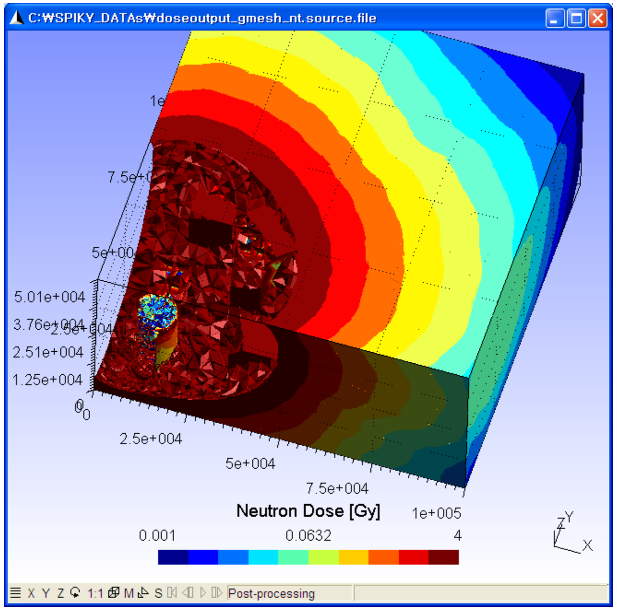
Other Business:

CAD-based MC/Deterministic

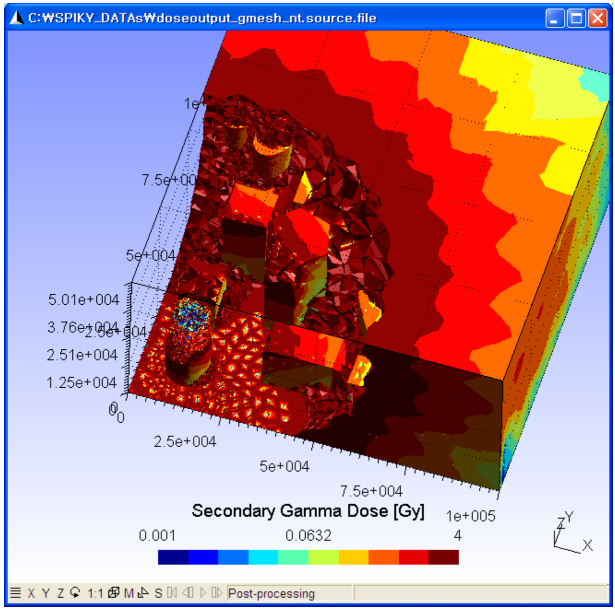
n/gamma transport code

development

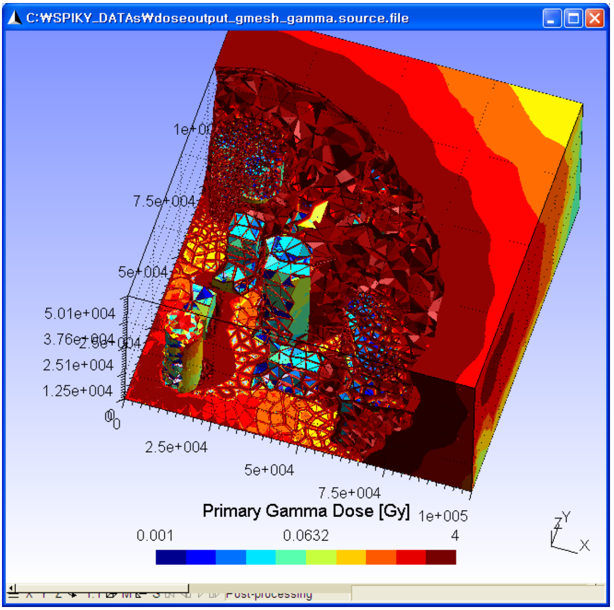




Neutron



Secondary gamma



Primary gamma

핵데이터 인프라 구축 로드맵

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

측정

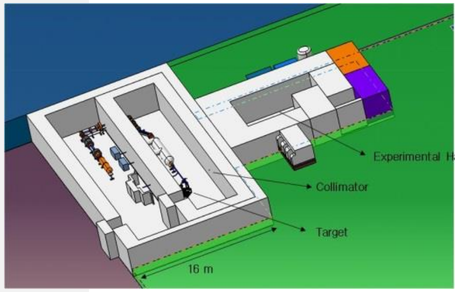
KAERI 전자가속기 기반 keV급 펄스형 고속중성자 TOF 구축

상세설계 → 측정시설 구축

핵반응 측정기술 확보

국내/외 시설 사용 핵반응 측정인프라 확보

2016년까지 인프라구축



중이온가속기 중성자과학설비 구축

상세설계 → 측정시설 구축

양성자가속기 중성자원 시설 구축

펄스빔장치 개발 → 표적시스템 구축

광대역 펄스중성자원 네트워 구축/운영

- **-포항 전자가속기 기반 ~ eV (기존시설)**
- **-KAERI 전자가속기 기반 ~수십 keV**
- **-KAERI 양성자가속기 기반 ~ 수 MeV**
- **-IBS/RISP (중이온가속기) ~100 MeV**

14MeV 중성자 조사시설 활용

평가

검증

응용

최신 측정치 기반
선도적인 평가, 검증 및 응용 기술 개발

✓ 측정-평가-검증-응용 일관기술 확보