Experimental Fission Study using Multi-nucleon Transfer Reactions

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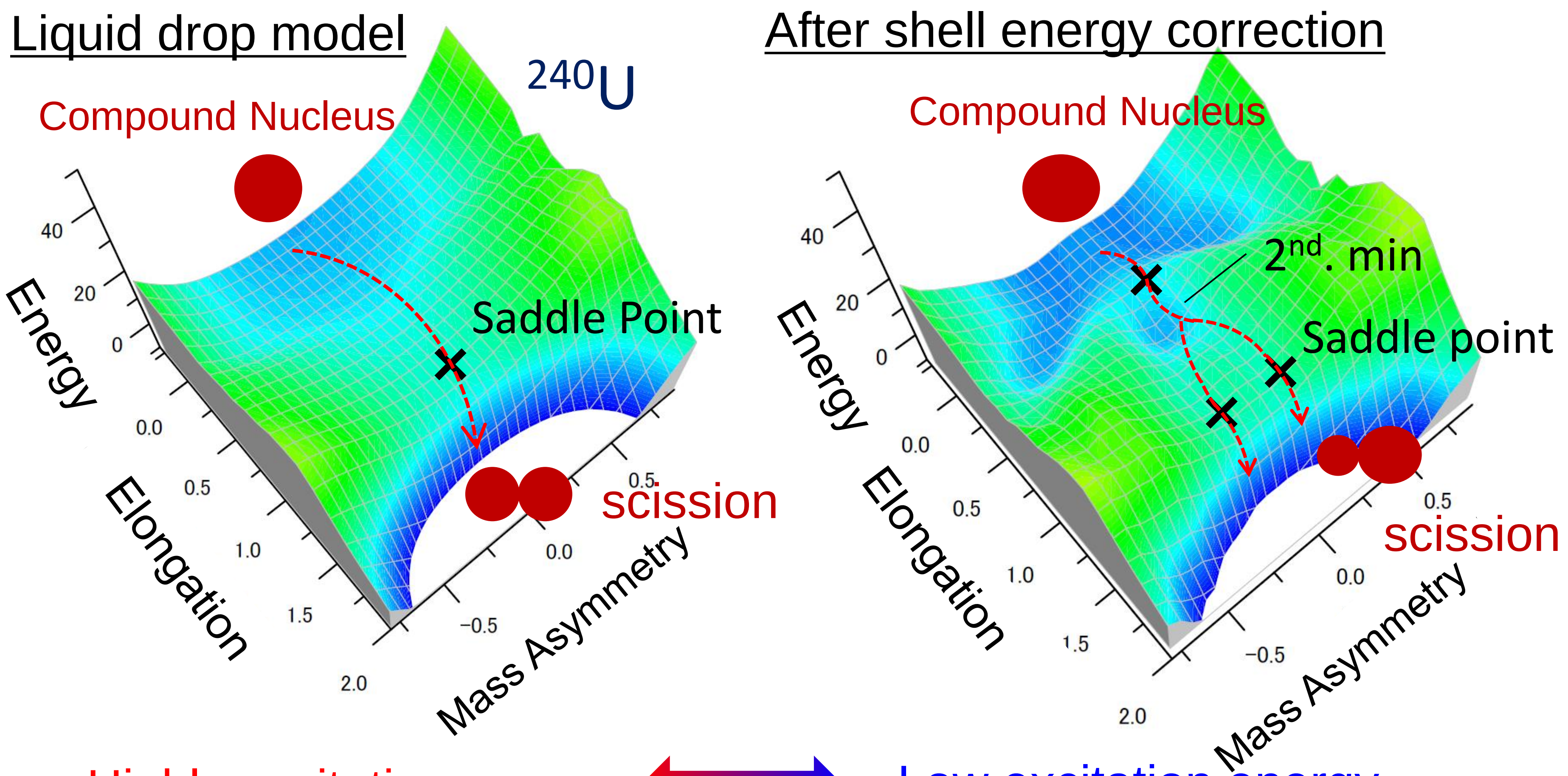
J-PARC
Tandem facility

Potential Energy and Fission



Highly excitation energy ⟷ Low excitation energy

Measured Fragment Mass/Charge Yield

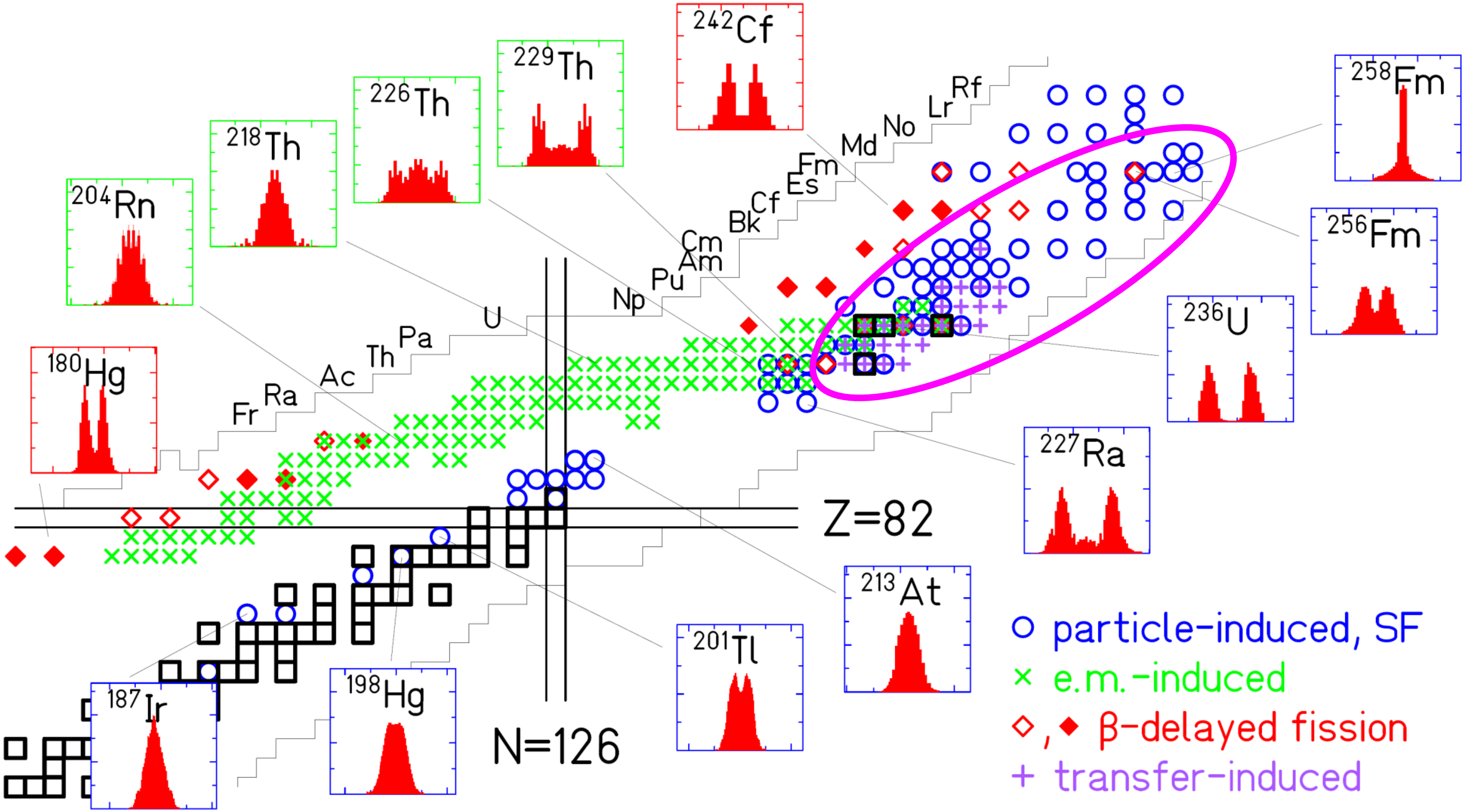
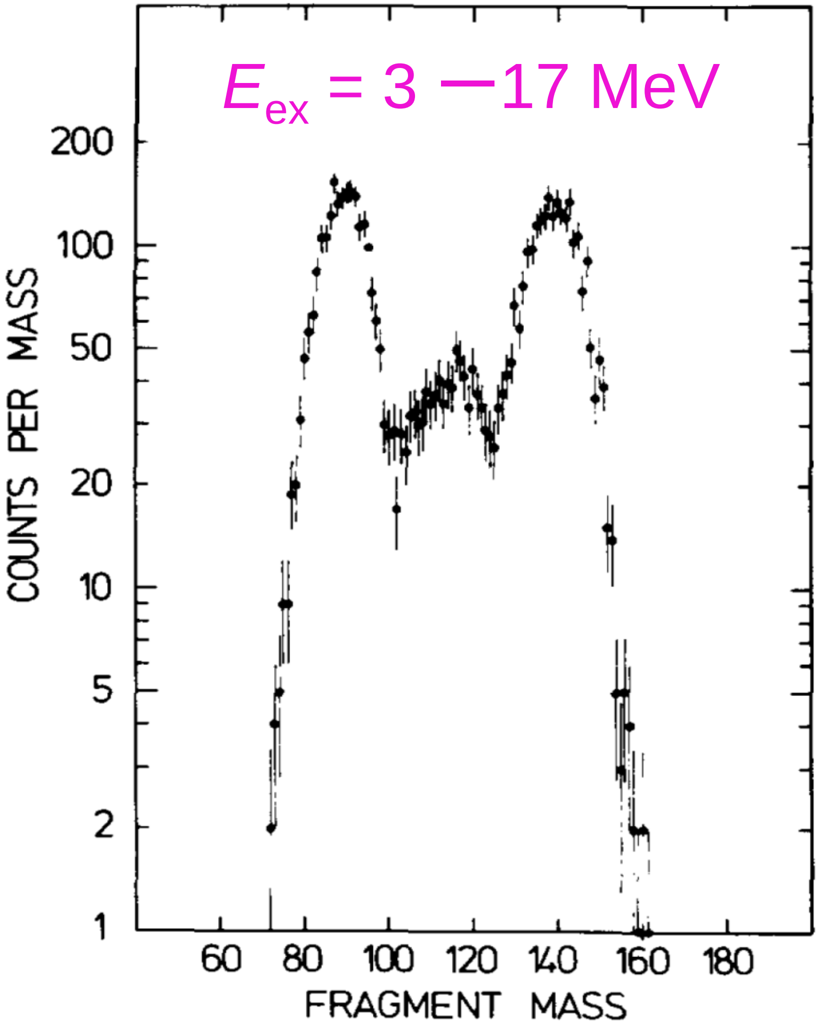


Figure from K.-H. Schmidt

JAEA Data, see for example: R. Léguillon *et al*., Phys. Lett. B **761** (2016) 125.

One-nucleon Transfer Induced Fission

$^{226}Ra(^{3}He,d)^{227}Ac^{*}$

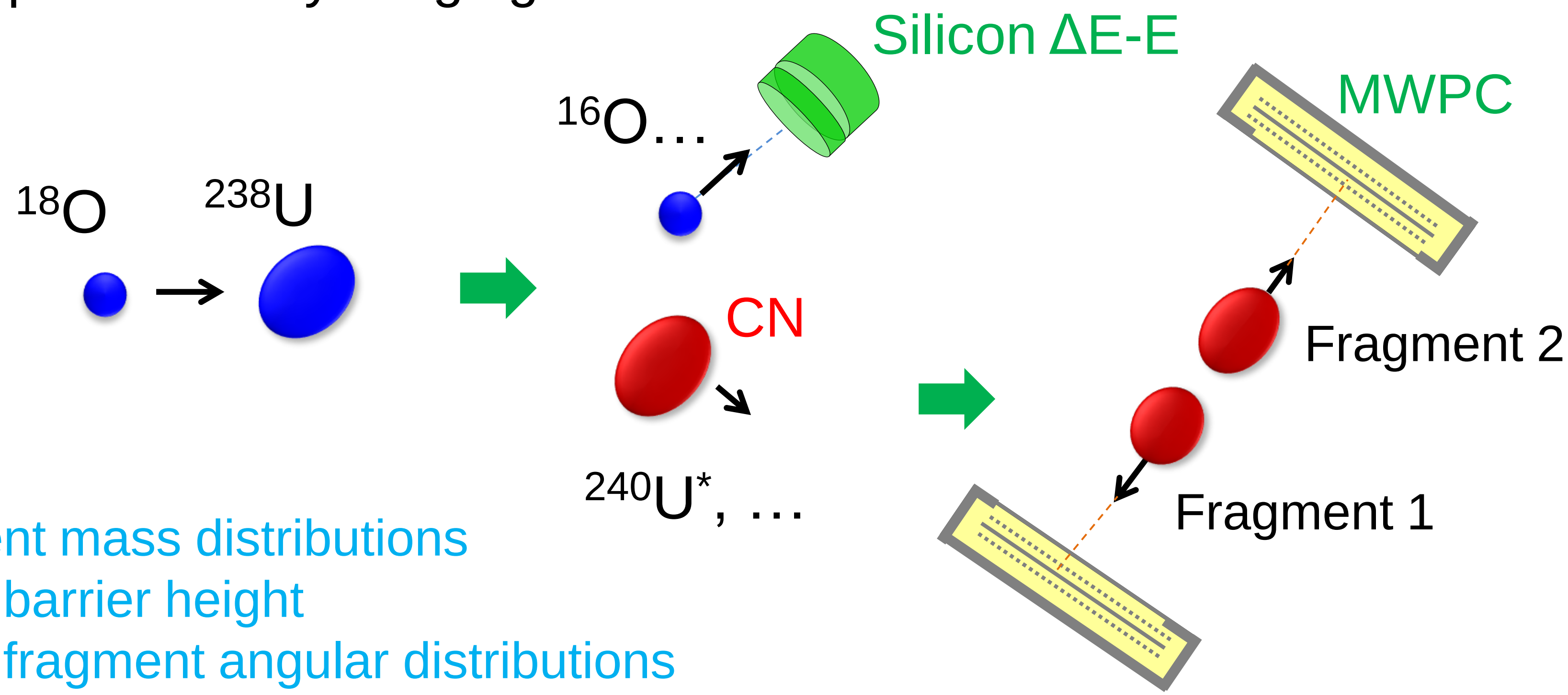


E. Konecny *et al*., Phys. Lett. **45B**, (1973) 329.

Multi-nucleon Transfer Reaction and Fission

Multi-nucleon transfer reaction

can produce many compound nuclei including neutron rich isotopes.
can populate widely-ranging excited states.

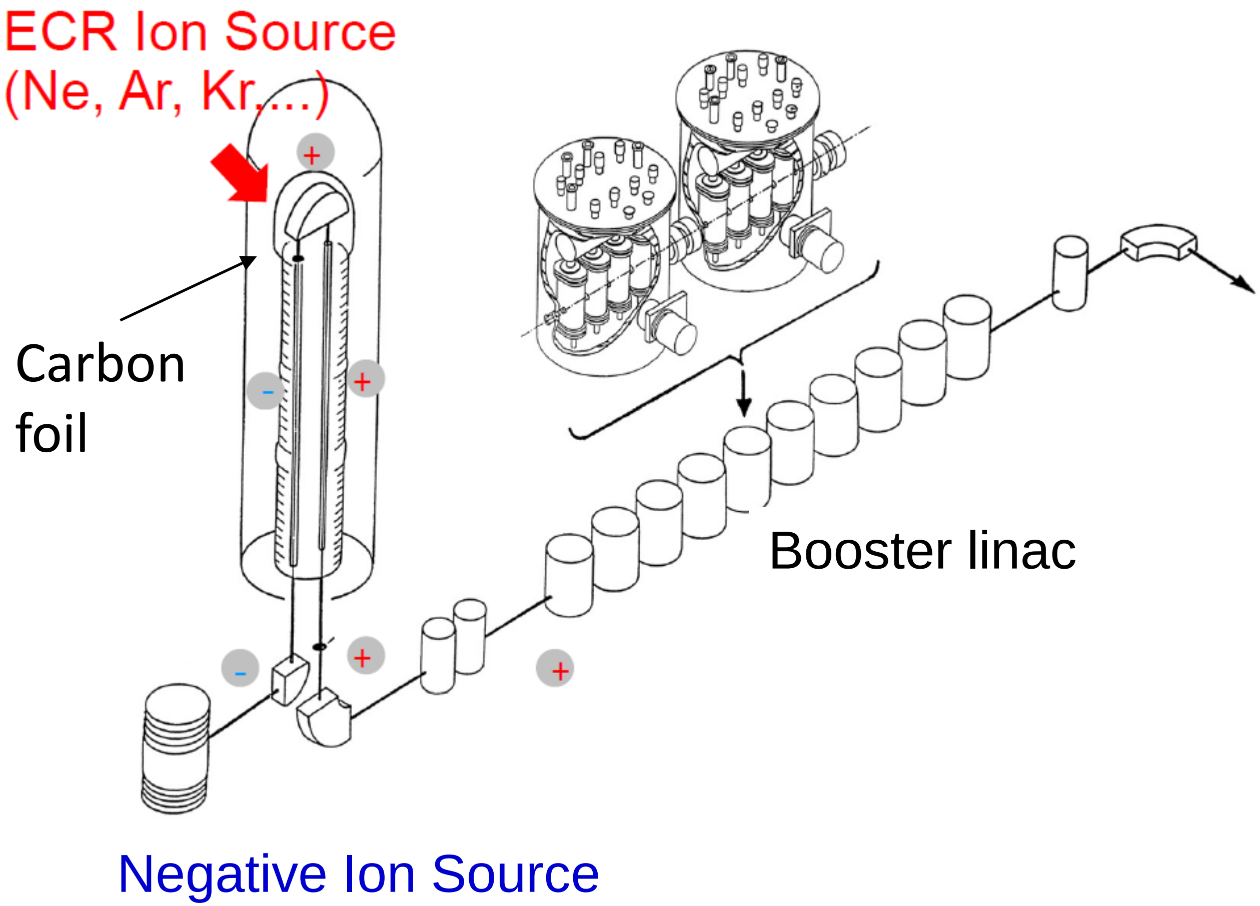


Fragment mass distributions
Fission barrier height
Fission fragment angular distributions
…

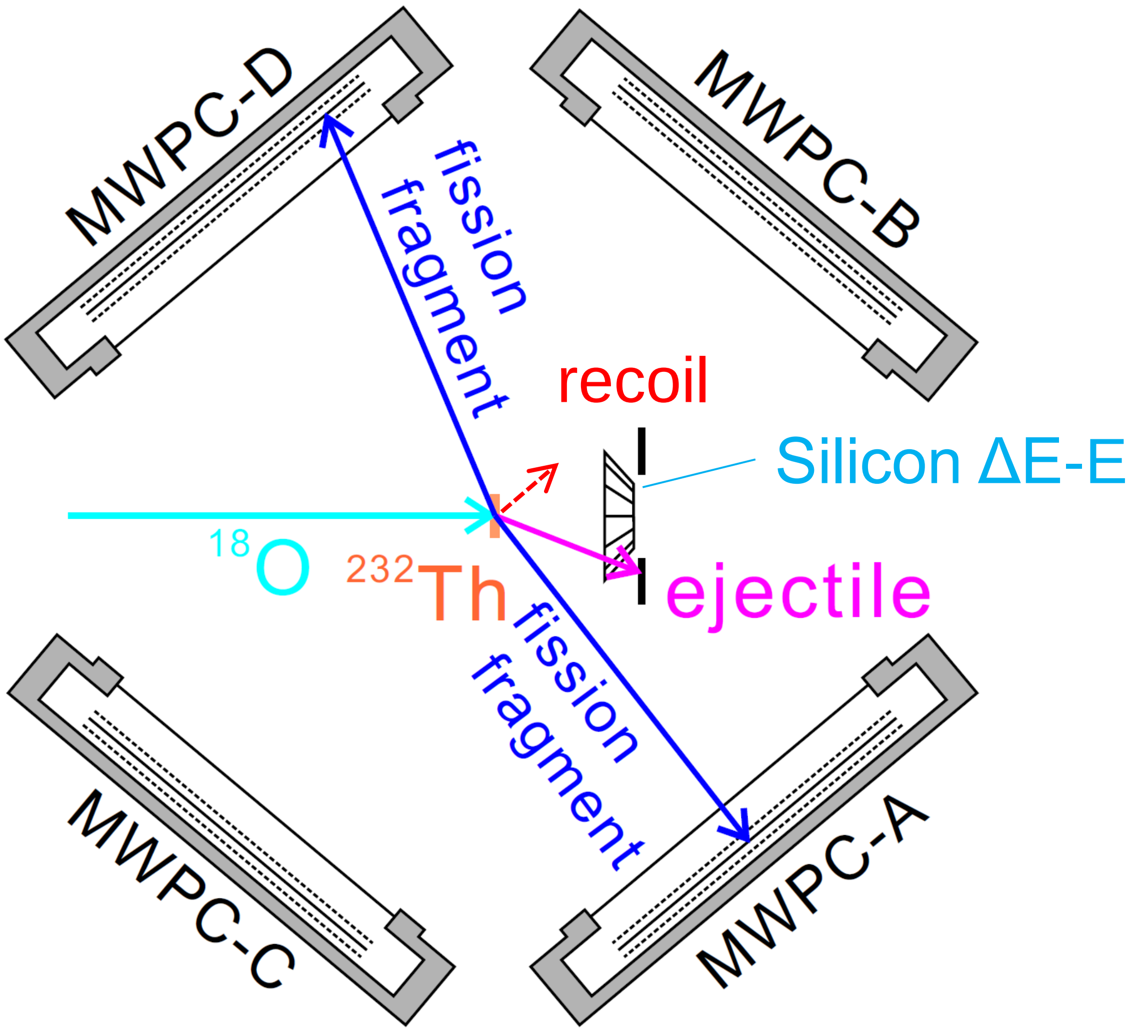
Measured and Planned experiments using ^{18}O beam and targets of ^{232}Th, ^{238}U, ^{248}Cm, ^{237}Np, ^{243}Am, ^{231}Pa, ^{249}Cf, (^{226}Ra, ^{254}Es)

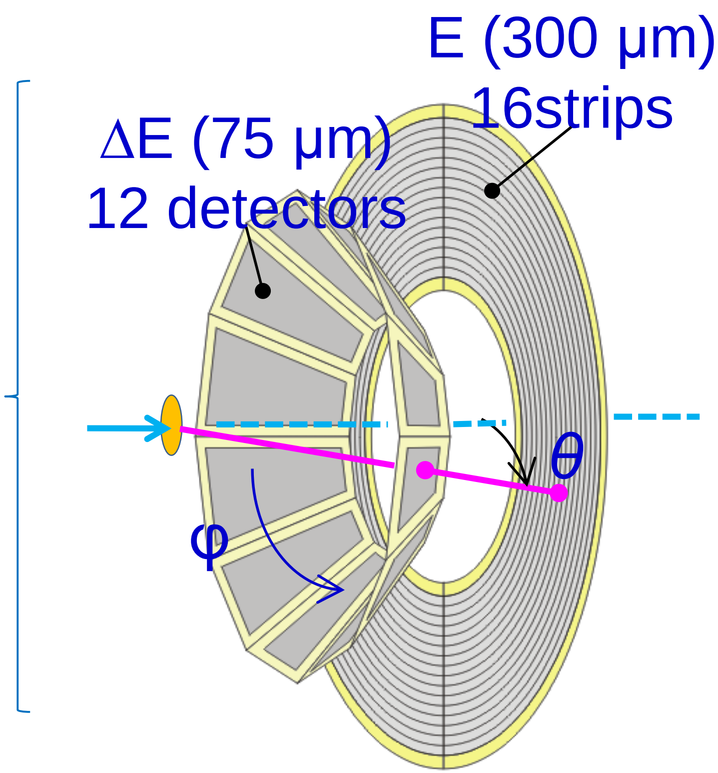
JAEA Tandem facility

20 MV Tandem accelerator (20UR)
Super-conducting Booster Liniac (~20MeV/u)
ECR Ion Source on the terminal



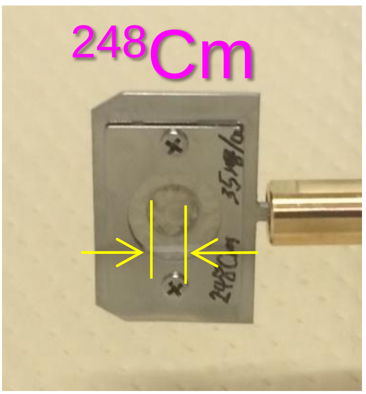
Experimental Setup





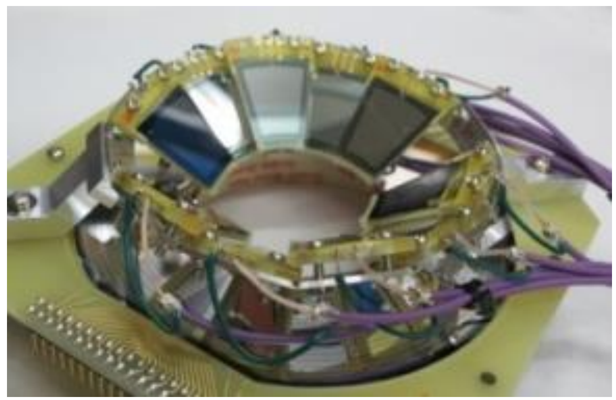
Targets and Detectors

Target



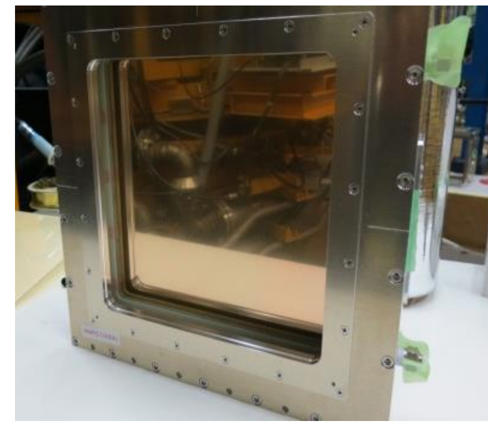
~ 30 μg/cm^2
ø2.0 mm (1.0 μg)
ø0.8 mm (0.16 μg)

Silicon ΔE-E detector



ΔE = 75 μm
Thickness fluctuation < 1 μm.

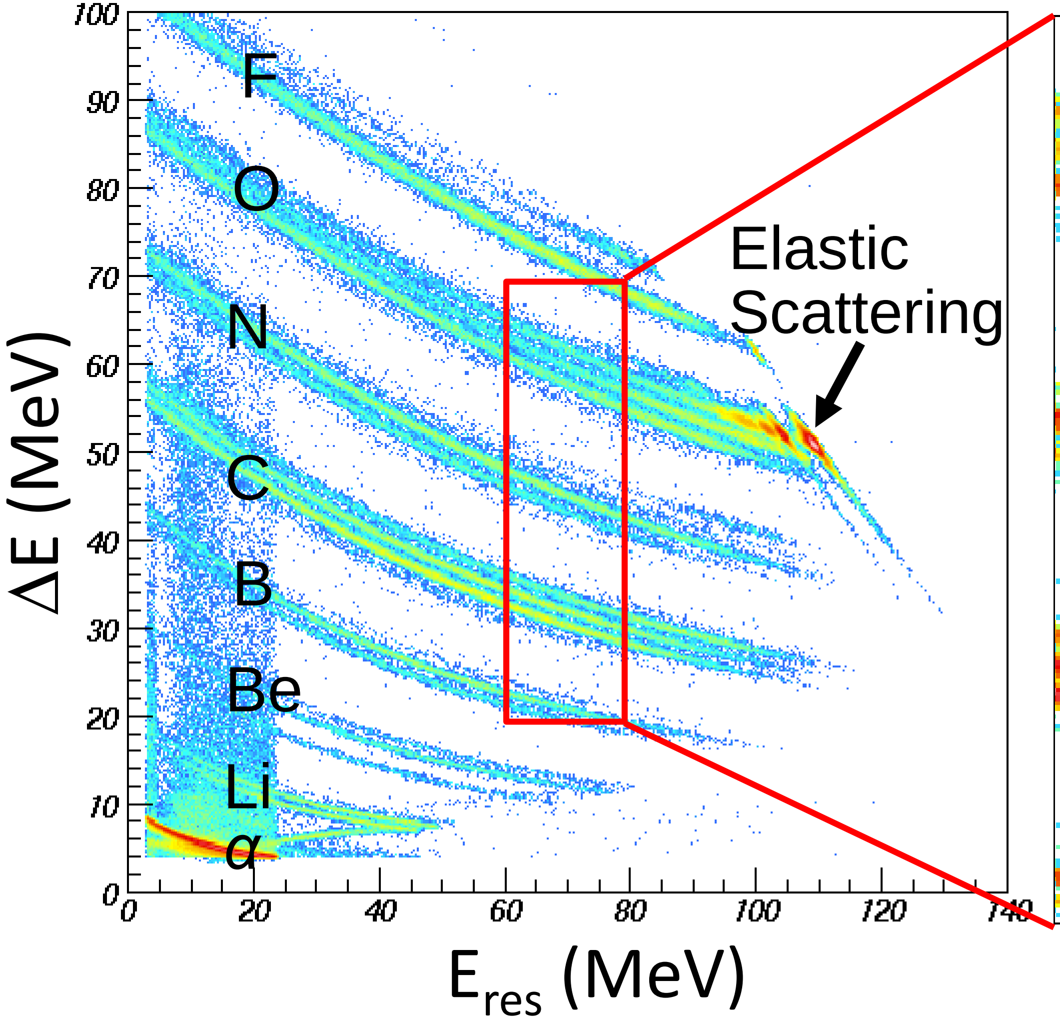
Multi-Wire Proportional Counter

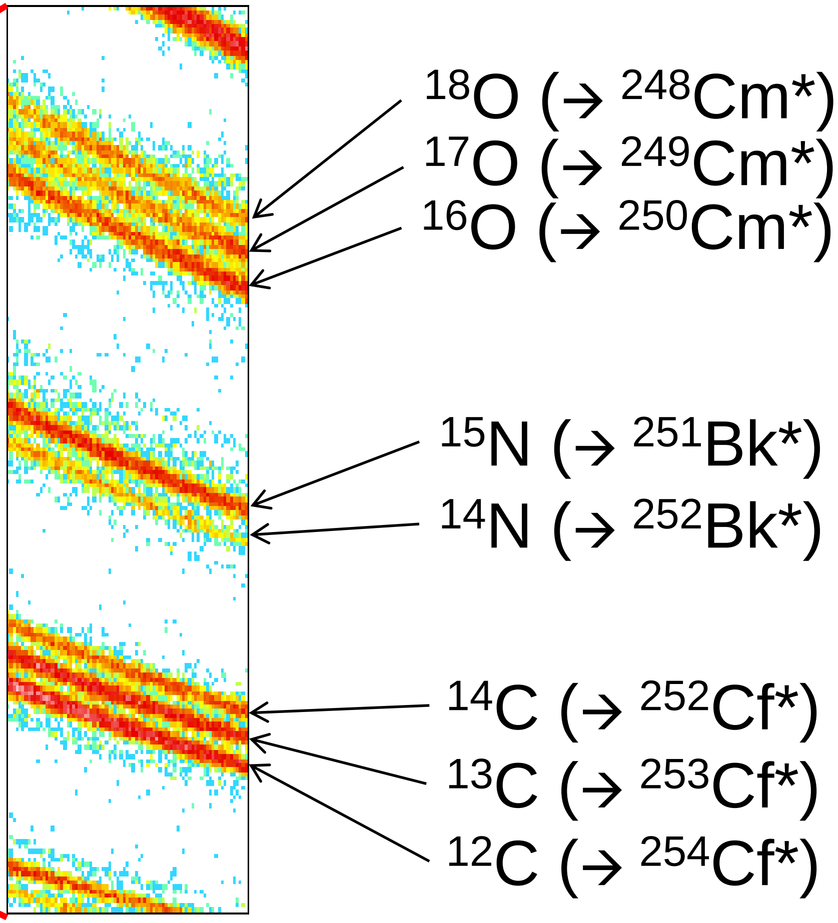


Position Sensitive
200 x 200 mm^2

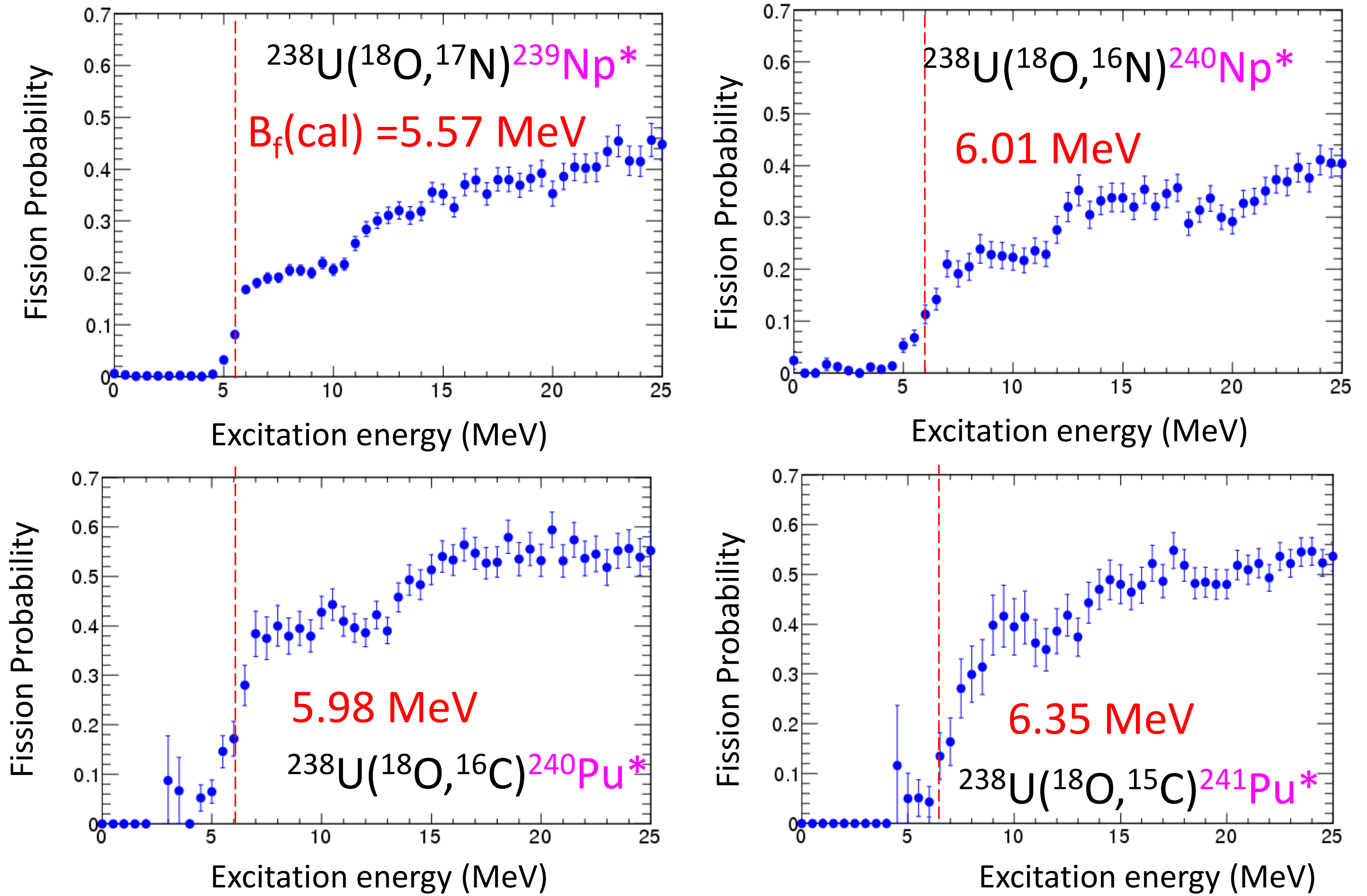
ΔE – E Spectrum

$^{18}O + ^{248}Cm$ (E_{beam}= 162MeV)



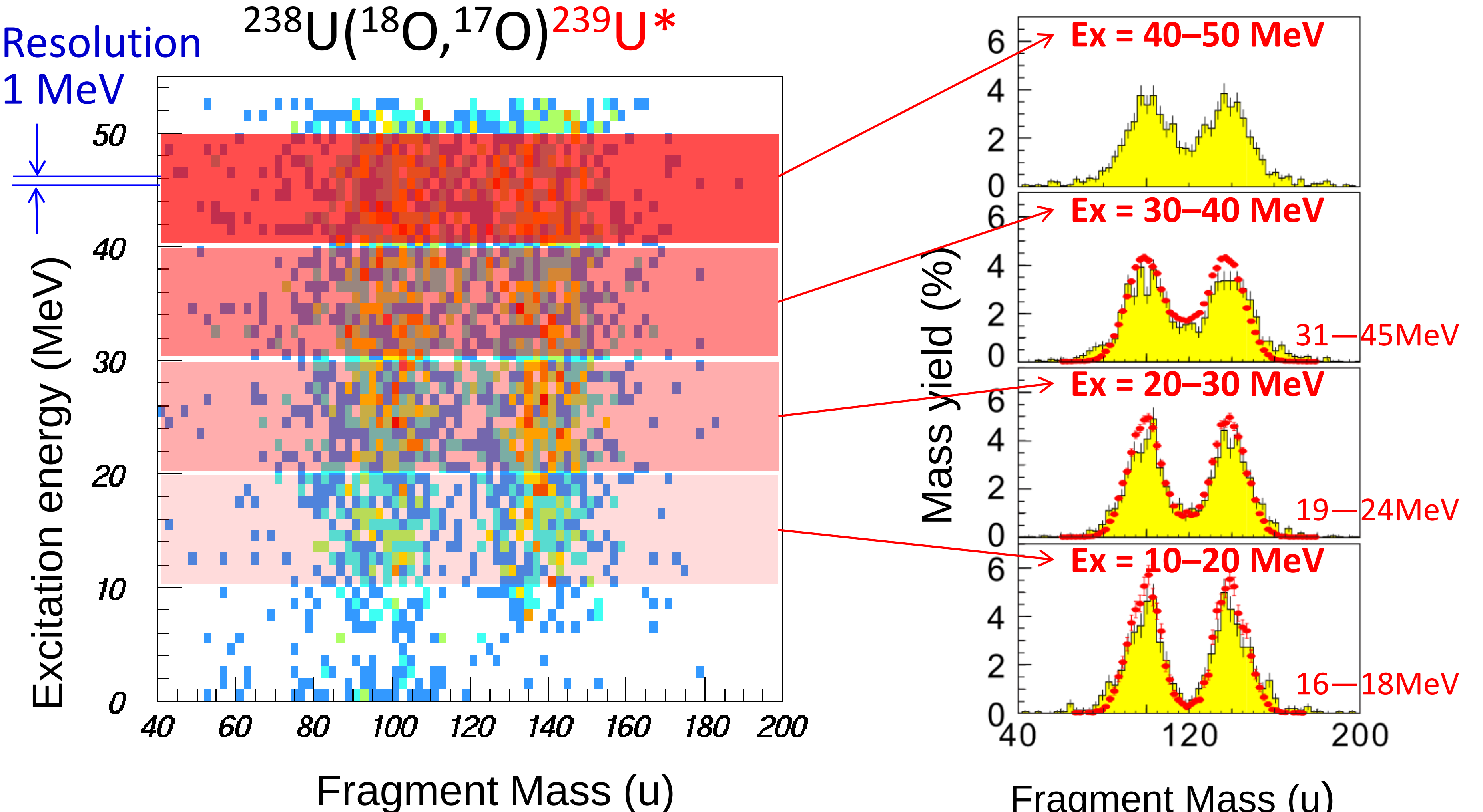


Fission Probability and Fission Barrier Height



Fission barrier Calc from P. Moller et al., PRC 79, 064304 (2009)

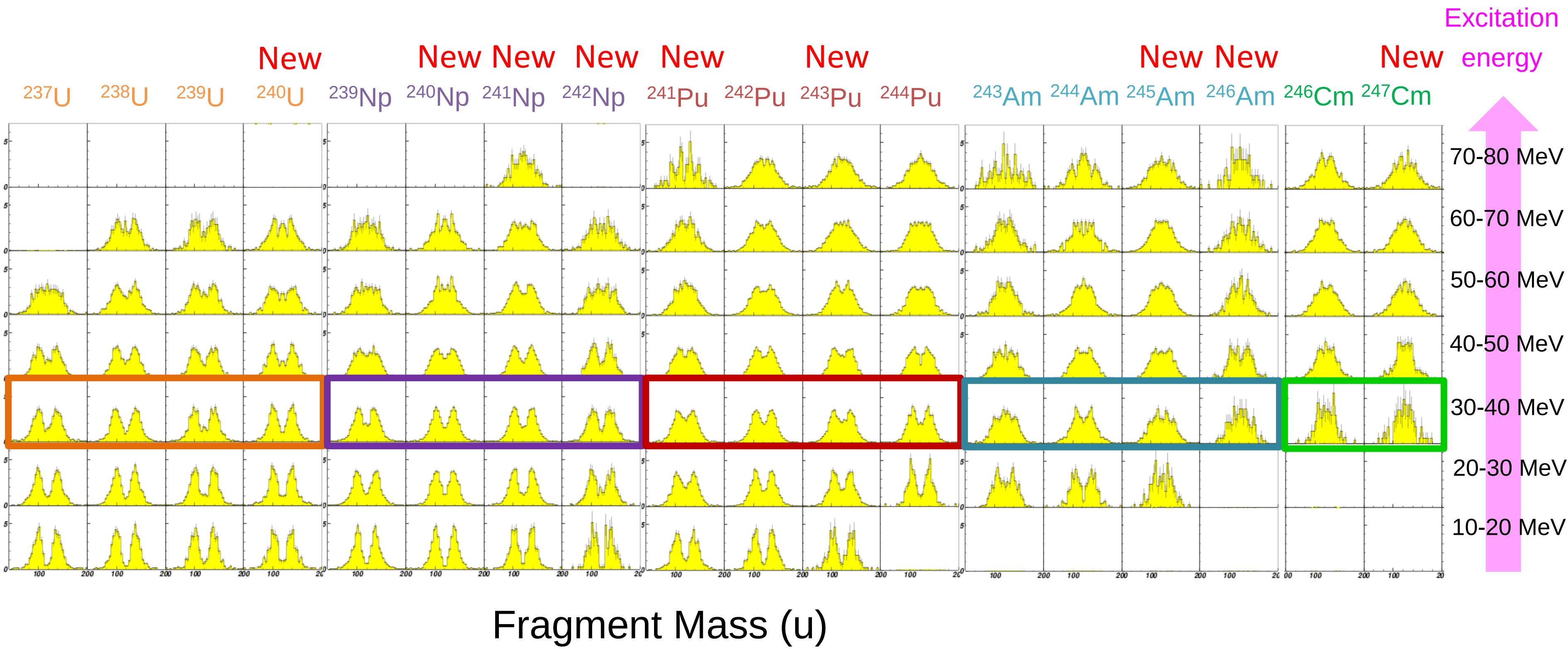
Fission Events on Fragment Mass and Excitation Energy



n + ^{238}U, V.D.Simutkin et al.
Nuclear Data Sheets 119(2014)331

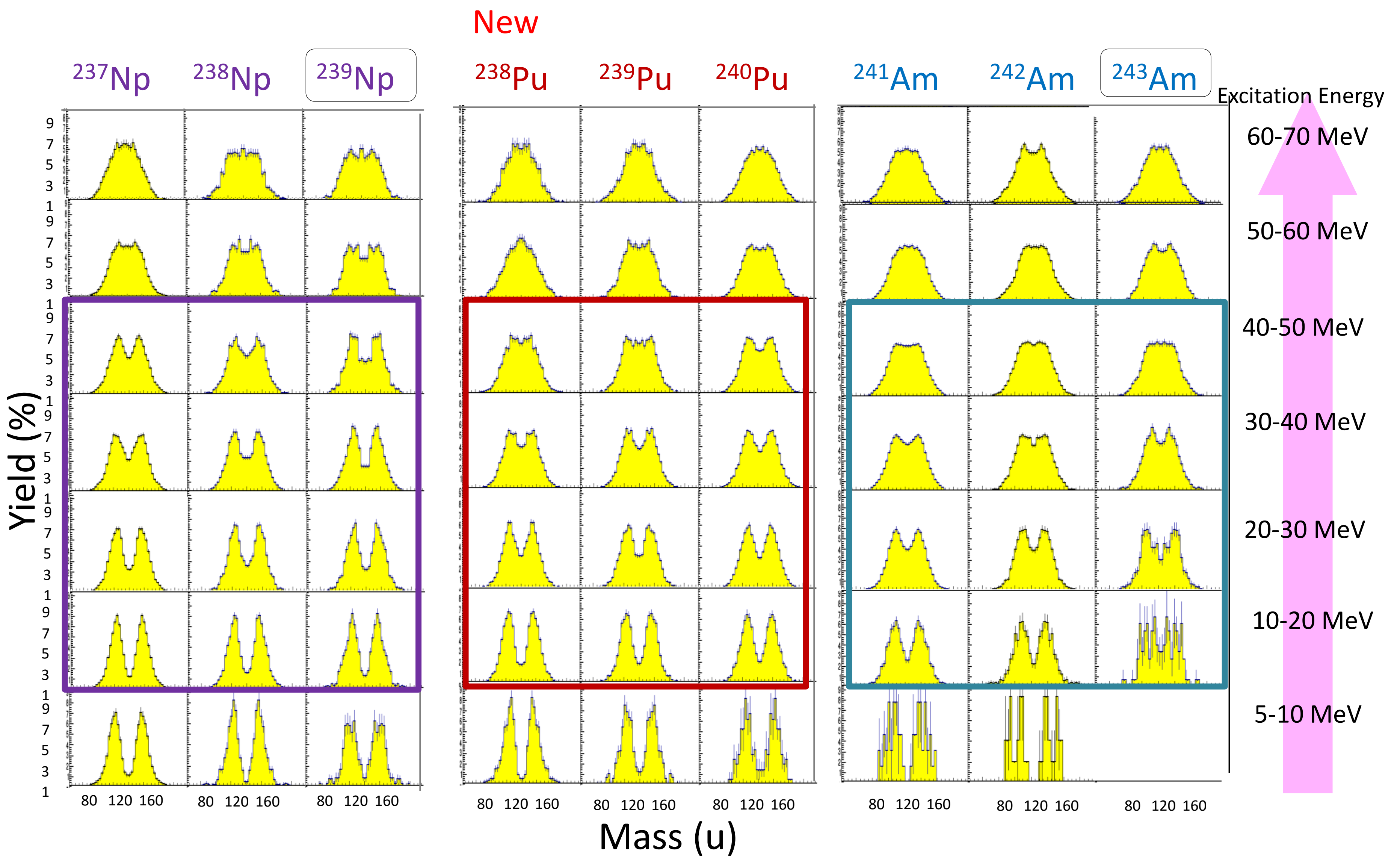
Fission Fragment Mass Distributions of U, Np, Pu, Am, Cm Isotopes

$^{18}O + ^{238}U$ (E_{lab}=157.5MeV)

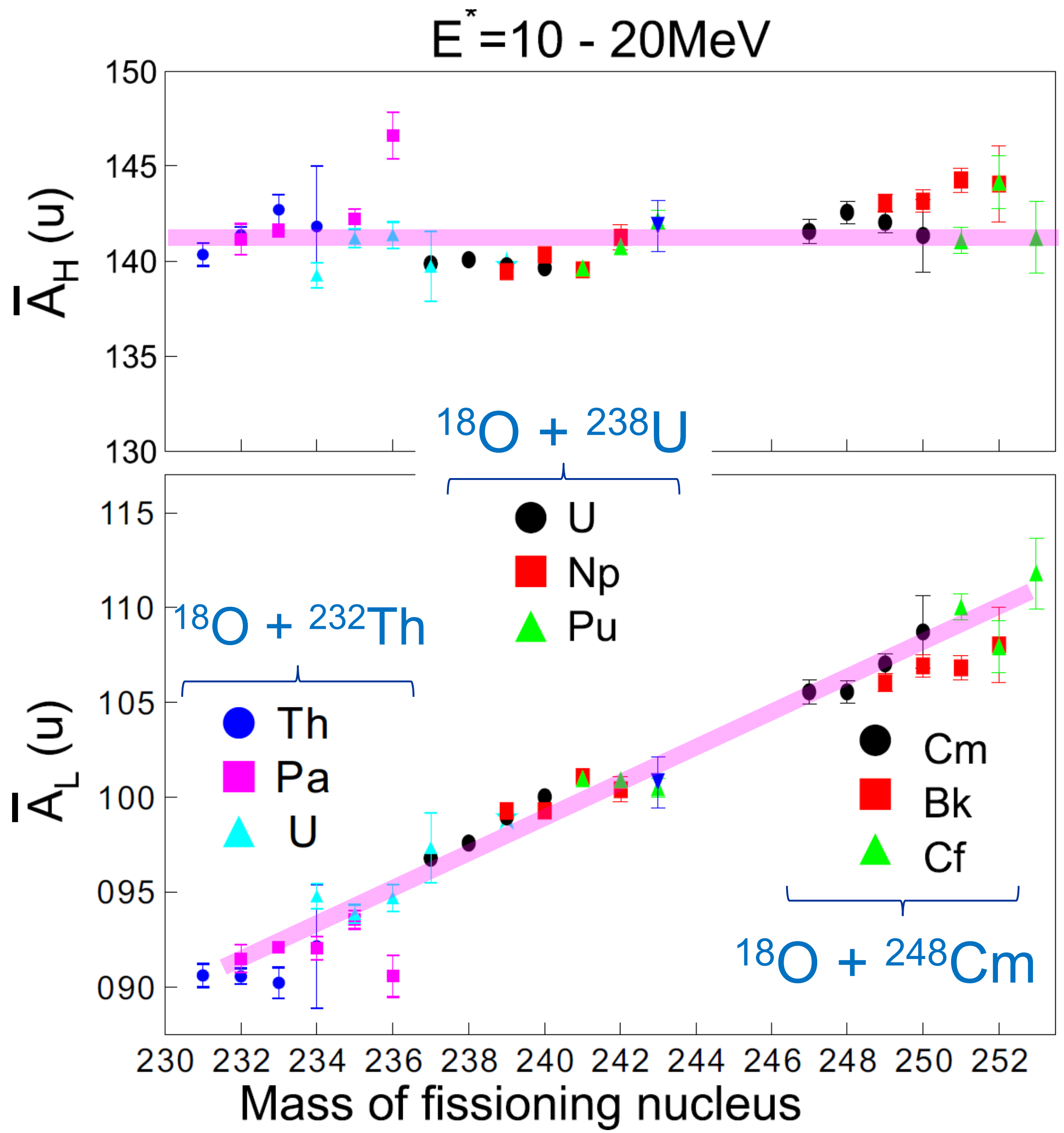


Heavier elements are structure less.

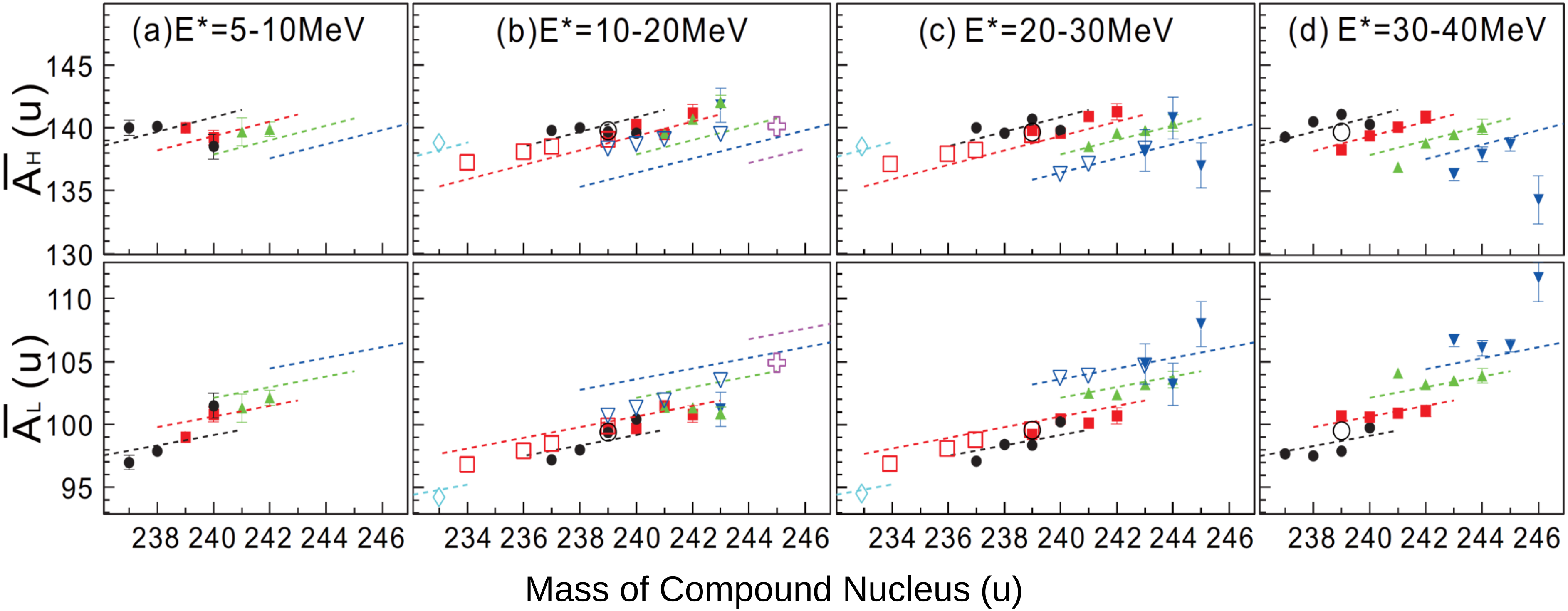
Fission Fragment Mass Distributions obtained from $^{18}O + ^{237}Np$

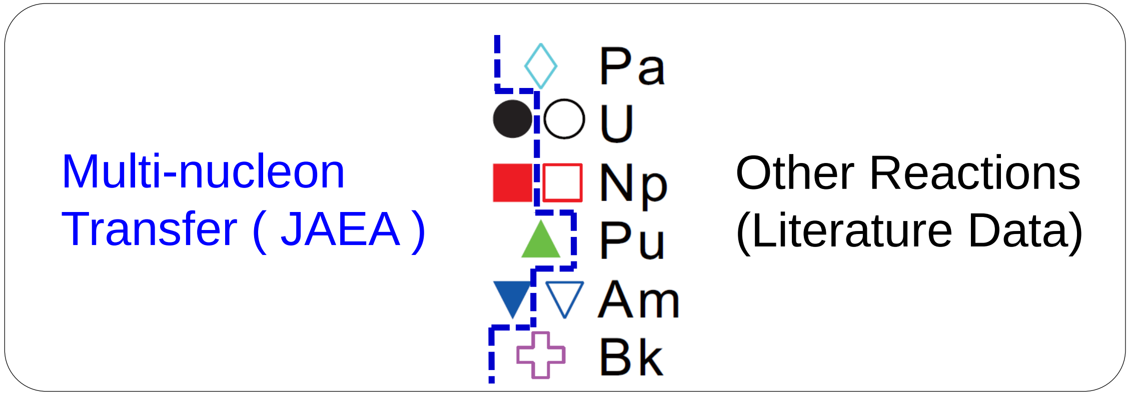


Average Mass of Heavy（H） and Light（L） Fragments



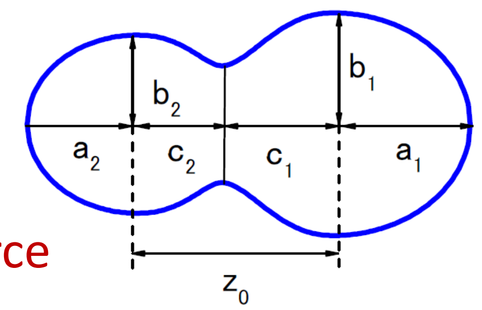
Excitation Energy Dependence of $\bar{A}_L$ and $\bar{A}_H$





3D Langevin Calculation

Nuclear Shape, q_i
- Charge-Center Distance, z_0
- Mass Asymmetry, α
- Deformation, δ

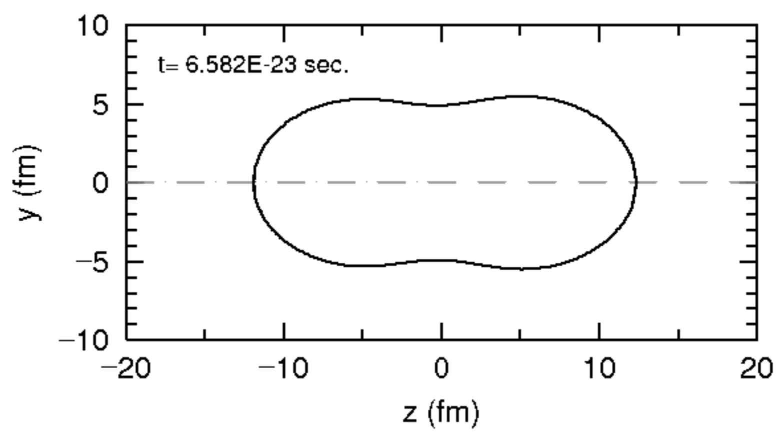


Friction dissipation

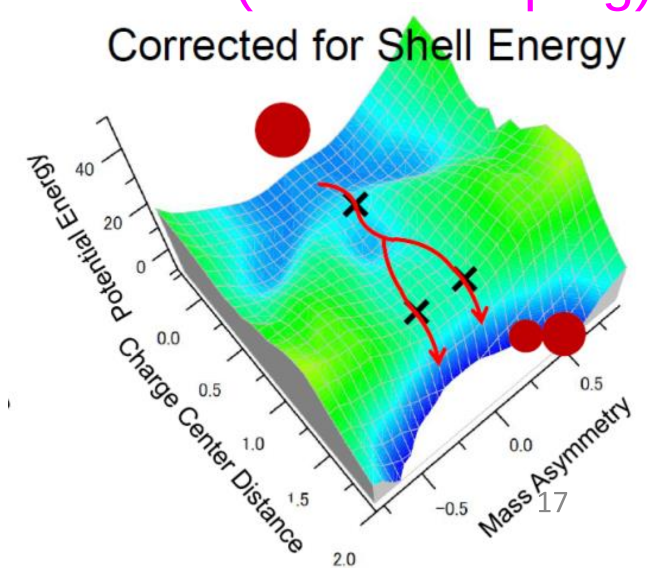
Random force fluctuation

$$\begin{cases} \dfrac{dq_i}{dt} = \left(m^{-1}\right)_{ij} p_j \\ \dfrac{dp_i}{dt} = -\dfrac{\partial \boxed{V}}{\partial q_i} - \dfrac{1}{2}\dfrac{\partial}{\partial q_i}\left(m^{-1}\right)_{jk} p_j p_k - \gamma_{ij}\left(m^{-1}\right)_{jk} p_k + g_{ij} R_j(t) \end{cases}$$

$$\Delta E_{Shell}(E^*) = \Delta E^0_{Shell} * exp\left({}^{-E^*}/_{E_D} \right),$$ E_D = 20 MeV (Shell Damping)



Y. Aritomo and S. Chiba, Phys. Rev. C **88**, 044614 (2013)

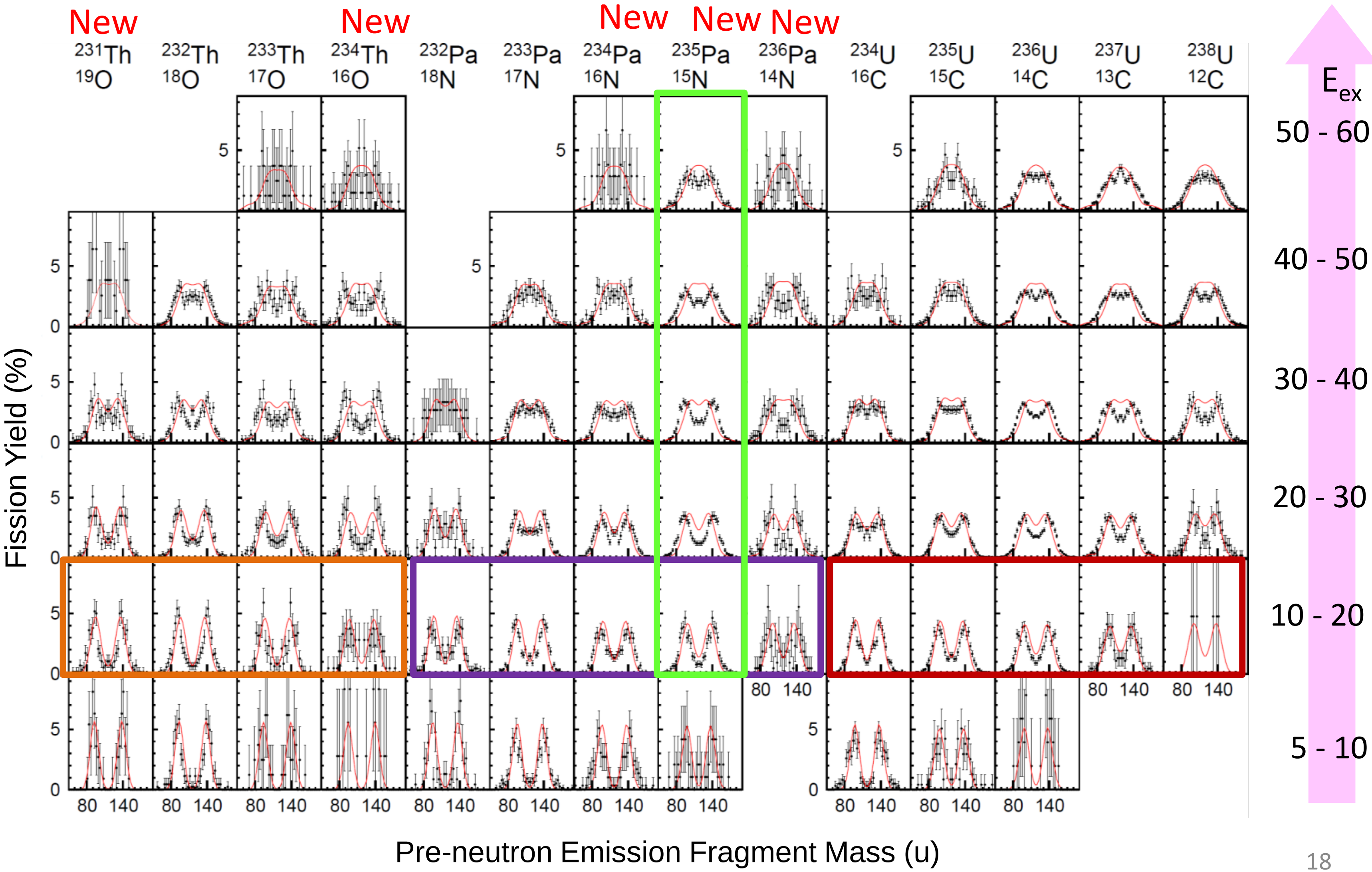


Comparison with Langevin Calculation

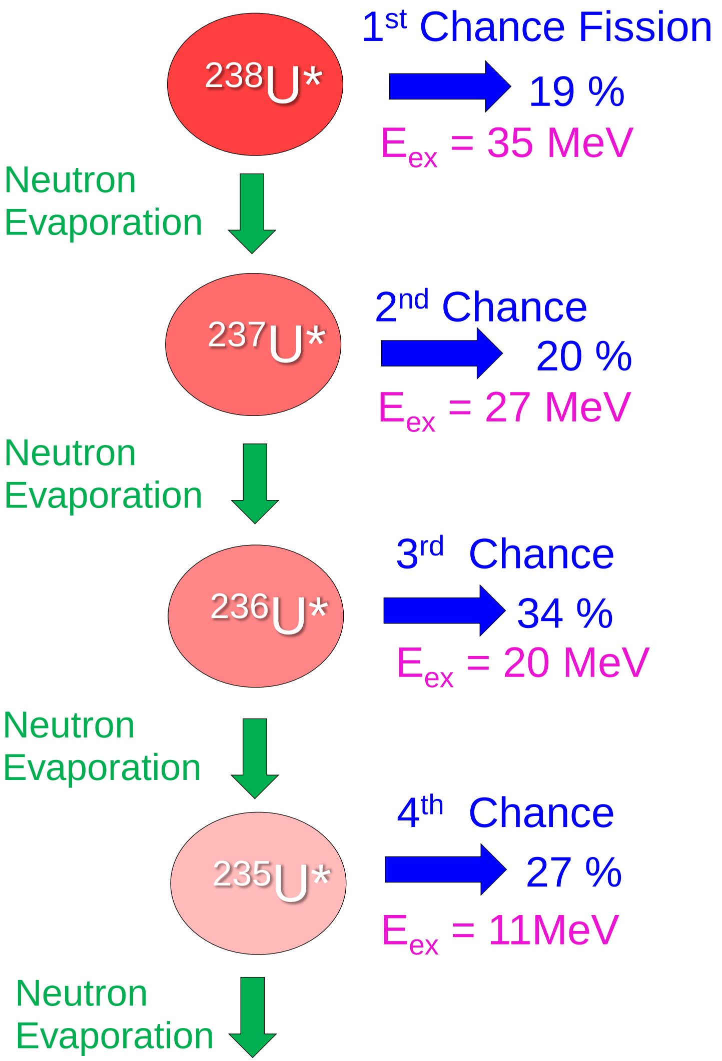
Experimental data from $^{18}O + ^{232}Th$ at JAEA Tandem

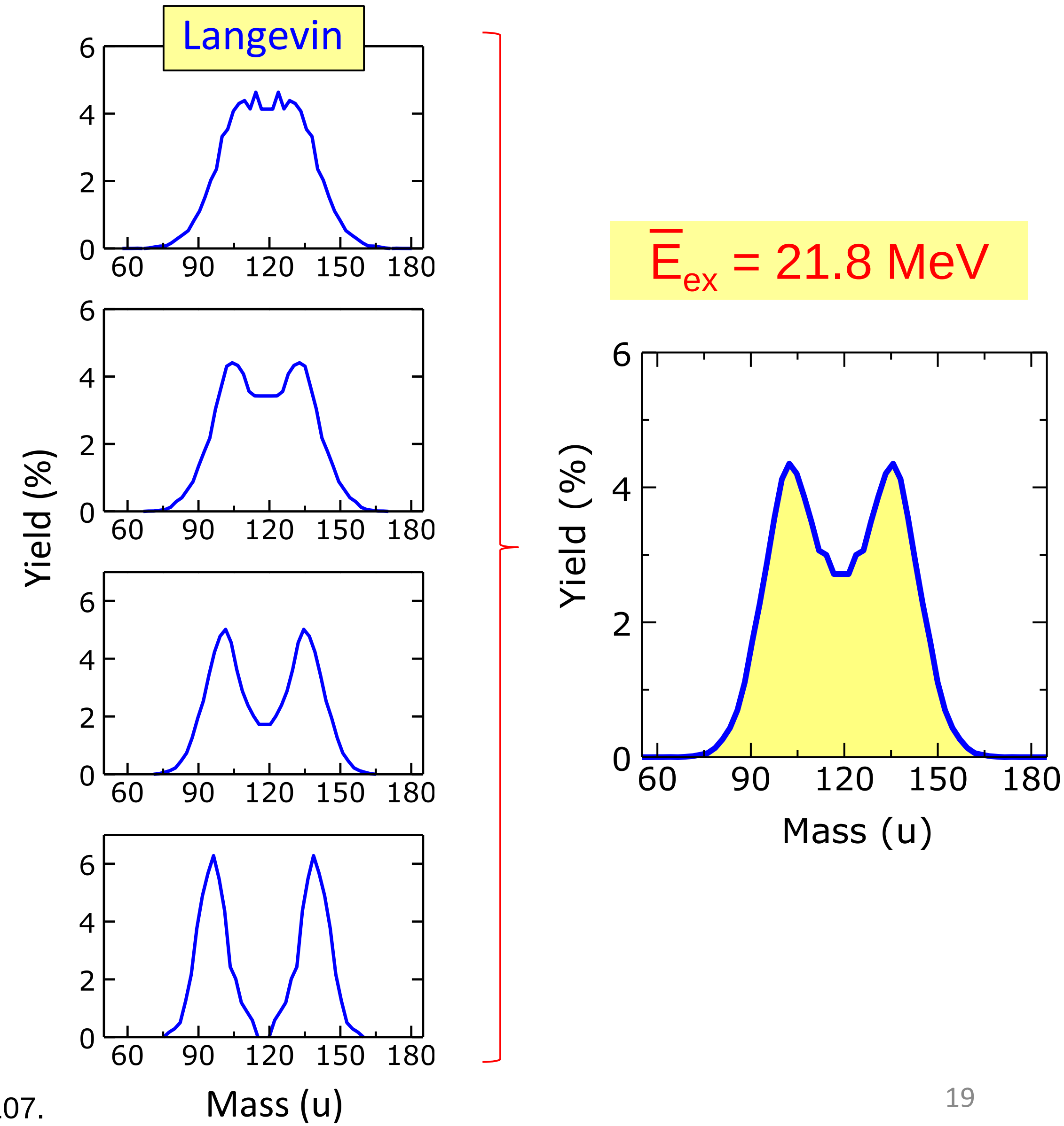
Langevin Calculation

R. Léguillon *et al.*, Phys. Lett. B **761** (2016) 125.



Effects of CN neutron-emission on FFMDs

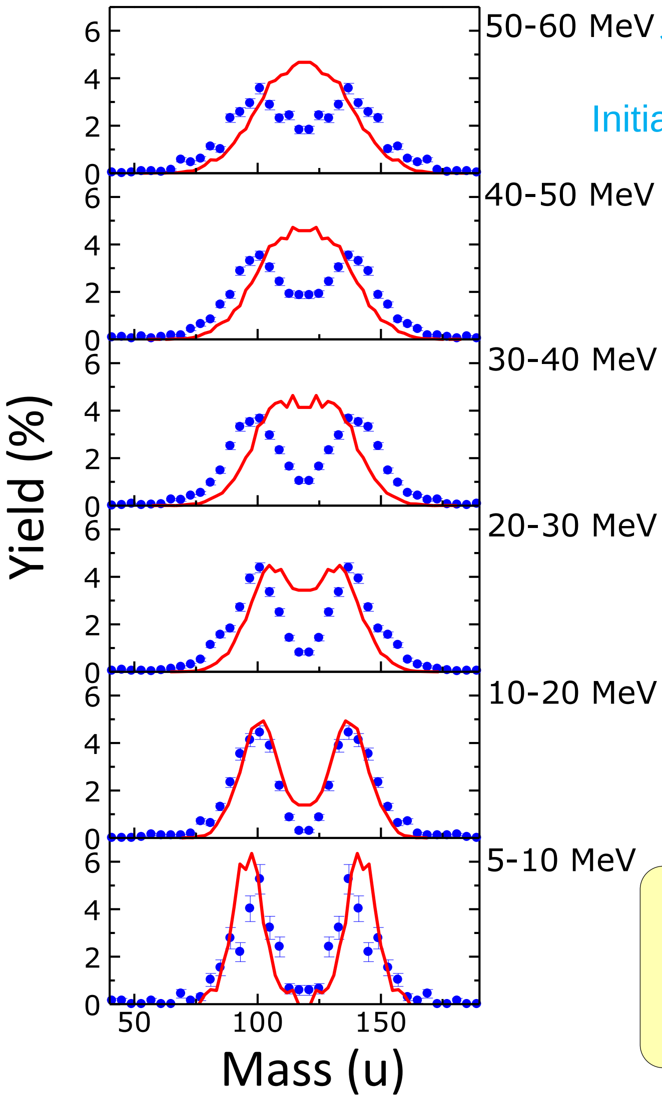




Neutron Evaporation (GEF-code)
K.-H. Schmidt et al., Nucl. Data Sheets, 131 (2016) 107.

Effects of Neutron Evaporation on FFMDs (Calcu. for $^{238}U^*$)

No neutron evaporation

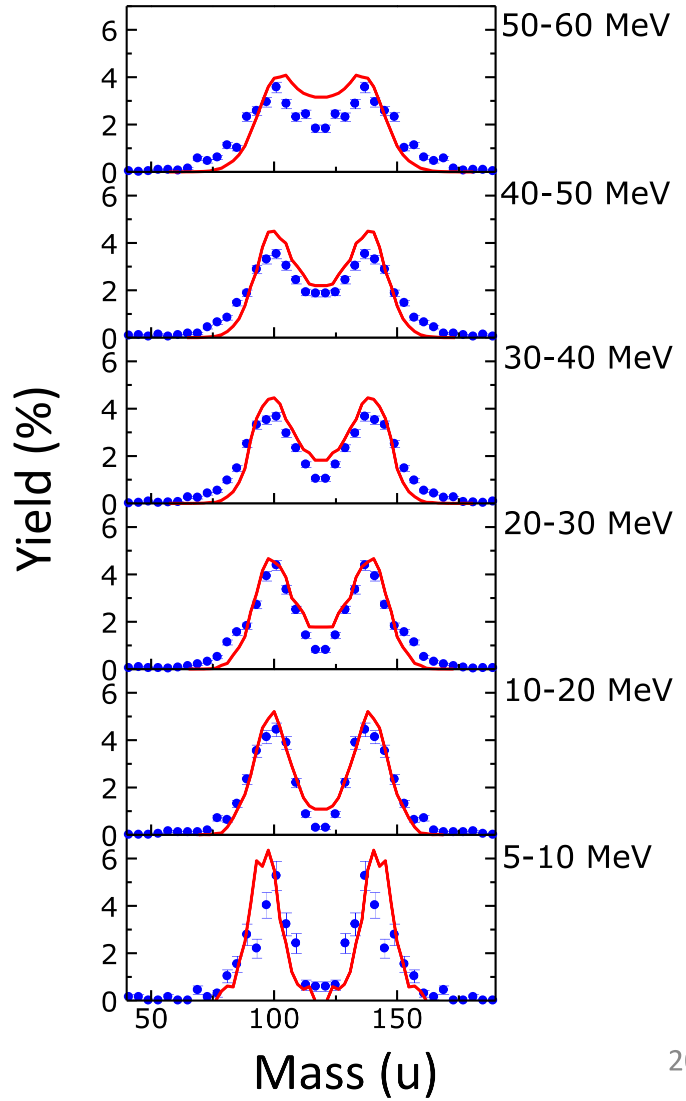


Initial Excitation Energy

$^{238}U(^{18}O,^{18}O)^{238}U^*$

E_D = 20 MeV is reasonable.

Neutron evaporation considered

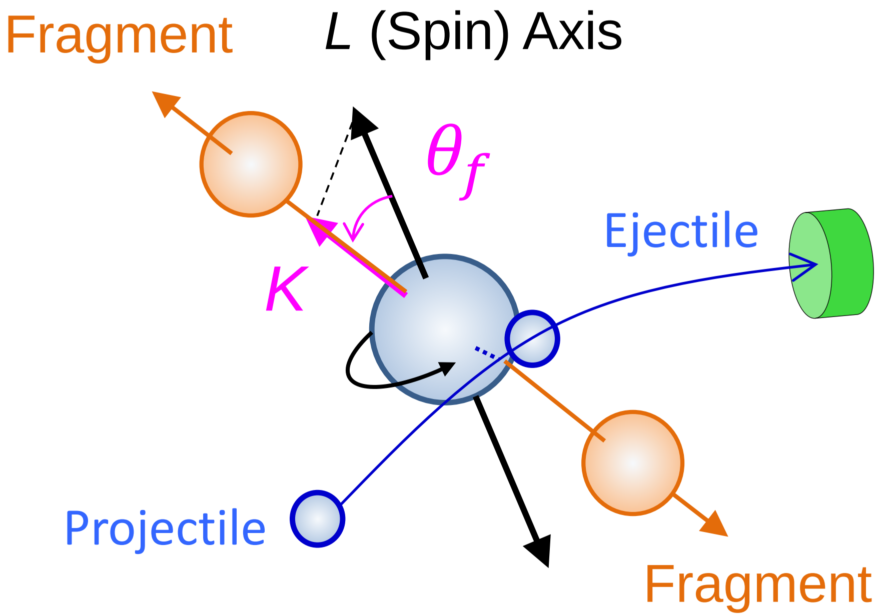


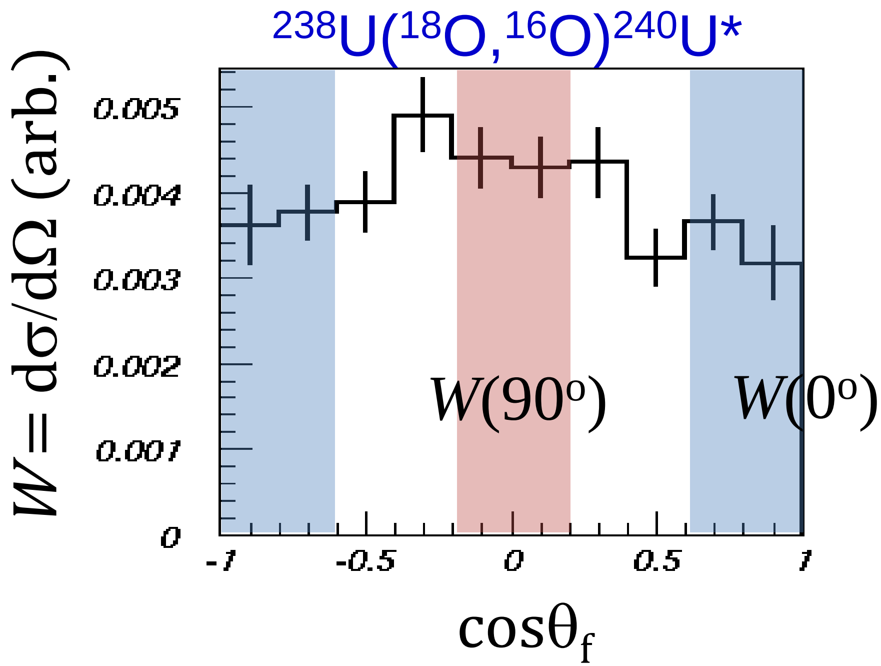
Expt.

Langevin

Fission Fragment Angular Distribution

How we can get information on spin *J* in multi-nucleon transfer reactions ?

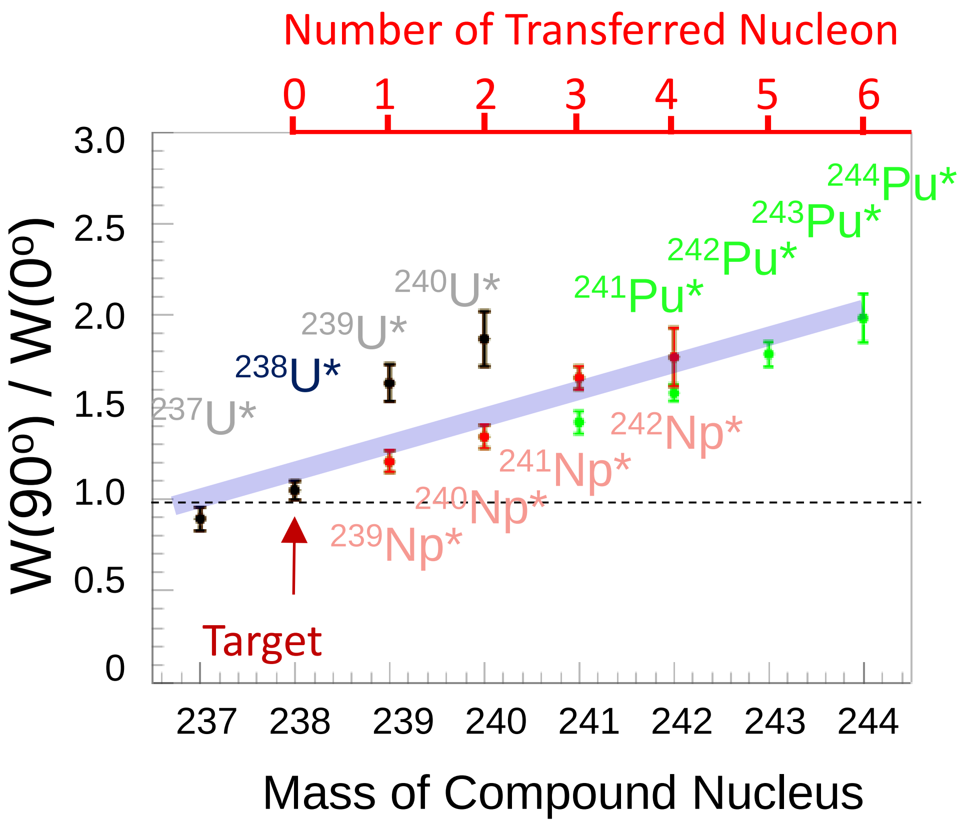




$$\text{Fission fragment angular anisotropy} = \frac{W(90^o)}{W(0^o)}$$

Fission-fragments Angular Anisotropy

$^{18}O + ^{238}U$ (E_{lab} = 157.5 MeV)



$$\frac{W(90^o)}{W(0^o)} \approx 1 + \frac{\langle J^2 \rangle}{4\,K_0^{\,2}} = 1 + \frac{\langle J^2 \rangle \hbar^2}{4\,I_{eff}\,T}$$

J : Total Angular momentum

I_{eff} : Effective moment inertia at the saddle point

T : Temperature at the saddle point

Correlation between Fission Fragments and Neutrons (Plan)

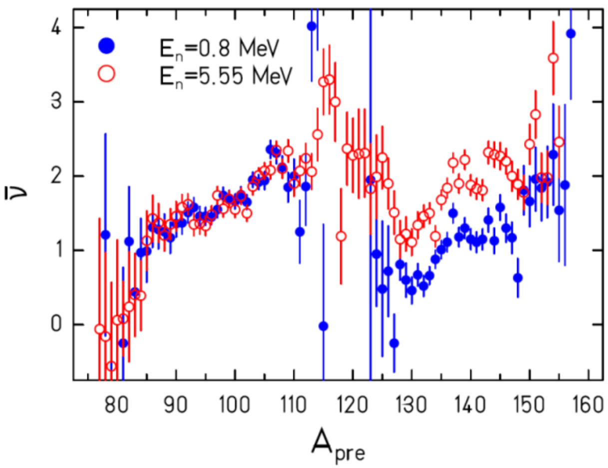
☑ Neutron Multiplicity as a Function of Fragment Mass & TKE, and its variation with excitation energy of CN. (Almost neutron-background free)

☑ Neutron Energy Spectrum

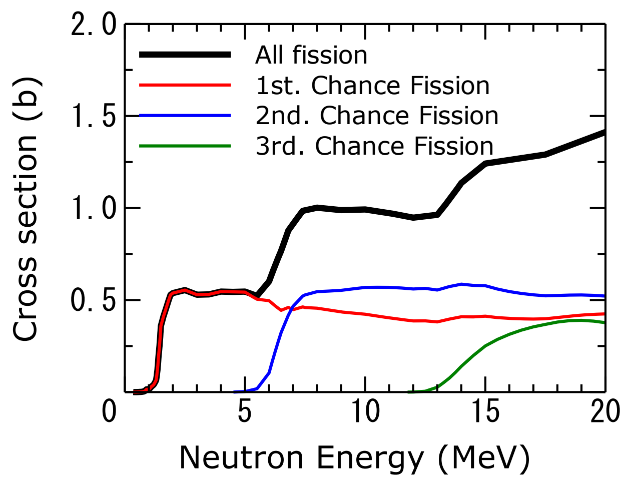
☑ Pre-scission Neutron and Multi-chance Fission

n + ^{237}Np

(E_n = 0.8 MeV, 5.5 MeV)



A.A. Naqvi *et al*., Phys. Rev. C, **34** (1986) 218.



JENDL. 4.0
K. Shibata *et al*., J. Nucl. Sci. Technol. **48**, (2011) 1.

Installing 38 Neutron Detectors
(Ø5" x *d* 2" Liquid Organic Scint.)

Summary

☑ Multi-nucleon transfer reaction is a powerful too study fission for various nuclei and wide range of excitation energies.

☑ FFMDs are reproduced by the Langevin-type calculation with E_d = 20MeV. Multiple-chance fission should be considered.

☑ $\langle J^2 \rangle$ increases linearly with the number of transferred nucleons, suggested from the fission fragment angular distribution.

☑ We have a plan for correlation measurement of FFs and prompt neutrons : $\nu(A)$, ν_{pre}, …

Collaborator in Fission Study

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