Compound nuclear reaction cross sections from surrogate measurements

B.K. Nayak
Nuclear Physics Division
Bhabha Atomic Research Centre, Mumbai- 400 085

Compound Nuclear cross sections

Cross sections for reactions of neutron and light charged particles with target nuclei across the isotopic chart taking place at energies several KeV to tens of MeV is required for :

- Nuclear astrophysics
- National security
- Nuclear energy

Indirect methods

- Many of these nuclei are difficult to produce
- or too short-lived to serve as a target

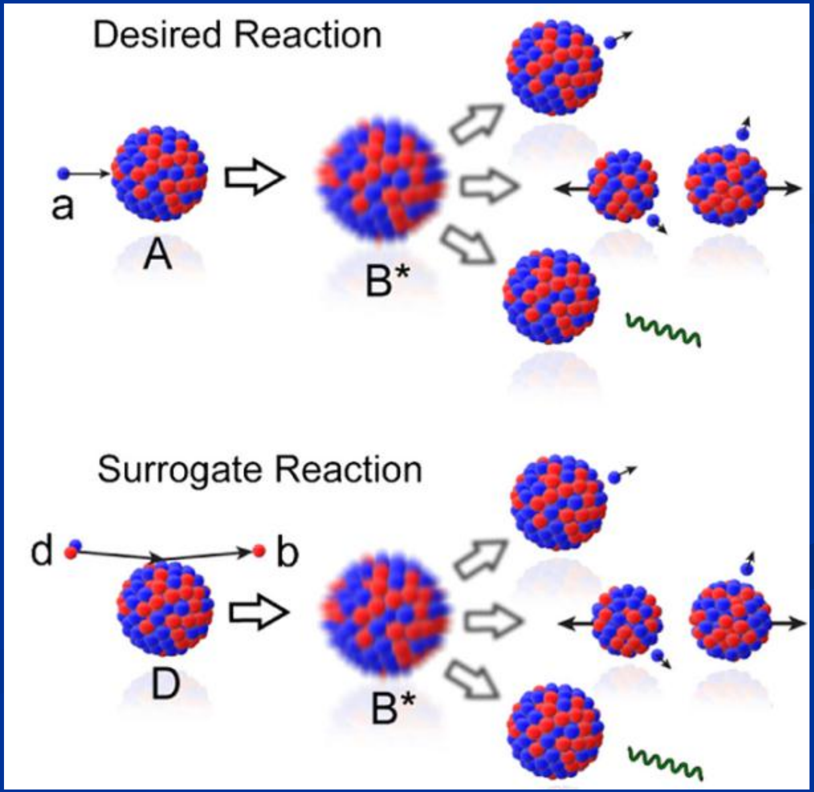
- ANC, Coulomb Dissociation and trojan-hourse methods: (time scale $\approx 10^{-22}$ sec)

- A complementary method, *surrogate reaction method:*
(slow time scale $\gg 10^{-22}$ sec)

Surrogate reaction methods

- (n, *f*) cross sections
- (n,γ) cross sections

$$\sigma^{n,f}(E)=\sigma^{CN}(E_n)\times P_f(E)$$



Three stage Nuclear power program of DAE

Stage I:

Development of Pressurized heavy water reactors (PHWR)

Stage II:

Fast Breeder Reactor: To breed ^{239}Pu and ^{233}U from ^{238}U and ^{232}Th

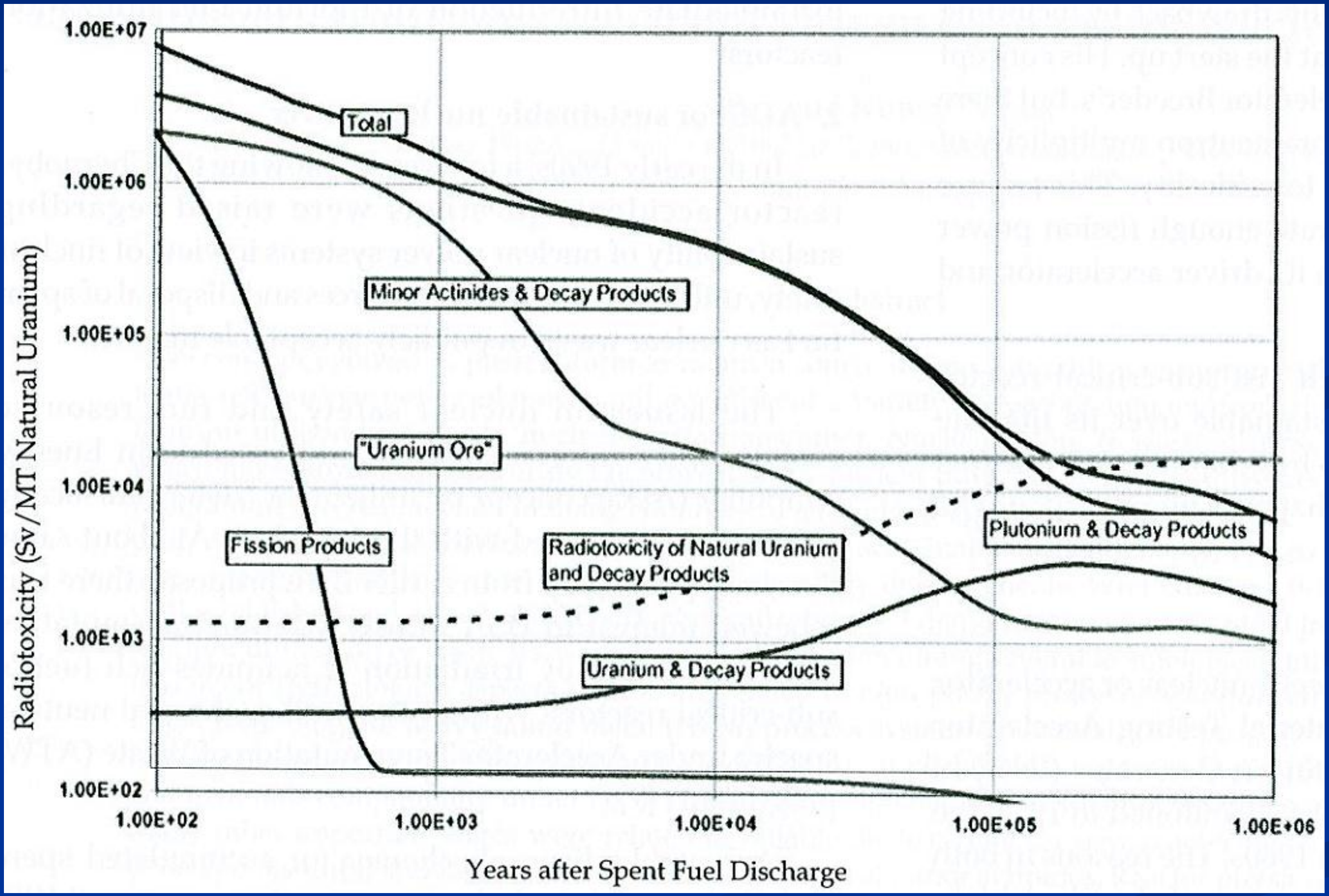
Stage III:

Advance nuclear power system:

Consists in use of ^{232}Th and ^{233}U

AHWR, Accelerator Driven reactor system (ADS)

Nuclear waste transmutation



Natural decay time for long-lived radiotoxic species in spent fuel- reference to Uranium ore.

Surrogate reaction methods

- Absolute surrogate method
- Ratio surrogate method
- Hybrid surrogate ratio method

Surrogate reaction methods

- Absolute surrogate method
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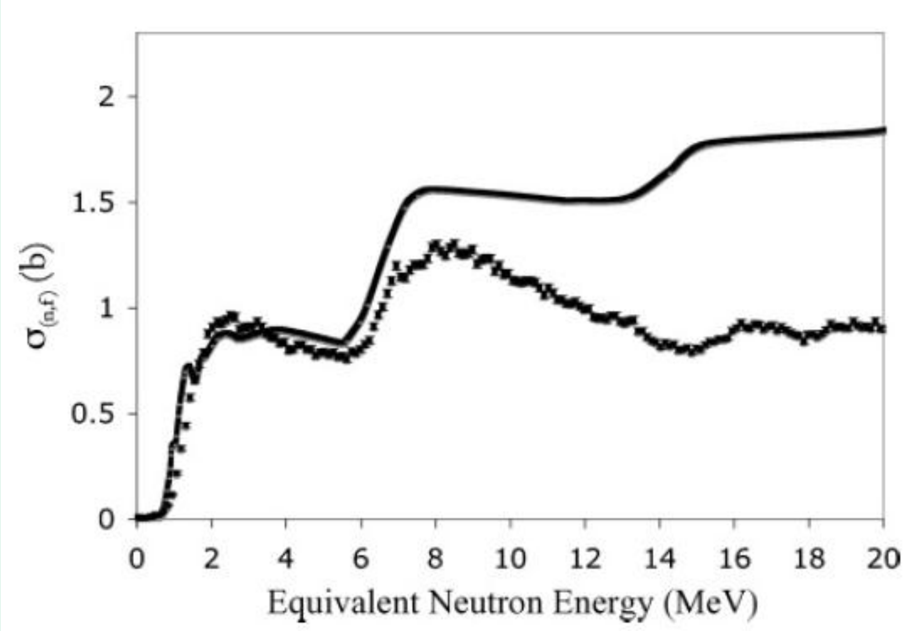
Absolute Surrogate method

$$\sigma^{n,f}(E_n) = \sigma^{CN}(E_n) \times P_{(^3He,\alpha f)}(E_{ex})$$

$$P_{(^3He,\alpha f)}(E) = N_{(^3He,\alpha f)}/N_{(^3He,\alpha)}$$

Uncertainty



^{236}U(n,f) cross section obtained from absolute surrogate method using ^{238}U(^{3}He,αf) reaction. The solid line ENDF/B-VII library result.

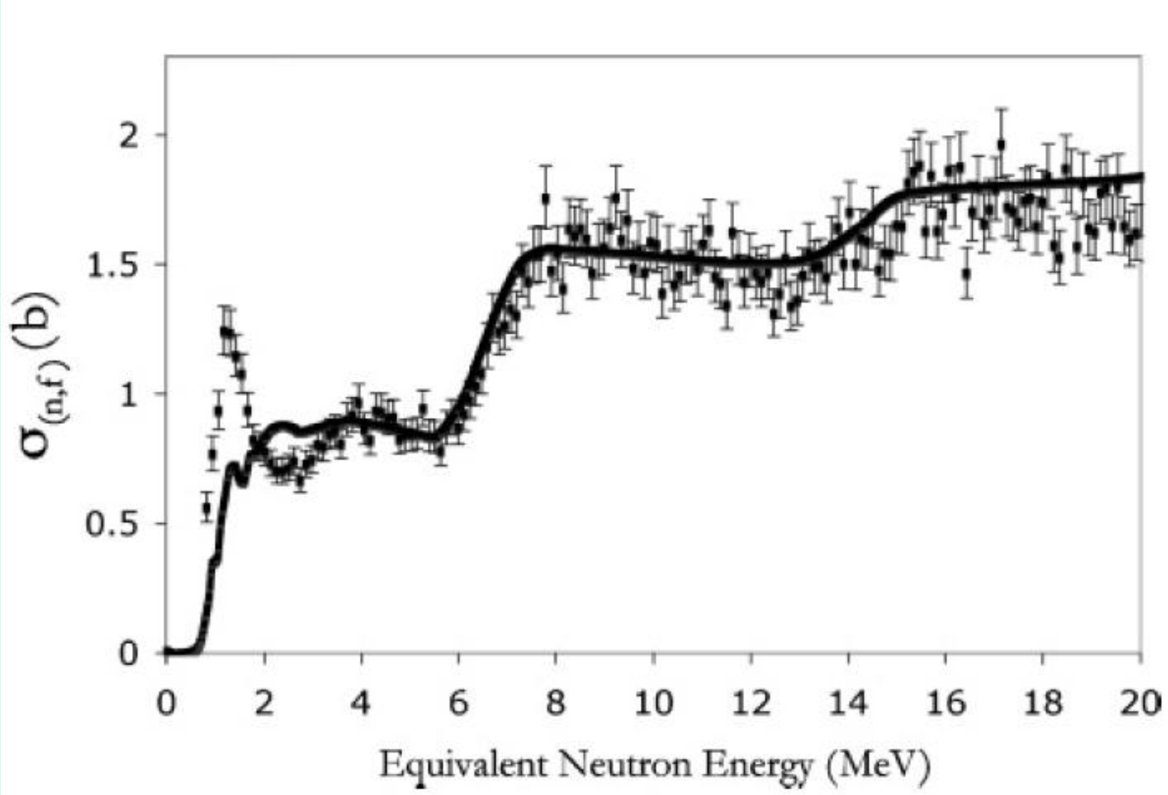
B. F.Lyles *et al*., P RC **76, 014606 (2007)**

Surrogate ratio method

In this method the ratio of the cross sections, of two compound-nucleus reactions, for same excitation energy (E_{ex}) are determined experimentally.

$$R(E_{\mathrm{ex}}) = \frac{\sigma_{\alpha_1\chi_1}(E_{ex})}{\sigma_{\alpha_2\chi_2}(E_{ex})},$$

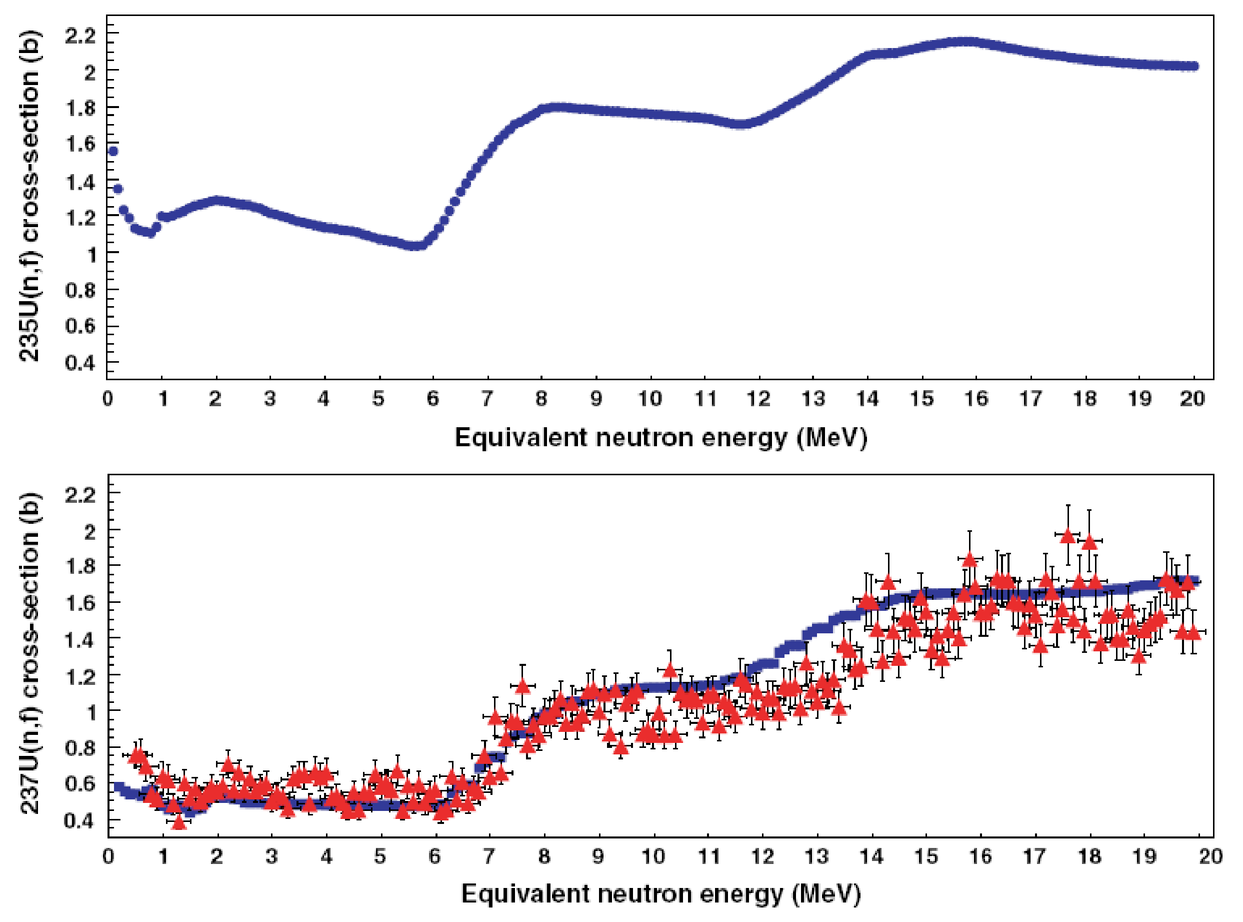
An independent determination of one of the above cross sections then allows one to infer the other by using the ratio $R(E)$.



The ^{236}U(n,f) cross section determined using SRM relative to ^{233}U(n,f) using ^{238}U(^{3}He,αf) and ^{235}U(^{3}He,αf) reactions. The solid line is the ENDF/B-VII library evaluation for this cross section.

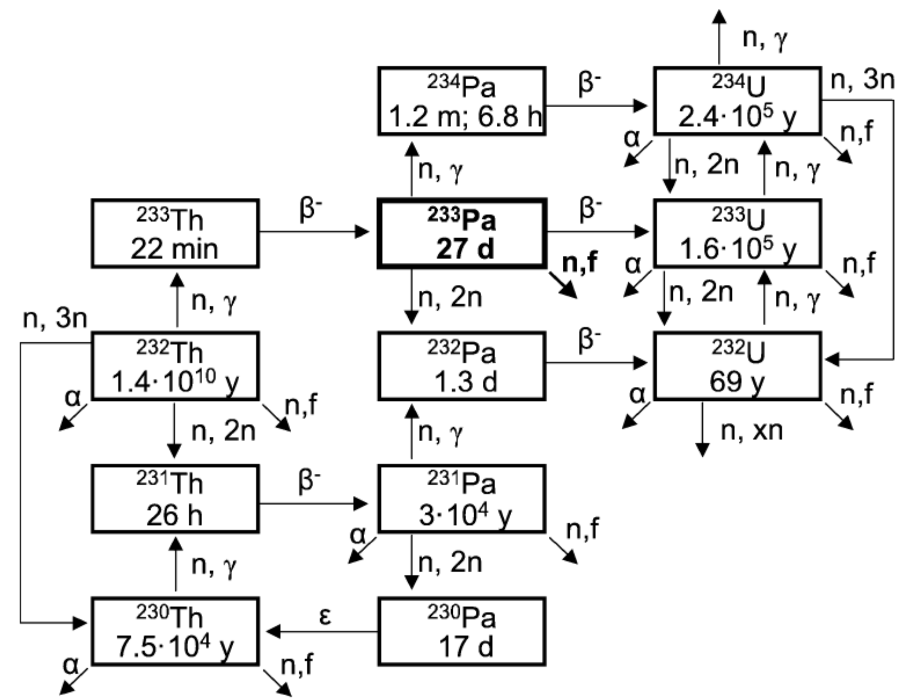
^{237}U(n,f) cross section

PRC 73, 054604 (2006)



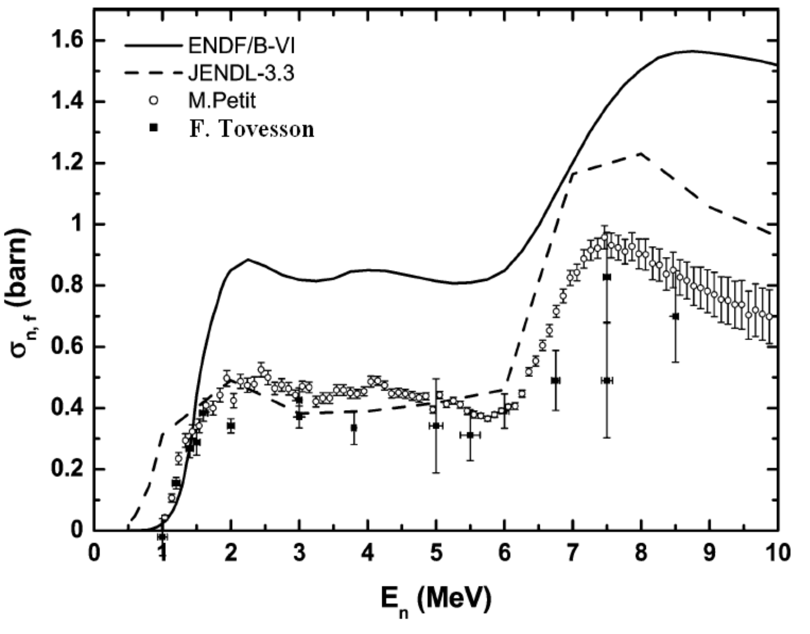
^{237}U(n,f)/ ^{235}U(n,f)=P[^{238}U(α, α'f)]/P[^{236}U(α, α'f)]

Isotopes in the Th-U fuel cycle



Schematic view of the thorium fuel cycle.

Review of ^{233}Pa(n,f) data



Direct measurement: (1.0 MeV to 8.5 MeV) by F. Tavesson et al.(2004)

T(p,n)^{3}He and D(d,n)^{3}H

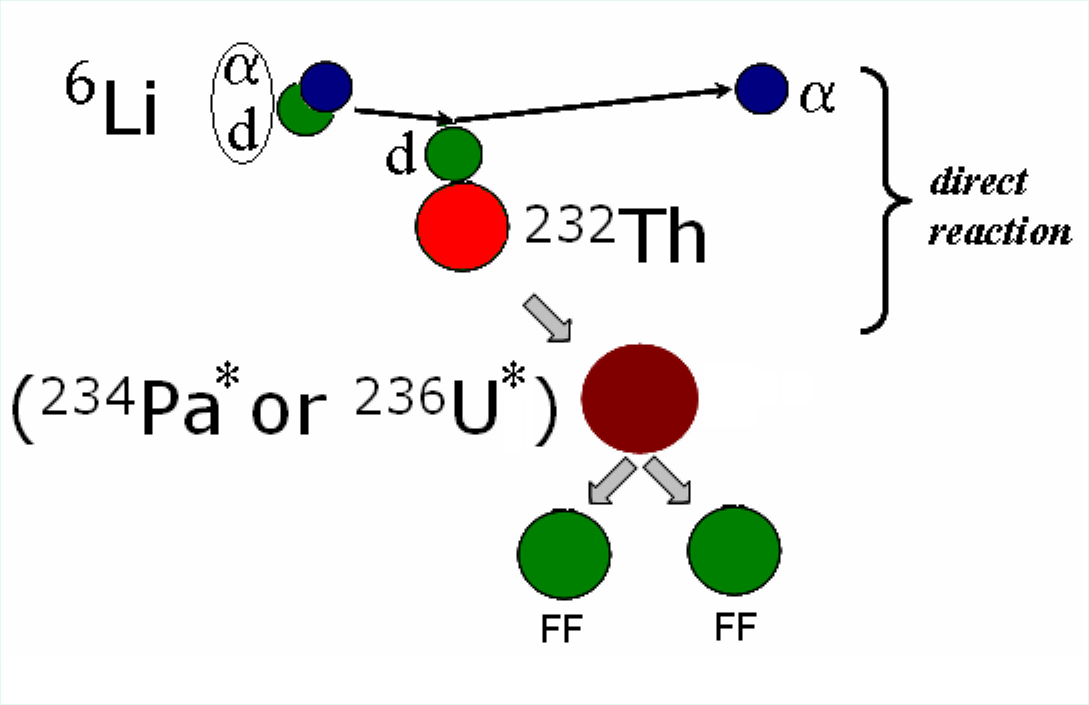
Indirect measurement: (1.0 MeV to 10.0 MeV) by M. Petit el al. (2004)

By employing the ^{232}Th(^{3}He, p)^{234}Pa transfer reaction :

$$\sigma^{n,f}(E)=\sigma^{CN}(E_n)\times P_f(E)$$

^{233}Pa(n,f) cross section is not known beyond 10.0 MeV neutron energy and there is no data on ^{234}Pa(n,f) .

^{6}Li+ ^{232}Th transfer reaction (as the Hybrid Surrogate reaction)



By carrying out PLF-FF coincidence measurement, we can determine the decay probability of the compound residues.

$^{6}Li+^{232}Th$ transfer reaction

$^{232}Th(^{6}Li, \alpha)\rightarrow{}^{234}Pa$

$Q_{gg}=6.769$ MeV

$^{232}Th(^{6}Li, d)\rightarrow{}^{236}U$

$Q_{gg}=-6.047$ MeV

$Q_{opt}= [(Z_f/Z_i)-1)]E_{c.m.}$

$E_x=Q_{gg}+Q_{opt}$

At E_{lab}= 38.0 MeV

($^{234}Pa^{*}$) α -peak = 19.0 MeV

($^{236}U^{*}$) d-peak = 18.5 MeV

^{7}Li+^{232}Th transfer reaction

^{232}Th(^{7}Li, α)$\rightarrow$^{235}Pa

Q_{gg}=5.6011 MeV

^{232}Th(^{7}Li, t)$\rightarrow$^{236}U

Q_{gg}=-7.03968 MeV

$Q_{opt}= [(Z_f/Z_i)-1)]E_{c.m.}$

$E_x=Q_{gg}+Q_{opt}$

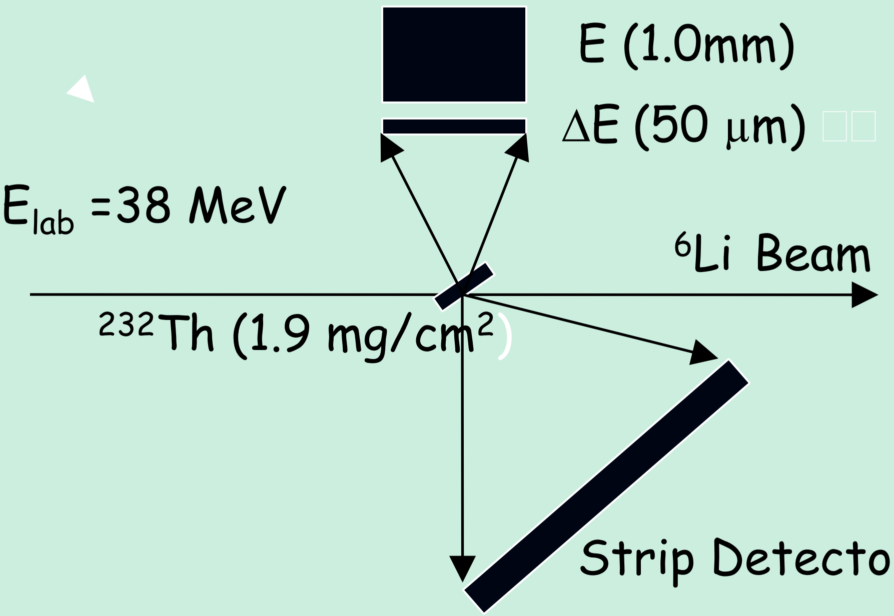
At E_{lab}= 39.5 MeV

(^{235}Pa*) α -peak = 19.36 MeV

(^{236}U*) t-peak = 19.38 MeV

EXPERIMENTAL SETUP

- Two ΔE-E telescope for PLF
- A Strip detector (16 strips) for FF.



PLF Detector

E (1.0mm)

ΔE (50 µm)

E_{lab} =38 MeV

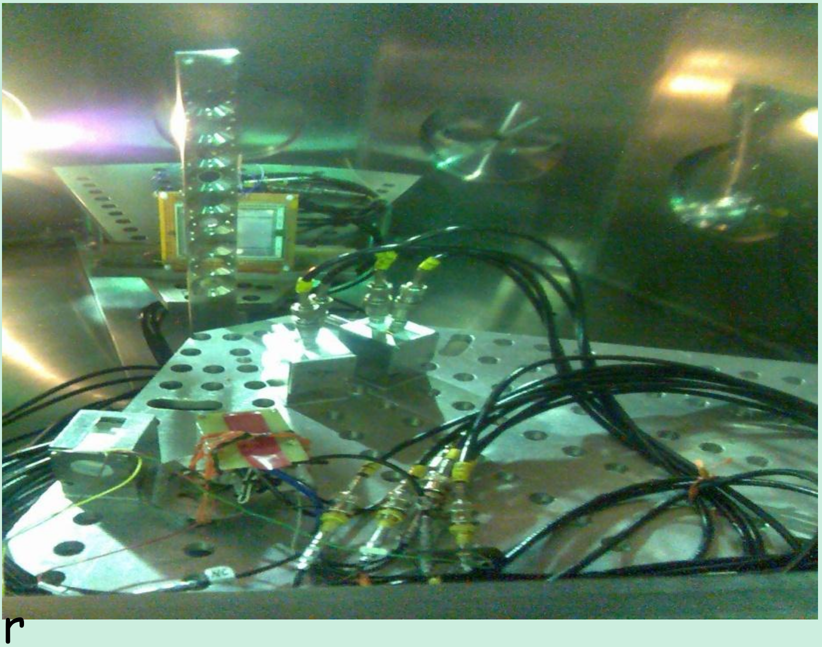
^{6}Li Beam

^{232}Th (1.9 mg/cm^{2})

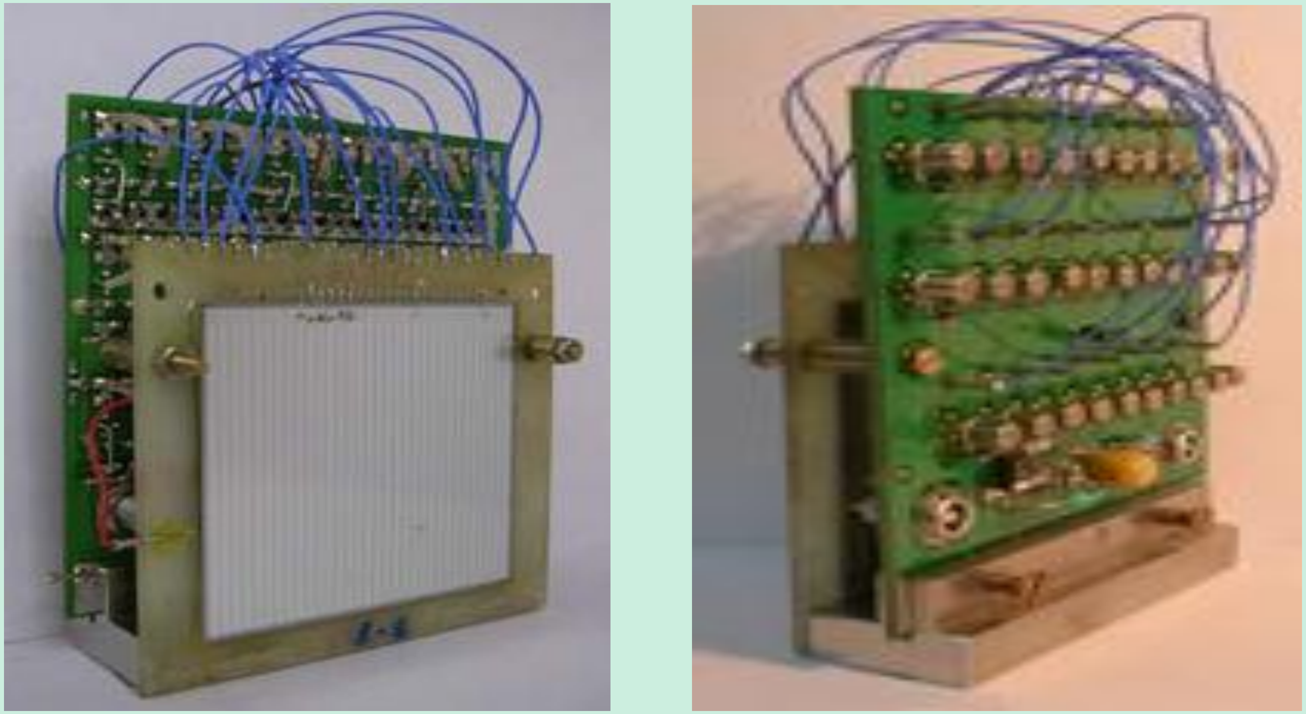
Strip Detector

Fission Detector

(141° to 158°)

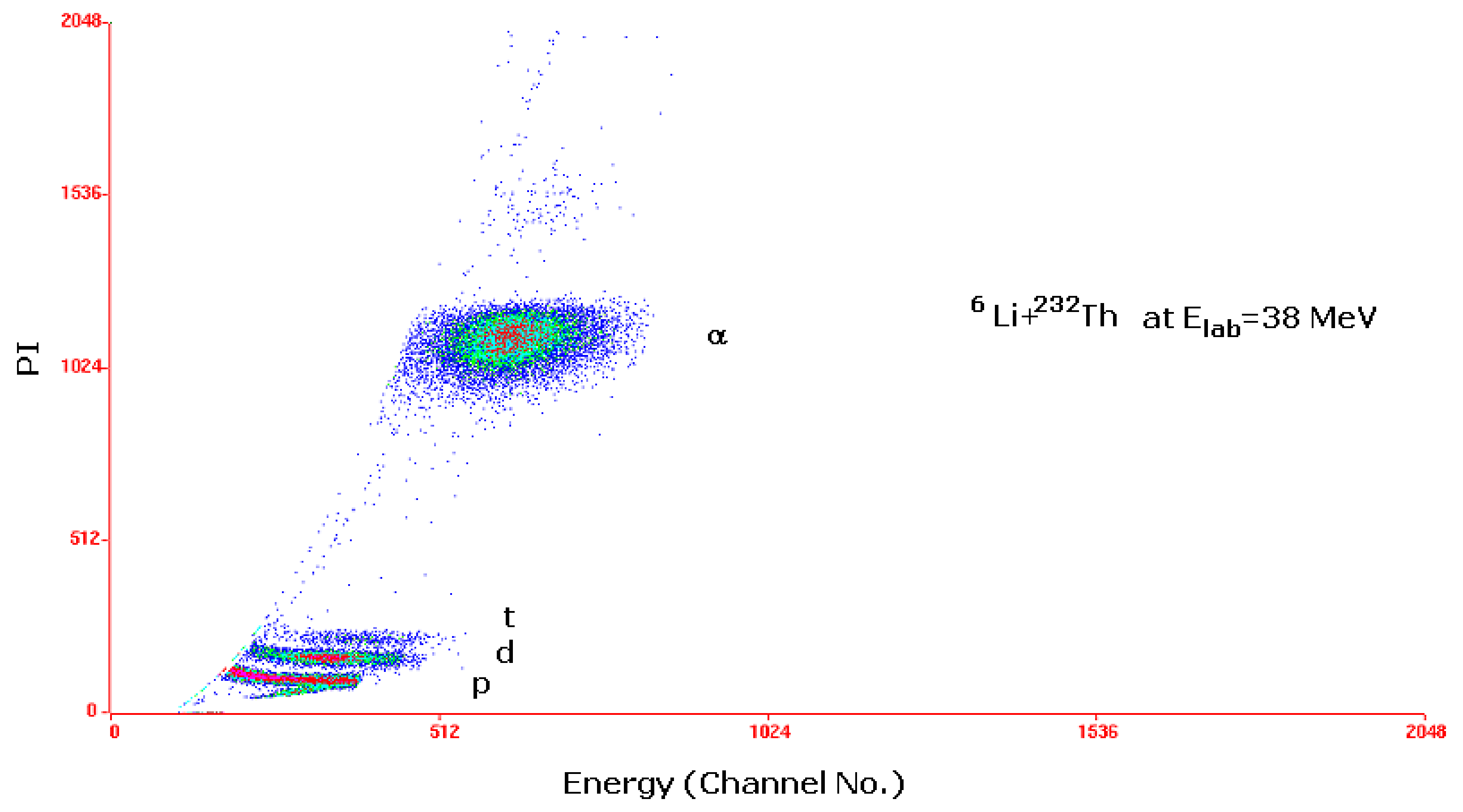


32 strip Si solid state detector

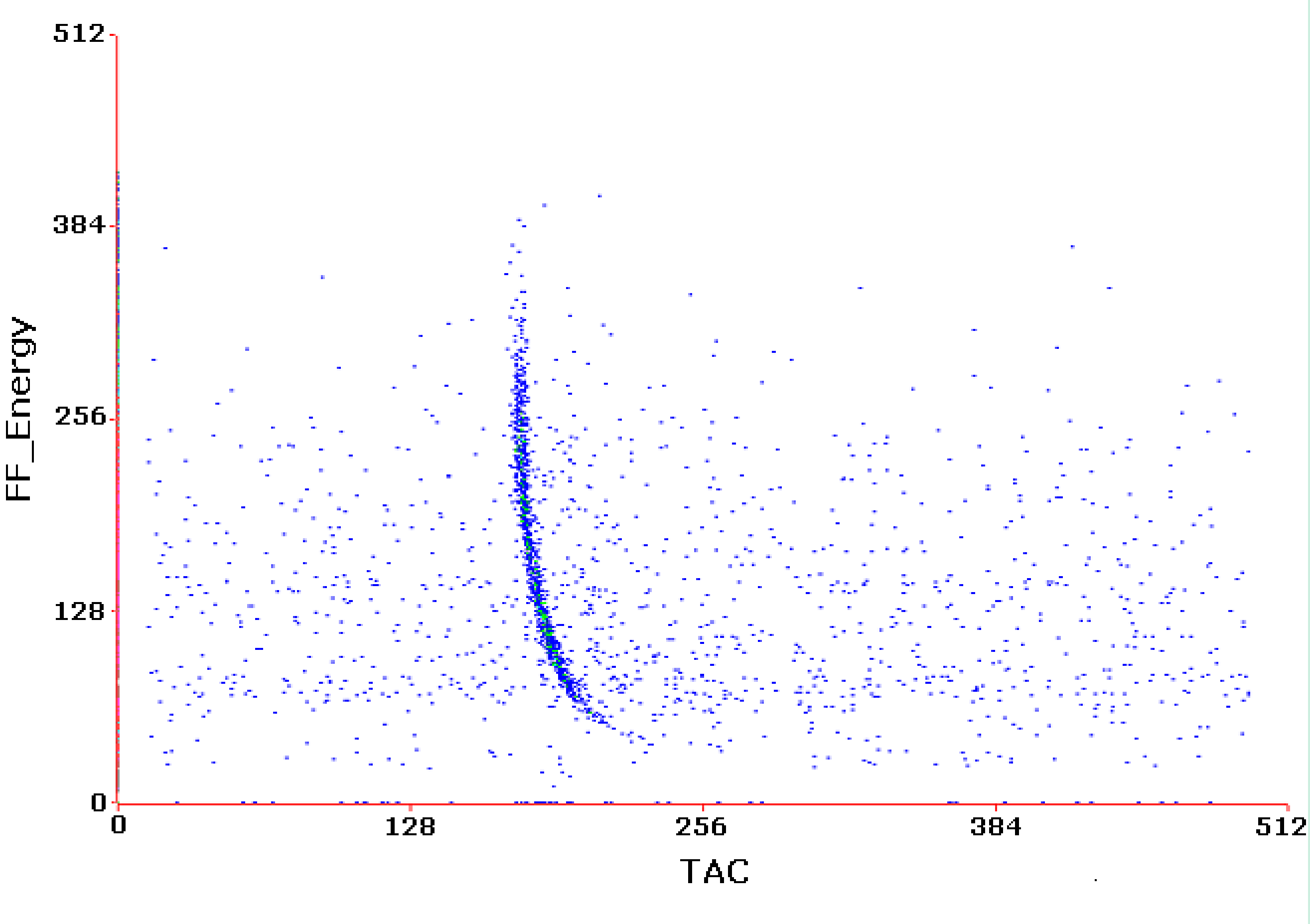


R.P. Vind et al.,NIM A,580 (2007) 1435

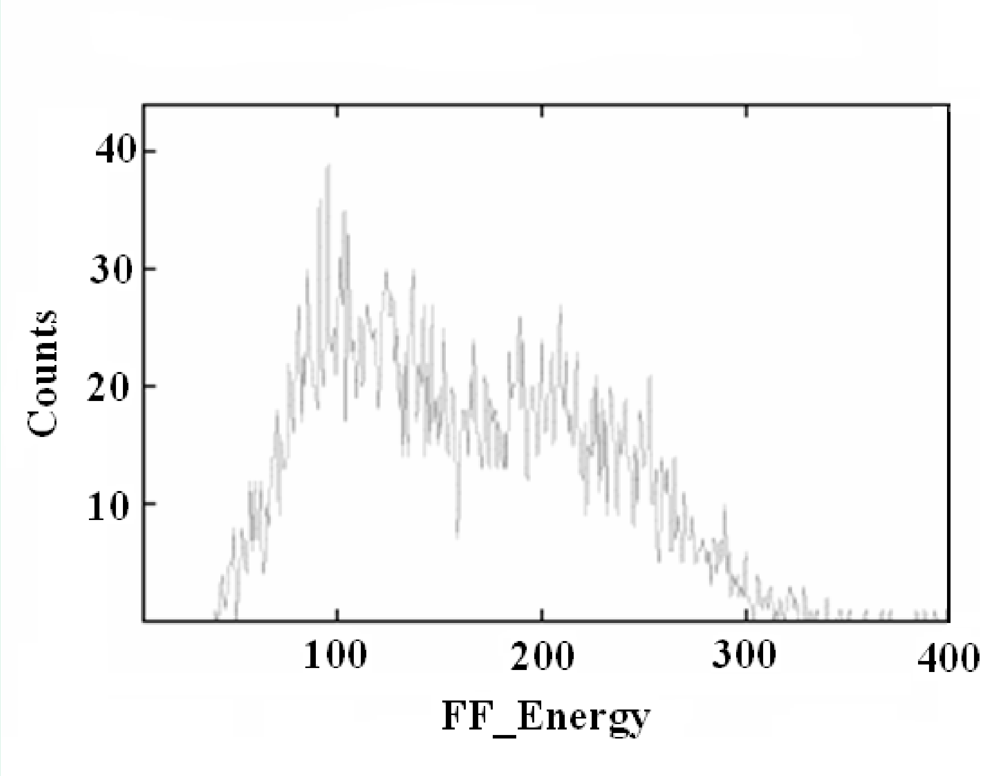
Particle Identification Plot



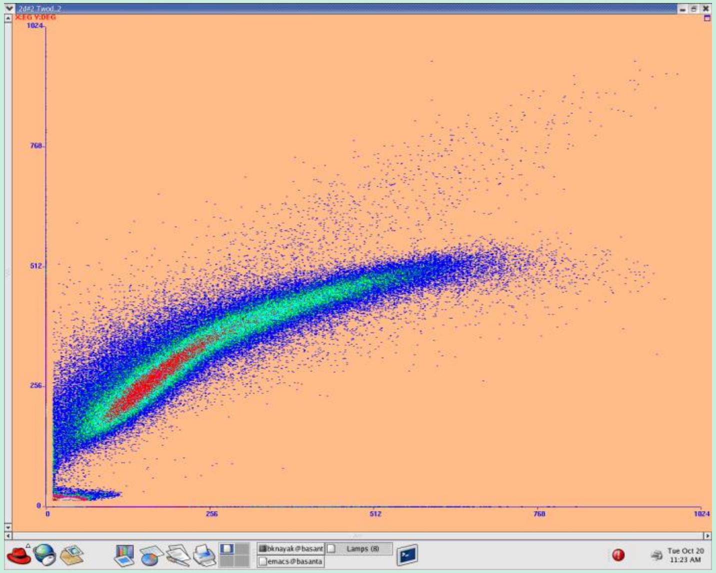
Typical PLF-FF TAC verses FF energy Plot



$^{6}Li+^{232}Th$

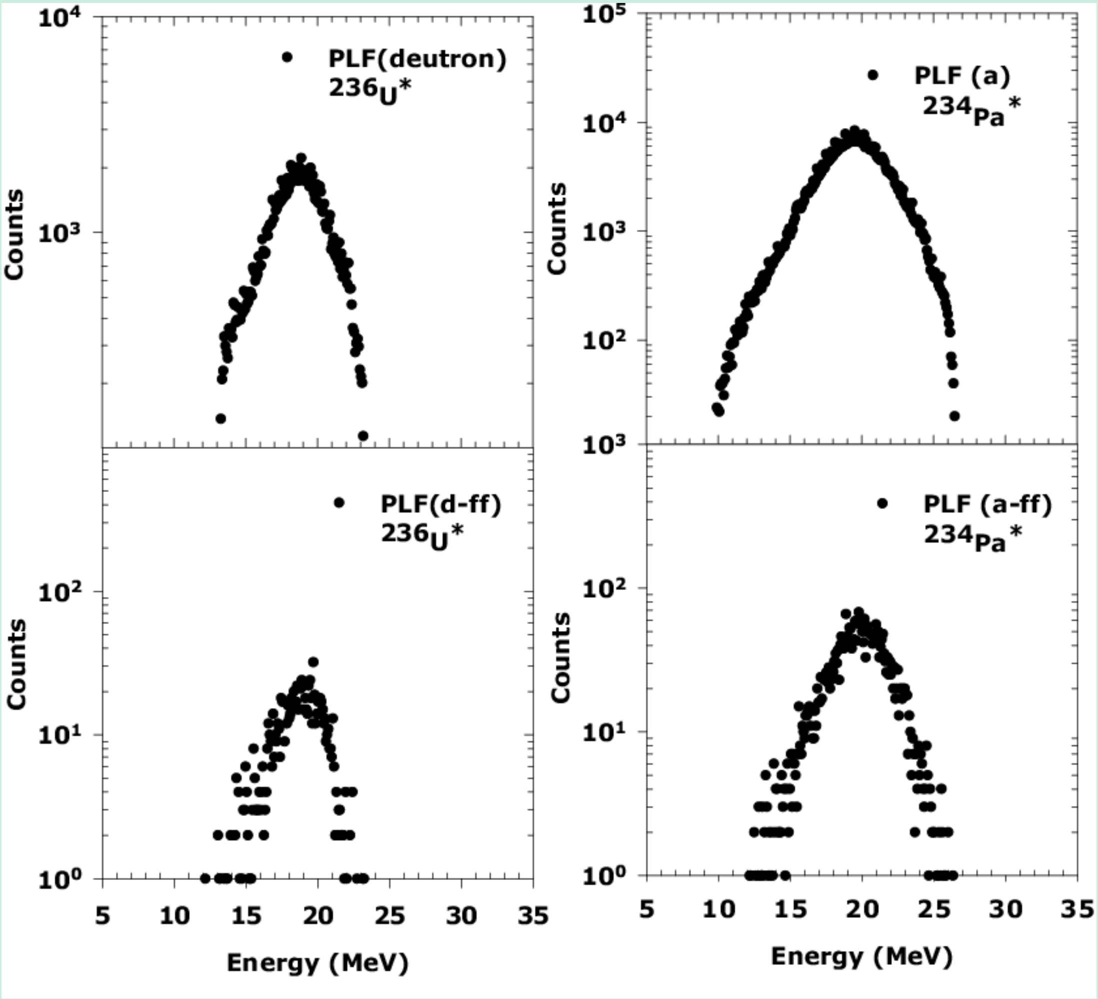


FF_Energy spectrum in transfer induced fission reaction.



A Typical 2-D Spectra of Fission Fragments in Gas Detector

Excitation energy spectrum



Excitation energy range 16-22 MeV

Hybrid Surrogate ratio method

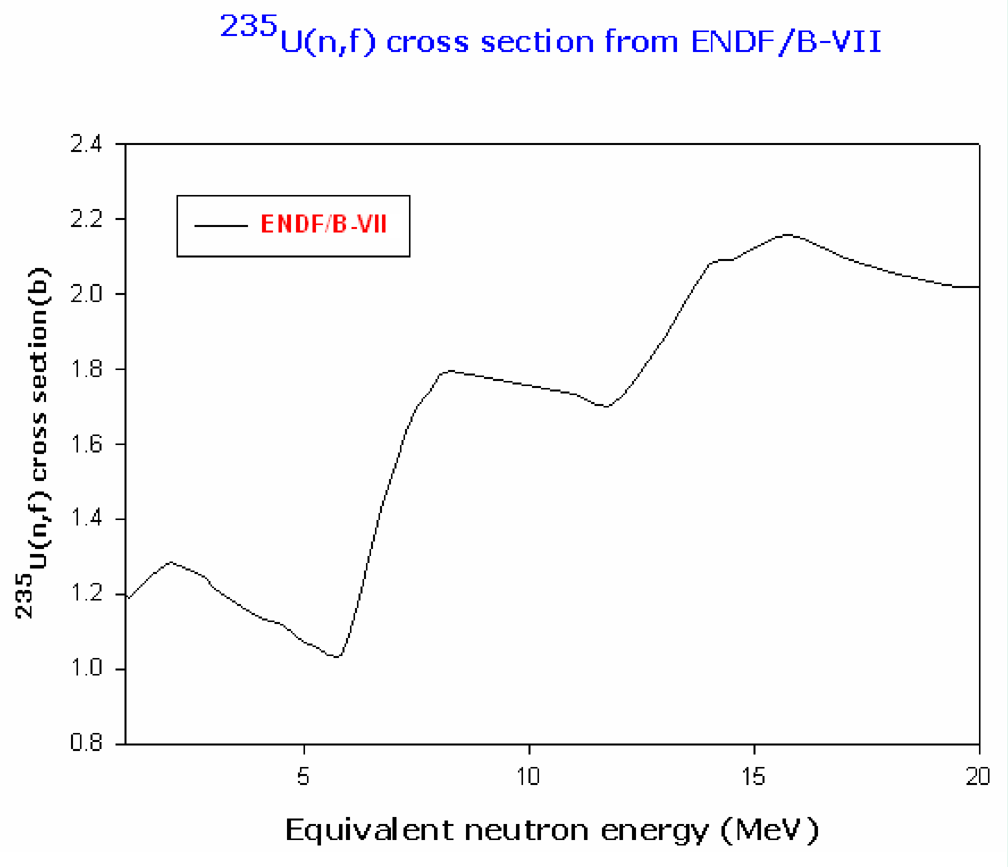
The fission decay probabilities for ^{234}Pa and ^{236}U are obtained by dividing PLF-F coincidence with corresponding single data.

$$\Gamma_f^{\mathrm{CN}}(E_{\mathrm{ex}}) = \frac{N_{\alpha_i - f}}{N_{\alpha_i}}, \qquad (1)$$

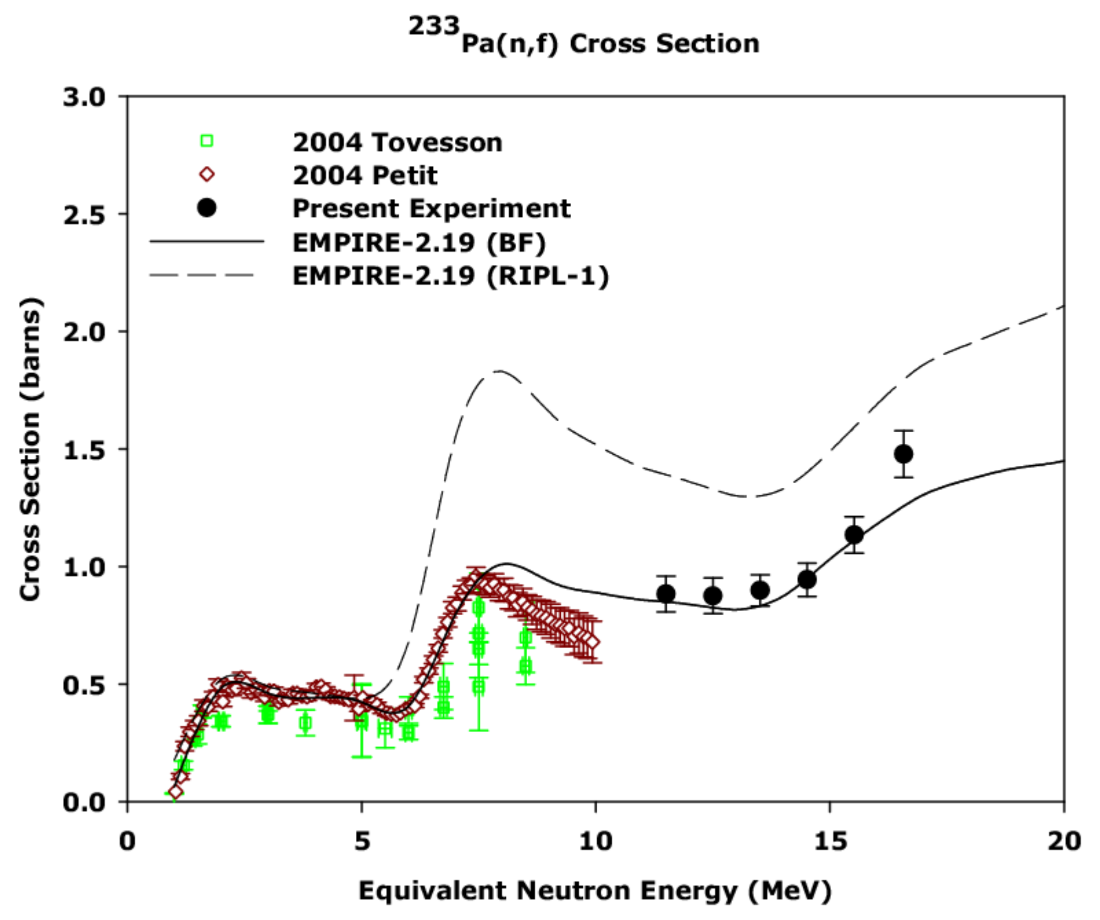
Ratio of the neutron induced fission cross section is given as follows:

$$\frac{\sigma_f^{n+{}^{233}\mathrm{Pa}\rightarrow{}^{234}\mathrm{Pa}}(E_{\mathrm{ex}})}{\sigma_f^{n+{}^{235}\mathrm{U}\rightarrow{}^{236}\mathrm{U}}(E_{\mathrm{ex}})} = R(E_{\mathrm{ex}}) = \frac{\sigma_{n+{}^{233}\mathrm{Pa}}^{\mathrm{CN}}(E_{\mathrm{ex}})}{\sigma_{n+{}^{235}\mathrm{U}}^{\mathrm{CN}}(E_{\mathrm{ex}})} \frac{\Gamma_f^{{}^{234}\mathrm{Pa}}(E_{\mathrm{ex}})}{\Gamma_f^{{}^{236}\mathrm{U}}(E_{\mathrm{ex}})}. \qquad (2)$$

^{235}U(n,f) cross section data



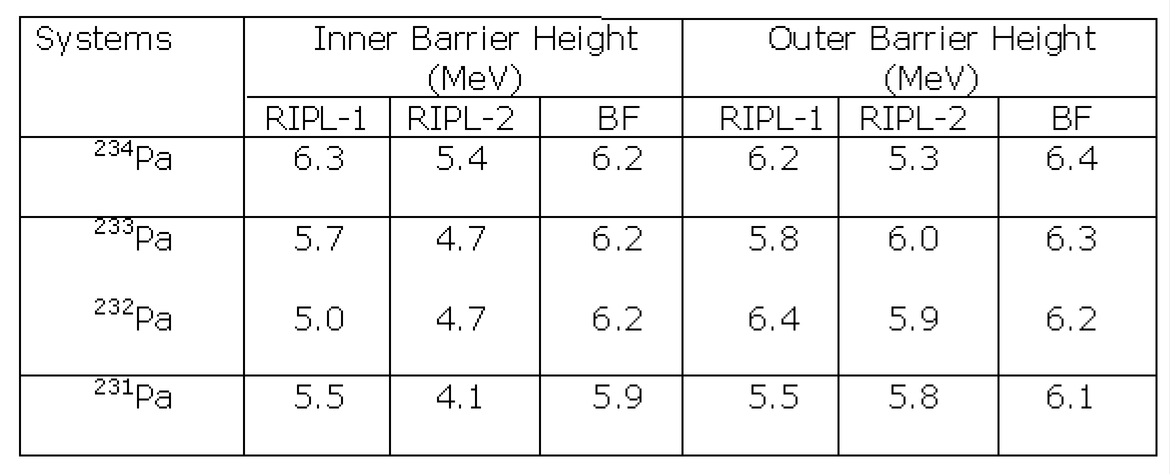
^{233}Pa(n,f) Excitation function



^{233}Pa(E$_{ex}$, n, f))=^{233}Pa ((233/234)E$_n$+S$_n$(^{234}Pa), n, f)

B. K. Nayak et al.,PRC78,061602 (R)(2008)

The values of fission barrier heights used in Empire-2.19 calculations in case of RIPL-1, RIPL-2 and Barrier Formula (BF).



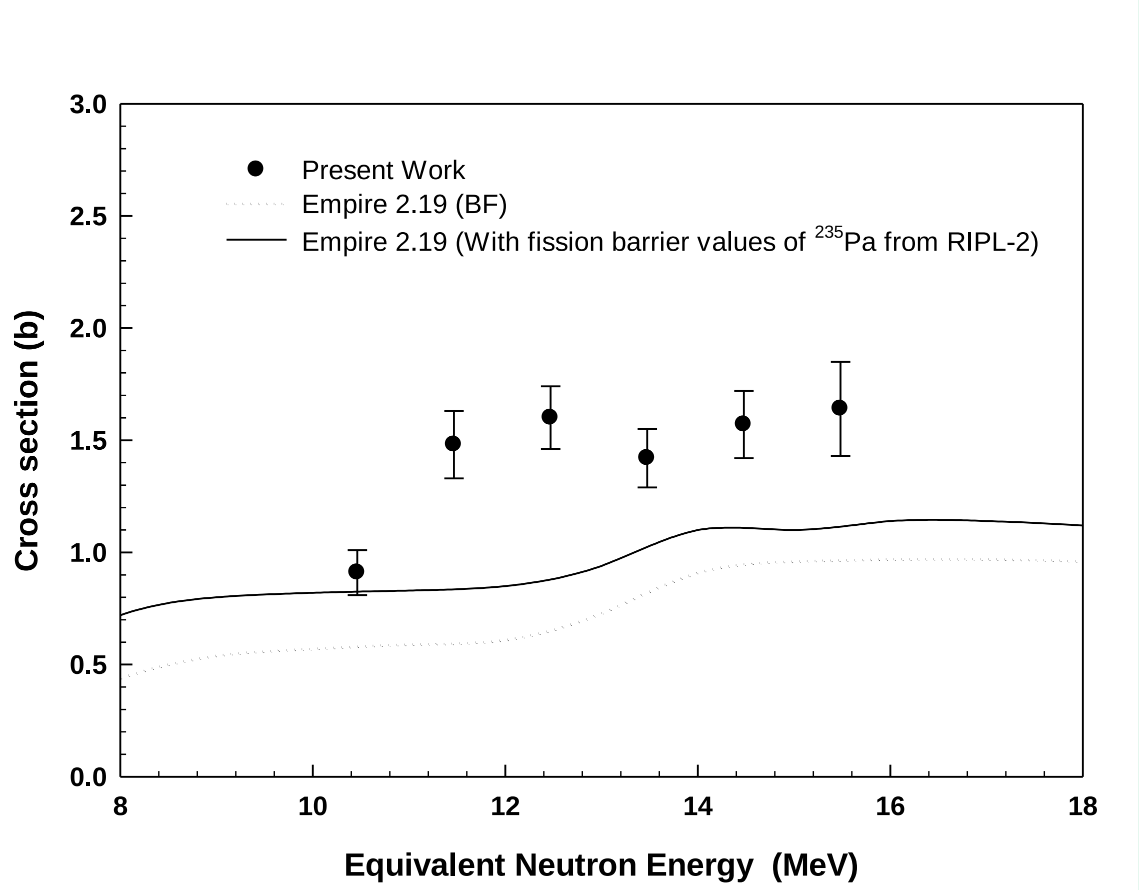
Systems	Inner Barrier Height (MeV)			Outer Barrier Height (MeV)		
	RIPL-1	RIPL-2	BF	RIPL-1	RIPL-2	BF
^{234}Pa	6.3	5.4	6.2	6.2	5.3	6.4
^{233}Pa	5.7	4.7	6.2	5.8	6.0	6.3
^{232}Pa	5.0	4.7	6.2	6.4	5.9	6.2
^{231}Pa	5.5	4.1	5.9	5.5	5.8	6.1

RIPL-1: Compiled by V.M. Maslov for post thorium systems.

RIPL-2: IAEA

BF: Which has been fitted to reproduce the fission barriers given by S. Bjornholm and J. E. Lynn

^{234}Pa(n,f) Excitation function
Preliminary results



^{235}Pa

RIPL-2: 5.1 MeV, 5.7 MeV
BF: 5.8 MeV, 6.1 MeV

Surrogate reaction techniques with RIB

- Isotopes further from stability: Inverse kinematics
- Holifield Radioactive Ion Beam facility (HRIBF)
- (d,p) reaction looks promising : Helical Orbit Spectrometer (HELIOS) at ANL.

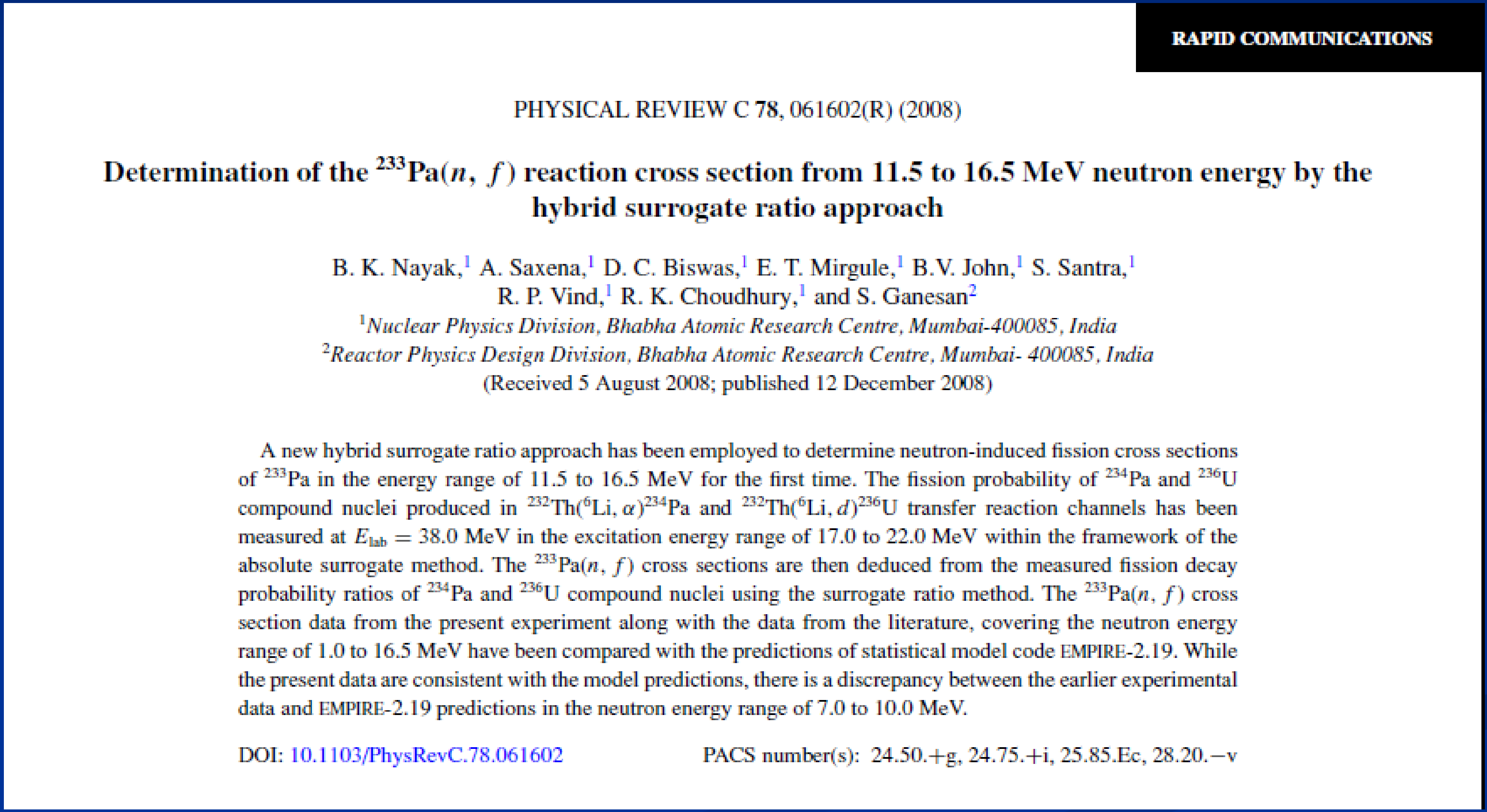
Conclusions

- The surrogate reaction methods can be used as a tool to determine compound nuclear reaction cross sections for difficult to produce targets.

- The (n,f) cross sections extracted from surrogate measurement show reasonable agreement with directly measured cross sections for neutron energy above 1-2 MeV.

- Using surrogate reactions a wide-range of cross sections for exotic and short-lived isotopes will be accessible to study at many existing and future high intensity RIB facilities around the world.

Thank You



RAPID COMMUNICATIONS

PHYSICAL REVIEW C **78**, 061602(R) (2008)

Determination of the ^{233}Pa(n, f) reaction cross section from 11.5 to 16.5 MeV neutron energy by the hybrid surrogate ratio approach

B. K. Nayak,[1] A. Saxena,[1] D. C. Biswas,[1] E. T. Mirgule,[1] B.V. John,[1] S. Santra,[1]
R. P. Vind,[1] R. K. Choudhury,[1] and S. Ganesan[2]
[1]*Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai-400085, India*
[2]*Reactor Physics Design Division, Bhabha Atomic Research Centre, Mumbai- 400085, India*

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A new hybrid surrogate ratio approach has been employed to determine neutron-induced fission cross sections of ^{233}Pa in the energy range of 11.5 to 16.5 MeV for the first time. The fission probability of ^{234}Pa and ^{236}U compound nuclei produced in ^{232}Th(^{6}Li, α)^{234}Pa and ^{232}Th(^{6}Li, d)^{236}U transfer reaction channels has been measured at $E_{\text{lab}} = 38.0$ MeV in the excitation energy range of 17.0 to 22.0 MeV within the framework of the absolute surrogate method. The ^{233}Pa(n, f) cross sections are then deduced from the measured fission decay probability ratios of ^{234}Pa and ^{236}U compound nuclei using the surrogate ratio method. The ^{233}Pa(n, f) cross section data from the present experiment along with the data from the literature, covering the neutron energy range of 1.0 to 16.5 MeV have been compared with the predictions of statistical model code EMPIRE-2.19. While the present data are consistent with the model predictions, there is a discrepancy between the earlier experimental data and EMPIRE-2.19 predictions in the neutron energy range of 7.0 to 10.0 MeV.

DOI: 10.1103/PhysRevC.78.061602 PACS number(s): 24.50.+g, 24.75.+i, 25.85.Ec, 28.20.−v

Review of $^{233}Pa(n,f)$ data

Direct measurement: (1.0 MeV to 8.5 MeV) by F. Tavesson et al.(2004)

T(p, n)^{3}He and D(d, n)^{3}H reactions were used to produce neutrons with energies of E_n = 1.0-3.8 MeV and E_n = 5.0-8.5 MeV, respectively.

Indirect measurement: (1.0 MeV to 10.0 MeV) by M. Petit el al. (2004)

By employing the $^{232}Th(^{3}He, p)^{234}Pa$ transfer reaction the fission probability of the compound nucleus in neutron-induced fission of ^{233}Pa was determined,

The $^{233}Pa(n, f)$ cross section was then calculated as the product of the experimental fission probability and the theoretical compound nucleus formation cross section.

$$\sigma^{n,f}(E)=\sigma^{CN}(E_n)\times P_f(E)$$

In the Hauser-Feshbach formalism, the compound nuclear cross section is given by

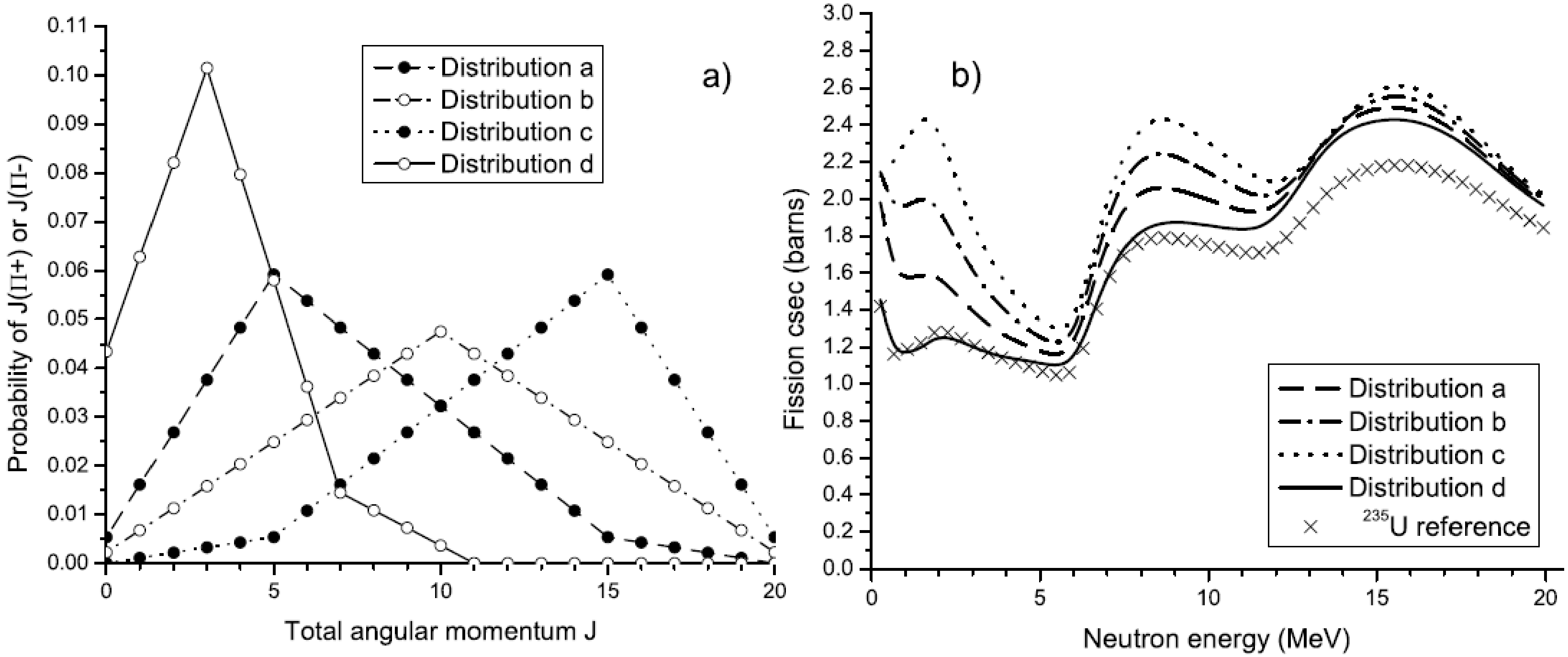
$$\sigma_{\alpha\chi}(E_a) \quad = \quad \sum_{J,\pi} \sigma_{\alpha}^{CN}(E_{ex}, J, \pi) \;\; G_{\chi}^{CN}(E_{ex}, J, \pi)$$

If Weisskopf-Ewing approximation hold, the formula for desired cross section simplifies to

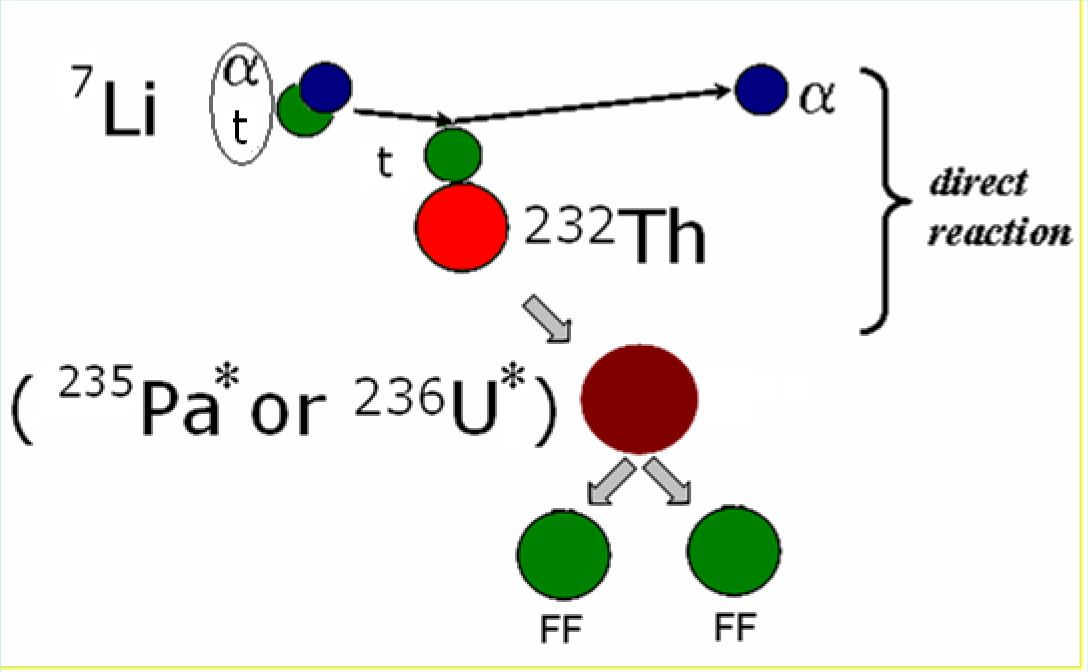
$$\sigma_{\alpha\chi}(E^*) = \sigma_{\alpha}^{CN}(E^*) G_{\chi}^{CN}(E^*)$$

Most applications of the Surrogate method so far have been based on the assumption that the Weisskopf-Ewing limit is valid for the cases of interest.

Testing the validity of the Weisskopf-Ewing assumption ^{235}U(n,f) reaction



^{7}Li+ ^{232}Th transfer reaction (as the hybrid Surrogate reaction)



By carrying out PLF-FF coincidence measurement, we can determine the decay probability of the compound residues