Fission product yield compilation

V. Semkova

Institute for Nuclear Research and Nuclear Energy,
Bulgarian Academy of Sciences
Sofia, Bulgaria

Content

- Fission process , products and observables
- Experimental techniques and detectors used for fission fragments mass distribution measurements:
  - Measurements based on kinematic properties (Exercise I);
  - Measurements based on mass spectrometry;
  - Isotopic quntification based on gamma spectrometry (Exercise II).
- New horizons reached from measurements in inverse kinematics, with radioactive ion beams and surrogate (multi-nucleon transfer) reaction (Exercise III).

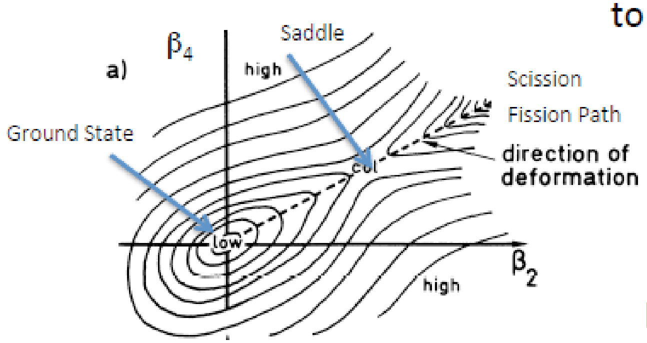
Liquid drop model

$$B = a_v A - a_s A^{2/3} - a_c Z(Z-1) A^{-1/3} - a_{sym} A^{-1} (A-2Z)^2 + a_p A^{-1/2}$$

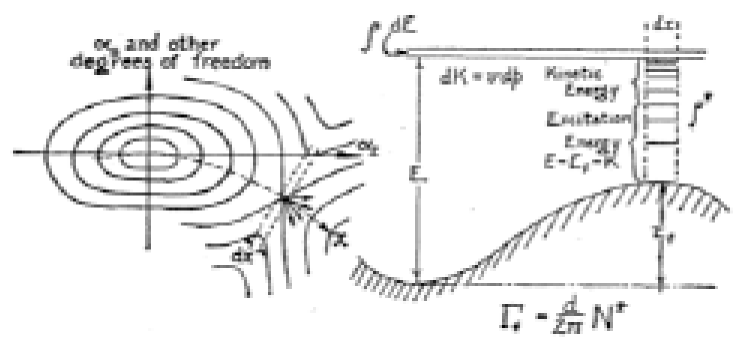
Vol. Surface Coulomb Isospin Parity

For liquid drop model volume is constant. So, the potential energy of the system during deformation and oscillation is determined by the changes in Coulomb and surface energies terms.

Bohr and Wheeler applied LDM to explain fission, which occurs when the nucleus stretches and oscillate. They presented the nuclear deformation by a Legendre expansion about the nuclear radius with coefficients β_n and describe the potential energy of the system as a function of β_2 and β_4.



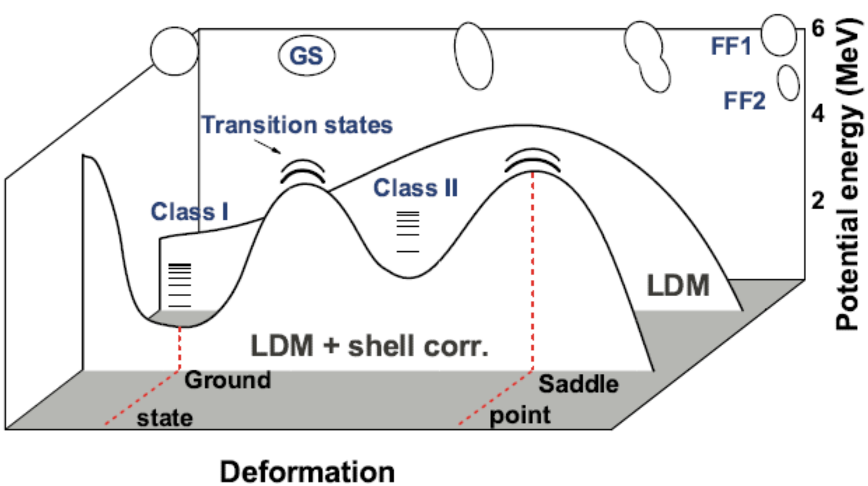
to



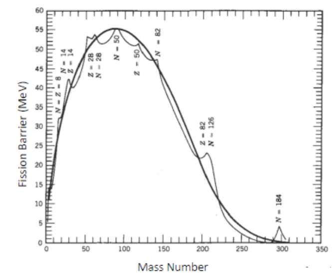
Adding shell model corrections to the LDM

Strutinsky added shell model corrections that transformed LDM shape to double-humped barrier. That changed the fission barrier penetrability giving: rise to subthreshold fission and transmission resonances.

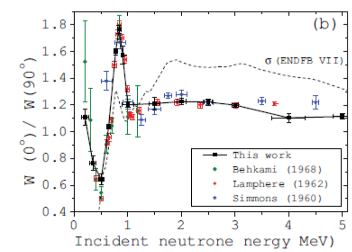
But not only that. The shell structure of the compound nucleus and the two nascent fragments define the yield, energy and angular distribution of all fission products

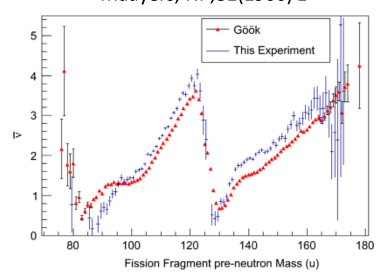


K.-H. Schmidt and B. Jurado. *Phys. Rev.*, C83:061601, (2011).

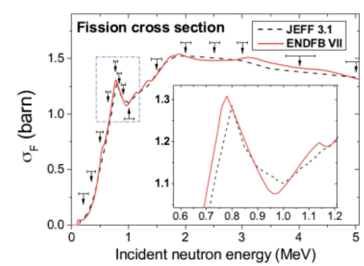


Maayers, NP,81(1966) 1





M.O. Frégeau, NIM/A,817 (1026)35



A. Al-Adili, PR/C,94,034603 (2016)

Energy released from fission

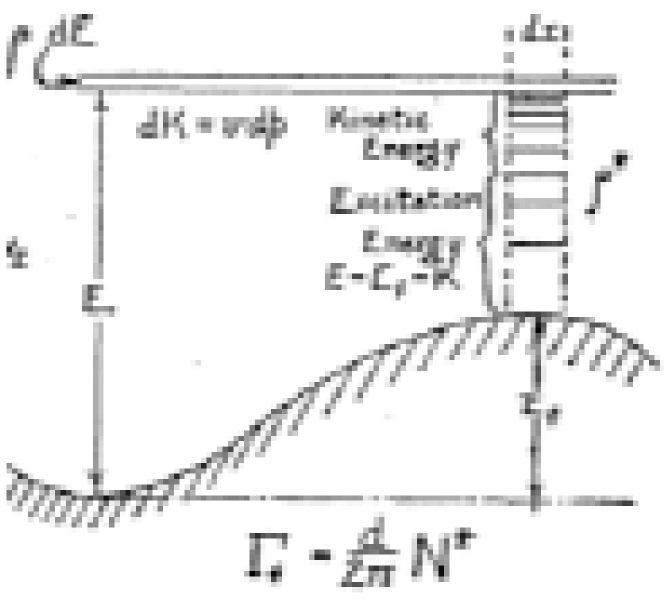
Total available energy: $E_t = [M(Z,A) - M_L(Z_L,A_L) - M_H(Z_H,A_H) + m_n]\, c^2 + E_n$

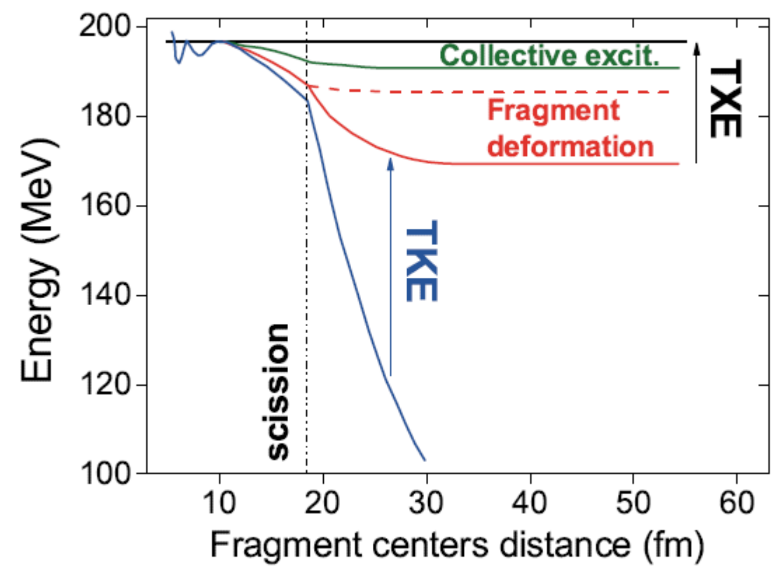
^{235}U thermal neutron fission

Approximate Prompt Energy Release	MeV
Fission Fragments	170
Fission Neutrons	5
Prompt γ emission	7
γ emission from fission fragments	7
β emission from fission fragments	8
ν from fission products	12
Total Energy per Fission	209

Fission fragments energy balance

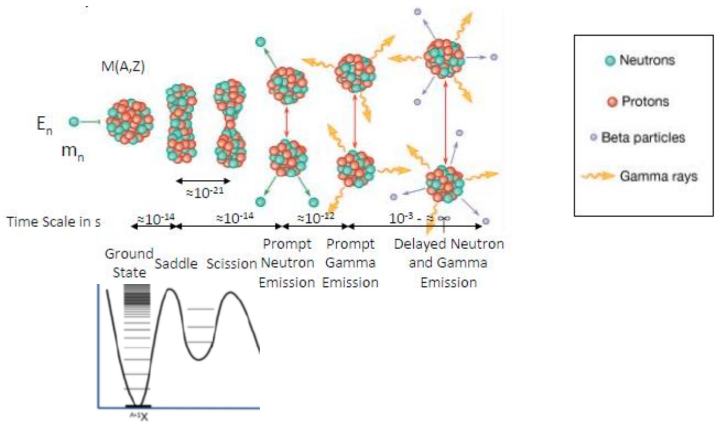
- Fragments total kinetic energies (TKE)
  - $TKE = 1.44(Z_1 Z_2 / D)$ at scission
- Fragments total excitation energy (TXE)
  - Intrinsic excitation
  - Deformation excitation
  - Collective excitation

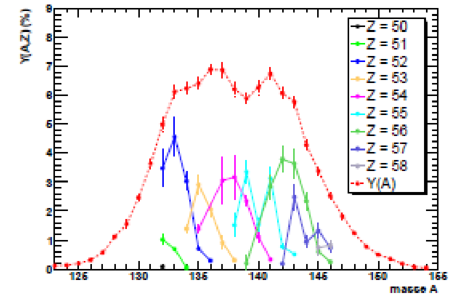


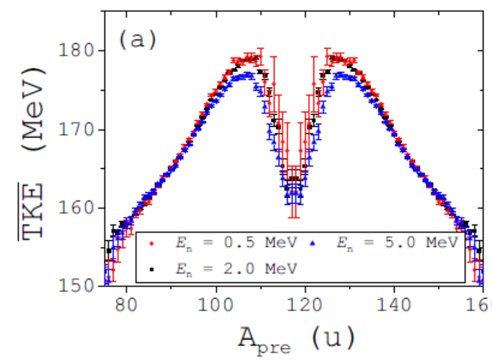


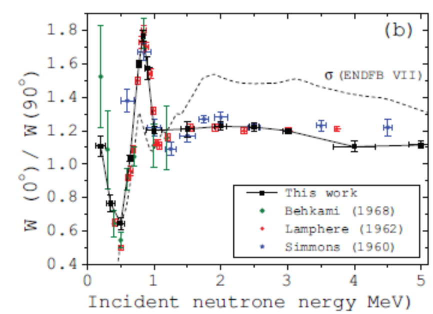
K.-H. Schmidt and B. Jurado. *Phys. Rev.*, C83:061601, (2011).

Fission products and observables









- Fission cross-sections for particles/nuclides involved as a function of energy
- Fission fragments kinetic energy, mass/charge yield and angular distribution
- Prompt neutrons and gamma rays multiplicity, energy and angle distributions
- Fragments beta and gamma decay
- Delayed neutrons emission from fragments

Fission yields measurement

- $\sum Y(Z,A) = 200\ \%$
- Y(A) fragment mass measurements: energy, time-of-flight
- Y(Z,A) isotopic measurements: gamma spectrometry; energy-loss; energy + time-of flight
- Y(Z) atomic number identification: energy-loss, X-rays measurements

Methods for fission fragments yield measurements

- Measurements based on kinematic properties. Typical method in prompt-fission experiments. Both FF are detected in coincidence to determine their mass and kinetic energy from the mass and momentum-conservation low;
- Gamma spectrometry. Allows isotope identification, but often cumulative fission product yields are obtained. Recently in beam gamma-spectrometry has been applied in some laboratories providing independent FFMD;
- Mass spectrometry.

Detectors employed in kinematic properties measurements

- Proportional Counters + grids to obtain angular information (Frisch-gridded IC)
- Multiwire proportional counter (MWPCs) = Parallel plate ionization chamber and Parallel plate avalanche counters
- Gas scintillation chambers
- Solid-state silicon detectors
- Diamond detectors (poly-crystalline and single-crystal chemical vapor-deposited (pCVD and sCVD))
- Time projection chamber. 3D ionization profile allows particle identification and separation. NIFFTE Collaboration operating TPC is aiming at realistic reduction of systematic uncertainty to 1%

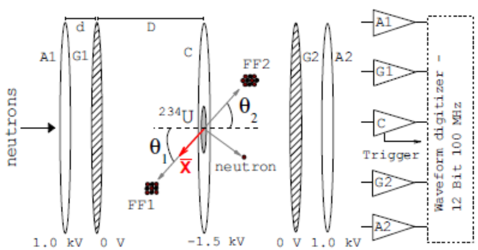
The double-energy (2E) technique

Frisch-grid ionization chamber

Conservation of momentum and mass

Fission product after prompt neutron and gamma emission but before beta-delayed neutron emission.

high efficiency, but limited mass resolution 2-3 amu



Energies and emission angles of FF1 and FF2 are determined + Prompt neutron emission estimated

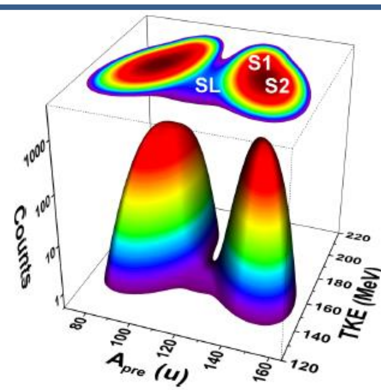
$$E^{lab}_{pre} = \frac{A_{pre}}{A_{pre} - \nu(A,TKE)} E^{lab}_{post},$$

assumed

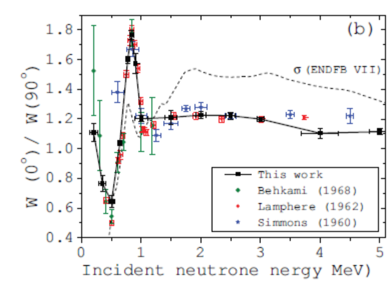
$$E^{c.m.} = E^{lab} + A_{CN}^{-2} A_n A_{pre} E_n^{lab} \pm 2 A_{CN}^{-1} \sqrt{A_{pre} A_n E^{lab} E_n^{lab}} \cos\theta^{lab}.$$

$$A_{1,pre} = A_{CN} E^{c.m.}_{2,pre} \left(E^{c.m.}_{1,pre} + E^{c.m.}_{2,pre}\right)^{-1},$$
$$A_{2,pre} = A_{CN} E^{c.m.}_{1,pre} \left(E^{c.m.}_{1,pre} + E^{c.m.}_{2,pre}\right)^{-1}.$$

Fission Fragments Mass Distribution & Total Kinetic Energy (TKE)



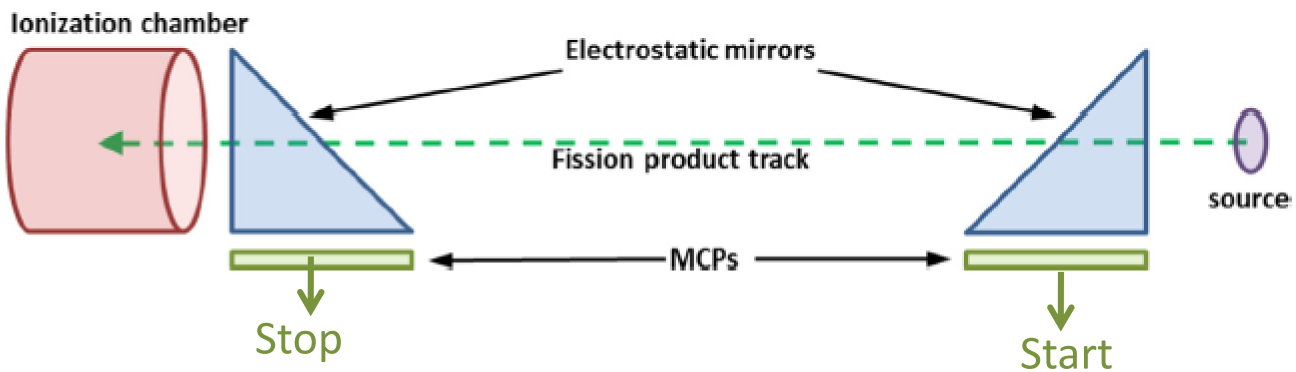
Angular anisotropy



The double energy – double velocity (2E-2v) method

Ionization chamber + time-of-flight spectrometer (SPIDER)

high efficiency and mass resolution 1 amu

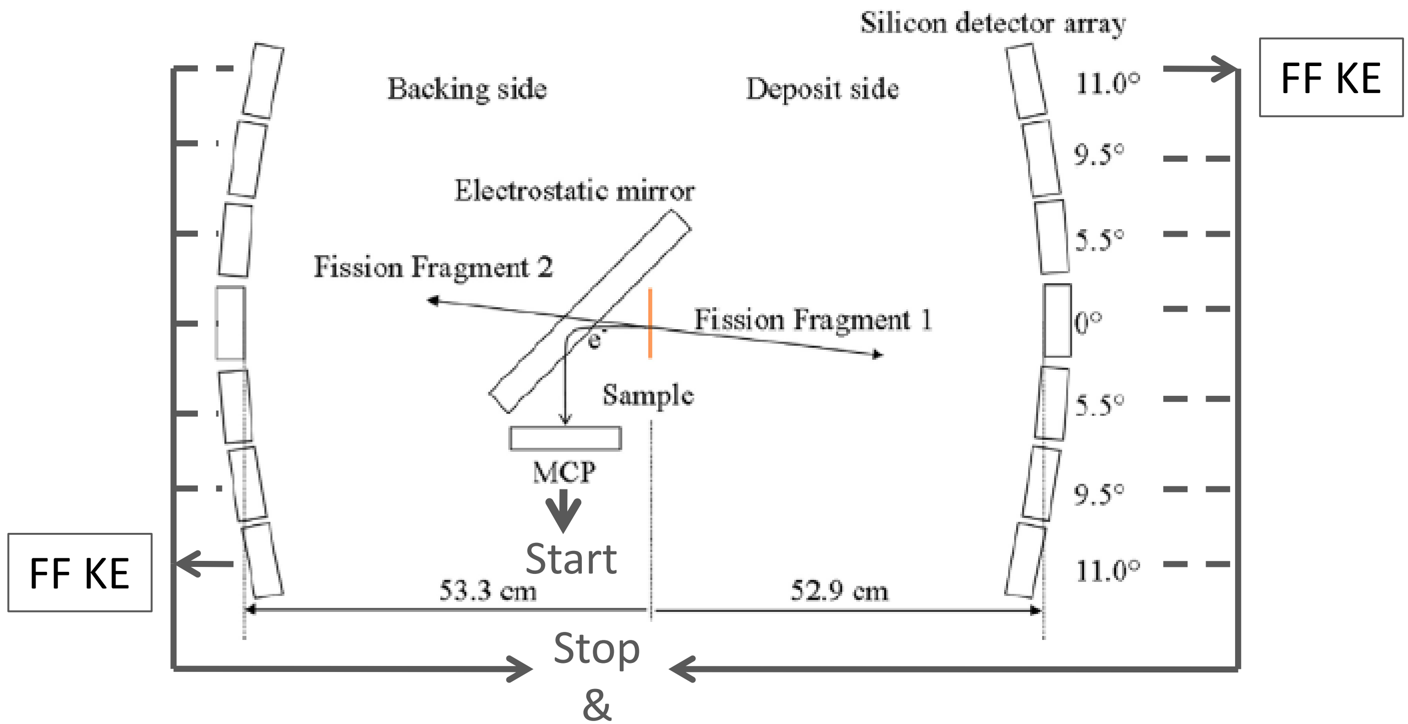


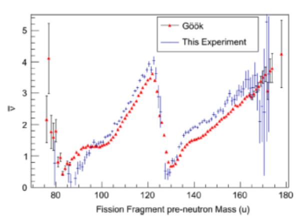
Energies and velocity of FF1 and FF2 are determined	+	Prompt neutron emission spectrum effectively measured by coincidences between FF1 and FF2	→	Fission fragments masses distribution; resolution 1 amu

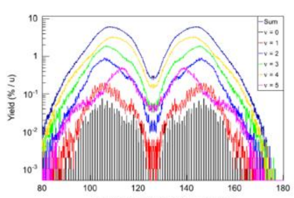
The double energy – double velocity (2E-2v) method

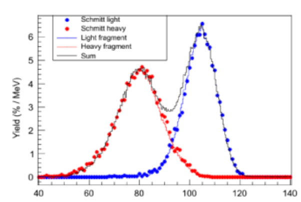
VERDY is a two arm time-of-flight spectrometer

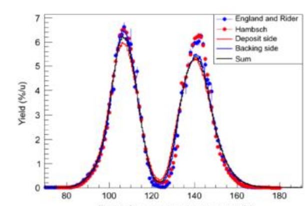
Simultaneous measurements of the pre- and post-neutron fragment characteristics

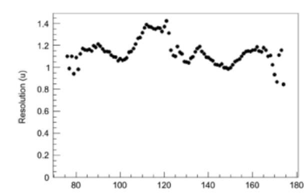












M.F. Fregeau, NIM/A 817 (2016) 35

End of Part I

We will continue with the compilation of:

PHYSICAL REVIEW C **93**, 034603 (2016)

Fragment-mass, kinetic energy, and angular distributions for $^{234}U(n,f)$ at incident neutron energies from $E_n = 0.2$ MeV to 5.0 MeV

A. Al-Adili,[1,2] F.-J. Hambsch,[1,*] S. Pomp,[2] S. Oberstedt,[1] and M. Vidali[1]
[1]*European Commission, Joint Research Centre, Institute for Reference Materials and Measurement (IRMM), B-2440 Geel, Belgium*
[2]*Department of Physics and Astronomy, Uppsala University, Box 516, 751 20 Uppsala, Sweden*
(Received 19 August 2015; published 3 March 2016)

This work investigates the neutron-induced fission of ^{234}U and the fission-fragment properties for neutron energies between $E_n = 0.2$ and 5.0 MeV with a special highlight on the prominent vibrational resonance at $E_n = 0.77$ MeV. Angular, energy, and mass distributions were determined based on the double-energy technique by means of a twin Frisch-grid ionization chamber. The experimental data are parametrized in terms of fission modes based on the multimodal random neck-rupture model. The main results are a verified strong angular anisotropy and fluctuations in the energy release as a function of incident-neutron energy.

DOI: 10.1103/PhysRevC.93.034603