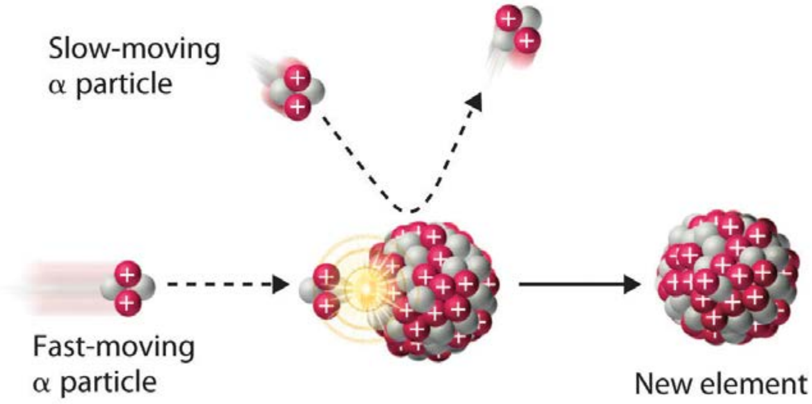
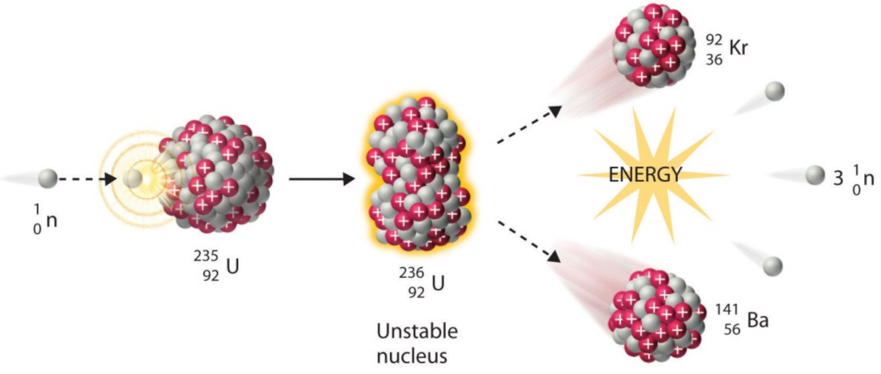
RDCH 702 Lecture 8: Accelerators and Isotope Production

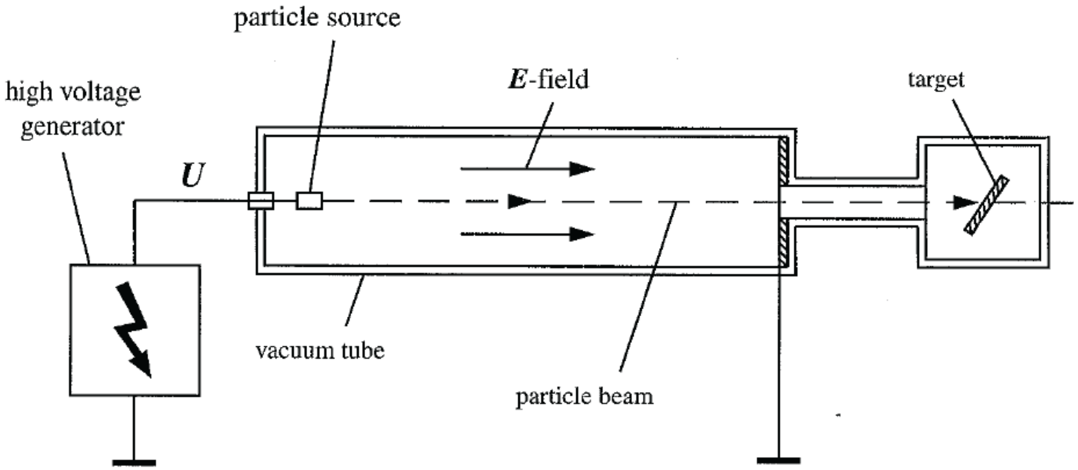
- **Particle generation**
- **Accelerator**
  - **Direct Voltage**
  - **Linear**
  - **Cyclotrons**
  - **Synchrotrons**
    - **→Photons**
      - **XAFS**
      - **Photonuclear**
  - **Heavy Ions**
- **Neutrons sources**
  - **Fission products and reactor**
  - **Spallation**





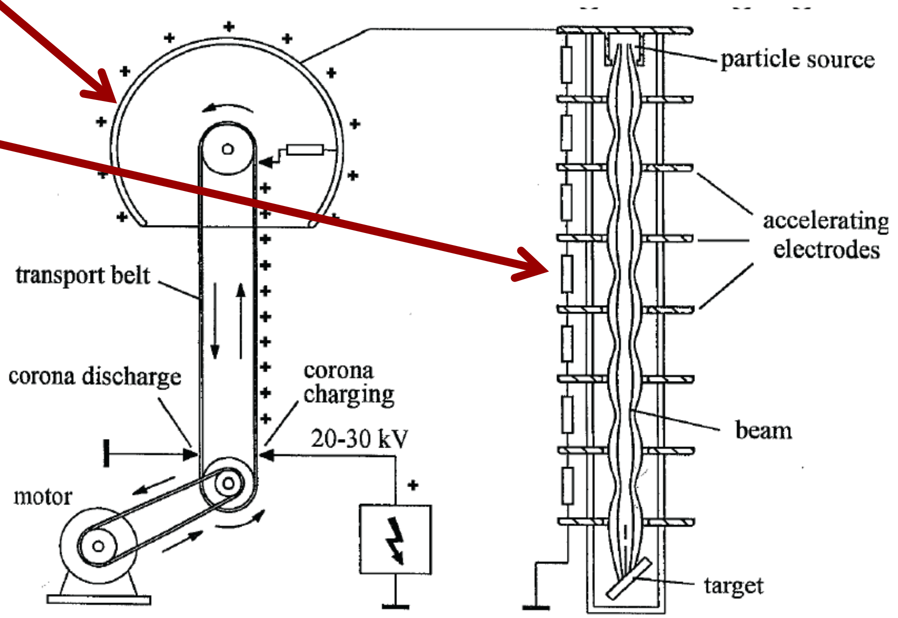
Charged Particle Accelerators: Direct Voltage

- Use of electric fields to accelerate particles
- First used in 1932 for protons
- Cascade Rectifiers and Transformers
  - Direct application of voltage between terminals
    →Maximum voltage defined energy limit
  - Use multiple stages of voltage doubling circuits
- Still used as injectors for high energy accelerator and neutron sources
- Commercially produced



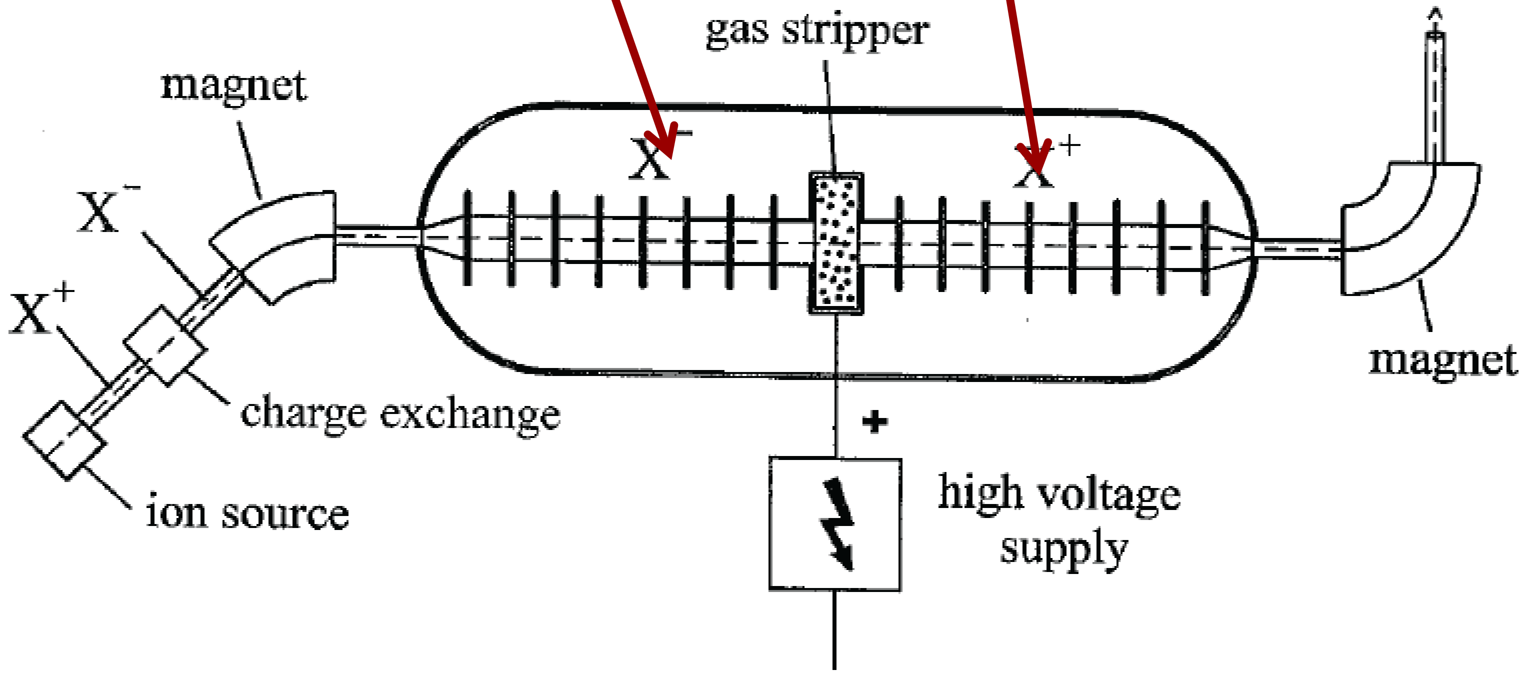
Van de Graaff Generator

- Electrostatic Generator
  - All potential provide at one source
  - Higher potential than direct voltage
- First built in 1929,
  - positive charges collected on a belt and used to charge a sphere
  - equilibrium between build up and loss dictates charge on sphere
- Ion source or electron gun produces ions or electrons which are focused into accelerating tube
  - Accelerating tube
    - under vacuum
    - sections of metal define path
    - focused at ends of metal
  - Well focused beams can be produced
  - Magnetic analyzer may be needed to purify beam
    - H^+, H_2^+, H_3^+ all accelerated



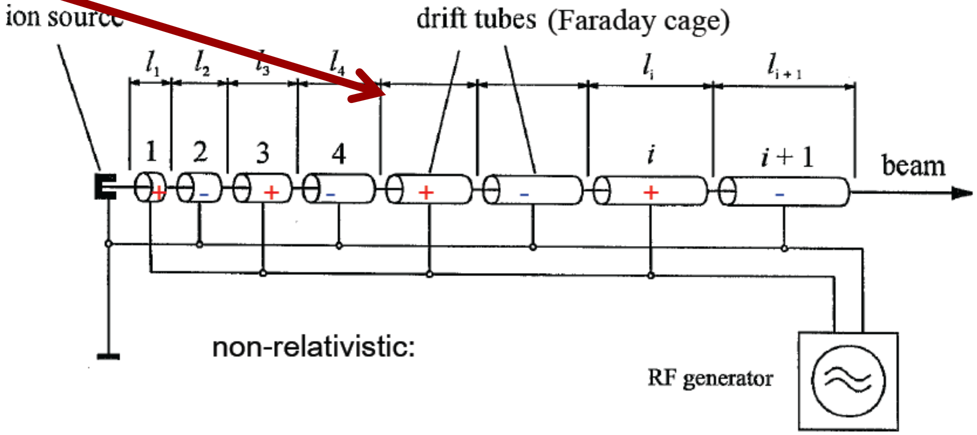
Tandem Van de Graaff Accelerator

- Negative ions (H^-) are accelerated towards positive terminal
- Inside terminal ions are stripped of electrons
- Positive ions further accelerated towards ground
- Can couple more stages
- Proton energies 25-45 MeV

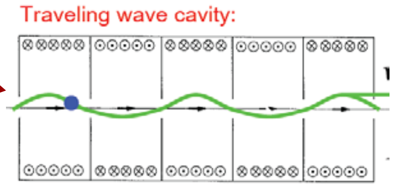


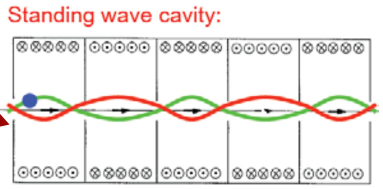
Linear Accelerator

- Repeated accelerations through small potentials
  - Can use other accelerator output as source



- Connection of coaxial sections
- Alternating voltage
- Ions accelerated at gap
- First made in 1928
- Range of cavities
  - Constant or varied in size
    - → Traveling wave
    - → Standing wave


Traveling wave cavity:


Standing wave cavity:

- Electron accelerators on similar principle
  - Pulsed machines
  - Up to 20 GeV
  - Positron acceleration possible (at lower energies)
  - Used for electron scattering, photonuclear reactions, radiation therapy, industrial processing
  - SLAC around 2 miles

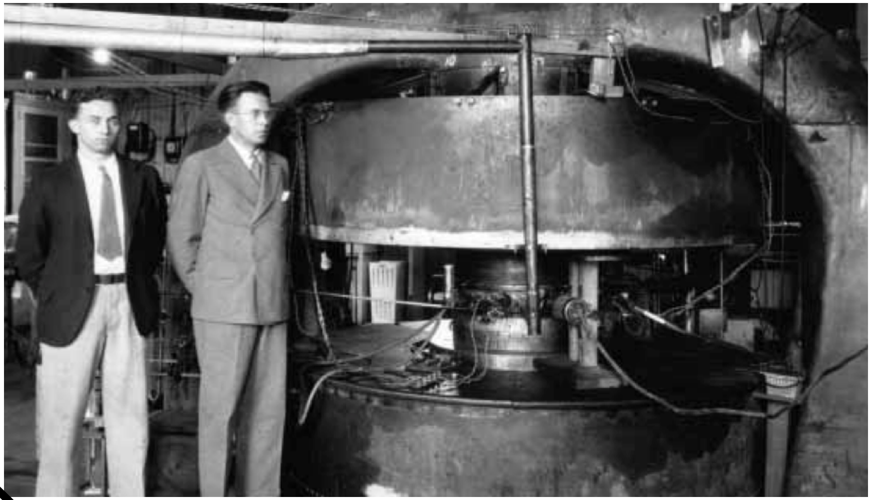
Proton Linacs

- Protons and other positive ions have large velocity increase with energy
- Standing wave acceleration
- Drift tubes need to increase in length
- Acceleration at gap between tubes
- Large energies (up to 800 MeV at LANSCE)
- Use protons as production tool
  - Mesons
  - Neutrons
  - Spallation products

HILACS

- Heavy ion linear accelerator at LBL
- Construction similar to tandem Van de Graaffs
- Accelerate all types of heavy ions, up to U
  - Energies in range of 10 MeV/amu
  - Used in
    - →relativistic experiments
    - →nuclear structure
    - →high energy nuclear collisions
    - →injectors

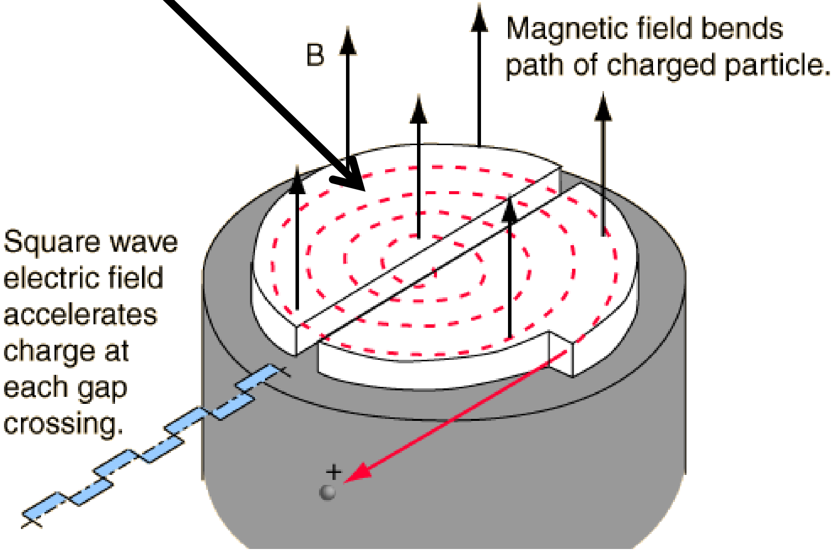
Cyclotrons



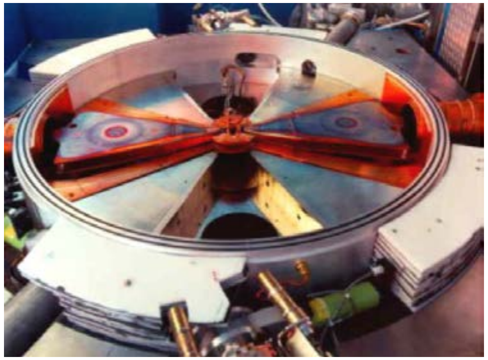
- First built in 1930
- Multiple acceleration by potential
- Ions travel in spiral
- Alternation of “dee” potential accelerates particles
- Obeys equations of motion
  - mass m
  - charge q
  - velocity V
  - magnetic field B
  - radius R

angular velocity $\omega = \frac{V_\perp}{R} = \frac{qB}{m}$,

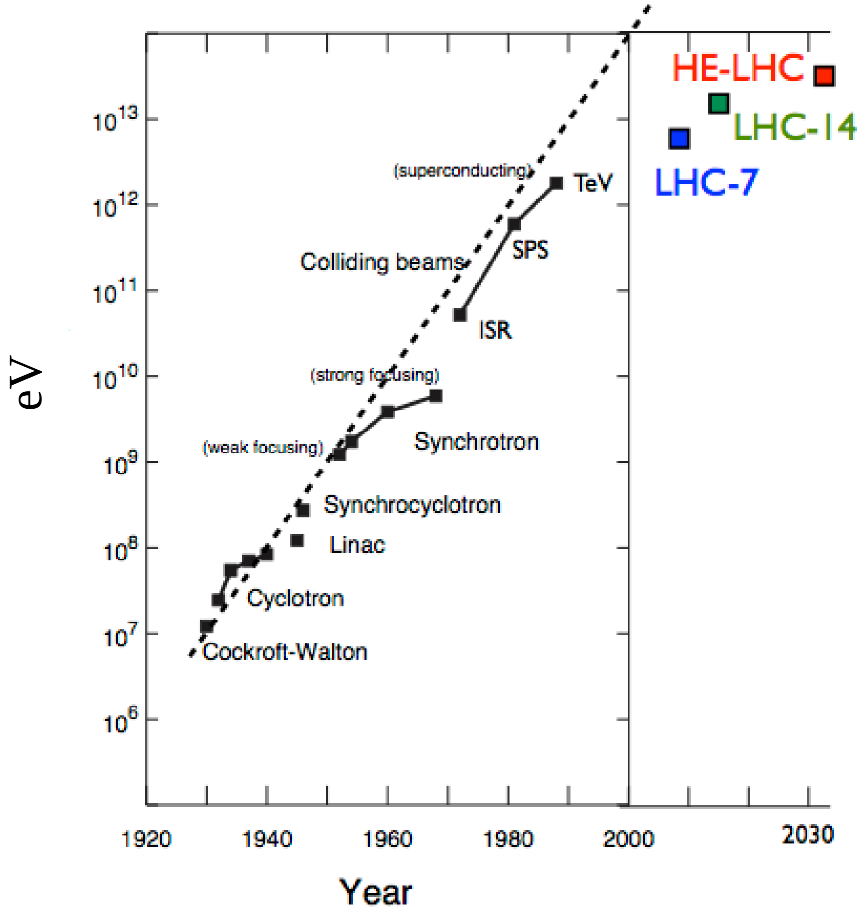
- Can control energy by varying terms
  - R often fixed, B can be varied



Cyclotrons



- Fixed Frequency
  - accelerates chosen e/M ratio
  - different energies since M dependent
- Sector focused
  - useful for heavier ions
  - creates hill and valley in regions
- Cyclotrons can be combined with Linacs for high energy

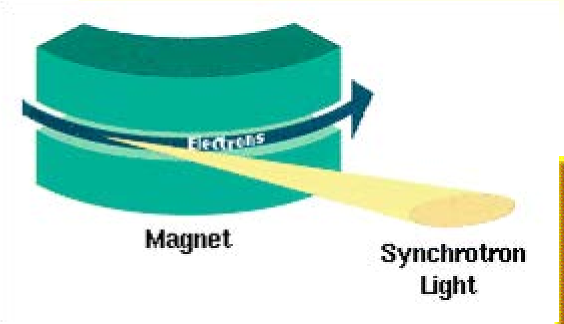


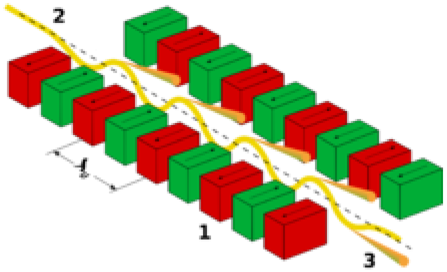
Photon Sources

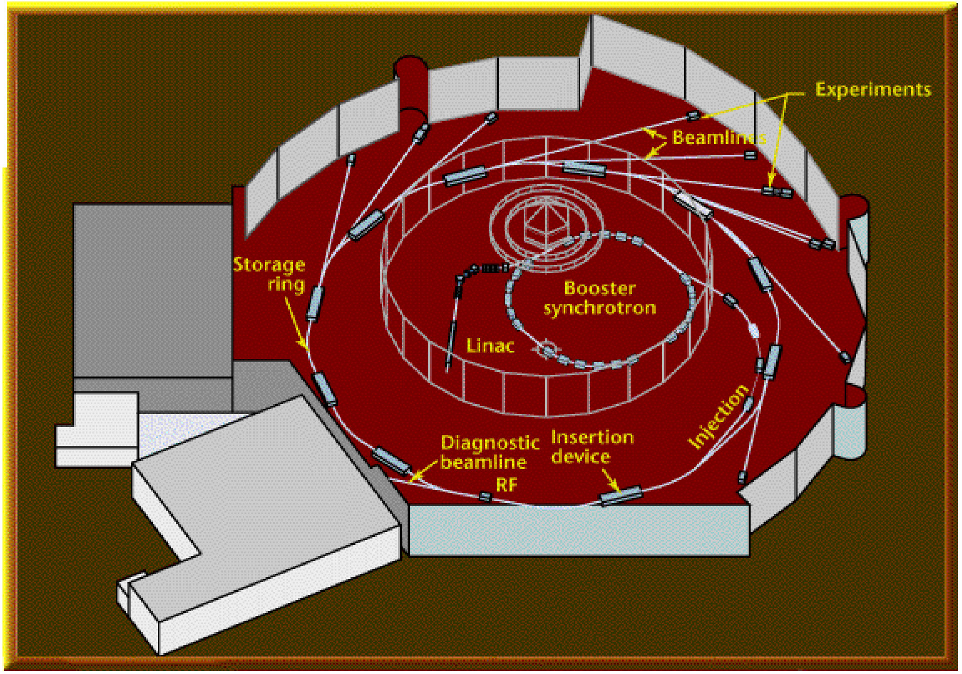
- Continuous spectra of EM radiation is emitted when relativistic electrons are in a curved path in a magnetic field
    - → Relativistic velocity changes observed frequency due to Doppler effect
        - * Lorentz factor (γ)
            - ✂ Time contraction also increase frequency by γ
    - → Forward directed radiation
- can choose wavelength of photons
- useful for determining structure
    - IP, PES, EXAFS, XANES
- Solid state physics
- Reaction mechanisms
- Perform many experiments simultaneously

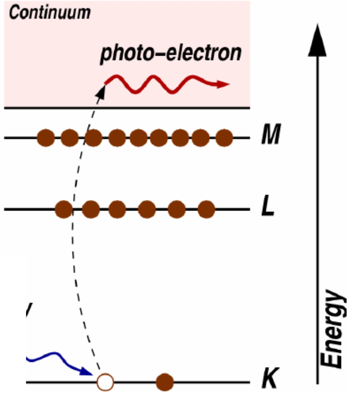
$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{dt}{d\tau}$$

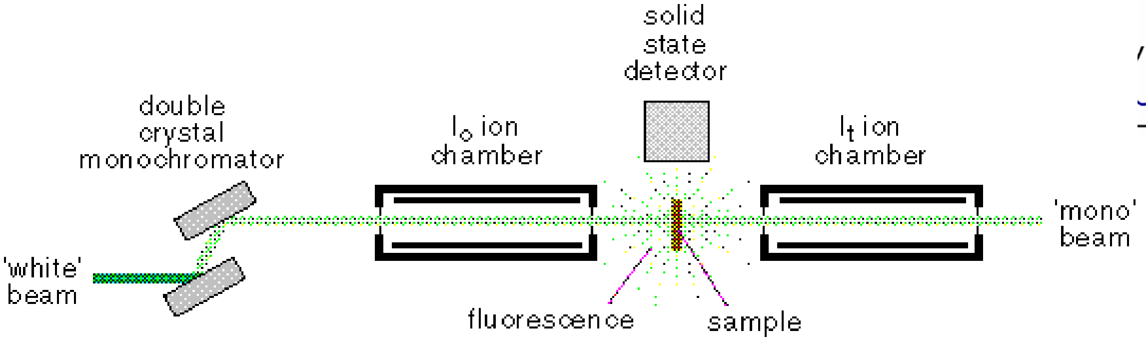
XAS Setup


Electrons
Magnet
Synchrotron Light


2
1
3
λ

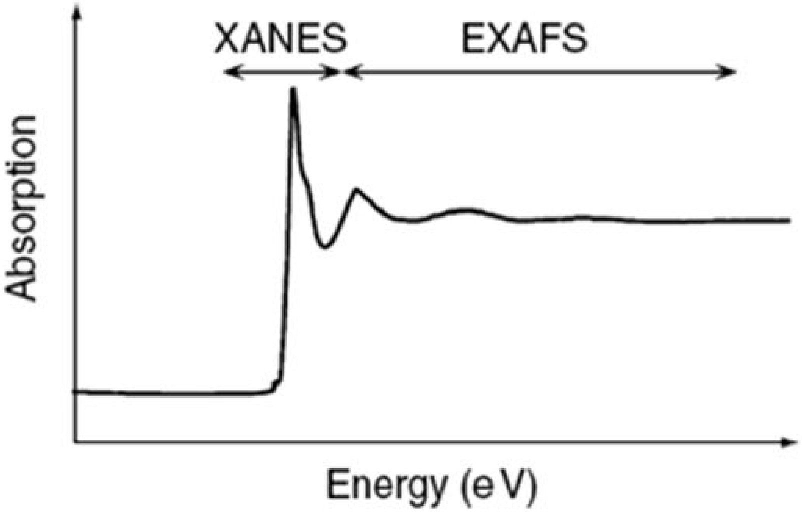

Experiments
Beamlines
Storage ring
Booster synchrotron
Linac
Diagnostic beamline
Insertion device
RF
Injection


Continuum
photo-electron
M
L
K
Energy


solid state detector
double crystal monochromator
I₀ ion chamber
Iₜ ion chamber
'white' beam
'mono' beam
fluorescence
sample

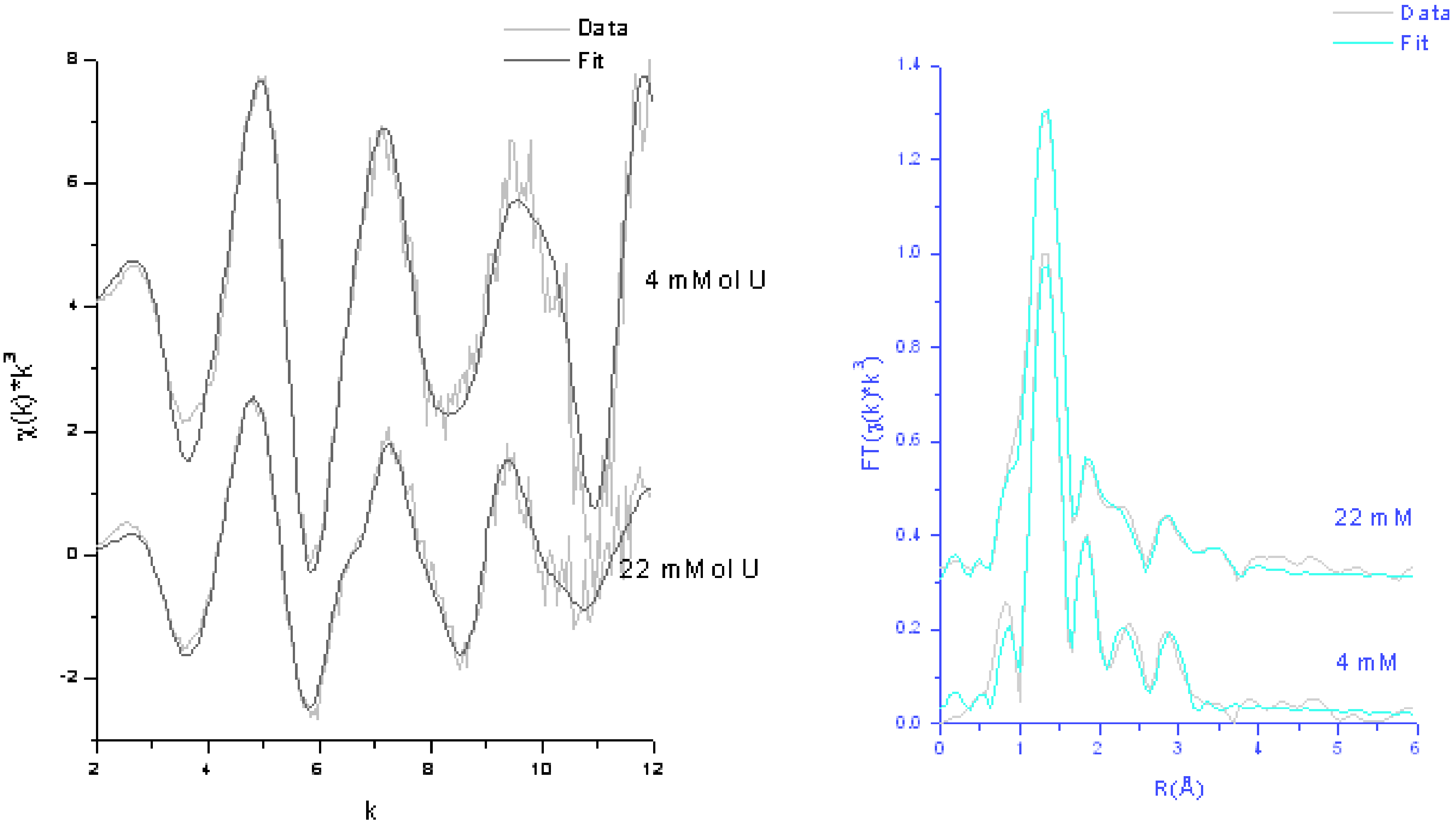
XANES and EXAFS

- **X-Ray Absorption Near Edge Spectroscopy (XANES)**
- **Region between absorption edge and start of EXAFS oscillations, up to 40 eV above edge**
- **Absolute position of edge contains information on oxidation state**
- **Also contains information on vacant orbitals, electronic configuration, and site symmetry**
- **Extended X-ray Absorption Fine Structure (EXAFS)**
- **Above absorption edge, photoelectrons created by absorption of x-ray**
- **Backscattering photoelectrons effect x-ray absorption**
    - **Oscillations in absorption above edge**
    - **Oscillations used to determine atomic number, distance, and coordination number of nearest neighbors**



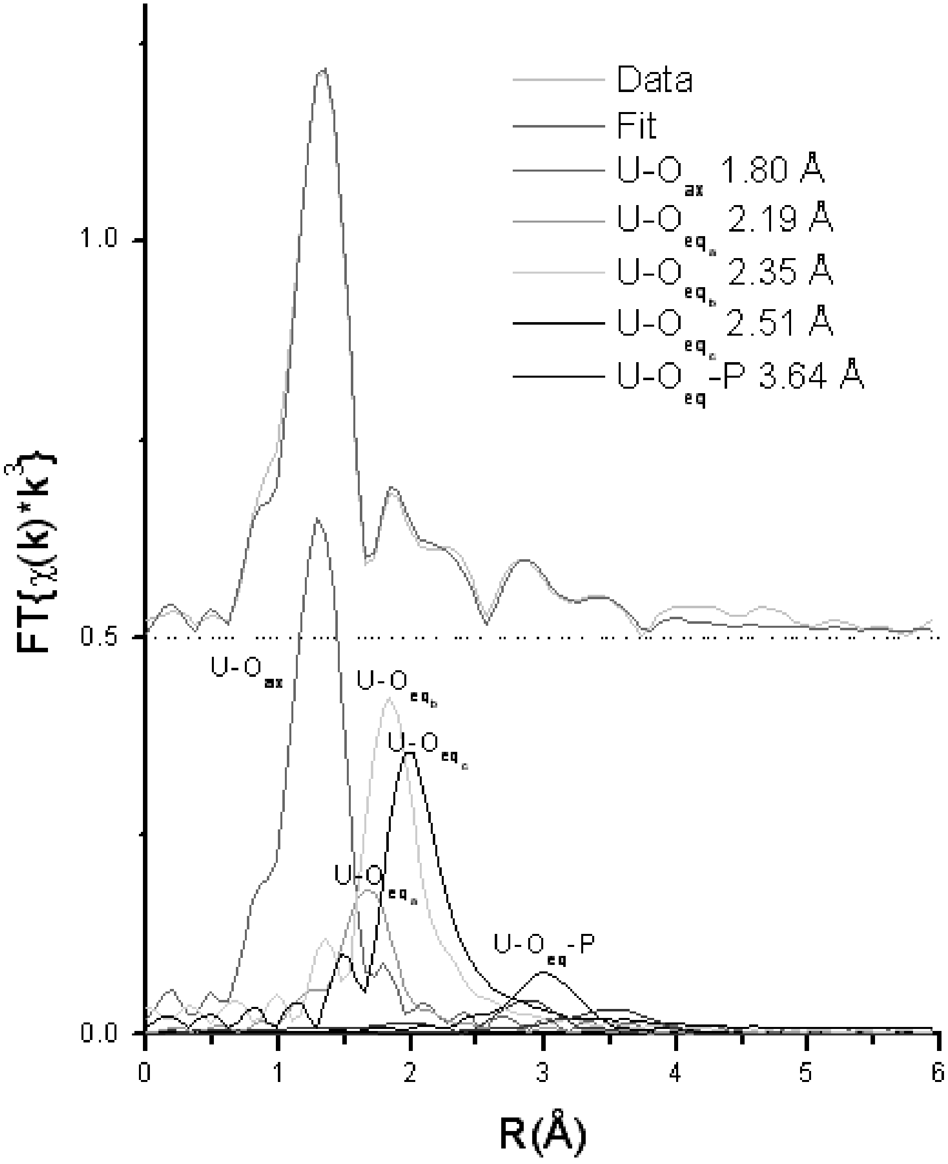
$$\chi(k) = \sum_j \frac{N_j f_j(k) e^{-2k^2\sigma_j^2}}{k R_j{}^2} \sin[2kR_j + \delta_j(k)]$$

Bacteria EXAFS



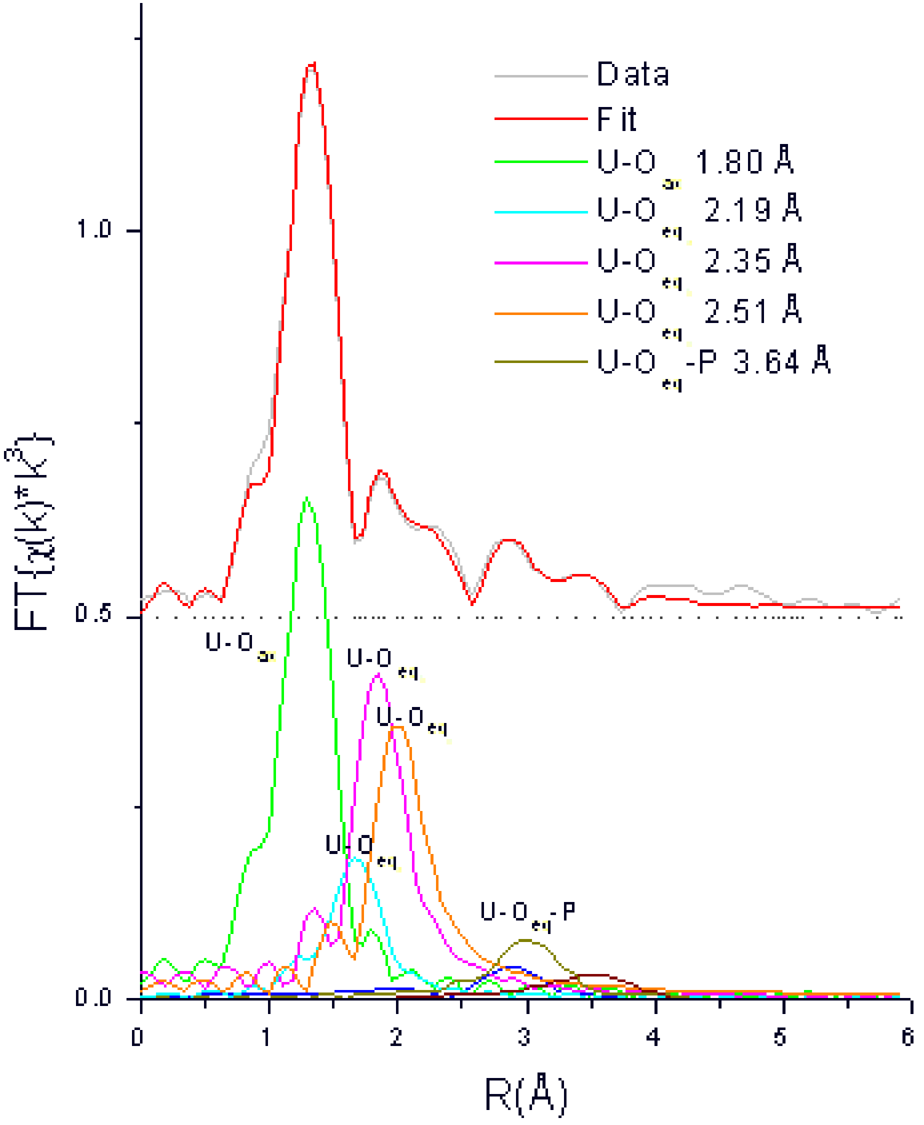
EXAFS and Fourier transforms. Slight structural differences can be seen.

EXAFS Analysis



- **Structure is consistent with uranyl phosphate**
- **Monodentate and bidentate P at 3.61 and 3.04 Å**

EXAFS Analysis



- **22 mM Sample**
  - **Mixture of phosphate and acetate structures**
  - **Due to high U concentration, phosphate possibly saturated**

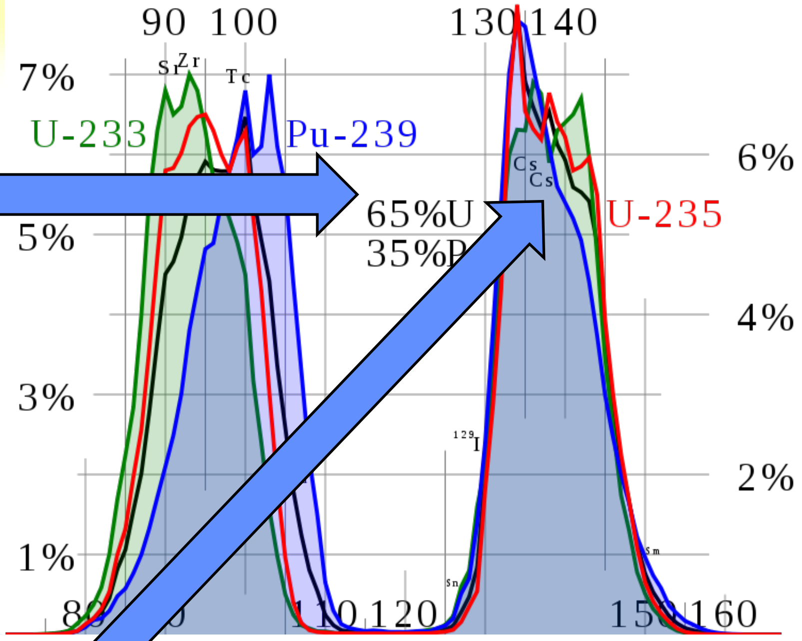
Neutron Sources

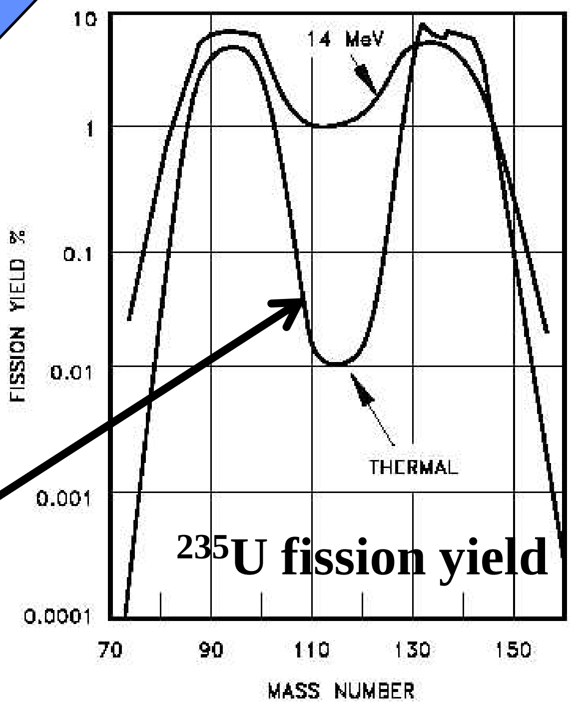
- Radioactive sources (^{252}Cf, reactions)
- Accelerators
  - $^{2}H(d,n)^{3}H$
  - $^{3}H(d,n)^{4}He$

    → Neutron energy fast
  - also (γ,n) with ^{2}H or ^{9}Be
- Alpha-neutron sources
  - Pu-Be sources
- Reactors
  - specific design
  - high amount of ^{235}U

Fission Process

- Usually asymmetric mass spli
  - $M_H/M_L \approx 1.4$ for uranium and plutonium
  - due to shell effects, magic numbers
    - → Heavy fragment peak near A=132, Z=50, N=82
  - Symmetric fission is suppressed by at least two orders of magnitude relative to asymmetric fission
- Occurs in nuclear reactions
  - Competes with evaporation of nucleons in region of high ato ic numbers
- Location of heavy peak in fission remains constant for ^{233,235}U and ^{239}Pu
  - position of light peak increases
- 2 peak areas for U and Pu thermal neutron induced fission
- Influence of neutron energy observed



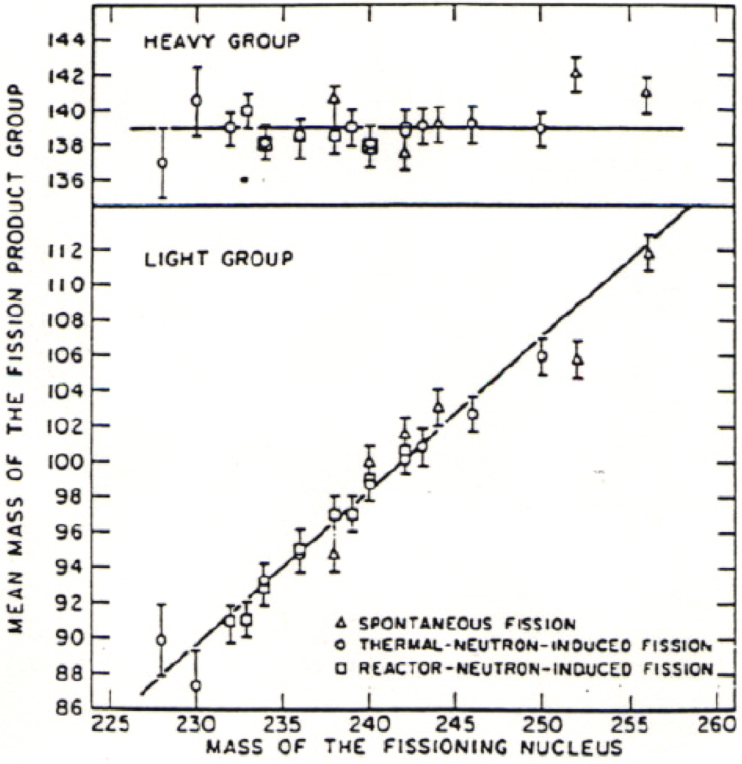


^{235}U fission yield

Fission Process

- Fission yield distribution varies with fissile isotope
- Heavier isotopes begin to demonstrate symmetric fission
    - Both fission products at Z=50 for Fm
- As mass of fissioning system increases
    - Location of heavy peak in fission remains constant
    - position of light peak increases

Average masses of the light and heavy fragments as a function of the mass of the fissioning system. From Flynn [10]



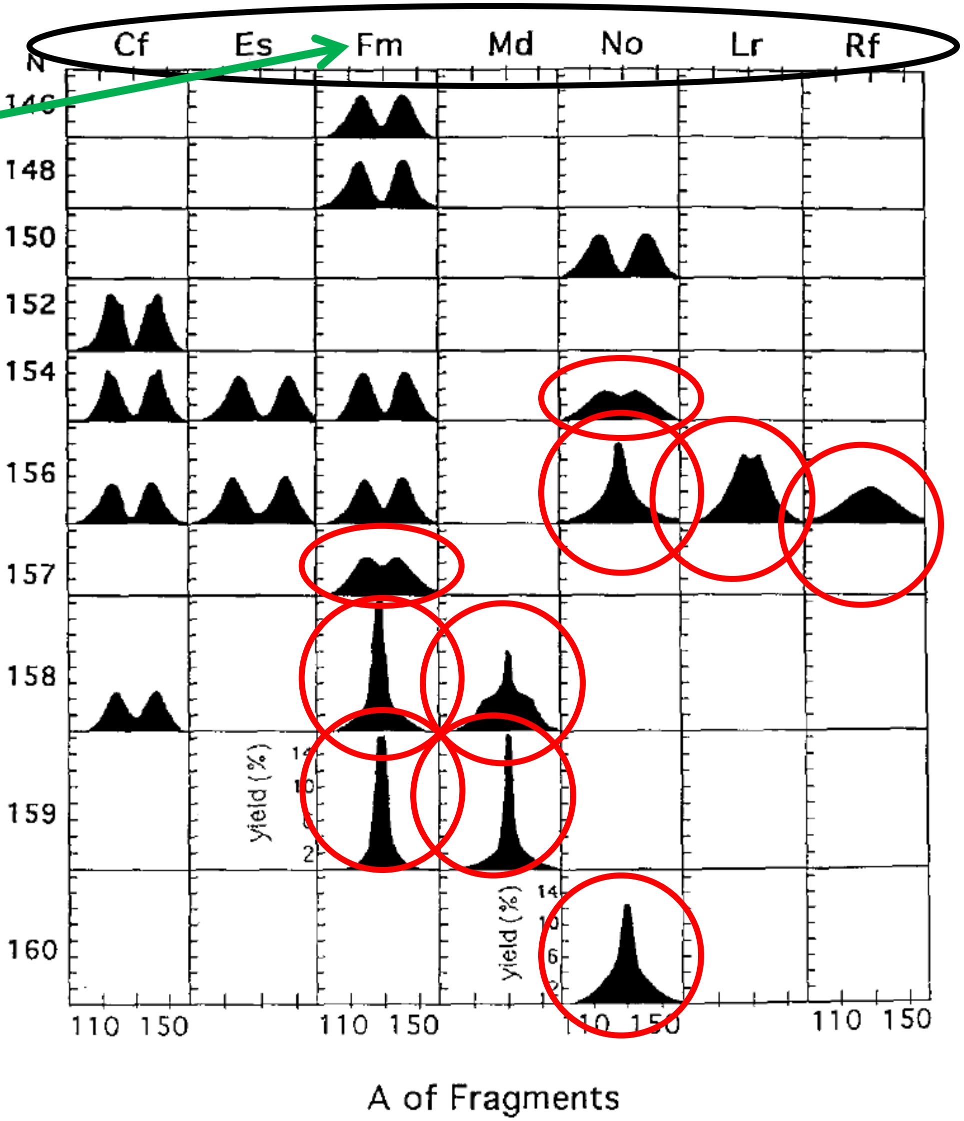
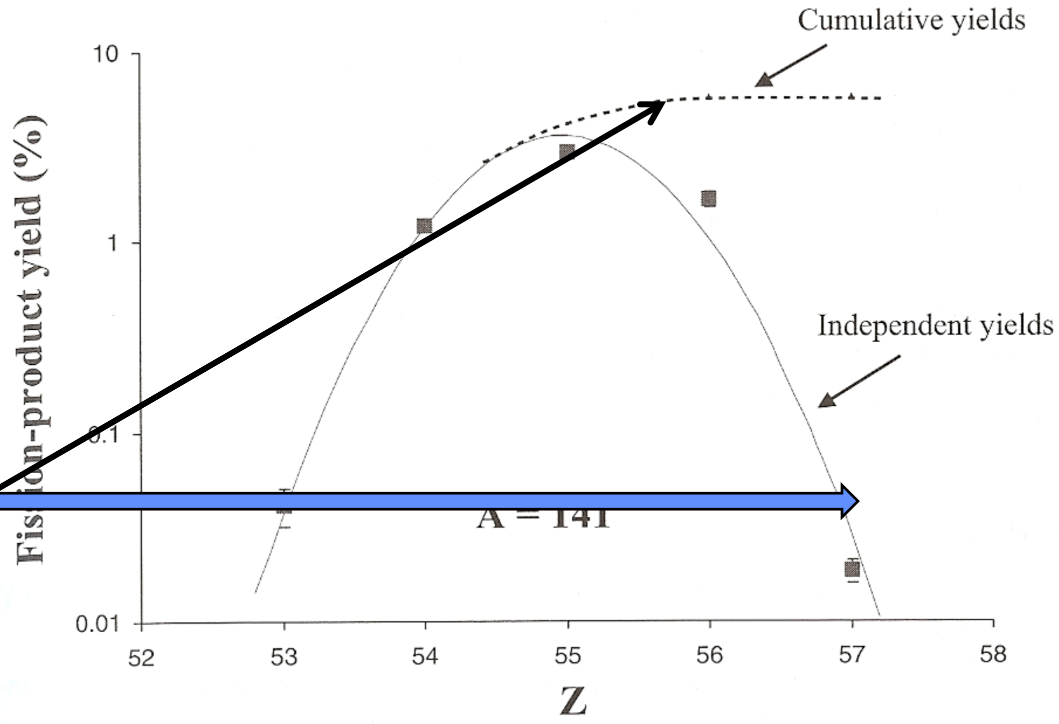


Fig. 8. Schematic representation of mass yield distributions (normalized to 200% fission fragment yield) for SF of trans-Bk isotopes [4].

Fission products

- Primary fission products always on neutron-excess side of β stability
  - high-Z elements that undergo fission have much larger neutron-proton ratios than stable nuclides in fission product region
  - primary product decays by series of successive β^- processes to its stable isobar
- Yields can be determined
  - Independent yield: specific for a nuclide
  - Cumulative yield: yield of an isobar
    - → Beta decay to valley of stability
  - Data for independent and cumulative yields can be found or calculated



Comparison of cumulative and independent yields for A=141

http://www-nds.iaea.org/sgnucdat/c2.htm

Fission Process

- Nucleus absorbs energy
  - Excites and deforms
  - Configuration “transition state” or “saddle point”
- Nuclear Coulomb energy decreases during deformation
  - Nuclear surface energy increases
- Saddle point key condition
  - rate of change of Coulomb energy is equal to rate of change of nuclear surface energy
  - Induces instability that drives break up of nucleus
- If nucleus deforms beyond this point it is committed to fission
  - Neck between fragments disappears
  - Nucleus divides into two fragments at “scission point.”
    - → two highly charged, deformed fragments in contact
- Large Coulomb repulsion accelerates fragments to 90% final kinetic energy within 10^{-20} s

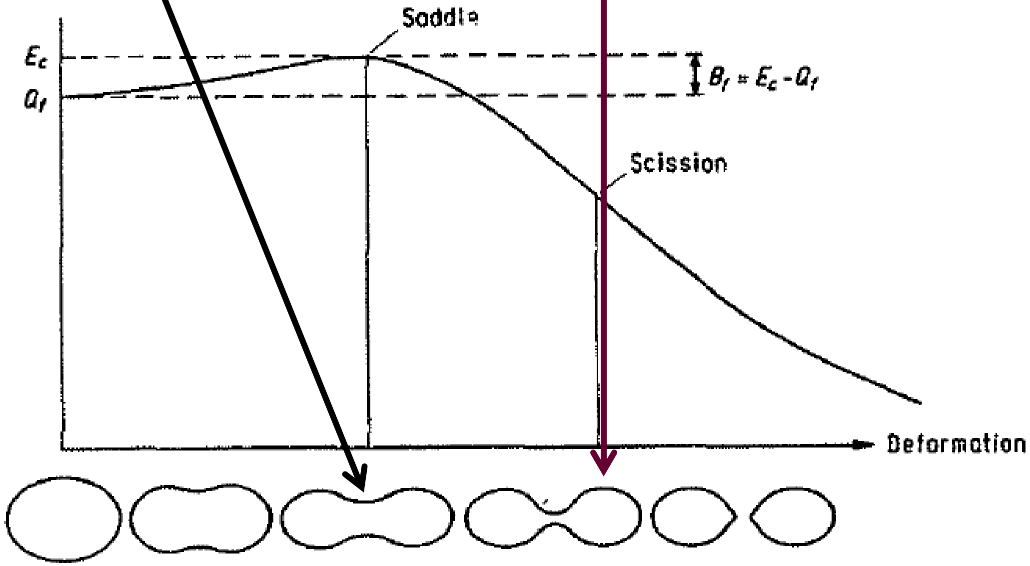


Fig. 3-7 Potential energy as a function of deformation in a simple liquid-drop picture. The fission barrier B_f, the saddle point (critical deformation), and the scission point (separation into two fragments) are indicated. The distortion of an initially spherical nucleus is schematically shown beneath the potential-energy diagram.

Proton induced fission

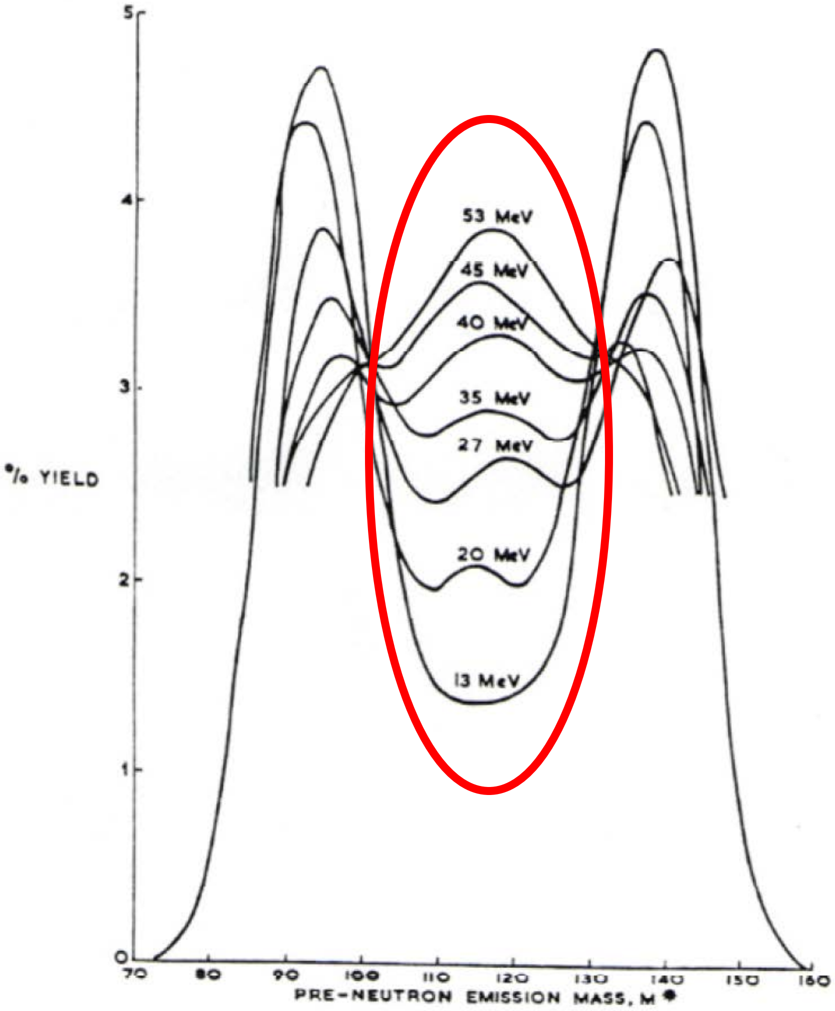


Figure 11-17. Fission mass distributions for ^{232}Th(p, f)

- Energetics impact fragment distribution
- excitation energy of fissioning system increases
  - Influence of ground state shell structure of fragments would decrease
  - Fission mass distributions shows increase in symmetric fission

Review Notes

- Describe accelerators
  - Linear
  - Cyclotrons
  - Synchrotrons
    - →XANES and EXAFS
- Describe utilization of photons from synchrotrons
- Provide example of neutron sources

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