Nuclear Physics and Astrophysics

PHY-302

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Lecture 15 - Nuclear Fission

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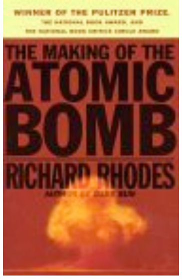
Introduction

- Fission can occur for any nuclei if enough excitation energy is provided
- Only realistically important for Z>90
- Applicability of fission for energy release came soon after discovery
- Rutherford considered commercial applications of fission "ridiculous"
- Fission not only produces large amounts of energy, but also several fast neutrons
- Chain reactions can rapidly occur...

  ...in either controlled or uncontrolled way
- Nuclear reactors and bombs are the legacy of fission research
- Course will not cover socio-political effects of fission (we can do this after the lectures)
- We will discuss the technology and methods

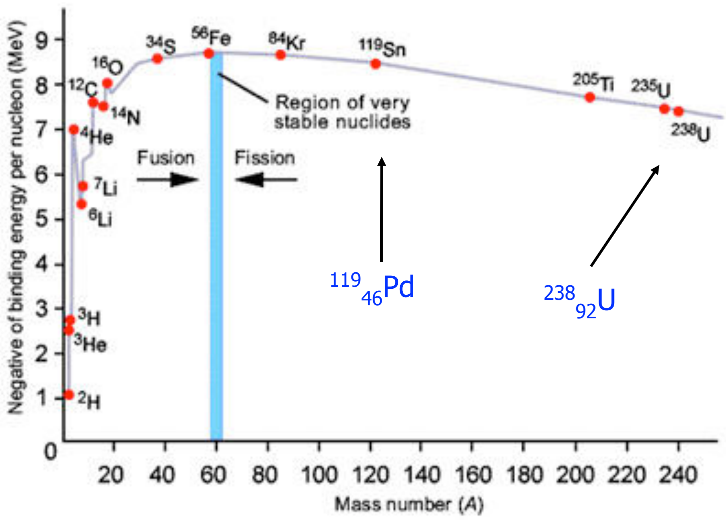


How Fission Was Discovered

- Neutron was predicted by Rutherford (1920) - nuclei have small charge:mass ratios
- Imagined to be proton electron fused
- In 1932 Rutherford's assistant, Chadwick discovered neutron (awarded 1935 Nobel prize)
- Obvious experiments performed: expose nuclei to neutron beams
- Such nuclei often became β^- emitters (i.e. neutron converts to proton, Z increases)
- Enrico Fermi awarded 1938 Nobel prize for this work
- Uranium: heaviest naturally occurring element
- Physicists tried to create heavier (transuranic) elements via neutron bombardment
- Use chemical analysis to determine properties of new elements
- Results confusing: radium and or barium appeared to be produced
- Many other low A elements also appeared...
- In 1939 Meitner & Frisch proposed U after n capture highly unstable ® splits in two
- energy released was huge ~200 MeV ! 20% of nucleon mass converted to energy!

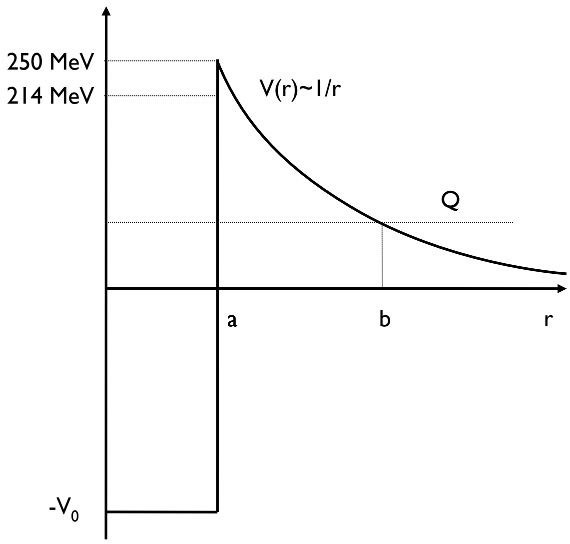
20% of my mass converted to energy = 10^9 MJ / energy output of Dungeoness in 1 month

Why Does Fission Occur?



- ^{238}U has B/A ~ 7.6 MeV/nucleon
- If it splits in two (A=119) then B/A=8.5 MeV/nucleon
- Much more tightly bound nucleus
- Releases (8.5-7.6)*238 = 214 MeV!
- Compare with <10 MeV for Q_α
- Energy mostly kinetic - Coulomb repulsion of fragments

How Does Spontaneous Fission Occur?



- ^{238}U is also alpha emitter
- $t_{1/2}=10^9$ y but partial $t_{1/2}$ for fission is 10^{16} y
- Something inhibits fission...
- Fission occurs due to balance of strong and Coulomb forces in nucleus
- Lets loosely consider fission like an α-decay process
- ^{238}U can briefly exist as two fragments ^{119}Pd
- Coulomb potential for 2 fragments touching = 250 MeV
- Very similar to 214 MeV released in process
- Calculation is very crude!
fission to two identical fragments may not be realistic
additional neutron release can make large differences
Coulomb repulsion effect for 2 hard edged sphere ...

Nevertheless refined calcs show that coulomb barrier is only just greater than energy release

How Does Spontaneous Fission Occur?

In fact spontaneous fission is important for A>250 (compare ^{238}U)

From alpha emission discussion (lecture 10) we have:

Probability to penetrate barrier is $P = e^{-2G}$

G is Gamov factor: $$G = \sqrt{\frac{2m}{\hbar^2}} \int_a^b \sqrt{V(r) - Q}\,\mathrm{d}r$$

Exponential factor G is proportional to √m thus barrier penetration is heavily suppressed for large A~100 compared to small A=4 → factor 10^7 reduction in tunnelling prob. P
Note: this is a simplistic view of quantum tunneling

But it is possible to excite a nucleus: **induced fission**

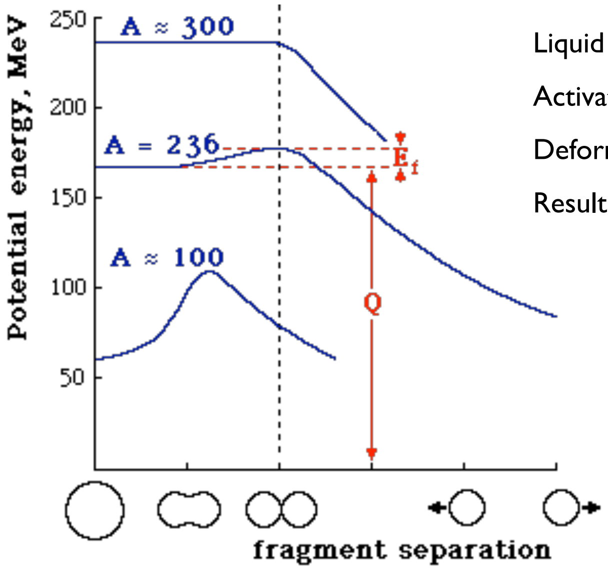
For some nuclei absorption of thermal neutron may be sufficient

Depends crucially on situation under consideration

Some nuclei do not form at all: barrier to fission is zero (for A=300?)

How Does Induced Fission Occur?

More detailed calculation of fission process using liquid drop model:



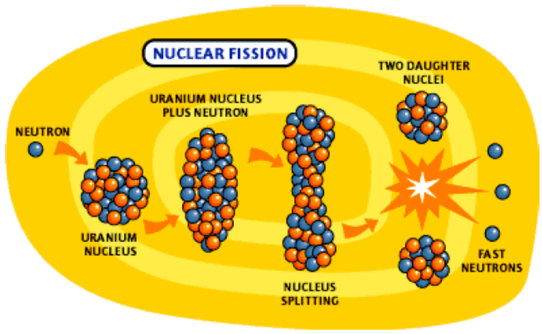
E_f is the **activation energy:** height of barrier above ground state

Liquid drop models provides intuitive picture of fission

Activation energy creates a deformation of the nucleus

Deformation becomes extreme

Results in nucleus splitting into 2



Understanding Fission

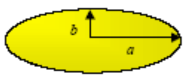
The SEMF provides another approach to understanding fission

Consider the nuclear 'stretching' keeping constant volume

Surface and Coulomb terms will change according to the deformation

Stretched nucleus is ellipsoid with axes a and b

Volume of ellipsoid is: $\frac{4}{3}\pi ab^2$



Deviation of ellipsoid from sphere of radius R is given by distortion parameter ε

$$a = R(1+\epsilon)$$
$$b = R(1+\epsilon)^{-1/2}$$

$$B(Z,A) = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A,Z)$$

Only surface & Coulomb terms are affected - other are independent of shape
Difference in binding energy between stretched and unstretched nucleus (with const. volume) is:

ΔE = decrease in binding energy!

For large Z then Z(Z-1) → Z^2

$$\begin{aligned}\Delta E =& B(\epsilon) - B(\epsilon = 0) \\ =& -a_S A^{\frac{2}{3}}(1 + \frac{2}{5}\epsilon^2 + \dots) - a_C Z(Z-1)A^{-\frac{1}{3}}(1 - \frac{1}{5}\epsilon^2 + \dots) \\ &+ a_S A^{\frac{2}{3}} + a_C Z(Z-1)A^{\frac{1}{3}} \\ \simeq& (-\frac{2}{5}a_S A^{\frac{2}{3}} + \frac{1}{5}a_C Z^2 A^{-\frac{1}{3}})\epsilon^2\end{aligned}$$

If second term is larger than first, energy difference is positive: energy is gained
Thus condition for fission is:

a_C ~ 0.72 MeV
a_S ~ 16.8 MeV

$$\frac{1}{5}a_C Z(Z-1)A^{-1/3} > \frac{2}{5}a_S A^{2/3}$$

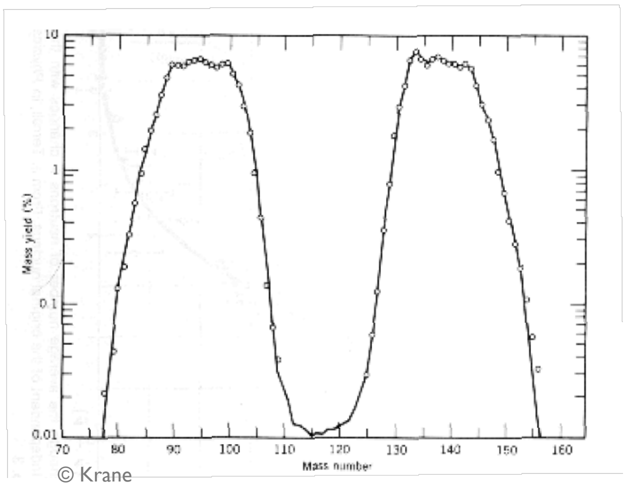
Using the known values of a_C and a_S this can be written as:

$$\frac{Z^2}{A} > 47$$

= 36 for ^{238}U

Note: this should be modified to include fission by QM tunnelling (when ΔE<0)

Mass Distribution of Fission Fragments



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Fission products are not unique
A distribution of masses is produced
Characteristic of low n energy induced fission
One example:

^{235}U + n → ^{93}Rb + ^{141}Cs + 2n

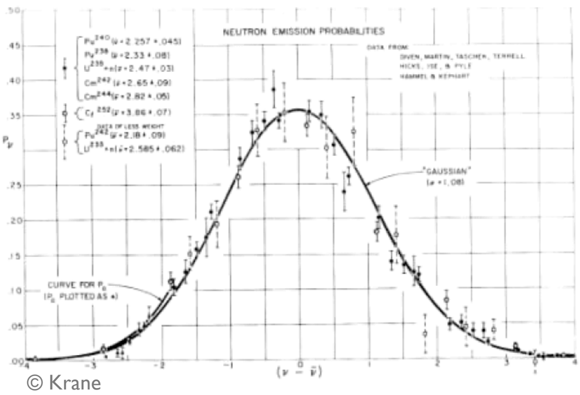
Note: distribution is symmetric
Note: equal A fragments are suppressed
This is not yet understood

why are additional neutrons emitted?

Prompt Neutrons

- Remember: For low A nuclei, N=Z, but for larger A, N>Z (dilutes Coulomb repulsion effects)
- U is very neutron rich
- If all neutrons spread between (lower A) fission fragments → yields **very** n rich fragments
- Excess neutrons shed at moment of fission → **Prompt Neutrons**
- Average number of prompt neutrons called ν
- Do not confuse this with neutrinos! One is a particle, the other is a number!
- ν is characteristic for each fission process

ν = 2.42 for ^{235}U and ν = 2.86 for ^{239}Pu



But, distribution of ν about mean value is same for all fissioning nuclei

Implies same process occurs

Similar to evaporation type process

Delayed Neutrons

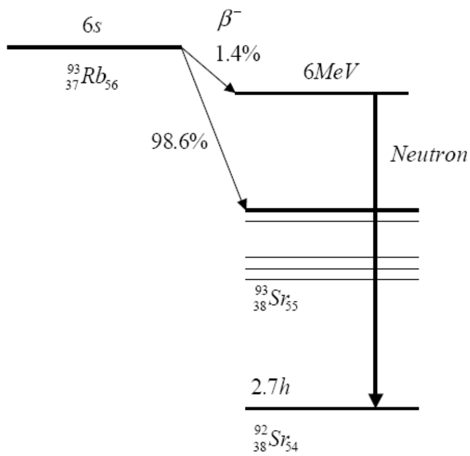
Often delayed neutrons are also observed

These are emitted ~ seconds after fission

Come from beta decay of fragments which then emit a neutron

If fragment is in excited state & energy is larger than neutron separation energy neutron is emitted from nucleus

For ^{93}Rb (fission fragment of ^{235}U) energy diagram is:



In this case number of delayed neutrons is ~1 per 100 fissions

These are vital to control of nuclear reactions...