more history of nuclear physics

Nuclear transmutation

As discussed earlier Rutherford & collaborators used α particles emitted by Po + Ra w/ typical $T = 5$ MeV to probe atomic structure.

For heavy targets (Z_2 large), Coulomb barrier prevents α from getting too close to nucleus, which therefore behaves as a point charge w/ $\frac{d\sigma}{d\Omega} \sim \frac{1}{\sin^4 \frac{\theta}{2}}$.

Scattering from lighter nuclei begins to depart from this suggesting a finite size for nucleus.

If α gets close enough (~ 1 fm), strong force can cause some of its particles to be absorbed

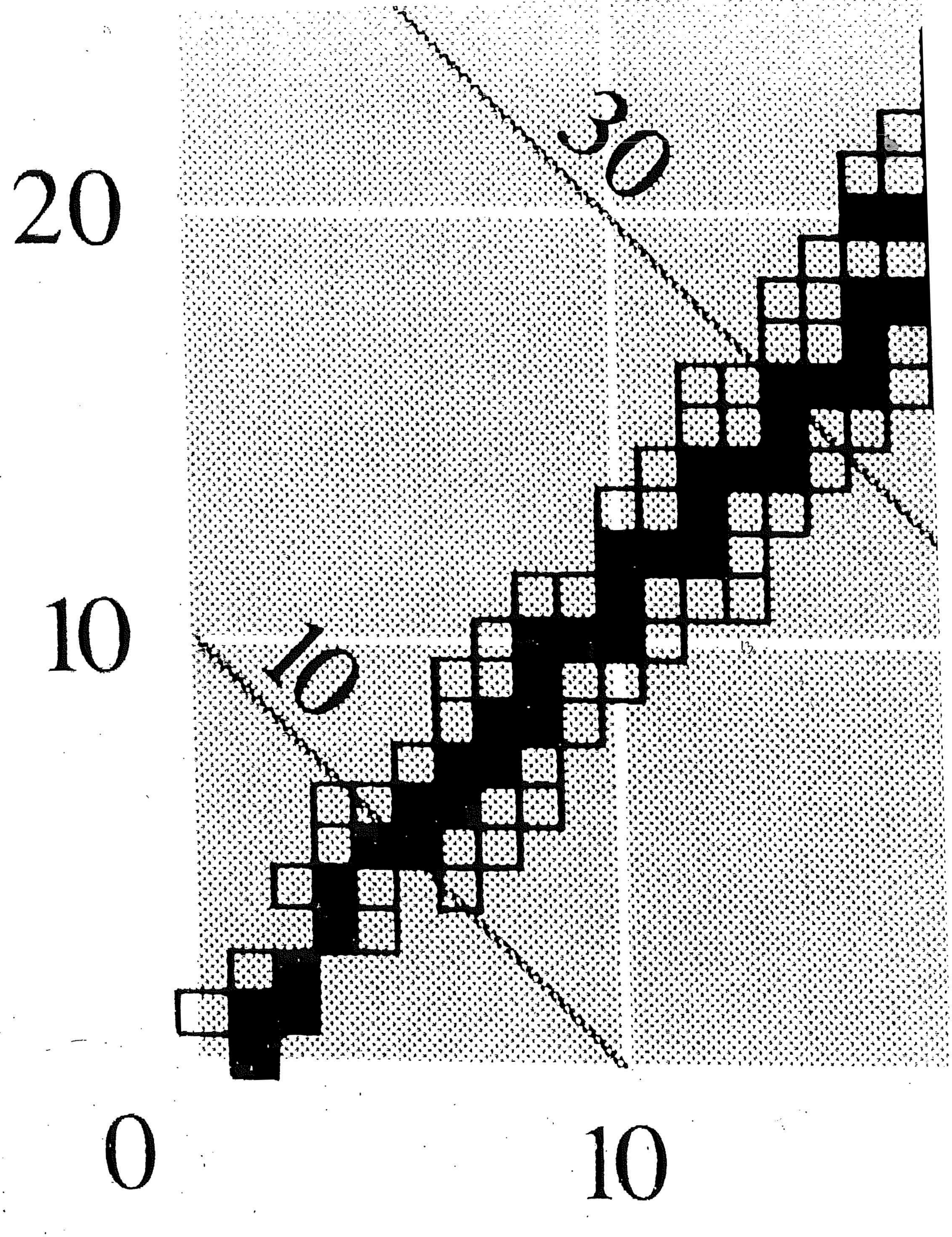
1919 Nuclear transmutation (Rutherford)

observed scintillation due to p

$$\alpha + {}^{14}_{7}N \longrightarrow {}^{17}_{8}O + p$$

1932 Cockcroft/Walton [designed a] linear accelerator to accelerated protons to ~ 0.5 MeV, and [with this, they] "split the atom"

$$p + {}^{7}Li \longrightarrow \alpha + \alpha$$



20
10
0
10
30
10

1932 Chadwick discovers the neutron : → neutral particle knocks protons out of paraffin

$$\alpha + {}^{9}_{4}Be \rightarrow {}^{12}_{6}C + n$$

[also Bothe & Becker 1930]

1934 Artificially radioactive isotopes (Joliot & I. Curie)

$$\alpha + {}^{27}_{13}Al \rightarrow {}^{30}_{15}P + n$$

↓ 3 minutes

$${}^{30}_{14}Si + e^{+} + \nu_e$$

[first β^{+} decay] (→ because on proton rich side)

Nobel Chemistry 1935

[today's directions = tomorrow's tools]

Neutrons as probes [no Coulomb barrier; but can't accelerate them either]

$$n + {}^{16}_{8}O \rightarrow {}^{17}_{8}O \rightarrow {}^{13}_{6}C + \alpha$$

(Meitner & Philipp)

$$n + {}^{19}_{9}F \rightarrow {}^{20}_{9}F \rightarrow {}^{16}_{7}N + \alpha$$

(Fermi & Rasetti)

↓

$${}^{16}_{8}O + e^{-} + \bar{\nu}_e$$

Many artificially radioactive isotopes produced [nothing below fluorine]

even beyond uranium (transuranic)

$$n + {}^{238}_{92}U \rightarrow {}^{239}_{92}U \rightarrow {}^{239}_{93}Np + e^{-} + \bar{\nu}_e$$

↓

$${}^{239}_{94}Pu + e^{-} + \bar{\nu}_e$$

[international character of physics]

$n + {}^{16}_{8}O \rightarrow {}^{17}_{8}O$ $\quad Q = 8.071 + (-4.737) - (-0.809)$

$= 4.143$ meV

$n + {}^{16}_{8}O \rightarrow {}^{13}_{6}C + \alpha$ $\quad Q = 8.071 + (-4.737) - (3.125) - (2.424)$

$= -2.215$ MeV

process requires $K_n \geq 2.2$ MeV

$n + {}^{19}_{9}F \rightarrow {}^{16}_{7}N + \alpha$ $\quad Q = 8.071 + (-1.487) - (5.682) - (2.424)$

$= -1.522$ MeV

process requires $K_n \geq 1.5$ meV

Note international (or at least European)
nature of this research

Also, one of the physicists, Lise Meitner
was one of the few women doing physics research
at that time.

She was Austrian by birth, educated at U Vienna,
+ working in Berlin at Kaiser Wilhelm Institute
w/ Otto Hahn (a chemist)

Besides laboring under the disadvantages
suffered by women scientists in that era,
she was also Jewish, which was problematic
in Germany in the 1930's — most German Jewish
scientists had been fired in 1933 after Hitler came
to power.
She was protected by her Austrian citizenship
until 1938, when Germany annexed Austria
In immediate danger, friends helped her to escape
to Netherlands & then to Sweden.

We'll encounter her again later

Neutron absorption by nuclei

$R = A^{1/3} r_0 \,, \quad r_0 = 1.2 \text{ fm}$

Geometrical cross-section

$\sigma = \pi R^2 = \pi A^{2/3} r_0^2$

E.g., for $A \sim 100$ [Ruthenium],

$\sigma \sim 100 \text{ fm}^2 = 10^{-24} \text{ cm}^2$

Absorption cross-section for medium energy ($T \approx 20$ MeV) neutrons by nuclei $\approx$ geometric cross section

[See Evans, fig 2.3]

[suggests all neutrons that "hit" the nucleus are absorbed]

[like hitting the broadside of a barn]

unit of cross-section: 1 barn $= 100 \text{ fm}^2 = (10 \text{ fm})^2$

[For higher energy neutrons, σ ↓ so not all neutrons are absorbed "partial translucency"]

[HW: $^{238}U \Rightarrow \sigma = 1.7$ barns]

R.D. Evans, p. 458

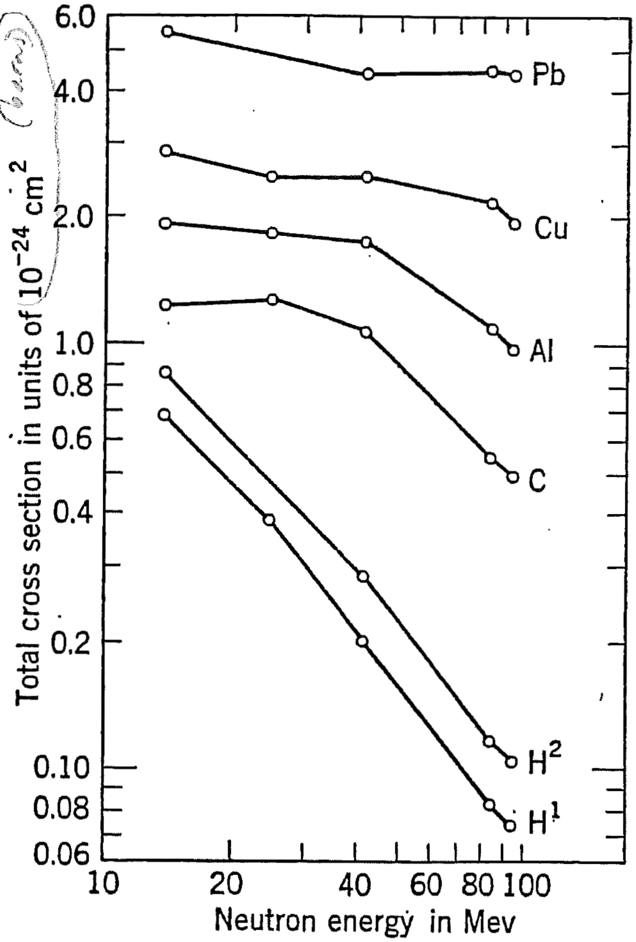
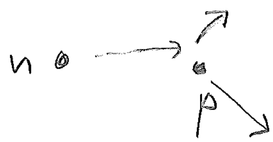


Fig. 2.3 Total neutron cross sections σ_t of five elements for neutrons of 14, 25, 42, 84, and 95 Mev. The decrease in σ_t at the higher neutron energies suggests that all neutrons which strike the target area $\pi(R + \lambda\!\!\!^{-})^2$ are not captured and that nuclear matter is slightly transparent to swift neutrons. [*From Hildebrand and Leith* (H51).]

Neutrons, being neutral, cannot be accelerated or steered but they can be slowed down by collisions, or by absorption + re-emission



Fermi found that absorption $\sigma \uparrow$ for low energy n

[Evans fig 2.1]

slow neutrons more likely to be absorbed!

Cadmium ~ 2000 barns for slow neutrons

[empirically $\sigma \sim \frac{1}{v}$]

R. D. Evans, p. 455

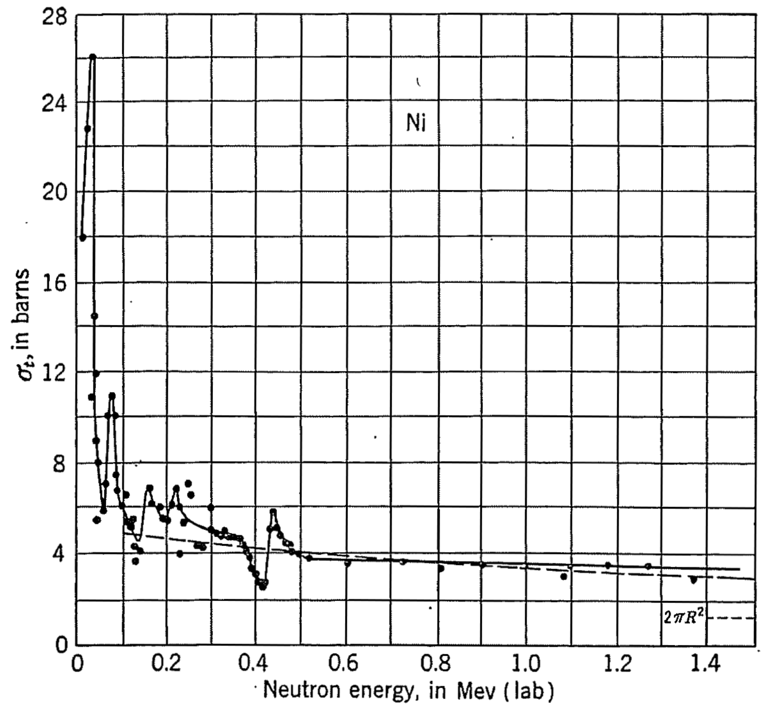


Fig. 2.1 The total cross section (absorption plus scattering) of nickel for neutrons from 0.01 to 1.5 Mev. Approximately monoenergetic neutrons (± 20 kev below 0.5 Mev; ± 150 kev above 0.5 Mev) were produced by bombarding a thin Li target with protons accelerated by an electrostatic generator. The dotted line is from the continuum theory of Feshbach and Weisskopf (F49), assuming a nuclear radius of 4.6×10^{-13} cm. [*The experimental data are from Barschall, Bockelman, and Seagondollar* (B15).]

R.D Evans, p. 443

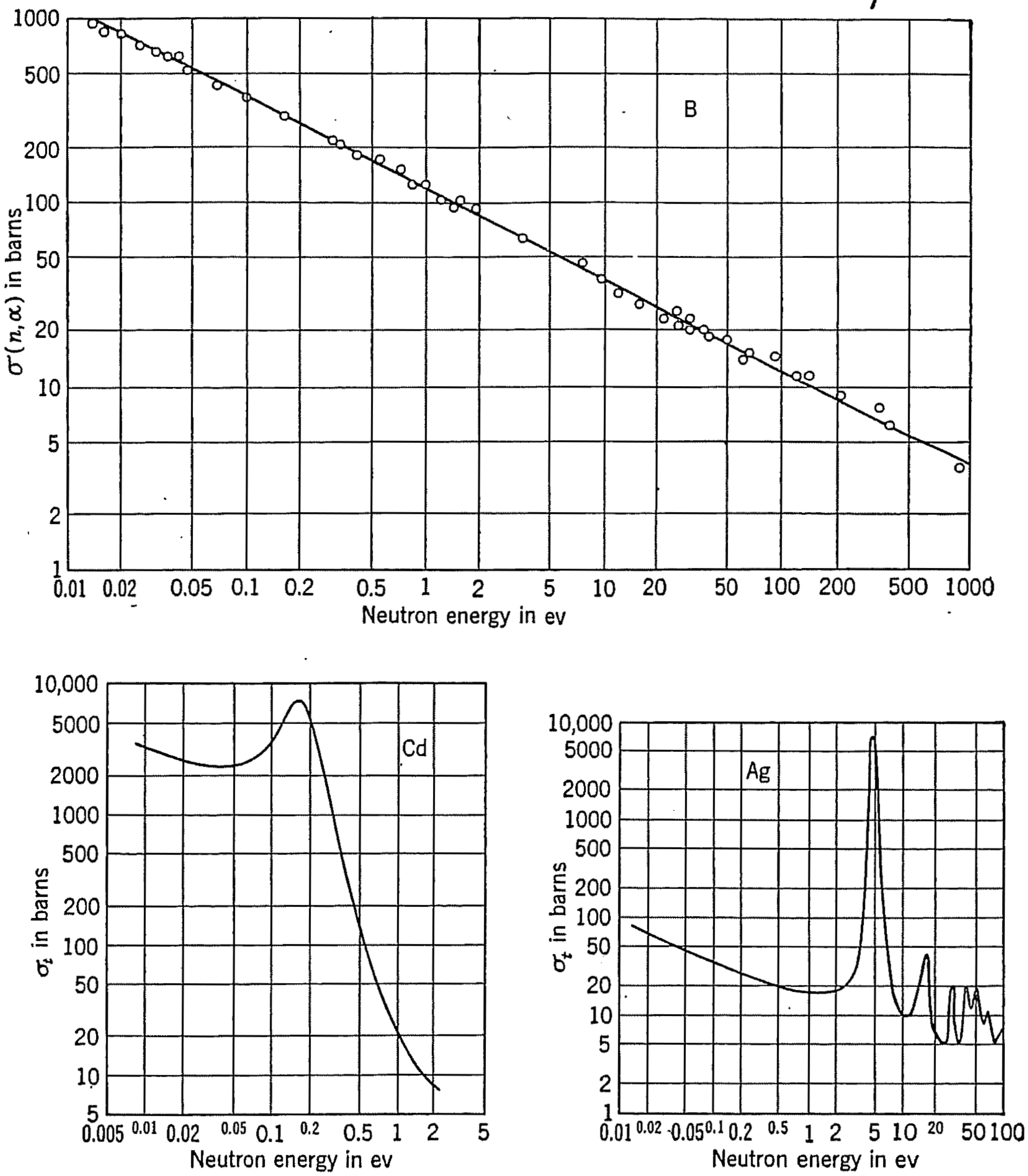


Fig. Introduction.1 Total neutron cross sections for B, Cd, and Ag, illustrating typical combinations of $1/V$ dependence (pure, in the case of boron) and slow-neutron resonances. The resonance in Cd at $E_0 = 0.176$ ev has a total width $\Gamma = 0.115$ ev and a maximum value of $\sigma_0 = 7{,}200$ barns. The curves are for the normal isotopic mixtures. In Cd, the 0.176-ev resonance is due entirely to Cd^{113} (relative abundance, 12.3 per cent); hence $\sigma_0 \simeq 57{,}000$ barns for Cd^{113} alone. The complex γ-ray spectrum leading to the ground level of Cd^{114} has been measured by Bartholomew and Kinsey (B16). [*From Goldsmith, Ibser, and Feld* (G29) *and Hughes* (H68).]

An old note to self (copied)

How does $\sigma_{fission}$ depend on E of incident n?

Naively $E \sim v^2 \sim \frac{1}{\lambda^2} \sim \frac{1}{\sigma}$

so $\sigma \sim \frac{1}{E}$

but σ(thermal) ~ 640 E-24 cm²

σ(MeV) ~ 1.3 E-24 cm²

only factor of 500

[skipped in 2019]

Why? wave properties of neutrons

de Broglie wavelength $\lambda = \frac{h}{p}$

Define reduced wavelength $\bar{\lambda} = \frac{\lambda}{2\pi} = \frac{\hbar}{p}$

Consider non-relativistic neutron ($T \ll m_n c^2 \sim 1000$ MeV)

$$T = \frac{p^2}{2m} = \frac{1}{2m}\left(\frac{\hbar}{\bar{\lambda}}\right)^2 = \frac{1}{2mc^2}\left(\frac{\hbar c}{\bar{\lambda}}\right)^2 = \frac{1}{2(1000\,\text{MeV})}\left(\frac{200\,\text{MeV fm}}{\bar{\lambda}}\right)^2$$

$$= (20\,\text{MeV})\left(\frac{1\,\text{fm}}{\bar{\lambda}}\right)^2$$

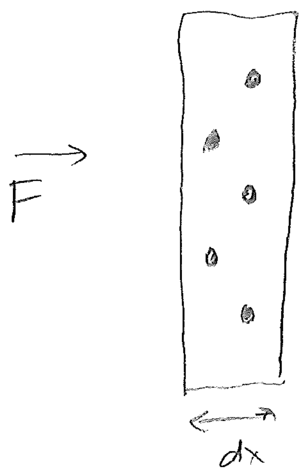
$$\frac{\bar{\lambda}}{1\,\text{fm}} = \sqrt{\frac{20\,\text{MeV}}{T}}$$

For $T \gtrsim 20$ MeV, $\bar{\lambda} < 1$ fm, neutron acts as a particle ($\bar{\lambda} \ll R$)

Small T, $\bar{\lambda} \gg R$, acts like a wave, σ ϕ

Neutrons of $T \sim \frac{3}{2}kT \sim 0.05$ eV are called "thermal neutrons"

Let incident flux of neutrons be F



σ = cross-section for absorption

n = Number density of nuclei

targets $n(A\,dx)$

"area" of targets $n\sigma A\,dx$

Probability of absorption by nuclei in film of thickness dx

$$f = n\sigma(dx)$$

$\Rightarrow$ Flux correspondingly diminishes

$$dF = -(n\sigma\,dx)F$$

$$\frac{dF}{F} = -n\sigma\,dx$$

$$\ln F = -n\sigma x + \ln F_0$$

$$F = F_0 e^{-n\sigma x}$$

[HW] show $\ell = \frac{1}{n\sigma}$ = mean free path of neutrons

e [HW]

$n = \frac{\rho}{A} N_A$ $\quad \rho$ = mass density

$U \rightarrow \rho = 19\ \frac{g}{cm^3} \Rightarrow n = 4.8E28\ m^{-3}$

$\sigma = 1.7E-28\ m^2$

$\ell \simeq 0.12\ m$

1938 Hahn & Strassmann (chemists)
thought they observed

$$n + {}_{92}U \xrightarrow{?} {}_{88}Ra$$

but no physical process could explain this

- why did they think it was radium?
- Because it had similar chemical properties to Ba and a radioactive product was precipitating out of soln w/Ba
- But they then tried to separate Ra from Ba and failed
- What did they do? consulted a physicist.

Former colleague Lise Meitner
an Austrian Jew. when Hitler annexed Austria, she lost her citizenship
In 1938, she escaped to Sweden;
She discussed it w/ nephew Otto Frisch
and decided it <u>was</u> Ba.

1939 Meitner & Frisch propose

$$n + U \longrightarrow Ba + Kr$$

(Ba ← radioactive; Kr ?)

"nuclear fission"

Why didn't anyone think of this before?

$\frac{B}{A}$ for U ~ 7.5 MeV

$\frac{B}{A}$ for Ba, Kr ~ 8.2 MeV

about 0.7 MeV released per nucleon

⇒ ~170 MeV per fission.

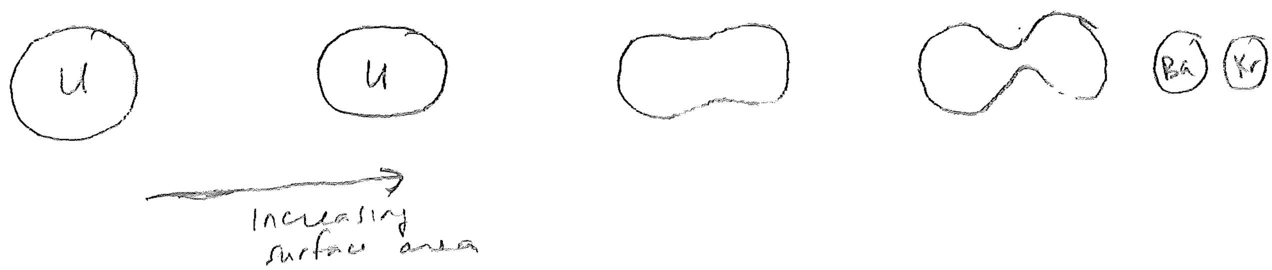
→ kinetic energy of decay products

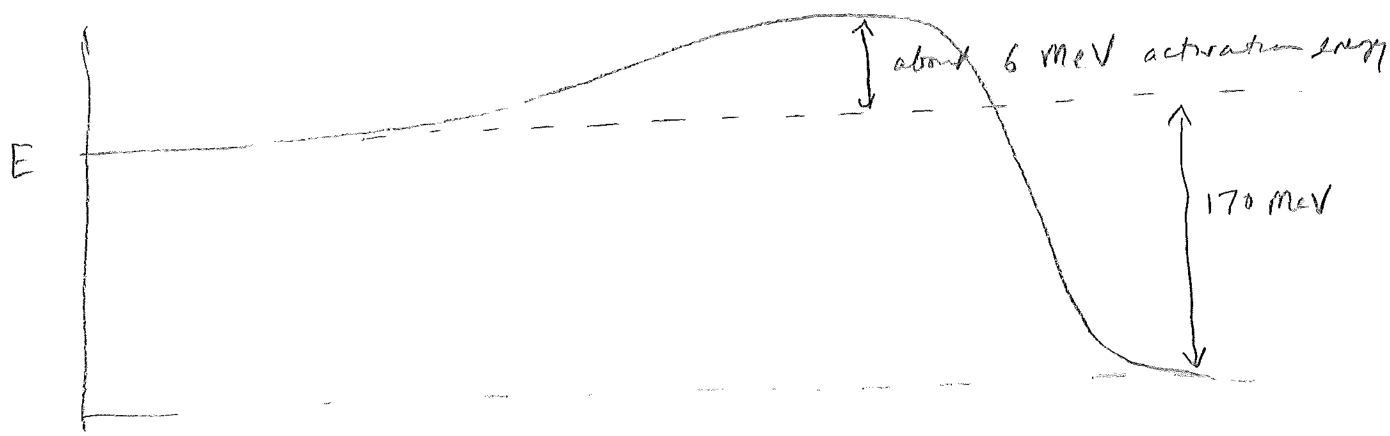
Frisch in his lab verified energy of fragments.

If U less stable than Ba, Kr why doesn't it just decay?

Think α-decay. Coulomb barrier holds them in.

Alternative picture. Liquid drop model (surface tension)





Tunnelling through barrier can occur but is rare

"Spontaneous fission"

$T_{\frac{1}{2}} \sim 3.5 \times 10^{17}$ years [HRK, p. 1169]

(α-decay is more likely)

Incident neutron supplies energy

$$n + {}^{238}U \longrightarrow {}^{239}U$$

n → (U) (U) wobble

$$Q = \Delta({}^{238}U) + \Delta(n) - \Delta({}^{239}U) = 4.8 \text{ MeV}$$

[47.306
8.071
− 51.571
4.806]

energy released causes drop to wobble
but activation energy of 239U is 6.6 MeV

∴ neutrons must have $T > 1.8$ MeV
to initiate fission

[? 5.7 MeV in HRK, 1156]

"fast neutron fission of ^{238}U", $\frac{v}{c} \sim \sqrt{\frac{2T}{mc^2}} \sim 0.06$

But Hahn & Strassmann were using slow (thermal) neutrons
($T < 1$ eV)

1939 Bohr realized that they were observing
"slow neutron fission of 235U"

238U 99.3%
235U 0.7%

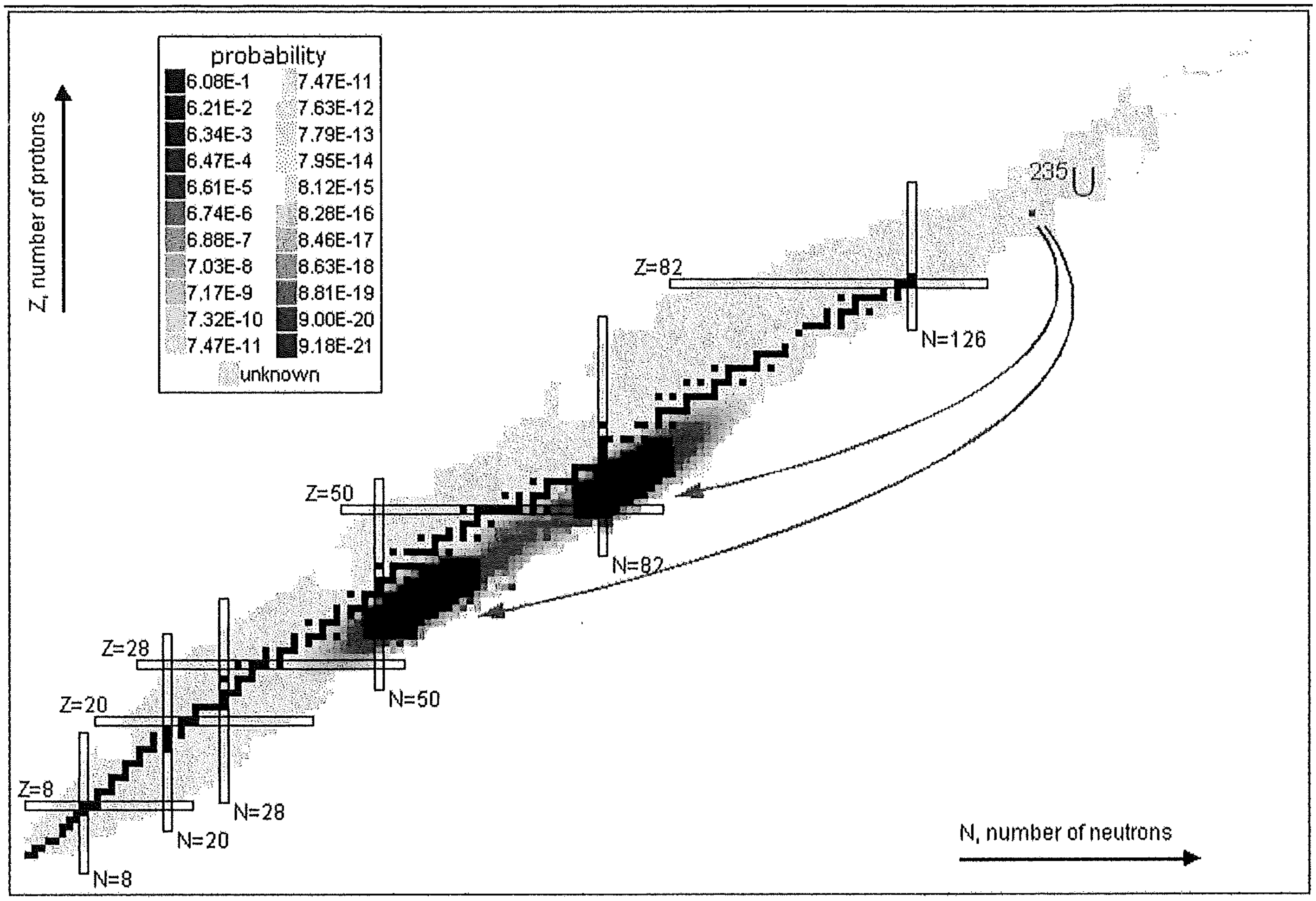
$$n + {}^{235}U \longrightarrow {}^{236}U$$

$Q = 6.5$ MeV ⟹ why different? even → odd vs odd → even

[40.916
8.071
− 42.442
6.545]

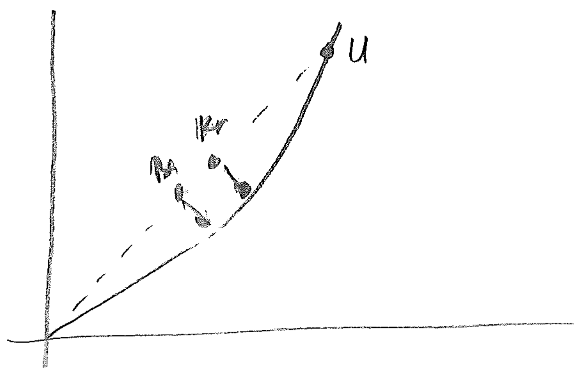
and activation energy of 236U is 6.2 MeV
no additional kinetic energy required!

[? 5.2 in HRK]



labDemmingLounge ~~.blogspot~~ blogspot.com

[Why are Ba + Kr radioactive? Because they are neutron rich] ↓ [think about α decay?]



Fission often releases 2 or 3 neutrons in addition to fission fragments

For example

$$n + {}^{235}_{92}U \xrightarrow{e.g.} {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3n$$

$$\xrightarrow{e.g.} {}^{140}_{54}Xe + {}^{94}_{38}Sr + 2n$$ [note: asymmetric]

Released neutrons can initiate further fissions

⇒ chain reaction — Leo Szilard

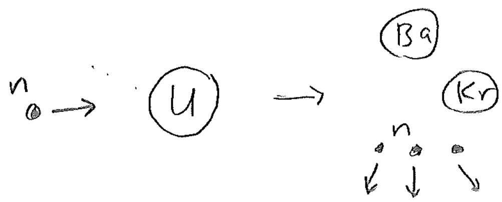
controlled ⇒ nuclear reactor
uncontrolled ⇒ weapons

about 200 MeV released per fission
vs 1-10 eV released in chemical reactions [⇒ factor of 10^7 to 10^8]

Leo Szilard convinced Einstein to write to Roosevelt...

First controlled nuclear reaction (Dec 2, 1942)
— U of Chicago squash courts (Fermi)

$$n + {}^{235}U \longrightarrow {}^{236}U \xrightarrow{e.g.} {}^{141}Ba + {}^{92}Kr + 3n$$



Secondary neutrons,
avg # ~ 2.47/fission
avg T ~ 2 MeV
(some are delayed)

- escape through surface w/o causing fission
  - ↓ solution
  - increase volume + surface ratio (critical mass)
  - ↓ depends on mass for pell
- fast n fission of ^{238}U
  - [possible since $\bar{E} > 1.8$ MeV]
  - occurs < 20% of time
  - [because of low cross-sect for fast n absorption]
  - → not sustainable
  - [need at least 40%]
- slowed by inelastic collisions w/ ^{238}U (> 80% of time)
  - ↓ captured re-emitted w/ E < 1 MeV
  - → slow neutrons absorbed by $^{238}U \to {}^{239}U$ w/o subsequent fission (between 1-100 eV) capture resonances
  - → slow n fission of ^{235}U
- slowed by a moderator (water, heavy water, ultrapure graphite) below 1 eV
  - ↓ slow n fission of ^{235}U w/ thermal neutrons (0.04 eV)

For sustained rxn, need
① critical mass,
② pure moderator

Def k - multiplication factor: # secondary neutrons that go on to produce subsequent fission

k < 1 subcritical
k = 1 critical (self-sustaining)
k > 1 supercritical

$$P(t) = P_0 k^{\frac{t}{t_{gen}}}$$

or ③ enrichment above natural abundance
(Use neutron absorbers to keep reaction from going supercritical
eg Cadmium control rods)

[Richard Rhodes, Making of the Atomic Bomb]

Just talk about this :

[What if want a supercritical rxn, ie a bomb?]

- slow n fission not suitable, energy release causes U to expand & ∴ n's will all escape
- fast n fission of ^{238}U impossible because $k<1$.
- fast n fission of ^{235}U is possible

- enrichment: electromagnetic separation, gaseous diffusion } Oak Ridge, TN ($2 Billion)

Little Boy ~ 80% ^{235}U (about 50 kg)

(critical mass ~10 cm)

[$n + {}^{238}U \rightarrow {}^{239}U' \rightarrow {}^{239}Np \rightarrow {}^{239}Pu$]

^{239}Pu is fissionable

[Fat Man]

Hanford, WA

Nuclear physics

Neutron - biography (Sime)
(also Philip Ball: serving the Reich)

1919 Rutherford induced nuclear rxns w/ α

$$\alpha + {}^{14}N \rightarrow {}^{17}O + p$$

but not until 1924 was it realized that α was absorbed, not scattered. (Blackett). These rxns ⇒ existence of a strong attractive force that cd overcome Coulomb repulsion

Nuclei heavier than ? never absorbed α's, however, nor did Li, Be, C. ?.

→ ~~But~~ (1930) Bothe & Becker discovered a new penetrating type of radiation from α (from Po) bombardment of Be, Li, B. Joliot & Irene Curie (1932) found that this radiation ejected p from paraffin, & interpreted it as γ, but Chadwick proved it was really neutrons (1932)

$$\alpha + {}^{9}Be \rightarrow {}^{12}C + n$$

→ Then

$$n + {}^{14}_{7}N \rightarrow {}^{11}_{5}B + \alpha$$ was observed by Norman Feather

$$n + {}^{16}_{8}O \rightarrow {}^{13}_{6}C + \alpha$$ " Meitner & Philipp

1934 Fermi theory of β decay, which used Pauli's ν idea

1934 Joliot & Curie produced artificial radioactivity

$$\alpha + {}^{27}Al \rightarrow {}^{30}P + n$$

$$\hookrightarrow {}^{30}Si + e^{+} + \nu \quad \text{(3 minutes)}$$

1934 Fermi ~~begs~~ ~~has~~ & Rasetti bombarded elts w/ n producing artificial radioactivity of F, Al, Si, P, Cu, ... ~~all~~ up thru U

$$n + {}^{238}U \rightarrow {}^{239}U \rightarrow {}^{239}Np \rightarrow {}^{239}Pu$$

this was hypothesized but not proved

Fermi observed (n, α) rxns & (n, p) rxns any lighter elts

$n + {}^{27}Al \rightarrow {}^{24}Na + \alpha$

$n + {}^{28}Si \rightarrow {}^{28}Al + p$

and (n, γ) " " any heavier

$n + {}^{127}I \rightarrow {}^{128}I + \gamma \rightarrow {}^{128}Xe + e^- + \bar{\nu}$

and ... the radioactive ... always emitted e^-

~~Meitner + Hahn~~ decided to start ~~studying~~ ~~transuranics~~

Szilard + Chalmers observed

γ + ⁹Be ... + n followed by n ... → ¹²⁸I

~~...~~ (lower energy)
Meitner found that the n could not be absorbed by Al, Na, Si
which required higher energies to split off α or p's
but only in capture processes by heavier nuclei Ag, I, Au

She suggested that slower neutrons are more easily ... than fast neutrons

1934 Fermi showed that paraffin, etc. slowed the n, after which they were more easily absorbed by Ag, Cu, I, ~~...~~

Uranium enrichment

Manh. project
- → electromagnetic separation
- → gaseous diffusion

→ large gas centrifuges (most common & economical)

3–5% ^{235}U ⇒ power reactors

70–90% ^{235}U ⇒ weapons

Hiroshima ⇒ 64 kg of ^{235}U ⇒ 15 kilotons
could do it w/ 25 kg (size of a melon)

Trinity ⇒ 6 kg of ^{239}Pu ⇒ 20 kilotons
could do it w/ 5 kg or less (size of a plum)