Neutron physics: *past & future*

Ecole Joliot-Curie 2015

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Part I: History & first applications

Part II: Present day: from UCN to medicine

The neutron : *early years*

1909,1919 (and 1933!): E.Rutherford

1932: J.Chadwick, then Heisenberg

1934: F.Joliot and E.Fermi

1935: I.Yukawa

1939: O.Hahn and L.Meitner

1960’s: Kendall, Taylor & Gell-Mann

Why wasting time with history ?

1. « History is a lie, but a lie that isn't disputed anymore. »

   Napoleon Bonaparte

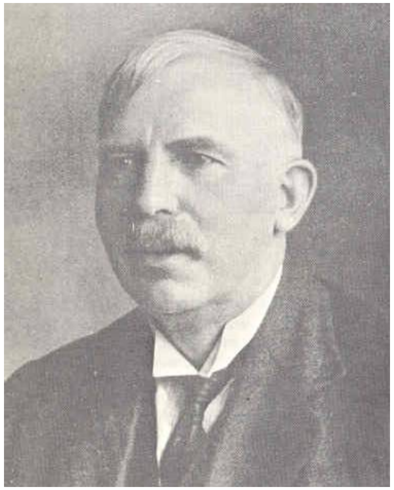
2. We can learn a lot from those instructive « mistakes »

   (committed by Nobel Price winners !)

3. « Old » thematics are still alive:

   - how to distinguish n/γ ?

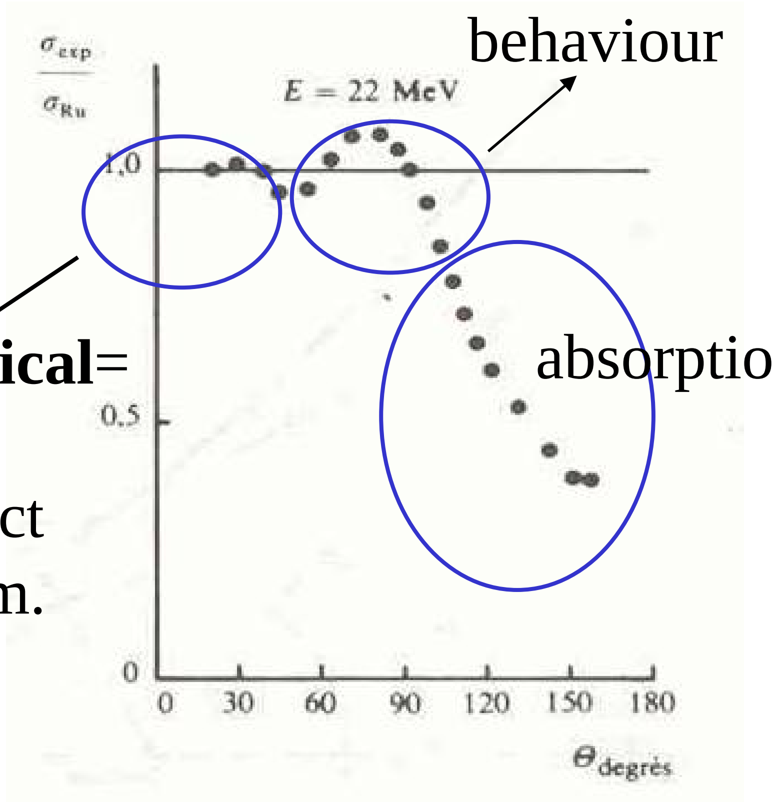
   - J.Chadwick's brilliant idea (= *tracking* charged secondaries) is still in the heart of very very « modern » things like CMOS Active Pixel Detectors…



The mother of all experiments

E.Rutherford, 1909

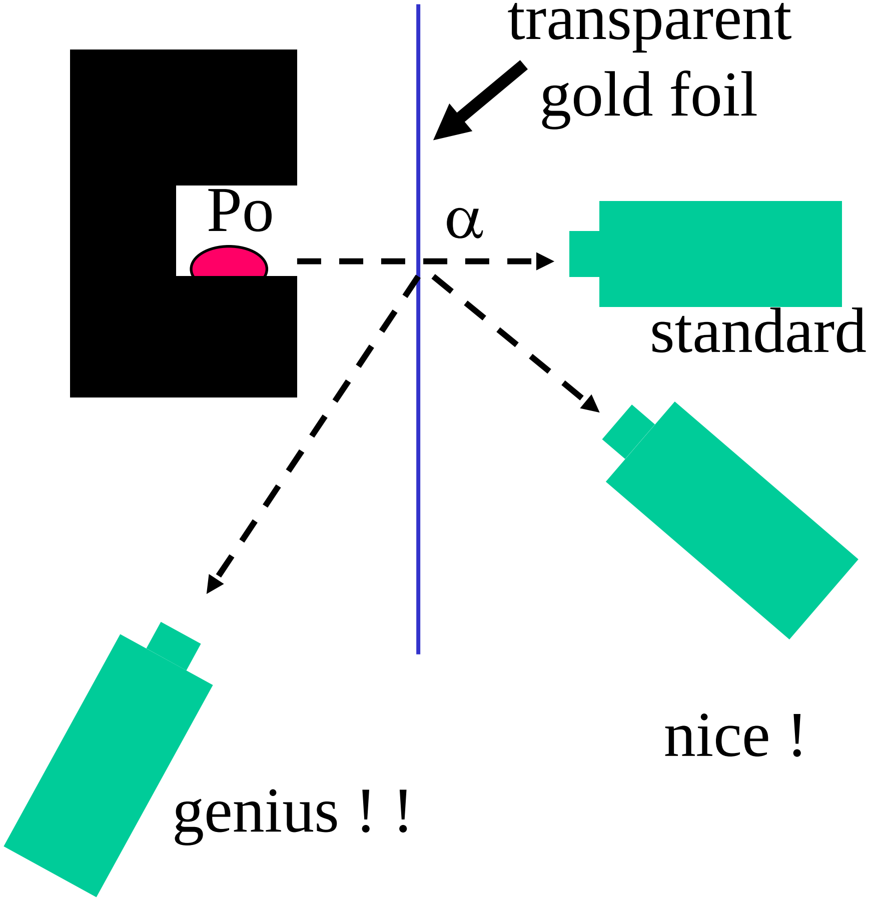
(J.J.Thomson's student…)



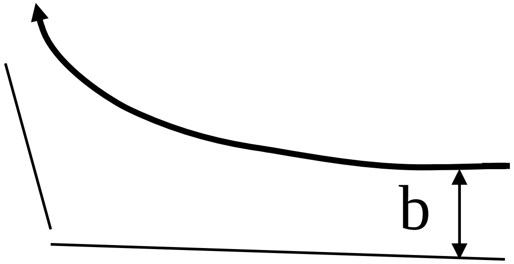
glance of quantum behaviour

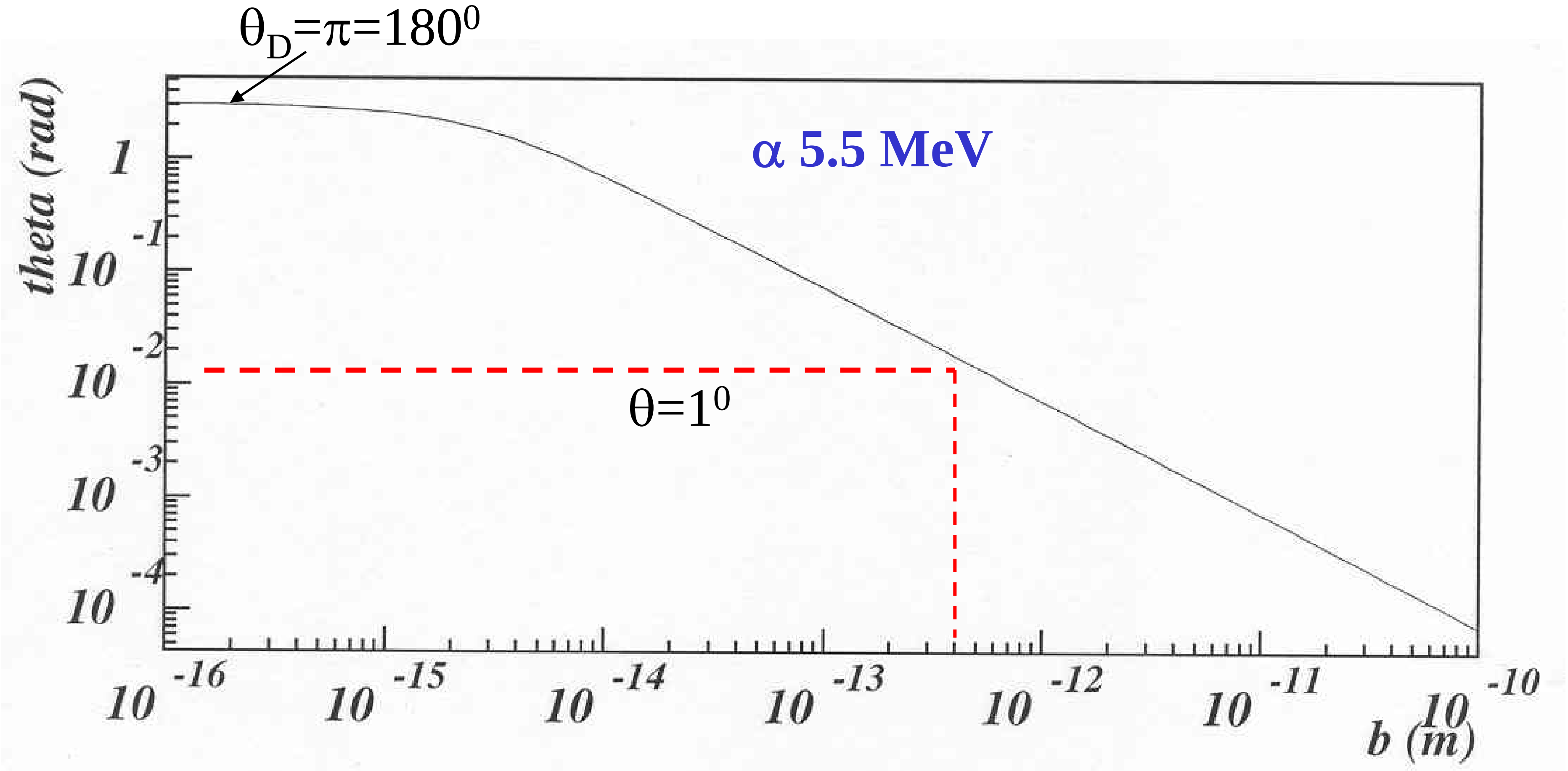
classical= large impact param.

absorption!



Exact calculation: $tg(\theta_D/2)=e^2/2E_\alpha \mathbf{b}$

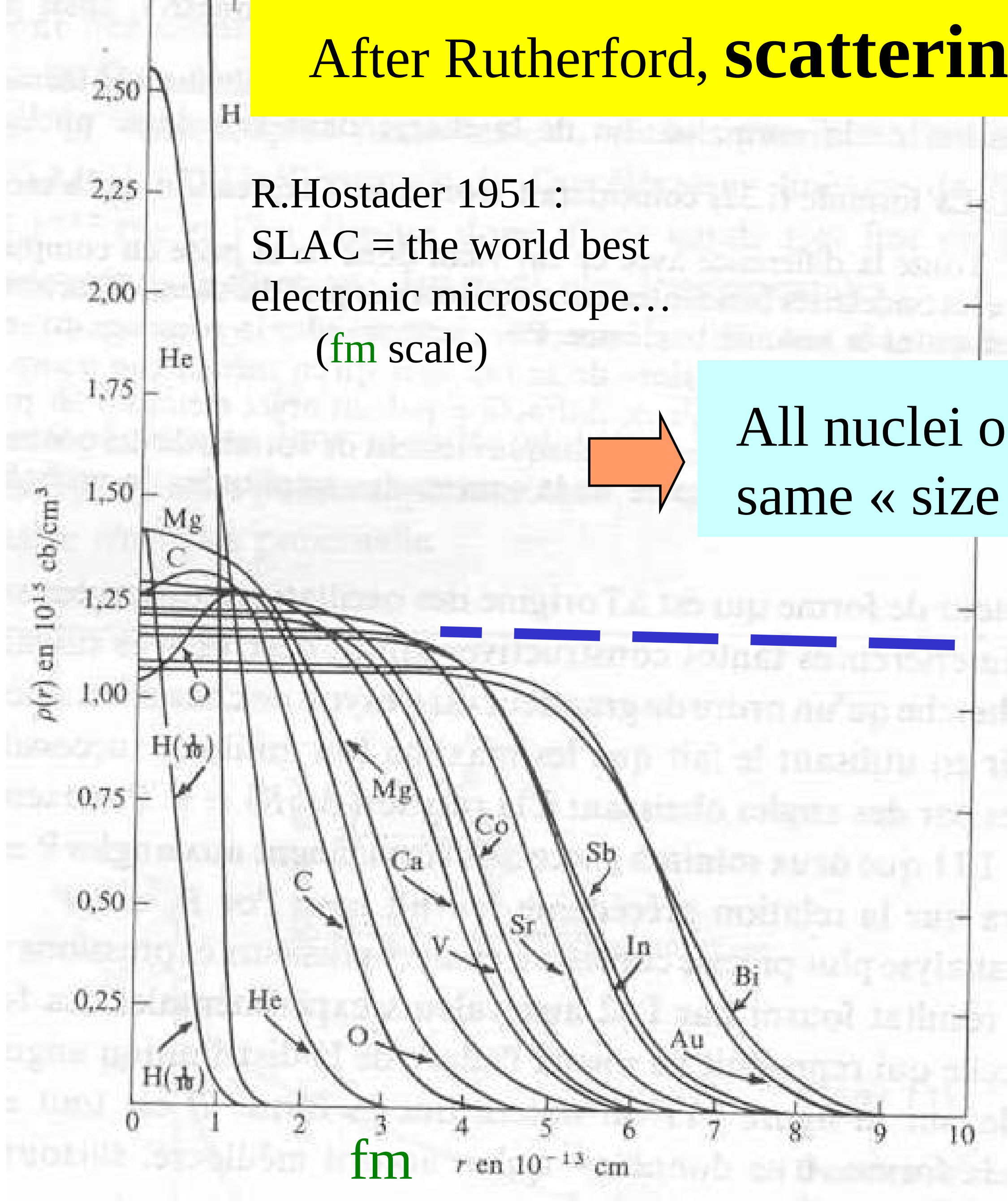




Rare but ***large*** recoils

« matter = void »

After Rutherford, **scattering** = the royal method



R.Hostader 1951 :
SLAC = the world best
electronic microscope…
(fm scale)

fm

All nuclei of same « size » : $r = r_0 \,.\, A^{1/3}$

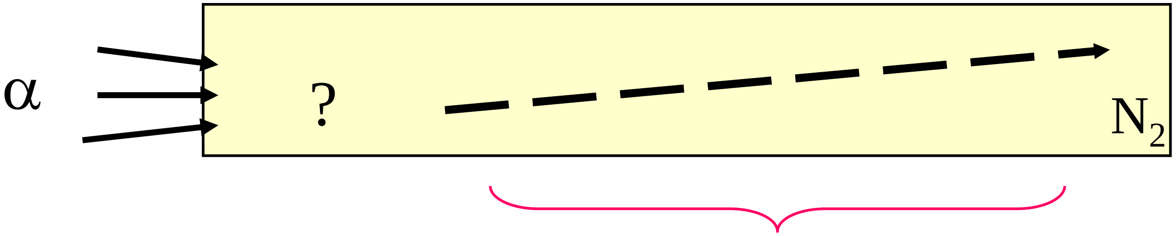
mind this nb…

$\rho_{nuc} = A/(4/3.\pi r^3)$
$= C^{te}$

Nuclear matter has **constant density**
(=10^{15} times ordin.matter..)

1919: Rutherford (again!)

The very first **transmutation**:
(not Pb ➔Au OK, but nice anyway…)



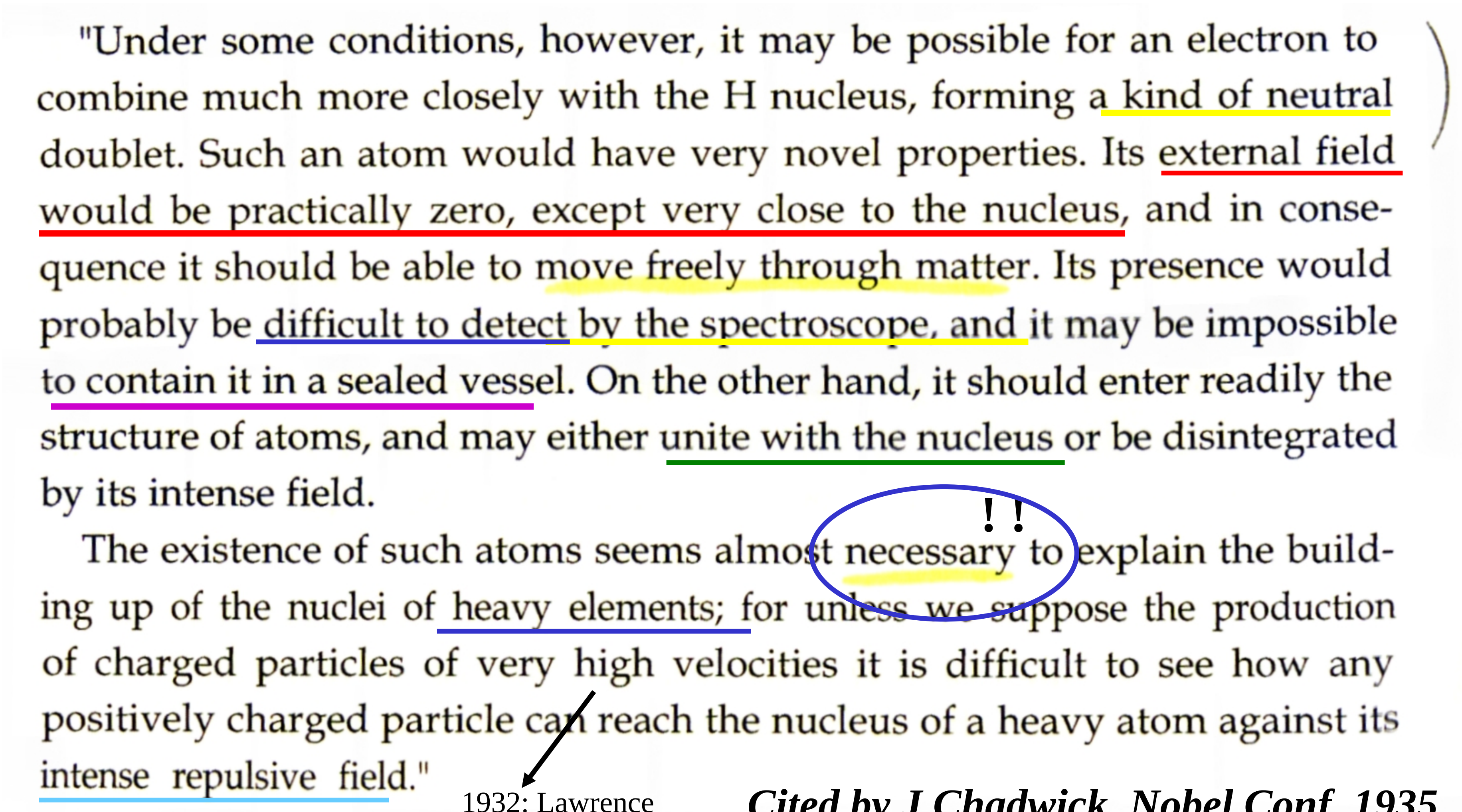
What *exactly* was observed ? Just a very long ***range*** (>>α) : hello ***p*** !!

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

E.R.: transmutation possible BUT very difficult (high $\vec{E}$) !

→ a NEUTRAL particle would be very very fine….

1920: Rutherford WELL inspired !



"Under some conditions, however, it may be possible for an electron to combine much more closely with the H nucleus, forming a kind of neutral doublet. Such an atom would have very novel properties. Its external field would be practically zero, except very close to the nucleus, and in consequence it should be able to move freely through matter. Its presence would probably be difficult to detect by the spectroscope, and it may be impossible to contain it in a sealed vessel. On the other hand, it should enter readily the structure of atoms, and may either unite with the nucleus or be disintegrated by its intense field.

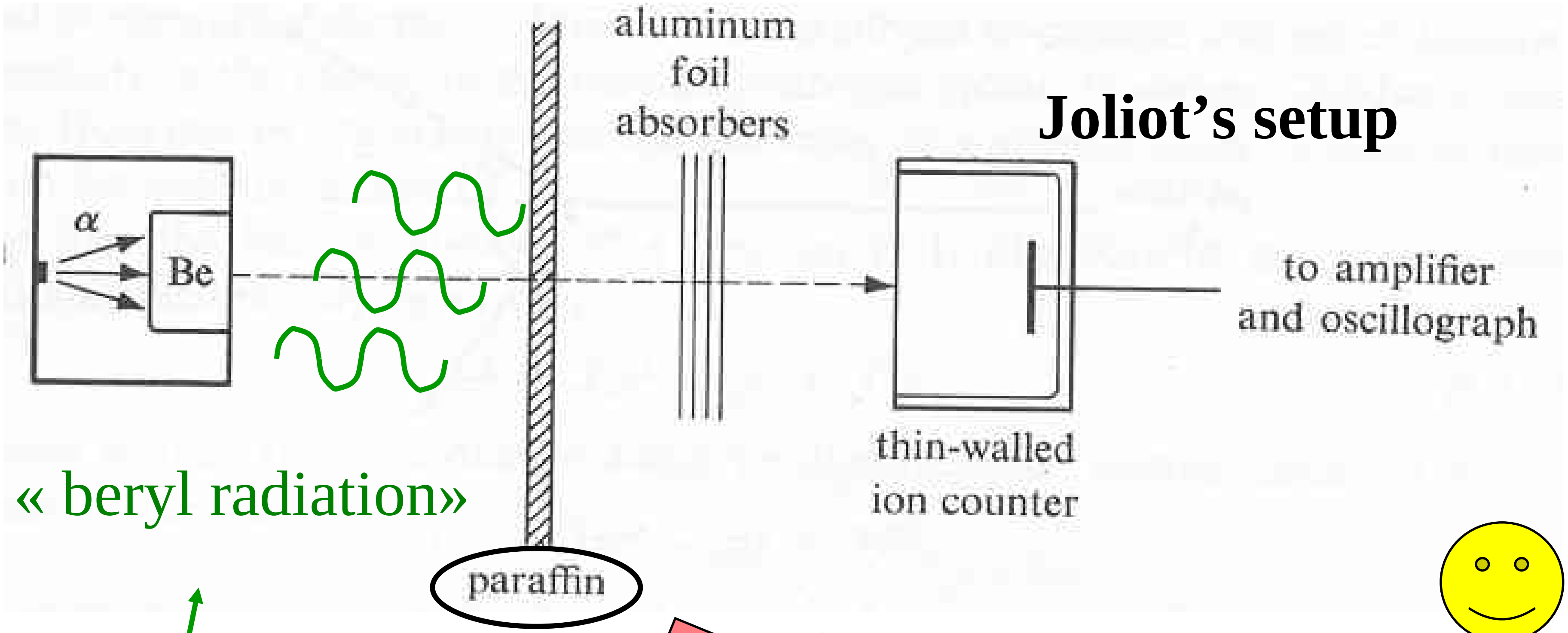
!!

The existence of such atoms seems almost necessary to explain the building up of the nuclei of heavy elements; for unless we suppose the production of charged particles of very high velocities it is difficult to see how any positively charged particle can reach the nucleus of a heavy atom against its intense repulsive field."

1932: Lawrence

Cited by J.Chadwick, Nobel Conf. 1935

Twelve years later: 1932



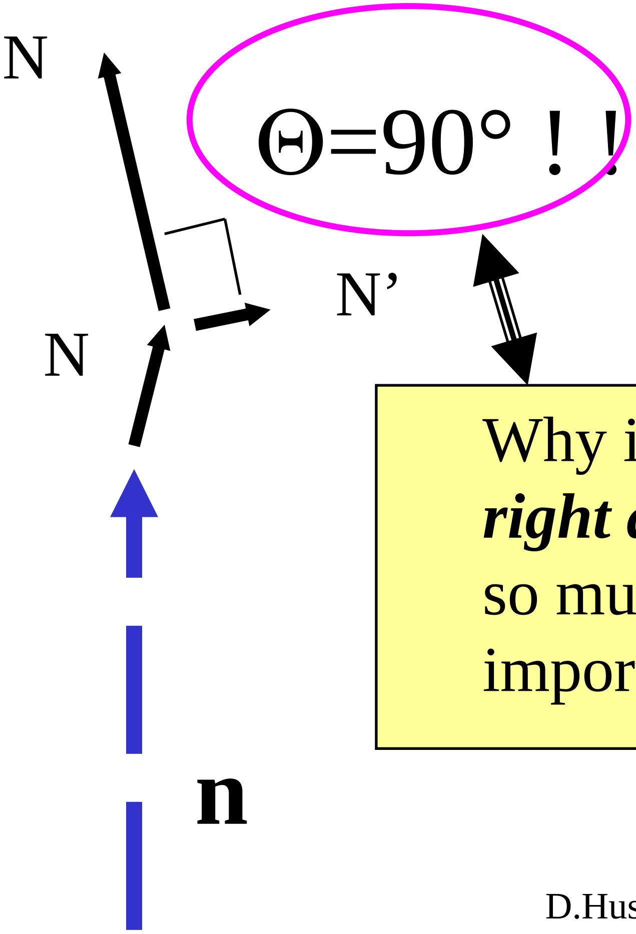
Joliot’s setup

« beryl radiation»

(1930:W.Bothe)

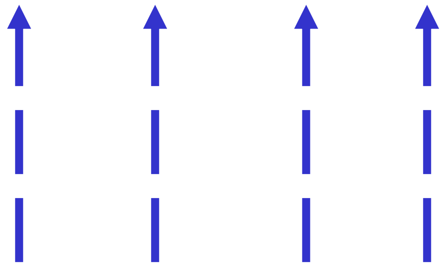
Chadwick: « let’s put paraffin ***inside*** a Wilson chamber ! »

Chadwick's billiard game



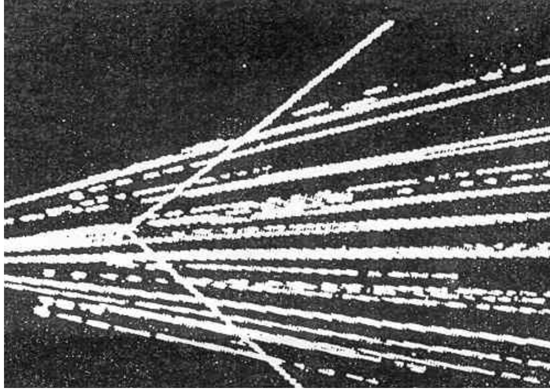
Why is this ***right angle*** so much important ?

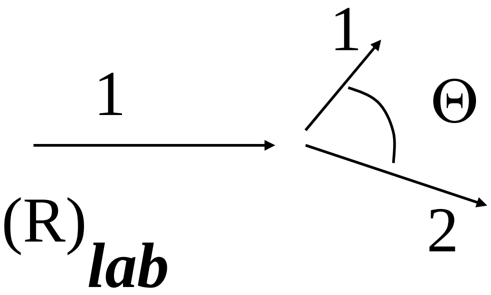
N_2 filled Wilson chamber



incident « beryl radiation »

The power of conservation laws





(1) momentum: $\vec{p}_1+\vec{0}=\vec{p}_1'+\vec{p}_2$

(2) if elastic: $E_1=E_1'+E_2'$

(3) if, in addition, ***m₂=m₁***, then:

$$\boxed{\Theta = 90°}$$

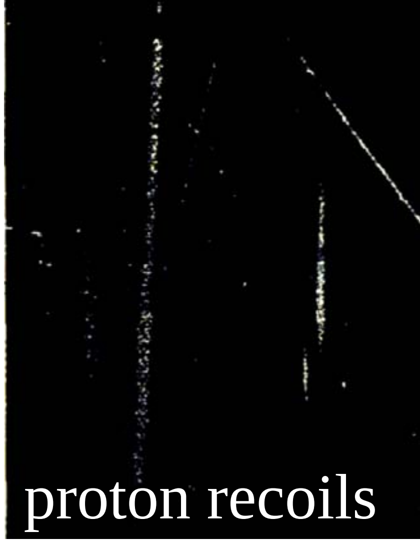
m1=m2 ⇒ $\begin{cases} \vec{v}_1=\vec{v'}_1+\vec{v}_2 \\ v_1^2=v'^2_1+v_2^2 \end{cases}$

⇒ $\cos\Theta = 0$

⇒ $\Theta = \pi/2$

this (N,N') angle is **the** proof:
a « ***beryl quantum*** » is able
to push away a ***Nitrogen*** ion ! !

Chadwick’s demonstration



proton recoils

NB: ***v of the postulated neutral massive particle is unknown !***

Chadwick’s reasoning: on maximal values

1) For hydrogen:

$$\left.\begin{array}{l} m\vec{v}=m_H\vec{v}_H+m\vec{v}' \\ mv^2=m_Hv_H^2+mv'^2 \end{array}\right\}$$

2) Eliminate v’ and set $\vec{v}.\vec{v}_H$ to its ***max*** value = $v.v_H$

$$(v_H)_{max}= v.\frac{2m}{m+m_H}$$

3) Same for nitrogen ions:

$$(v_N)_{max}= v.\frac{2m}{m+m_N}$$

4) Ratio (eliminates v!) :

$$\frac{(v_H)_{max}}{(v_N)_{max}} = \frac{m+m_N}{m+m_H} \sim 7.8$$

m~$0.9\ m_H$

measured

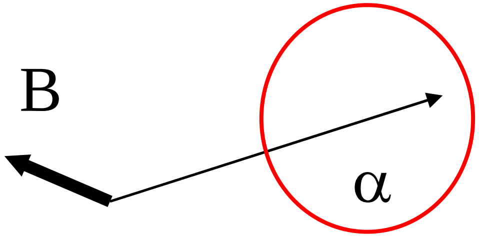
$37\ \ 10^6$ m/s

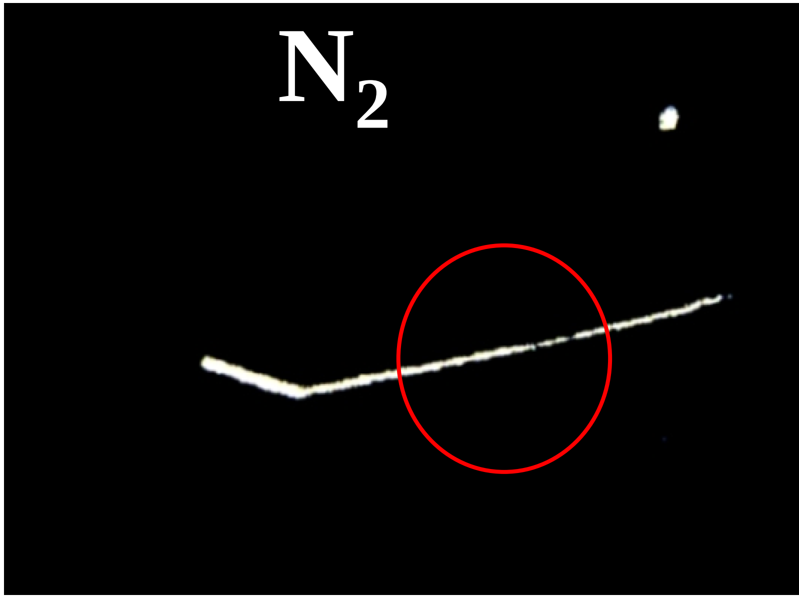
$4.7\ \ 10^6$ m/s

Other nice surprises of Chadwick's billiard…

Rare event: ***Transmutation*** again !

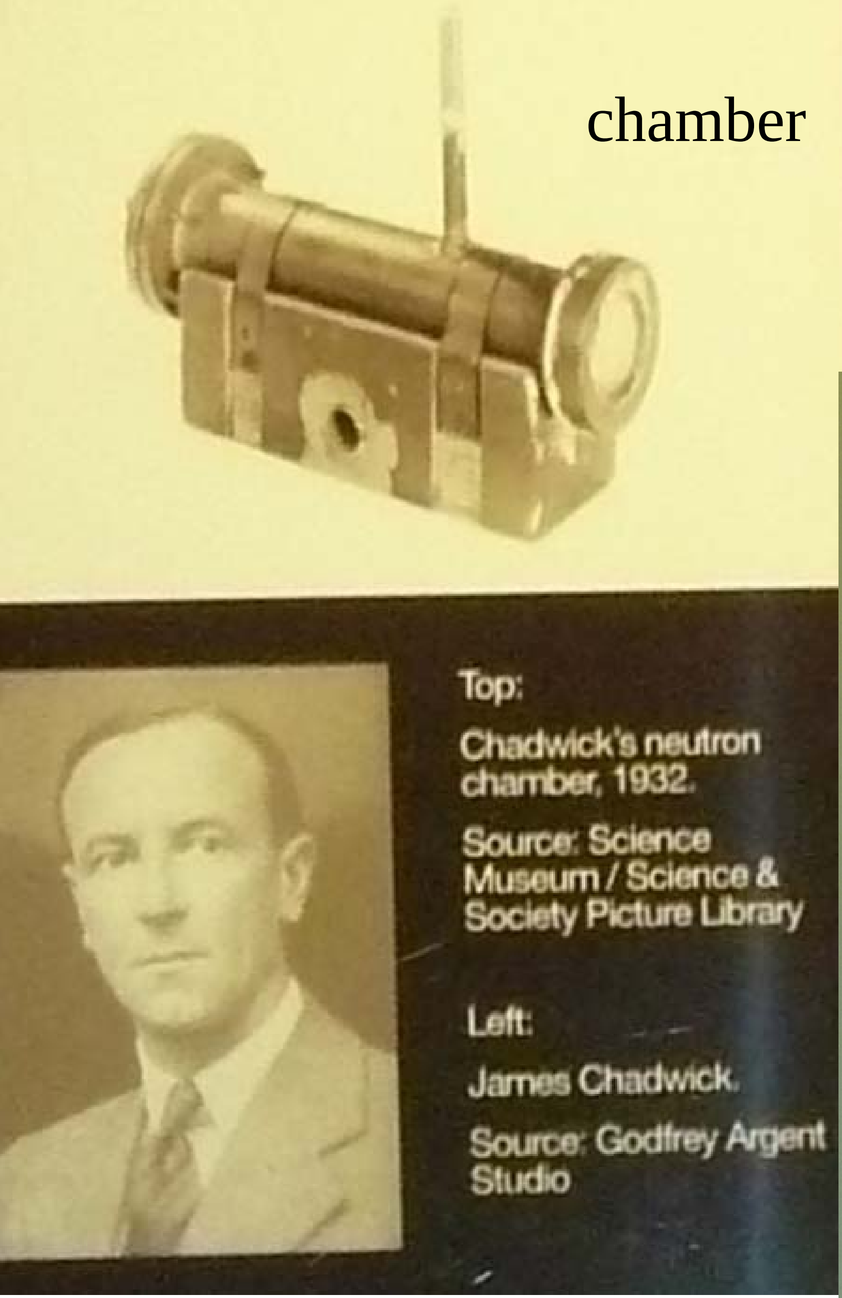
$$\mathbf{n + {}^{14}_{7}N \rightarrow {}^{11}_{5}B + {}^{4}_{2}He}$$





This process behaves exactly as Rutherford and Fermi predicted:
« much more easy » (σ x 100) ! !

What it really looked like…



chamber

Top:

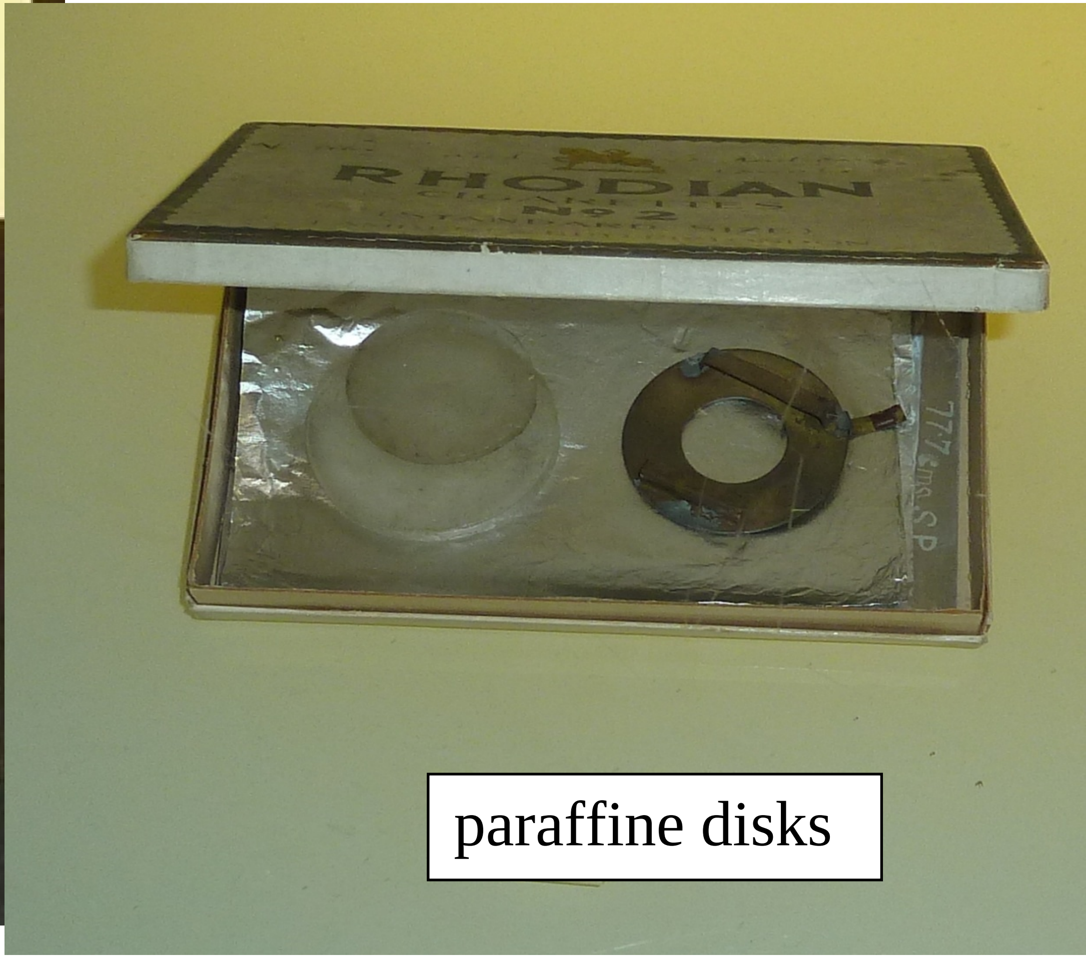
Chadwick's neutron chamber, 1932.

Source: Science Museum / Science & Society Picture Library

Left:

James Chadwick.

Source: Godfrey Argent Studio

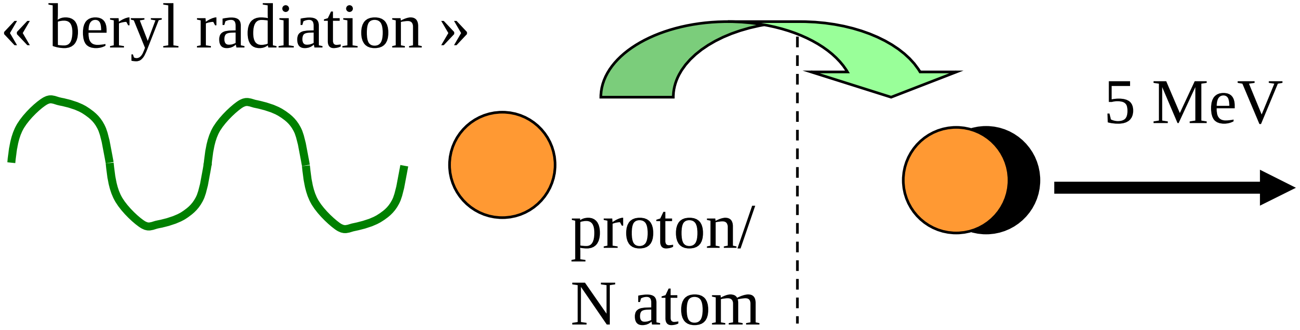


paraffine disks

1931: Joliot's historical mistake

What exactly is « beryl radiation »??

> « To believe (with Joliot) that **photons** are able to eject protons out of matter is as stupid as trying to displace dumbbells by bombarding them with golf balls »
>
> ***Ettore Majorana***


« beryl radiation »

proton/ N atom

5 MeV recoils observed!

Can PHOTONS do this ? ? ? ? ?

Let's calculate!

$$\begin{cases} E_p = p^2/2M \\ p = h\nu/c \end{cases} \longrightarrow \boxed{h\nu = 100 \text{ MeV ! ! !}}$$

➡ Joliot misses the *neutron*, but…

1934

….F.Joliot does NOT miss *artificial radioactivity!*

$$ {}_{2}\alpha + {}_{13}Al \longrightarrow X + \boxed{e^{+}} $$

Joliot's hard work

Bombarding everything with α particles is like climbing high Coulomb barriers…but:

Nobel Price (1935)

During 1934-1935: Fermi & al. submit everything to ***neutrons*** (much better probe indeed):

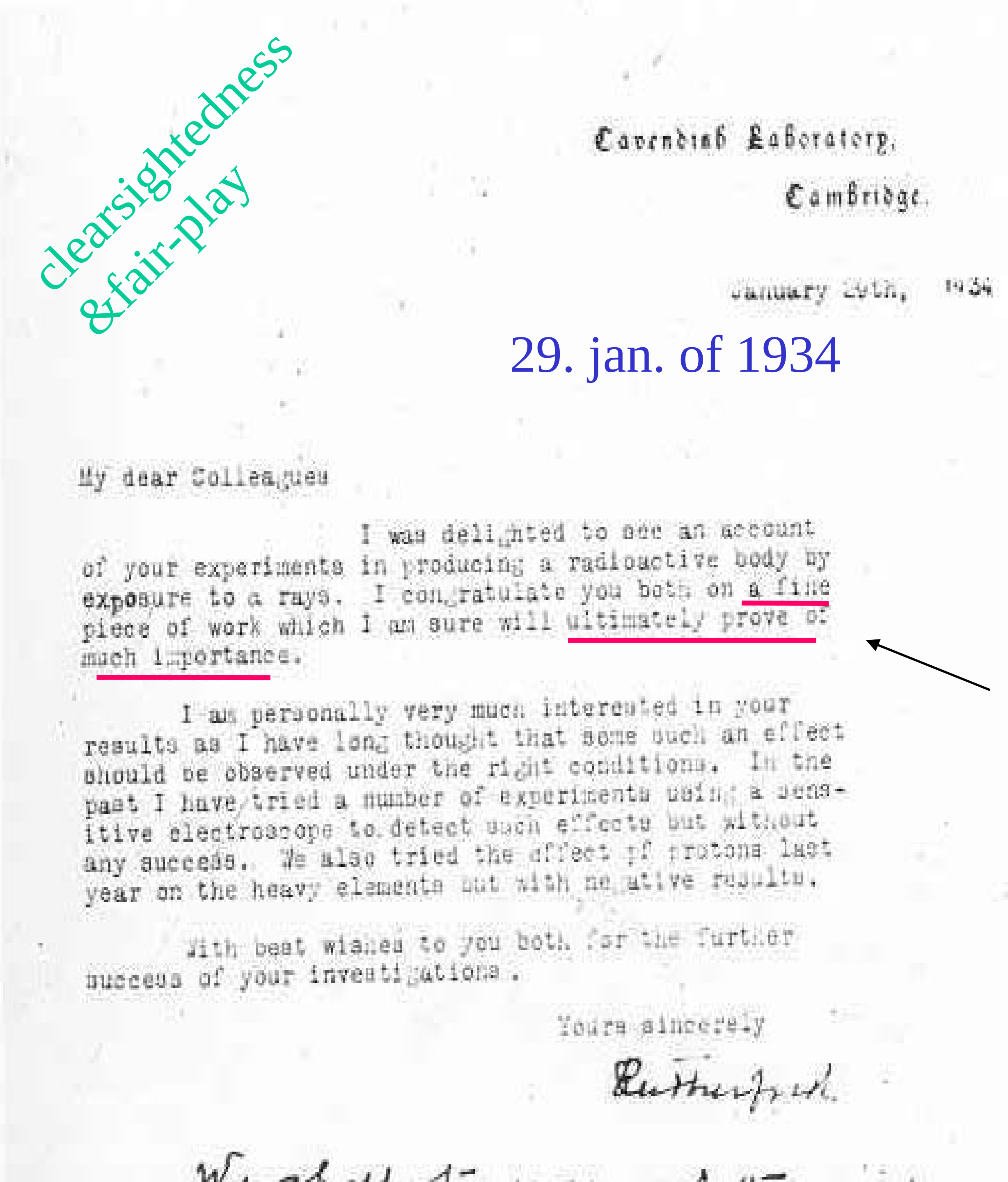
1) Nearly all elements undergo β+

2) Additional surprises!

fission, transuranians…

${}_{93}Np$ ${}_{94}Pu$ …

clearsightedness
&fair-play



Cavendish Laboratory,
Cambridge.

January 29th, 1934

29. jan. of 1934

My dear Colleagues

I was delighted to see an account of your experiments in producing a radioactive body by exposure to α rays. I congratulate you both on a fine piece of work which I am sure will ultimately prove of much importance.

I am personally very much interested in your results as I have long thought that some such an effect should be observed under the right conditions. In the past I have tried a number of experiments using a sensitive electroscope to detect such effects but without any success. We also tried the effect of protons last year on the heavy elements but with negative results.

With best wishes to you both for the further success of your investigations.

Yours sincerely

Rutherford.

« a fine piece of work…which will ultimately prove of much importance »

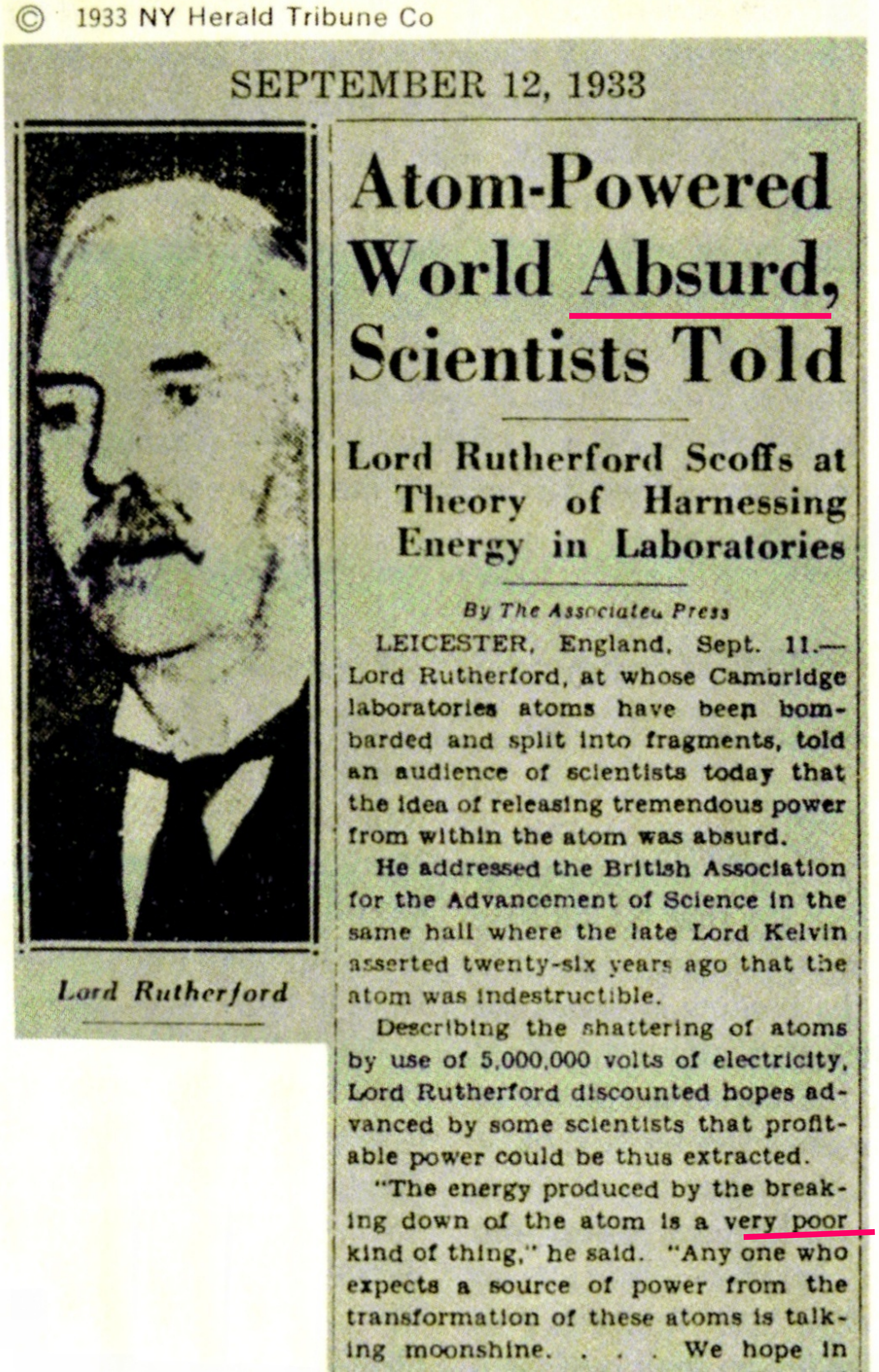
(today: positon cameras,TEP…)

1933: Nuclear energy ?
Rutherford: « no chance ! »

- Fermi + Rutherford agree: « neutral particles should easily penetrate heavy nuclei… »
- But E.Rutherford **dismisses** the possibility of extracting the (huge) energy stored inside nuclei

1x 100 MeV~0.1 nJ…

mistake is here !



SEPTEMBER 12, 1933

Atom-Powered World Absurd, Scientists Told

Lord Rutherford Scoffs at Theory of Harnessing Energy in Laboratories

Lord Rutherford

By The Associated Press

LEICESTER, England, Sept. 11.—Lord Rutherford, at whose Cambridge laboratories atoms have been bombarded and split into fragments, told an audience of scientists today that the idea of releasing tremendous power from within the atom was absurd.

He addressed the British Association for the Advancement of Science in the same hall where the late Lord Kelvin asserted twenty-six years ago that the atom was indestructible.

Describing the shattering of atoms by use of 5,000,000 volts of electricity, Lord Rutherford discounted hopes advanced by some scientists that profitable power could be thus extracted.

"The energy produced by the breaking down of the atom is a very poor kind of thing," he said. "Any one who expects a source of power from the transformation of these atoms is talking moonshine. . . . We hope in

6 jan.1939: chemist O.Hahn detects **baryum** in his uranyl salts…and calls Lise Meitner for help

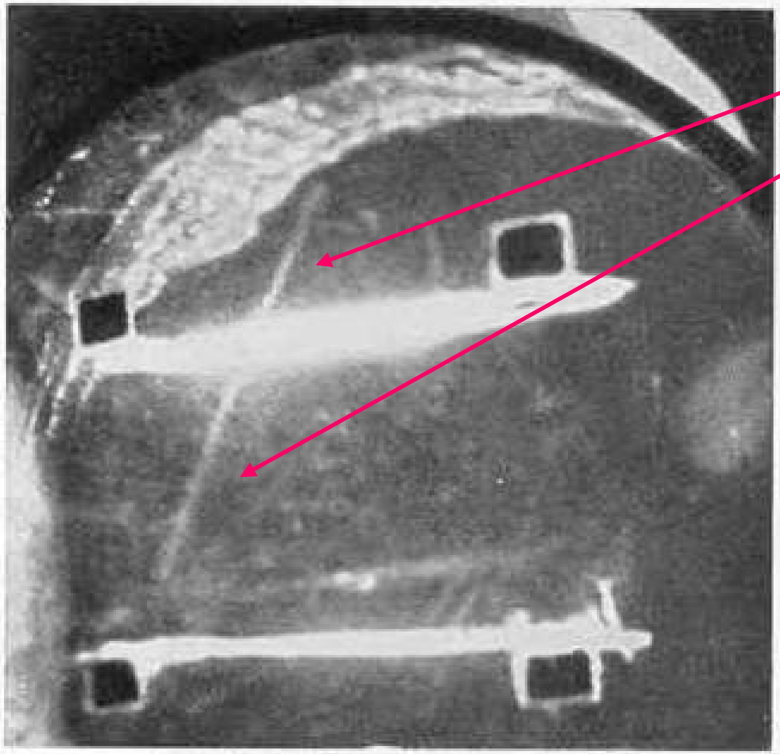


Fig. 157. Cloud-chamber photograph of HAHN and STRASSMANN's fission of a uranium nucleus upon absorption of a neutron. The two fission products leave the upper horizontal uranium plate in opposite directions with a combined energy of 160 Mev. (Photograph by CORSON and THORNTON)

FF @ 180°

What Rutherford *couldn't* know:

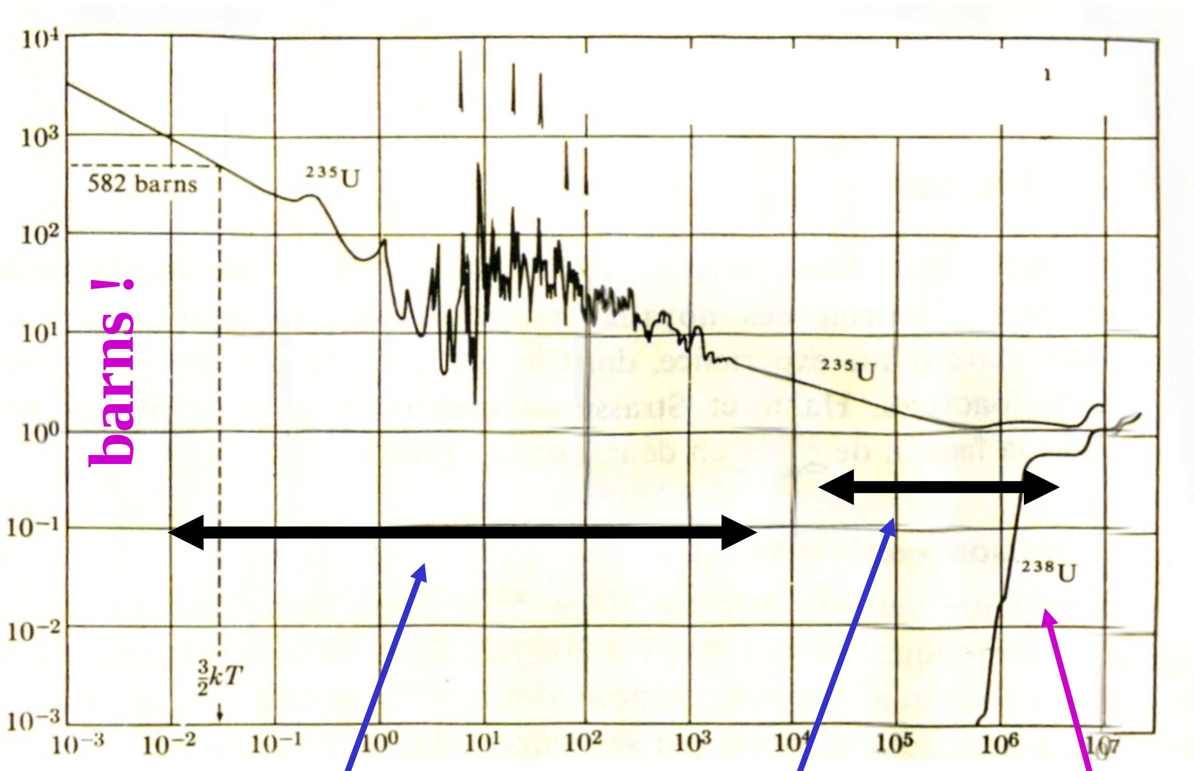
1) **Fission** happens

AND

2) N_n=**2.416** / fiss

THE condition for *chain reaction* !
(= macroscopic energy release)

Fission: all in *one* slide…



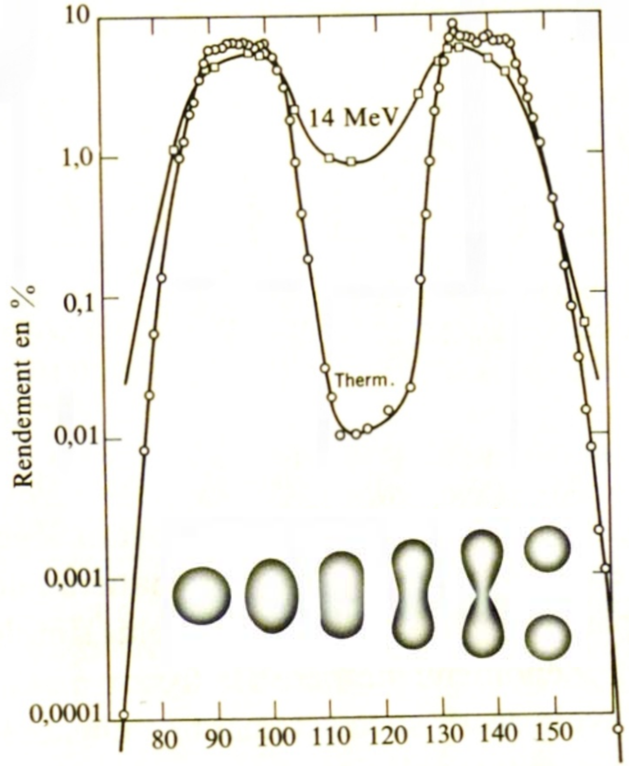
barns !

^{238}U: no!

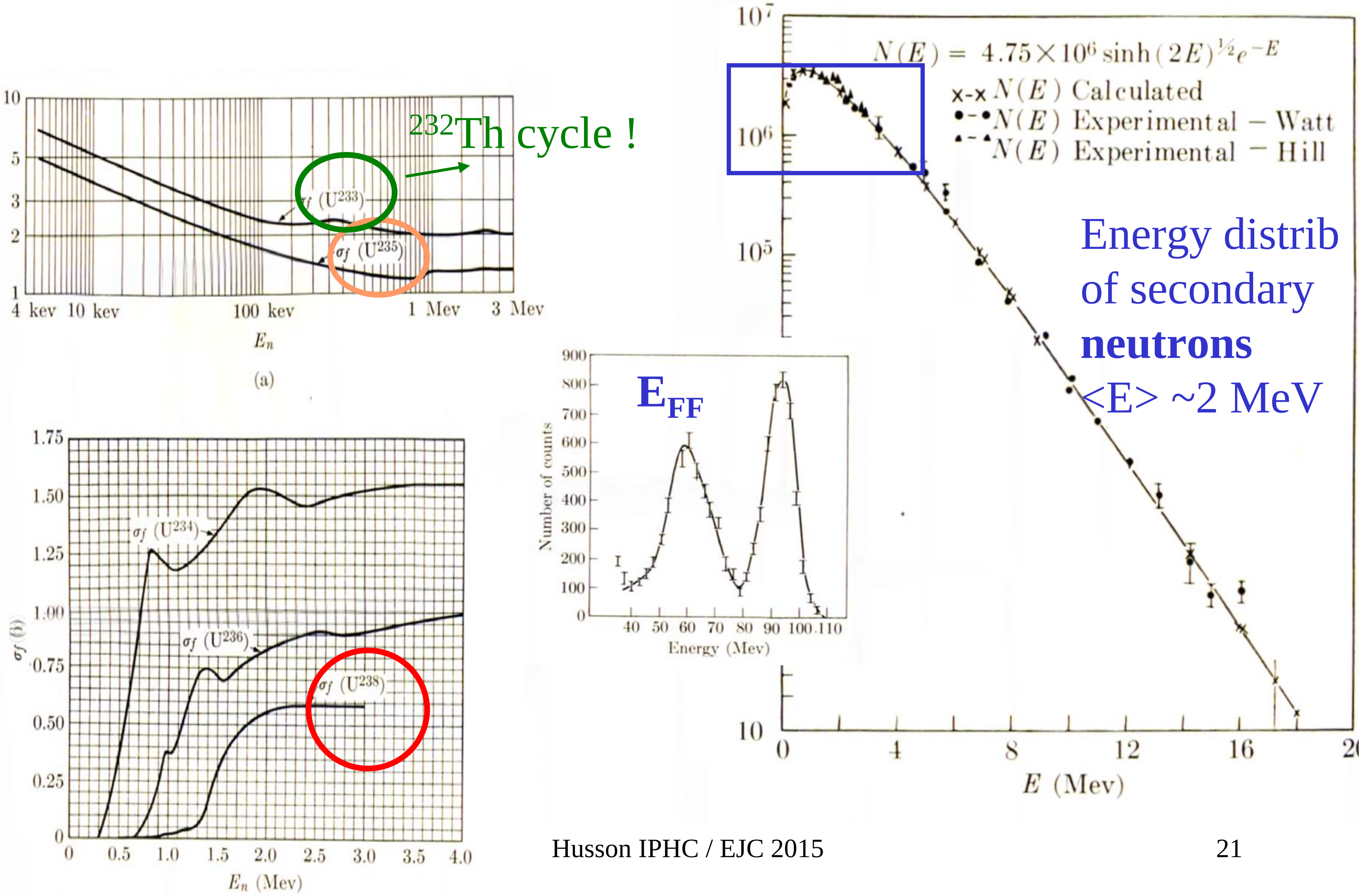
Additional *n* at creation

Additional n after moderation: σ X 500 !

FF yield and mass distribution



Fission: a little bit more



^{232}Th cycle !

E_{FF}

Energy distrib of secondary **neutrons**
<E> ~2 MeV

The neutron is a quantum object!

a) Diffusion states:

  a) De Broglie wavelength:

   $\lambda = h/mv$ (*beams*) *or* $h/(2mkT)^{1/2}$ (« *bottles* »)

  b) Cross sections: $\boldsymbol{\sigma} \sim \lambda^2 \sim \mathrm{fm}^2$

  $\sim 10^{-26}\ \mathrm{cm}^2$= barns!

b) Bound states:

  a) 2-particles system: the deuteron

  b) N-particle systems: shells / mirror nuclei

a) the DeBroglie neutron

$\boldsymbol{\lambda = h/p}$

$= h/(2mE)^{1/2}$ (< 20 MeV)

or hc/E (relativistic)

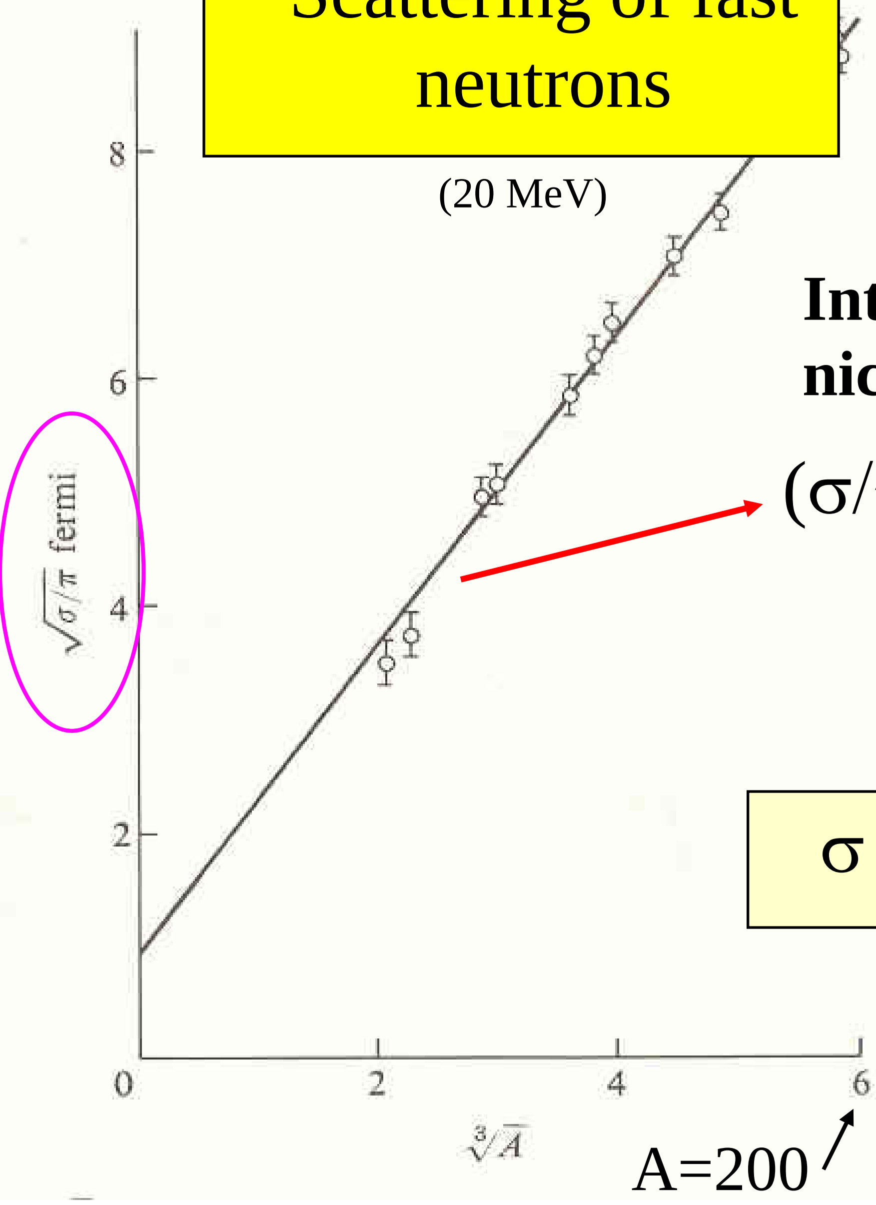
E	v (km/s)	β_{Lo}	λ
0.1 meV	0.14		**$3.\ 10^{-9}$**
1 keV	440		9.10^{-13}
20 MeV	6.10^{4}	0.2	**6.10^{-15}**

(=6 cm/ns: limit of ToF…)

atomic scale

nuclear scale

Scattering of fast neutrons



(20 MeV)

A=200

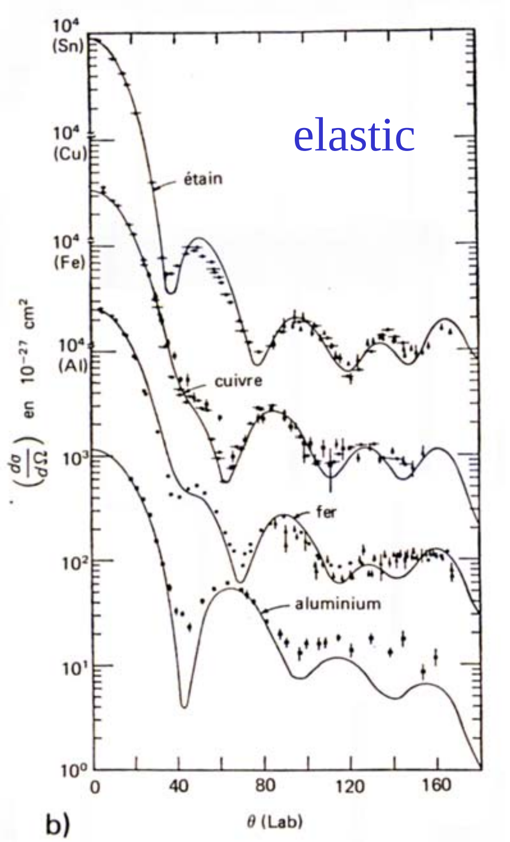
Integrated σ :
nicely __linear__ !

$(\sigma/\pi)^{1/2} \sim A^{1/3}$!

$\sim r_{nuc}$! !

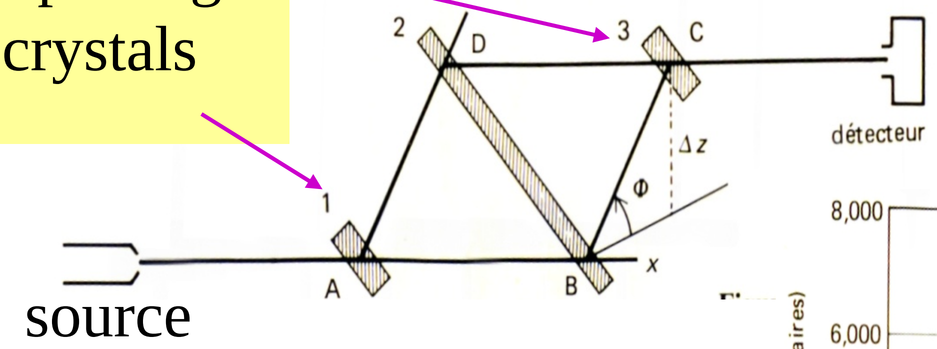
$$\boxed{\sigma \sim \pi\, r_{nuc}{}^2}$$

Differential dσ/dθ:
wave mechanics!

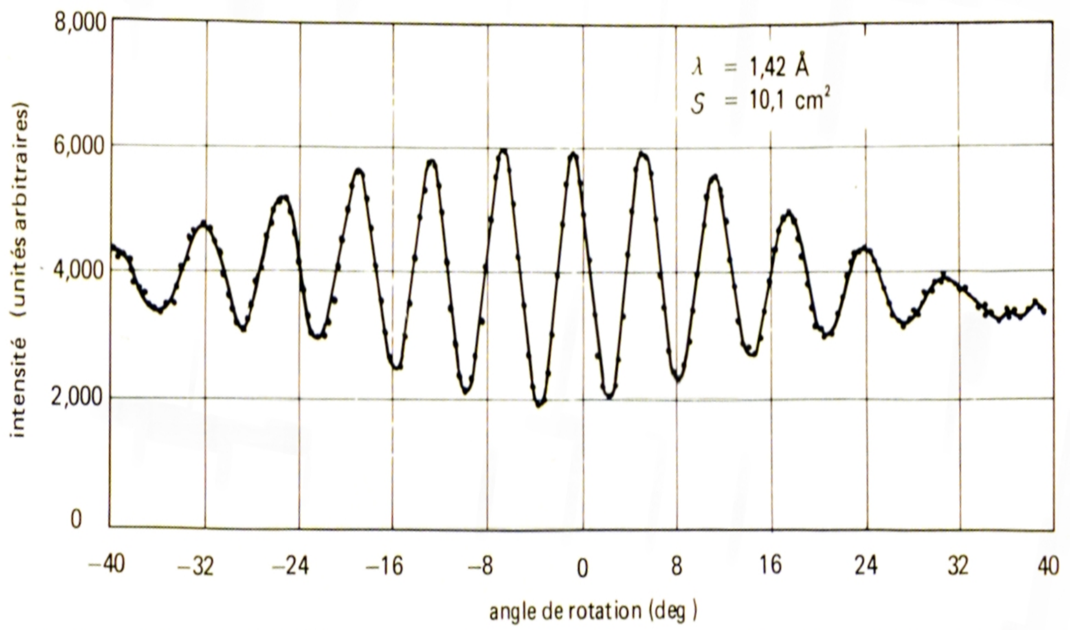


If the ***n*** is a quantic object, it should exhibit interferences…with himself

Splitting crystals



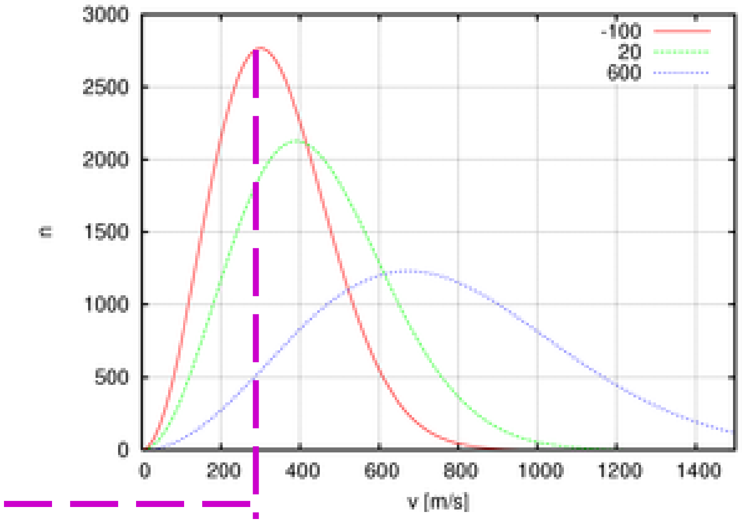
Mach-Zender interferom.



[J.L. Staudenmann, S.A. Werner, R. Colella, A.W. Overhauser, Phys. Rev. A *21*, 1419 (1980)]

…and it does !

Reactor neutrons: thermal velocities



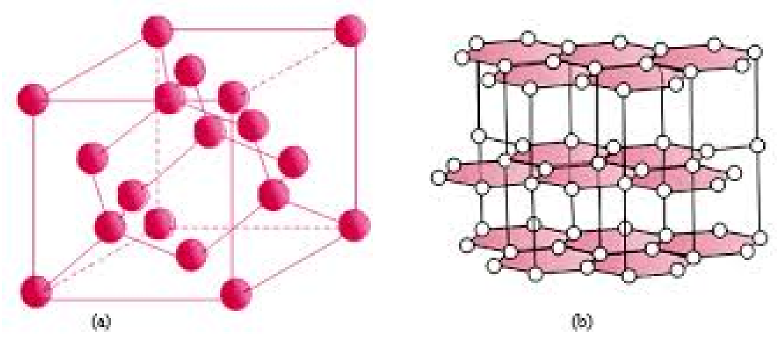
-Maxw-Boltzmann: $\mathbf{v_{mp} = (2kT/m)^{1/2}}$

= **2200 m/s** @ T=293 K

-MB+DeBroglie: $\lambda = h / mv_{th} \Rightarrow \lambda = h / (2mk\mathbf{T})^{1/2}$

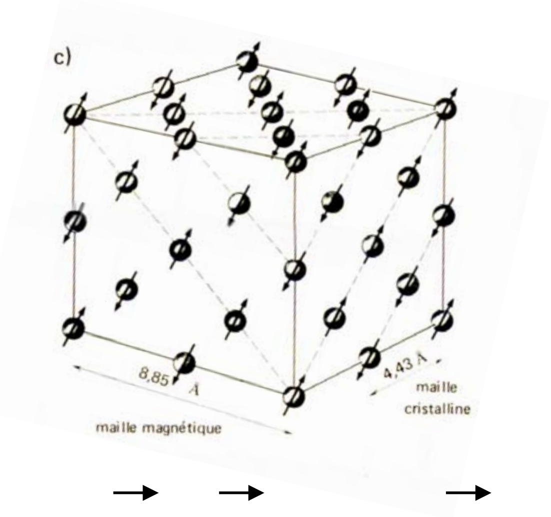
= **0.18 nm** @ T=293 K (or 1.8 nm @ **3 K**)

magnetic studies



UCN…

Diffraction peaks ⟺ cond. matter physics



Ex: Mn^{++} has magnetic moment

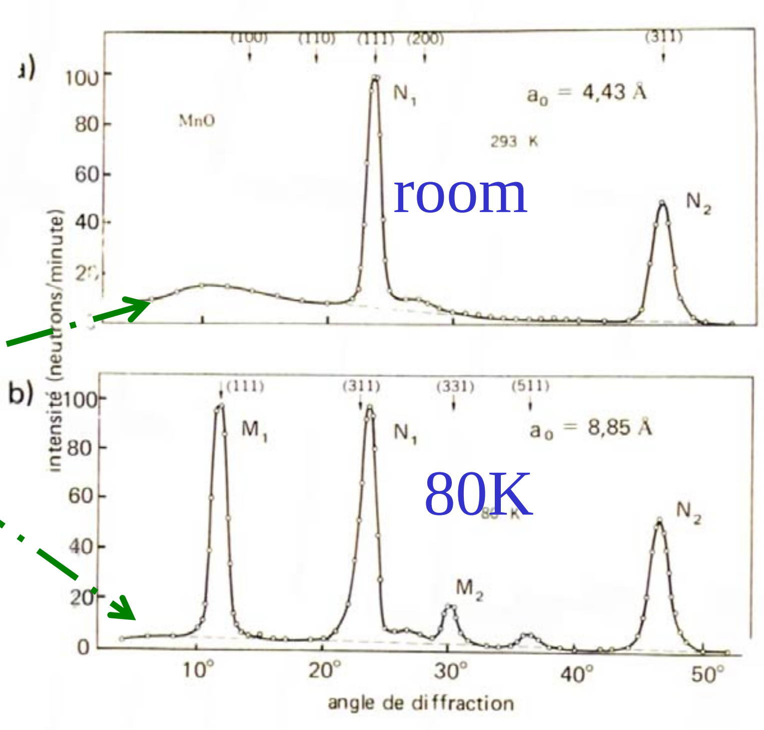
⇒ cubic MnO is anti-ferromagnetic

$\vec{J}_{tot}=\vec{L}(\sim 0)\ \ +\vec{S}(n)+\vec{S}(Mn)$

-General case: J_{tot} non zero, diffusion *probabilities* add up uncoherently.

-If polarization is prepared such as J_{tot}=0, two opp situations: outgoing ***n*** has S + or – : coherent sum of ***amplitudes***.

Total: sum of uncoh. backgr.+narrow peaks



Waves ➔ interferences, diffraction peaks or…images !

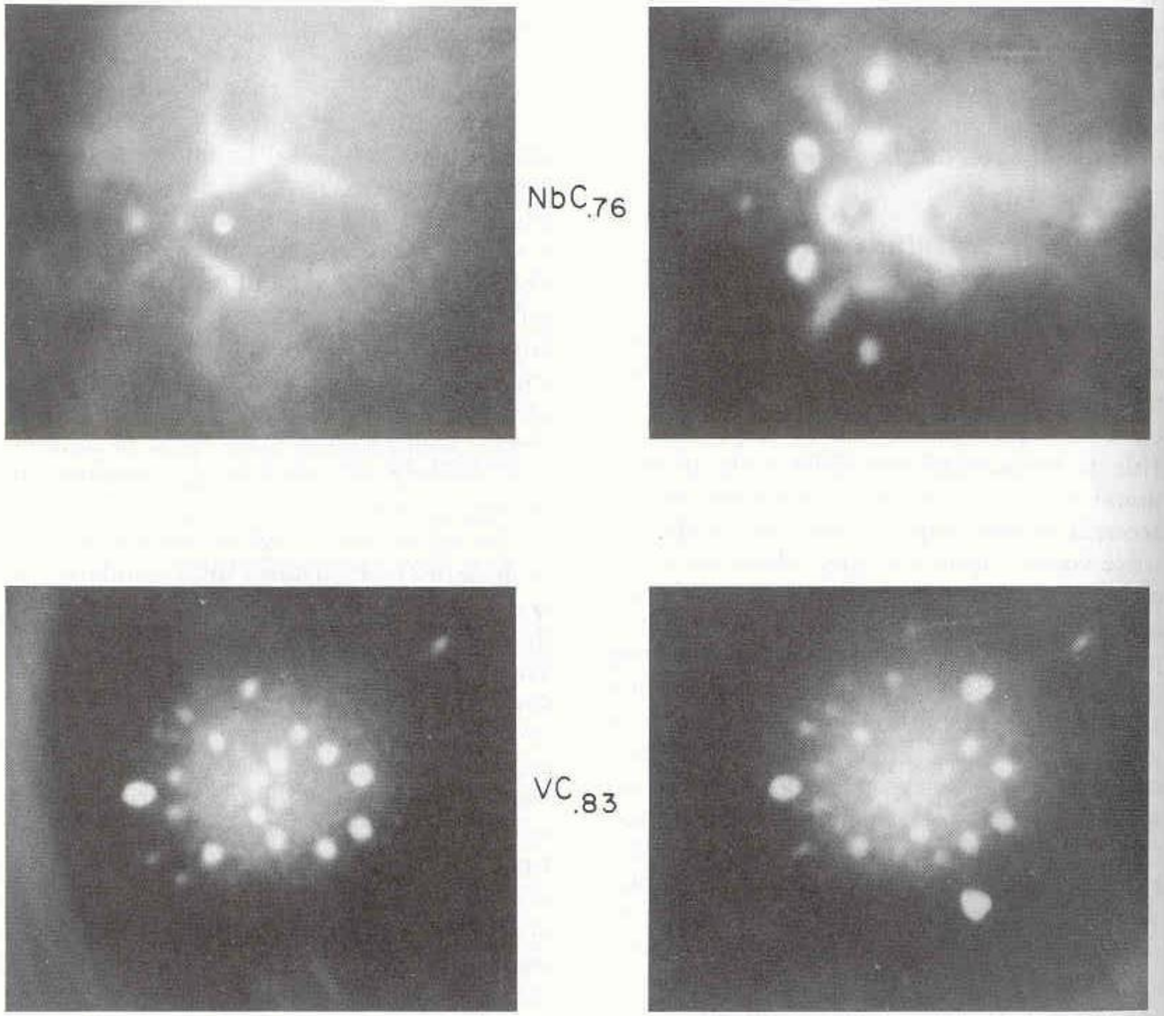


FIG. 16. The diffuse scattering pattern in $NbC_{0.76}$ due to SRO and static displacements, and the sharp Bragg reflections in $VC_{0.83}$ due to the LRO of the carbon vacancies in the crystal. (Reproduced with permission of H.

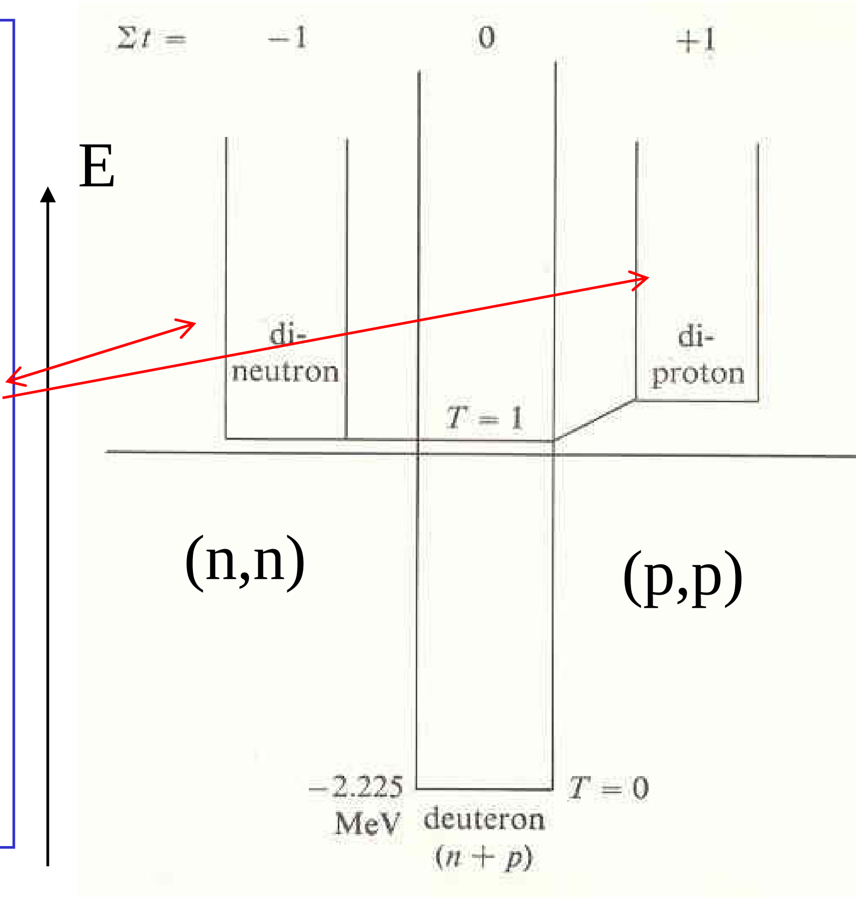
b) « royal » bound state: the deuteron

- (np) system = simplest nucleus after bare proton
- many *diffusion* states (spin dependent!) but…

ONE single *bound* state !!!

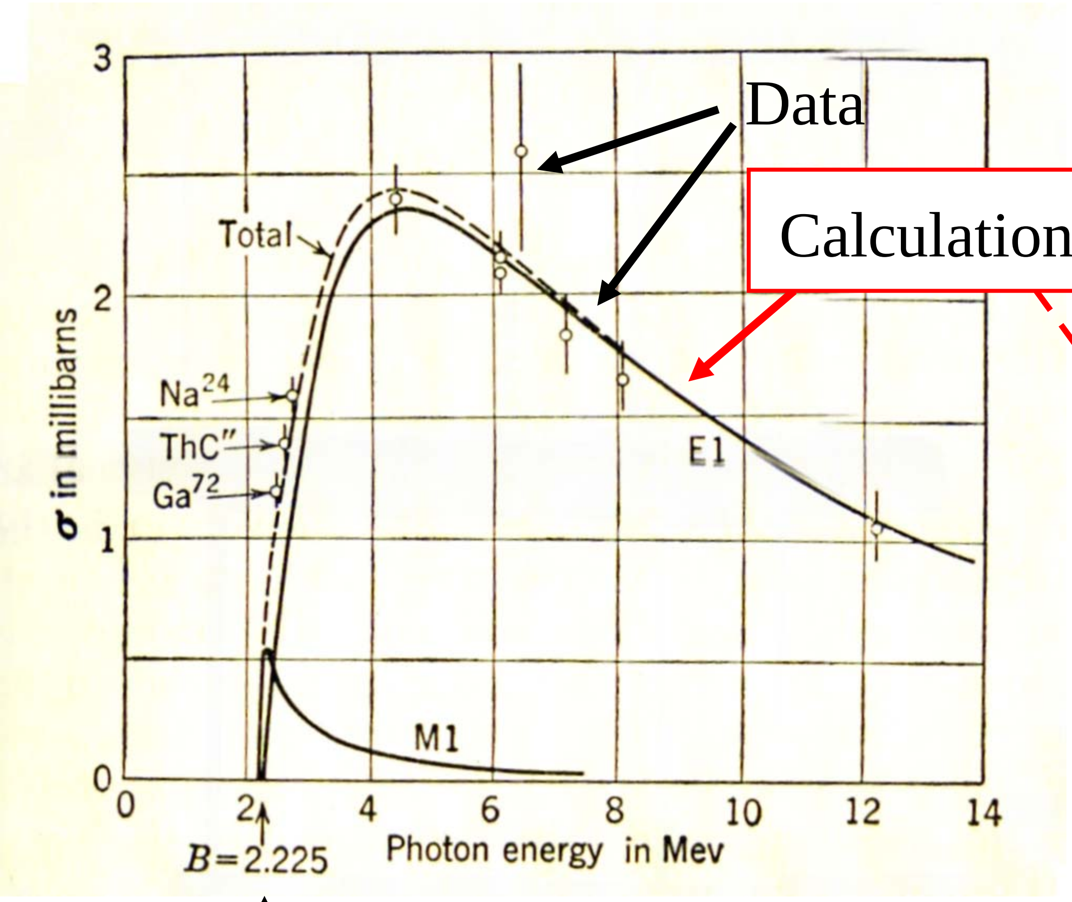
- QM prediction: Ψ must be AS
- E_1=-2.22 MeV; spins:↑↑
- E_2 state =*non-binding* (spins:↑↓)
- …but **E_2 contribues** to total σ_{diff}
- (n,n) or (p,p) states: Pauli-forbidden

Isospin symmetry :
under SU(2) Group Transf° :
p=(1,0) and n=(0,1)



More about the deuteron (I)

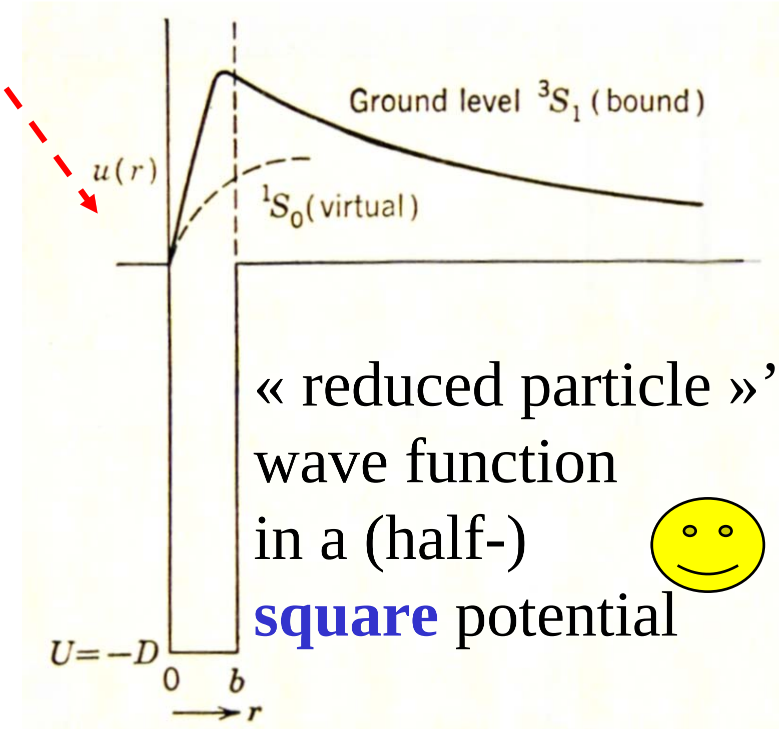
Photo-dissociation: $\gamma + d \longrightarrow n + p$ (inverse of fusion reaction)



Data

Calculation: excellent agreement!

Threshold = 2.22 MeV

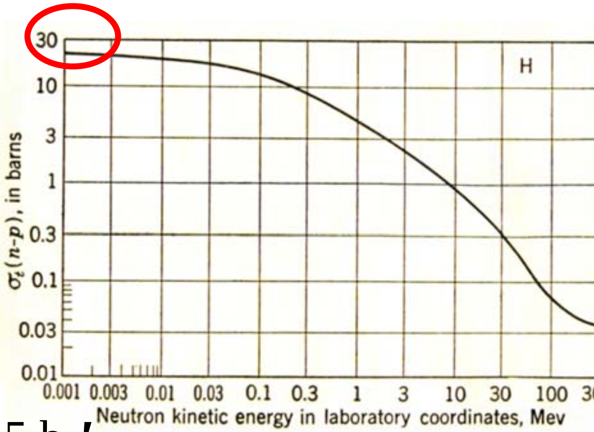


« reduced particle »'s wave function in a (half-) **square** potential

More about the deuteron (II)

Bound state OK (D=-35 MeV, b=2.10^{-15}m. However! Total (n,p) at E_n~1 keV:

σ_{calc} = 3.5 b (single bound state); σ_{meas}=20.36 b ! ***(big failure !)***



Radial pure s-wave: $\psi = u(r)/r = e^{ikx} + f(\theta)e^{ikr}/r$.

With l=0: $f_0 = [\exp(2i\delta_0)-1]/2ik = \exp(i\delta_0)\,.\sin(\delta_0)/k$

and $\sigma = 4\pi|f_0|^2 = 4\pi \sin^2\delta_0 /k^2$.

Lim $E_n \to 0$: δ_0 must → 0 , $\exp(ik\delta_0) \to 1$ and $f_0 \to \delta_0/k = \boxed{-a}$

a=« scattering length »: > 0 (bound) or <0 (unbound) ⤢

and $\sigma_0 = 4\pi a^2$ whatever >0 or <0 …. Calculation at low energy: 3.5 b *!*

<u>E.Wigner</u>: why should singulet and triplet (bound st.) be of same amplitude?

With unpol.neutron beam: $\sigma_0 = 3/4({}^3\sigma_0) + 1/4({}^1\sigma_0)$ (as 2S+1=3 if S=1)

…and obviously: ${}^1\sigma_0 >> {}^3\sigma_0$!

<u>Proposed test !</u> orth/para-H_2: $\sigma_{orth}/\sigma_{para}$~1.5 if ${}^1a$=+20.10^{-15}, but 14 if -20 fm

Exp: σ_{ortho}~120, σ_{para}~ 4 b

$\uparrow\uparrow$ $\downarrow\uparrow$

(epitherm. neutrons).

<u>Conclusions:</u>

1) ^{3}(n,p) ≠ ^{1}(n,p) : ***strongly*** spin-dept

2) ${}^1a$ <0: singlet state is ***unbound***

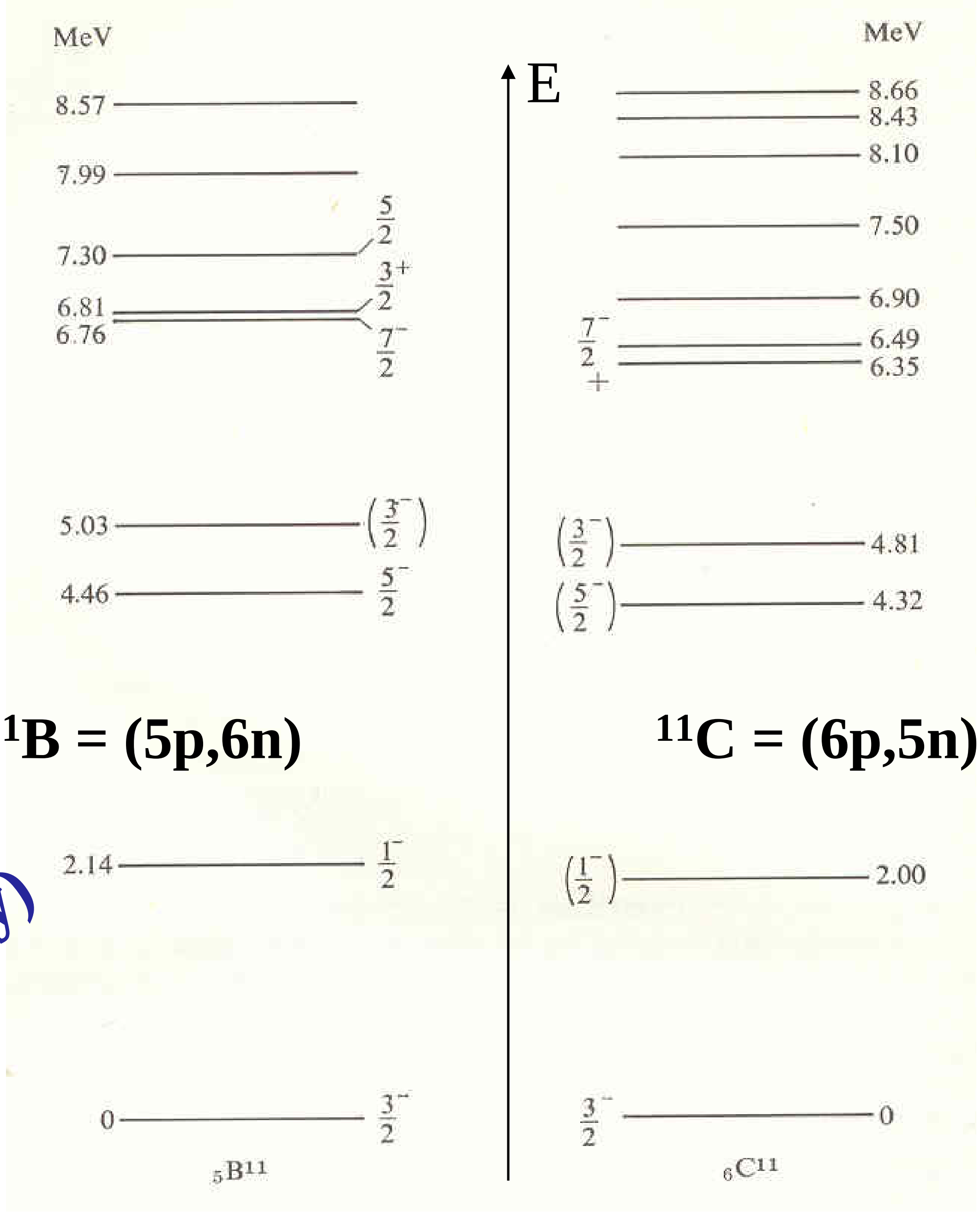
and also: 3) s(n)=1/2, not 3/2

Heavier nuclei:
Heisenberg’s idea

Isospin !

Obvious charge independance of nuclear forces (inside nuclei, just one object: the nucleon)

Mirror nuclei:
same E_n and Qu.Nbs (spin/parity)



^{11}B = (5p,6n)

^{11}C = (6p,5n)

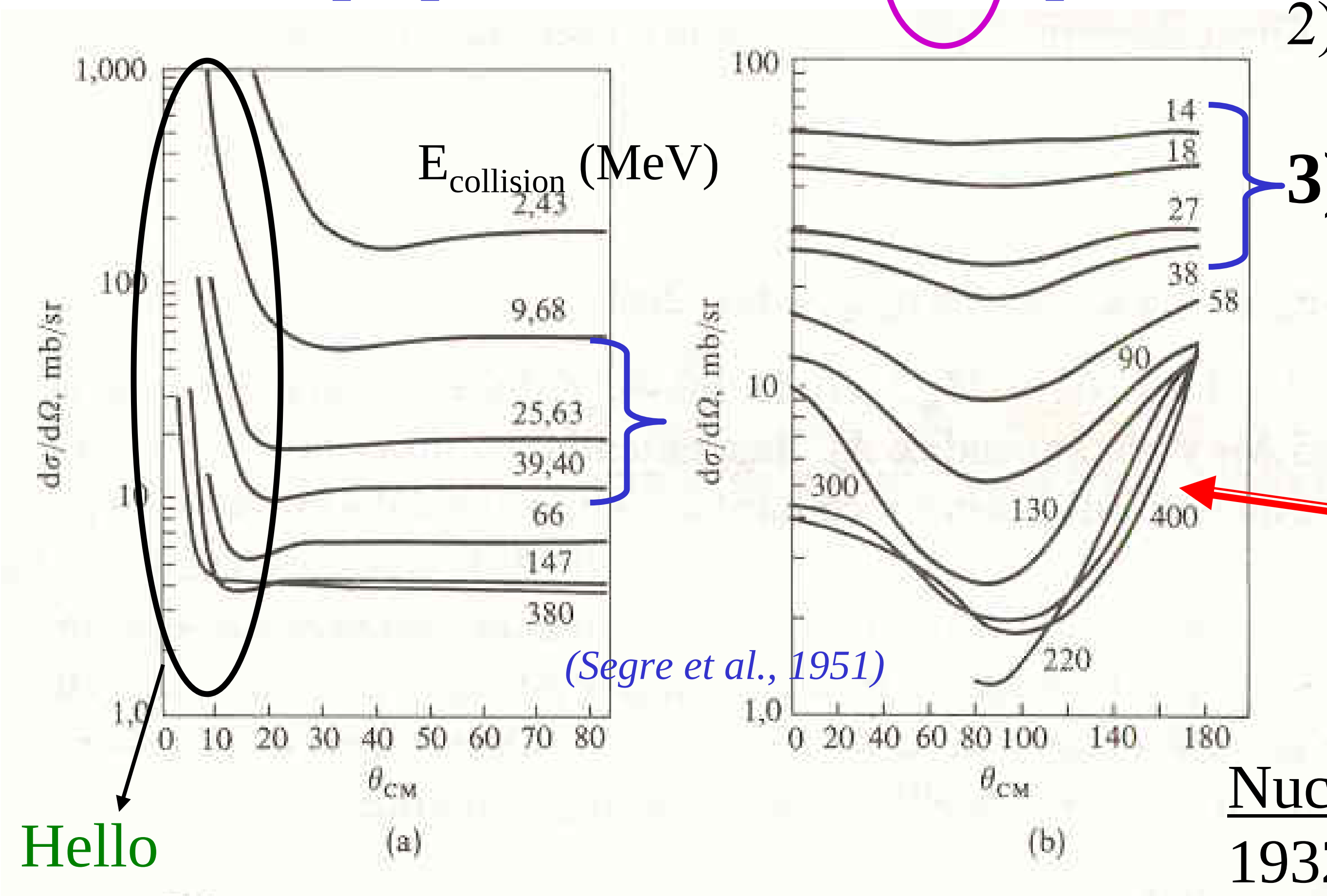
J.Chadwick, Nobel conference paper (12 dec.1935):

« It appears that the interaction between proton and neutron is of the highest signifiance in nuc. structure, and governs the stability of the nucleus. The meagre information we have does, to some degree, support the view that the interaction is of the exchange type.
Dr.Feather and I hope to obtain more information on that by an extensive study of the collisions of neutrons and protons. »

A step deeper: what is nuclear « force »?
➔ the answer was *really* in nucleon-nucleon diffusion!

p+p

n+p



(Segre et al., 1951)

Hello
Rutherford !

1) 10 mbarns/sr
2) $\sigma = \sigma_{Ruth}$ for p,p

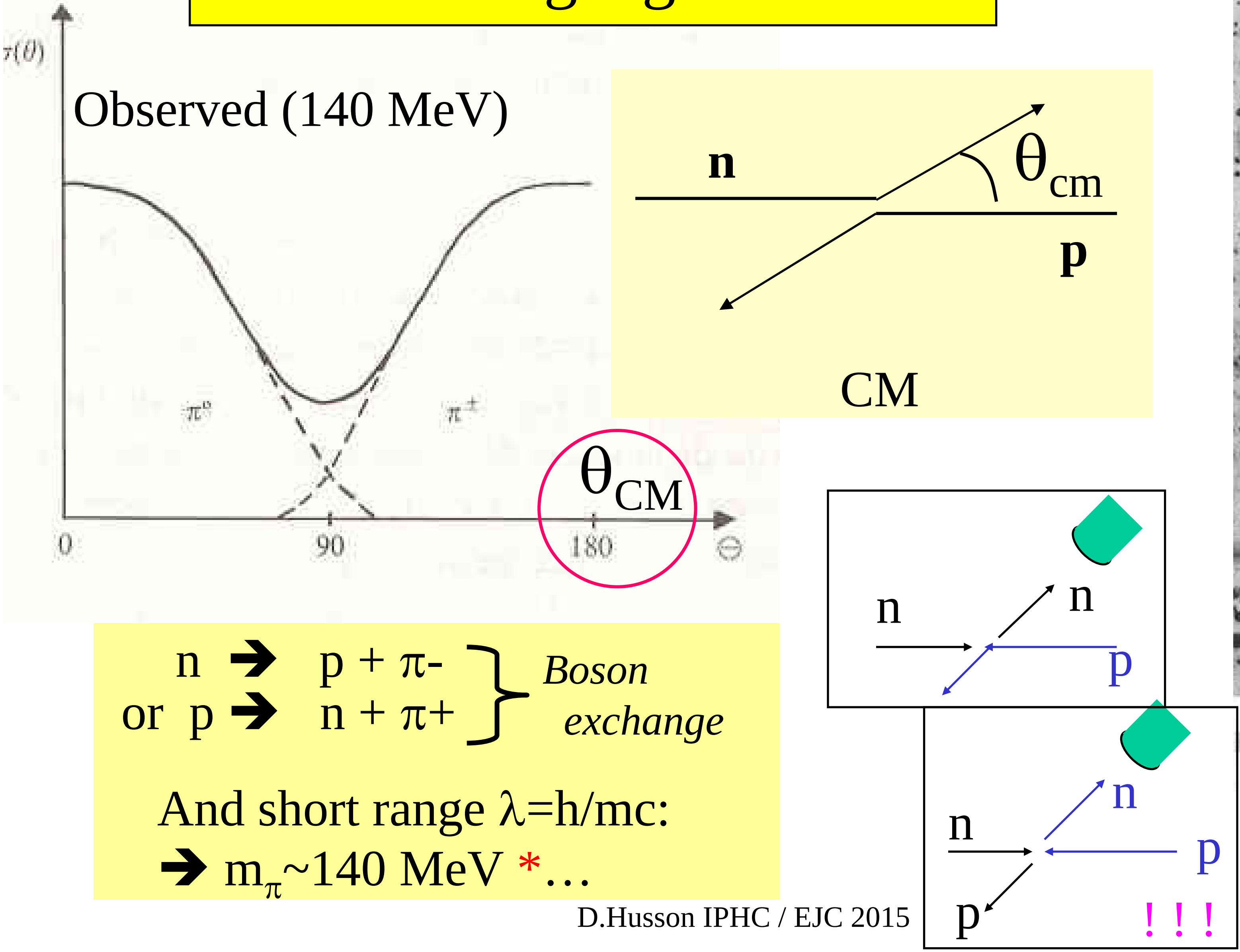
3) n ~ p (low E)

+

4) someth.new
at 130 MeV !!

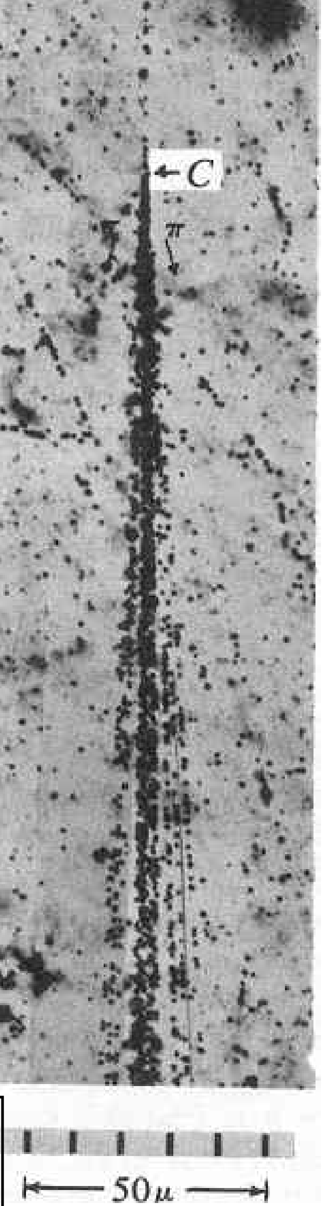
Nuc Exchange Forces !
1932: Heisenberg
1935: Yukawa

Ideki Yukawa (1935) opens the road to gauge theories



n ➔ p + π- } *Boson*
or p ➔ n + π+ } *exchange*

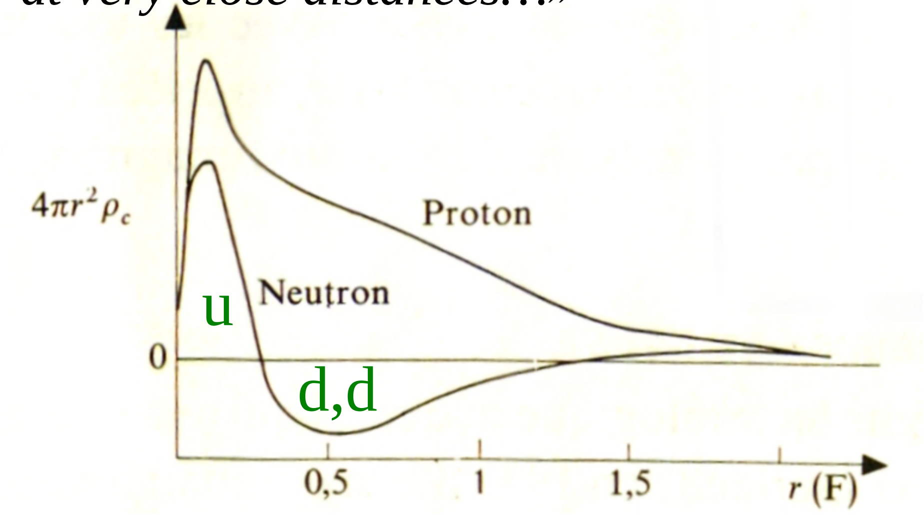
And short range λ=h/mc:
➔ m_π~140 MeV *…



Powell *
(1947)

Another step deeper: inside the neutron !

Remember Rutherford (1920) ? « *this neutral object should have* **vanishing electric field** *except at very close distances…»*



1961, Kendall,Taylor, Friedman
(scattering, again and again…)

Magnetic moment :

$$\vec{\mu} = \frac{1}{2}\oint \vec{r}\,\Lambda\,\vec{j}\; d^3r$$

$\mu_p = +\,2.79\ \mu_N$ *($\mu_N = e.\hbar/2.m_p = 5\ 10^{-27}$ J/T)*

$\mu_n = -\ 1.91\ \mu_N$ not zero ! Net charge=0, but non-trivial $\rho(r)$ spatial distribution

⇨ Quark model (1963): p=(uud) ; ***n***=(udd)

What do we do today with neutrons ?

- Fundamental Physics

1) Theory
    - a) Nuclear (nuc.models, halo, dynamic processes like pre-equil./evaporation, nucleon spin…)
    - b) Other (ν osc., UCN, quantum mechanics,…)

2) Experimental
    - Calibrate sources (beams) + detectors
    - ⇒ measure $\sigma\{A(n,x)B\}$of interest (astrophys.)

- Applied Science

- a) materials (magnetism, irradiation limits,…)
- b) reactors: present+future (ADR,ITER), fuel cycle
- c) production of rare isotopes: ^{3}H,^{3}He,^{60}Co,^{99}Tc,..
- d) biology/medical/radioprotection

Outmost important reactions for ***n*** detection

- ^{157}Gd: splendid gamma *signature* (ν physics)
- ^{197}Au *activation* : precision Φ_n
- ^{181}Hf: nice *thickness* measurement (~nm)
- $^{108\text{-}113}$Cd: efficient *absorption* of ***slow n***

capture

- H(n,p) elastic : historical ***and*** actual for fast ***n***
- ^{10}**B**(n,α)^{7}Li, ^{3}He(n,p)= fundamental reactions for :
  a) slow n *detection* b) *neutron-therapy (***B***NCT)*

..and of course:

- ^{235}U / ^{243}Am: nuclear reactors+fuel cycle (+fiss.det)
- H/D: *moderators* => UCN, Bonner spheres…

The ***n*** for neutrino physics

- Discovery (1956): $\nu + p \rightarrow n + e^+$

Shavannah River Reactor: detection of

BOTH ***n*** and positon through scintillation

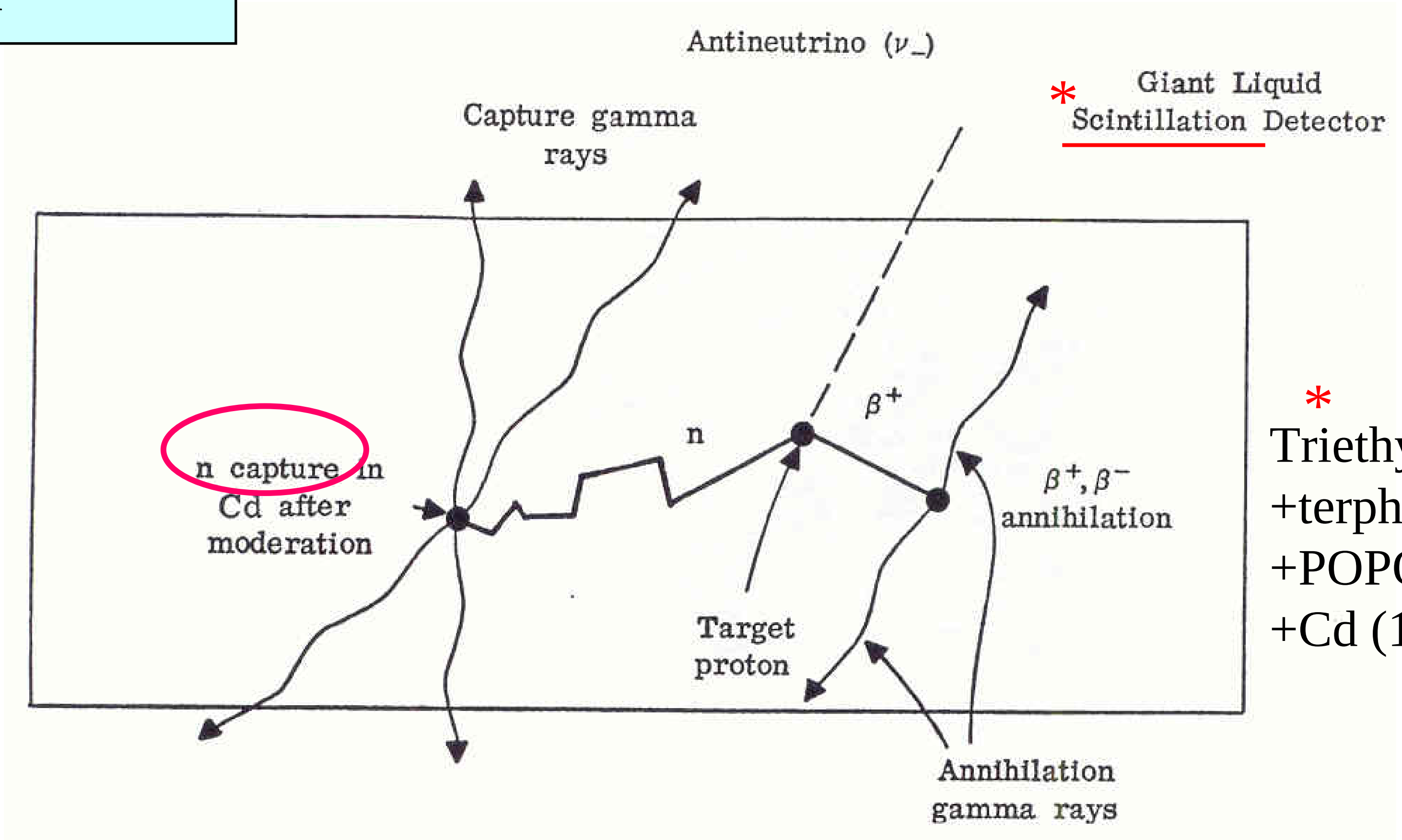
- Double CHOOZ (2015): measurement of ν mass / mixing angles (oscillation setup = 2 distant det.):

  = same idea (just a little bit larger…)

1956: Cowan & Reines

Savannah River

$\bar{\nu}+p \rightarrow n+e^{+}$



*

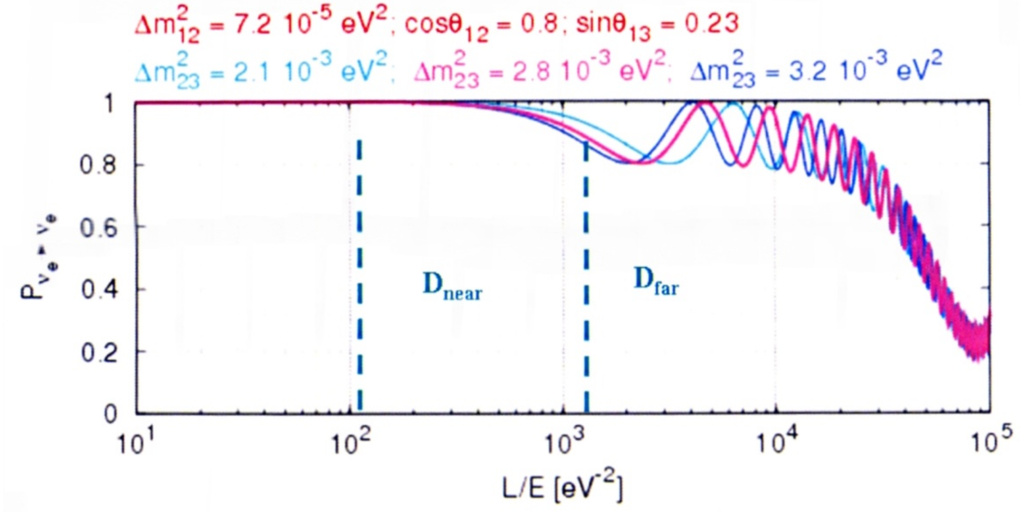
Triethylbenzene
+terphenyl (3g/l)
+POPOP (0.2g/l)
+Cd (1.8g/l)

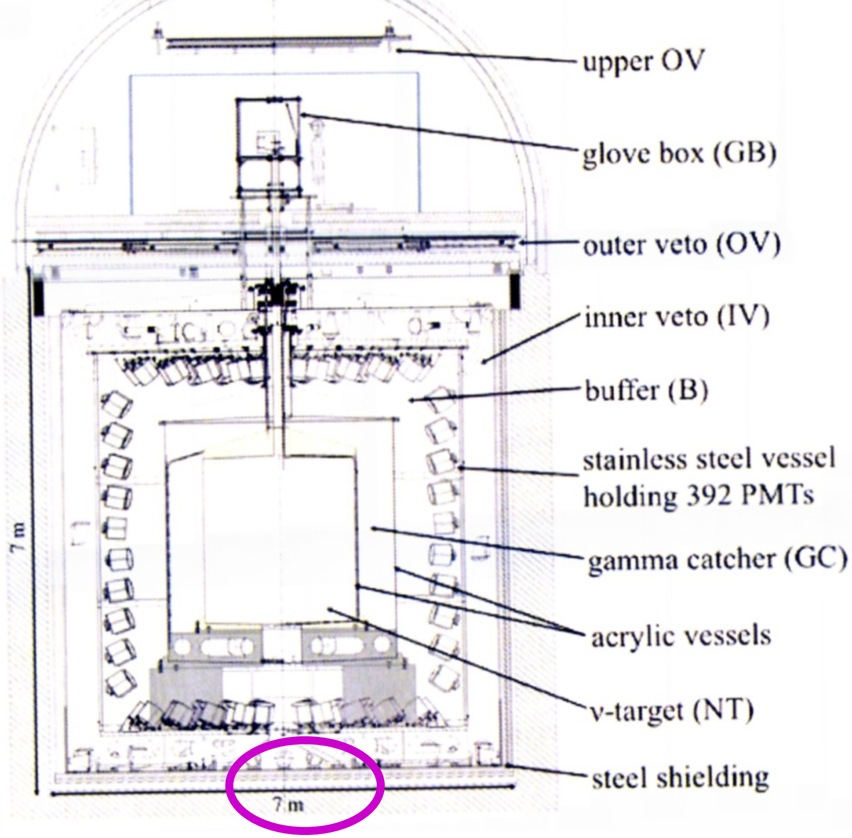
Detecting the **n** *and* the positon => proof of the 5 first (anti-)**neutrinos**

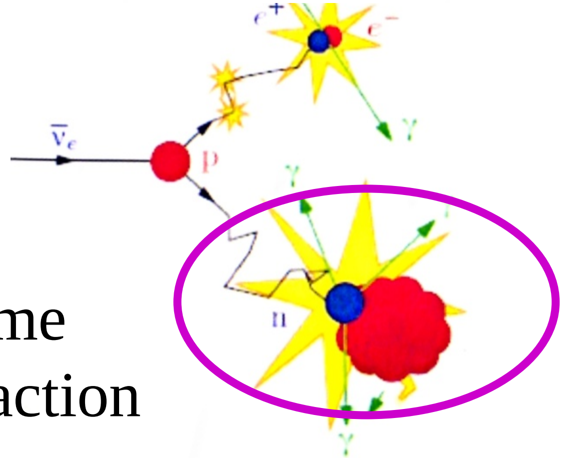
2015: Double CHOOZ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

other
context







same
reaction

bigger
size..

Material activation

Very looooooooong list of materials !

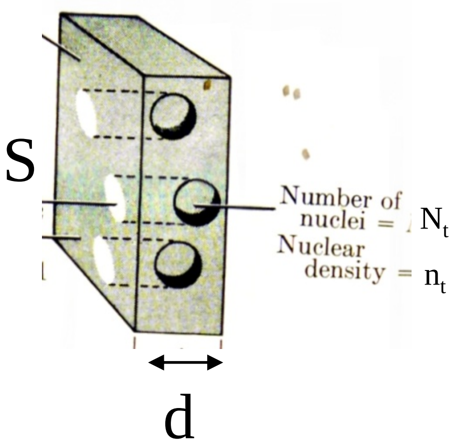
Short list of most famous targets:

Gd,Au,Al,Cu: $A(n,\gamma)B$ (⇨ γ detectors)

Plenty of applications:

- *n* metrology: secondary Φ_n standards compared to ^{198}Au
- Expertise for museums (chemical tracks at the ppm level)
- Measuring tiny impurity concentrations (metallurgy)
  or very small thicknesses (microelectronics)
- ……

Measuring cross sections: how?

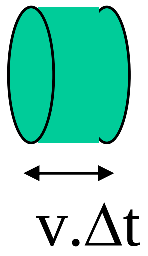


Hard spheres: $\sigma \sim \pi\, r_N^2 \sim A^{2/3}$

Collision proba: $P=N_{coll}/N_{target}=\sigma/S$ (thin foil approx)

- Target density: $n_t=N_t/(S.d)$ or $N_t/S=n_t.d$
- Beam density $\rho(v)$ @ v ➡ fluence $\Phi_{inc}= \rho.v$

cm^{-3} $cm.s^{-1}$ $cm^{-2}.s^{-1}$



➡ Reaction rate: $R.R. = (\rho.v).(N_t.\sigma/S) = \Phi_n.n_t.d.\sigma$

From $CR_\gamma=\varepsilon_\gamma.RR$: $\boxed{\sigma = CR_\gamma/(\Phi_n.n_t.d.\varepsilon_\gamma) \quad (1)}$

Two steps procedure:

1) Choose a known material + [E1;E2] interval where $\sigma = K/v$: $RR_1=K.\rho.n_t.d$!!

➡ one measures ρ (i.e. Φ) (beam calibration)

2) Take your new target, select v (or E), measure CR_2 and get the unknown **σ** through (1)

→ *choppers, TOF,……*

The σ ~1/v « law »

- Bohr (1933): for A(n,y)B, $\sigma(n,y)=\sigma_{\text{compound nuc}} \cdot \Gamma_y / \Gamma_{tot}$

- Breit-Wigner (1936): close to resonance (E_0,Γ):

$$\sigma(n,y)=(\lambda^2/4\pi) \cdot \frac{1}{(E-E_0)^2+(\Gamma/2)^2} \cdot (\Gamma_n\Gamma_y) \cdot (\text{add.factors})$$

de Broglie

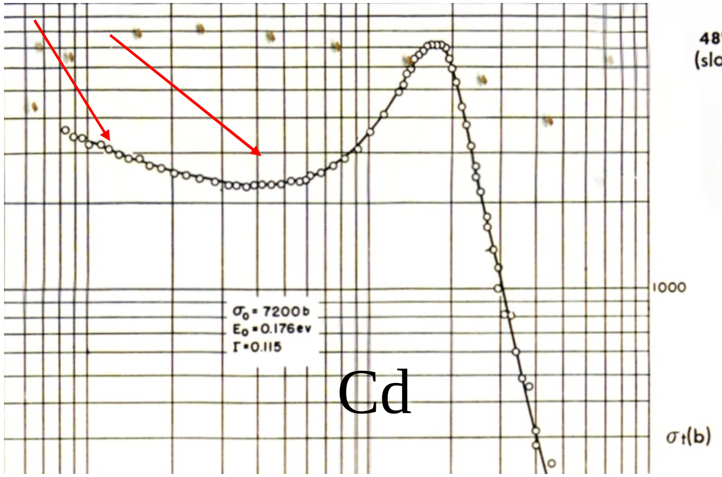
Phys.Rev.49(1936)519

Nice feature of BW: works even ***far away from resonances*** !!

$$\begin{cases} - \Gamma_n = \hbar / \Delta t \text{ or } \int 4\pi p^2.dp/E \sim \mathbf{v} \\ - \lambda = h/m\mathbf{v} \end{cases}$$

$$\boxed{\sigma \sim 1/v}$$

Excellent approx. in thermal region for B,Al, Au,…

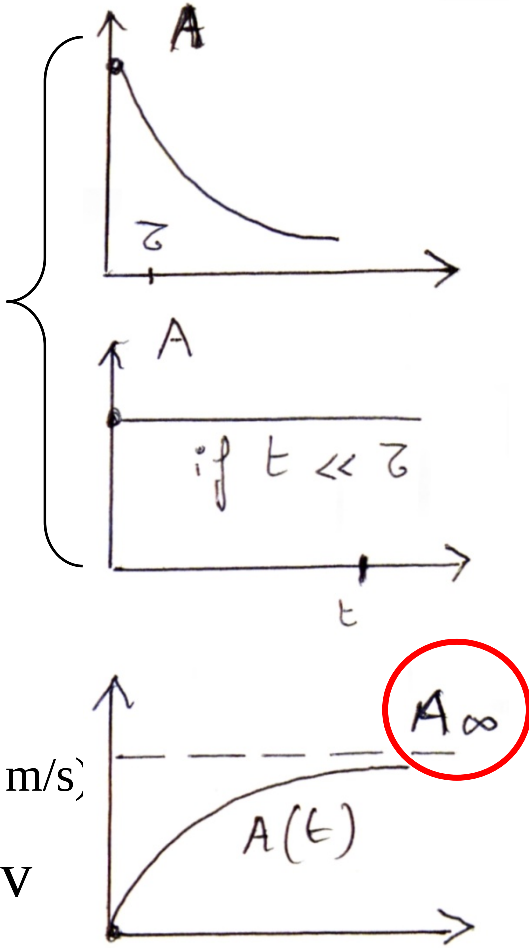


Metrology of *n* beams: activated ^{198}Au to calibrate in-beam ^{10}B chambers

-Standard decay: X ➔ Y with $N_x(t)=N_0\, e^{-t/\tau}$

$$A(t) = -dN/dt = N/\tau = N_0/\tau\, e^{-t/\tau}$$

-Decay during creation: X ➔ Y ➔ Z :



$$A_\infty = \frac{A(t)}{1-\exp(-t/\tau)} = N_{Au}\, S\,.\, \sigma_0\, \boxed{\Phi_n}$$

cm^{-3}

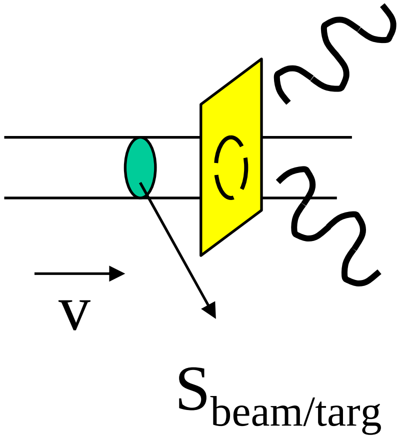
97.7 b (for **Au**)

(=1/v part of σ @ v=2200 m/s)

$$\text{with } \Phi_n = \int v\,\rho\, dv = v_0 \int \rho\, dv$$

(here ρ (v)= n density per unit velocity)

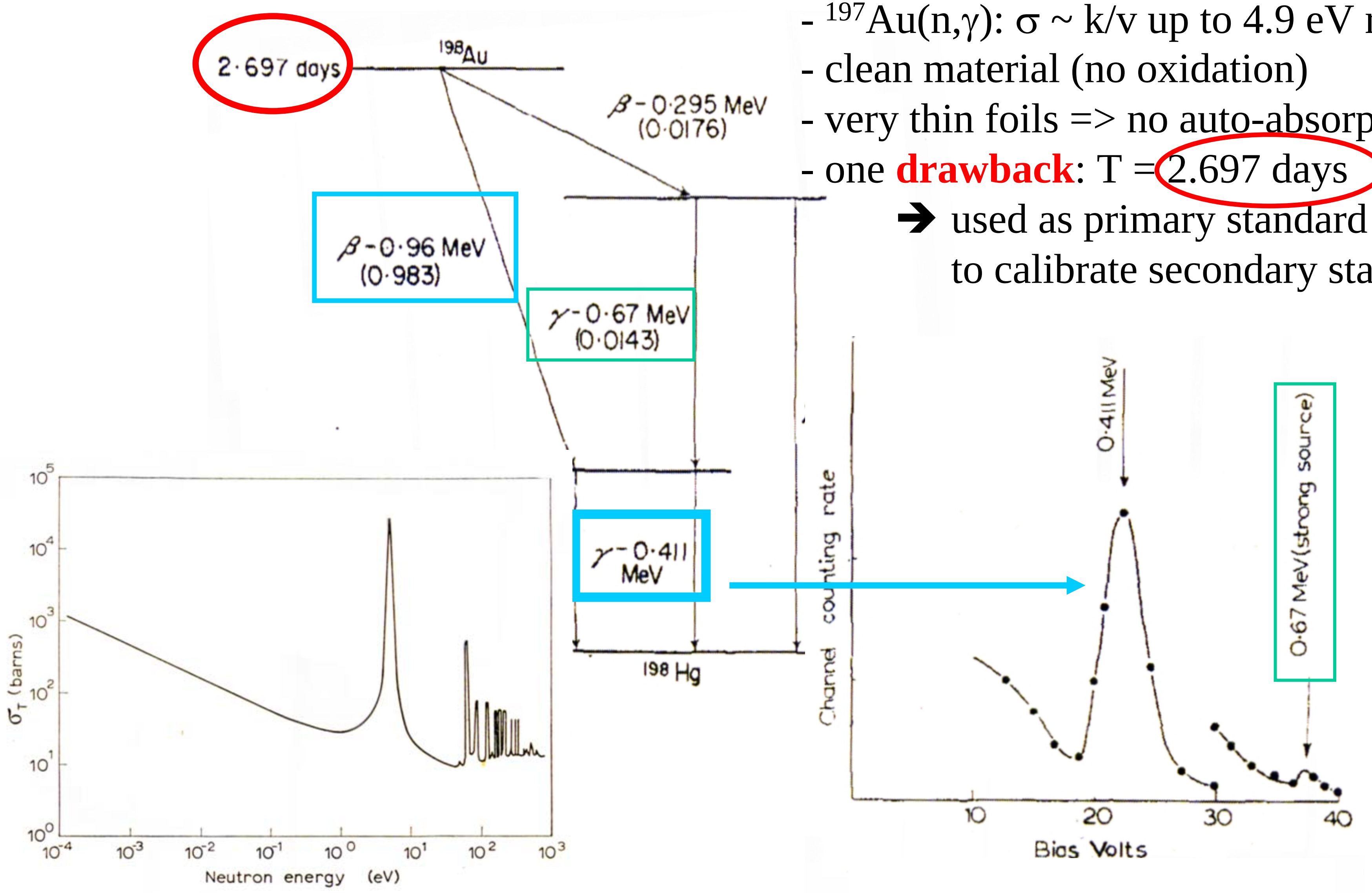
JF.Raffle, Jou.Nuc.En (1959) 10, 8



Pb: $T_{1/2}$(Au)=1/λ=2.697 days : real time in-beam impossible!
and $^{10}BF_3$ chambers are fast (no $T_{1/2}$!) but unaccurate.
Solution: ***thin*** ^{10}B layers inside prop.chambers =
good ***secondary standard*** (➔ fast & 1% precis. after **calib**!)

Why ***gold*** ?

- ^{198}Au : a very <u>simple</u> decay scheme…
- … plus a nice β–γ coïncidence !
- ^{197}Au(n,γ): σ ~ k/v up to 4.9 eV reson.
- clean material (no oxidation)
- very thin foils => no auto-absorption
- one **drawback**: T = 2.697 days
  - ➔ used as primary standard to calibrate secondary standards

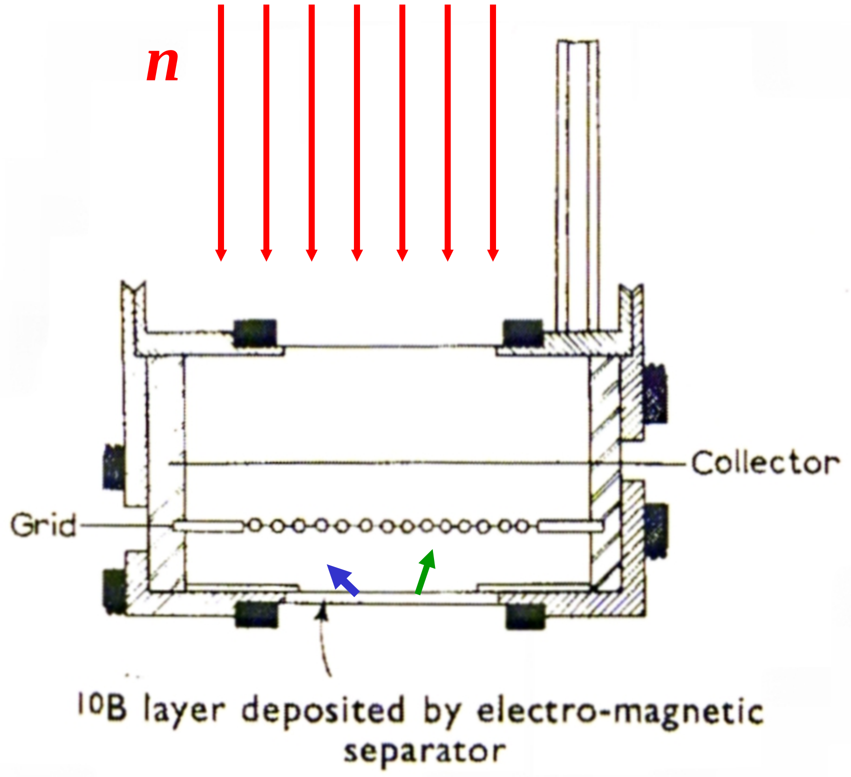


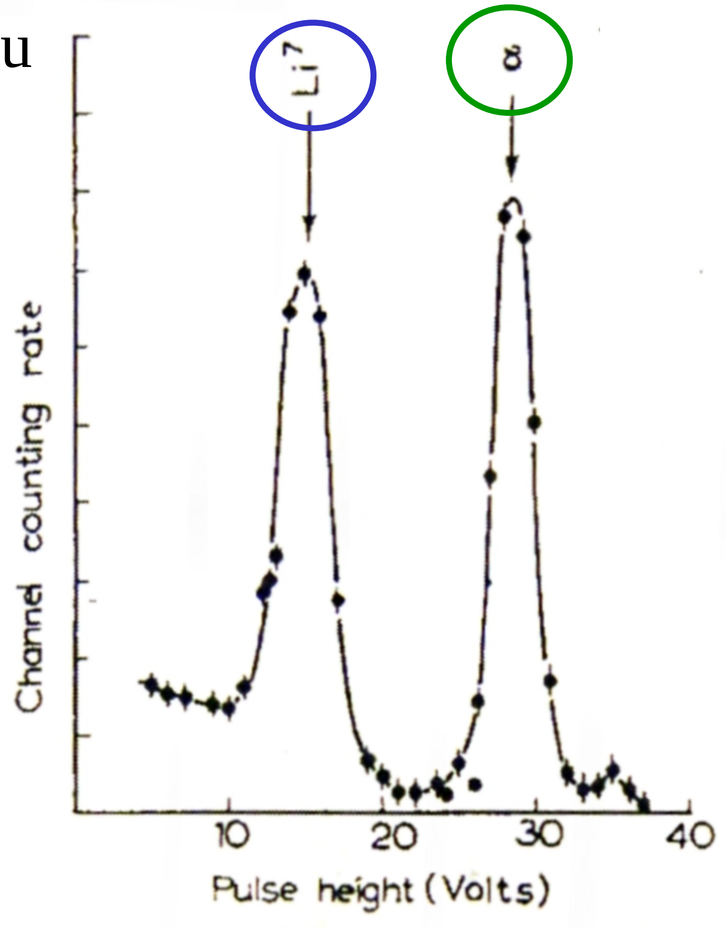
NOW the ^{10}B thin foil chamber is useful as a secondary standard:

a) accurate because ***thin*** foil (absorpt~0)

b) fast (no decay time) => ***real time*** !

c) peak height calibrated against ^{198}Au





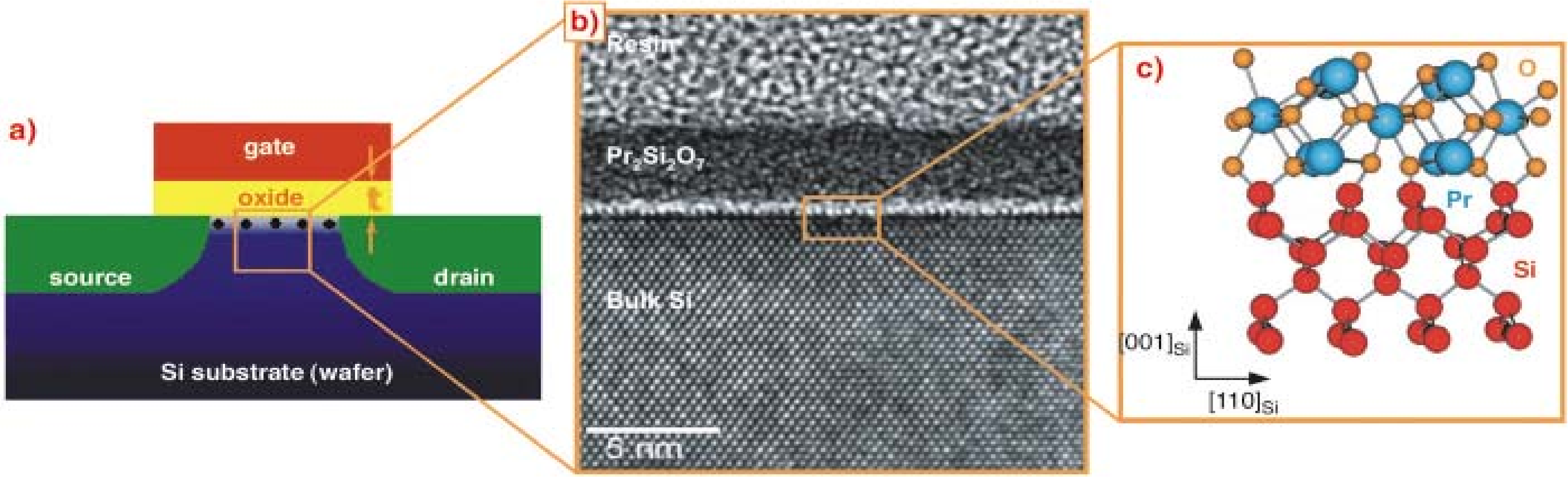
$n+^{10}B \rightarrow \alpha + ^{7}Li$

Analysis of historical paintings

-Method: Neutron activation
autoradiography (NAAR)
-Complementary to XRR
and macro-X-fluoresc.
- Only $4/10^{12}$ atoms sensitive to ***n***
- Able to reveal special pigments, e.g. Mn,Cu (azurite) , As, Co, Pb (lead white), Hg(vermilion) and mainly P under opaque layers

M.Alfeld et al., Appl.Phys A (2015)179

Nanoscale transistors need « high-k » dielectrics !



Roadmap for microelectronics =

desperate run to ***smallest sizes*** + same performances!

➔ But : just a little problem to keep $\varepsilon_r\varepsilon_0 S/d$ with S ↘ …

➔ exotic oxides/metals (Pr, Hf) to get ε ~SiO_2 x20, x50…

for dielectrics of 5-6 atomic layers !

Neutrons for « high-k » dielectrics

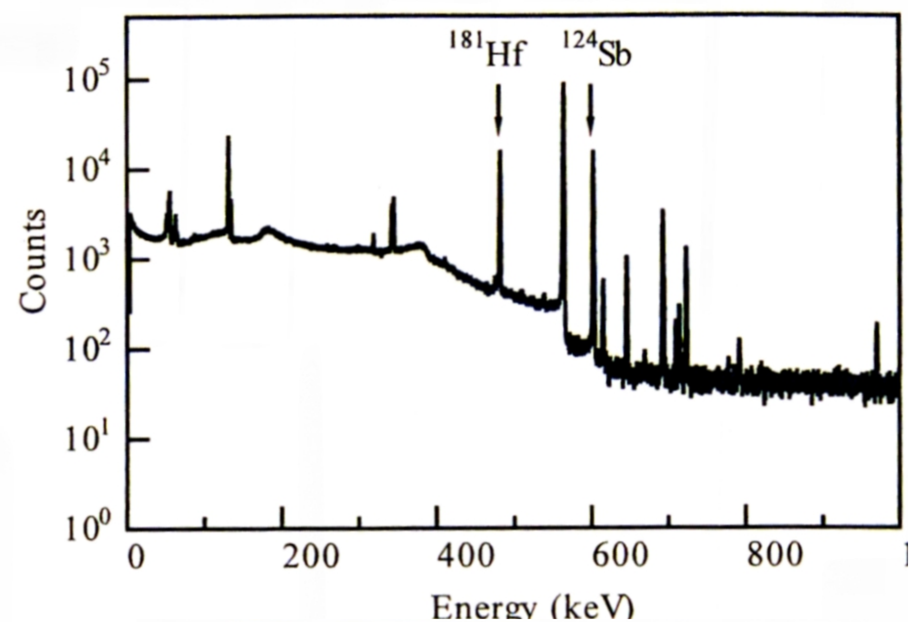
Microelectronics standards:

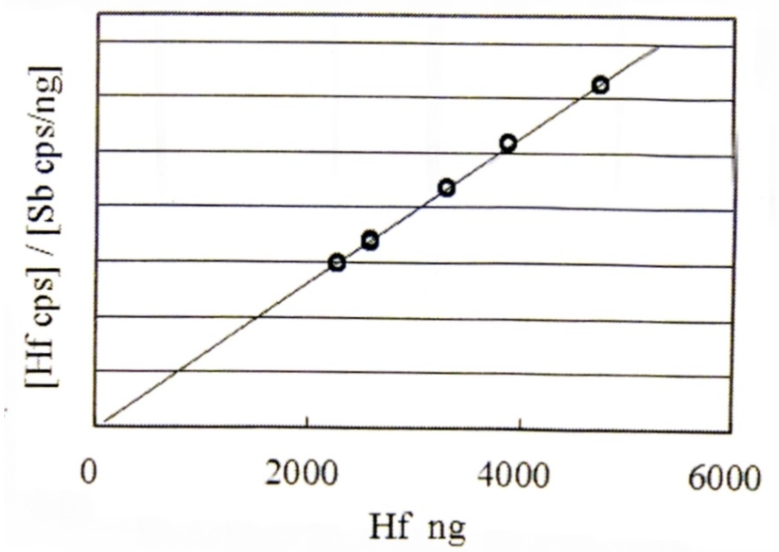
process control at *4 %*

Nice candidate: ^{181}Hf !

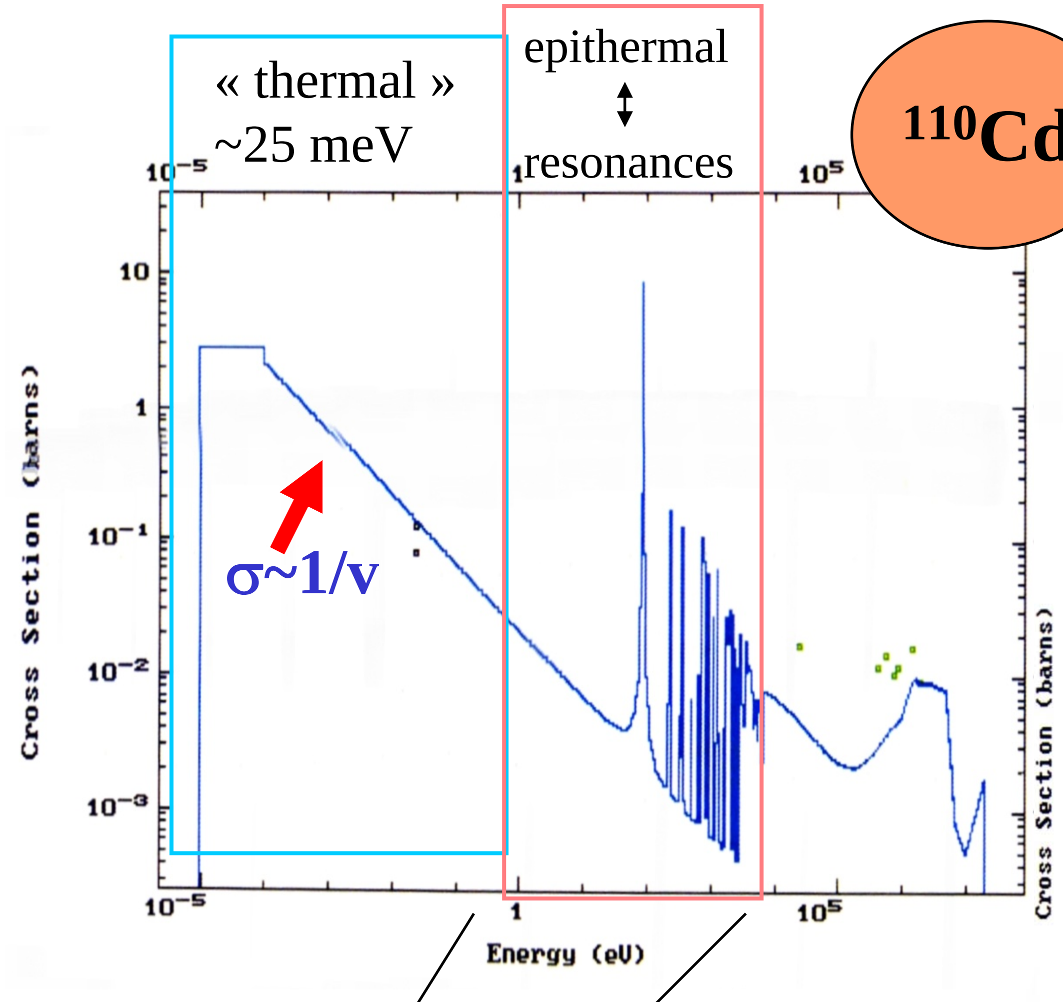
- $\varepsilon = 24$ (compare SiO_2: 3.9)
- HfO_2 compatible with Si lattice
- ^{181}Hf = γ-emitter (482 keV)
- Precision peak integration with ^{124}Sb/Hf ratio (4 h ***n*** irrad)

➔ Obtained precision = 0.92%





Cadmium, the multipurpose ***absorber***



« thermal »
~25 meV

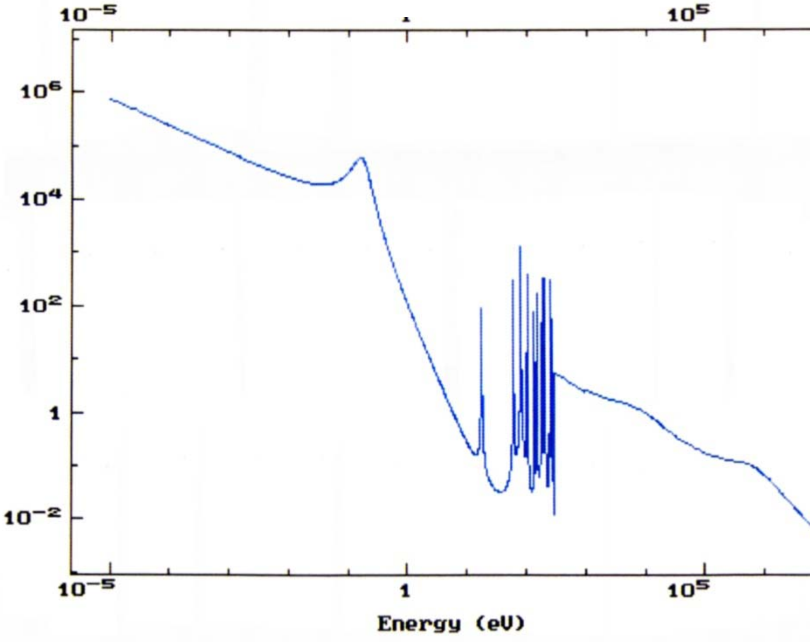
epithermal
↕
resonances

^{110}Cd

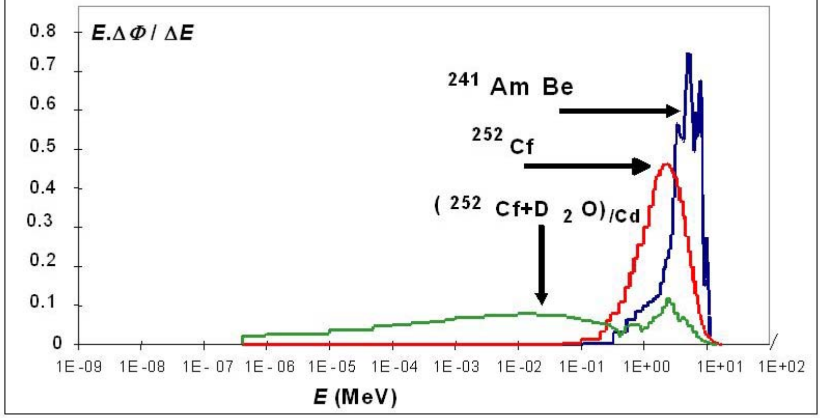
σ~1/v

1 eV   10 keV

^{113}Cd (12% of natural Cd):
higher σ (thermal region)
but no longer 1/v law…



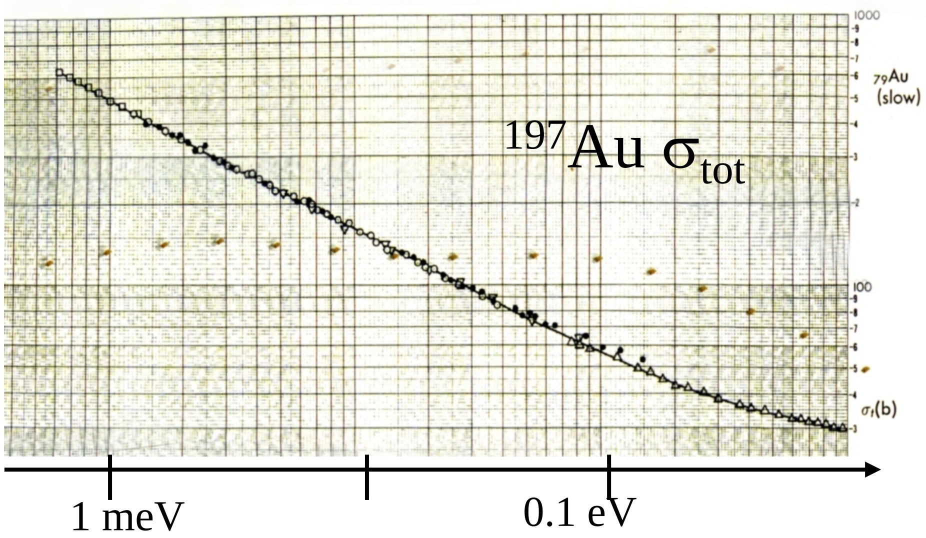
Applications of Cd

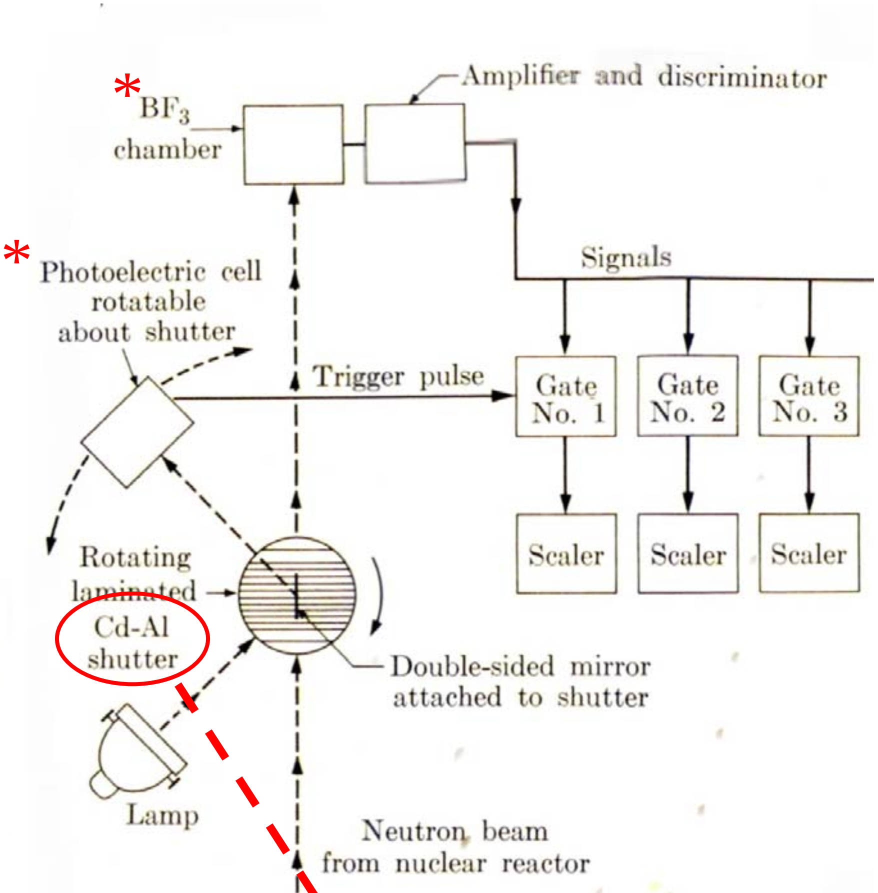


1) modified spectra (slow-*n* enriched)

2) velocity selectors (« choppers »)

→ nice $\sigma=f(E)$

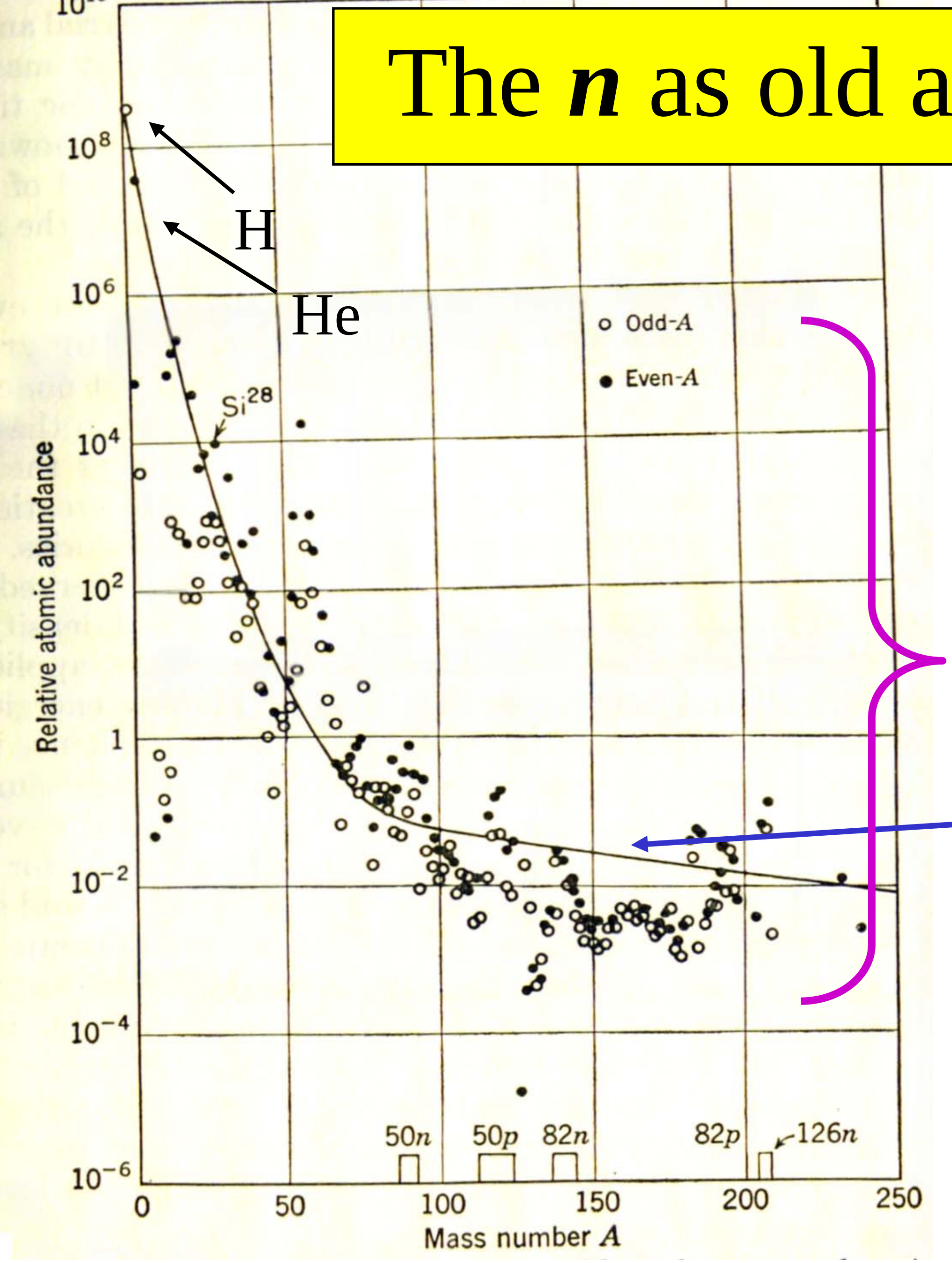


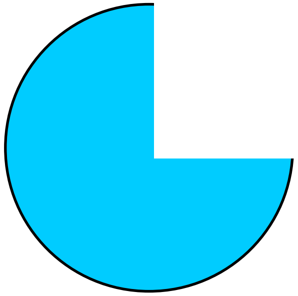


Al quite transparent
Cd very absorbing

Coinc.PM*-BF_3 → select. v

The *n* as old as the Universe…





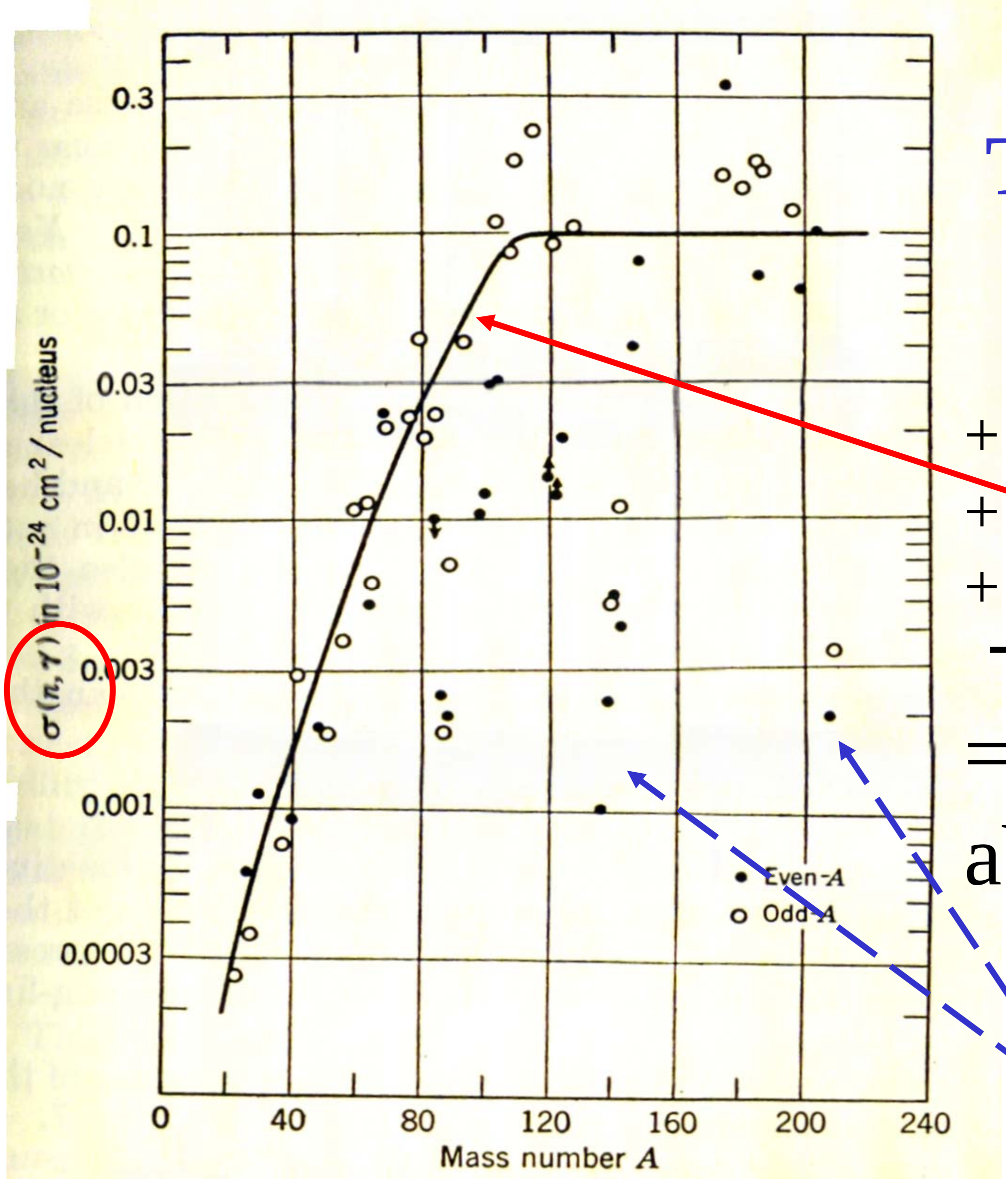
Our universe:
= 75% H
+25% He…
+ small ε

This ε(A) can be computed with pretty nice precision !
(full line = calculation)

What kind of « calculation »???

« Hadronic era »

T°(Univ) ~10^{12}K ~MeV:

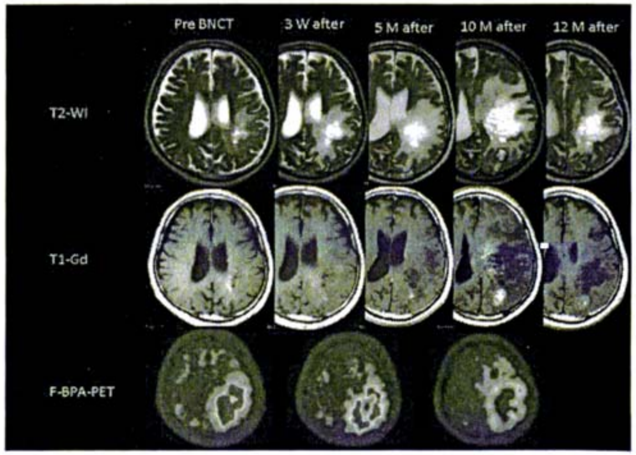


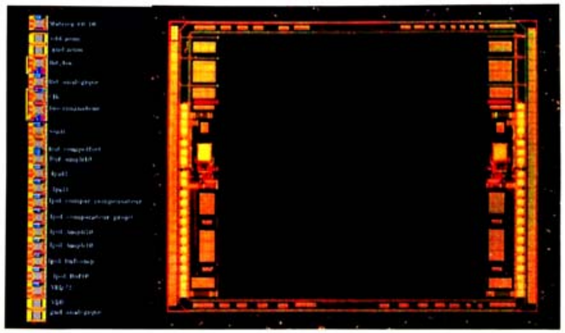
Take a baryonic (p,n)- « soup »
+ « equilibrium » state with $\pi^{+-°}$
+ adiabatic expansion (Δt~0.1 μs)
+ ***neutron capture*** cross section

= the ***observed*** relative abundance of elements !

(=previous plot)

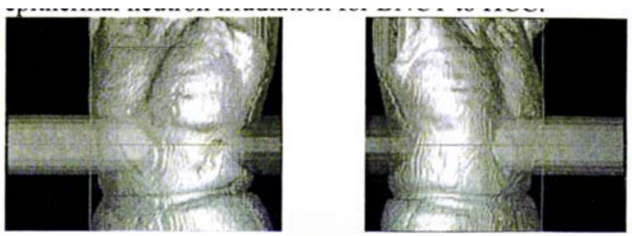
(detail: closed shells => ~~additional neutron~~)



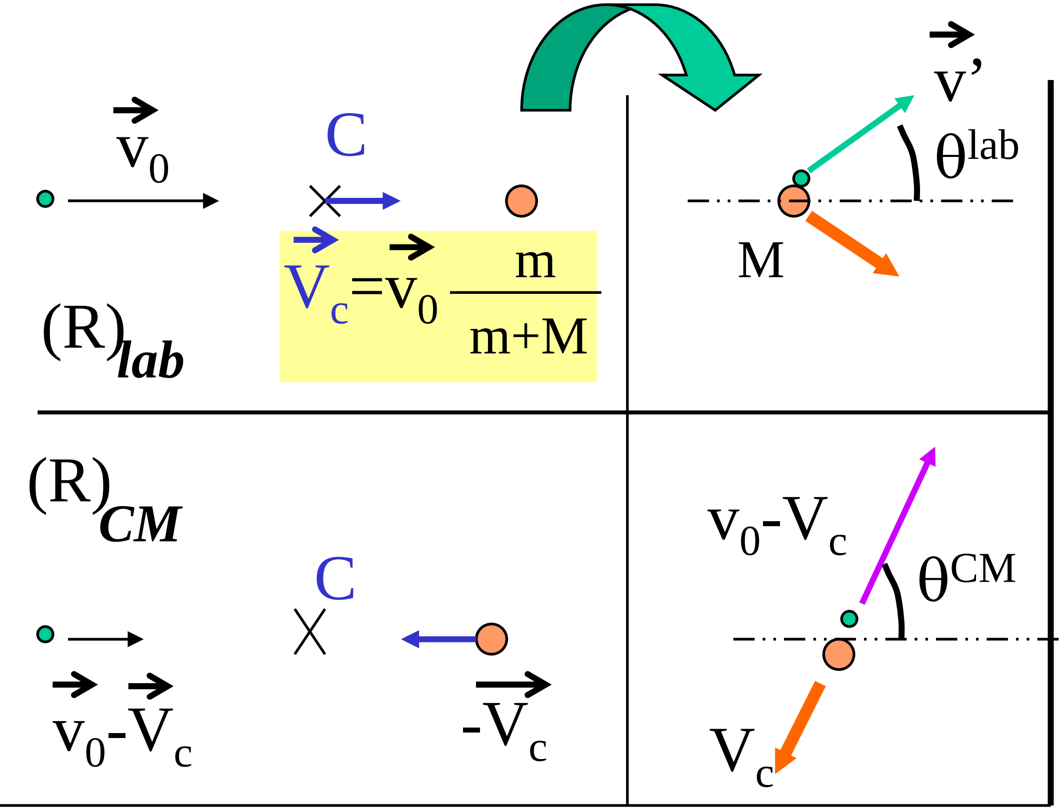


See you soon…

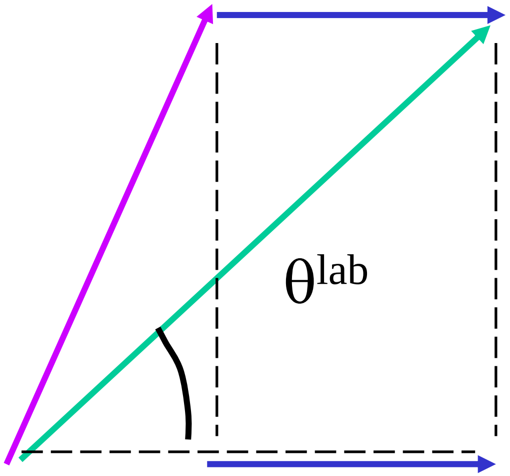
…for part II !



Changing the reference frame



$$\vec{V}_c = \vec{v}_0 \frac{m}{m+M}$$



$$\text{tg } \theta^{lab} = \frac{\sin \theta^{CM} v_0 (M/M+m)}{V_c + \cos \theta^{CM} v_0 (M/M+m)}$$

$$\boxed{\text{tg } \theta^{lab} = \frac{\sin \theta^{CM}}{m/M + \cos \theta^{CM}}}$$

The rules of billiard game (detail)

Elastic (n,p) behaves like ***hard spheres*** (square nuc.potential !)

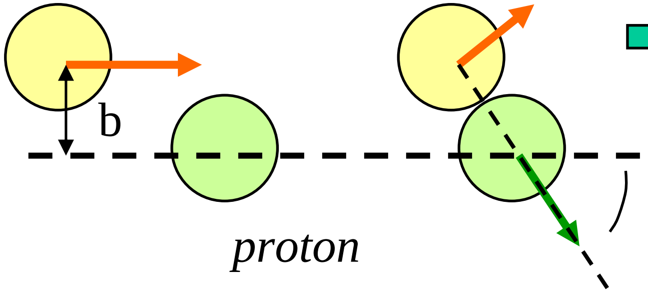
$\sin \theta_p^{LAB} = b/2R$

MC guys!

Distributions: ***n***-beam uniform ➡ $f(b^2)db^2$ uniform

➡ $\sin^2\theta_p$ uniform (*not* θ_p, and *not* $\sin \theta_p$!)

➡ $\cos^2\theta_p$ uniform also



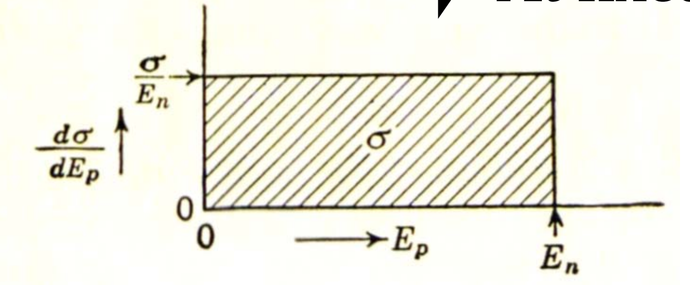
θ_p

➡ At fixed E_n:

$E_p=E_n.\cos^2\theta_p$ distribution is flat !

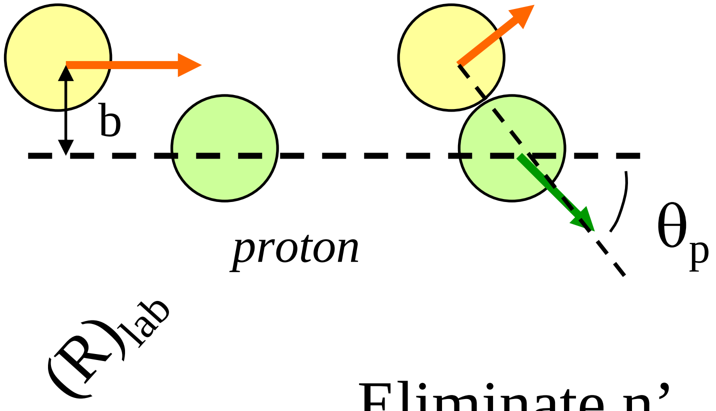
and $<E_p> = E_n/2$ (LAB)

(all this is ⇔ to isotropy in CM…)



The rules of billiard (detail of detail)

Demonstration of $E_p=E_n.\cos^2\theta_p$



From $\vec{p}$ and $E_n=E_{n'}+E_p$: $\theta_n+\theta_p=\pi/2$ *

$$\vec{p}_n=\vec{p}_{n'}+\vec{p}_p \quad : \quad \left\{ \begin{array}{l} p_n= p_{n'} \cos\theta_n + p_p \cos\theta_p \\ 0 \;=\; p_{n'} \sin\theta_n - p_p \sin\theta_p \end{array} \right.$$

Eliminate n' ⇨

$$p = p_p \{ \sin\theta_p \cos\theta / \sin\theta + \cos\theta \}$$
$$= p_p \,.\, \sin(\theta_p+\theta)^{*} / \sin(\theta)$$
$$= p_p / \sin(\theta)$$

⇨ $p_p=p_n.\sin\theta_n = p_n.\cos\theta_p$

or $\mathbf{E_p=E_n.cos^2\,\theta_p}$ (as $m_p=m_n$)

Behind the « Cloud chamber »