β- DECAY

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e^- ~~LABEL~~ or β^- DECAY WAS 1ST RADIATION DETECTED ~~OR DISCOVERED~~

e^+ OR β^+ DECAY WAS NOT OBSERVED UNTIL 1934

E.C. DISCOVERED 1938

ALL THREE PROCESSES LUMPED UNDER "β- DECAY"

- BASIC β- DECAY IS THE CONVERSION OF A PROTON INTO A $_0^1n$ OR OF A $_0^1n$ → INTO A PROTON.
- IN THE NUCLEUS, β- DECAY CHANGES BOTH Z + N BY ONE UNIT

$$Z \to Z \pm 1, \quad N \to N \mp 1, \quad A = Z + N = \text{CONSTANT}$$

- β- DECAY PROCESS "CREATES" AN e^- FROM AVAILABLE DECAY ENERGY AT THE INSTANT OF DECAY (CONTRASTING THE PRE-FORMED α PARTICLE MODEL)
- BASIC DECAY PROCESSES ARE

$_0^1n \to {}_1^1p + e^-$ "β^-" or negative beta decay

$_1^1p \to {}_0^1n + e^+$ "β^+" OR POSITIVE BETA DECAY

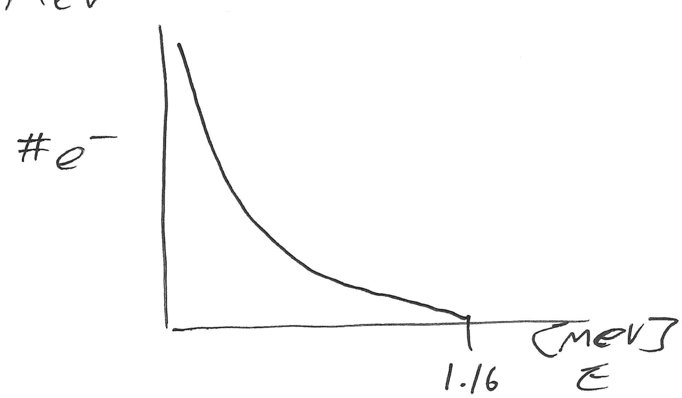
$_1^1p + e^- \to {}_0^1n$ ORBITAL ELECTRON CAPTURE (ε, EC)

UNLIKE α-DECAY, WHOSE α-ENERGY ARE SHARPLY DEFINED, EQUAL TO MASS ENERGY DIFFERENCE BETWEEN INITIAL & FINAL STATES

β PARTICLES HAVE A CONTINUOUS DISTRIBUTION OF ENERGIES FROM 0 → UPPER LIMIT KNOWN AS "END POINT" ENERGY

- IF β-DECAY WERE A 2-BODY PROCESS WE WOULD EXPECT ALL OF THE β-PARTICLE ENERGY TO BE UNIQUE & DISCRETE.

i.e. ^{210}Bi FROM MASS DIFFERENCE CALCULATION YOU'D EXPECT THE e^- TO HAVE K.E. OF 1.16 MeV YET THERE IS A CONTINUOUS SPECTRUM 0 → UP TO 1.16 MeV



W. PAULI PROPOSED ANOTHER, NON-DETECTABLE, PARTICLE
ENRICO FERMI NAMED IT THE "NEUTRINO"

- VERY PENETRATING RADIATION
- CHARGE CONSERVATION $\Rightarrow \nu$ IS NEUTRAL
- CONS. OF ANG. MOMENTUM $\Rightarrow$ SPIN $1/2$ (LIKE THE ELECTRON)

TWO TYPES OF NEUTRINOS: NEUTRINO & ANTINEUTRINO

ν $\bar{\nu}$

β^- IS ACCOMPANIED BY $\bar{\nu}$

EC + β^+ IS ACCOMPANIED BY ν

β-DECAY ENERGETICS, CONSIDER DECAY OF

FREE NEUTRON $T_{1/2} \sim 15$ MIN

$${}^1_0n \rightarrow {}^1_1p + e^- + \bar{\nu}$$

DEFINE Q AS ~~THE~~ DIFFERENCE BETWEEN INITIAL &

FINAL NUCLEAR MASS ENERGIES

$$Q = (m_n - m_p - m_e - m_{\bar{\nu}})c^2$$

& FOR DECAY @ REST

$$Q = T_p + T_{e^-} + T_{\bar{\nu}}$$

IGNORE PROTON RECOIL ENERGY ($T_p \sim 0.3$ keV)

THE e^- + $\bar{\nu}$ WILL SHARE THE DECAY ENERGY.
ACCOUNTING FOR THE CONTINUOUS ENERGY SPECTRUM.

MAX e^- MIN $\bar{\nu}$ + VICE VERSUS

IN ${}^1_0n$ DECAY, MAX MEASURED e^- ~~E~~. ENERGY
IS 0.782 ± 0.013 MeV, ~~FROM~~ ~~WHICH~~ WE
CAN ALSO COMPUTE Q VALUE USING ${}^1_0n$, ${}^1_1p$, + e^- MASS
VALUES

$$Q = m_n c^2 - m_p c^2 - m_e c^2 - m_{\bar{\nu}} c^2$$

$$= 939.573 \text{ MeV} - 938.280 \text{ MeV} - 0.511 \text{ MeV} - m_{\nu} c^2$$

$$= 0.782 \text{ MeV} - m_{\nu} c^2 \quad ?$$

$$\approx 0$$

FROM THIS WE CAN INFER $\bar{\nu}$ IS MASSLESS

IF WE ASSUME ~~E~~ $\bar{\nu}$, ν IS MASSLESS, THEN IT
MOVES AT THE SPEED OF LIGHT.

ONE CAN CONSIDER ITS TOTAL RELATIVISTIC E_ν
THE SAME AS ITS KINETIC ENERGY.

PART II

INTERACTION OF e^- W/ MATTER

β-PARTICLES CAN EXCITE + IONIZE MATTER,
THEY CAN ALSO RADIATE BY "BREMSSTRAHLUNG"
BUT IS ONLY IMPORTANT HIGH ENERGIES.

~100 MeV RADIATIVE POWER IS ~50% IN H_2O

CONSIDER SEPERATELY COLLISIONAL STOPPING POWER

$$-\left(\frac{dE}{dX}\right)_{COL}$$

+ RADIATIVE STOPPING POWER

$$-\left(dE/dx\right)_{RAD}$$

β-PARTICLES CAN ALSO BE SCATTERED ELASTICALLY BY ATOMIC e^-, A PROCESS THAT HAS A SIGNIFICANT EFFECT ON β-PARTICLE PENETRATION

- CANNOT DISTINGUISH BETWEEN INCIDENT + STRUCK ELECTRON AFTER THE COLLISION, CONVENTION ~~B~~ HAS ENERGY LOSS DEFINED AS e^- WITH LOWER ENERGY AFTER COLLISION IS "STRUCK" e^-

COLLISION STOPPING POWER

$$\left(-\frac{dE}{dx}\right)^{\pm}_{col} = \frac{4\pi k_0^2 e^4 n}{mc^2\beta^2}\left[\ln\frac{mc^2\tau\sqrt{\tau+2}}{\sqrt{2}\,I} + F^{\pm}(\beta)\right]$$

WHERE FOR ELECTRONS

$$F^{-}(\beta) = \frac{1-\beta^2}{2}\left[1 + \frac{\tau^2}{8} - (2\tau+1)\ln(2)\right]$$

+ FOR POSITRONS :

$$F^{+}(\beta) = \ln 2 - \frac{\beta^2}{24}\left[23 + \frac{14}{\tau+2} + \frac{10}{(\tau+2)^2} + \frac{4}{(\tau+2)^3}\right]$$

WHERE $\tau = T/mc^2$ + K.E. OF β^- OR β^+ PARTICLE IS EXPRESSED IN MULTIPLES OF e^- REST MASS ENERGY, mc^2.

$$\left(-\frac{dE}{dx}\right)^{\pm}_{col} = \frac{5.08\times10^{-31} n}{\beta^2}\left[\ln\frac{3.61\times10^5\,\tau\sqrt{\tau+2}}{I_{ev}} + F^{\pm}(\beta)\right] \mathrm{MeV/cm}$$

PUT INTO A GENERAL FORM

$$\left(-\frac{dE}{dx}\right)^{\pm}_{col} = \frac{5.08\times10^{-31} n}{\beta^2}\left[G^{\pm}(\beta) - \ln(I_{ev})\right] \mathrm{MeV/cm}$$

$$G^{\pm}(\beta) = \ln\left(3.61\times10^5\,\tau\sqrt{\tau+2}\right) + F^{\pm}(\beta)$$

EXAMPLE CALCULATE STOPPING POWER OF WATER FOR 1-MeV e^-

SOLUTION: FIND $\left(-\frac{dE}{dx}\right)^-_{COL}$

COMPUTE β^2, $F^-(\beta)$, + $G^-(\beta)$

WE HAVE $n = 3.34 \times 10^{29}\ e^-/m^3$

$\ln(I_{eV}) = 4.31$

FIND β^2: $1\ MeV = 0.511\ MeV \left(\frac{1}{\sqrt{1-\beta^2}} - 1\right)$

$\beta^2 = 0.886$

$\tau = \frac{T}{mc^2} = \frac{1}{0.511} = 1.96$

$\therefore F^-(\beta) = \frac{1-0.886}{2}\left[1 + \frac{(1.96)^2}{8} - (2 \times 1.96 + 1)\ln(2)\right]$

$= -0.11$

$\therefore G^-(\beta) = \ln\left(3.61 \times 10^5 \times 1.96\sqrt{1.96+2}\right) - 0.110 = 14.0$

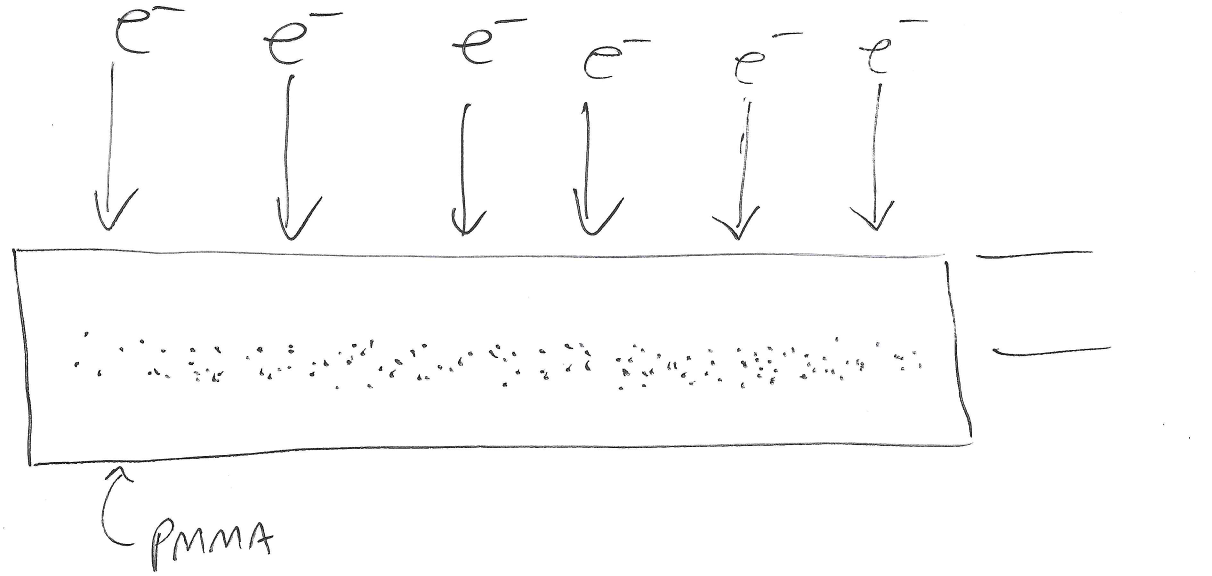
PULL IT ALL TOGETHER:

$\left(-\frac{dE}{dx}\right)^-_{COL} = \frac{5.08 \times 10^{-31} \times 3.34 \times 10^{29}}{0.886}\left[14 - 4.31\right]$

$= 1.86\ MeV/cm$

LICHTENBERG FIGURE DEMONSTRATION + DISCUSSION

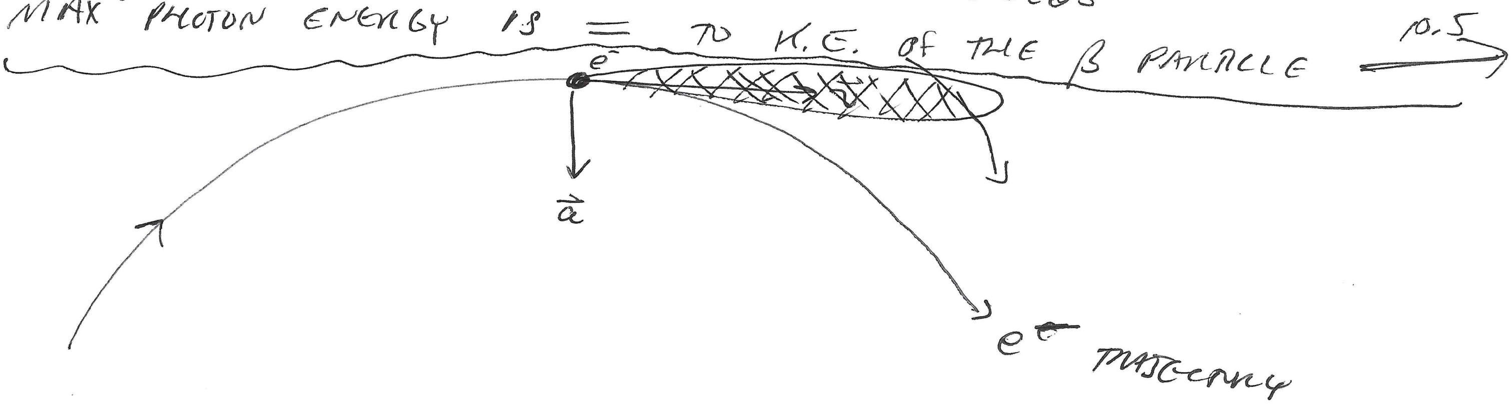
— DEPTH, THICKNESS



RADIATING STOPPING POWER

BREMSSTRAHLUNG
"BREAKING RADIATION"

- DEPENDS ON HOW CLOSE TO THE NUCLEUS
- MAX emitted PHOTON ENERGY IS = TO K.E. OF THE β PARTICLE



EXAMPLES OF LIGHT SOURCES

CALCULATING RADIATIVE STOPPING POWER

$\left(-\frac{dE}{dx}\right)^{\pm}_{RAD}$ IS FROM NUMERICAL PROCESSCES. THE PROCESS IS VERY DIFFENT FROM IONIZATION & EXCITATION

- THE EFFICIENCY OF BREMSTRAHLUNG IN DIFFERENT ELEMENTS VARIES WITH Z^2.
- THUS "CONVERSION" TO PHOTON IS MUCH GREATER ~~[illegible]~~ WITH HIGH Z-MATERIAL, SUCH AS LEAD
- APPROXIMATED RATIO OF RADIATIVE & COLLISIONAL STOPPING POWERS FOR AN ELECTRON <u>TOTAL</u> ENERGY E, IN MeV:

$$\frac{\left(-\frac{dE}{dx}\right)^{-}_{RAD}}{\left(-dE/dx\right)^{-}_{COL}} \cong \frac{ZE}{800}$$

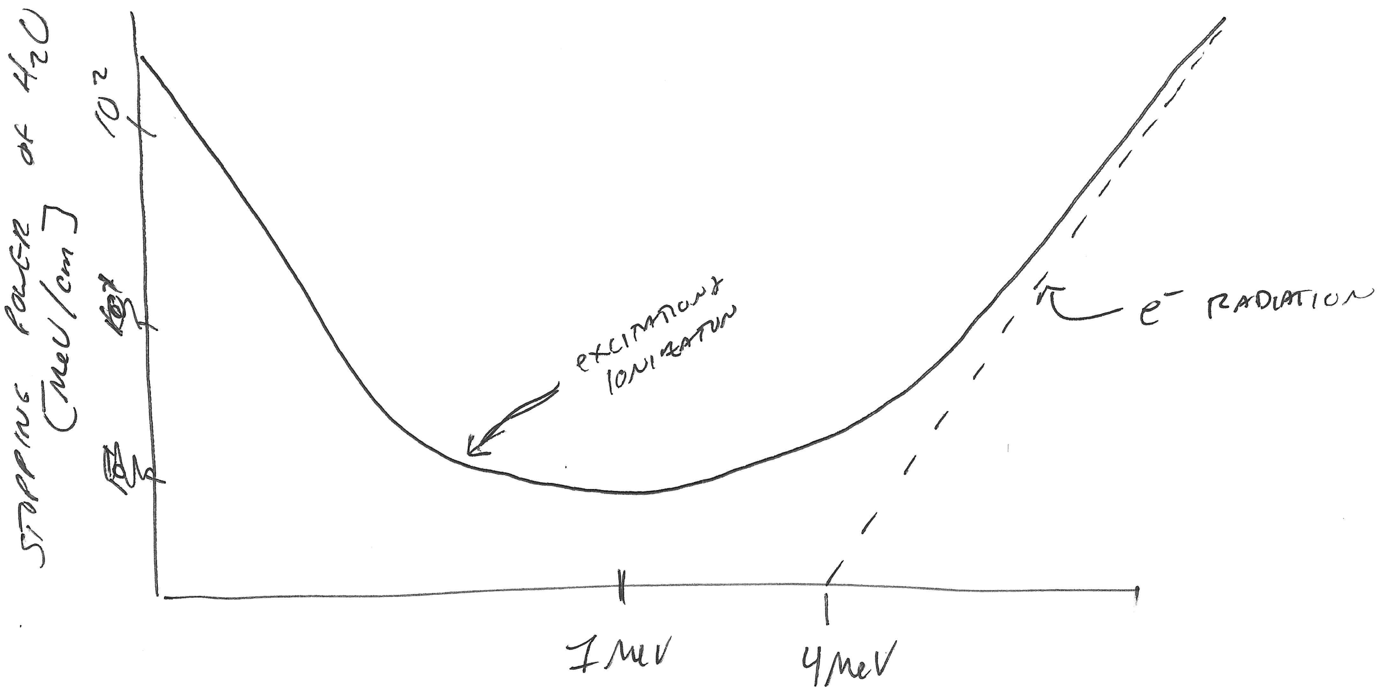
FOR $Z = 82$:

$$\frac{82E}{800} \cong 1\ \text{MeV} \rightarrow E \sim 9.8\ \text{MeV}$$

K.E. $T = E - mc^2 \cong 9.3$ MeV

OXYGEN $Z = 8$, $E \cong 100$ MeV

IN WATER:



"MINIMUM IONIZING"

- AN ESTIMATE OF RADIATION YIELD ~~CALC~~

INITIAL e^- KE IS T [MeV] STOPPING IN Z

THEN RADIATION YIELD IS

$$Y \cong \frac{6\times10^{-4}\, Z\, T}{1 + 6\times10^{-4}\, Z T}$$

EXAMPLE: 2 MeV β SHIELDED BY Al. & Pb

Al: $ZT = 13\times2 = 26$ $\quad Y \cong 0.016/1.016 = 0.016 \rightarrow 1.6\%$ IN RAD.

Pb: $ZT = 164$ $\quad Y = 0.090 \rightarrow 9\%$

RANGE

SIMILAR TO HEAVY PARTICLES, e^- RANGE

"R" ≡ RANGES ARE EXPRESSED IN

$$[g/cm^2]$$

FOR $0.01 \le T \le$ MeV

$$R = 0.412\, T^{1.27 - 0.0954 \ln(T)}$$

FOR $T > 2.5$ MeV

$$R = 0.530T - 0.106 \qquad d = \frac{R}{\rho} = [cm]$$

EXAMPLE: 2.2 MeV e^- IN LUCITE:

$$R = (0.412)(2.2)^{1.27 - 0.0954 \ln(2.2)} = 1.06\, g/cm^2$$

$$d = \frac{R}{\rho} = \frac{1.06\, g/cm^2}{1.19\, g/cm^3} = 0.891\ cm$$

OPTIONAL — LAB —

DISCUSS LAB