LECTURE 4

α- PARTICLES

1/

PART 1. GENERATION

- "α-RAYS", REALLY α-PARTICLES, 1ST IDENTIFIED ~~BY~~ FROM N.O.R.M. 1903 RUTHERFORD MEASURED THEIR Q/M RATIO BY DEFLECTING FROM Ra BY E+M FIELDS. HIS RESULT WAS ONLY 25% HIGHER THAN PRESENT DAY VALUE

- α-EMISSION IS A COULOMB REPULSIVE EFFECT.

  COULOMBIC FORCE GROWS AS Z^2

  NUCLEAR BINDING FORCE GROWS AS Z

- WHY THE α-PARTICLE, AS THE AGENT TO SPONTANEOUSLY CARRY AWAY POSITIVE CHARGE?

  SPONTANEOUS BECAUSE SOME K.E. HAS APPEARED FOR NO APPARENT ~~[illegible]~~. CAUSE.

THE α-PARTICLE HAS BECAUSE IT IS A VERY STABLE + TIGHTLY BOUND STRUCTURE HAS A RELATIVELY SMALL MASS COMPARED TO ITS CONSTITUENT PIECES.

IT IS THE MOST ENERGETICALLY FAVORED AS IT IS LIGHT AS POSSIBLE, ~~[illegible]~~ THUS ~~[illegible]~~ GET THE LARGEST K.E. POSSIBLE

TAKE FOR EXAMPLE ^{232}U DECAY MODES.

EMITTED PARTICLE	ENERGY RELEASE
^1_0n	−7.26 MeV
^1_1p	−6.12 MeV
$^2_1$Deuteron	−10.7 MeV
TRITON	−10.24 MeV
^4_2He	+5.41

OPTIONAL

- MOST NUCLEI WITH A>190 ARE ENERGETICALLY UNSTABLE AGAINST α-EMISSION
- α-DECAY PROCESS

$$^{A}_{Z}X_{N} \rightarrow \, ^{A-4}_{Z-2}X'_{N-2} + \alpha$$

- DECAY PROCESS MUST CONSERVE ENERGY, LINEAR MOMENTUM, & ANGULAR MOMENTUM.

1ST

ENERGY CONSERVATION.

- ASSUME DECAYING PARENT, X, NUCLEAS TO BE AT REST.

$\Rightarrow$ REST ENERGY, X, $M_X C^2$

THE FINAL STATE CONSISTS OF X' + α EACH OF WHICH WILL BE IN MOTION.
(CONSERVE LINEAR MOMENTUM)

THUS FINAL ENERGY IS

$$M_{X'}C^2 + T_{X'} + M_\alpha C^2 + T_\alpha$$

CONSERVATION OF ENERGY

$$M_X C^2 = M_{X'}C^2 + T_{X'} + M_\alpha C^2 + T_\alpha$$

$$\underbrace{(M_X - M_{X'} - M_\alpha)C^2} = T_{X'} + T_\alpha$$

THIS IS THE "Q" VALUE

THE DECAY WILL OCCUR ONLY IF $Q > 0$!

WHEN MASSES ARE EXPESSED IN A.M.U., $C^2 = \frac{931.502 \text{ MeV}}{U}$
YIELDS Q VALUES DIRECTLY IN MeV

$$Q = T_{X'} + T_\alpha$$

2/ CONSERVE LINEAR MOMENTUM.

IF X IS INITIALLY AT REST, THEN ITS LINEAR MOMENTUM IS ~~AB~~ ZERO.

$$P_\alpha = P_{X'} \quad \text{or} \quad P_\alpha - P_{X'} = 0$$

TYPICAL α-DECAY ~5 MeV RELEASED ENERGY

THUS $X' + \alpha$ $T \ll mc^2$ (NON-RELATIVISTIC)

$$T = p^2/2m$$

K.E. IN TERMS OF "Q" VALUE

$$T_\alpha = \frac{Q}{(1 + m_\alpha/m_{X'})}$$

FOR X' HEAVY (i.e. $A > 192$)

$$T_\alpha = Q(1 - 4/A)$$

α-PARTICLES CARRIES ~ 98% OF THE Q-VALUE.

FOR TYPICAL Q VALUE OF 5 MeV, RECOILING NUCLEUS HAS AN ENERGY OF ABOUT 100 keV, THIS IS FAR ~~IN~~ GREATER THAN THEN BINDING ENERGY OF SOLIDS, SO RECOILING NUCLEI IF NEAR THE SURFACE CAN ESCAPE INTO THE ENVIRONMENT. IF DAUGHTER PRODUCT IS ALSO RADIOACTIVE, THEN THIS IS RESULT IN SPREAD OF RADIOACTIVITY.

TIDBIT: K.E. OF α-PARTICLE CAN EASILY BE MEASURED IN A SPECTROMETER..

→ GIVING Q VALUE OF A DECAY, WHICH IN TURN CAN BE USED TO DETERMINE ATOMIC MASSES OF SHORT LIVED NUC~~LEI~~

DECAY SYSTEMATICS

• α- EMITTING ISOTOPES, IN GENERAL, WHICH HIGH LARGE DISITIGRATION ENERGIES, HAVE SHORT HALF LIVES, + CONVERSELY, THOSE OF LOW DISITIGRATION ENERGY, HAVE ~~VES~~ LONG HALF LIVES. "GEIGER-NUTTALL" LAW

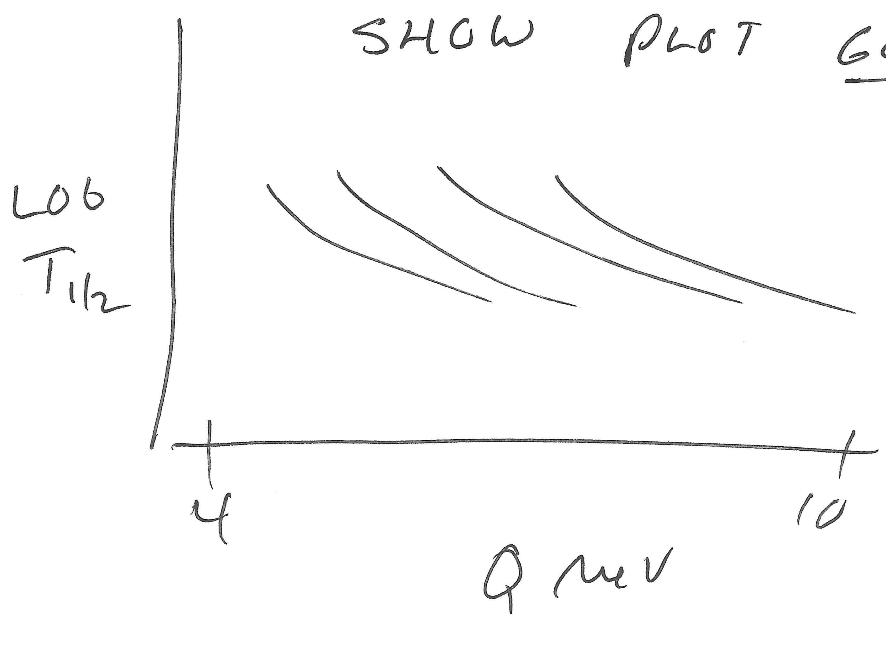
VARIATION IS VAST~~ED~~! BRACKETING EXAMPLE ~~CASES~~:

$^{232}Th: Q = 4.08 \text{ MeV} \rightarrow T_{1/2} = 1.4 \times 10^{10}$ years

$^{218}Th: Q: 9.85 \text{ MeV} \rightarrow T_{1/2} = 1.0 \times 10^{-7}$ seconds

FACTOR OF 2 IN ENERGY, FACTOR 10^{24} IN $T_{1/2}$

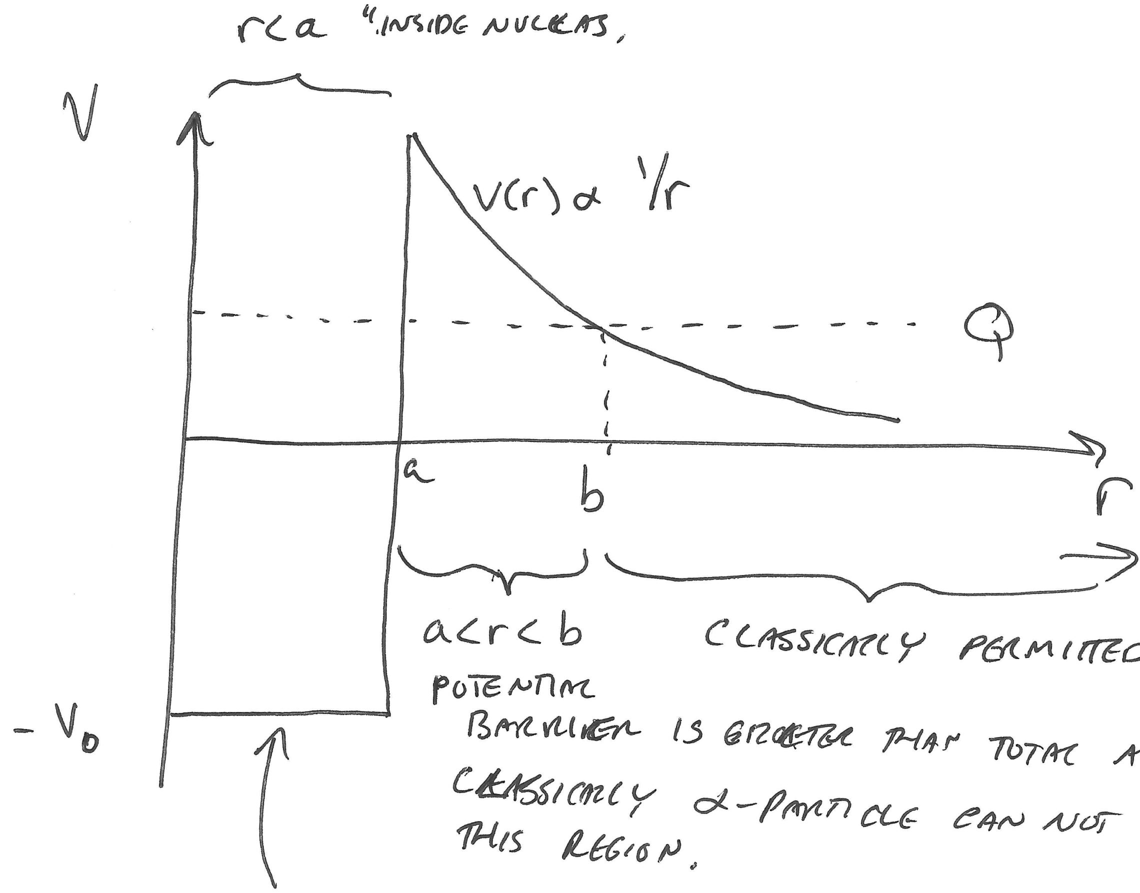
SHOW PLOT GEIGER-NUTTALL



THEORY OF α EMISSION

SIMPLISTIC QUANTUM MECHANICAL ~~[illegible]~~, MODEL

- α-PARTICLE IS PRE-FORMED AND ASSUMED TO MOVE IN A SPHERICAL REGION DETERMINED BY THE <u>DAUGHTER</u> NUCLEUS.



CLASSICALLY PERMITTED REGION

POTENTIAL BARRIER IS GREATER THAN TOTAL AVAILABLE Q, CLASSICALLY α-PARTICLE CAN NOT ENTER THIS REGION.

CLASSICALLY α MOVES WITH K.E. $Q + V_0$, BUT CAN'T ESCAPE.

CLASSICAL VIEW α PARTICLE WOULD SHARPLY REVERSE ITS MOTION EVERY TIME IT TRIED TO PASS $r = a$,

- IN Q.M. THERE IS A CHANCE OF "LEAKAGE" OR "TUNNELING" THROUGH THIS BARRIER.
- BARRIER PUTS UP A FIGHT... AND IS WHY α-UNSTABLE NUCLEI DO NOT DECAY IMMEDIATELY.
- THE ALPHA PARTICLE MUST KNOCK ONTO THE BARRIER SURFACE TIME & TIME AGAIN UNTIL IT FINALLY TUNNELS THRU.

EXAMPLE OF ^{238}U PROBABILITY IS SO SMALL, α-PARTICLES MAKE ABOUT 10^{38} TRIES BEFORE IT ESCAPES. ABOUT 10^{21}/SEC FOR 1 BILLION YEARS !

- ANGULAR MOMENTUM MUST BE CONSERVED,
- HEAVILY Q.M. DOMINATED DISCUSSION; PLEASE SEE CHAPTER ..? IN I.N.P.

PART 2 α - INTERACTION WITH MATTER.

A "HEAVY" CHARGED PARTICLES TRAVERSING MATTER ~~FREE~~ LOSES ENERGY PRIMARILY THROUGH THE IONIZATION + EXCITATION OF ATOMS.

THE MOVING CHARGED PARTICLE EXERTS E-M FORCES ON ATOMIC e^- + IMPARTS ENERGY TO THEM. SUFFICENT TO:

- KNOCK AN ELECTRON OUT OF AN ATOM + THUS IONIZE IT, OR
- MAY LEAVE THE ATOM IN AN EXCITED, BUT, NON-IONIZED STATE.

- EACH ~~THE~~ ELECTRONIC INTERACTION CAN ONLY IMPART A SMALL FRACTION OF THAT ENERGY + DEFLECTION IS NEGLIGIBLE.

MODEL OF AN ^ENERGETIC HEAVY PARTICLE TRAVEL IN A STRAIGHT PATH

Q/ WHAT IS MAXIMUM ENERGY TRANSFER IN A SINGLE COLLISION?

Radiation Interactions with Matter: Energy Deposition

Biological effects are the end product of a long series of phenomena, set in motion by the passage of radiation through the medium.

[Image removed due to copyright considerations]

Interactions of Heavy Charged Particles

Energy-Loss Mechanisms

- The basic mechanism for the slowing down of a moving charged particle is **Coulombic interactions** between the particle and electrons in the medium. This is common to all charged particles

- A heavy charged particle traversing matter loses energy primarily through the **ionization** and **excitation** of atoms.

- The moving charged particle exerts **electromagnetic forces** on atomic electrons and imparts energy to them. The energy transferred may be sufficient to knock an electron out of an atom and thus **ionize** it, or it may leave the atom in an **excited, nonionized state.**

- A heavy charged particle can transfer only a **small fraction** of its energy in a single electronic collision. Its **deflection in the collision is negligible.**

- All heavy charged particles travel essentially **straight paths** in matter.

[Image removed due to copyright considerations]

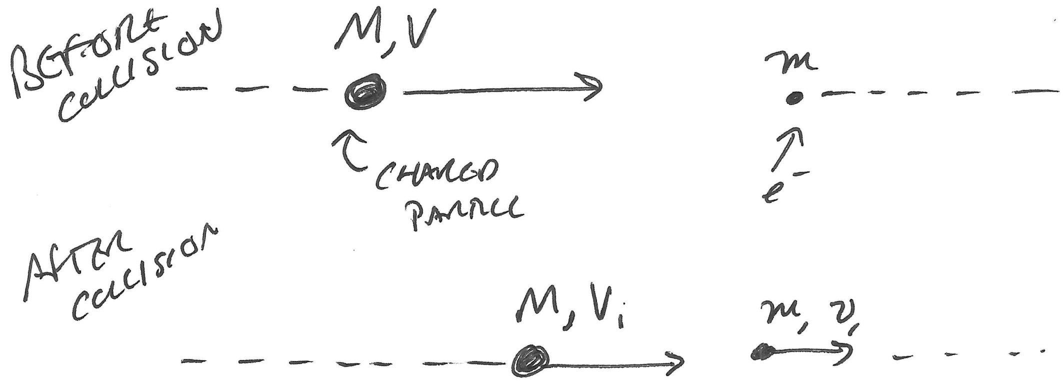
[Tubiana, 1990]

MAX ENERGY THAT A C.P. CAN LOSE IN COLLIDING WITH AN ATOMIC e^-.

- C.P. MOVES RAPIDLY COMPARED W/ e^-
- ENERGY TRANSFERRED IS LARGE COMPARED TO BINDING ENERGY,

$\rightarrow$ e^- FREE + AT REST.

ASSUME HEAD ON COLLISION



$$\frac{1}{2} M V^2 = \frac{1}{2} M V_1^2 + \frac{1}{2} m v_1^2$$

+

$$M V = M V_1 + m v_1$$

SOLVE v_1 + SUBSTITUTE

$$V_1 = \frac{(M-m)V}{M+m}$$

MAX ENERGY TRANSFER IS THEN:

$$Q_{max} = \frac{1}{2} M V^2 - \frac{1}{2} M V_1^2 = \frac{4 m M E}{(M+m)^2}$$

$E = \frac{MV^2}{2}$ INITIAL K.E. OF HEAVY INCIDENT PARTICLE

Maximum Energy Transfer in a Single Collision

The maximum energy transfer occurs if the collision is head-on.

[Image removed due to copyright considerations]

Assumptions:

- The particle moves rapidly compared with the electron.
- For maximum energy transfer, the collision is head-on.
- The energy transferred is large compared with the binding energy of the electron in the atom.
- Under these conditions the electron is considered to be initially free and at rest, and the collision is elastic.

Conservation of kinetic energy:

$$\frac{1}{2}MV^2 = \frac{1}{2}MV_1^2 + \frac{1}{2}mv_1^2$$

Conservation of momentum:

$$MV = MV_1 + mv_1.$$

$$Q_{max} = \frac{1}{2}MV^2 - \frac{1}{2}MV_1^2 = \frac{4mME}{(M+m)^2},$$

Where E $= MV^2/2$ is the initial kinetic energy of the incident particle.

Q_{max} values for a range of proton energies.

Except at extreme relativistic energies, the maximum fractional energy loss for a heavy charged particle is small.

Maximum Possible Energy Transfer, Q_{max}, in Proton Collision with Electron

Proton Kinetic Energy E (MeV)	Q_{max} (MeV)	Maximum Percentage Energy Transfer $100Q_{max}/E$
0.1	0.00022	0.22
1	0.0022	0.22
10	0.0219	0.22
100	0.229	0.23
10^3	3.33	0.33
10^4	136	1.4
10^5	1.06×10^4	10.6
10^6	5.38×10^5	53.8
10^7	9.21×10^6	92.1

$$Q_{\max} = \frac{4mME}{(M+m)^2}$$

- SPECIAL CASE WHERE $M = m$

$$Q_{max} = E$$

TOTAL ~~TRANSFER~~ TRANSFER IN 7-COLLISION, BILLIARD BALL

- THE EXACT EXPRESSION FOR MAX. ENERGY TRANSFER ACCOUNTING FOR RELATIVISTIC EFFECTS:

$$Q_{max} = \frac{2\gamma^2 m_e V^2}{1 + 2\gamma m_e/M + m_e^2/M^2}$$

WHERE

$$\gamma = 1/\sqrt{1-\beta^2} \qquad \beta = V/c \qquad c = \text{S.O.L.}$$

TYPICALLY $\gamma m_e/M \ll 1$

$$\rightarrow Q_{max} = 2\gamma^2 m_e V^2$$

EXAMPLE OF 10-MeV PROTON LOSE IN SINGLE ELECTRONIC COLLISION

- NON-REL IS GOOD ENOUGH 10 MeV ~ 938 MeV
- m IS NEGLIGIBLE W.R.T M

$$Q_{max} \approx \frac{4mE}{M} = \underline{4 \times 1 \times 10\ \text{MeV}}/1836 = 2.18 \times 10^{-2}\ \text{MeV}$$

OR 21.8 keV 0.22% PROTON'S ENERGY.

STUDD