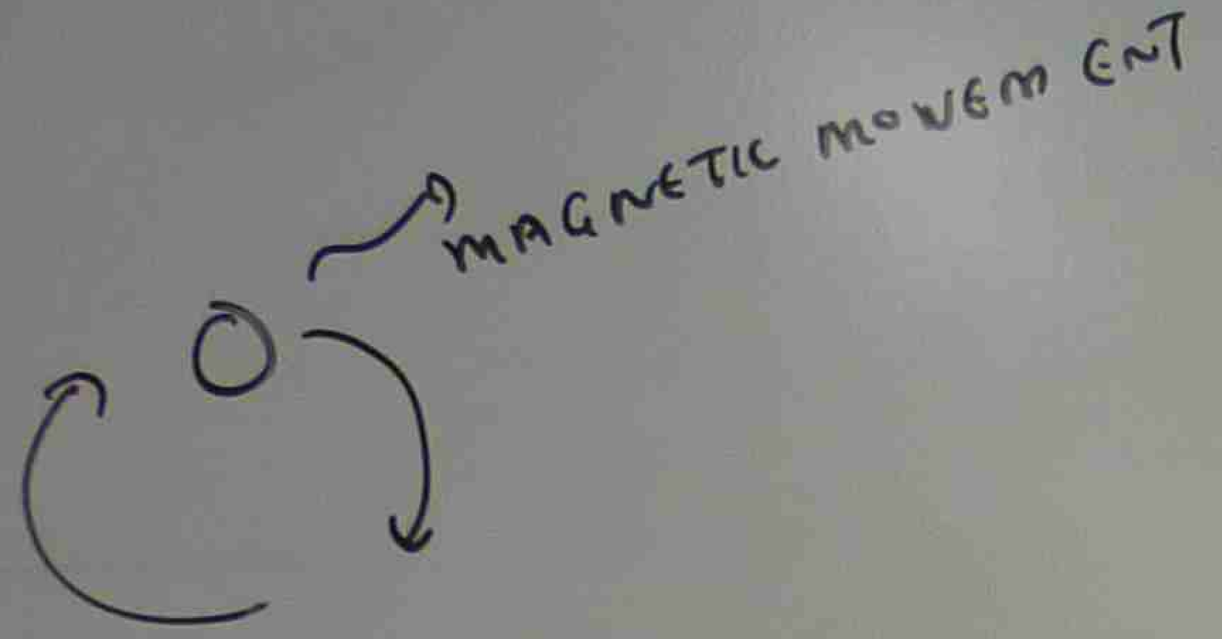
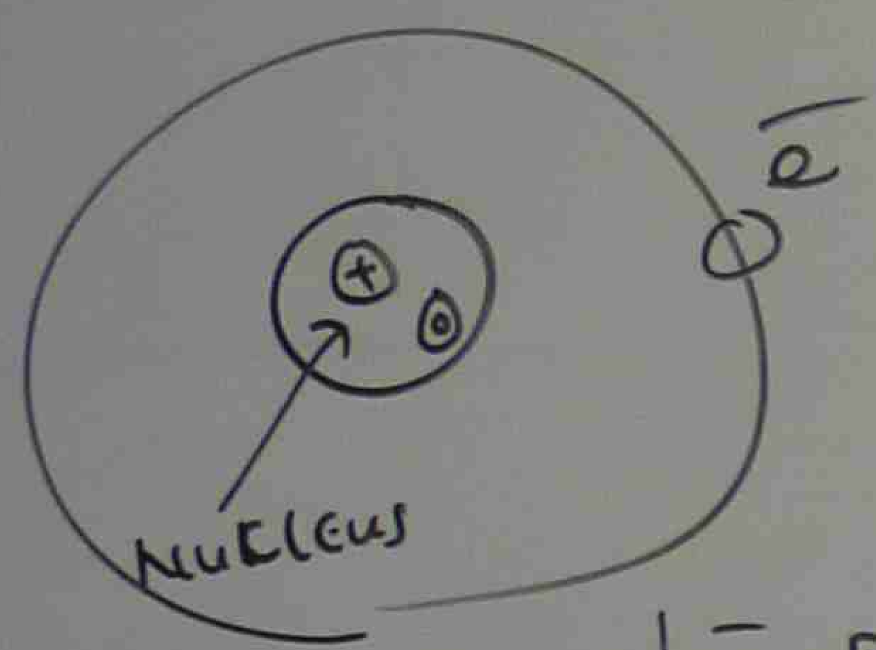
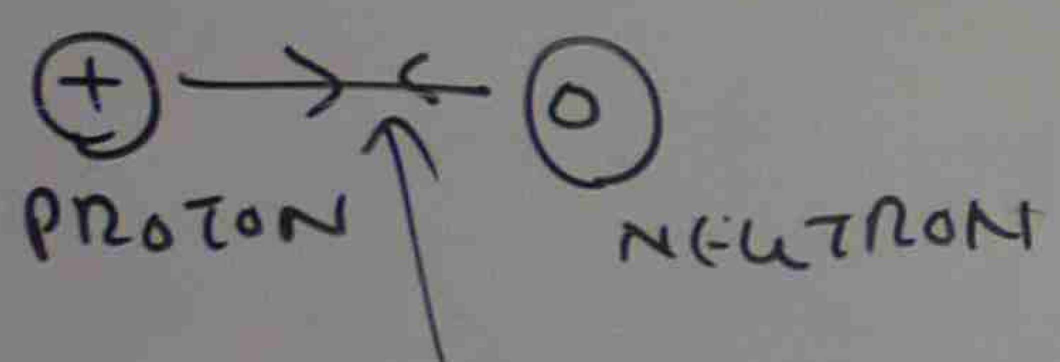
NUCLEAR SPIN AND MAGNETISM





$\oplus$ - PROTON | $\bar{e}$ - ELECTRON

$\odot$ NEUTRON



BINDING FORCE

STRONG FORCE

THE NUCLEAR FORCE THAT BINDS NEUTRONS AND PROTONS IS THE SECONDARY (OR) SPILL OVER EFFECT THAT BINDS

QUARKS TOGETHER TO FORM PROTON AND NEUTRON

Pb WHAT IS THE DENSITY OF NUCLEAR VOLUME?

$$\rho = \frac{A\,m}{\frac{4}{3}\pi r^3}$$

THE MASS OF A NUCLEUS CONTAINING 'A NUCLONS' IS Am

r = RADIUS OF NUCLEUS

$r = r_0 A^{1/3}$

$r^3 = r_0^3 A$

$$\rho = \frac{\cancel{A}\,m}{\frac{4}{3}\pi r_0^3 \cancel{A}} = \frac{m}{\frac{4}{3}\pi r_0^3}$$

$$= \frac{1.67 \times 10^{-27}\ \text{kg}}{\frac{4}{3} \times 3.1416 \times (1.2 \times 10^{-15})^3}$$

$$= 2 \times 10^{7}\ \text{kg}/\text{m}^3$$

BINDING ENERGY OF NUCLEON

pr WHAT IS THE BINDING ENERGY PER NUCLEON FOR 120 Sm?

120 Sm nucleus $\longrightarrow$ 50 (SEPARATE PROTONS) + 70 (SEPARATE NEUTRONS)

$$50\,(m_H c^2) + 70\,(m_n c^2) - M_{Sm} c^2$$

$$50\,(1.00825\,u)\,c^2 + 70\,(1.008665\,u)\,c^2 - (119.902197\,u)\,c^2$$

$$1.095603\,u\,c^2$$

$$1.095603\,u \times 931.494013\ \text{MeV}/u$$

$$= 1020.5\ \text{MeV}$$

$$\text{BINDING ENERGY PER NUCLEON} = \frac{\text{BINDING ENERGY CHANGE}}{\text{ATOMIC NUMBER}}$$

$$= \frac{1020.5\ \text{MeV}}{120}$$

$$= 8.5\ \text{MeV}/\text{NUCLEON}$$

$9.902147u) c^2$

RADIO ACTIVE DECAY

RADIO ACTIVE DECAY RATE

$$R = -\frac{dN}{dt} = \lambda N_0 e^{-\lambda t}$$

$$R = R_0 e^{-\lambda t}$$

λ = DECAY / DISINTEGRATION CONSTANT

t_0 = INITIAL TIME

RATE OF DECAY

1 BECQUEREL = 1 Bq = 1 DECAY / SEC

HALF LIFE $T_{1/2}$

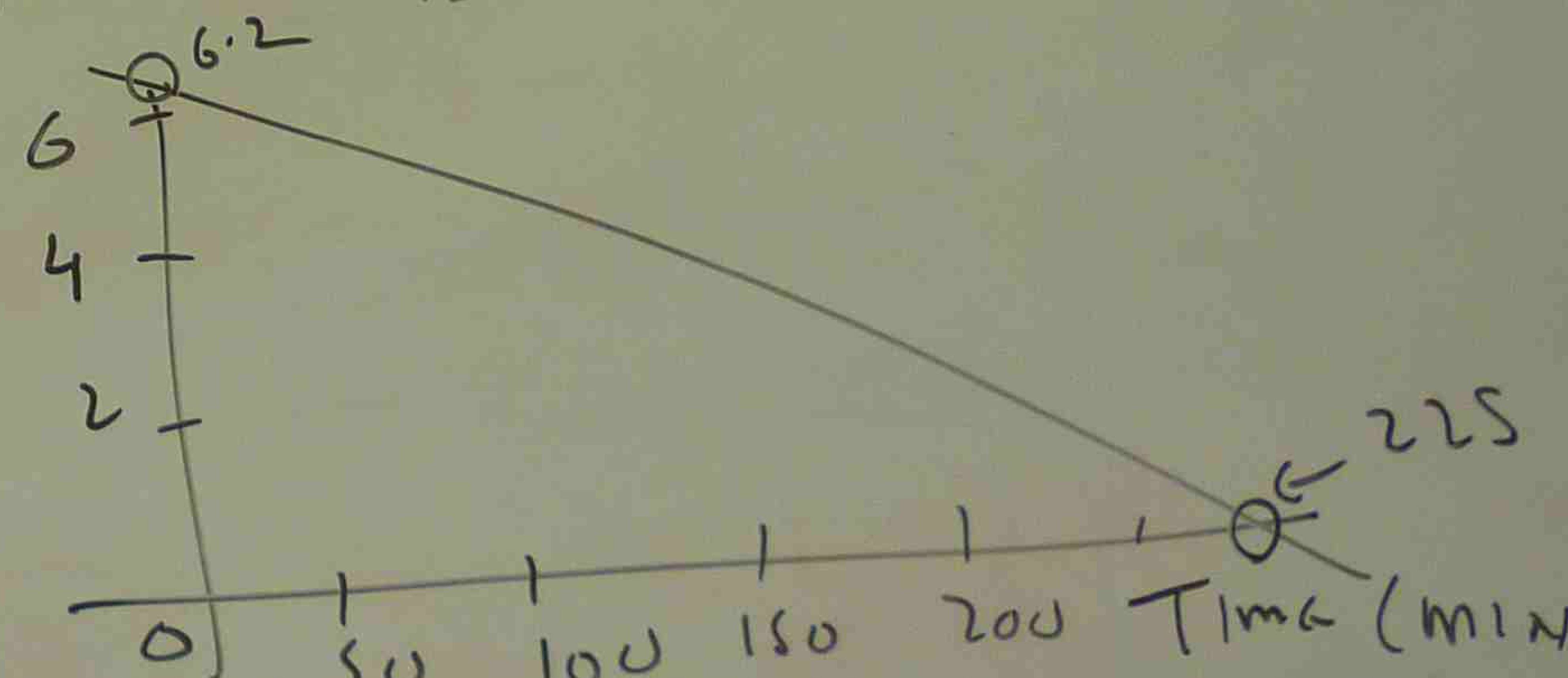
$$T_{1/2} = \tau \ln 2$$

τ = TIME CONSTANT

Pb THE TABLE THAT FOLLOWS SOME MEASUREMENTS OF THE DECAY RATE OF ^{128}I, A RADIO NUCLIDE OFTEN USED MEDICALLY AS A TRACER TO MEASURE THE RATE AT WHICH IODINE IS ABSORBED BY THE THYROID GLAND

TIME (MIN)	R COUNTS/S	TIME (MIN)	R COUNTS/S
4	392.2	132	10.9
36	161.4	164	4.56
68	65.5	196	1.86
100	26.8	218	1.00

FIND THE DISINTEGRATION CONSTANT λ AND HALF LIFE $T_{1/2}$ FOR THIS RADIONUCLIDE



Ln R=

SLOPE=

$-\lambda$

$T_{1/2}$

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pb. THE TABLE THAT follows some measurements of THE DECAY RATE of ^{128}I, A RADIO NUCLIDE often USED MEDICALLY AS A TRACER TO MEASURE THE RATE AT WHICH IODINE IS ABSORBED BY THE THYROID GLAND

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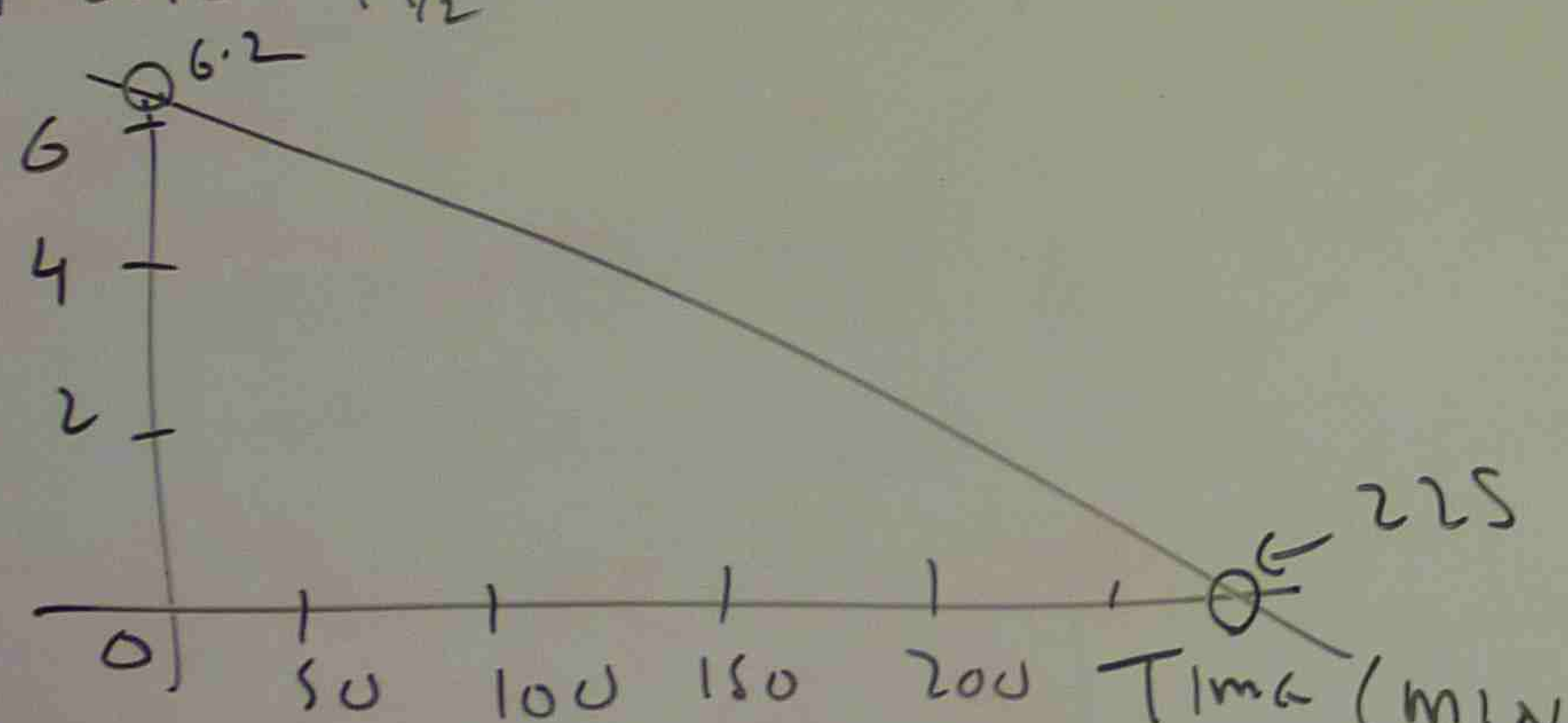

$$\ln R = \ln R_0 e^{-\lambda t} = \ln R_0 + \ln e^{-\lambda t}$$
$$= \ln R_0 - \lambda t$$

$$\text{SLOPE} = \frac{0 - 6.2}{225\ \text{min} - 0} = -0.0276\ \text{min}^{-1}$$

$$-\lambda = -0.0276\ \text{min}^{-1}$$
$$\lambda = 0.0276\ \text{min} = 1.7\ h^{-1}$$

$$T_{1/2} = \tau \ln 2$$
$$= \frac{1}{\lambda} \ln 2$$
$$= \frac{\ln 2}{0.0276} = 25\ \text{min}$$

ALPHA DECAY

WHEN A NUCLEUS UNDERGOES ALPHA DECAY, IT TRANSFORMS TO A DIFFERENT NUCLIDE BY EMITTING AN ALPHA PARTICLE

URANIUM ^{238}U ALPHA DECAY

$$^{238}U \rightarrow {}^{234}Th + {}^{4}He$$

THE E... DECAY ... DIS INT... pb WE ... MAS... 23... 23... 23... Pa... C...

$e^{-\lambda t} = \ln R_0 + \ln e^{-\lambda t}$

$= \ln R_0 - \lambda t$

$= -0.0276 \; min^{-1}$

$0.0276 \; min^{-1}$

$0.0276 \; min = 1.7 \; h^{-1}$

$\ln 2$

$\ln 2$

$\frac{\ln 2}{0.0276} = 25 \; min$

DECAY

NUCLEUS UNDERGOES ALPHA DECAY, TRANSFORMS TO A DIFFERENT NUCLEUS BY EMITTING AN ALPHA

^{238}U ALPHA DECAY

$\rightarrow {}^{234}Th + {}^{4}He$

THE ENERGY RELEASED IN THE THE DECAY PROCESS

$Q = m_i c^2 - m_f c^2$

DISINTEGRATION ENERGY

pb WE ARE GIVEN THE FOLLOWING ATOMIC MASSES.

^{238}U 238.05079 u ^{4}He 4.00260 u

^{234}Th 234.04363 u ^{1}H 1.00783 u

^{237}Pa 237.05121 u

Pa = SYMBOL FOR THE ELEMENT PROCTACTINIUM

(a) CALCULATE THE ENERGY RELEASED DURING THE ALPHA DECAY OF ^{238}U

$^{238}U \longrightarrow {}^{234}Th + {}^{4}He$

$Q = (238.05079u)c^2 - (234.04363u + 4.00260u)c^2$

$= (0.00456 \; u) c^2$

$= (0.00456 \; u) \times 931.494013 \; MeV/u = 4.25 \; MeV$

BETA DECAY

A NUCLEUS THAT ... ELECTRON (OR) POSI... THE MASS OF AN EL... DECAY.

$^{32}P \longrightarrow$

$^{64}Cu \longrightarrow$

$U =$ NE...

RADIO ACTIVE ...

THE DECAY ... USED TO ...

RADIONU... STABLE ...

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N...

LEASED IN THE THE

$- M_f \; c^2$

NERGY

HE FOLLOWING ATMOIC

079u ^{4}He 4.00260u

363u ^{1}H 1.00783u

5121 u

THE ELEMENT PROCTACTINIUM

THE ENERGY RELEASED DURING

DECAY OF ^{238}U

$^{238}U \longrightarrow {}^{234}Th + {}^{4}He$

$794u)c^2 - (234.04363u + 4.002604u)c^2$

$u)\,c^2$

$u) \times 931.494013\ meV/u = 4.25\ meV$

BETA DECAY

A NUCLEUS THAT DECAYS SPONTANEOUSLY BY EMITTING AN ELECTRON (OR) POSITRON (A POSITIVELY CHARGED PARTICLE WITH THE MASS OF AN ELECTRON) IS SAID TO UNDERGO BETA DECAY.

$$^{32}P \longrightarrow {}^{32}S + e^{-} + v$$

$$^{64}Cu \longrightarrow {}^{64}Ni + e^{+} + v$$

v = NEUTRINO - NEUTRAL PARTICLE WITH VERY SMALL MASS.

RADIO ACTIVE DATING

THE DECAY OF VERY LONG LIVE NUCLIDES CAN BE USED TO MEASURE THE AGE OF ROCK

RADIONUCLIDE ^{40}K DECAYS TO ^{40}Ar STABLE ISOTOPE OF NOBLE GAS ARGON

HALF LIFE DECAY $= 1.25 \times 10^{9}$ YEARS.

$$\boxed{N_K = N_0 e^{-\lambda t}}$$

Pb A GAMMA-RAY DOSE OF 3 Gy IS LETHAL TO HALF THE PEOPLE EXPOSED TO IT. IF THE EQUIVALENT ENERGY WERE ABSORBED AS HEAT, WHAT IS THE RISE IN BODY TEMPERATURE?

$$\Delta T = \frac{Q/m}{c} = \frac{3\ J/kg}{4180\ J/kgK} = 0.7\ mK$$

NUCLEAR MODEL

THE NUCLEONS MOVING AROUND WITHIN THE NUCLEUS AT RANDOM ARE IMAGINED TO INTERACT STRONGLY WITH EACH OTHER.

NUCLEAR REACTION FORM

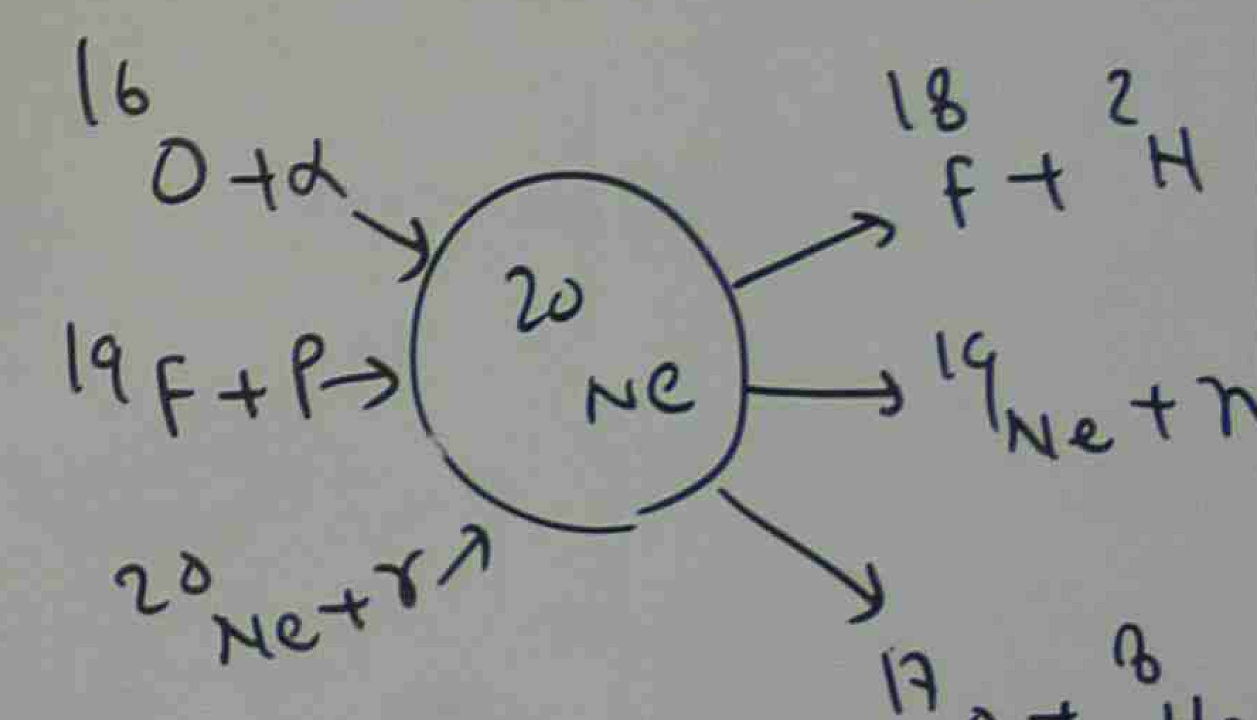
$$X + a \longrightarrow C \longrightarrow \underline{Y + b}$$

TARGET NUCLEUS X

PROJECTILE (a)

COMPOUND NUCLEUS 'C' EXCITATION ENERGY

DECAY



THREE FORMATION MODES

THREE DECAY MODES

THE FORMATIONS MODE AND THE DECAY MODES OF THE COMPOUND NUCLEUS ^{20}Ne

COMBINED MO

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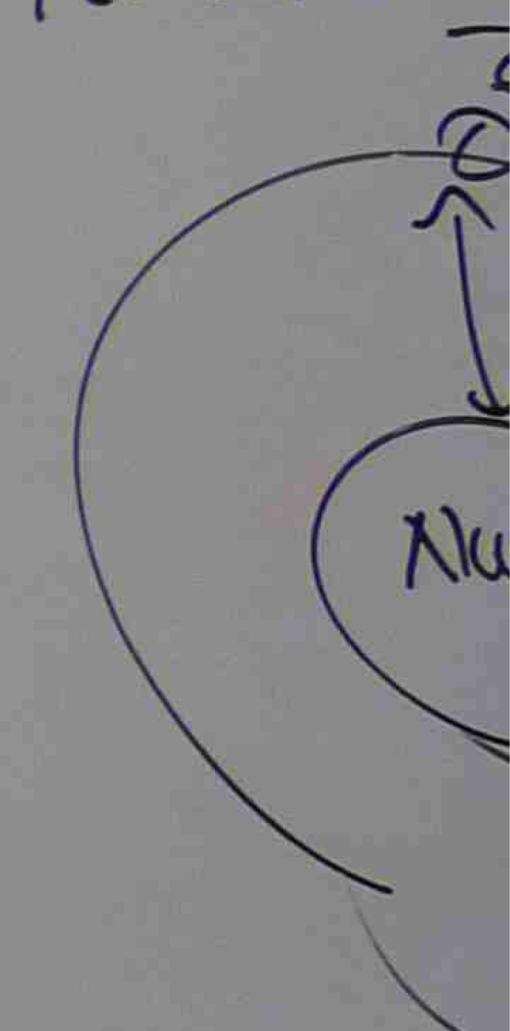

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NUCLEAR MODEL

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NUCLEAR REACTION FORM

$$X + a \longrightarrow C \longrightarrow \underline{Y + b}$$

TARGET NUCLEUS X — PROJECTILE 'a' — COMPOUND NUCLEUS 'C' EXCITATION ENERGY — DECAY

$$^{16}O + \alpha \rightarrow \qquad\qquad \rightarrow {}^{18}F + {}^{2}H$$
$$^{19}F + p \rightarrow \quad {}^{20}Ne \quad \rightarrow {}^{19}Ne + n$$
$$^{20}Ne + \gamma \rightarrow \qquad\qquad \rightarrow {}^{17}O + {}^{3}He$$

THREE FORMATION MODES

THREE DECAY MODES

THE FORMATIONS MODE AND THE DECAY MODES OF THE COMPOUND NUCLEUS ^{20}Ne

COMBINED

A NUCLEUS

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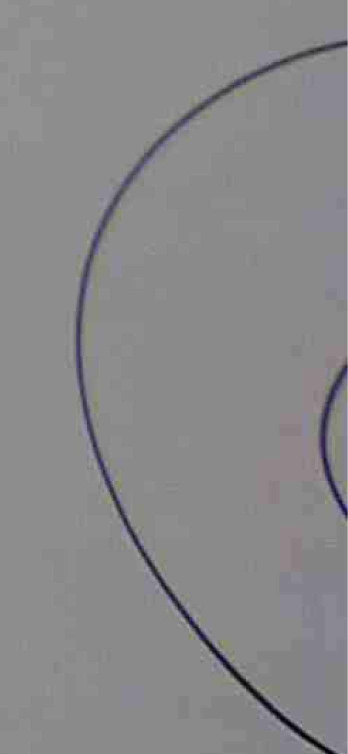

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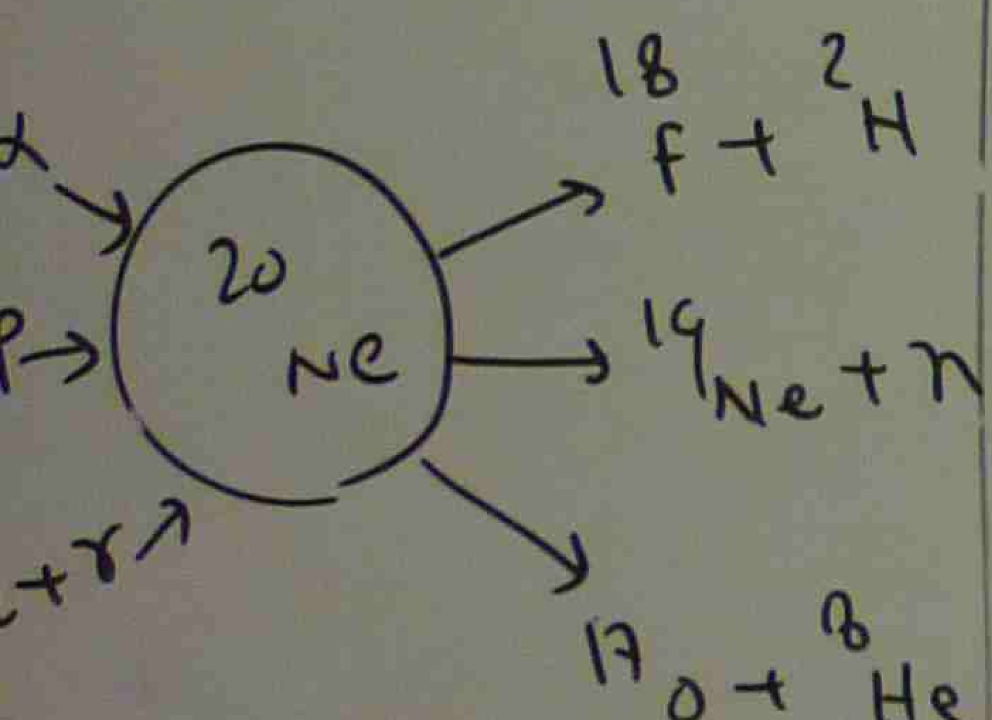


THREE FORMATION MODES

THREE DECAY MODES

...TIONS MODE AND
...AY MODES OF
...MPOUND NUCLEUS
Ne

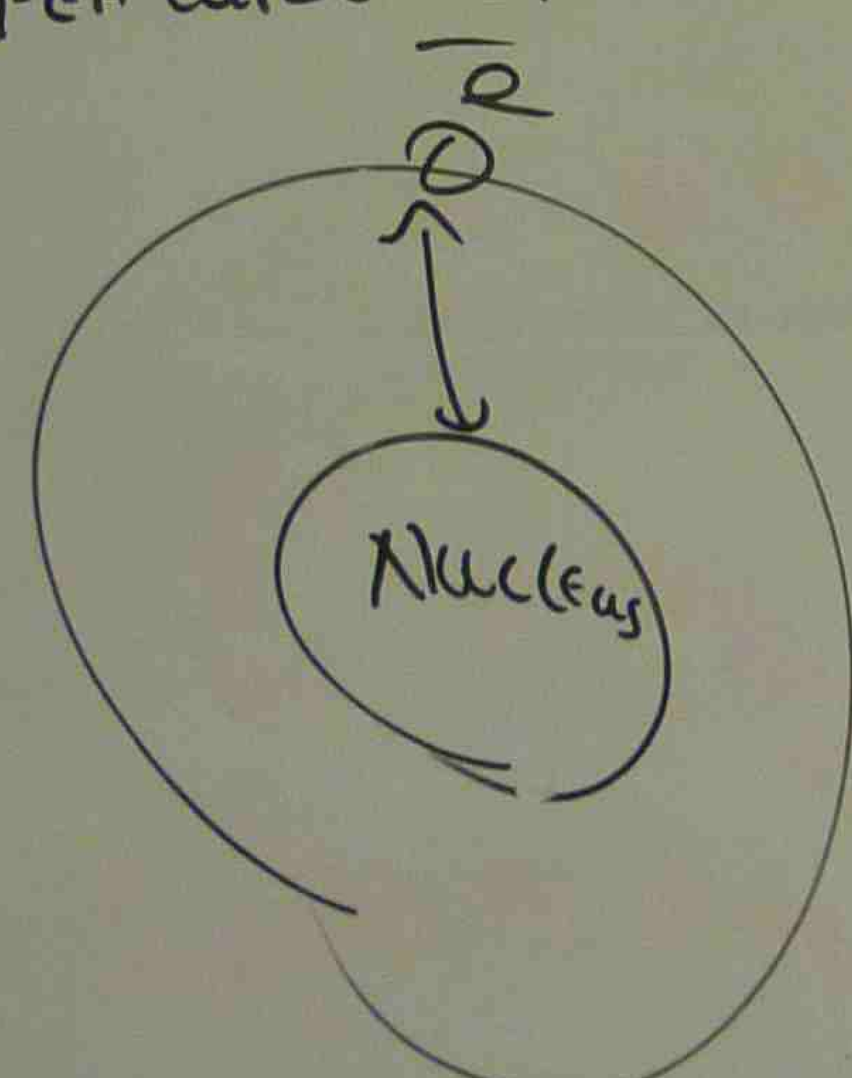
COMBINED MODEL

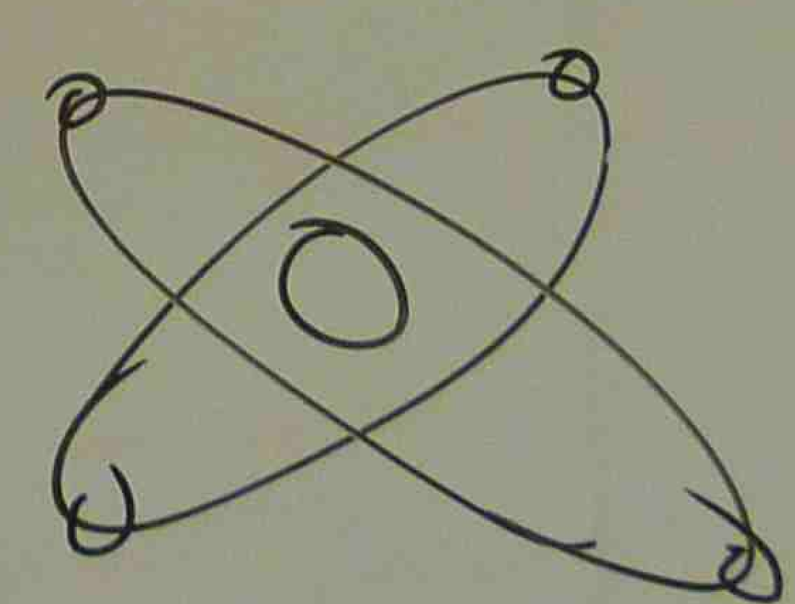
A NUCLEUS IN WHICH A SMALL NUMBER OF NEUTRONS (OR) PROTONS EXIST OUTSIDE A CORE OF CLOSED SHALL THAT CONTAINS MAGIC NUMBER OF NEUTRONS (OR) PROTONS.

THE OUTSIDE NUCLEONS OCCUPY QUANTIZED STATES IN A POTENTIAL WELL. ESTABLISHED BY THE CENTRAL CORE.

THE OUTSIDE NUCLEONS INTERACT WITH CENTRAL CORE DEFORMING IT AND SETTING UP TIDAL WAVE MOTIONS OF ROTATION (OR) VIBRATION WITHIN IT.

THE COLLECTIVE MOTIONS OF THE CORE PRESERVE THE CENTRAL FEATURE OF THE COLLECTIVE MODEL.





ELECTRONS A...
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(OR) PROTONS EXIST
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IN A POTENTIAL WELL.

CORE DEFORMING
OF ROTATION (OR)

E, THE CENTRAL

ELECTRONS ARE HELD IN ATOMS BY ELECTRO MAGNETIC COLOMB FORCE IT TAKES ONLY A FEW ELECTRON VOLT TO PULL ONE OF THEM OUT NUCLEONS ARE HELD IN NUCLEI BY THE STRONG FORCE. IT TAKES A FEW MILLION ELECTRON VOLT TO PULL ONE OF THEM OUT. THIS FACTOR OF A FEW MILLION IS REFLECTED IN THE FACT THAT WE CAN EXTRACT A FEW MILLION TIMES MORE ENERGY FROM A KILOGRAM OF URANIUM THAN WE CAN FROM A KILOGRAM OF COAL.

IN BOTH ATOMIC AND NUCLEAR BURNING, THE RELEASE OF ENERGY IS ACCOMPANIED BY A DECREASE IN MASS

$$Q = -\Delta m c^2$$

ENERGY RELEASED BY 1kg OF MATTER

FORM OF MATTER	PROCESS	TIME
WATER	A 50m WATER FALL	5 sec
COAL	BURNING	8 hr
ENRICHED UO_2	FISSION IN REACTOR	690 Y
^{235}U	COMPLETE FISSION	3×10^4 Y
HOT DEUTERIUM GAS	COMPLETE FISSION	3×10^4 Y
MATTER AND ANTI MATTER	COMPLETE ANNIHILATION	3×10^7 Y

NUCLEAR FISSION

THERMAL NEUTRO

WHEN 235 U
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FRAGMENTS
^{140}Xe (Z =
235

MODEL FOR

NEUTRON

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THIS FACTOR
WE CAN EXTRACT
OF URANIUM

ELEASE OF

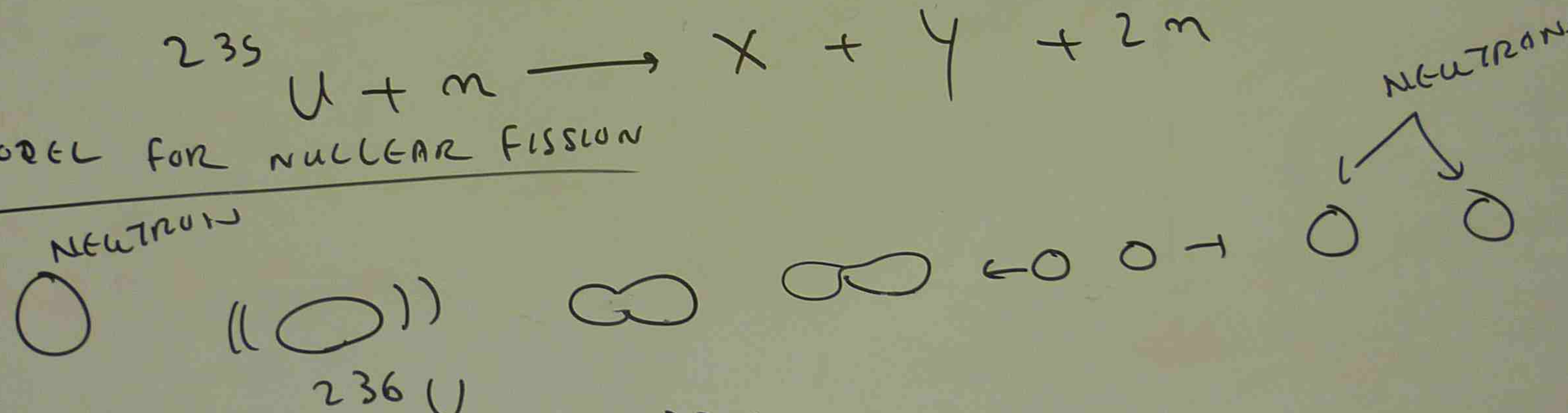
NUCLEAR FISSION

THERMAL NEUTRON - SLOWLY MOVING NEUTRONS IN THERMAL EQUILIBRIUM WITH SURROUNDING MATTER AT ROOM TEMPERATURE.

WHEN ^{235}U IS BOMBARDED WITH THERMAL NEUTRONS, A ^{235}U NUCLEUS ABSORBS A THERMAL NEUTRON PRODUCING A COMPOUND NUCLEUS ^{236}U IN A HIGHLY EXCITED STATE. IT IS THIS NUCLEUS THAT ACTUALLY UNDERGOES FISSION, SPLITTING IN TO TWO FRAGMENTS. THESE FRAGMENTS BETWEEN THEM - RAPIDLY EMIT TWO NEUTRONS LEAVING ^{140}Xe $(Z = 54)$ AND ^{94}Sr $(Z = 38)$ AS FISSION FRAGMENTS.

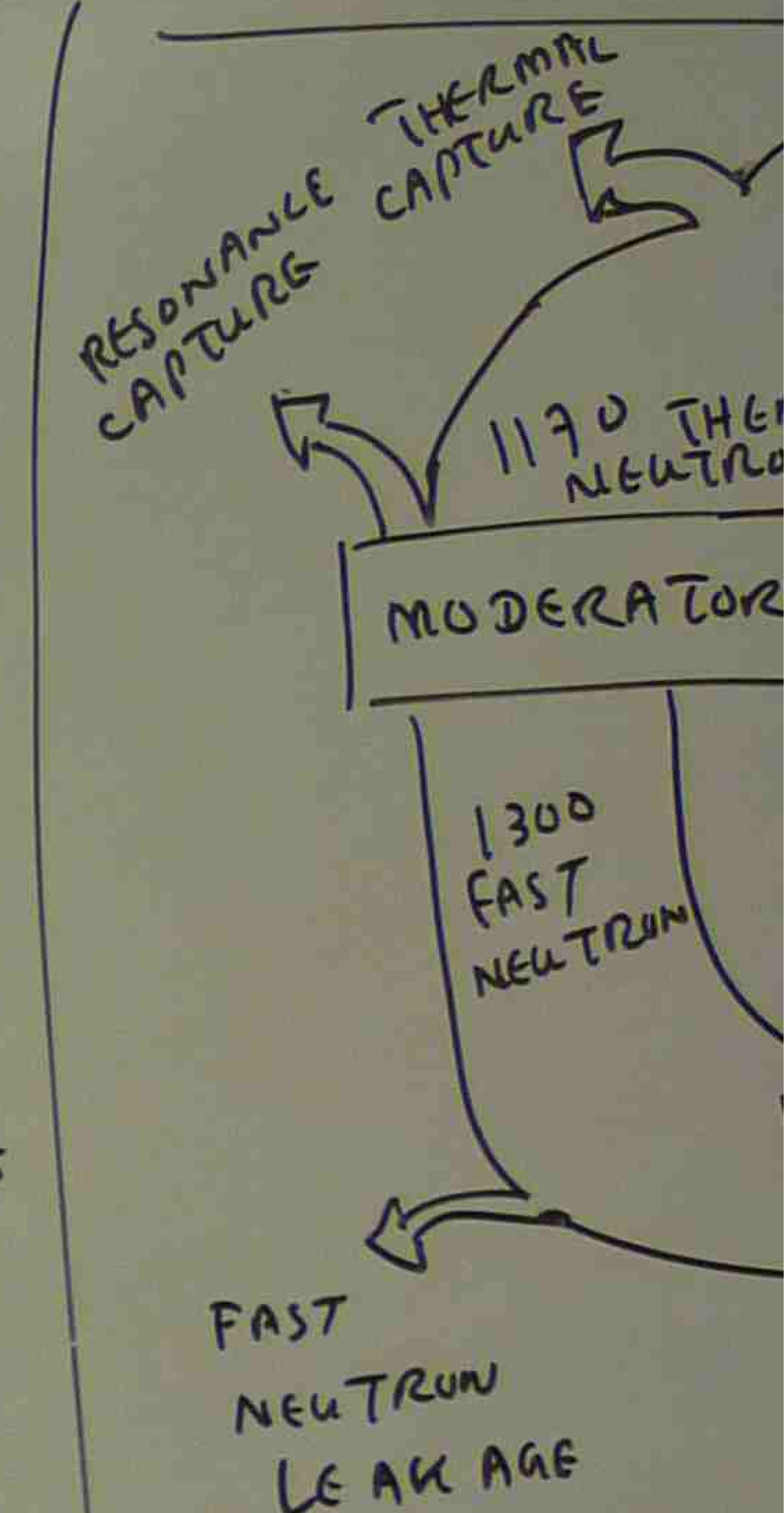
$$^{235}U + n \longrightarrow X + Y + 2n$$

MODEL FOR NUCLEAR FISSION



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

NUCLEAR REACT



NEUTRON

SOME OF NEU
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NEUTRON

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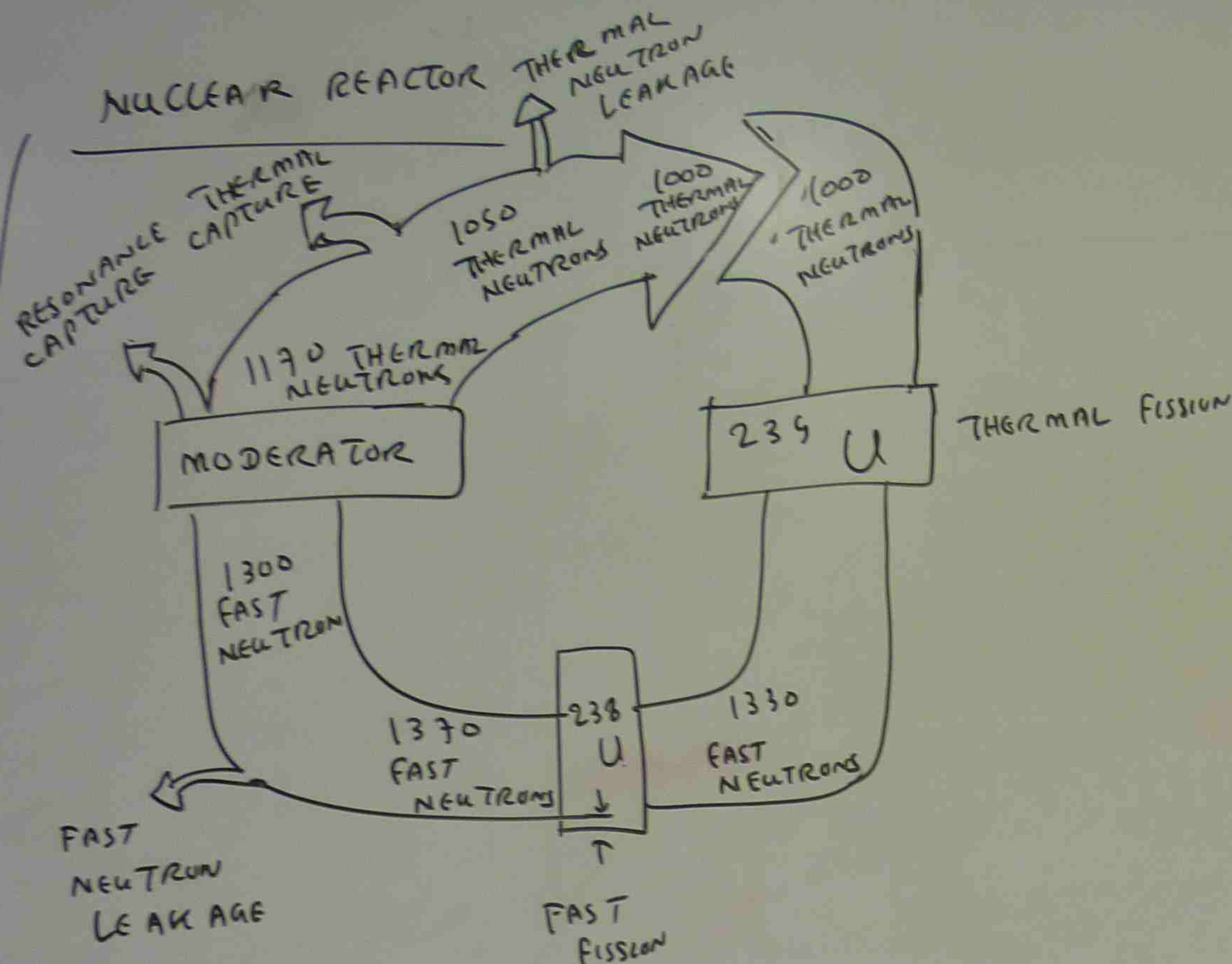
NUCLEAR REACTOR



NEUTRON LEAKAGE PROBLEM

SOME OF NEUTRONS PRODUCED BY FISSION WILL LEAK OUT OF REACTOR

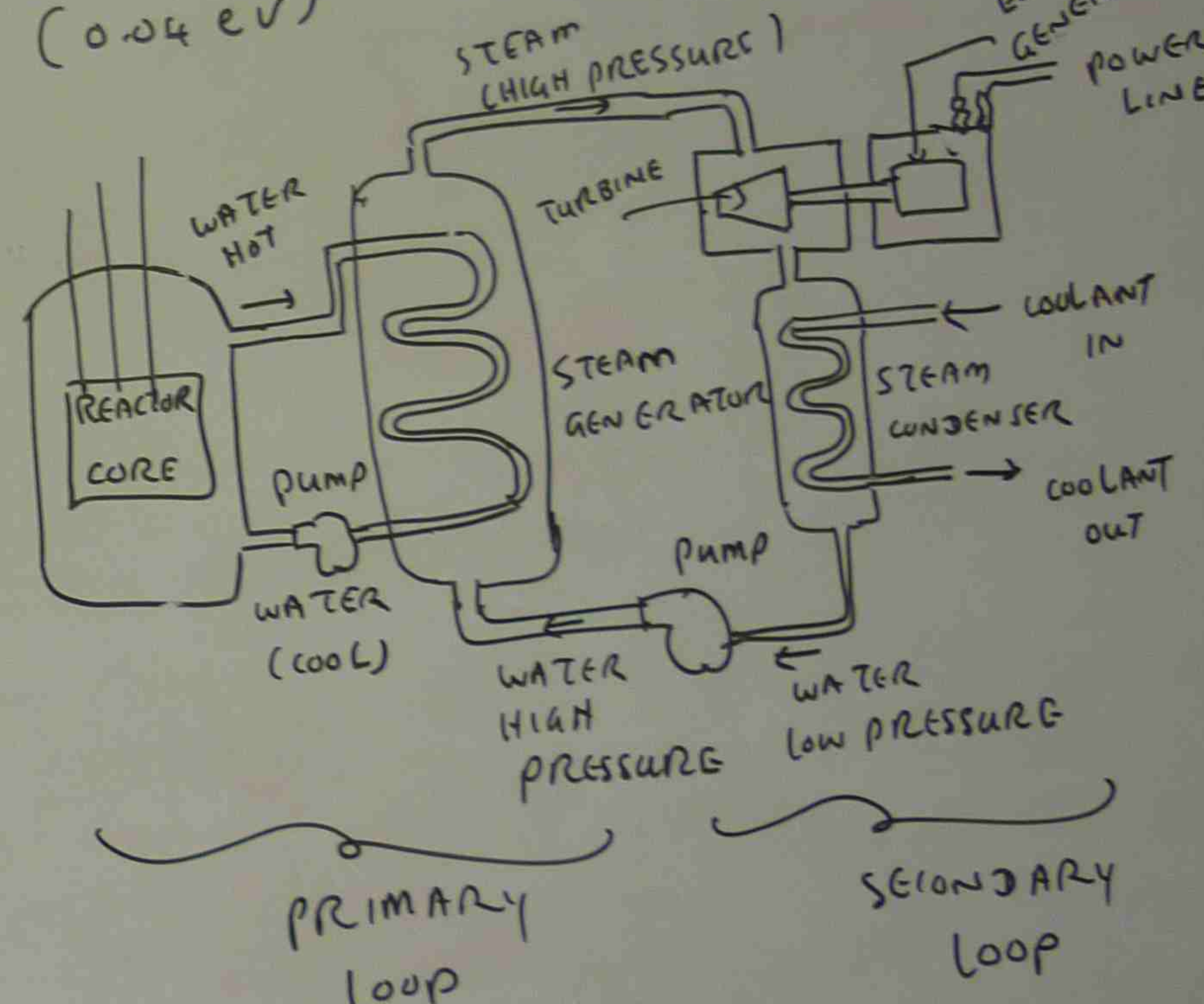
NEUTRON ENERGY PROBLEM

NEUTRONS PRODUCED BY FISSION ARE FAST WITH KINETIC ENERGY ABOUT 2 MeV.

THE FAST NEUTRON IS SLOWER BY MIXING WITH SUBSTANCE – MODERATOR

NEUTRON CAPTURE PROBLEM

AS THE FAST (2 MeV) NEUTRONS GENERATED BY FISSION ARE SLOWED DOWN IN THE MODERATOR TO THERMAL ENERGIES (0.04 eV)



A large electric generating station is powered by a pressurized-water nuclear reactor. The thermal power produced in the reactor core is 3400 MW, and 1100 MW of electricity is generated by the station. The *fuel charge* is 8.60×10^4 kg of uranium, in the form of uranium oxide, distributed among 5.70×10^4 fuel rods. The uranium is enriched to 3.0% ^{235}U.

(a) What is the station's efficiency?

KEY IDEA The efficiency for this power plant or any other energy device is given by this: Efficiency is the ratio of the output power (rate at which useful energy is provided) to the input power (rate at which energy must be supplied).

Calculation: Here the efficiency (eff) is

$$\text{eff} = \frac{\text{useful output}}{\text{energy input}} = \frac{1100 \text{ MW (electric)}}{3400 \text{ MW (thermal)}}$$

$$= 0.32, \text{ or } 32\%. \qquad \text{(Answer)}$$

The efficiency—as for all power plants—is controlled by the second law of thermodynamics. To run this plant, energy at the rate of 3400 MW − 1100 MW, or 2300 MW must be discharged as thermal energy to the envi-

and (2) the nonfissio
fourth that rate.

Calculations: The to

$(1 + 0.25)(1.06 \times 10$

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Thus, the mass of each
kg). Then the rate at w

$$\frac{dM}{dt} = (1.33 \times 10^{2}$$

$$= 5.19 \times 10^{-5}$$

(d) At this rate of fuel
fuel supply of ^{235}U las

Calculation: At star
of ^{235}U is 3.0% of th
So, the time T requi
^{235}U at the steady rate

(0.030)(8.

energy input   3400 MW (thermal)

$= 0.32$, or 32%. (Answer)

The efficiency—as for all power plants—is controlled by the second law of thermodynamics. To run this plant, energy at the rate of 3400 MW − 1100 MW, or 2300 MW, must be discharged as thermal energy to the environment.

(b) At what rate R do fission events occur in the reactor core?

KEY IDEAS (1) The fission events provide the input power P of 3400 MW ($= 3.4 \times 10^9$ J/s). (2) From Eq. 43-6, the energy Q released by each event is about 200 MeV.

Calculation: For steady-state operation (P is constant), we find

$$R = \frac{P}{Q} = \left(\frac{3.4 \times 10^9 \text{ J/s}}{200 \text{ MeV/fission}}\right)\left(\frac{1 \text{ MeV}}{1.60 \times 10^{-13} \text{ J}}\right)$$
$$= 1.06 \times 10^{20} \text{ fissions/s}$$
$$\approx 1.1 \times 10^{20} \text{ fissions/s.} \quad \text{(Answer)}$$

(c) At what rate (in kilograms per day) is the ^{235}U fuel

fuel supply of

Calculation: At of ^{235}U is 3.0% So, the time T ^{235}U at the stead

$$T = \frac{(0.03}{}$$

In practice, the batches) before

(e) At what rate of energy by the

KEY IDEA The forms of energy duces the input sion capture of affect the rate at

Calculation: Fr write

$$\frac{dm}{dt} =$$

the energy Q released by each event is about 200 MeV.

Calculation: For steady-state operation (P is constant), we find

$$R = \frac{P}{Q} = \left(\frac{3.4 \times 10^9 \text{ J/s}}{200 \text{ MeV/fission}}\right)\left(\frac{1 \text{ MeV}}{1.60 \times 10^{-13} \text{ J}}\right)$$
$$= 1.06 \times 10^{20} \text{ fissions/s}$$
$$\approx 1.1 \times 10^{20} \text{ fissions/s.} \quad \text{(Answer)}$$

(c) At what rate (in kilograms per day) is the ^{235}U fuel disappearing? Assume conditions at start-up.

KEY IDEA ^{235}U disappears due to two processes: (1) the fission process with the rate calculated in part (b)

KEY IDEA Th

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Calculation: F

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$$\frac{dm}{dt}$$

We see that the

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$$= \frac{1100 \text{ MW (electric)}}{3400 \text{ MW (thermal)}}$$

(Answer)

power plants—is controlled
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on events occur in the reactor

n events provide the input
4×10^9 J/s). (2) From Eq. 43-6,
ch event is about 200 MeV.

ate operation (P is constant),

$$\left(\frac{^9 \text{ J/s}}{\text{fission}}\right)\left(\frac{1 \text{ MeV}}{1.60 \times 10^{-13} \text{ J}}\right)$$

Thus, the mass of each ^{235}U atom is 235 u ($= 3.90 \times 10^{-25}$ kg). Then the rate at which the ^{235}U fuel disappears is

$$\frac{dM}{dt} = (1.33 \times 10^{20} \text{ atoms/s})(3.90 \times 10^{-25} \text{ kg/atom})$$

$$= 5.19 \times 10^{-5} \text{ kg/s} \approx 4.5 \text{ kg/d}. \qquad \text{(Answer)}$$

(d) At this rate of fuel consumption, how long would the fuel supply of ^{235}U last?

Calculation: At start-up, we know that the total mass of ^{235}U is 3.0% of the 8.60×10^4 kg of uranium oxide. So, the time T required to consume this total mass of ^{235}U at the steady rate of 4.5 kg/d is

$$T = \frac{(0.030)(8.60 \times 10^4 \text{ kg})}{4.5 \text{ kg/d}} \approx 570 \text{ d}. \qquad \text{(Answer)}$$

In practice, the fuel rods must be replaced (usually in batches) before their ^{235}U content is entirely consumed.

(e) At what rate is mass being converted to other forms of energy by the fission of ^{235}U in the reactor core?

KEY IDEA The conversion of mass energy to other forms of energy is linked only to the fissioning that produces the input power (3400 MW) and not to the nonfission capture of neutrons (although both these processes affect the rate at which ^{235}U is consumed).

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SION OF ^{235}U IN

(a) $\text{Efficiency} = \dfrac{\text{useful output}}{\text{energy input}}$

$= \dfrac{1100 \text{ MW}}{3400 \text{ MW}}$

$= 0.32$ (or) 32%

(b) $R = \dfrac{P}{Q} = \dfrac{3.4 \times 10^{9} \text{ J/s}}{200 \text{ MeV/fission}} \times \dfrac{1 \text{ MeV}}{1.6 \times 10^{-13} \text{ J}}$

$= 1.06 \times 10^{20}$ fissions/s

$\sim 1.1 \times 10^{20}$ fissions/s.

(c) $(1 + \underline{0.25}) \times 1.06 \times 10^{20}$ atom/sec

↑ Efficency

$\simeq 1.33 \times 10^{20}$ atom

$\dfrac{dm}{dt} = 1.33 \times 10^{20} \text{ atoms/s} \times 3.9 \times 10^{-25} \text{ kg/atom}$

$\simeq 5.19 \times 10^{-5}$ kg/s

$\simeq 5.19 \times 10^{-5} \times 3000 \text{ sec} \times 24 \text{ HR}$

$= 4.5$ kg/day

(d) ^{235}U

DAY =

(e)

$\dfrac{dm}{dt} =$

$E = mc^2$

$\dfrac{E}{c^2} = m$

$\therefore \dfrac{dm}{dt} = \dfrac{d}{dt} \dfrac{E}{c}$

...PUT
...T

...) 32%
$$\frac{\ldots^{9}\ J/s}{\ldots V / \text{fission}} \times \frac{1\,\text{meV}}{1.6\times10^{-13}\ J}$$

... fissions / s

... fissions / s.

... 1.06×10^{20} Atom / sec

$\approx 1.33\times10^{20}$ Atom

...toms / s $\times\ 3.9\times10^{-25}$ kg / Atom

... kg / s

... $\times$ 3600 sec $\times$ 24 HR

... / DAY

(d) ^{235}U 3% of 8.6×10^{4} kg. $= 0.03\times 8.6\times10^{4}$ kg.

$$\text{DAY} = \frac{0.03\times 8.6\times10^{4}\ \text{kg}}{4.5\ \text{kg} / \text{DAY}} = 570\ \text{DAYS.}$$

(e)

$$\frac{dm}{dt} = \frac{dE/dt}{c^2} = \frac{3400\times10^{6}\ W}{(3.3\times10^{10})^2}$$

$E = mc^2$

$\frac{E}{c^2} = m$

$\therefore \frac{dm}{dt} = \frac{d}{dt}\frac{E}{c^2}$

$= 3.8\times10^{-9}$ kg/s

$= 3.3$ g / DAY

THE...

T...

F...

NUCLEAR FUSION

THE BINDING ENERGY CURVE OF NUCLEAR ENERGY SHOWS THAT THE NUCLEI COMBINE TO FORM A SINGLE LARGER NUCLEUS A PROCESS CALLED NUCLEAR FUSION.

COULOMB BARRIER DEPENDS ON THE CHARGES AND THE RADII OF TWO INTERACTING MODELS.

THERMO NUCLEAR FUSION

$$K = kT$$

K = KINETIC ENERGY CORRESPONDING TO THE MOST PROBABLE SPEED

AT ROOM TEMPERATURE, $K = 0.03\ eV$.