WES HITT

15.1) LET'S FIRST CONSIDER THE RELAVENT REACTION'S KINEMATICS.

THE NEUTRON WILL BE MOST EFFICIENTLY DETECTED MEASURING THE CHARGED REM~~E~~NANTS OF THE REACTION;

$$^{6}_{3}Li + ^{1}_{0}n \longrightarrow ^{3}_{1}t + ^{4}_{2}\alpha \quad , \quad Q = 4.78 \text{ MeV}$$

CONSERVING ENERGY AND MOMENTUM, THE EXIT CHANNEL IS DESCRIBED BY;

$$E_t + E_\alpha = Q + E_n \qquad ①$$

$$\sqrt{2 m_t E_t} = \sqrt{2 m_\alpha E_\alpha} \qquad ②$$

FOR THE α-ENERGY WE HAVE;

FROM ①; $$E_\alpha = Q + E_n - E_t$$

SUBSTITUTING ②: $$E_\alpha = Q + E_n - \frac{m_\alpha}{m_t} E_\alpha$$

$$= \frac{Q + E_n}{\left(1 + \frac{m_\alpha}{m_t}\right)} \quad , \quad m_\alpha = 3728.4 \text{ MeV}/c^2$$

$$m_t = 2809.4 \text{ MeV}/c^2$$

$$E_\alpha = \frac{(4.78 \text{ MeV}) + (1 \text{ MeV})}{\left(1 + 3728.4/2809.4\right)}$$

$$\boxed{E_\alpha = 2.48 \text{ MeV}}$$

WITH THIS RESULT AND ① WE HAVE FOR THE TRITON ENERGY;

$$\boxed{E_t = 3.30 \text{ MeV}}$$

AT 1 MeV INCIDENT NEUTRON ENERGY, THE CROSS SECTION FOR THIS REACTION CAN BE READ FROM FIG. 15.9, p. 546;

$$\sigma \sim 2.3 \times 10^{-1} \, b \qquad ✓$$

$$\sigma \sim 0.23 \times 10^{-24} \text{ cm}^2$$

THE REACTION PROBABILITY PER UNIT PATH LENGTH (OR 'MACROSCOPIC' CROSS SECTION) IS GIVEN BY EQ. 2.26, p. 56 AS;

$$\Sigma = \sigma N_{Li}$$

WHERE N_{Li} IS THE NUMBER DENSITY OF ^{6}Li NUCLEI. WE CALCULATE IT

USING THE DENSITY OF LiI LISTED IN TABLE 8.3;

$$\rho_{LiI} = 4.08 \ g/cm^3$$

AND A MOLAR MASS OF 133 g/MOL FOR LiI, WE HAVE FOR N_{Li};

$$N_{Li} = \frac{\rho_{LiI} A_v}{M}$$

$$= \frac{(4.08 \ g/cm^3)(6.02 \times 10^{23} \ mol^{-1})}{(133 \ g/mol)}$$

$$\boxed{N_{Li} \cong 1.85 \times 10^{22} \ cm^{-3}} \ \checkmark$$

THEREFORE,

$$\Sigma = \sigma N_{Li}$$

$$= (0.23 \times 10^{-24} cm^2)(1.85 \times 10^{22} cm^{-3})$$

$$\boxed{\Sigma \cong 0.00425} \ (cm^{-1})$$

MULTIPLYING THIS BY THE NEUTRON PATH LENGTH GIVES THE INTERACTION PROBABILITY;

$$P = d\Sigma$$

$$= (0.4 \ cm)(0.00425 \ cm^{-1})$$

$$\boxed{P \cong 0.00170} \ \checkmark$$

correct for small Σ

ALSO FROM TABLE 8.3, WE HAVE LIGHT YIELD AND WAVELENGTH OF THAT LIGHT FOR LiI; $\text{YIELD} = 11{,}000 \ \frac{\text{PHOTONS}}{\text{MeV}}$ AND $\lambda = 470 \ nm$

HOWEVER, THIS LIGHT YIELD IS FOR ELECTRONS AND WE WILL INSTEAD BE MEASURING EJECTILE ALPHA'S AND TRITONS. THE 'α-TO-β' RATIO FOR NaI IS ~0.6 AND THIS IS VALID FOR SIMILAR COMPOUNDS SUCH AS LiI. FOR TRITONS, SINCE ENERGY LOSSES $dE \propto Z^2$, A SIMILAR GUESS FOR A 't-TO-β' RATIO MIGHT BE ~0.15. SO A MORE ACCURATE VALUE FOR THE LIGHT YIELD/EVENT MIGHT BE;

$$\frac{\text{YIELD}}{\text{EVENT}} = (E_\alpha \cdot 0.6 + E_t \cdot 0.15) \times 11{,}000 \ \frac{\text{PHOTONS}}{\text{MeV}}$$

$$= (2.48 \ \text{MeV} \cdot 0.6 + 3.30 \ \text{MeV} \cdot 0.15) \times 11{,}000 \ \frac{\text{PHOTONS}}{\text{MeV}}$$

$$\boxed{\frac{\text{YIELD}}{\text{EVENT}} = 21{,}813 \ \text{PHOTONS}}$$

THE LIGHT ENERGY PER EVENT THEN IS;

$$\frac{E_\gamma}{\text{EVENT}} = \frac{\text{YIELD}}{\text{EVENT}} \times \frac{2\pi\hbar c}{\lambda}$$

$$= (21{,}813) \times \frac{2\pi\,(197.3 \text{ eV}\cdot\text{nm})}{470 \text{ nm}}$$

$$\boxed{\frac{E_\gamma}{\text{EVENT}} \cong 57.5 \text{ keV}}$$

THE EFFICIENCY OF A SCINTILLATOR IS DEFINED AS THE FRACTION OF INCIDENT PARTICLE ENERGY CONVERTED TO LIGHT ENERGY. THIS SHOULD BE WEIGHTED BY THE PROBABILITY OF A REACTION SO;

$$\varepsilon = \frac{P \times \frac{E_\gamma}{\text{EVENT}}}{E_n}$$

$$= \frac{(0.00170)(57.5 \text{ keV})}{(1{,}000 \text{ keV})}$$

$$\boxed{\varepsilon \cong 0.01\,\%, \quad E_n = 1 \text{ MeV}}$$

REPEATING THE ABOVE CONSIDERATIONS FOR THERMAL NEUTRONS ($E_n = 0.025$ eV) WE HAVE;

KINEMATICS: $E_\alpha = 2.05$ MeV AND $E_t = 2.73$ MeV

CROSS SECTION: $\sigma = 900 \times 10^{-24}$ cm^2 AND $\Sigma \cong 3.7$ cm^{-1}

SINCE Σ IS LARGE, WE MUST TREAT THE EFFICIENCY CALCULATION DIFFERENTLY;

IN THIS CASE, $$\varepsilon = 1 - e^{-N_0 \sigma d}$$

$$= 1 - e^{-\Sigma d}$$

$$= 1 - e^{-(3.7 \text{ cm}^{-1} \times 0.4 \text{ cm})}$$

$$= 0.9987$$

$$\boxed{\varepsilon = 99.87\,\%},$$

SINCE 4 MM LiI IS SUFFICIENT TO STOP THERMAL NEUTRONS.

WES HITT

15.4) TO CALCULATE A REASONABLE RANGE FOR THE ESTIMATE, WE CONSIDER THE NEUTRON MOST LIKELY THERMALIZED IN THE MODERATOR BUT POTENTIALLY HAVING ENERGY AS HIGH AS THE CADMIUM-CUTOFF, SO THAT

$$0.025\,eV \leq E_n \leq 0.5\,eV \leftarrow \text{(THE CHOOSEN BOUNDARY WITH FAST NEUTRONS)}$$

THE ENERGY RELATES TO THE VELOCITY AS;

$$E_n = \frac{1}{2} M_n v_n^2$$

$$v_n = \sqrt{\frac{2E_n}{M_n}} \quad , \quad M_n = 939.573\ MeV/c^2$$

$$\sqrt{\frac{2 \times 0.025 \times 10^{-6} \cancel{MeV}}{939.573\ \cancel{MeV}/c^2}} \leq v_n \leq \sqrt{\frac{2 \times 0.5 \times 10^{-6} \cancel{MeV}}{939.573\ \cancel{MeV}/c^2}}$$

$$7.29 \times 10^{-6} c \leq v_n \leq 3.26 \times 10^{-5} c$$

$$2.19 \times 10^{5}\ cm/s \leq v_n \leq 9.78 \times 10^{5}\ cm/s$$

THE CORRESPONDING TRAVEL TIMES FOR A DISTANCE OF 10 cm ARE;

$$t = \frac{d}{v_n}$$

$$\frac{10\ cm}{9.78 \times 10^5\ cm/s} \leq t \leq \frac{10\ cm}{2.19 \times 10^5\ cm/s}$$

$$\boxed{10.2\ \mu s \leq t \leq 45.7\ \mu s}$$

✓

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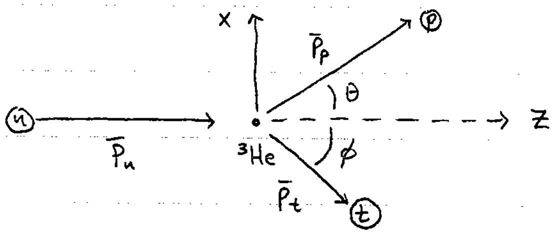
15.6)



FIRST, WE STATE CONSERVATION OF MOMENTUM;

$$P_{nz} = P_{pz} + P_{tz} \qquad \text{AND} \qquad P_{px} = P_{tx}$$

$$① \quad P_n = P_p \cos\theta + P_t \cos\phi \qquad ② \quad P_p \sin\theta = P_t \sin\phi$$

AND CONSERVATION ENERGY;

$$M_n c^2 + E_n + M_{^3He} c^2 = M_t c^2 + E_t + M_p c^2 + E_p$$

$$E_n + \underbrace{(M_n + M_{^3He} - M_t - M_p) c^2}_{Q \,\equiv\, \text{REACTION Q-VALUE} \ (0.764 \text{ MeV})} = E_t + E_p$$

$$E_n + Q = E_t + E_p \quad ③$$

SINCE WE ARE INTRESTED IN THE PROTON ENERGY;

FROM ③: $\quad E_p = E_n - E_t + Q$

NOW WE USE ① & ② TO ELIMINATE DEPENDENCE ON THE TRITON VARIABLES E_t AND ϕ;

$$E_p = E_n - \frac{1}{2M_t}\left(P_{tx}^2 + \overset{=0}{\cancel{P_{ty}^2}} + P_{tz}^2\right) + Q$$

SUBSTITUTING ①&②:

$$= E_n - \frac{1}{2M_t}\left(P_p^2 \sin^2\theta + (P_n - P_p\cos\theta)^2\right) + Q$$

$$= E_n - \frac{1}{2M_t}\left(P_p^2 \sin^2\theta + P_n^2 + P_p^2\cos^2\theta - 2P_nP_p\cos\theta\right) + Q$$

$$= E_n - \frac{1}{2M_t}\left\{P_p^2 \overset{=1}{\cancel{(\sin^2\theta + \cos^2\theta)}} + P_n^2 - 2P_nP_p\cos\theta\right\} + Q$$

$$= E_n - \frac{1}{2M_t}\left\{\frac{2M_p}{2M_p}P_p^2 + \frac{2M_n}{2M_n}P_n^2 - 2\sqrt{2M_nE_n}\sqrt{2M_pE_p}\cos\theta\right\} + Q$$

$$= E_n - \frac{1}{2M_t}\left\{2M_pE_p + 2M_nE_n - 2\sqrt{4M_nM_pE_nE_p}\cos\theta\right\} + Q$$

$$E_p = E_n - \frac{M_p}{M_t}E_p - \frac{M_n}{M_t}E_n + \frac{2}{M_t}\sqrt{M_nM_pE_nE_p}\cos\theta + Q$$

$$E_p\left(1 + \frac{M_p}{M_t}\right) = E_n\left(1 - \frac{M_n}{M_t}\right) + \frac{2}{M_t}\sqrt{M_nM_pE_nE_p}\cos\theta + Q$$

WRITING THIS IN THE FAMILIAR QUADRATIC FORM;

$$E_p\left(1 + \frac{M_p}{M_t}\right) - \frac{2}{M_t}\sqrt{M_nM_pE_n}\sqrt{E_p}\cos\theta - E_n\left(1 - \frac{M_n}{M_t}\right) - Q = 0$$

$$\frac{E_p}{\cancel{M_t}}(M_t + M_p) - \frac{2}{\cancel{M_t}}\sqrt{M_nM_pE_n}\cos\theta\sqrt{E_p} - \frac{E_n}{\cancel{M_t}}(M_t - M_n) - \frac{QM_t}{\cancel{M_t}} = 0$$

SINCE THIS EQUATION IS QUADRATIC IN $\sqrt{E_p}$, THE SOLUTION IS;

$$\sqrt{E_p} = \frac{2\sqrt{M_n M_p E_n}\cos\theta \pm \sqrt{4 M_n M_p E_n \cos^2\theta + 4(M_t + M_p)\left[E_n(M_t - M_n) + Q M_t\right]}}{2(M_t + M_p)}$$

$$= \frac{1}{(M_t + M_p)}\left\{\sqrt{M_n M_p E_n}\cos\theta \pm \sqrt{M_n M_p E_n \cos^2\theta + (M_t + M_p)\left[E_n(M_t - M_n) + Q M_t\right]}\right\}$$

THIS FUNCTION, AND THEREFORE THE PROTON ENERGY, IS MAXIMIZED WHEN WE TAKE $\theta = 0°$ AND THE GREATER ROOTS OF THE EQUATION SINCE E_p IS DOUBLE-VALUED. SO, WE HAVE FOR THE MAXIMUM PROTON ENERGY;

$$\boxed{E_p^{MAX} = \left[\frac{1}{(M_t + M_p)}\left\{\sqrt{M_n M_p E_n} + \sqrt{M_n M_p E_n + (M_t + M_p)\left[E_n(M_t - M_n) + Q M_t\right]}\right\}\right]^2}$$

NUMERICALLY THIS IS FOR GIVEN VALUES;

$E_n = 1.5\ \text{MeV}$, $Q = 0.764\ \text{MeV}$

$$\boxed{E_p^{MAX} \cong 2.24\ \text{MeV}}$$

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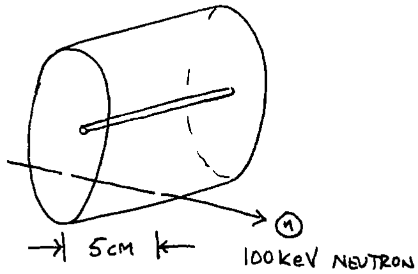
15.8).



SINCE THIS PROPORTIONAL COUNTER IS FILLED WITH CH_4 AT 1atm, IT WILL FUNCTION BEST AS A DETECTOR FOR FAST NEUTRONS BY EXPLOITING THEIR SCATTERING ON PROTONS. THE EFFICIENCY OF A RECOIL DETECTION DEVICE IS GIVEN BY EQ. 15.8b, p 557 FOR MIXED BULK AS;

$$\varepsilon = \frac{N_H \sigma_H}{N_H \sigma_H + N_C \sigma_C} \left\{ 1 - \exp\left(-\left(N_H \sigma_H + N_C \sigma_C \right) d \right) \right\}$$

WHERE $N_{H,C}$ ARE NUMBER DENSITIES OF HYDROGEN AND CARBON NUCLEI, $\sigma_{H,C}$ ARE THE CORRESPONDING NEUTRON ELASTIC CROSS-SECTIONS, AND d IS THE NEUTRON PATH LENGTH THROUGH THE DETECTOR. TO CALCULATE ε WE MUST FIRST DETERMINE THE NUMBER DENSITIES $N_{H,C}$; TO GOOD APPROXIMATION, AT 1 atm CH_4 BEHAVES AS AN IDEAL GAS SO IT IS TRUE THAT;

$$PV = n_{CH_4} kT \quad , \quad n_{CH_4} \equiv \text{NO. } \cancel{\text{DENSITY}} \text{ OF } CH_4 \text{ MOLECULES}$$

$$\frac{n_{CH_4}}{V} = \frac{P}{kT} \quad , \quad \frac{n_{CH_4}}{V} \equiv N_{CH_4} \text{ NO. DENSITY OF } CH_4 \text{ MOLECULES}$$

$$N_{CH_4} = \frac{P}{kT}$$

ASSUMING THE DETECTOR IS AT ROOM TEMPERATURE;

$$N_{CH_4} = \frac{(1 atm)}{(1.38066 \times 10^{-23} \frac{N \cdot m}{\cancel{K}})(300\cancel{K})} \quad , \quad 1atm = 101,325\ Pa, \quad Pa = \frac{N}{m^2}$$

$$= \frac{101,325 \frac{\cancel{N}}{m^2}}{1.38066 \times 10^{-23} \cancel{N} \cdot m\ (300)}$$

$$\boxed{\begin{aligned} N_C &= N_{CH_4} = 2.45 \times 10^{25}\ m^{-3} \\ N_H &= 4N_{CH_4} = 9.79 \times 10^{25}\ m^{-3} \end{aligned}}$$

NEXT, WE NEED VALUES FOR THE NEUTRON ELASTIC CROSS-SECTIONS. FROM FIGURE 15.15a,b, p. 557 WE READ;

$\sigma_H \sim 13\,b$ AND $\sigma_C \sim 4.2\,b$

$$\boxed{\sigma_H \sim 13 \times 10^{-24}\,cm^2} \qquad \boxed{\sigma_C \sim 4.2 \times 10^{-24}\,cm^2}$$

NOW WE HAVE THE EFFICIENCY;

$$\varepsilon = \frac{N_H \sigma_H}{N_H \sigma_H + N_C \sigma_C} \left\{ 1 - \exp\left(-\left(N_H \sigma_H + N_C \sigma_C\right) d\right) \right\}$$

$$= \frac{(9.79 \times 10^{19}\,cm^{-3})(13 \times 10^{-24}\,cm^2)}{(9.79 \times 10^{19}\,cm^{-3})(13 \times 10^{-24}\,cm^2) + (2.45 \times 10^{19}\,cm^{-3})(4.2 \times 10^{-24}\,cm^2)} \times$$

$$\times \left\{ 1 - \exp\left(-\left((9.79 \times 10^{19}\,cm^{-3})(13 \times 10^{-24}\,cm^2) + (2.45 \times 10^{19}\,cm^{-3})(4.2 \times 10^{-24}\,cm^2)\right)(5\,cm)\right) \right\}$$

$$\boxed{\varepsilon = 0.63\,\%}$$ ✓ good

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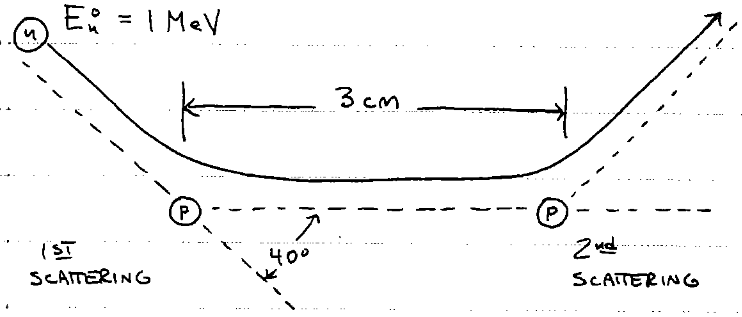
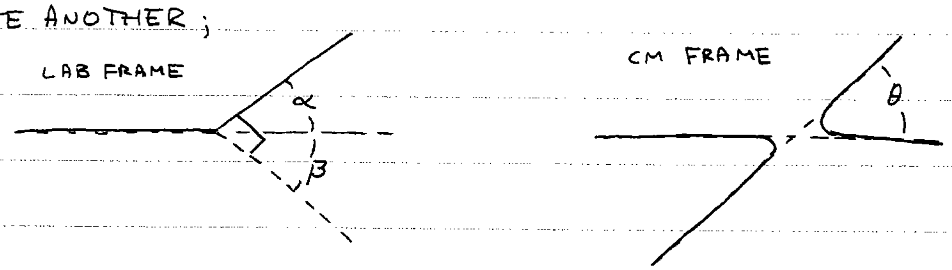
15.9)



$E_n^\circ \ll M_n c^2 \Rightarrow$ NO RELATIVISTIC EFFECTS (< 1%)

FIRST, CONSIDER SOME GENERAL SIMPLIFICATIONS THAT CAN BE MADE. IF WE MAKE THE APPROXIMATION THAT THE PROTON AND NEUTRON MASSES ARE EQUAL, THEN IN THE LAB FRAME THE NEUTRON SCATTERING ANGLE (α) AND THE PROTON RECOIL ANGLE (β) ARE AT A RIGHT ANGLE TO ONE ANOTHER;



THEREFORE $\alpha + \beta = \pi/2$. THE PROTON RECOIL ANGLE IS RELATED TO THE SCATTERING ANGLE IN THE C.M. FRAME (θ) BY $\beta = \frac{1}{2}(\pi - \theta)$ THEN.

NOW, LET'S USE THESE FACTS TO HELP CALCULATE THE ATTENUATION OF THE NEUTRON AFTER THE FIRST SCATTERING;

$$E_n' = E_n^\circ - E_R$$

WHERE E_n° IS THE INITIAL NEUTRON ENERGY (1 MeV) AND E_R IS THE RECOIL ENERGY OF THE TARGET. FROM EQ. 15.3, p. 554 THE RECOIL ENERGY OF THE TARGET IN TERMS OF ITS OWN SCATTERING ANGLE (β) IS;

$$E_R = \frac{4A}{(1+A)^2} \cos^2\beta \, E_n^\circ$$

FOR THE PROTON $A = 1$ SO,

$$E_p = \cos^2\beta \, E_n^\circ$$

Therefore, we may write

$$
\begin{aligned}
E_n' &= E_n^\circ - E_p \\
&= E_n^\circ - \cos^2\beta \, E_n^\circ \\
&= E_n^\circ \left(1 - \cos^2\beta\right) \\
&= E_n^\circ \sin^2\beta \quad , \quad \text{RECALL; } \alpha + \beta = \frac{\pi}{2} \Rightarrow \beta = \frac{\pi}{2} - \alpha \\
&= E_n^\circ \sin^2\left(\frac{\pi}{2} - \alpha\right) \\
E_n' &= E_n^\circ \cos^2\alpha
\end{aligned}
$$

The lab frame scattering angle (α) of the neutron after the first scattering is given as $40°$ so;

$$E_n' = (1\,\text{MeV}) \cos^2(40°)$$

$$\boxed{E_n' \cong 586.8 \text{ keV}}$$

Now we can use this result to calculate the neutron velocity and finally flight time;

$$
\begin{aligned}
E_n' &= \frac{P_n'^2}{2M_n} \\
&= \frac{1}{2} M_n v_n'^2 \\
v_n'^2 &= \frac{2E_n'}{M_n} \\
v_n' &= \sqrt{\frac{2E_n'}{M_n}} = \sqrt{\frac{2 \cdot 0.5868 \cancel{\text{MeV}}}{939.573 \cancel{\text{MeV}}/c^2}} \\
&= 0.0353\, c
\end{aligned}
$$

$$\boxed{v_n' = 1.059 \times 10^9 \text{ cm/s}}$$

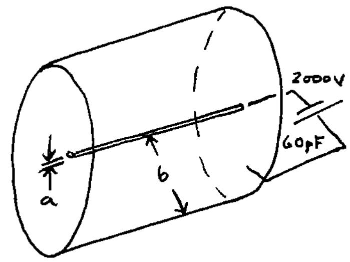
For a 3 cm flight path to the second scattering center, the flight time (t) is;

$$
\begin{aligned}
t &= \frac{d}{v_n'} \\
&= \frac{3 \cancel{\text{cm}}}{1.059 \times 10^9 \cancel{\text{cm}}/\text{s}} \\
&= 2.86 \times 10^{-9} \text{s}
\end{aligned}
$$

$$\boxed{t = 2.86 \text{ ns}}$$

For $RC = 20$ ns for the PMT, this is the $RC \gtrsim t_c$ limit. Therefore, the PMT will <u>not</u> be able to resolve the two scattering events.

WES HITT

15.12)  FROM TABLE 6.1, p. 171 THE PROPERTIES OF CH_4 FILL GAS ARE;

$$K_{CH_4} = 6.9 \times 10^4 \ \frac{V \cdot atm}{cm}$$

AND $$\Delta V_{CH_4} = 36.5 \ V$$

THE REMAINING RELEVANT PARAMETERS OF THE PROPORTIONAL COUNTER ARE GIVEN;

PRESSURE $p = 0.75$ atm , ANODE RADIUS $a = 0.005$ cm,

BIAS $V = 2000$ V , CATHODE RADIUS $b = 2$ cm,

CAPACITANCE $C = 60$ pF

THE MULTIPLICATION FACTOR (M) OF THE TUBE IS BY EQ 6.8, p. 170;

$$\ln M = \frac{V}{\ln(b/a)} \cdot \frac{\ln 2}{\Delta V} \left\{ \ln\left(\frac{V}{pa \ln(b/a)}\right) - \ln K \right\}$$

NUMERICALLY THIS IS;

$$\ln M = \frac{2000 \cancel{V}}{\ln(2\cancel{cm}/0.005\cancel{cm})} \cdot \frac{\ln 2}{36.5 \cancel{V}} \left\{ \ln\left(\frac{2000 \cancel{V}}{0.75 \cancel{atm} \cdot 0.005 \cancel{cm} \ln(2cm/0.005cm)}\right) - \ln\left(6.9 \times 10^4 \frac{\cancel{V \cdot atm}}{\cancel{cm}}\right) \right\}$$

$$\ln M \cong 1.615 \Rightarrow \boxed{M \cong 5.026} \checkmark$$

THE MAXIMUM POSSIBLE PULSE AMPLITUDE THEN IS;

$$V = \frac{Q}{C}$$

WHERE, $$Q = n_o e M$$

AND n_o IS THE NUMBER OF ION PAIRS GENERATED PER EVENT. THIS IS;

$$n_o = \frac{E_n}{W_{CH_4}}$$

WHERE E_n IS THE NEUTRON ENERGY AND W_{CH_4} IS THE ENERGY REQUIRED TO PRODUCE AN ION PAIR IN CH_4. THE VALUE OF W_{CH_4} IS GIVEN IN TABLE 5.1, p. 130 HOWEVER, IT IS ONLY FOR ELECTRONS AND ALPHA PARTICLES, NOT NEUTRONS.

EMPIRICALLY HOWEVER, W-VALUES IN GENERAL ARE ONLY SLOWLY VARYING FUNCTIONS OF GAS SPECIES, RADIATION SPECIES AND INCIDENT ENERGY (5.I.A. p.130). SO AS LONG THE NEUTRON IS STOPPED (OR AT LEAST THERMALIZED IN THE GAS) OUR CALCULATION REMAINS STRAIGHTFORWARD.

SINCE THE PROTON IN THE HYDROGEN OF CH_4 MAY RECIEVE ALL OF THE NEUTRON'S KINETIC ENERGY (APPROXIMATELY POSSIBLE SINCE $m_n \simeq m_p$) USING THE FULL 7 MeV IN OUR CALCULATION IS JUSTIFIED FOR ESTIMATING THE MAXIMUM PULSE HEIGHT. THUS,

$$V = \frac{Q}{C} = \frac{eM}{C} n_0$$

$$= \frac{eM}{C}\frac{E_n}{W_{CH_4}} \quad , \quad W_{CH_4} \sim 28 \frac{eV}{\text{ION PAIR}} \text{ (ROUGHLY)}$$

29 in Table 5.1

$$= \frac{1.602\times10^{-19}C \cdot 5.026}{60\times10^{-12}F} \times \frac{10^6 \cancel{eV}}{28\,\cancel{eV}/\text{ION PAIR}}$$

$$= 4.79\times10^{-4}\ \frac{C}{F}$$

$$\boxed{V \cong 0.48\ mV}$$