PRENOS NABITIH DELCEV SKOZI SNOV

TEŽKI DELCI ($M \gg m_e$), DELUJEJO PA TUDI $e^{+/-}$

- IZGUBLJAJO E
- SPREMINJAJO SMER

} SUHOTRONI PROCESI

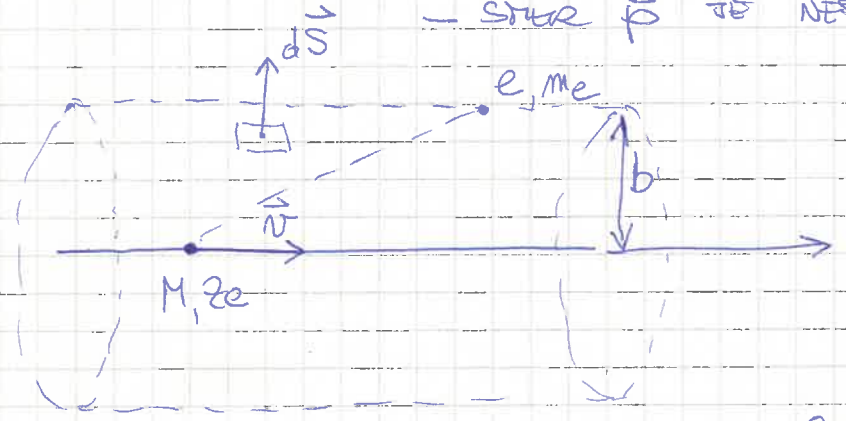
TO JE POSLEDICA
- NEPROŽNIH TRKOV Z e^- V SNOVI
- PROŽNIH TRKOV Z JEDRI V SNOVI (MANJ POMEMBNI)

- ODBOJNEGA SEVANJA
- ZAVORNO SEVANJE
- JEDRSKE REAKCIJE

} MANJ POMEMBNI

BOHROV KLASIČNI IZRAČUN ENERGIJSKE IZGUBE V SNOVI

PREDPOSTAVKE
- e^- V SNOVI SO V PROSTI
- E e^- IN $\vec{p}$ DELCA V KONST MED INTERAKCIJO (LE MALO SE V TEM ČASU PREMAKNEJO)
- INTER. TRAJA KRATEK ČAS
- SMER $\vec{p}$ JE NESPREMENJENA ($m_p \gg m_e$)



SPREMEMBA GIB. KOL. e^- $\Delta p = \int F_\perp dt = e \int E_\perp dt$

(LONGIT. KOMP SE IZNIČI)

$$\Delta p = e \int E_T \frac{dx}{v}$$

$$\oint \vec{E} \cdot d\vec{S} = \frac{Q}{\varepsilon_0} \Rightarrow \int E_T 2\pi b \, dx = \frac{Ze}{\varepsilon_0}$$

$$\int E_T dx = \frac{Ze}{2\pi\varepsilon_0 b} \Rightarrow \Delta p = \frac{Ze^2}{2\pi\varepsilon_0 v b}$$

e^- SE SPREMENI E (PREJME ENERGIJO) $\Delta p = p'$

$$\Delta E(b) = \frac{\Delta p^2}{2m_e} = \frac{Z^2 e^4}{8\pi^2 \varepsilon_0^2 m_e v^2 b^2}$$

GOSTOTA e^- V SNOVI n_e, IZGUBE ENERGIJE DELCA ZARADI INTER. Z e^- MED b IN $b+db$

$$dE = -\Delta E \, n_e \, dV = -\Delta E \, n_e \, 2\pi b \, db \, dx$$

SPECIFIČNE IONIZACIJSKE IZGUBE

$$-\frac{dE}{dx} = \frac{z^2 e^4 n_e}{8\pi^2 \varepsilon_0^2 m_e v^2 \beta^2} 2\pi b\, db = \frac{z^2 e^4 m_e}{4\pi \varepsilon_0^2 m_e^2 v^2} \frac{db}{b}$$

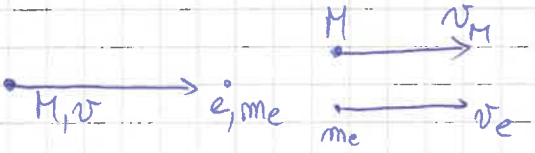
→ INTEGRIRATI PO b (NE $0 \to \infty$) – GLEJ PREDPOSTAVKE

$$-\frac{dE}{dx} = \frac{z^2 e^4 n_e}{4\pi \varepsilon_0^2 m_e^2 v^2} \cdot \ln \frac{b_{max}}{b_{min}}$$

b_{min}: IZGUBA E PRI "ENEM" TRKU $\Delta E \propto \frac{1}{b^2}$

$$\Rightarrow \Delta E_{max} \propto \frac{1}{b^2_{min}}$$

CELNI TRK



$$\left.\begin{aligned} Mv &= Mv_M + m_e v_e \\ Mv^2 &= Mv_M^2 + m_e v_e^2 \end{aligned}\right\} \quad v_e = \frac{2v}{1+\frac{m_e}{M}} \approx 2v$$

$$\Rightarrow \Delta E_{max} = \frac{1}{2} m_e (2v)^2 = \frac{z^2 e^4}{8\pi^2 \varepsilon_0^2 v^2 m_e} \cdot \frac{1}{b^2_{min}}$$

(PRIBLIŽNO UPOŠTEVANJE RELATIVISTIČNE POPRAVLJAVE Z ZAMENJAVO $v \to \gamma v$)

$$\frac{1}{2} m_e (2\gamma v)^2 = \frac{z^2 e^4}{8\pi^2 \varepsilon_0^2 m_e v^2} \frac{1}{b^2_{min}}$$

$$b_{min} = \frac{ze^2}{4\pi \varepsilon_0 m_e v^2 \gamma}$$

b_{max}: ČAS TRETJANJA NOT. KVANTNEGA (e⁻ SE V TEM ČASU NE PRETAKNE ZANIMIVO)

e⁻ VEZANI V ATOMU, $W_{VEZ} = h\nu$

KARAKTERISTIČNI ČAS "PREMIKA" e⁻ V ATOMU $\tau = \frac{1}{\nu}$

ČAS TRETJANJA INTERAKCIJE – OCENA $t \sim \frac{b}{v}$

$t < \tau$ → SPET RELAT. POPR.

$$\to t \to \frac{t}{\gamma} \Rightarrow \frac{t}{\gamma} < \frac{1}{\nu}$$

$$\frac{b}{v\gamma} < \frac{1}{\nu} \Rightarrow b_{MAX} \sim \frac{\gamma v}{\gamma} = \frac{\gamma h \nu}{W_{VEZ}}$$

SPEC. IONIZ. IZGUBE

$$-\frac{dE}{dx} = \frac{z^2 e^4 n_e}{4\pi \varepsilon_0^2 m_e v^2} \ln \frac{\gamma^2 v^3 4\pi \varepsilon_0 m_e h}{z e^2 W_{VEZ}}$$

$$n_e = \frac{dN_e}{dV} = z_A \frac{dn_A}{dV} = z_A \rho_A \frac{dm_A}{dm} = z_A \rho_A \frac{N_A}{M_A}$$

(ŠTEVILO ATOMOV)

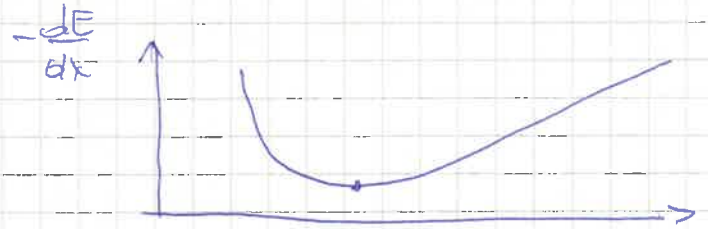
KLASIČNI RADIJ e: r_e: $m_e c^2 = \frac{e^2}{4\pi\varepsilon_0 r_e}$

$$r_e = \frac{e^2}{4\pi\varepsilon_0 m c^2}$$

$$-\frac{dE}{dx} = \underbrace{\frac{z^2 e^2}{\beta^2}\cdot\frac{r_e}{\varepsilon_0}}_{\text{PROJEKTIL}} \underbrace{Z_A \rho_A \frac{N_A}{M_A}}_{\text{SNOV}} \ln\frac{\gamma^2\beta^3 c\hbar}{z r_e \overline{W}_{VEZ}} \qquad \beta = \frac{v}{c}$$

$$-\frac{dE}{dx} = \frac{a}{\beta^2}\ln(a\gamma^2\beta^3) \qquad a' = \frac{c\hbar}{z r_e \overline{W}_{VEZ}}$$

$$a = \frac{z^2 e^2 r_e}{\varepsilon_0} Z_A \rho_A \frac{N_A}{M_A}$$



MINIMUM $\beta \approx 0{,}96$

$\beta\gamma \approx \emptyset 4$

MIP ≡ MINIMUM IONIZING PART.

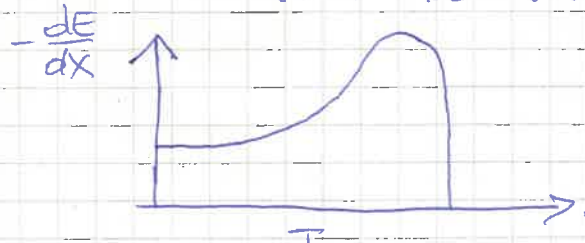
IONIZ. IZGUBE ZA ELEKTRONE (IN POZITRONE)

ZGORNJA IZPELJAVA ZA TEŽKE DELCE $M \gg m_e$

ZA e POTREBNO UPOŠTEVATI RELATIVISTIČNE POPR.

DOSEG V SNOVI

PROTON DELCA: $\frac{dE}{dx} \underset{\beta\ll 1}{\propto} \frac{1}{\beta^2}$



BRAGGOVA KRIVULJA

TEHNIJ ZA HADRONSKO TERAPIJO TUMORJEV

$$R(T) = -\int_0^T \left(\frac{dE}{dx}\right)^{-1} dT$$

$T = E - Mc^2$ KINETIČNA E.

$E = \gamma \cdot Mc^2$

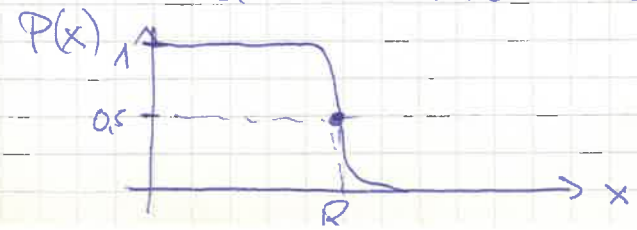
$$\gamma - 1 = -1 + \frac{1}{\sqrt{1-\beta^2}} = \frac{1-\sqrt{1-\beta^2}}{\sqrt{1-\beta^2}} \approx$$

$$\underset{\beta\ll 1}{\approx} \frac{\beta^2}{2}$$

$$-\frac{dE}{dx} \propto \frac{1}{\beta^2} \underset{\beta\ll 1}{\propto} \frac{1}{T}$$

$$R(T) \propto -\int_0^T T\,dT \propto T^2$$

IONIZ. IZGUBE: STOHASTIČEN PROCES → NIMAJO VSI DELCI Z ENAKO ZAČETNO E ENAK DOSEG V SNOVI



IZ POVPREČEN DOSEG,

STRESANCE