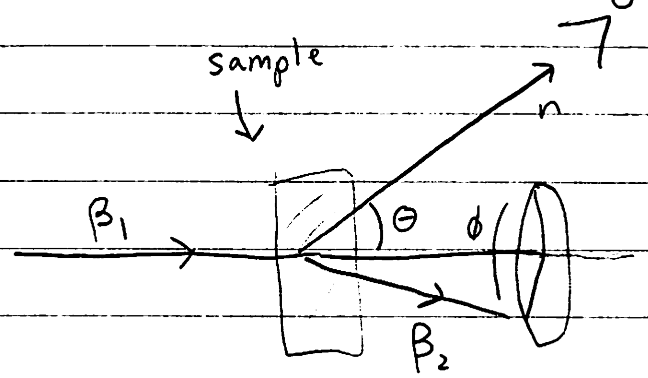
Last Time

Discussed Radiation During Collisions

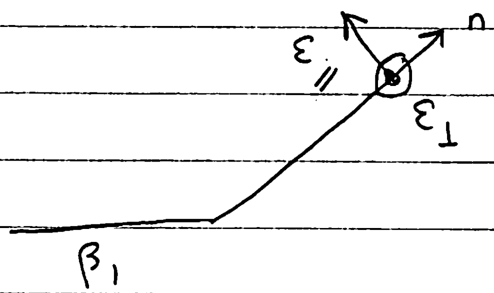


For grazing collisions, $\vec{\beta}_2 \simeq \vec{\beta}_1 + \Delta\vec{\beta}$, and ϕ is often random

Found that

$$\vec{E}(\omega) = \frac{q}{4\pi r c^2} e^{ikr} \left(\frac{n \times n \times \vec{v}_2}{(1 - n\cdot\beta_2)} - \frac{n \times n \times \vec{v}_1}{(1 - n\cdot\beta_1)} \right)$$

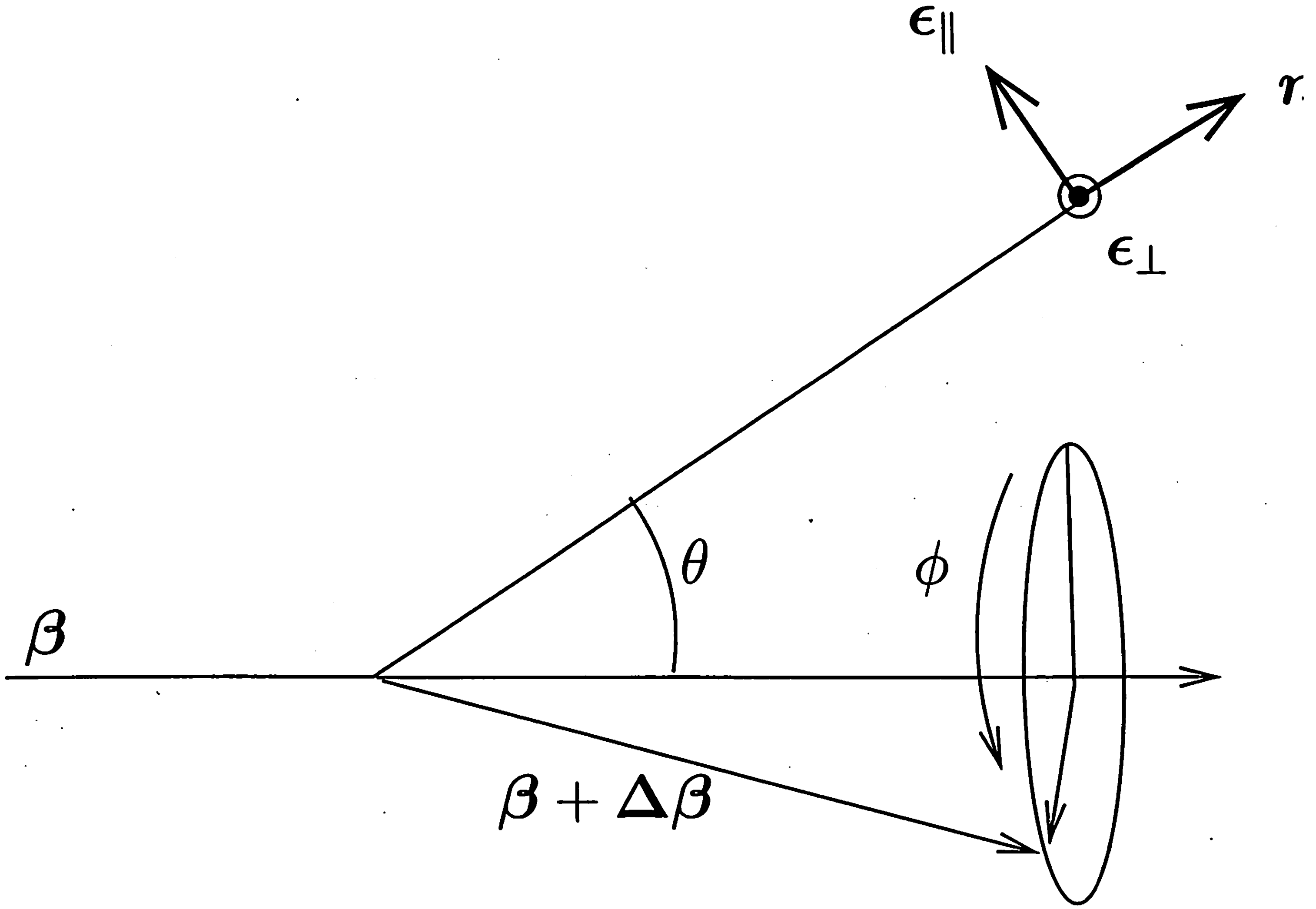
More generally decompose the outgoing light into two polarization vectors



$$\vec{E} = E_{\parallel} \vec{\varepsilon}_{\parallel} + E_{\perp} \cdot \vec{\varepsilon}_{\perp}$$

Then more generally ε's can be complex, for example:

$\varepsilon = (0, 1, i, 0)$ records circularly light



$\epsilon_\parallel$
r
$\epsilon_\perp$
θ
ϕ
β
$\beta + \Delta\beta$

Last time Continued

The properties that we derived from the analys of waves are, $\vec{E} \equiv E_1 \vec{\mathcal{E}}_1 + E_2 \vec{\mathcal{E}}_2$

$$\vec{\mathcal{E}}_a^{\,*} \cdot \vec{\mathcal{E}}_b = \delta_{ab} \quad \leftarrow \text{orthogonal}$$

$$\vec{n} \cdot \mathcal{E}_a = 0 \quad \leftarrow \text{transverse to direction}$$

Then we write the energy per frequency der solid angle with polarization $\parallel$ (in $\vec{n}, \vec{\beta}$ plane) and $\perp$ (out of $\vec{n}, \vec{\beta}$ plane) as

$$2\pi \frac{dW_\parallel}{d\omega\, d\Omega} = c\,|\vec{\mathcal{E}}_\parallel^{\,*} \cdot E|^2 r^2$$

$$2\pi \frac{dW}{d\omega \Omega} = c\,|\mathcal{E}_\perp^{*} \cdot E|^2 r^2$$

Then since for this example $\vec{n} \times \vec{n} \times \vec{v}$ is already transverse we have

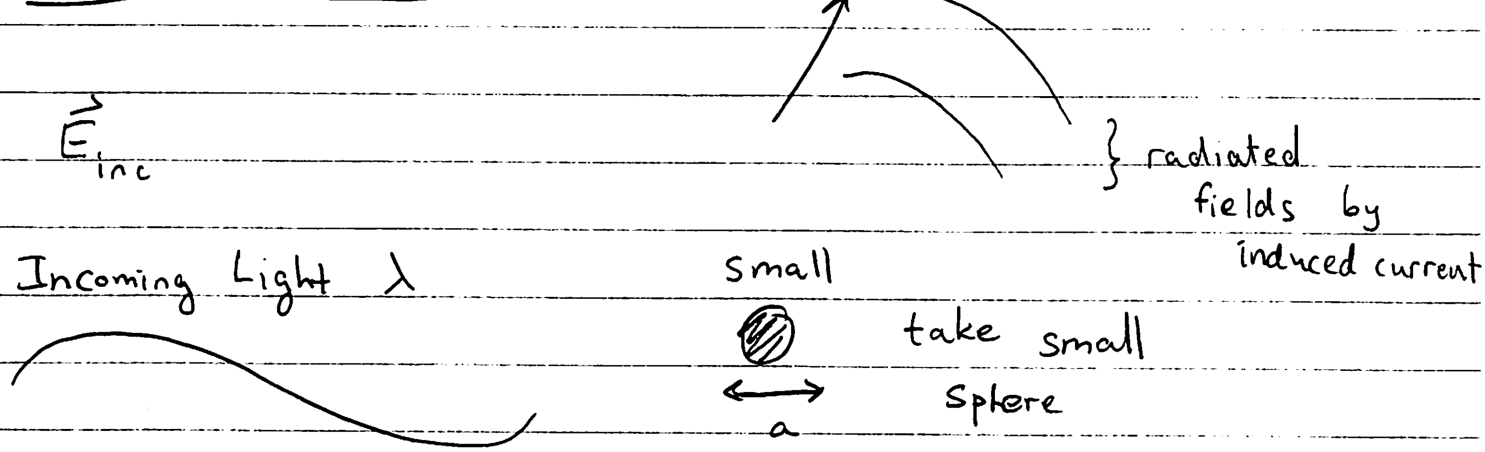
$$E_\parallel = \frac{-q\, e^{ikr}}{4\pi r c^2} \left[\frac{\vec{\mathcal{E}}_\parallel^{\,*} \cdot \vec{v}_2}{(1 - n\cdot\beta)_2} - \frac{\mathcal{E}_\parallel^{*} \cdot \vec{v}_1}{(1 - n\cdot\beta_1)} \right]$$

And the frequency spectrum is

$$2\pi \frac{dW_\parallel}{d\omega\, d\Omega} = \frac{q}{16\pi c^3} \left| \frac{\mathcal{E}_\parallel^{*} \cdot V_2}{(1 - n\cdot\beta_2)} - \frac{\mathcal{E}_\parallel \cdot V_1}{(1 - n\cdot\beta_1} \right|^2$$

You will need this of homework

Scattering of Radiation



- Initially study the scattering of radiation by <u>small</u> objects $\lambda \gg a$

- Why does light scatter? The light induces currents in the object. The induced currents radiate.

  So, if you want to know hom much light was scattered. You should first compute how the incoming field accelerates the charge, and then compute how the accelerated charges radiate

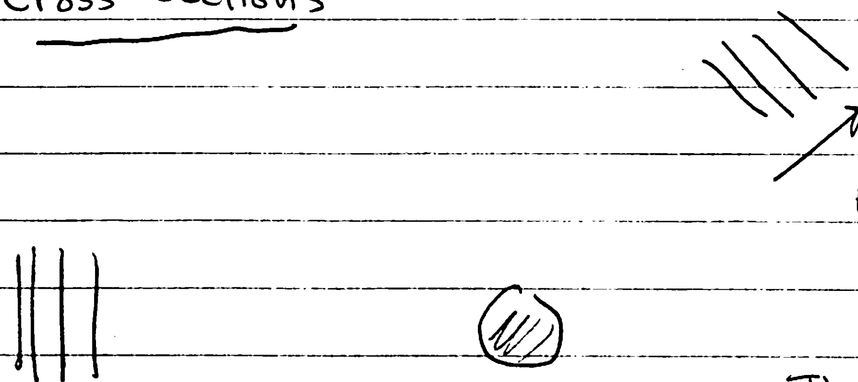
- For an extended object the acceleration in one point can create fields at another which influences the other points leading to a complicated standing wave.
  Treat small objects

Suggests Approximations

(1) Small objects. $\lambda \gg a$. The field can be considered constant over the extent of object

(2) Weak scattering. The induced fields, $\vec{E}_{scatt}$, are small compared to $\vec{E}_{inc}$

Cross Sections



$$E_{scatt} = \frac{\text{Const}\, e^{i\vec{k}\cdot\vec{r} - i\omega t}}{r}$$

$$\vec{E}_{inc} = \varepsilon_0 \vec{E}_0\, e^{ikz - i\omega t}$$

The const is a vector which depends on direction and is $\propto E_0$

$$E_{scatt} = E_0\, \vec{f}(\vec{k})\, \frac{e^{i\vec{k}\cdot\vec{r} - i\omega t}}{r}$$

"Scattering amplitude"

units meters

Then

$$\vec{E} = \vec{E}_{inc}(r) + \vec{E}_{scatt}(r)$$

The <u>incoming</u> <u>energy</u> is:

$$\overline{\vec{S}\cdot\hat{z}} = \underset{\text{time ave}}{\frac{1}{2}} c\,|E_{inc}|^2$$

$\leftarrow$ time averaged energy per area per time

The <u>outgoing</u> <u>energy</u> per solid angle

$$\frac{\overline{dP}(\varepsilon)}{d\Omega} = r^2\, \overline{\vec{S}_\varepsilon}\cdot\vec{n} = \frac{1}{2} c\,|\vec{r}\; \varepsilon^{*}\cdot\vec{E}_{scatt}|^2$$

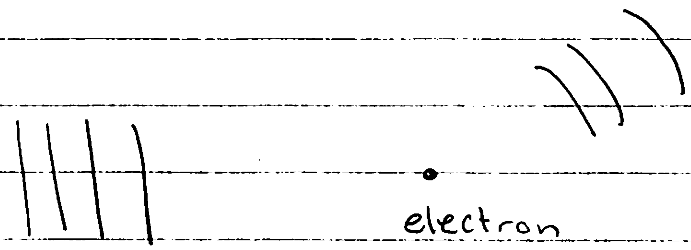
So define the cross section

$$\frac{d\sigma}{d\Omega}(\varepsilon;\varepsilon_0) = \frac{\frac{1}{2}c\,|r\vec{\varepsilon}^{*}\cdot E_{scatt}|^2}{\frac{1}{2}c\,|E_0|^2} = \left|\vec{\varepsilon}^{*}\cdot\vec{f}(k)\right|^2 \propto (\text{meters})^2$$

energy scattered (per solid angle + polarization ε) per incoming flux.

Thomson Cross Section

· Light electron scattering



$$\sigma = \frac{\langle \text{Power radiated} \rangle}{\frac{1}{2} c |E_{inc}|^2} = \frac{P}{\frac{1}{2} c |E_{inc}|^2}$$

For an non-rel electron experiencing acceleration a

$$\overline{P} = \frac{q^2}{4\pi} \frac{2}{3c^3} \overline{a^2}$$

The force/accel is determined by the incoming Light

$$\vec{a} = \frac{q \vec{E}_{inc}}{m} e^{-i\omega t}$$

Then

$$\overline{a^2} = \frac{1}{2} |a|^2 = \frac{q^2}{m^2} \frac{1}{2} |E_{inc}|^2$$

Thus

$$\sigma = \frac{\frac{q^2}{4\pi}\frac{2}{3c^3}\frac{q^2}{m^2}\frac{1}{2}|E_{inc}|^2}{\frac{1}{2}c\,|E_{inc}|^2}$$

$$= \frac{8\pi}{3}\underbrace{\left(\frac{q^2}{4\pi mc^2}\right)}^2 \equiv \frac{8\pi}{3} r_e^2$$

this is known as the classical electron radius

$$r_e = \frac{q^2}{4\pi mc^2}$$

Note

$$r_e = \left(\frac{q^2}{4\pi\hbar c}\right)\left(\frac{\hbar}{mc}\right) = \alpha\, \lambda\!\!\!^{-}_c$$

$\leftarrow$ compton wavelength (by 2π)

α: $1/137$

$\lambda_c = \frac{h}{mc}$ $\quad \lambda\!\!\!^{-}_c = \frac{\hbar}{mc}$

Numerically

$$\lambda\!\!\!^{-}_c = \frac{\hbar c}{m_e c^2} = \frac{197\,\text{eV nm}}{0.5\,\text{MeV}}$$

Then

$$r_e = 2.8\,\text{fm} = 2.8 \text{ femptometers} = 2.8 \text{ fermi}$$

The cross section is

$$\sigma = \frac{8\pi}{3} r_e^2 = 66 \text{ fm}^2$$

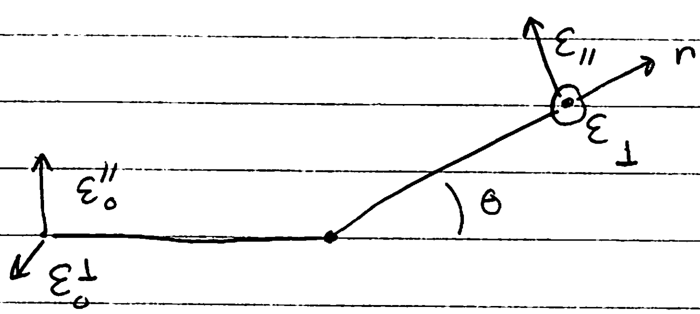
$1 \text{ fm}^2 = 10$ millibarn

$$= 660 \text{ millibarn}$$

$1 \text{ barn} = 10^{-24} \text{ cm}^2$

$$= 0.66 \text{ barns}$$ $\leftarrow$ units of cross section

Polarization



Want to show that the polarized cross section is

$$\frac{d\sigma}{d\Omega}(\vec{\varepsilon}; \vec{\varepsilon}_0) = r_e^2 \, |\varepsilon^* \cdot \varepsilon_0|^2$$

First Recall

$$E_{rad} = n \times n \times \frac{1}{c}\frac{\partial A_{rad}}{\partial t} = \frac{q}{4\pi r c^2}\, n \times n \times \vec{a}(t_e)$$

Lets Rederive this result, by approximating Lienard-Wiechert

$$A_{rad} = \frac{q}{4\pi r} \frac{V(T)/c}{(1 - n \cdot V(T)/c)} \qquad T = t - \frac{r}{c} + \frac{n \cdot r_*(T))}{c}$$

$$\simeq t - \frac{r}{c} \equiv t_e$$

The non-rel approximation replaces $T \simeq t_e = t - \frac{r}{c}$, and expands $V/c \ll 1$,

$$A_{rad} \simeq \frac{q}{4\pi r} \vec{V}(t_e)/c$$

And so

$$E_{rad} = \frac{q}{4\pi r c^2}\, n \times n \times \vec{a}(t_e)$$

The acceleration is along $\vec{\varepsilon}_o$

$$\vec{a} = \vec{\varepsilon}_o \frac{q}{m} E_o e^{-i\omega t}$$

Then we want to compute

$$|\varepsilon^* \cdot E_{rad}|^2 \propto |\varepsilon^* \cdot (n \times n \times \vec{a})|^2$$

final polarization

Polarization pg. 3

Using $b(ac) - (ab)c$

$$\vec{\varepsilon}^* \cdot (n \times n \times a) = \varepsilon^* \cdot (-\vec{a} + \vec{n}(\vec{n} \cdot \vec{a}))$$

$$= -\vec{\varepsilon}^* \cdot \vec{a}$$

(since ε^* is transverse to $\vec{n}$ it projectso out the longitudinal pieces)

Then

$$\overline{|\varepsilon_0 \cdot n \times n \times a|^2} = \frac{q^2}{m^2} \overset{\text{time ave}}{\frac{1}{2}} |E_0|^2 \, |\vec{\varepsilon}^* \cdot \vec{\varepsilon}_0|^2$$

So we compute:

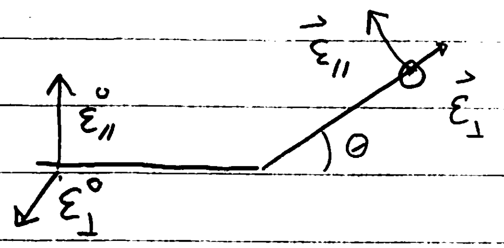
$$\frac{d\sigma(\vec{\varepsilon}; \vec{\varepsilon}_0)}{d\Omega} = \frac{\overline{dP/d\Omega}}{\frac{c}{2}|E_0|^2} = \frac{\frac{1}{2} r^2 c |\varepsilon^* \cdot E_{rad}|^2}{\frac{1}{2} c |E_0|^2}$$

$$= \underbrace{\left(\frac{q^2}{4\pi m c^2}\right)^2}_{\equiv r_e^2} |\varepsilon^* \cdot \varepsilon_0|^2$$

$$= r_e^2 \, |\varepsilon^* \cdot \varepsilon_0|^2$$

Transverse and Parallel polarized Cross section

There are four cases here



① $\varepsilon_{\parallel}^{0*} \cdot \varepsilon_{\parallel} = \cos\theta$ (see figure)

② $\varepsilon_{\perp}^{0*} \cdot \varepsilon_{\perp} = 1$

③ $\varepsilon_{\parallel}^{0*} \cdot \varepsilon_{\perp} = 0$

④ $\varepsilon_{\perp}^{0*} \cdot \varepsilon_{\parallel} = 0$

So the cross section for initially unpolarized light (i.e. $\vec{\varepsilon}^{\,0}$ is 50% of time $\parallel$ & 50% of time $\perp$) to produce light polarized in the $\parallel$ or $\perp$ direction

$$\frac{d\sigma_{\parallel}}{d\Omega} = \frac{1}{2}\left[\frac{d\sigma}{d\Omega}(\varepsilon_{\parallel}; \varepsilon_{\parallel}^{0}) + \cancelto{0}{\frac{d\sigma}{d\Omega}(\varepsilon_{\parallel}; \varepsilon_{\perp}^{0})}\right]$$

$$= \frac{1}{2} r_e^2 \cos^2\theta$$

$$\frac{d\sigma_{\perp}}{d\Omega} = \frac{1}{2}\left[\cancelto{0}{\frac{d\sigma}{d\Omega}(\varepsilon_{\perp}; \varepsilon_{\parallel}^{0})} + \frac{1}{2}\frac{d\sigma}{d\Omega}(\varepsilon_{\perp}, \varepsilon_{\perp}^{0})\right]$$

$$= \frac{1}{2} r_e^2$$

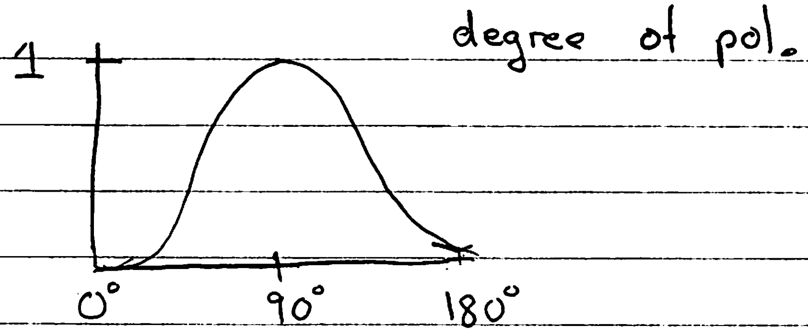
The cross section to produce light of <u>any</u> polarization by initially unpolarized light is

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{\parallel}}{d\Omega} + \frac{d\sigma_{\perp}}{d\Omega}$$

$$= r_e^2 \left(\frac{1+\cos^2\theta}{2}\right)$$

The degree of polarization depends on the angle

$$\text{degree of pol} = \frac{d\sigma_{\perp} - d\sigma_{\parallel}}{d\sigma_{\perp} + d\sigma_{\parallel}} = \frac{(1-\cos^2\theta)}{(1+\cos^2\theta)}$$



<u>Question:</u> Why is the light 100% transversely polarized at 90°?

<u>Ans.</u> : At 90°/a the current is up and down for the parallel case. Thus there is no component of the current transverse

Ans: continued ...

to the observation. Thus the cross section for this case vanishes