THE FEATURES OF TRANSITION AND
CHERENKOV RADIATION OF MULTI-
CHARGED IONS

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Nobel Prize Laureates. Discoverers of the Cherenkov and Transition radiation

I. Tamm, I. Frank, P. Cherenkov, V. Ginsburg
Radiation emitted by heavy multiply charged ions in the amorphous targets

Bremsstrahlung, Transition Radiation, Cherenkov Radiation

The main problems:
For heavy multiply charged ions we have to take into account the stopping power and charge exchange with the target.

In this report:
• Short review of charge exchange effects on the Cherenkov Radiation.
• Some expected effects of charge exchange in Transition Radiation.
When heavy ions penetrate into the target, the ion-atom collisions cause fluctuations of the projectile charge due to electrons loss or capture.

\[ Q(k, \omega) = -\frac{1}{8\pi^4} \text{Im} \left[ \frac{4\pi}{\omega \varepsilon} |j_\parallel|^2 + \frac{4\pi \omega}{c^2} \frac{|j_\perp|^2}{\omega^2 \varepsilon - \frac{k^2}{\mu}} \right] \]
The radiation of a time-varying charge moving in a medium with a constant speed

Amatuni A.C., Garibyn G.M., Elbakyan S.S.
Proceedings of the Academy of Sciences of the Armenian SSR.
The correlation between various charge state values can arise in the Stopping Power, Bremsstrahlung, Transition and Cherenkov radiation

**AUTOCORRELATION FUNCTION:**

\[
\langle Z(t)Z(t') \rangle = Z_{eq}^2 + \langle \xi(t)\xi(t') \rangle \\
\langle \xi(t)\xi(t') \rangle = \Lambda^2 \exp(-\Gamma |t-t'|)
\]

**LONGITUDINAL WAVES:**


**TRANSVERSE WAVES (HUYGENS PRINCIPLE):**

Correlation effects
The threshold condition is satisfied


\[ \frac{d^2W}{d\omega dl} \approx \frac{d^2W^{(TF)}}{d\omega dl} \]

\[ \frac{d^2W}{d\omega dl} \approx \frac{d^2W^{(TF)}}{d\omega dl} \left(1 + \frac{\Lambda^2}{Z_{eq}^2}\right) \]
A single electron capture (loss)


\[
\begin{align*}
v < c_p & \quad \frac{d^2W}{d\omega d\Omega} = \frac{e^2v^2\sqrt{\epsilon'(\omega)} \sin^2 \theta}{(2\pi)^2} \left(1 - v\sqrt{\epsilon'(\omega) \cos \theta}\right)^2 \\
v > c_p & \quad \frac{1}{L} \frac{d^2W}{d\omega d\Omega} = \frac{\omega^2ve^2\sqrt{\epsilon'(\omega)} \sin^2 \theta}{2\pi} \left(Z_1 - 1/2\right)^2 \delta(\omega - kv).
\end{align*}
\]

"Average" charge \[
\left[Z_1 + (Z_1 - 1)\right] / 2 = Z_1 - 1/2
\]
A single electron capture (loss)


The threshold condition is not satisfied

Capture probability ~ 1

\[ \frac{d^2W}{d\omega d\Omega} = \frac{e^2 v^2 \sqrt{\varepsilon'(\omega)} \sin^2 \theta}{(2\pi)^2} \frac{1}{(1 - v\sqrt{\varepsilon'(\omega)} \cos \theta)^2} \]

\[ V < c_p \]
Transition radiation

Formulation of the problem

Capture or Loss

\[ \theta \]

\[ \varepsilon = 1 \]

\[ \varepsilon \neq 1 \]
Transition radiation

Basic approximation

\[ L_{\text{coh}} \gg L_{\text{eq}} \]

\[ L_{\text{eq}} \approx 1/\sigma n_e \]

\[ L_{\text{coh}} \approx \lambda \frac{\beta(1+\beta)}{1-\beta^2} \]

- \( L_{\text{coh}} \) - the coherence length of the radiation (formation zone)
- \( L_{\text{eq}} \) - the length of the equilibrium charge formation
- \( \varepsilon=1 \), \( \varepsilon \neq 1 \)
Transition radiation

Maxwell's equations in the first and second media

\[ \Delta A - \frac{1}{c^2} \frac{\partial^2 A}{\partial t^2} = -\frac{4\pi}{c} Z_1 e v \delta(r - vt), \]

\[ \Delta \varphi - \frac{1}{c^2} \frac{\partial^2 \varphi}{\partial t^2} = -4\pi Z_1 e \delta(r - vt). \]

\[ \Delta A - \frac{\varepsilon}{c^2} \frac{\partial^2 A}{\partial t^2} = -\frac{4\pi}{c} Z_2 e v \delta(r - vt), \]

\[ \Delta \varphi - \frac{\varepsilon}{c^2} \frac{\partial^2 \varphi}{\partial t^2} = -\frac{4\pi}{\varepsilon} Z_2 e \delta(r - vt). \]

Fields are found from the condition of continuity of normal and tangential components.
Transition radiation
Spectral- angular density

\[
\frac{d^2 W_1}{d\omega d\Omega'} = \frac{e^2 \sin^2 \vartheta' \cos^2 \vartheta'}{\pi^2 c} \left| \frac{\beta}{\varepsilon \cos \vartheta' + \sqrt{\varepsilon - \sin^2 \vartheta'}} \right|^2 F_1(\vartheta')
\]

\[
F_1(\vartheta') = \frac{Z_1(\varepsilon - \beta \sqrt{\varepsilon - \sin^2 \vartheta'})}{1 - \beta^2 \cos^2 \vartheta'} - \frac{Z_2}{1 + \beta \sqrt{\varepsilon - \sin^2 \vartheta'}}.
\]

\[
\frac{d^2 W_2}{d\omega d\Omega} = \frac{e^2 \varepsilon^{5/2} \sin^2 \vartheta \cos^2 \vartheta}{\pi^2 c} \left| \frac{\beta}{\cos \vartheta + \varepsilon^{1/2} \sqrt{1 - \varepsilon \sin^2 \vartheta}} \right|^2 F_2(\vartheta)
\]

\[
F_2(\vartheta) = \frac{Z_1}{1 - \beta \sqrt{1 - \varepsilon \sin^2 \vartheta}} - \frac{Z_2 \left(1 + \beta \varepsilon \sqrt{1 - \varepsilon \sin^2 \vartheta}\right)}{\varepsilon \left(1 - \beta^2 \varepsilon \cos^2 \vartheta\right)}.
\]

If \( Z_1 = Z_2 \) we obtain the well-known Ginsburg – Frank formulas.
If \( Z_1 = 1, Z_2 = 0, \epsilon \to \infty \) we obtain the backward Transition Radiation from metal surface:

\[
\frac{d^2 W_I}{d \omega d \Omega'} = \frac{e^2 \sin^2 \vartheta'}{\pi^2 c} \frac{\beta^2}{(1 - \beta^2 \cos^2 \vartheta')^2}.
\]

If \( Z_1 = 0, Z_2 = 1, \epsilon = 1 \) we obtain the radiation of the electron which starts suddenly:

\[
\frac{d^2 W_{1,2}}{d \omega d \Omega} = \frac{e^2 \sin^2 \vartheta}{4\pi^2 c} \frac{\beta^2}{(1 - \beta \cos \vartheta)^2}.
\]
**Transition radiation (some calculations)**

**Forward radiation in the vacuum ultraviolet**

\[
Z_2 / Z_1 = 1 - C \exp(-\nu / \nu_B Z_1^\gamma)
\]


**Charge exchange in the medium increases the intensity of the Transition radiation**

\[
\frac{d^3W}{d\omega d\Omega} \text{, arb. units}
\]

\[
Au, \beta = 0.99
\]

\[
Au, \beta = 0.95
\]
Transition radiation (some calculations)

Backward radiation in the optical range

\[
dW^i/d\omega d\Omega = \frac{e^2 \sin^2 \theta' \cos^2 \theta'}{\pi^2 c} \left| \begin{array}{c} \beta (\varepsilon + \sqrt{\varepsilon - \sin^2 \theta'}) \\ \varepsilon \cos \theta' + \sqrt{\varepsilon - \sin^2 \theta'} \left(1 - \beta^2 \cos^2 \theta'\right) \end{array} \right|^2
\]

\[
dW^l/d\omega d\Omega = \frac{e^2 \sin^2 \theta' \cos^2 \theta'}{\pi^2 c} \left| \begin{array}{c} \beta \\ \varepsilon \cos \theta' + \sqrt{\varepsilon - \sin^2 \theta'} \left(1 + \beta \sqrt{\varepsilon - \sin^2 \theta'}\right) \end{array} \right|^2
\]

Capture

Loss

Electron capture

Electron loss

\( \beta = 0.8 \)

\( \varepsilon = 1.5 \)
Thank you for your attention!