PHY 712 Electrodynamics
10-10:50 AM MWF Olin 103

Discussion for Lecture 33:

Including topics from Chaps. 13 & 15 in JDJ

1. **Radiation from collisions of charged particles**
    a. **X-ray tube**
    b. **Radiation from Rutherford scattering**
2. **Cherenkov radiation**

Thursday 4/11/2024 at 9-10 AM in ZSR auditorium

Ph.D. Defense — Laxman Poudel, Physics Graduate Student, "Unveiling the Interplay of Nitric Oxide Signaling and Physiological Thiols; Novel Insights" (Advisor: D. Kim-Shapiro)

Abstract:

Nitric oxide (NO) stands as a pivotal signaling molecule garnering significant research attention in the realm of cardiovascular health. Its crucial role in sustaining heart and blood vessel well-being is underscored by its ability to widen blood vessels, facilitating improved blood flow, and thwarting platelet activation and aggregation to stave off clot formation and vessel obstruction. Additionally, NO safeguards the integrity of vascular endothelial cells. Its production primarily stems from Nitric Oxide Synthases (NOS), including those housed within vascular endothelial cells, and through the reduction of nitrite by deoxyhemoglobin, converting it into Nitrosyl hemoglobin (HbNO).

Physics Colloquium

Thursday

4 PM in Olin 101

April 11th, 2024

High-Frequency Flexible Organic Thin-Film Transistors

Organic thin-film transistors (TFTs) can often be fabricated at temperatures around or below 100 degrees Celsius and thus on a wide range of unconventional substrates, including flexible and transparent polymers, such as polyethylene naphthalate (PEN). This makes organic TFTs a potential alternative to TFTs based on inorganic semiconductors, such as low-temperature polycrystalline silicon (LTPS) and indium gallium zinc oxide (IGZO), which typically require higher process temperatures that limit the choice of flexible substrate materials to ultrathin glass and polyimide. For circuit and display applications, an important TFT parameter is the transit frequency, which is the highest frequency at which transistors are able to switch or amplify electrical signals. A field-effect transistor's transit frequency depends critically on the channel length and the parasitic gate-to-source and gate-to-drain overlaps. Most of the highest transit frequencies reported for organic TFTs to date have been achieved with channel lengths and gate-to-contact overlaps of around 1 μm. To explore the static and dynamic performance of flexible organic TFTs with nanoscale dimensions, we have used electron-beam lithography and fabricated low-voltage organic TFTs with channel lengths and gate-to-contact overlaps as small as 100 nm on flexible PEN substrates. These TFTs display useful static and dynamic characteristics, including on/off current ratios of nine orders of magnitude, subthreshold swings below 100 mV/decade, turn-on voltages of 0 V, negligibly small threshold-voltage roll-off, contact resistances below 1 kOhm-cm, and switching delays below 20 ns.

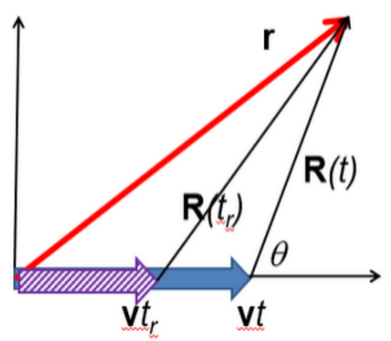
Dr. Hagen Klauk
Max Planck Institute
Stuttgart, Germany

			localized oscillating sources		
25	Wed: 03/20/2024	Chap. 9	Radiation from localized oscillating sources	#20	03/25/2024
26	Fri: 03/22/2024	Chap. 9 & 10	Radiation and scattering	#21	03/25/2024
27	Mon: 03/25/2024	Chap. 11	Special Theory of Relativity	#22	04/01/2024
28	Wed: 03/27/2024	Chap. 11	Special Theory of Relativity	#23	04/01/2024
29	Fri: 03/29/2024	Chap. 11	Special Theory of Relativity		
30	Mon: 04/01/2024	Chap. 14	Radiation from moving charges	#24	04/08/2024
31	Wed: 04/03/2024	Chap. 14	Radiation from accelerating charged particles	#25	04/08/2024
32	Fri: 04/05/2024	Chap. 14	Synchrotron radiation and Compton scattering	#26	04/08/2024
33	Mon: 04/08/2024	No class	Eclipse related absences		
33	Wed: 04/10/2024	Chap. 13 & 15	Other radiation -- Cherenkov & bremsstrahlung	#27	04/22/2024
34	Fri: 04/12/2024		Special topic: E & M aspects of superconductivity		
	Mon: 04/15/2024		Presentations I		
	Wed: 04/17/2024		Presentations II		
	Fri: 04/19/2024		Presentations III		
35	Mon: 04/22/2024		Special topic: Quantum Effects in E & M		
36	Wed: 04/24/2024		Special topic: Quantum Effects in E & M		
37	Fri: 04/26/2024		Special topic: Quantum Effects in E & M		
38	Mon: 04/29/2024		Review		
39	Wed: 05/01/2024		Review		

PHY 712 -- Assignment #27

Assigned: 4/10/2024 Due 4/22/2024

1. In the context of analyzing Cherenkov radiation , we considered a particle of charge q moving at constant velocity **v** along the x axis producing electric and magnetic fields at time t at a position **r** in the x-y plane. The fields can be evaluated using the Liénard-Wiechert analysis given in Lecture 33 for example, evaluated at the retarded time t_r.



The analysis depends on the ratio of the speed of the particle v to the speed c_n of electromagnetic waves with the medium -- β_n. We showed the following relationship between the lengths $R(t)$, $R(t_r)$, and the angle θ with the x axis.

$$R(t_r) = \frac{R(t)}{\beta_n^2 - 1}\left(-\beta_n \cos\theta \pm \sqrt{1-\beta_n^2 \sin^2\theta}\right)$$

   a. First consider the case of the particle moving in vacuum so that $\beta_n < 1$. Determine the physical solutions in terms of choice of signs and range of angles θ for this case.
   b. Now consider the case of the particle moving in a dielectric medium and moving fast enought so that $\beta_n > 1$. Determine the physical solutions in terms of choice of signs and range of angles θ for this case.

PHY 712 Presentation Schedule

Monday 4/15/2024

	Presenter Name	Topic
10:00-10:24	Thilini Karunarathna	Work out the details of a similar problem to Jackson problem 7.2.
10:25-10:50	Joe Granlie	Qual. Problem (on capacitors probably)

Wednesday 4/17/2024

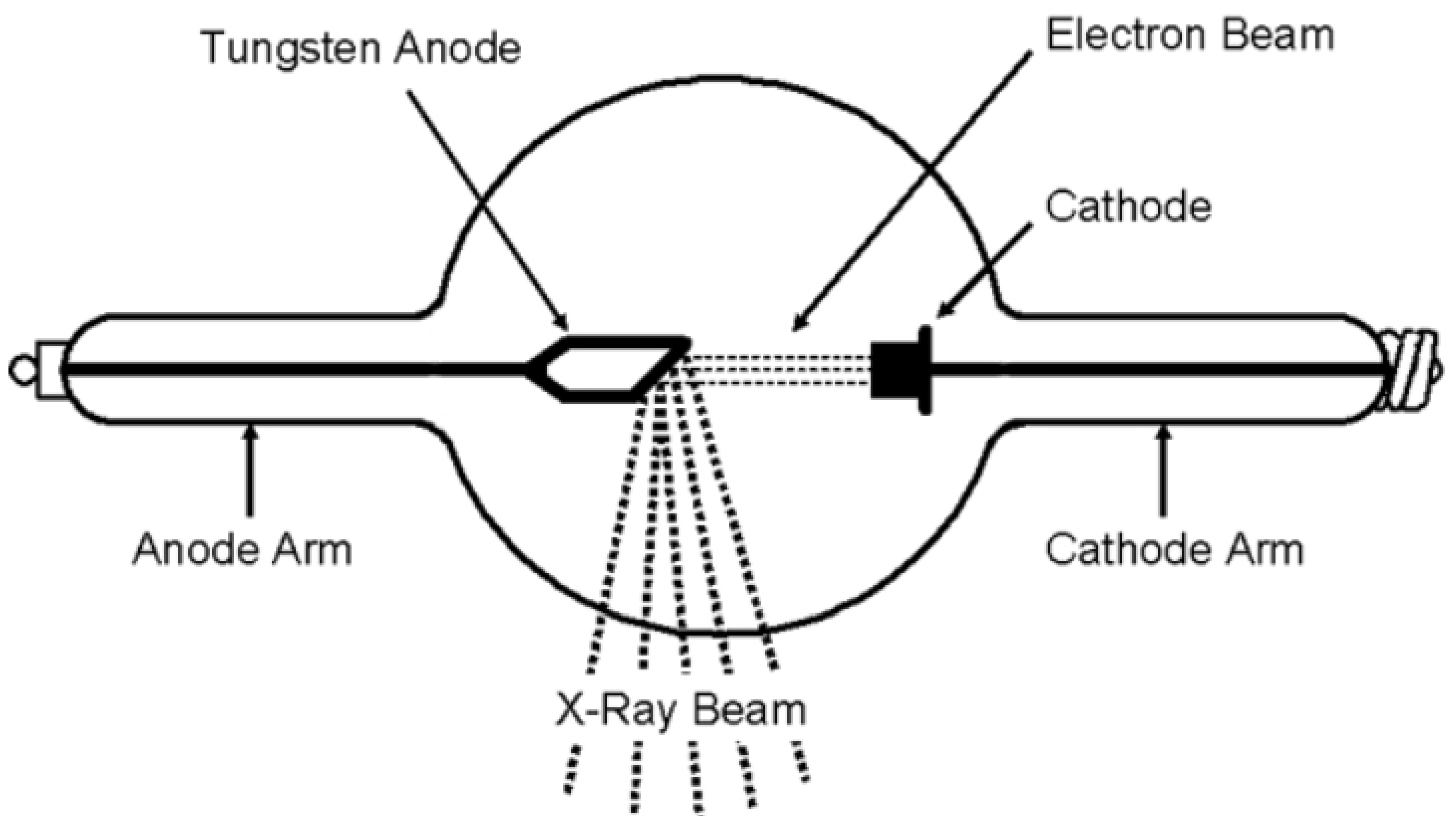
	Presenter Name	Topic
10:00-10:24	Gabby Tamayo	Qualifying exam problem (tbd)
10:25-10:50	Mitch Turk	Detailed analysis of problem 14.26

Friday 4/19/2024

	Presenter Name	Topic
10:00-10:24	Athul Prem	Workout problem 7.2a

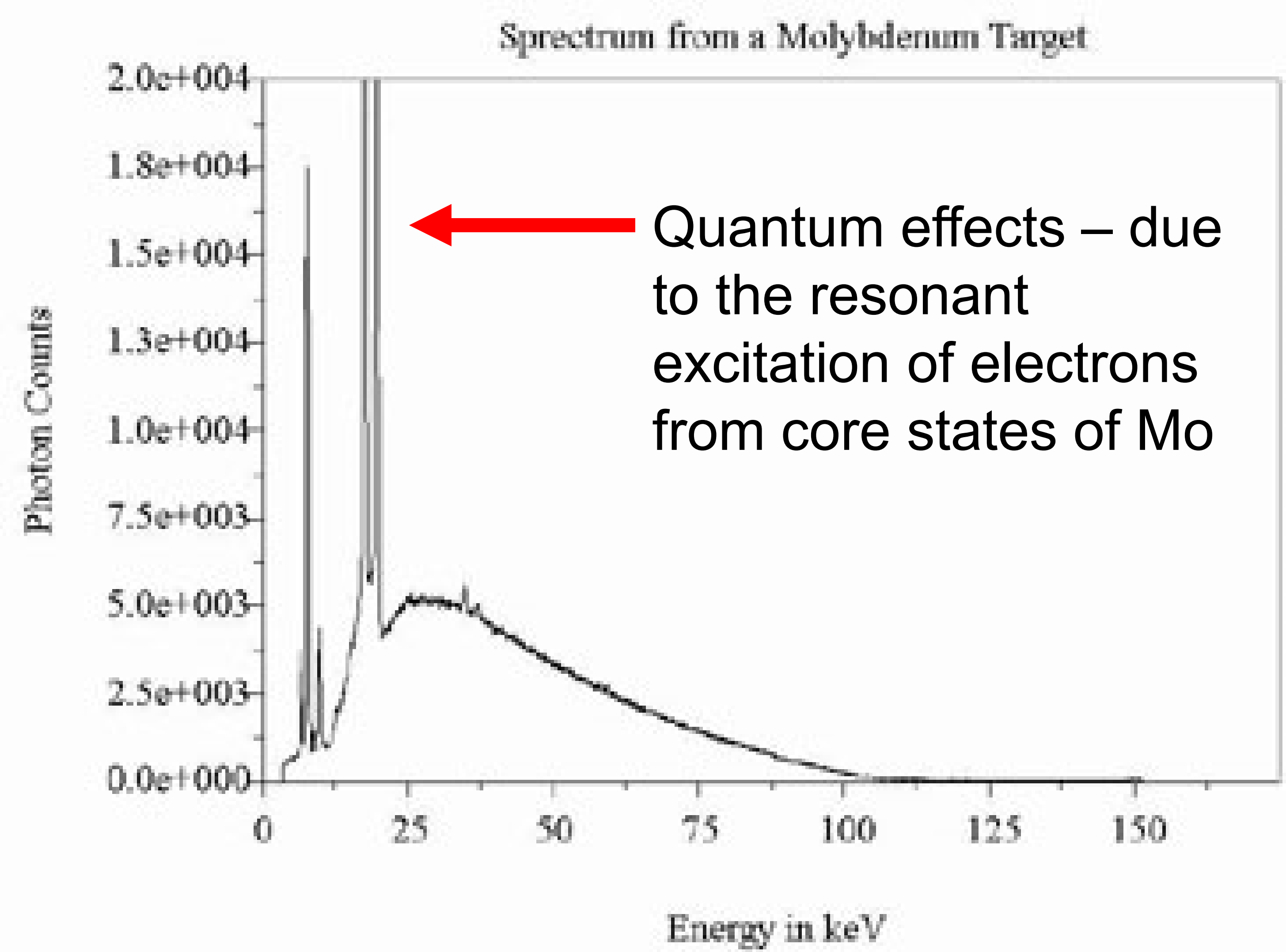
Generation of X-rays in a Coolidge tube

https://www.orau.org/ptp/collection/xraytubescoolidge/coolidgeinformation.htm



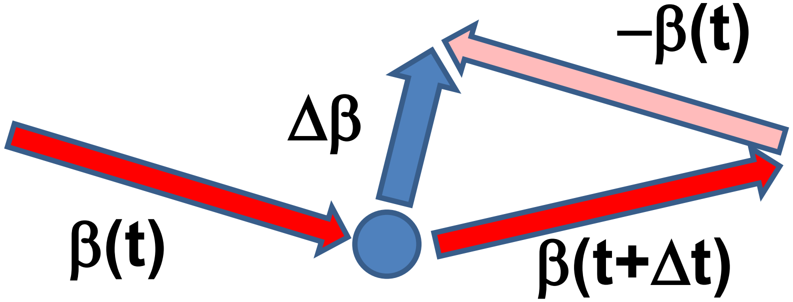
Invented in 1913. Associated with the German word "bremsstrahlung" – meaning breaking radiation.

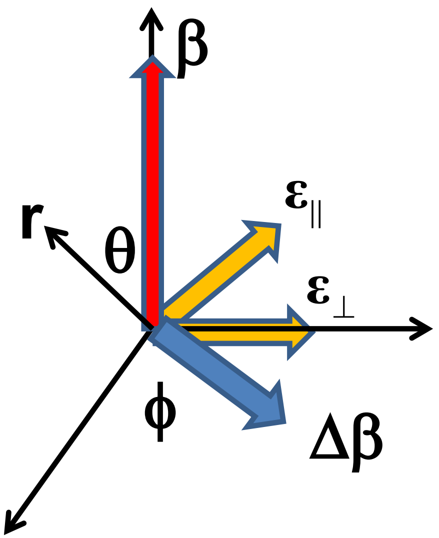
http://www.ndt-ed.org/EducationResources/CommunityCollege/Radiography/Physics/xrays.htm



Quantum effects – due to the resonant excitation of electrons from core states of Mo

Radiation during collisions of charged particles





$\boldsymbol{\varepsilon}_{||}$ is in the plane of $\boldsymbol{\beta}$ and $\mathbf{r}$

$\boldsymbol{\varepsilon}_{\perp}$ is perpendicular to the plane of $\boldsymbol{\beta}$ and $\mathbf{r}$

Results from previous analyses:

Spectral intensity of radiation from accelerating charged particle :

$$\frac{d^2 I}{d\omega d\Omega} = \frac{q^2}{4\pi^2 c}\left|\int dt\ e^{i\omega\left(t-\hat{\mathbf{r}}\cdot\mathbf{R}_q(t)/c\right)}\frac{d}{dt}\left[\frac{\hat{\mathbf{r}}\times\left(\hat{\mathbf{r}}\times\boldsymbol{\beta}\right)}{1-\hat{\mathbf{r}}\cdot\boldsymbol{\beta}}\right]\right|^2$$

Note that in the following slides we are taking the limit $\omega \rightarrow 0$ but keeping the notation of the differential intensity….

For a collision of duration τ emitting radiation with polarization $\boldsymbol{\varepsilon}$ and frequency $\omega \rightarrow 0$;

$$\frac{d^2 I}{d\omega d\Omega} = \frac{q^2}{4\pi^2 c}\left|\boldsymbol{\varepsilon}\cdot\left(\frac{\boldsymbol{\beta}(t+\tau)}{1-\hat{\mathbf{r}}\cdot\boldsymbol{\beta}(t+\tau)} - \frac{\boldsymbol{\beta}(t)}{1-\hat{\mathbf{r}}\cdot\boldsymbol{\beta}(t)}\right)\right|^2$$

Note that $\boldsymbol{\varepsilon}$ is perpendicular to **r**.

Radiation during collisions -- continued

For a collision of duration τ emitting radiation with polarization $\boldsymbol{\varepsilon}$ and frequency $\omega \to 0$:

$$\frac{d^2 I}{d\omega d\Omega} = \frac{q^2}{4\pi^2 c}\left|\boldsymbol{\varepsilon}\cdot\left(\frac{\boldsymbol{\beta}(t+\tau)}{1-\hat{\mathbf{r}}\cdot\boldsymbol{\beta}(t+\tau)} - \frac{\boldsymbol{\beta}(t)}{1-\hat{\mathbf{r}}\cdot\boldsymbol{\beta}(t)}\right)\right|^2$$

We will evaluate this expression for two cases:

Non-relativistic limit:

$$\frac{d^2 I}{d\omega d\Omega} = \frac{q^2}{4\pi^2 c}\left|\boldsymbol{\varepsilon}\cdot(\Delta\boldsymbol{\beta})\right|^2 \qquad \Delta\boldsymbol{\beta} \equiv \boldsymbol{\beta}(t+\tau) - \boldsymbol{\beta}(t)$$

Relativistic collision with small $\left|\Delta\boldsymbol{\beta}\right| \equiv \boldsymbol{\beta}(t+\tau) - \boldsymbol{\beta}(t)$:

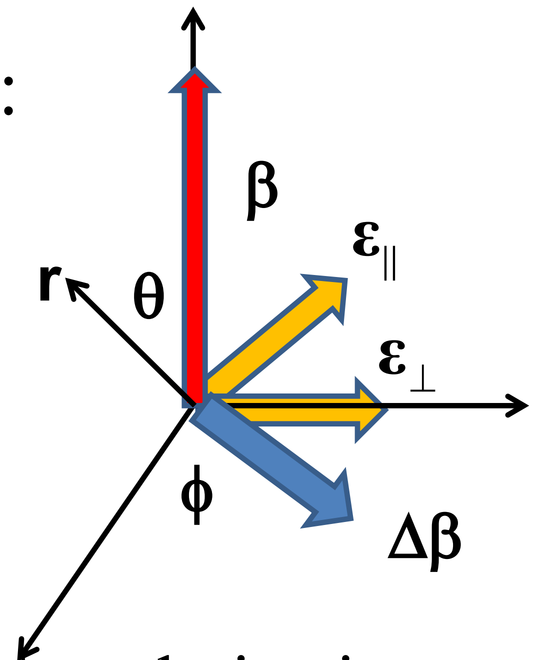
$$\frac{d^2 I}{d\omega d\Omega} = \frac{q^2}{4\pi^2 c}\left|\boldsymbol{\varepsilon}\cdot\left(\frac{\Delta\boldsymbol{\beta} + \hat{\mathbf{r}}\times(\boldsymbol{\beta}\times\Delta\boldsymbol{\beta})}{(1-\hat{\mathbf{r}}\cdot\boldsymbol{\beta})^2}\right)\right|^2$$

In the limit $\beta \to 0$, this is the same as the non-relativistic case.

Radiation during collisions -- continued

Relativistic collision with small $|\Delta\boldsymbol{\beta}|$:

$$\frac{d^2 I}{d\omega d\Omega} = \frac{q^2}{4\pi^2 c}\left|\boldsymbol{\varepsilon}\cdot\left(\frac{\Delta\boldsymbol{\beta} + \hat{\mathbf{r}}\times(\boldsymbol{\beta}\times\Delta\boldsymbol{\beta})}{(1-\hat{\mathbf{r}}\cdot\boldsymbol{\beta})^2}\right)\right|^2$$



Also assume $\Delta\boldsymbol{\beta}$ is perpendicular to $\boldsymbol{\beta}$ direction

Expressions (averaging over φ) for $\|$ or $\perp$ polarization:

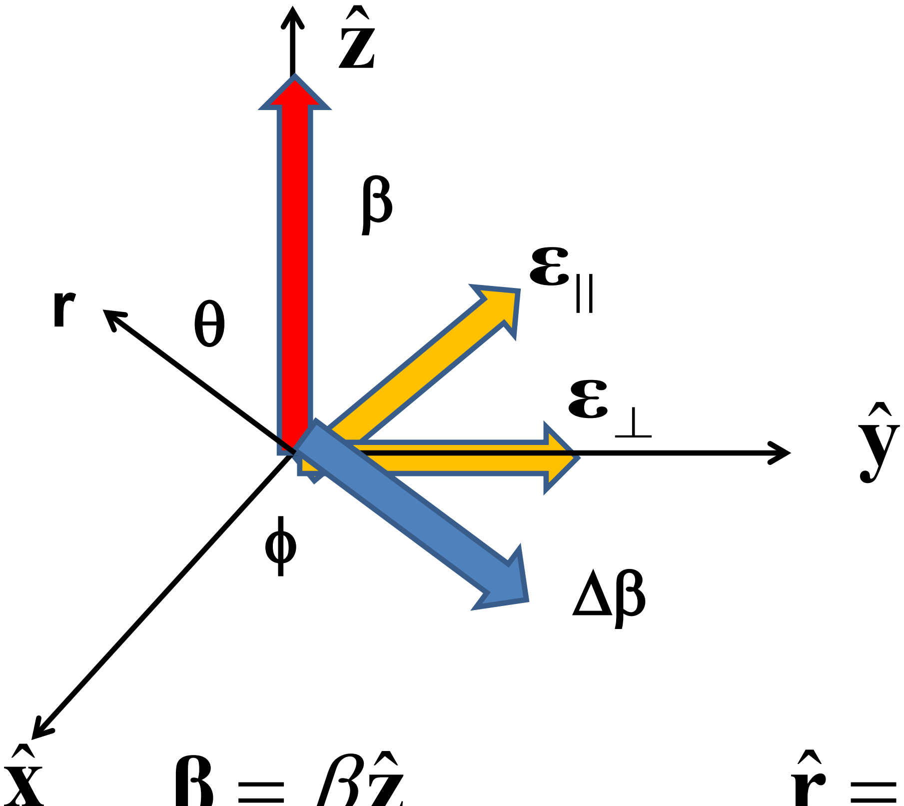
$$\frac{d^2 I_{\|}}{d\omega d\Omega} = \frac{q^2}{8\pi^2 c}|\Delta\boldsymbol{\beta}|^2 \frac{(\beta-\cos\theta)^2}{(1-\beta\cos\theta)^4}$$

polarization in $\boldsymbol{r}$ and $\boldsymbol{\beta}$ plane

$$\frac{d^2 I_{\perp}}{d\omega d\Omega} = \frac{q^2}{8\pi^2 c}|\Delta\boldsymbol{\beta}|^2 \frac{1}{(1-\beta\cos\theta)^2}$$

polarization perpendicular to $\boldsymbol{r}$ and $\boldsymbol{\beta}$ plane

Some details:



(using geometry of Fig. 15.2 in Jackson)

$$\boldsymbol{\beta} = \beta\hat{\mathbf{z}} \qquad \hat{\mathbf{r}} = \sin\theta\hat{\mathbf{x}} + \cos\theta\hat{\mathbf{z}}$$

$$\boldsymbol{\varepsilon}_{||} = -\cos\theta\hat{\mathbf{x}} + \sin\theta\hat{\mathbf{z}} \qquad \boldsymbol{\varepsilon}_{\perp} = \hat{\mathbf{y}}$$

$$\Delta\boldsymbol{\beta} = \Delta\beta\left(\cos\phi\hat{\mathbf{x}} + \sin\phi\hat{\mathbf{y}}\right)$$

Note: This is a wild assumption!

Some details -- continued:

$$\hat{\mathbf{r}} = \sin\theta\hat{\mathbf{x}} + \cos\theta\hat{\mathbf{z}}$$

$$\boldsymbol{\varepsilon}_{\perp} = \hat{\mathbf{y}} \qquad \boldsymbol{\varepsilon}_{||} = -\cos\theta\hat{\mathbf{x}} + \sin\theta\hat{\mathbf{z}}$$

Consistent with radiation from charged particles.

$$\boldsymbol{\beta} = \beta\hat{\mathbf{z}}$$

Convenient geometry

$$\Delta\boldsymbol{\beta} = \Delta\beta\left(\cos\phi\hat{\mathbf{x}} + \sin\phi\hat{\mathbf{y}}\right)$$

Wild guess

$$\Delta\boldsymbol{\beta} + \hat{\mathbf{r}}\times\left(\boldsymbol{\beta}\times\Delta\boldsymbol{\beta}\right) = \Delta\boldsymbol{\beta}\left(1-\hat{\mathbf{r}}\cdot\boldsymbol{\beta}\right) + \boldsymbol{\beta}\left(\hat{\mathbf{r}}\cdot\Delta\boldsymbol{\beta}\right)$$

$$\boldsymbol{\varepsilon}_{\perp}\cdot\left(\Delta\boldsymbol{\beta} + \hat{\mathbf{r}}\times\left(\boldsymbol{\beta}\times\Delta\boldsymbol{\beta}\right)\right) = \Delta\beta\sin\phi\left(1-\beta\cos\theta\right)$$

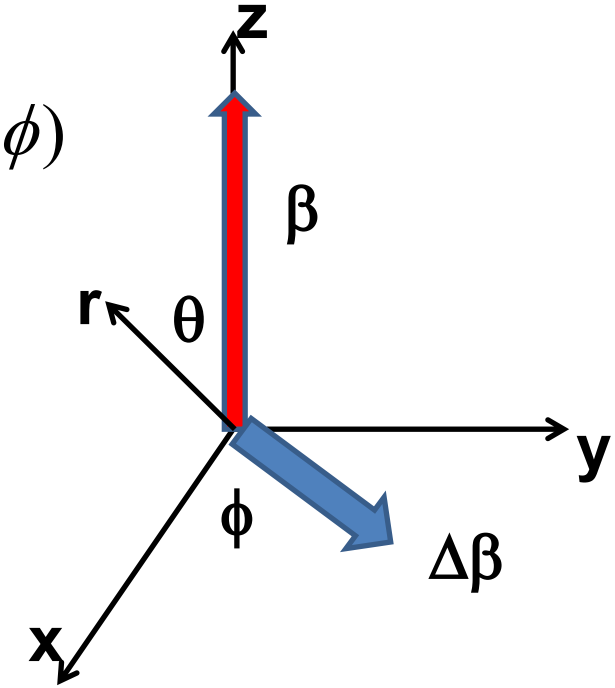
$$\boldsymbol{\varepsilon}_{||}\cdot\left(\Delta\boldsymbol{\beta} + \hat{\mathbf{r}}\times\left(\boldsymbol{\beta}\times\Delta\boldsymbol{\beta}\right)\right) = \Delta\beta\cos\phi\left(\beta-\cos\theta\right)$$

Radiation during collisions -- continued

Intensity expressions: (averaging over ϕ)

$$\frac{d^2 I_{\parallel}}{d\omega d\Omega} = \frac{q^2}{8\pi^2 c}|\Delta\boldsymbol{\beta}|^2 \frac{(\beta - \cos\theta)^2}{(1-\beta\cos\theta)^4}$$

$$\frac{d^2 I_{\perp}}{d\omega d\Omega} = \frac{q^2}{8\pi^2 c}|\Delta\boldsymbol{\beta}|^2 \frac{1}{(1-\beta\cos\theta)^2}$$



Relativistic collision at low ω and with small $|\Delta\boldsymbol{\beta}|$ and $\Delta\boldsymbol{\beta}$ perpendicular to plane of $\hat{\mathbf{r}}$ and $\boldsymbol{\beta}$, as a function of θ where $\hat{\mathbf{r}}\cdot\boldsymbol{\beta} = \beta\cos\theta$;

Integrating over solid angle:

$$\frac{dI}{d\omega} = \int d\Omega\left(\frac{d^2 I_{\parallel}}{d\omega d\Omega} + \frac{d^2 I_{\perp}}{d\omega d\Omega}\right) = \frac{2}{3\pi}\frac{q^2}{c}\gamma^2 \; |\Delta\boldsymbol{\beta}|^2$$

Some more details:

$$\int d\Omega \frac{d^2 I_{\parallel}}{d\omega d\Omega} = \frac{q^2}{8\pi^2 c}|\Delta\boldsymbol{\beta}|^2 \, 2\pi \int_{-1}^{1} d\cos\theta \frac{(\beta-\cos\theta)^2}{(1-\beta\cos\theta)^4}$$

$$= \frac{q^2}{4\pi c}|\Delta\boldsymbol{\beta}|^2 \frac{2}{3}\frac{1}{(1-\beta^2)}$$

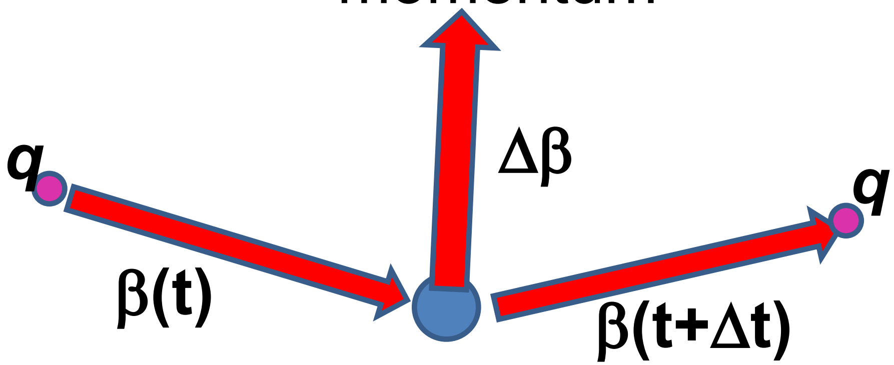
$$\int d\Omega \frac{d^2 I_{\perp}}{d\omega d\Omega} = \frac{q^2}{8\pi^2 c}|\Delta\boldsymbol{\beta}|^2 \int_{-1}^{1} d\cos\theta \frac{1}{(1-\beta\cos\theta)^2}$$

$$= \frac{q^2}{4\pi c}|\Delta\boldsymbol{\beta}|^2 \frac{2}{(1-\beta^2)}$$

$$\frac{dI}{d\omega} = \int d\Omega \left(\frac{d^2 I_{\parallel}}{d\omega d\Omega} + \frac{d^2 I_{\perp}}{d\omega d\Omega} \right) = \frac{2}{3\pi}\frac{q^2}{c}\gamma^2 \; |\Delta\boldsymbol{\beta}|^2$$

Estimation of $\Delta\beta$

Need to consider the mechanics of collision; it is convenient to parameterize in terms of momentum --



Momentum transfer:

$$Qc \equiv \left|\mathbf{p}(t+\tau) - \mathbf{p}(t)\right| c \approx \gamma M c^2 \left|\mathbf{\Delta\beta}\right|$$

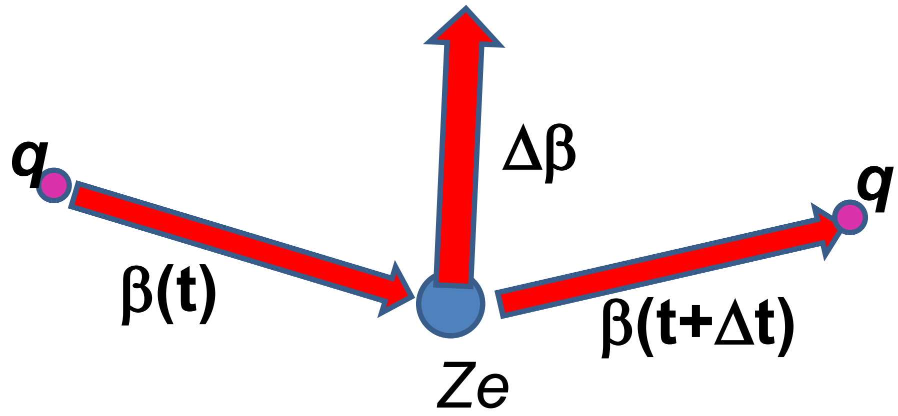
mass of particle having charge *q*

$$\frac{dI}{d\omega} = \frac{2}{3\pi}\ \frac{q^2}{c}\gamma^2\left|\mathbf{\Delta\beta}\right|^2 \approx \frac{2}{3\pi}\ \frac{q^2}{M^2c^3}Q^2$$

What are the conditions for the validity of this result?

What are possible mechanisms for the momentum transfer Q?

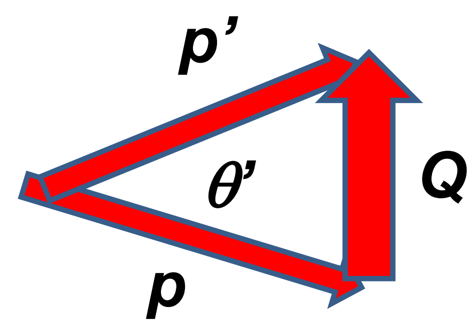
Estimation of Δβ or *Q* -- for the case of Rutherford scattering



Assume that target nucleus (charge *Ze*) has mass >>M;

Rutherford scattering cross-section in center of mass analysis:

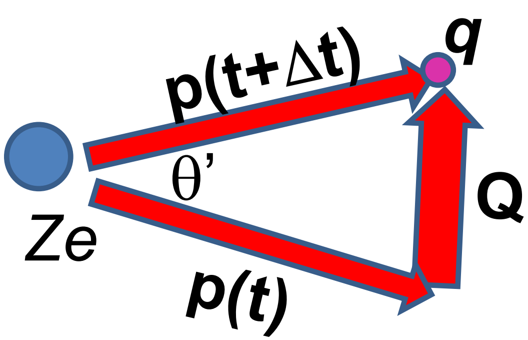
$$\frac{d\sigma}{d\Omega} = \left(\frac{2Zeq}{pv}\right)^2 \frac{1}{\left(2\sin\left(\theta'/2\right)\right)^4}$$



Assuming elastic scattering:

$$Q^2 = \left(2p\sin\left(\theta'/2\right)\right)^2 = 2p^2\left(1-\cos\theta'\right)$$

Case of Rutherford scattering -- continued



Rutherford scattering cross-section:

$$\frac{d\sigma}{d\Omega} = \left(\frac{2Zeq}{pv}\right)^2 \frac{1}{\left(2\sin\left(\theta'/2\right)\right)^4}$$

$$\frac{d\sigma}{dQ} = \int_{\varphi'} \frac{d\sigma}{d\Omega} \left|\frac{d\Omega}{dQ}\right| d\varphi'$$

$$d\Omega = d\varphi' d\cos\theta'$$

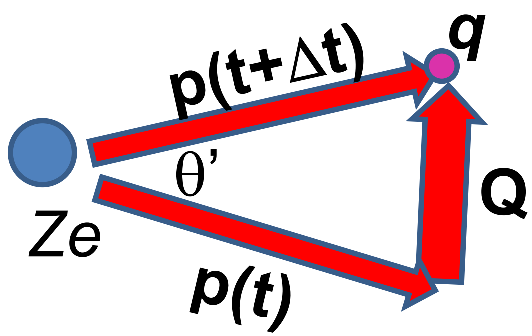
$$Q^2 = \left(2p\sin\left(\theta'/2\right)\right)^2 = 2p^2\left(1-\cos\theta'\right)$$

$$dQ = -\frac{p^2}{Q} d\cos\theta'$$

$$\Rightarrow \quad \frac{d\sigma}{dQ} = 8\pi \left(\frac{Zeq}{\beta c}\right)^2 \frac{1}{Q^3}$$

Does the algebra work out?

Case of Rutherford scattering -- continued



Differential radiation cross section :

$$\frac{d^2\chi}{d\omega dQ} = \frac{dI}{d\omega}\frac{d\sigma}{dQ} = \left(\frac{2}{3\pi}\frac{q^2}{M^2c^3}Q^2\right)\left(8\pi\left(\frac{Zeq}{\beta c}\right)^2\frac{1}{Q^3}\right)$$

$$= \frac{16}{3}\frac{(Ze)^2}{c}\left(\frac{q^2}{Mc^2}\right)^2\frac{1}{\beta^2}\frac{1}{Q}$$

Differential radiation cross section -- continued

Integrating over momentum transfer

$$\frac{d\chi}{d\omega} = \int_{Q_{\min}}^{Q_{\max}} dQ \frac{d^2\chi}{d\omega dQ} = \frac{16}{3}\frac{(Ze)^2}{c}\left(\frac{q^2}{Mc^2}\right)^2 \frac{1}{\beta^2}\ln\left(\frac{Q_{\max}}{Q_{\min}}\right)$$

How do the limits of Q occur?

Jackson suggests that these come from the limits of validity of the analysis.

1. Seems like cheating?
2. Perhaps fair?

Comment on frequency dependence --

Original expression for radiation intensity:

$$\frac{d^2 I}{d\omega d\Omega} = \frac{q^2}{4\pi^2 c}\left|\int dt\; e^{i\omega\left(t-\hat{\mathbf{r}}\cdot\mathbf{R}_q(t)/c\right)}\frac{d}{dt}\left[\frac{\hat{\mathbf{r}}\times\left(\hat{\mathbf{r}}\times\boldsymbol{\beta}\right)}{1-\hat{\mathbf{r}}\cdot\boldsymbol{\beta}}\right]\right|^2$$

In the previous derivations, we have assumed that

$$\omega\left(t-\hat{\mathbf{r}}\cdot\mathbf{R}_q(t)/c\right) << 1.$$

$$\omega\left(t-\hat{\mathbf{r}}\cdot\mathbf{R}_q(t)/c\right) = \omega\left(t-\hat{\mathbf{r}}\cdot\int_0^t dt'\boldsymbol{\beta}(t')\right) \approx \omega\tau\left(1-\hat{\mathbf{r}}\cdot\langle\boldsymbol{\beta}\rangle\right)$$

In the non-relativistic case, this means $\omega\tau \ll 1.$

Here τ is the effective collision time.

How to estimate the collision time?

Jackson uses the following analysis in terms of the impact parameter *b:*

Using classical mechanics and assuming $v \ll c$:

$$\tau \approx \frac{b}{v} \ll \frac{1}{\omega} \quad \text{and} \quad Q \approx \frac{2Zeq}{bv}$$

$$\text{Assume that } Q_{\min} = \frac{2Zeq}{b_{\max} v} = \frac{2Zeq\omega}{v^2}$$

Differential radiation cross section -- continued

Radiation cross section in terms of momentum transfer

$$\frac{d\chi}{d\omega} = \int_{Q_{\min}}^{Q_{\max}} dQ \frac{d^2\chi}{d\omega dQ} = \frac{16}{3}\frac{(Ze)^2}{c}\left(\frac{q^2}{Mc^2}\right)^2 \frac{1}{\beta^2}\ln\left(\frac{Q_{\max}}{Q_{\min}}\right)$$

Note that: $Q^2 = 2p^2(1-\cos\theta') \quad \Rightarrow Q_{\max} = 2p$

In general, $Q_{\min}$ is determined by the collision time

condition $\omega\tau < 1 \quad \Rightarrow Q_{\min} \approx \dfrac{2Zeq\omega}{v^2}$

Radiation cross section for classical non - relativistic process

$$\frac{d\chi}{d\omega} = \frac{16}{3}\frac{(Ze)^2}{c}\left(\frac{q^2}{Mc^2}\right)^2 \frac{1}{\beta^2}\ln\left(\frac{\lambda M v^3}{Zeq\omega}\right)$$

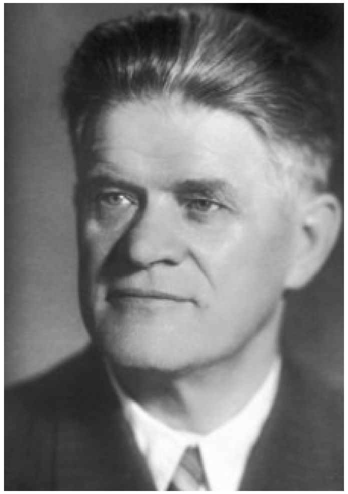
λ= “fudge factor” of order unity

Cherenkov radiation

Cherenkov radiation emitted by the core of the Reed Research Reactor located at Reed College in Portland, Oregon, U.S. *Cherenkov radiation*. Photograph. *Encyclopædia Britannica Online*. Web. 12 Apr. 2013.
http://www.britannica.com/EBchecked/media/174732

The Nobel Prize in Physics 1958

Pavel A. Cherenkov
Il´ja M. Frank
Igor Y. Tamm



Affiliation at the time of the award: P.N. Lebedev Physical Institute, Moscow, USSR

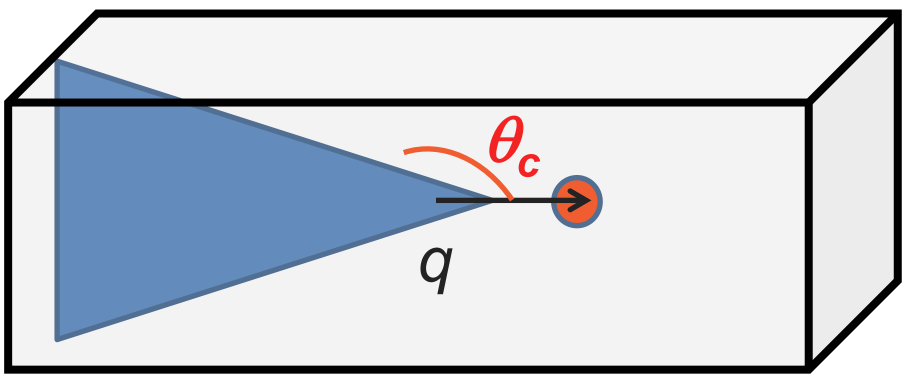
Prize motivation: "for the discovery and the interpretation of the Cherenkov effect."

https://www.nobelprize.org/prizes/physics/1958/ceremony-speech/

References for notes: Glenn S. Smith, *An Introduction to Electromagnetic Radiation* (Cambridge UP, 1997), Andrew Zangwill, Modern Electrodynamics (Cambridge UP, 2013)

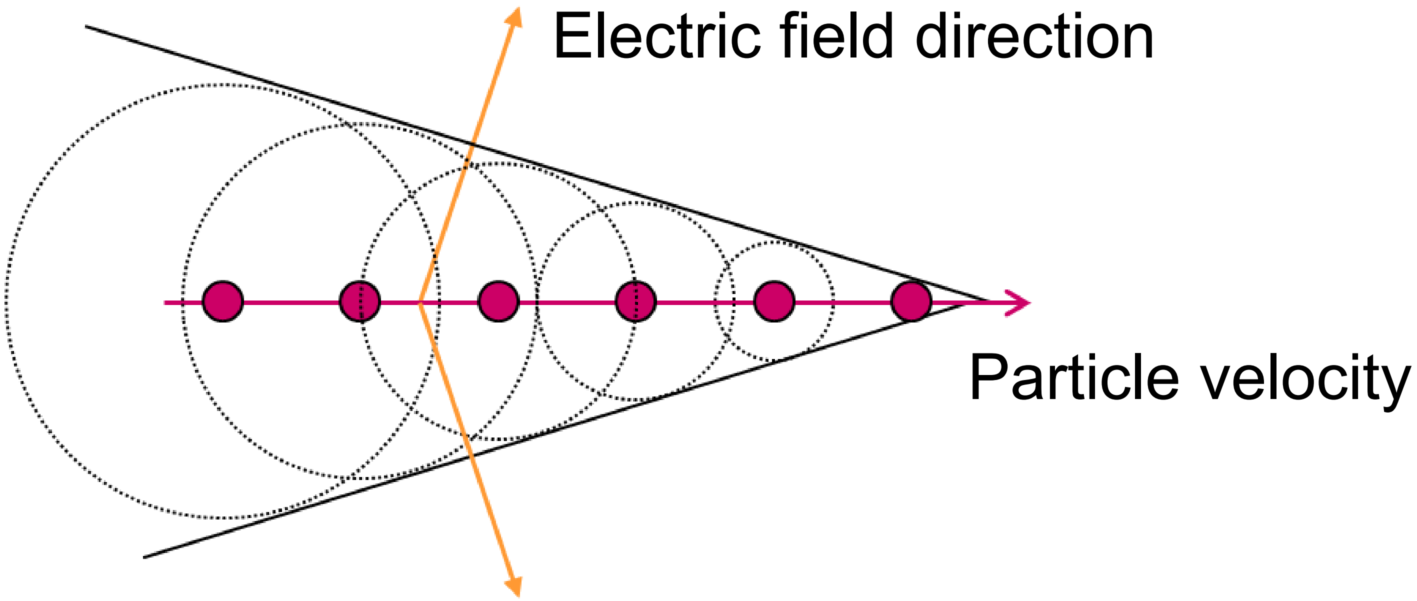
Cherenkov radiation

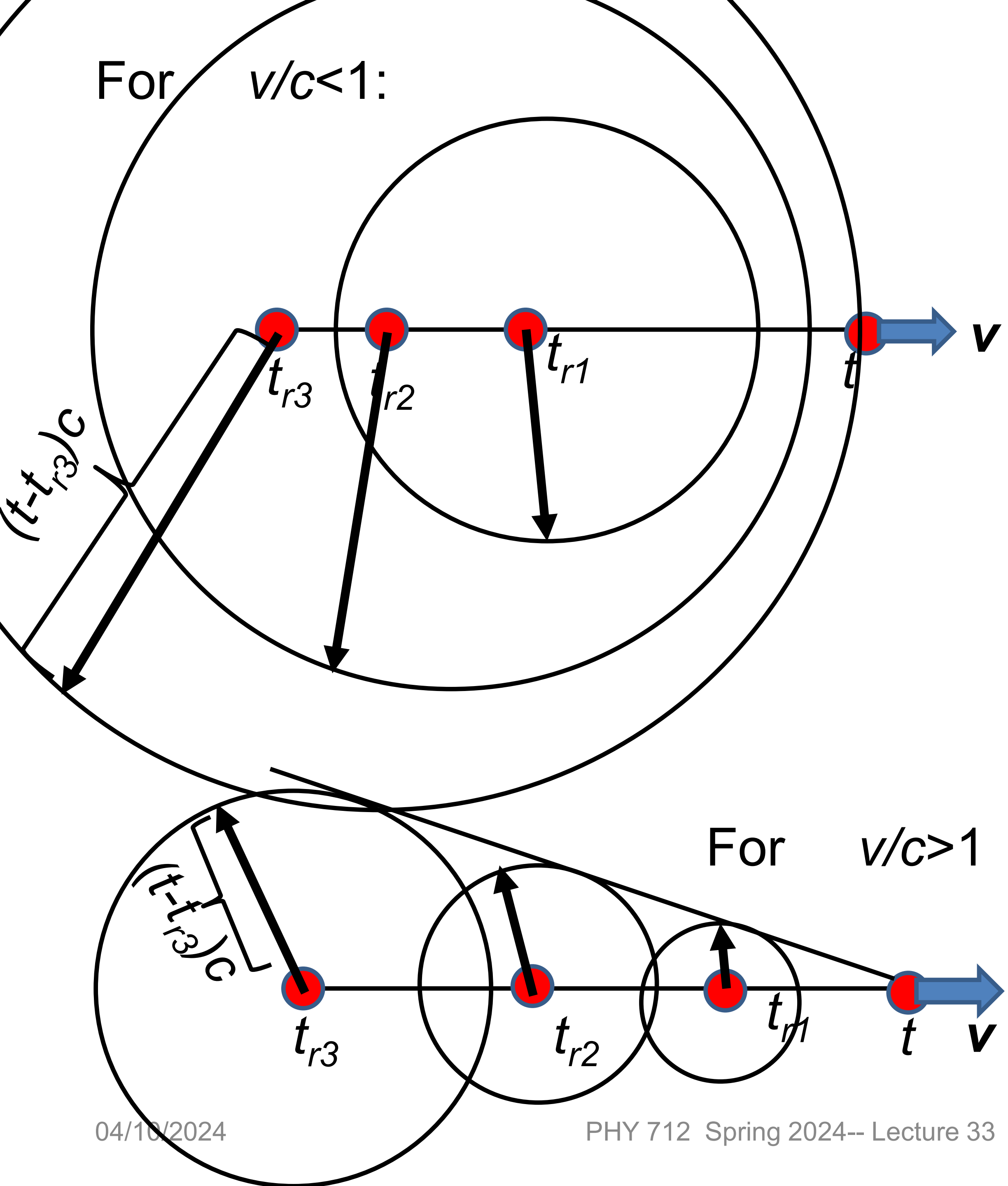
Discovered ~1930; bluish light emitted by energetic charged particles traveling within dielectric materials



Note that some treatments give a different definition of the critical angle θ_c

From: http://large.stanford.edu/courses/2014/ph241/alaeian2/





For v/c<1:
v
t
t_r1
t_r2
t_r3
(t-t_r3)c
For v/c>1
v
t
t_r1
t_r2
t_r3
(t-t_r3)c

Maxwell's potential equations within a material having permittivity and permeability (Lorentz gauge; cgs Gaussian units)

$$\nabla^2 \Phi - \mu\varepsilon \frac{1}{c^2}\frac{\partial^2 \Phi}{\partial t^2} = -\frac{4\pi}{\varepsilon}\rho$$

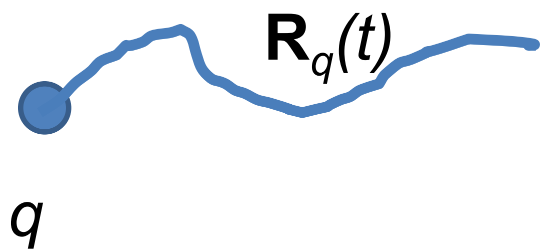
$$\nabla^2 \mathbf{A} - \mu\varepsilon \frac{1}{c^2}\frac{\partial^2 \mathbf{A}}{\partial t^2} = -\frac{4\pi\mu}{c}\mathbf{J}$$

Here the values of μ and ε depend on the material and on frequency.

Source: charged particle moving on trajectory $\mathbf{R}_q(t)$:

$$\rho(\mathbf{r},t) = q\delta\left(\mathbf{r} - \mathbf{R}_q(t)\right)$$

$$\mathbf{J}(\mathbf{r},t) = q\dot{\mathbf{R}}_q(t)\delta\left(\mathbf{r} - \mathbf{R}_q(t)\right)$$



Liénard-Wiechert potential solutions for charged particle moving within a material with refractive index *n*:

$$\Phi(\mathbf{r},t)=\frac{q}{\varepsilon}\frac{1}{\left|R(t_r)-\boldsymbol{\beta}_n\cdot\mathbf{R}(t_r)\right|}$$

$$\mathbf{A}(\mathbf{r},t)=q\mu\frac{\boldsymbol{\beta}_n}{\left|R(t_r)-\boldsymbol{\beta}_n\cdot\mathbf{R}(t_r)\right|}$$

$$\mathbf{R}(t_r)\equiv\mathbf{r}-\mathbf{R}_q(t_r)$$

$$\boldsymbol{\beta}_n(t_r)\equiv\frac{\dot{\mathbf{R}}_q(t_r)}{c_n}\qquad c_n\equiv\frac{c}{\sqrt{\mu\varepsilon}}\equiv\frac{c}{n}$$

$$t_r=t-\frac{R(t_r)}{c_n}$$

Example --

$$\beta_n \equiv \frac{v}{c_n} \qquad c_n \equiv \frac{c}{\sqrt{\mu\varepsilon}} \equiv \frac{c}{n} \qquad \beta_n \equiv \frac{vn}{c}$$

Consider water with $n \approx 1.3$

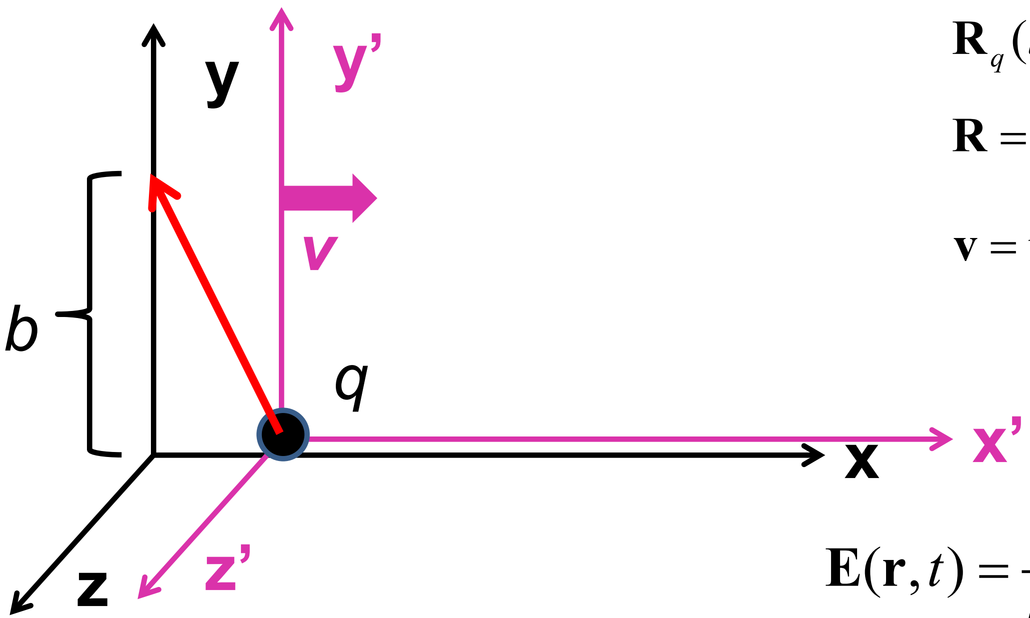
Which of these particles could produce Cherenkov radiation?

1. A neutron with speed c?
2. An electron with speed 0.6c?
3. A proton with speed 0.6c?
4. An electron with speed 0.8c?
5. An alpha particle with speed 0.8c?
6. None of these?

Further comment –

As discussed particularly in Chap. 13 of Jackson, a particle moving within a medium is likely to be slowed down so that the Cherenkov effect will only happen while $\beta_n>1$.

Recall – in Lecture 29, we considered a particle moving at constant velocity v in vacuum:



$$\mathbf{R}_q(t_r) = vt_r\hat{\mathbf{x}} \qquad \mathbf{r} = b\hat{\mathbf{y}}$$

$$\mathbf{R} = b\hat{\mathbf{y}} - vt_r\hat{\mathbf{x}} \qquad R = \sqrt{v^2 t_r^2 + b^2}$$

$$\mathbf{v} = v\hat{\mathbf{x}} \qquad t_r = t - \frac{R}{c}$$

$$\mathbf{E}(\mathbf{r},t) = \frac{q}{\left(R - \frac{\mathbf{v}\cdot\mathbf{R}}{c}\right)^3}\left[\left(\mathbf{R} - \frac{\mathbf{v}R}{c}\right)\left(1 - \frac{v^2}{c^2}\right)\right]$$

Electric and magnetic fields produced →

$$\mathbf{B}(\mathbf{r},t) = \frac{q}{c}\left[\frac{-\mathbf{R}\times\mathbf{v}}{\left(R - \frac{\mathbf{v}\cdot\mathbf{R}}{c}\right)^3}\left(1 - \frac{v^2}{c^2}\right)\right]$$

Some details for vacuum case --

$$\mathbf{E}(\mathbf{r},t)=\frac{q}{\left(R-\frac{\mathbf{v}\cdot\mathbf{R}}{c}\right)^3}\left[\left(\mathbf{R}-\frac{\mathbf{v}R}{c}\right)\left(1-\frac{v^2}{c^2}\right)\right]$$

$$\mathbf{B}(\mathbf{r},t)=\frac{q}{c}\left[\frac{-\mathbf{R}\times\mathbf{v}}{\left(R-\frac{\mathbf{v}\cdot\mathbf{R}}{c}\right)^3}\left(1-\frac{v^2}{c^2}\right)\right]$$

For our example:

$$\mathbf{R}_q(t_r)=vt_r\hat{\mathbf{x}} \qquad \mathbf{r}=b\hat{\mathbf{y}}$$

$$\mathbf{R}=b\hat{\mathbf{y}}-vt_r\hat{\mathbf{x}} \qquad R=\sqrt{v^2t_r^2+b^2}$$

$$\mathbf{v}=v\hat{\mathbf{x}} \qquad t_r=t-\frac{R}{c}$$

t_r must be a solution to a quadratic equation: where $\frac{v}{c}\leq 1;\ \ \gamma=\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$

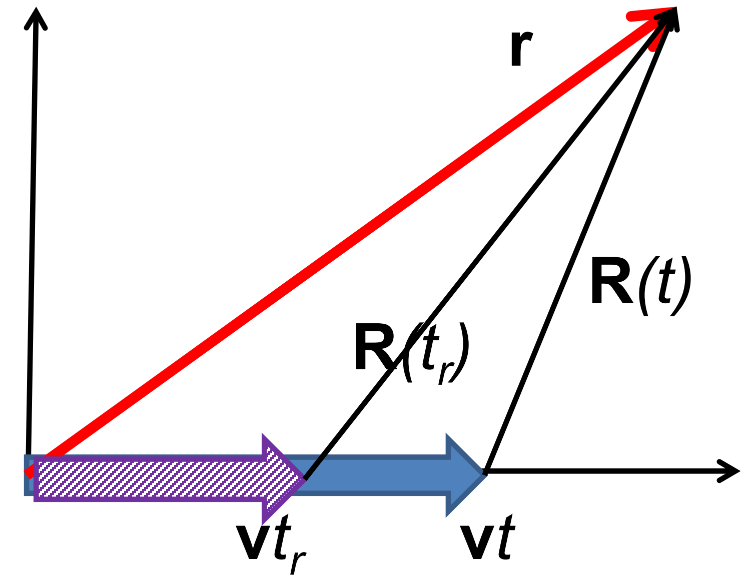
$$t_r-t=-\frac{R}{c} \qquad \Rightarrow \qquad t_r^2-2\gamma^2tt_r+\gamma^2t^2-\gamma^2b^2/c^2=0$$

with the physical solution:

$$t_r=\gamma\left(\gamma t-\sqrt{(\gamma^2-1)t^2+b^2/c^2}\right)=\gamma\left(\gamma t-\frac{\sqrt{(v\gamma t)^2+b^2}}{c}\right)$$

For Cherenkov case --

Consider a particle moving at constant velocity **v**; $v > c_n$



Some algebra

$$\mathbf{R}(t) = \mathbf{r} - \mathbf{v}t$$

$$\mathbf{R}(t_r) = \mathbf{r} - \mathbf{v}t_r = \mathbf{R}(t) + \mathbf{v}(t - t_r)$$

$$(t - t_r)c_n = R(t_r) = \left|\mathbf{R}(t) + \mathbf{v}(t - t_r)\right|$$

Quadratic equation for $(t - t_r)c_n$:

$$\left((t - t_r)c_n\right)^2 = R^2(t) + 2\mathbf{R}(t)\cdot\boldsymbol{\beta}_n(t - t_r)c_n + \beta_n{}^2\left((t - t_r)c_n\right)^2$$

$$\left(\beta_n{}^2 - 1\right)\left((t - t_r)c_n\right)^2 + 2\mathbf{R}(t)\cdot\boldsymbol{\beta}_n(t - t_r)c_n + R^2(t) = 0$$

Quadratic equation for $\left(t-t_r\right)c_n \equiv R(t_r)$:

$$\left(\beta_n{}^2-1\right)\left(\left(t-t_r\right)c_n\right)^2+2\mathbf{R}\left(t\right)\cdot\boldsymbol{\beta}_n\left(t-t_r\right)c_n+R^2\left(t\right)=0$$

For β_n>1, how can the equality be satisfied?

1. No problem
2. It cannot be satisfied.
3. It can only be satisfied for special conditions

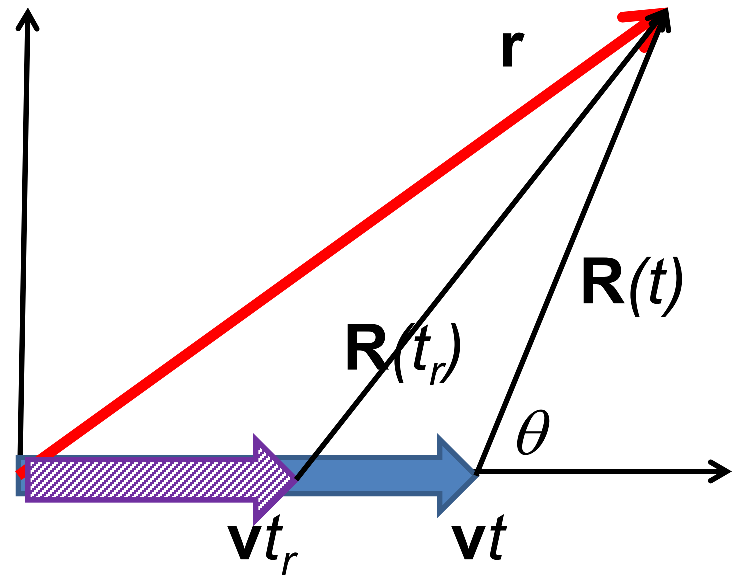
From solution of quadratic equation:

$$\left(t-t_r\right)c_n=R(t_r)=\frac{-\mathbf{R}\left(t\right)\cdot\boldsymbol{\beta}_n\pm\sqrt{\left(\mathbf{R}\left(t\right)\cdot\boldsymbol{\beta}_n\right)^2-\left(\beta_n{}^2-1\right)R^2\left(t\right)}}{\beta_n{}^2-1}$$

$$\Rightarrow \mathbf{R}\left(t\right)\cdot\boldsymbol{\beta}_n<0 \qquad \text{(initial diagram is incorrect!)}$$

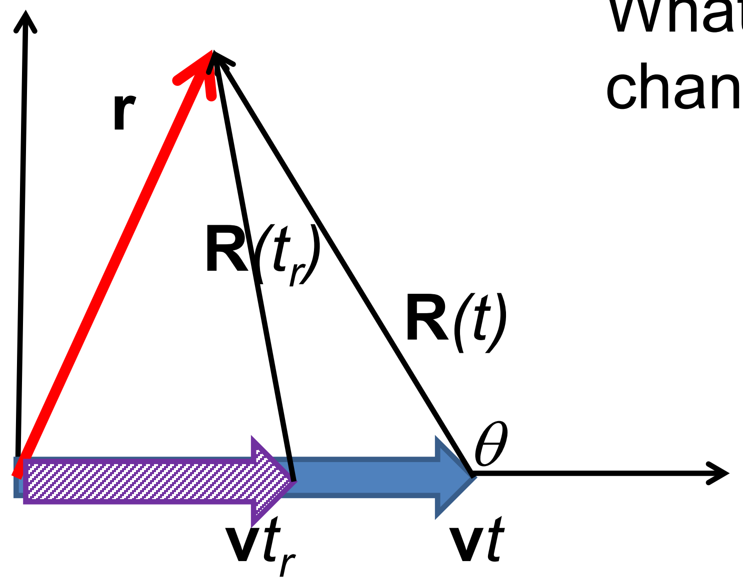
Moreover, there are two retarded time solutions!

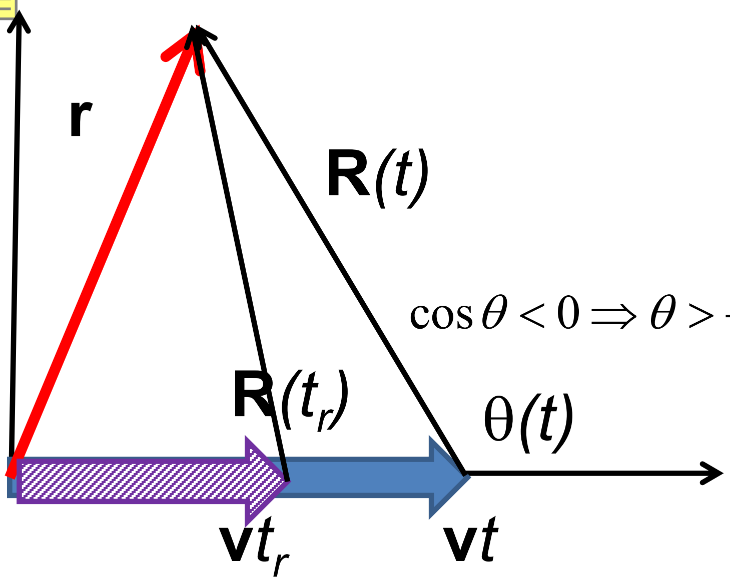
Original diagram:



What is the significance of changing the diagram?

New diagram:





$$\cos\theta < 0 \Rightarrow \theta > \frac{\pi}{2}$$

$$\cos\theta \equiv \hat{\mathbf{R}}(t)\cdot\hat{\mathbf{v}}$$

$$\mathbf{R}(t_r) = \mathbf{r} - \mathbf{v}t_r = \mathbf{R}(t) + \mathbf{v}(t - t_r)$$

$$(t - t_r)c_n = R(t_r)$$

$$R(t_r) - \mathbf{R}(t_r)\cdot\boldsymbol{\beta}_n =$$

$$(t - t_r)c_n\left(1 - \beta_n^2\right) - \mathbf{R}(t)\cdot\boldsymbol{\beta}_n$$

$$= R(t_r)\left(1 - \beta_n^2\right) - \mathbf{R}(t)\cdot\boldsymbol{\beta}_n$$

$$R(t_r) = \frac{-\mathbf{R}(t)\cdot\boldsymbol{\beta}_n \pm \sqrt{\left(\mathbf{R}(t)\cdot\boldsymbol{\beta}_n\right)^2 - \left(\beta_n{}^2 - 1\right)R^2(t)}}{\beta_n{}^2 - 1}$$

$$R(t_r) = \frac{R(t)}{\beta_n{}^2 - 1}\left(-\beta_n\cos\theta \pm \sqrt{1 - \beta_n{}^2\sin^2\theta}\right) = (t - t_r)c_n$$

$$R(t_r) - \mathbf{R}(t_r)\cdot\boldsymbol{\beta}_n = \mp R(t)\sqrt{1 - \beta_n{}^2\sin^2\theta}$$

Recall the Liénard-Wiechert potential solutions:

$$\Phi(\mathbf{r},t)=\frac{q}{\varepsilon}\frac{1}{\left|R(t_r)-\boldsymbol{\beta}_n\cdot\mathbf{R}(t_r)\right|}$$

$$\mathbf{A}(\mathbf{r},t)=q\mu\frac{\boldsymbol{\beta}_n}{\left|R(t_r)-\boldsymbol{\beta}_n\cdot\mathbf{R}(t_r)\right|}$$

$$\mathbf{R}(t_r)\equiv\mathbf{r}-\mathbf{R}_q(t_r)$$

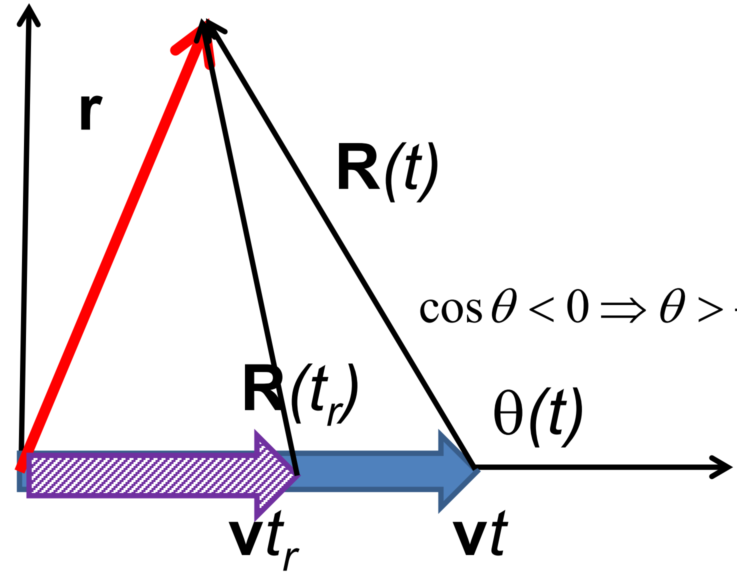
$$\boldsymbol{\beta}_n(t_r)\equiv\frac{\dot{\mathbf{R}}_q(t_r)}{c_n} \qquad c_n\equiv\frac{c}{\sqrt{\mu\varepsilon}}\equiv\frac{c}{n}$$

$$t_r=t-\frac{R(t_r)}{c_n}$$

Liénard-Wiechert potentials for two solutions:

$$\Phi\left(\mathbf{r},t\right)=\frac{q}{\varepsilon}\frac{1}{\left|\mp R(t)\sqrt{1-\beta_n{}^2\sin^2\theta}\right|}$$

$$\mathbf{A}\left(\mathbf{r},t\right)=q\mu\frac{\boldsymbol{\beta}_n}{\left|\mp R(t)\sqrt{1-\beta_n{}^2\sin^2\theta}\right|}$$



$$\cos\theta<0\Rightarrow\theta>\frac{\pi}{2}$$

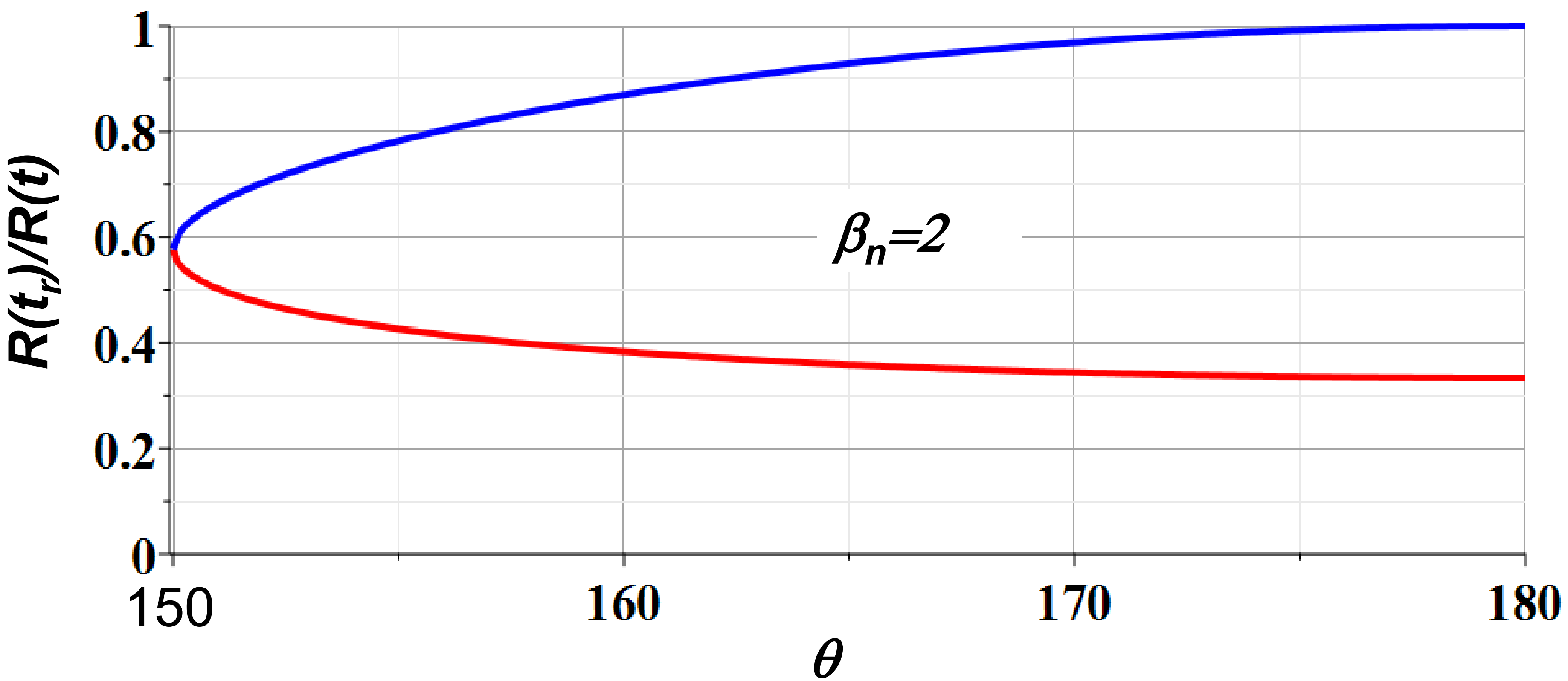
For $\beta_n>1,$ the range of θ is limited further:

$$R\left(t_r\right)=\frac{R(t)}{\beta_n{}^2-1}\left(-\beta_n\cos\theta\pm\sqrt{1-\beta_n{}^2\sin^2\theta}\right)\geq 0$$

$$\Rightarrow\left|\sin\theta\right|\leq\frac{1}{\beta_n}\equiv\left|\sin\theta_c\right|\quad\text{and}\quad\pi\geq\theta_c\geq\pi/2\qquad\cos\,\theta_c=-\sqrt{1-\frac{1}{\beta_n^2}}$$

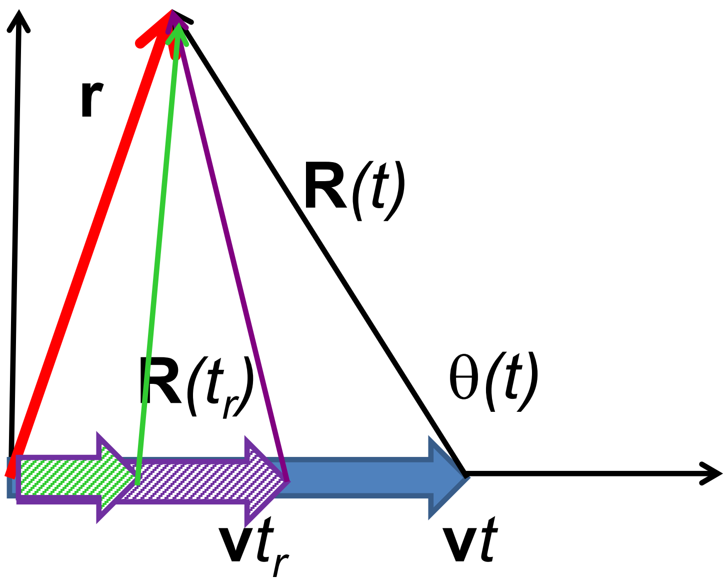
In this range, $\theta\geq\theta_c$

$$R(t_r) = \frac{R(t)}{\beta_n^{\,2} - 1}\left(-\beta_n \cos\theta \pm \sqrt{1 - \beta_n^{\,2}\sin^2\theta}\right)$$



$$\theta_c = 150^o \text{ for this case}$$

Physical fields for $\beta_n > 1$ -- two retarded solutions contribute



$$\theta \leq \sin^{-1}\left(\frac{1}{\beta_n}\right)$$

Define $\cos\theta_C \equiv -\sqrt{1-\frac{1}{\beta_n{}^2}}$

$$\Rightarrow \cos\theta \leq \cos\theta_C$$

Adding two solutions; in terms of Heaviside $\Theta(x)$:

$$\Phi\left(\mathbf{r},t\right) = \frac{2q}{\varepsilon}\frac{1}{R(t)\sqrt{1-\beta_n{}^2\sin^2\theta}}\Theta(\cos\theta_C - \cos\theta(t))$$

$$\mathbf{A}\left(\mathbf{r},t\right) = 2q\mu\frac{\boldsymbol{\beta}_n}{R(t)\sqrt{1-\beta_n{}^2\sin^2\theta}}\Theta(\cos\theta_C - \cos\theta(t))$$

Physical fields for $\beta_n > 1$

$$\Phi(\mathbf{r},t) = \frac{2q}{\varepsilon} \frac{1}{R(t)\sqrt{1-\beta_n{}^2 \sin^2\theta}} \Theta(\cos\theta_C - \cos\theta(t))$$

$$\mathbf{A}(\mathbf{r},t) = 2q\mu \frac{\boldsymbol{\beta}_n}{R(t)\sqrt{1-\beta_n{}^2 \sin^2\theta}} \Theta(\cos\theta_C - \cos\theta(t))$$

$$\mathbf{E}(\mathbf{r},t) = -\nabla\Phi - \frac{1}{c_n}\frac{\partial \mathbf{A}}{\partial t} \qquad \mathbf{B}(\mathbf{r},t) = \nabla \times \mathbf{A}$$

$$\mathbf{E}(\mathbf{r},t) = \frac{2q}{\varepsilon} \frac{\hat{\mathbf{R}}}{\left(R(t)\right)^2 \sqrt{1-\beta_n{}^2 \sin^2\theta}} \quad \times$$

$$\left(-\frac{\beta_n{}^2 - 1}{1-\beta_n{}^2 \sin^2\theta} \Theta(\cos\theta_C - \cos\theta(t)) + \sqrt{\beta_n{}^2 - 1}\; \delta(\cos\theta_C - \cos\theta(t)) \right)$$

$$\mathbf{B}(\mathbf{r},t) = -\beta_n \sin\theta \left(\hat{\theta} \times \mathbf{E}(\mathbf{r},t) \right)$$

From these results, we need to generate the power spectrum – following the approach in Sec. 23.7 in Zangwill's textbook.

When the dust clears, it can be shown the Cherenkov intensity per unit path length, per frequency is given by --

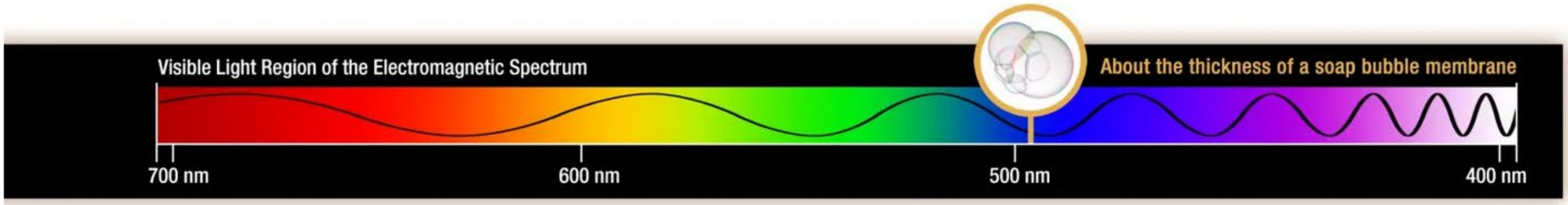
$$\frac{d^2 I}{d\ell d\omega} \propto \omega\left(\beta_n^2 - 1\right)$$

Noting that $c_n = \frac{c}{n(\omega)} = \frac{c}{\sqrt{\epsilon(\omega)}}$ $\qquad \beta_n = \frac{v}{c_n}$

$$\frac{d^2 I}{d\ell d\omega} \propto \omega\left(\epsilon(\omega)\frac{v^2}{c^2} - 1\right) = \frac{2\pi}{\lambda}\left(\epsilon(\omega)\frac{v^2}{c^2} - 1\right)$$

Visible Light Wavelengths --

700 **600** **500**



$$\frac{d^2 I}{d\ell d\omega} \propto \frac{2\pi}{\lambda}\left(\epsilon(\omega)\frac{v^2}{c^2} - 1\right)$$

If $\varepsilon \approx 1.8$ for water, what is the slowest particle speed that can generate Cherenkov radiation?

a. $v = 0.9c$

b. $v = 0.8c$

c. $v = 0.7c$

d. $v = 0.6c$