

Astrophysics

Lecture 07

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Four-velocity

The (infinitesimally small) difference between the coordinates of two events is also a four-vector. Dividing by the proper time yields a four-vector, the four-velocity:

$$U^\mu \equiv \frac{dx^\mu}{d\tau} \rightarrow U^0 = \frac{cdt}{d\tau} = c\gamma_u \quad \text{or} \quad U^i = \frac{dx^i}{d\tau} = \gamma_u u^i \quad \vec{U} = \gamma_u \begin{pmatrix} c \\ \mathbf{u} \end{pmatrix} \quad \text{where } \gamma_u \equiv (1 - u^2/c^2)^{-1/2}$$

$$u \equiv \left| \frac{d\mathbf{x}}{dt} \right|$$

length of the four-velocity : $\vec{U} \cdot \vec{U} = U^\mu U_\mu = -(\gamma_u c)^2 + (\gamma_u \mathbf{u})^2 = -c^2$

Transformation of the four-velocity:

$$\begin{aligned} U'^0 &= \gamma (U^0 - \beta U^1) & \gamma_{u'} c &= \gamma (c\gamma_u - \beta\gamma_u u^1) & \rightarrow & \gamma_{u'} = \gamma\gamma_u (1 - vu'/c^2) \\ U'^1 &= \gamma (-\beta U^0 + U^1) & \gamma_{u'} u'^1 &= \gamma (-\beta c\gamma_u + \gamma_u u^1) & \gamma_{u'} u'^1 &= \gamma\gamma_u (u^1 - v) \\ U'^2 &= U^2 & \gamma_{u'} u'^2 &= \gamma_u u^2 \\ U'^3 &= U^3 & \gamma_{u'} u'^3 &= \gamma_u u^3 \end{aligned}$$

The first two equations become:

$$\begin{aligned} \gamma_{u'} &= \gamma\gamma_u (1 - vu'/c^2) \\ \gamma_{u'} u'^1 &= \gamma\gamma_u (u^1 - v) \end{aligned}$$

Note: γ denotes the factor for the relative velocity between two frames.
 γ_u and $\gamma_{u'}$ are the factors for a velocity vector measured in K and K' , respectively.

velocity component:

$$u'^1 = \frac{u^1 - v}{1 - vu^1/c^2}$$

This is the previously derived formula.



speed:

$$\gamma_{u'} = \gamma\gamma_u \left(1 - \frac{vu^1}{c^2} \right)$$

This is the transform for speed.

Here, $u^1 = u \cos \theta$ and $u'^1 = u' \cos \theta'$

Momentum and Energy

- Four-momentum of a particle with a mass m_0 is defined by

$$P^\mu \equiv m_0 U^\mu \quad P^0 = m_0 c \gamma_v \quad P^i = \gamma_v m_0 \mathbf{v}$$

- In the nonrelativistic limit,

$$P^0 c = m_0 c^2 \gamma = m_0 c^2 \left(1 - \frac{v^2}{c^2} \right)^{-1/2} = m_0 c^2 + \frac{1}{2} m_0 v^2 + \dots$$

Therefore, we interpret $E \equiv P^0 c = \gamma_v m_0 c^2$ as the total energy of the particle.

The quantity $m_0 c^2$ is interpreted as the rest energy of the particle.

Then,

$\mathbf{p} \equiv \gamma_v m_0 \mathbf{v}$, $P^\mu = (E/c, \mathbf{p})$ Here, \mathbf{p} is the spatial component of the four-momentum.

Since $\vec{U}^2 = -c^2$, we obtain $\vec{P}^2 = -m_0^2 c^2$. Comparing with $\vec{P}^2 = -\frac{E^2}{c^2} + |\mathbf{p}|^2$, we obtain

$$E^2 = m_0^2 c^4 + c^2 |\mathbf{p}|^2$$

- Photons are massless, but we can still define

$$P^\mu = (E/c, \mathbf{p}), \quad E = |\mathbf{p}| c \quad \rightarrow \quad \vec{P}^2 = 0$$

Wavenumber vector and frequency

- Quantum relations:

$$\begin{aligned} E &= h\nu = \hbar\omega \\ p &= E/c = \hbar k \end{aligned} \quad \left(\begin{array}{l} \omega = 2\pi\nu \\ k = 2\pi/\lambda \end{array} \right)$$

We can define four wavenumber vector:

$$\vec{k} = \frac{1}{\hbar} \vec{P} = \left(\frac{\omega}{c}, \mathbf{k} \right)$$

Then, we obtain an invariant:

$$\vec{k} \cdot \vec{x} = k_\mu x^\mu = \mathbf{k} \cdot \mathbf{x} - \omega t$$

Note that it's a null vector:

$$\vec{k} \cdot \vec{k} = |\mathbf{k}|^2 - \omega^2/c^2 = 0$$

Therefore, **the phase of the plane wave is an invariant.**

- Transform of \vec{k} gives the Doppler shift formula.

$$\begin{aligned} k'^0 &= \gamma (k^0 - \beta k^1) & \longrightarrow & \omega' = \gamma (\omega - \beta c k^1) = \omega \gamma \left(1 - \frac{v}{c} \cos \theta \right) \\ k'^1 &= \gamma (-\beta k^0 + k^1) & & \uparrow \\ k'^2 &= k^2 \\ k'^3 &= k^3 \end{aligned}$$

* Tensor Analysis *

- Definition:

zeroth-rank tensor : Lorentz invariant (scalar) $s' = s$

first-rank tensor : four-vector $x'^\mu = \Lambda^\mu{}_\nu x^\nu$

second-rank tensor: $T'^{\mu\nu} = \Lambda^\mu{}_\sigma \Lambda^\nu{}_\tau T^{\sigma\tau}$

- Covariant components and mixed components:

$$T_{\mu\nu} = \eta_{\mu\sigma}\eta_{\nu\tau}T^{\sigma\tau} \quad T^\mu{}_\nu = \eta_{\nu\tau}T^{\mu\tau} \quad T_\mu{}^\nu = \eta_{\mu\sigma}T^{\sigma\nu}$$

- Transformation rules:

$$\begin{aligned} T'_{\mu\nu} &= \eta_{\mu\alpha}\eta_{\nu\beta}T'^{\alpha\beta} \\ &= \eta_{\mu\alpha}\eta_{\nu\beta}\Lambda^\alpha{}_\gamma\Lambda^\beta{}_\delta T^{\gamma\delta} \\ &= \eta_{\mu\alpha}\eta_{\nu\beta}\Lambda^\alpha{}_\gamma\Lambda^\beta{}_\delta\eta^{\gamma\sigma}\eta^{\delta\tau}T_{\sigma\tau} \\ &= \tilde{\Lambda}_\mu{}^\sigma\tilde{\Lambda}_\nu{}^\tau T_{\sigma\tau} \end{aligned}$$

$$\begin{aligned} T'^\mu{}_\nu &= \eta_{\nu\alpha}T'^{\mu\alpha} \\ &= \eta_{\nu\alpha}\Lambda^\mu{}_\sigma\Lambda^\alpha{}_\delta T^{\sigma\delta} \\ &= \eta_{\nu\alpha}\Lambda^\mu{}_\sigma\Lambda^\alpha{}_\delta\eta^{\delta\tau}T_\tau^\sigma \\ &= \Lambda^\mu{}_\sigma\tilde{\Lambda}_\nu{}^\tau T_\sigma^\tau \end{aligned}$$

$$\begin{aligned} T'_\mu{}^\nu &= \eta_{\mu\alpha}T'^{\alpha\nu} \\ &= \eta_{\mu\alpha}\Lambda^\alpha{}_\beta\Lambda^\nu{}_\tau T^{\beta\tau} \\ &= \eta_{\mu\alpha}\Lambda^\alpha{}_\beta\Lambda^\nu{}_\tau\eta^{\beta\sigma}T_\sigma{}^\tau \\ &= \tilde{\Lambda}_\mu{}^\beta\Lambda^\nu{}_\tau T_\sigma{}^\tau \end{aligned}$$

- Symmetric tensor = a tensor that is invariant under a permutation of its indices.

$$T^{\mu\nu} = T^{\nu\mu}$$

- Antisymmetric tensor : if it alternates sign when any two indices of the subset are interchanged.

$$T^{\mu\nu} = -T^{\nu\mu}$$

- Examples of the second-rank tensors

A product of two vectors: $A^\mu B^\nu$

$$A'^\mu B'^\nu = \Lambda^\mu{}_\sigma \Lambda^\nu{}_\tau A^\sigma B^\tau$$

The Minkowski metric:

$$\eta^{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

The Kronecker-delta:

$$\delta^\mu{}_\nu = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

- Higher-rank tensors
 - Addition: $A^\mu + B^\mu$, $F^{\mu\nu} + G^{\mu\nu}$
 - Multiplication: $A^\mu B^\nu$, $F^{\mu\nu} G_{\sigma\tau}$
 - Raising and Lowering Indices: The metric can be used to change contravariant indices into covariant ones, and vice versa, by the processes of raising and lowering.
 - Contraction: $A^\mu B_\nu \rightarrow A^\mu B_\mu$ scalar
 $T^{\mu\nu}_\sigma \rightarrow T^{\mu\nu}_\nu$ vector

$$T'^{\mu\nu}_\nu = \Lambda^\mu_\alpha \Lambda^\nu_\beta \tilde{\Lambda}_\nu^\tau T^{\alpha\beta}_\tau = \Lambda^\mu_\alpha \delta^\tau_\beta T^{\alpha\beta}_\tau = \Lambda^\mu_\alpha T^{\alpha\beta}_\beta$$

- Gradients of Tensor Fields: A tensor field is a tensor that is a function of the spacetime coordinates in Cartesian coordinate systems. The gradient operation $\partial/\partial x^\mu \equiv \partial_\mu$ acting on such a field produces a tensor field of on higher rank with μ as a new covariant index.

$$\lambda \rightarrow \frac{\partial \lambda}{\partial x^\mu} \equiv \partial_\mu \lambda \equiv \lambda_{,\mu} \quad \text{vector (gradient)} \quad A^\mu \rightarrow \frac{\partial A^\mu}{\partial x^\mu} \equiv \partial_\mu A^\mu \equiv A^\mu_{,\mu} \quad \text{scalar (divergence)}$$

- **Invariance of form or Lorentz covariance or covariance:** A fundamental property of a tensor equation is that if it is true in one Lorentz frame, then it is true in all Lorentz frames. Covariance plays a powerful role in helping decide what the proper equations of physics are.

[Covariance of Electromagnetic Phenomena]

- Equation of charge conservation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \mathbf{j} = 0$$

The above equation can be written as a tensor equation,

$$\frac{\partial j^\mu}{\partial x^\mu} = 0, \quad j^{\mu,\mu} = 0 \quad \text{or} \quad \partial_\mu j^\mu = 0$$

$$\partial_\mu \equiv \frac{\partial}{\partial x^\mu} = \left(\frac{\partial}{c\partial t}, \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right)$$

$$\partial^\mu \equiv \frac{\partial}{\partial x_\mu} = \left(-\frac{\partial}{c\partial t}, \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right)$$

if the **four-current** is defined by

$$j^\mu = \begin{pmatrix} \rho c \\ \mathbf{j} \end{pmatrix} \qquad j_\mu = \begin{pmatrix} -\rho c \\ \mathbf{j} \end{pmatrix}$$

- Note that the Jacobian (determinant) of the transformation from x_μ to x'_μ is simply the determinant of Λ , which is unity. Therefore, the **four-volume element** is an invariant.

$$dx'_0 dx'_1 dx'_2 dx'_3 = \det \Lambda dx_0 dx_1 dx_2 dx_3 = dx_0 dx_1 dx_2 dx_3$$

Since ρ is the zeroth component of the four-current, the charge element within a three-volume element is an invariant.

$$de = \rho dx_1 dx_2 dx_3$$

It is also an empirical fact that e is invariant.

- The set of vector and scalar wave equations in the Lorentz gauge is

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

$$\nabla^2 \phi - \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} = -\frac{4\pi}{c} (\rho c)$$

If we define the **four-potential**

$$A^\mu = \begin{pmatrix} \phi \\ \mathbf{A} \end{pmatrix}, \quad A_\mu = \begin{pmatrix} -\phi \\ \mathbf{A} \end{pmatrix},$$

then the wave equations can be written as the tensor equations

$$\frac{\partial^2 A^\mu}{\partial x^\nu \partial x_\nu} = -\frac{4\pi}{c} j^\mu, \quad \partial_\nu \partial^\nu A^\mu = -\frac{4\pi}{c} j^\mu, \quad A^{\mu,\nu} = -\frac{4\pi}{c} j^\mu$$

d'Alembertian operator: $\square \equiv \frac{\partial^2}{\partial x^\nu \partial x_\nu} \rightarrow \square A^\mu = -\frac{4\pi}{c} j^\mu$

- The Lorentz gauge should be preserved under Lorentz transformations.

$$\nabla \cdot \mathbf{A} + \frac{1}{c} \frac{\partial \phi}{\partial t} = 0 \rightarrow \frac{\partial A^\mu}{\partial x^\mu} = 0 \text{ or } A^\mu{}_\mu = 0$$

- **Electromagnetic field tensor:**

The fields are expressed in terms of the potentials as $\mathbf{E} = -\nabla\phi - \frac{1}{c}\frac{\partial\mathbf{A}}{\partial t}$
 $\mathbf{B} = \nabla \times \mathbf{A}$

The x components of the electric and magnetic fields are explicitly

$$\begin{aligned} E_x &= -\frac{1}{c}\frac{\partial A_x}{\partial t} - \frac{\partial\phi}{\partial x} = \partial^0 A^1 - \partial^1 A^0 \\ B_x &= \frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z} = \partial^2 A^3 - \partial^3 A^2 \end{aligned}$$

These equations imply that the electric and magnetic fields, six components in all, are the elements of a **second-rank, antisymmetric field-strength tensor**, because a rank two antisymmetric tensor has exactly six independent components.

$$F^{\mu\nu} \equiv \partial^\mu A^\nu - \partial^\nu A^\mu = \begin{pmatrix} 0 & E_x & E_y & E_z \\ -E_x & 0 & B_z & -B_y \\ -E_y & -B_z & 0 & B_x \\ -E_z & B_y & -B_x & 0 \end{pmatrix} \quad \longrightarrow \quad \begin{aligned} F^{0i} &= E_i \\ F^{i0} &= -E_i \\ F^{12} &= -F^{21} = B_3, \dots \end{aligned}$$

covariant field-strength tensor

$$F_{\mu\nu} = \eta_{\mu\alpha}\eta_{\nu\beta}F^{\alpha\beta}$$



$$F_{0i} = \eta_{0\alpha}\eta_{i\beta}F^{\alpha\beta} = -F^{0i}$$

$$F_{i0} = \eta_{i\alpha}\eta_{0\beta}F^{\alpha\beta} = -F^{i0}$$

$$F_{ij} = \eta_{i\alpha}\eta_{j\beta}F^{\alpha\beta} = F^{ij}$$

$$F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu = \begin{pmatrix} 0 & -E_x & -E_y & -E_z \\ E_x & 0 & B_z & -B_y \\ E_y & -B_z & 0 & B_x \\ E_z & B_y & -B_x & 0 \end{pmatrix}$$



$$F_{0i} = -E_i$$

$$F_{i0} = E_i$$

$$F_{12} = -F_{21} = B_3, \dots$$

- The two Maxwell equations containing sources (inhomogeneous equations):

$$\nabla \cdot \mathbf{E} = 4\pi\rho$$

$$\nabla \times \mathbf{B} - \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t} = \frac{4\pi}{c} \mathbf{j}$$



$$\sum_{i=1}^3 \partial_i E_i = \frac{4\pi}{c} j^0$$

$$\partial_2 B_3 - \partial_3 B_2 - \partial_0 E_1 = \frac{4\pi}{c} j^1$$



$$-\sum_{i=1}^3 \partial_i F^{i0} = \frac{4\pi}{c} j^0$$

$$-\partial_0 F^{01} - \partial_2 F^{21} - \partial_3 F^{31} = \frac{4\pi}{c} j^1$$

$$\partial_\mu F^{\mu\nu} = -\frac{4\pi}{c} j^\nu \quad \text{or} \quad \partial_\nu F^{\mu\nu} = \frac{4\pi}{c} j^\mu$$

$$\partial^\mu F_{\mu\nu} = -\frac{4\pi}{c} j_\nu \quad \text{or} \quad \partial^\nu F_{\mu\nu} = \frac{4\pi}{c} j_\mu$$

- The conservation of charge easily follows from the above equation and the asymmetric property.

$$\partial_\mu \partial_\nu F^{\mu\nu} = \partial_\nu \partial_\mu (-F^{\nu\mu}) = -\partial_\mu \partial_\nu F^{\mu\nu}$$

↑
index exchange

$$\therefore \boxed{\partial_\mu \partial_\nu F^{\mu\nu} = 0}$$

$$\partial_\nu j^\nu = -\frac{c}{4\pi} \partial_\nu \partial_\mu F^{\mu\nu} = 0$$

- The “internal” Maxwell equations (homogeneous equations):

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} + \frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} = 0 \quad \longrightarrow \quad \sum_{i=1}^3 \partial_i B_i = 0$$

$$\partial_2 E_3 - \partial_3 E_2 + \partial_0 B_1 = 0 \quad \longrightarrow \quad \begin{aligned} \partial_1 F^{23} + \partial_2 F^{31} + \partial_3 F^{12} &= 0 \\ \partial_2 F^{30} + \partial_3 F^{20} + \partial_0 F^{23} &= 0 \end{aligned}$$

$$\boxed{\partial_\mu F^{\nu\sigma} + \partial_\nu F^{\sigma\mu} + \partial_\sigma F^{\mu\nu} = 0} \quad \text{or} \quad \partial^\mu F_{\nu\sigma} + \partial^\nu F_{\sigma\mu} + \partial^\sigma F_{\mu\nu} = 0$$

The equation can be written concisely as $F^{[\mu\nu,\sigma]} = 0$ or $F_{[\mu\nu,\sigma]} = 0$, where [] around indices denote all permutations of indices, with even permutation contributing with a positive sign and odd permutation with a negative sign, for example,

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu = A_{[\nu,\mu]}$$

- Transformation of Electromagnetic Fields

- Since $F^{\mu\nu}$ is a second-rank tensor, its components transform in the usual way:

$$F'^{\mu\nu} = \frac{\partial x'^\mu}{\partial x^\alpha} \frac{\partial x'^\nu}{\partial x^\beta} F^{\alpha\beta} = \Lambda^\mu{}_\alpha \Lambda^\nu{}_\beta F^{\alpha\beta}$$

For a pure boost along the x -axis:

$$\Lambda^\mu{}_\nu = \begin{pmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \longrightarrow \begin{aligned} E'_x &= F'^{01} = \Lambda^0{}_0 \Lambda^1{}_1 F^{01} + \Lambda^0{}_1 \Lambda^1{}_0 F^{10} = \gamma^2 E_x - \beta^2 \gamma^2 E_x = E_x \\ E'_y &= F'^{02} = \Lambda^0{}_0 \Lambda^2{}_2 F^{02} + \Lambda^0{}_1 \Lambda^2{}_2 F^{12} = \gamma E_y - \beta \gamma B_z \\ E'_z &= F'^{03} = \Lambda^0{}_0 \Lambda^3{}_3 F^{03} + \Lambda^0{}_1 \Lambda^3{}_3 F^{13} = \gamma E_z + \beta \gamma B_y \\ B'_x &= F'^{23} = \Lambda^2{}_2 \Lambda^3{}_3 F^{23} = B_x \\ B'_y &= F'^{31} = \Lambda^3{}_3 (\Lambda^1{}_0 F^{30} - \Lambda^1{}_1 F^{31}) = \beta \gamma E_z + \gamma B_y \\ B'_z &= F'^{12} = \Lambda^1{}_0 \Lambda^2{}_2 F^{03} + \Lambda^1{}_1 \Lambda^2{}_2 F^{12} = -\beta \gamma E_y + \gamma B_z \end{aligned}$$

- In general,

$$\mathbf{E}'_{\parallel} = \mathbf{E}_{\parallel}$$

$$\mathbf{E}'_{\perp} = \gamma (\mathbf{E}_{\perp} + \boldsymbol{\beta} \times \mathbf{B})$$

$$\mathbf{B}'_{\parallel} = \mathbf{B}_{\parallel}$$

$$\mathbf{B}'_{\perp} = \gamma (\mathbf{B}_{\perp} - \boldsymbol{\beta} \times \mathbf{E})$$

The concept of a pure electric or pure magnetic is not Lorentz invariant.

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- Lorenz invariants:

dot product of F with itself or “square” of F :

$$F^{\mu\nu} F_{\mu\nu} = \sum_{i=1}^3 F^{0i} F_{0i} + \sum_{i=1}^3 F^{i0} F_{i0} + \sum_{i \neq j} F^{ij} F_{ij} = 2 (\mathbf{B}^2 - \mathbf{E}^2)$$

determinant of F :

$$\det F = (\mathbf{E} \cdot \mathbf{B})^2$$

[Relativistic Mechanics and the Lorentz Four-Force]

- We can define a **four-acceleration** a^μ in exactly the same way as we obtained the four-velocity.

$$a^\mu \equiv \frac{dU^\mu}{d\tau}$$

Note that the four-acceleration and four-velocity are orthogonal:

$$\vec{a} \cdot \vec{U} \equiv \frac{dU^\mu}{d\tau} U_\mu = \frac{1}{2} \frac{d}{d\tau} (U^\mu U_\mu) = \frac{1}{2} \frac{d}{d\tau} (-c^2) = 0$$

- We can also define the four-force F^μ from the Lorentz force, so as to obtain a relativistic form of Newton's equation.

$$F^\mu \equiv m_0 a^\mu = \frac{dP^\mu}{d\tau}$$

$$\vec{F} = \frac{d\vec{P}}{d\tau} = \gamma \frac{d\vec{P}}{d\tau} = \gamma \left(\frac{1}{c} \frac{dE}{dt}, \frac{d\mathbf{p}}{dt} \right)$$

Since $\mathbf{F}_{\text{Lorentz}} = q \left[\mathbf{E} + \frac{1}{c} (\mathbf{v} \times \mathbf{B}) \right]$, the **Lorentz four-force** should involve (1) the electromagnetic field tensor and (2) the four-velocity and should also be (3) a four-vector and (4) proportional to the charge of the particle. Therefore, the simplest possibility is

$$F_{\text{Lorentz}}^\mu = \frac{q}{c} F^{\mu\nu} U_\nu$$

- Let's check to see if it is indeed what we want.

$$F_{\text{Lorentz}}^0 = \frac{q}{c} F^{0\nu} U_\nu = \frac{q}{c} \sum_{i=1}^3 E_i \gamma v_i = \frac{q}{c} \gamma (\mathbf{E} \cdot \mathbf{v}) \longrightarrow \frac{dE}{dt} = q \mathbf{E} \cdot \mathbf{v} : \text{conservation of energy}$$

The rate of change of particle energy is the mechanical work done on the particle by the field.

$$\begin{aligned} F_{\text{Lorentz}}^1 &= \frac{q}{c} F^{1\nu} U_\nu = \frac{q}{c} (F^{10}(-\gamma c) + F^{12}\gamma v_2 + F^{13}\gamma v_3) \\ &= \frac{q}{c} \gamma (E_1 c + B_3 v_2 - B_2 v_3) \end{aligned} \longrightarrow \frac{d\mathbf{p}}{dt} = q \left(\mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B} \right)$$

Therefore, we obtained the desired expression for the four-Lorentz force.

- Note that **the four-force is always orthogonal to the four-velocity**:

$$\vec{F} \cdot \vec{U} = m_0 (\vec{a} \cdot \vec{U}) = 0$$

It implies that **every four-force must have some velocity dependence**.

For the Lorentz four-force, in particular, we find

$$\vec{F}_{\text{Lorentz}} \cdot \vec{U} = \frac{q}{c} F^{\mu\nu} U_\mu U_\nu = 0$$

because $F^{\mu\nu}$ is antisymmetric and $U_\mu U_\nu$ is symmetric.

Mathematical Formulae

- Gamma function

$$\Gamma(x) \equiv \int_0^\infty t^{x-1} e^{-t} dt, \quad \Gamma(x) = (x-1)! = (x-1)\Gamma(x-2), \quad \Gamma(3/2) = \frac{1}{2}\Gamma(1/2) = \frac{\sqrt{\pi}}{2}$$

- Euler-Mascheroni constant

$$\gamma \equiv \lim_{n \rightarrow \infty} \left(\sum_{k=1}^n \frac{1}{k} - \ln(n) \right) = - \int_0^\infty e^{-x} \ln x dx = 0.577215664901532$$

- Modified Bessel function of the second kind

$$K_n(x) \equiv \frac{\Gamma(n+1/2)(2x)^n}{\sqrt{\pi}} \int_0^\infty \frac{\cos t}{(t^2 + x^2)^{n+1/2}} dt$$

$$(1) \quad 0 < x < \sqrt{n+1}$$

$$K_n(x) \approx \begin{cases} -\ln\left(\frac{x}{2}\right) - \gamma & \text{if } n = 0 \\ \frac{\Gamma(n)}{2} \left(\frac{2}{x}\right)^n & \text{if } n > 0 \end{cases}$$

$$(2) \quad x \gg |n^2 - 1/4|$$

$$K_n(x) \approx \sqrt{\frac{\pi}{2x}} e^{-x} \left[1 + \frac{(4n^2 - 1)}{8x} \right]$$

Recurrence formulae

$$K_{n-1}(x) - K_{n+1}(x) = -\frac{2n}{x} K_n(x)$$

$$K_{n-1}(x) + K_{n+1}(x) = -2K'_n(x)$$

Integral formula

$$\begin{aligned} \int x K_n^2(x) dx &= \frac{1}{2} x^2 [K_n^2(x) - K_{n-1}(x)K_{n+1}(x)] \\ &= -x K_{n-1}(x) K_n(x) + \\ &\quad \frac{1}{2} x^2 [K_n^2(x) - K_{n-1}^2(x)] \end{aligned}$$

[Fields of a Uniformly Moving Charge]

- Let's find the fields of a charge moving with constant velocity v along the x axis. In the rest frame of the particle the fields are

$$\mathbf{E}' = (E'_x, E'_y, E'_z) = \frac{q}{r'^3} (x', y', z')$$

where $r' = (x'^2 + y'^2 + z'^2)^{1/2}$

$$\mathbf{B}' = (0, 0, 0)$$

inverse transformation of the previous one:

$$\begin{aligned} \mathbf{E}_{\parallel} &= \mathbf{E}'_{\parallel} & \mathbf{B}_{\parallel} &= \mathbf{B}'_{\parallel} \\ \mathbf{E}_{\perp} &= \gamma (\mathbf{E}'_{\perp} - \boldsymbol{\beta} \times \mathbf{B}') & \mathbf{B}_{\perp} &= \gamma (\mathbf{B}'_{\perp} + \boldsymbol{\beta} \times \mathbf{E}') \end{aligned}$$

$$\begin{aligned} E_x &= \frac{qx'}{r'^3} & B_x &= 0 \\ E_y &= \gamma \frac{qy'}{r'^3} & B_y &= -\gamma \beta \frac{qz'}{r'^3} \\ E_z &= \gamma \frac{qz'}{r'^3} & B_z &= \gamma \beta \frac{qy'}{r'^3} \end{aligned}$$

Since $x' = \gamma(x - vt)$, $y' = y$, $z' = z$, we obtain

$$\begin{aligned} E_x &= \gamma \frac{q(x - vt)}{r^3} & B_x &= 0 \\ E_y &= \gamma \frac{qy}{r^3} & B_y &= -\gamma \beta \frac{qz}{r^3} \\ E_z &= \gamma \frac{qz}{r^3} & B_z &= \gamma \beta \frac{qy}{r^3} \end{aligned}$$

where $r = [(x - vt)^2 + y^2 + z^2]^{1/2}$

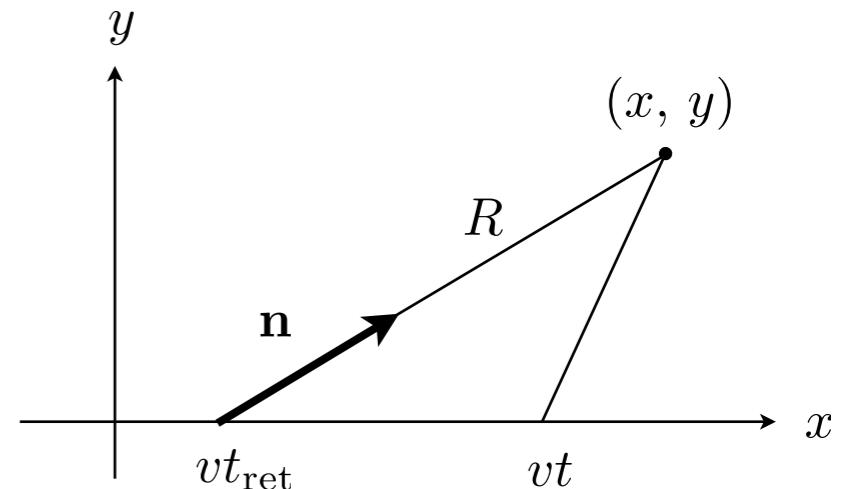
Is this equivalent to the fields given by the Lienard-Wiechert potentials?

- Velocity field from the retarded potential

- For simplicity, assume $z = 0$.

$$\begin{aligned}\mathbf{E} &= (E_x, E_y, E_z) = \gamma \frac{q}{r^3} (x - vt, y, z) \\ &= \gamma \frac{q}{(\gamma^2 \bar{x}^2 + y^2)^{3/2}} (\bar{x}, y, 0) \quad \text{where } \bar{x} \equiv x - vt\end{aligned}$$

Let us first find where the retarded position of the particle is.



$$t_{\text{ret}} \equiv t - R/c$$

$$R^2 = (x - vt_{\text{ret}})^2 + y^2 = (\bar{x} + \beta R)^2 + y^2$$

$$\mathbf{n} = \frac{(\bar{x} + \beta R)}{R} \hat{\mathbf{x}} + \frac{y}{R} \hat{\mathbf{y}} = \left(\frac{\bar{x}}{R} + \beta \right) \hat{\mathbf{x}} + \frac{y}{R} \hat{\mathbf{y}}$$

$$R \rightarrow (1 - \beta^2)^2 R^2 - 2\bar{x}\beta R - \bar{x}^2 - y^2 = 0$$

$$R^2 - 2\bar{x}\gamma^2\beta R - \gamma^2(\bar{x}^2 + y^2) = 0$$

$$R = \gamma^2\beta\bar{x} \pm [\gamma^4\beta^2\bar{x}^2 + \gamma^2(\bar{x}^2 + y^2)]^{1/2}$$

$$= \gamma^2\beta\bar{x} \pm \gamma[\gamma^2\beta^2\bar{x}^2 + (\bar{x}^2 + y^2)]^{1/2}$$

$$= \gamma^2\beta\bar{x} \pm \gamma(\gamma^2\bar{x}^2 + y^2)^{1/2}$$

positive solution $\rightarrow R = \gamma^2\beta\bar{x} + \gamma(\gamma^2\bar{x}^2 + y^2)^{1/2}$

$$(1) \quad \mathbf{n} - \boldsymbol{\beta} = \frac{\bar{x}}{R} \hat{\mathbf{x}} + \frac{y}{R} \hat{\mathbf{y}}$$

$$\mathbf{E} = \gamma \frac{q}{(\gamma^2 \bar{x}^2 + y^2)^{3/2}} (\mathbf{n} - \boldsymbol{\beta})$$

$$(2) \quad (\gamma^2 \bar{x}^2 + y^2)^{1/2} = \frac{R - \gamma^2 \beta \bar{x}}{\gamma} = R\gamma \left(\frac{1}{\gamma^2} - \frac{\beta \bar{x}}{R} \right)$$

$$= R\gamma \left(1 - \beta^2 - \frac{\beta \bar{x}}{R} \right)$$

$$= R\gamma \left[1 - \beta \left(\frac{\bar{x}}{R} + \beta \right) \right]$$

$$= R\gamma (1 - \mathbf{n} \cdot \boldsymbol{\beta}) = R\gamma \kappa$$

$$\therefore \mathbf{E} = q \frac{(\mathbf{n} - \boldsymbol{\beta})}{\gamma^2 \kappa^3 R^2} = q \frac{(\mathbf{n} - \boldsymbol{\beta})(1 - \beta^2)}{\kappa^3 R^2} \quad : \text{velocity field}$$

- Time-dependence of the electric field at a point

- Let us choose the field point to be at $(0, b, 0)$.

This involves no loss in generality. Then,

$$E_x = -\frac{q\gamma vt}{(\gamma^2 v^2 t^2 + b^2)^{3/2}} = -\frac{q}{b^2} \frac{\gamma vt/b}{(\gamma^2 v^2 t^2/b^2 + 1)^{3/2}}$$

$$E_y = \frac{q\gamma b}{(\gamma^2 v^2 t^2 + b^2)^{3/2}} = \frac{q\gamma}{b^2} \frac{1}{(\gamma^2 v^2 t^2/b^2 + 1)^{3/2}}$$

$$E_z = 0$$

$$B_x = 0$$

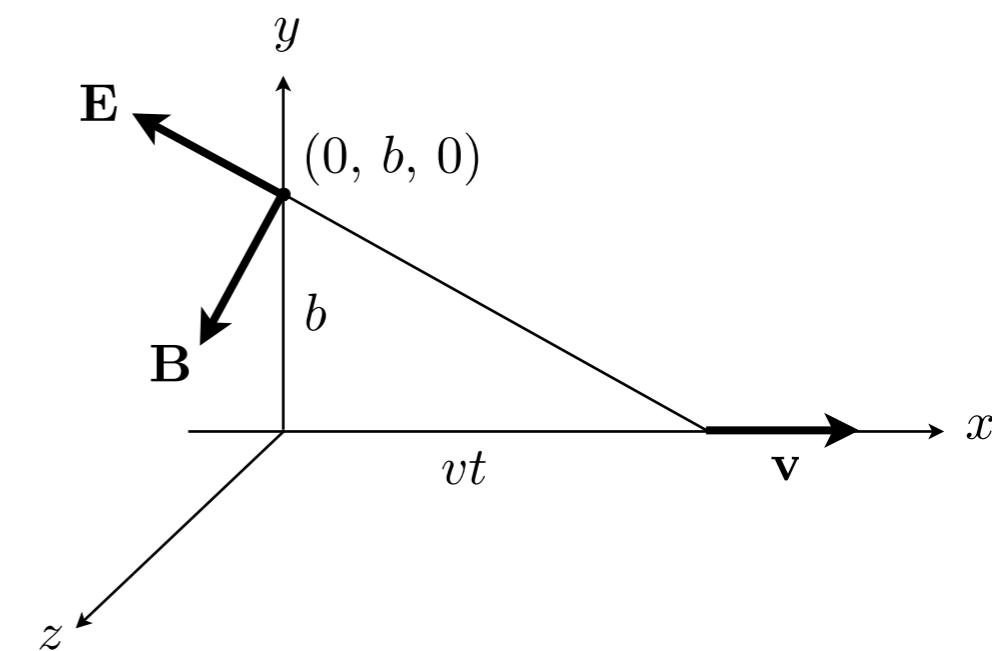
$$B_y = 0$$

$$B_z = \beta E_y$$

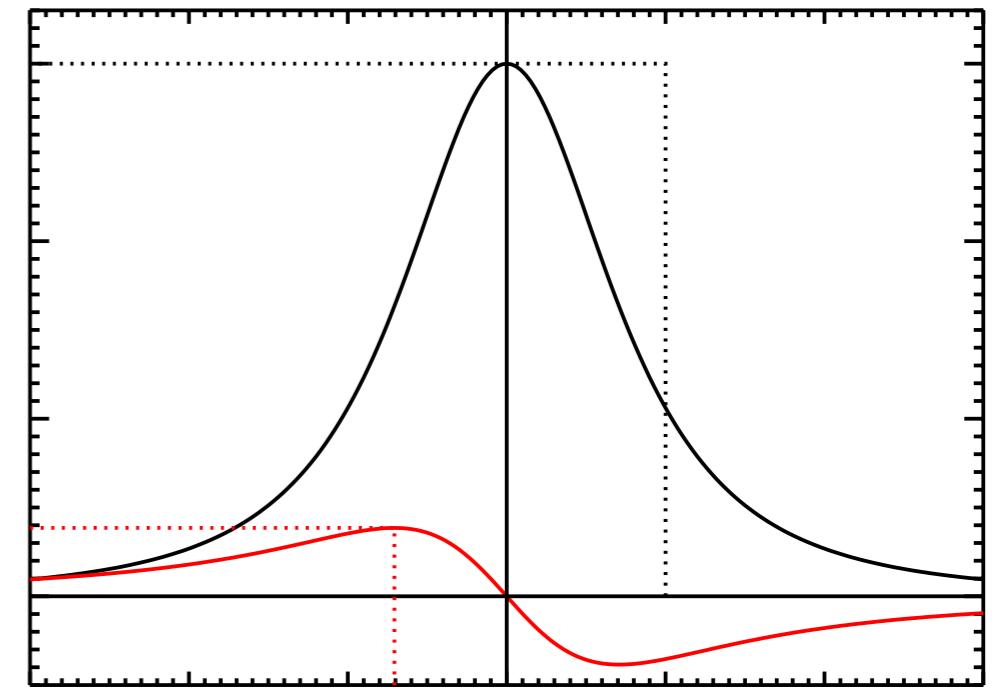
As $\gamma \gg 1 \rightarrow |E_x| \ll E_y$

The field of a highly relativistic charge appears to be a pulse of radiation traveling in the same direction as the charge and confined to the transverse plane.

$$\text{Max } E_x = \frac{2}{3^{3/2}} \frac{q}{b^2}$$



$$\text{Max } E_y = \gamma \frac{q}{b^2}$$



$$|t| = \frac{1}{\sqrt{2}} \frac{b}{\gamma v} \quad |t| \approx \frac{b}{\gamma v}$$

- Spectrum of the pulse

- Spectrum of this pulse of virtual radiation.

$$\begin{aligned}
 \hat{E}(\omega) &= \frac{1}{2\pi} \int E_y(t) e^{i\omega t} dt \\
 &= \frac{q\gamma b}{2\pi} \int_{-\infty}^{\infty} (\gamma^2 v^2 t^2 + b^2)^{-3/2} e^{i\omega t} dt = \frac{q\gamma b}{2\pi} \int_0^{\infty} (\gamma^2 v^2 t^2 + b^2)^{-3/2} (e^{i\omega t} + e^{-i\omega t}) dt \\
 &= \frac{q\gamma b}{\pi} \int_0^{\infty} (\gamma^2 v^2 t^2 + b^2)^{-3/2} \cos \omega t dt
 \end{aligned}$$

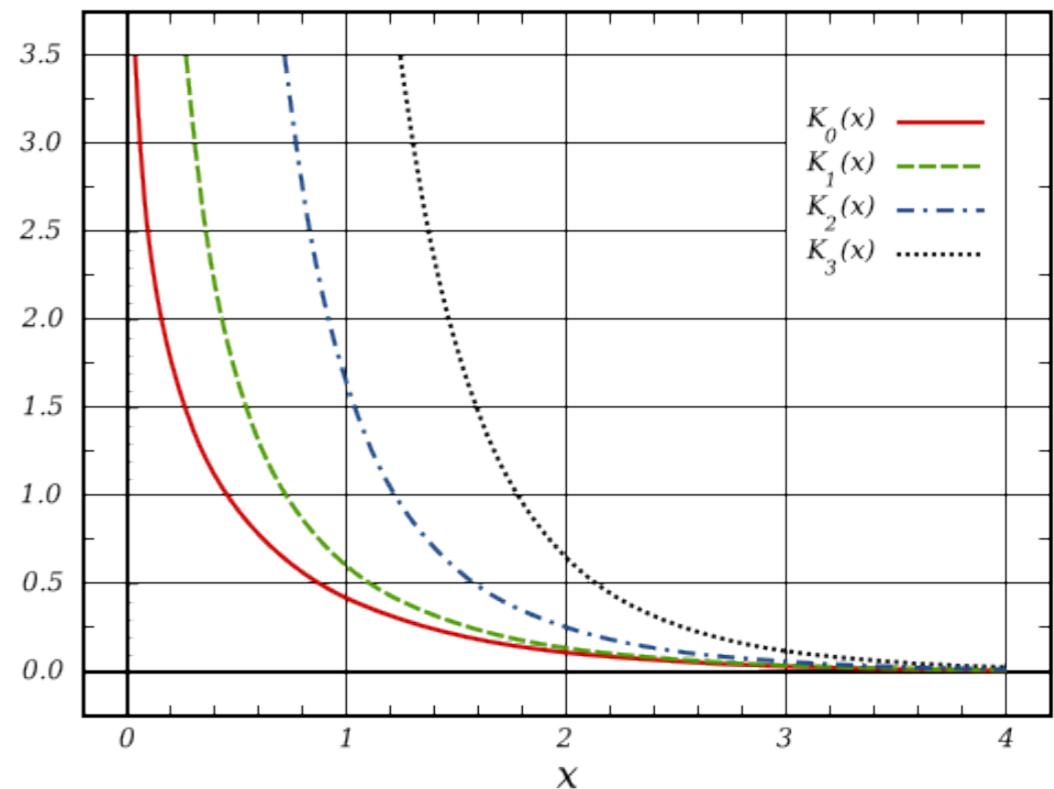
This integral can be done in terms of the modified Bessel function:

$$K_n(x) \equiv \frac{\Gamma(n + 1/2)(2x)^n}{\sqrt{\pi}} \int_0^{\infty} \frac{\cos t}{(t^2 + x^2)^{n+1/2}} dt \quad \text{Gamma function: } \Gamma(3/2) = \frac{1}{2}\Gamma(1/2) = \frac{\sqrt{\pi}}{2}$$

$$\begin{aligned}
 \hat{E}(\omega) &= \frac{q\gamma b}{\pi} \left(\frac{\gamma^2 v^2}{\omega^2} \right)^{-3/2} \frac{1}{\omega} \int_0^{\infty} \left(\omega^2 t^2 + \frac{b^2 \omega^2}{\gamma^2 v^2} \right)^{-3/2} (\cos \omega t) d(\omega t) \\
 &= \frac{q}{\pi b v} \frac{b \omega}{\gamma v} K_1 \left(\frac{b \omega}{\gamma v} \right)
 \end{aligned}$$

Thus the spectrum is

$$\frac{dW}{dA d\omega} = c |\hat{E}(\omega)|^2 = \frac{q^2}{\pi^2 b^2 v^2} \left(\frac{b \omega}{\gamma v} \right)^2 K_1^2 \left(\frac{b \omega}{\gamma v} \right)$$

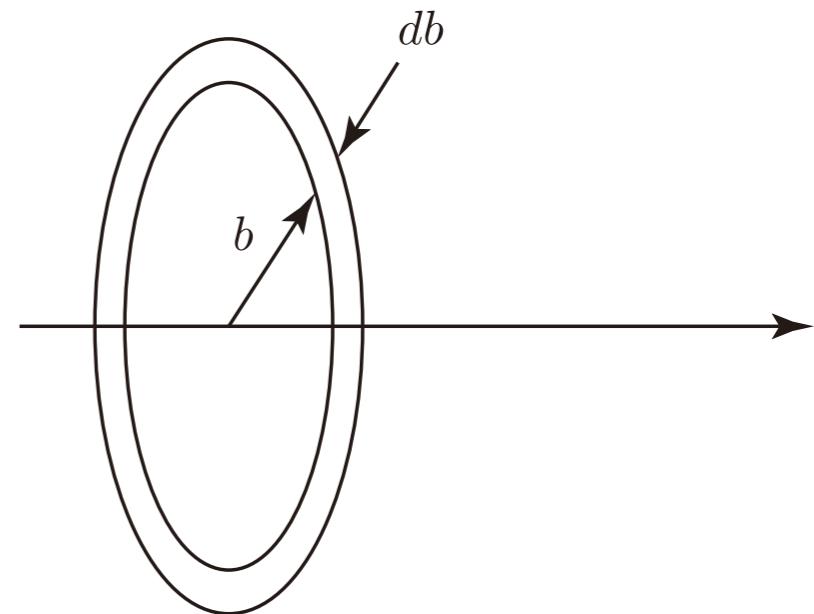


The spectrum starts cut off for $\omega > \gamma v/b$.

$$\Delta\omega \sim \frac{1}{\Delta t} \sim \gamma v/b$$

- Total energy per unit frequency range is obtained by

$$\frac{dW}{d\omega} = 2\pi \int_{b_{\min}}^{b_{\max}} \frac{dW}{dAd\omega} b db$$



The lower limit has been chosen as some minimum distance, such that the approximation of the field by means of classical electrodynamics and a point charge is valid.

$$\begin{aligned} \frac{dW}{d\omega} &= \frac{2q^2c}{\pi v^2} \int_x^\infty y K_1^2(y) dy \\ &= \frac{2q^2c}{\pi v^2} \left[x K_0(x) K_1(x) - \frac{1}{2} x^2 (K_1^2(x) - K_0^2(x)) \right] \end{aligned}$$

where $y \equiv \frac{\omega b}{\gamma v}$ and $x \equiv \frac{\omega b_{\min}}{\gamma v}$

-
- Two limiting cases:

$$(1) \quad \omega \ll \frac{\gamma v}{b_{\min}} \quad (x \ll 1),$$

$$\begin{aligned} & xK_0(x)K_1(x) - \frac{1}{2}x^2(K_1^2(x) - K_0^2(x)) \\ & \approx x(-\ln(x/2) - \gamma) \frac{1}{x} - \frac{x^2}{2} \left[\frac{1}{x^2} - (\ln(x/2) + \gamma)^2 \right] \quad \longrightarrow \quad \frac{dW}{d\omega} = \frac{2q^2c}{\pi v^2} \ln \left(0.68 \frac{\gamma v}{\omega b_{\min}} \right) \\ & \approx \ln \left[\frac{2}{x} e^{-(\gamma+1/2)} \right] \\ & = \ln \left(\frac{0.68}{x} \right) \end{aligned}$$

$$(2) \quad \omega \gg \frac{\gamma v}{b_{\min}} \quad (x \gg 1),$$

$$\begin{aligned} & xK_0(x)K_1(x) - \frac{1}{2}x^2(K_1^2(x) - K_0^2(x)) \\ & \approx x \frac{\pi}{2x} e^{-2x} - \frac{1}{2}x^2 \frac{\pi}{2x} e^{-2x} \left[\left(\frac{3}{8x} \right)^2 - \left(\frac{1}{8x} \right)^2 \right] \quad \longrightarrow \quad \frac{dW}{d\omega} = \frac{q^2c}{2v^2} \exp \left(-\frac{2\omega b_{\min}}{\gamma v} \right) \\ & = \frac{\pi}{4} e^{-2x} \end{aligned}$$

[Emission from Relativistic Particles]

- Total emitted power:

Imagine **an instantaneous rest frame K'** , such that the particle has zero velocity at a certain time. We can then calculate the radiation emitted by use of the dipole (Larmor) formula.

Suppose that the particle emits a total amount of energy dW' in this frame in time dt' . The momentum of this radiation is zero, $d\mathbf{p}' = 0$, because the emission is symmetrical in the frame.

The energy in a frame K moving with velocity $-\mathbf{v}$ w.r.t. the particle is:

$$dW = \gamma dW' \quad \longleftrightarrow \quad dE = cdP^0 = c\tilde{\Lambda}^0_{\mu} dP'^{\mu} = c\tilde{\Lambda}^0_0 dP^0 = \gamma dE'$$

The time interval dt is simply

$$dt = \gamma dt'$$

The total power emitted in frames K and K' are given by

$$P = \frac{dW}{dt}, \quad P' = \frac{dW'}{dt'}$$

Thus **the total emitted power is a Lorentz invariant** for any emitter that emits with front-back symmetry in its instantaneous rest frame.

$$P = P'$$

- the Larmor formula in covariant form:

Recall that $\vec{a} \cdot \vec{U} = 0$, and because $\vec{U} = (c, \mathbf{0})$ in the instantaneous rest frame of the particle, we have

$$a'_0 = 0 \quad \rightarrow \quad |\mathbf{a}'|^2 = a'_k a'^k = a'_\mu a'^\mu = \vec{a} \cdot \vec{a}$$

Therefore,

$$P' = \frac{2q^2}{3c^3} |\mathbf{a}'|^2 \quad \longrightarrow \quad P = \frac{2q^2}{3c^3} \vec{a} \cdot \vec{a}$$

- Expression of P in terms of the three-vector acceleration

Recall

$$dt = \gamma \left(dt' + \frac{v}{c^2} dx'_{||} \right)$$

$$u_{||} = \frac{u'_{||} + v}{1 + vu'_{||}/c^2}$$

$$u_\perp = \frac{u'_\perp}{\gamma (1 + vu'_{||}/c^2)}$$

$$\sigma \equiv \left(1 + uu'_{||}/c^2 \right)$$

$$dt = \gamma dt' \sigma$$

$$u_{||} = \frac{u'_{||} + v}{\sigma}$$

$$u_\perp = \frac{u'_\perp}{\gamma \sigma}$$

$$dt = \gamma dt' \sigma$$

$$du_{||} = \frac{du'_{||}}{\sigma} - \frac{u'_{||} + v}{\sigma^2} \frac{v}{c^2} du'_{||}$$

$$= \frac{du'_{||}}{\sigma^2} \left(1 - \frac{v^2}{c^2} \right) = \frac{du'_{||}}{\gamma^2 \sigma^2}$$

$$du_\perp = \frac{du'_\perp}{\gamma \sigma} - \frac{u'_\perp}{\gamma \sigma^2} \frac{v}{c^2} du'_{||}$$

$$= \frac{1}{\gamma \sigma^2} \left(\sigma du'_\perp - \frac{vu'_\perp}{c^2} du'_{||} \right)$$

Hence,

Transformation of three-vector acceleration:

$$a_{\parallel} = \frac{du_{\parallel}}{dt} = \frac{1}{\gamma^3 \sigma^3} \frac{du'_{\parallel}}{dt'}$$

$$a_{\perp} = \frac{du_{\perp}}{dt} = \frac{1}{\gamma^2 \sigma^3} \left(\sigma \frac{du'_{\perp}}{dt'} - \frac{vu'_{\perp}}{c^2} \frac{du'_{\parallel}}{dt'} \right) \quad \longrightarrow$$

In an instantaneous rest frame of a particle,

$$u'_{\parallel} = u'_{\perp} = 0, \quad \sigma = 1$$

$$a'_{\parallel} = \gamma^3 a_{\parallel}$$

$$a'_{\perp} = \gamma^2 a_{\perp}$$

Note $\tan \theta'_a \equiv \frac{a'_{\perp}}{a'_{\parallel}} = \frac{1}{\gamma} \frac{a_{\perp}}{a_{\parallel}} = \frac{1}{\gamma} \tan \theta_a$

$$a_{\parallel} = \frac{1}{\gamma^3 \sigma^3} a'_{\parallel}$$

$$a_{\perp} = \frac{1}{\gamma^2 \sigma^3} \left(\sigma a'_{\perp} - \frac{vu'_{\perp}}{c^2} a'_{\parallel} \right)$$

$$\text{where } \sigma \equiv \left(1 + \frac{vu'_{\parallel}}{c^2} \right)$$

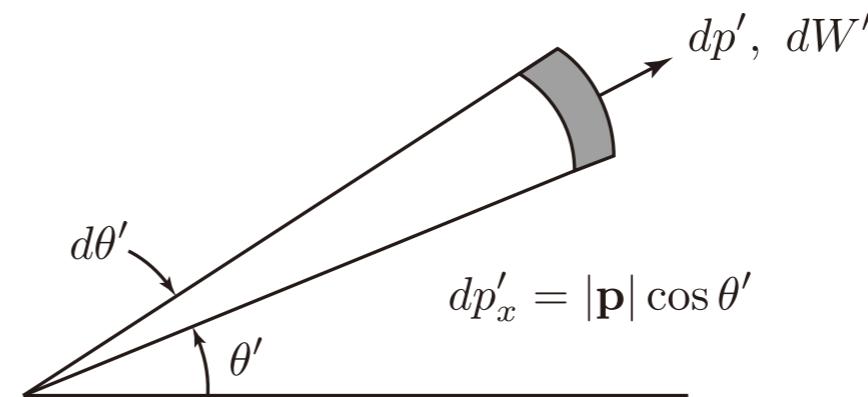
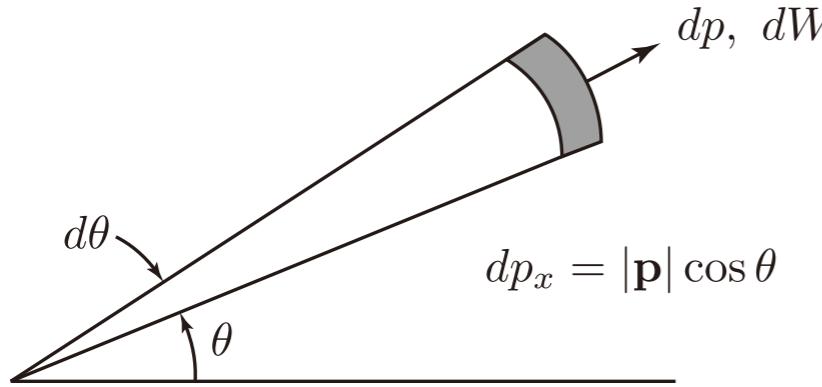
Thus we can write

$$P = \frac{2q^2}{3c^3} |\mathbf{a}'|^2 = \frac{2q^2}{3c^3} (a'^2_{\parallel} + a'^2_{\perp}) \quad \longrightarrow$$

$$P = \frac{2q^2}{3c^3} \gamma^4 (\gamma^2 a_{\parallel}^2 + a_{\perp}^2)$$

Differential Power

- Angular Distribution of Emitted and Received Power



Note:

$$d\phi' = d\phi$$

In the instantaneous rest frame of the particle, let us consider an amount of energy dW' that is emitted into the solid angle $d\Omega' = \sin \theta' d\theta' d\phi'$ (see the above figure).

$$\mu \equiv \cos \theta \rightarrow d\Omega = d\mu d\phi$$

$$\mu' \equiv \cos \theta' \rightarrow d\Omega' = d\mu' d\phi'$$

Recall the aberration formula:

$$\cos \theta = \frac{\cos \theta' + \beta}{1 + \beta \cos \theta'} \rightarrow \mu = \frac{\mu' + \beta}{1 + \beta \mu'} \rightarrow \mu' = \frac{\mu - \beta}{1 - \beta \mu}$$

$$d\mu = \frac{d\mu'}{\gamma^2 (1 + \beta \mu')^2} \longrightarrow$$

$$d\mu' = \frac{d\mu}{\gamma^2 (1 - \beta \mu)^2}$$

$$d\Omega = \frac{d\Omega'}{\gamma^2 (1 + \beta \mu')^2}$$

$$d\Omega' = \frac{d\Omega}{\gamma^2 (1 - \beta \mu)^2}$$

- Power

Recall that energy and momentum form a four-vector

$$\vec{P} = (E/c, \mathbf{p}) \quad \text{and} \quad |\mathbf{p}| = E/c \quad \longrightarrow \quad dW = \gamma(dW' + vdp'_x) = \gamma(1 + \beta\mu')dW'$$

$$\therefore dW = \gamma(1 + \beta\mu')dW'$$

$$dW' = \gamma(1 - \beta\mu)dW$$

$$\frac{dW}{d\Omega} = \gamma^3 (1 + \beta\mu')^3 \frac{dW'}{d\Omega'}, \quad \frac{dW'}{d\Omega'} = \gamma^3 (1 - \beta\mu)^3 \frac{dW}{d\Omega}$$

In the rest frame, **the power emitted in a unit time interval** is

$$\frac{dP'}{d\Omega'} \equiv \frac{dW'}{dt'd\Omega'}$$

However, in the observer's frame, there are two possible choices for the time interval to calculate the power.

(1) $dt = \gamma dt'$:

$$dt_A = \gamma(1 - \beta\mu)dt' \quad \text{or} \quad dt_A = \gamma^{-1}(1 + \beta\mu')^{-1}dt'$$

This is the time interval during which the emission occurs. With this choice we obtain **the emitted power**.

(2) $dt_A = \gamma(1 - \beta\mu)dt'$ or $dt_A = \gamma^{-1}(1 + \beta\mu')^{-1}dt'$:

This is the time interval of the radiation as received by a stationary observer in K . With this choice we obtain **the received power**.

- Thus we obtain the two results:

$$\frac{dP_e}{d\Omega} = \gamma^2 (1 + \beta\mu')^3 \frac{dP'}{d\Omega'} = \frac{1}{\gamma^4 (1 - \beta\mu)^3} \frac{dP'}{d\Omega'}$$

$$\frac{dP_r}{d\Omega} = \gamma^4 (1 + \beta\mu')^4 \frac{dP'}{d\Omega'} = \frac{1}{\gamma^4 (1 - \beta\mu)^4} \frac{dP'}{d\Omega'}$$

P_r is the power actually measured by an observer. It has the expected symmetry property of yielding the inverse transformation by interchanging primed and unprimed variables, along with a change of sign of β .

P_e is used in the discussion of emission coefficient.

In practice, **the distinction between emitted and received power is often not important, since they are equal in an average sense for stationary distributions of particles.**

- Beaming effect:

If the radiation if isotropic in the particle's frame, then the angular distribution in the observer's frame will be highly peaked in the forward direction for highly relativistic velocities.

The factor $\gamma^{-4} (1 - \beta\mu)^{-4}$ is sharply peaked near $\theta \approx 0$ with an angular scale of order $1/\gamma$.

$$\gamma^{-4} (1 - \beta\mu)^{-4} \approx \gamma^{-4} \left[1 - \left(1 - \frac{1}{2\gamma^2} \right) \left(1 - \frac{\theta^2}{2} \right) \right]^{-4} = \gamma^{-4} \left(\frac{1}{2\gamma^2} + \frac{\theta^2}{2} \right)^{-4} = \left(\frac{2\gamma}{1 + \gamma^2 \theta^2} \right)^{-4}$$

- Dipole emission from a slowly moving particle

$$\frac{dP'}{d\Omega'} = \frac{q^2 a'^2}{4\pi c^3} \sin^2 \Theta'$$

Θ' = the angle between the acceleration and the direction of emission.

Using $a'_{||} = \gamma^3 a_{||}$, $a'_{\perp} = \gamma^2 a_{\perp}$ and $\frac{dP_r}{d\Omega} = \gamma^{-4} (1 - \beta\mu)^{-4} \frac{dP'}{d\Omega'}$, we obtain

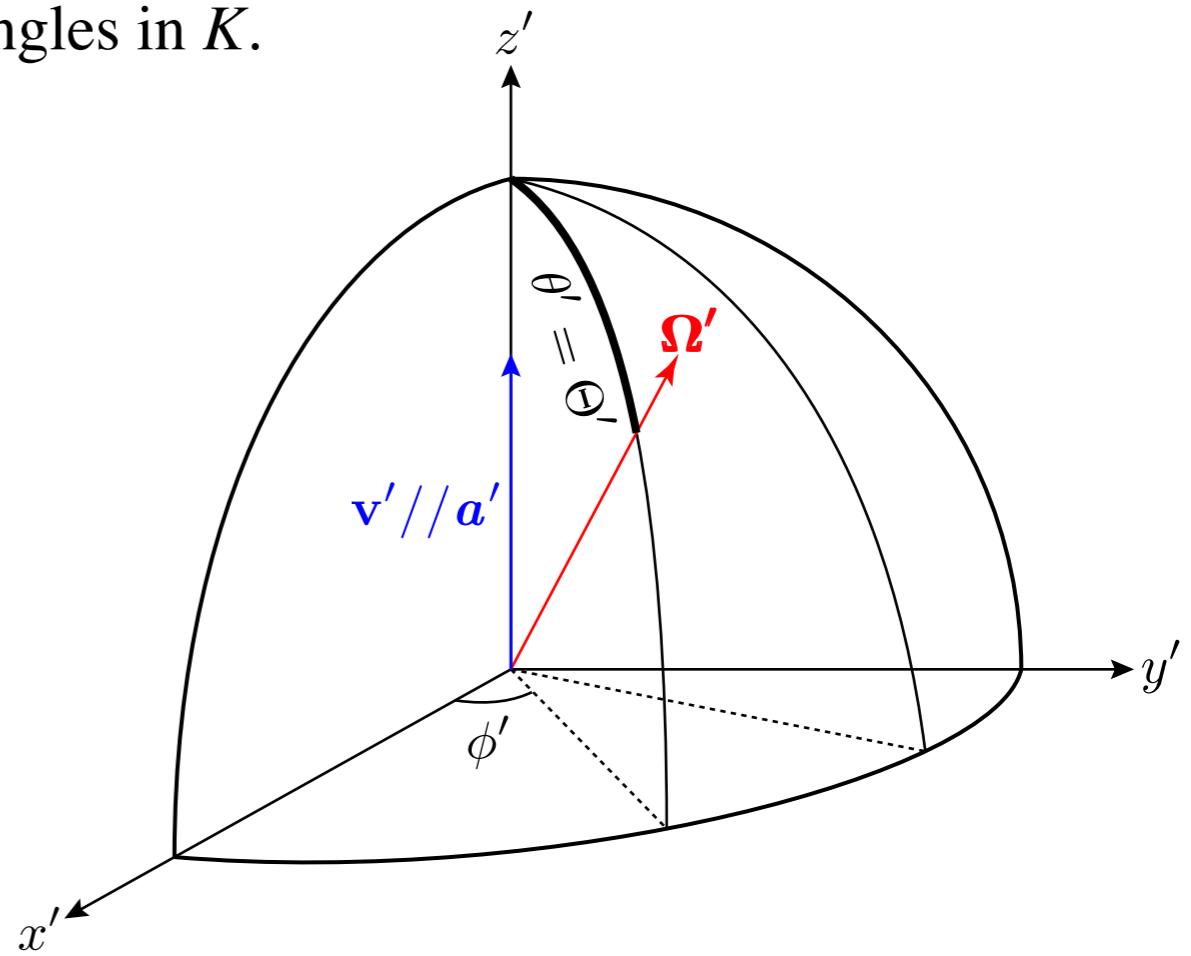
$$\boxed{\frac{dP_r}{d\Omega} = \frac{q^2}{4\pi c^3} \frac{(\gamma^2 a_{||}^2 + a_{\perp}^2)}{(1 - \beta\mu)^4} \sin^2 \Theta'}$$

To use this formula, we must relate Θ' to the angles in K .

(1) Acceleration parallel to velocity: $\Theta' = \theta'$, $a_{\perp} = 0$

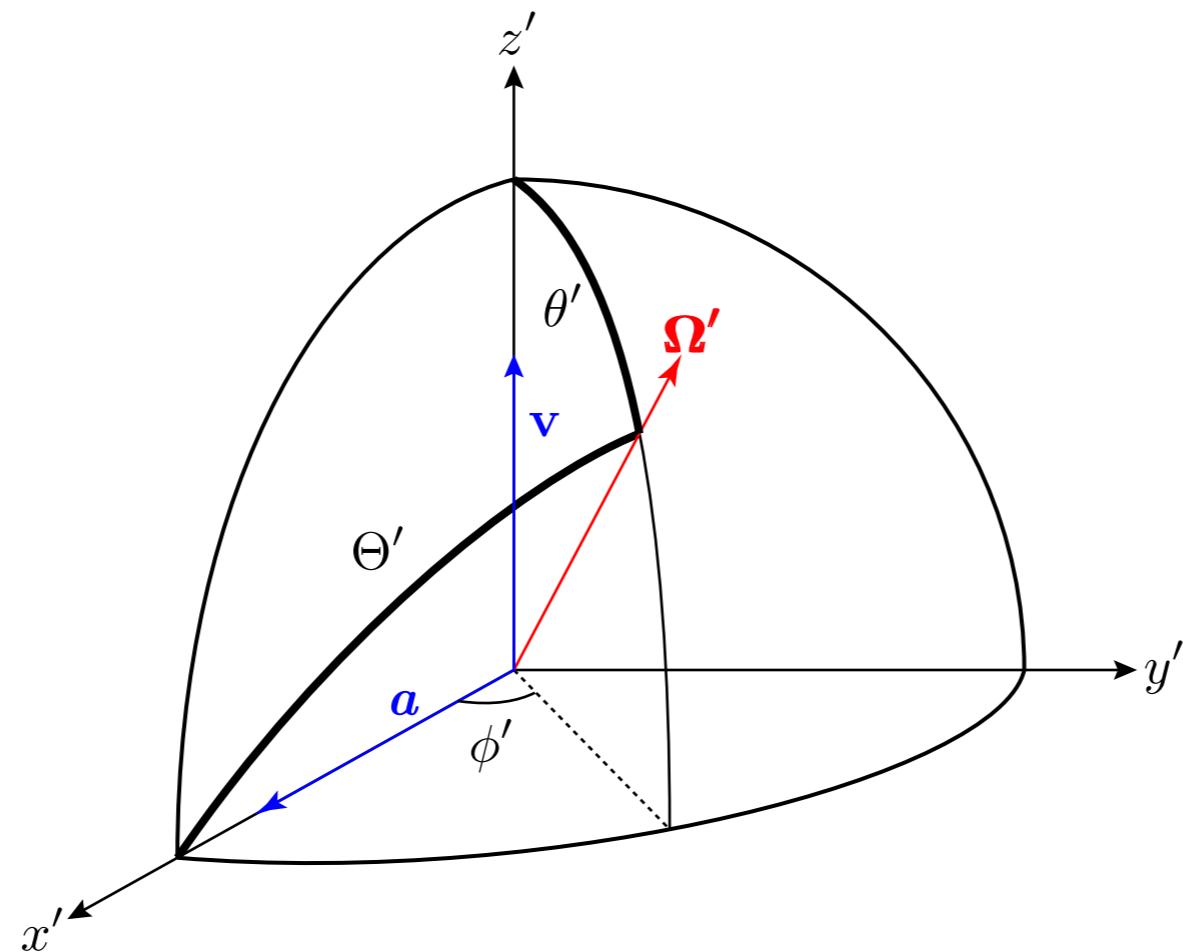
$$\sin^2 \Theta' = 1 - \mu'^2 = 1 - \left(\frac{\mu - \beta}{1 - \beta\mu} \right)^2 = \frac{1 - \mu^2}{\gamma^2 (1 - \beta\mu)^2}$$

$$\rightarrow \frac{dP_{r||}}{d\Omega} = \frac{q^2 a_{||}^2}{4\pi c^3} \frac{1 - \mu^2}{(1 - \beta\mu)^6}$$



(2) Acceleration perpendicular to velocity: $\cos \Theta' = \sin \theta' \cos \phi'$ (when a is in x -direction in the figure)

$$\sin^2 \Theta' = 1 - \frac{(1 - \mu^2) \cos^2 \phi}{\gamma^2 (1 - \beta\mu)^2} \quad \longrightarrow \quad \frac{dP_{r\perp}}{d\Omega} = \frac{q^2 a_\perp^2}{4\pi c^3} \frac{1}{(1 - \beta\mu)^4} \left[1 - \frac{(1 - \mu^2) \cos^2 \phi}{\gamma^2 (1 - \beta\mu)^2} \right]$$



(3) In general

$$\cos \Theta' = \mu' \mu'_a + (1 - \mu'^2)^{1/2} (1 - \mu_a'^2)^{1/2} \cos (\phi' - \phi'_a)$$

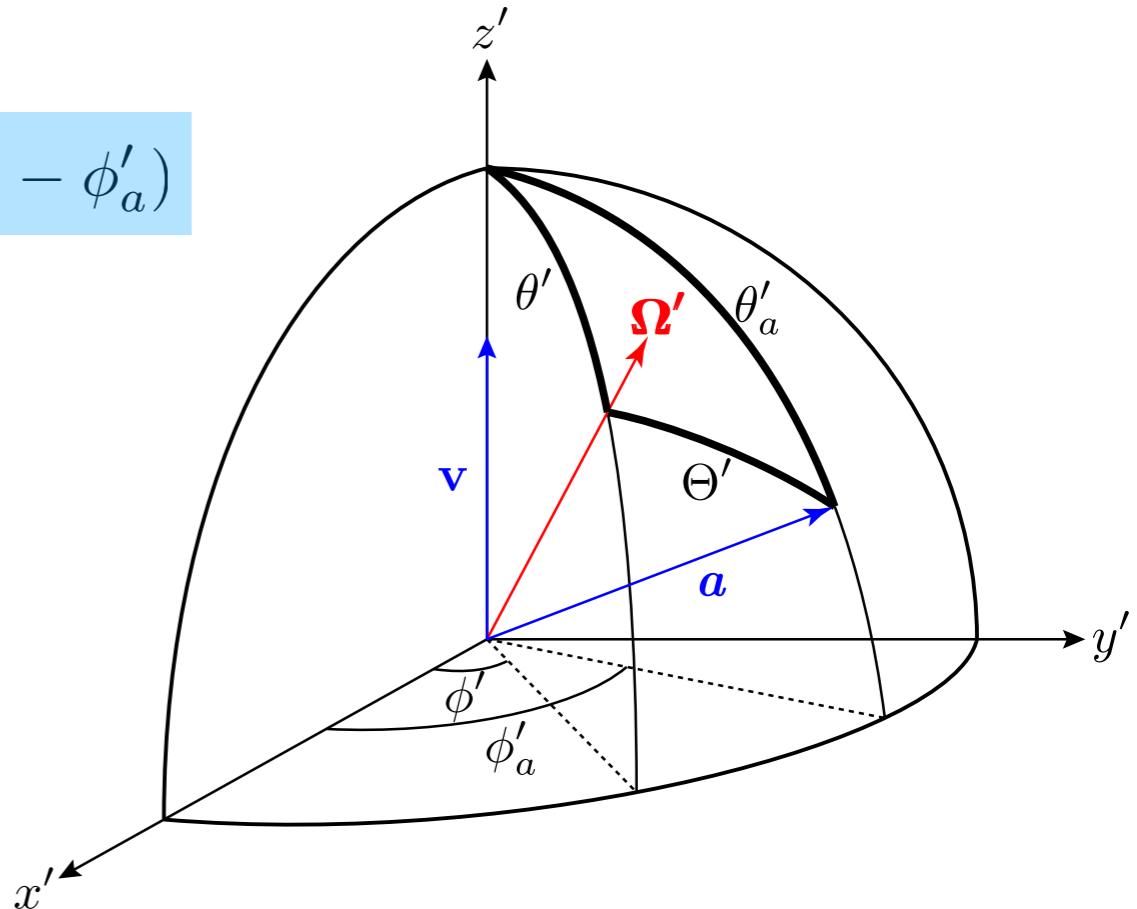
$$\mathbf{r}_1 = (\sin \theta_1 \cos \phi_1, \sin \theta_1 \sin \phi_1, \cos \theta_1)$$

$$\mathbf{r}_2 = (\sin \theta_2 \cos \phi_2, \sin \theta_2 \sin \phi_2, \cos \theta_2)$$

$$\cos \Omega = \mathbf{r}_1 \cdot \mathbf{r}_2$$

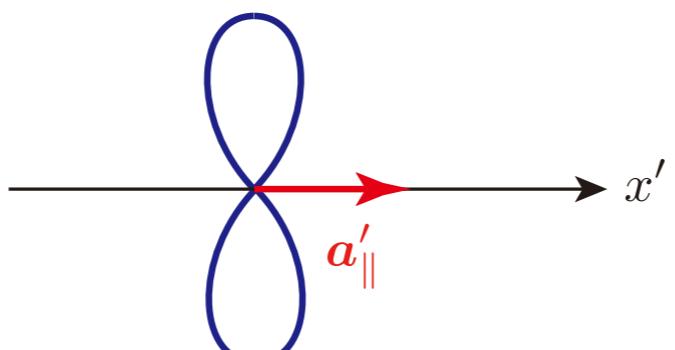
$$= \mu_1 \mu_2 + \sqrt{1 - \mu_1} \sqrt{1 - \mu_2} (\cos \phi_1 \cos \phi_2 + \sin \phi_1 \sin \phi_2)$$

- In the extreme relativistic limit, the radiation becomes strongly peaked in the forward direction.

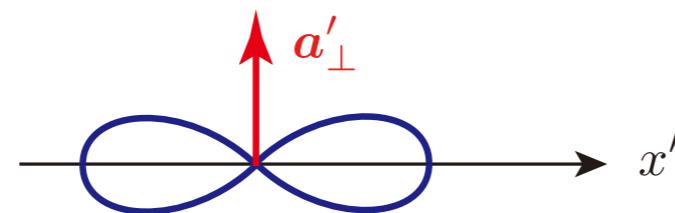


particle's rest frame:

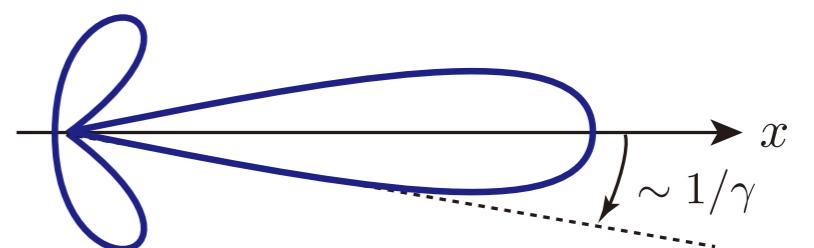
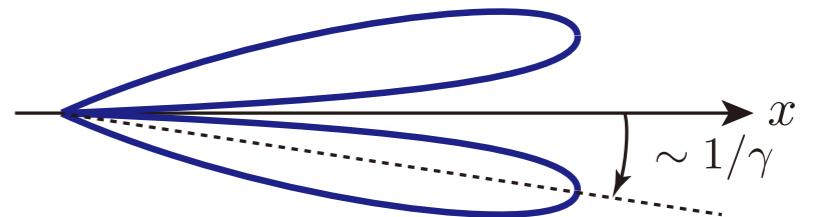
parallel acceleration:



perpendicular acceleration:



observer's frame:



[Invariant Phase Volumes and Specific Intensity]

- **Phase volume**

Consider a group of particles that occupy a slight spread in position and in momentum at a particular time. In a rest frame comoving with the particles, they occupy a spatial volume element and a momentum volume element.

$$\begin{aligned} d^3\mathbf{x}' &= dx' dy' dz' \\ d^3\mathbf{p}' &= dp'_x dp'_y dp'_z \end{aligned} \quad \longrightarrow \quad \text{phase volume in the comoving frame:}$$

$$d\mathcal{V}' \equiv d^3\mathbf{x}' d^3\mathbf{p}' = dx' dy' dz' dp'_x dp'_y dp'_z$$

In the observer's frame, $dx = \frac{1}{\gamma}dx'$ (length contraction), $dy = dy'$, $dz = dz'$

$$dp_x = \gamma (dp'_x + \beta dP'_0), \quad dp_y = dp'_y, \quad dp_z = dp'_z$$

We note that $dP'_0 = 0 + \mathcal{O}(dp'_x)^2$ because the velocities are near zero in the comoving frame and the energy is quadratic in velocity. Therefore, we have $dp_x = \gamma dp'_x$.

$$d\mathcal{V}' \equiv d^3\mathbf{x}' d^3\mathbf{p}' = d^3\mathbf{x} d^3\mathbf{p} \equiv d\mathcal{V}$$

: Lorentz invariant

This contains no reference to particle mass, and therefore it has applicability to photons.

The phase space density

$$f \equiv \frac{dN}{d\mathcal{V}} = \frac{dN}{d^3\mathbf{x} d^3\mathbf{p}}$$

is an invariant, since the number of particles within the phase volume element is a countable quantity and itself invariant.

- **Specific Intensity and Source Function**

Definition of the energy density per unit solid angle per frequency range.

$$h\nu \frac{dN}{dV} p^2 dp d\Omega d^3x = u_\nu(\Omega) d\Omega d\nu d^3x \longrightarrow u_\nu(\Omega) = h\nu \frac{dN}{dV} p^2 \frac{dp}{d\nu} \quad \leftarrow \quad p = \frac{h\nu}{c}$$

$$= h\nu \left(\frac{h\nu}{c} \right)^2 \left(\frac{h}{c} \right) \frac{dN}{dV}$$

Since $u_\nu(\Omega) = I_\nu/c$, we find that

$$\frac{I_\nu}{\nu^3} = \text{Lorentz invariant}$$

Because the source function occurs in the transfer equation as the difference $I_\nu - S_\nu$, the source function must have the same transformation properties as the intensity.

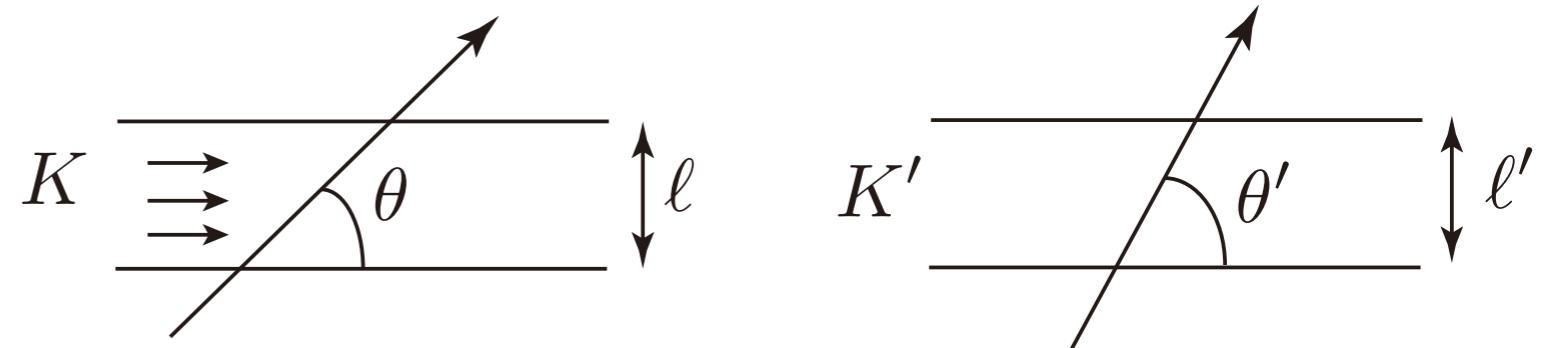
- **Optical Depth, Absorption Coefficient and Emission Coefficient**

The optical depth must be an invariant, since $\exp(-\tau)$ gives the fraction of photons passing through the material, and this involves simple counting.

$$\tau = \text{Lorentz invariant}$$

- **Absorption Coefficient and Emission Coefficient**

Consider the optical depth in two frames:



Then, the optical depth is

$$\tau_\nu = \frac{\ell \alpha_\nu}{\sin \theta} = \frac{\ell}{\nu \sin \theta} \nu \alpha_\nu = \text{Lorentz invariant}$$

Note that $\nu \sin \theta$ is proportional to the y component of the photon four-momentum $\vec{k} = (\omega/c, \mathbf{k})$.

Both k_y and ℓ are the same in both frames, being perpendicular to the motion. Therefore, we have

$$\nu \sin \theta \propto k_y, \quad k_y = k'_y, \quad \ell' = \ell$$

$$\nu \alpha_\nu = \text{Lorentz invariant}$$

Finally, we obtain the transformation of the emission coefficient from the definition of the source function:

$$S_\nu \equiv \frac{j_\nu}{\alpha_\nu}$$

$$\frac{j_\nu}{\nu^2} = \text{Lorentz invariant}$$