Critical Acceleration

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In collisions of ultra-intense laser-pulse with relativistic electrons, as well as in ultra relativistic heavy ion collisions at RHIC and at LHC it is possible to probe critical acceleration $a = mc^3/\hbar$, an object related to Planck scales but not burdened by G_N. The behavior of a particle undergoing critical acceleration challenges the limits of the current understanding of basic interactions: little is known about this physics frontier; both classical and quantum physics will need further development in order to be able to address this newly accessible area of physics. In this lecture I will review the foundations of current understanding of particles dynamics and inertia in presence of gravity, EM-fields and forces; and will discuss radiation reaction issues and possible theoretical extensions as well as the relation with quantum physics and strong field particle production phenomena.

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Towards Ultimate Understanding of the Universe

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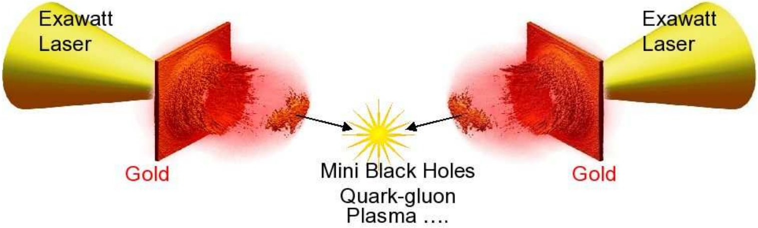
Overview

1. Introduction
2. Critical acceleration
3. Mach and Inertia, Aether Quantum Vacuum
4. EM Interaction and Radiation Reaction
5. Add Gravity, role of the quantum vacuum state



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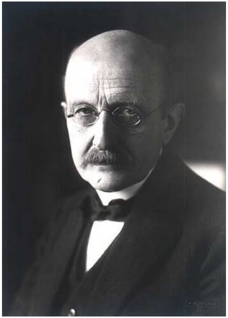
The 21st Century Foundational Physics Challenges

- What is inertia or/and (how) does the structured quantum vacuum control inertia, seen that it does characterize other laws of physics
- What is the origin of grand scales as expressed by e.g.
  a) the Planck mass: $M_{\rm Pl} = \sqrt{\hbar c/G_N} = 4.8\,10^{16}\langle h\rangle$ and
  b) Higgs VEV $\langle h\rangle = 254\ \mathrm{GeV}\ \simeq 10^{13} m_{\rm neutrino}$.
- Nature of interactions and space-time dimensionality
  (3+1) $\rightarrow$ $(n+1)$: $n > 3$?
  and structure: (Mem)brane? Lattice? Fractal dimension?
- Is there a deeper understanding of time?
  Rôle of the Universe expansion in defining time?

A discovery needs new experimental tools; this talk is about the opportunity offered by ultra high acceleration=strong fields

1899:
Planck units



$$h/k_B = a = 0.4818 \cdot 10^{-10} [\text{sec} \times \text{Celsiusgrad}]$$
$$h = b = 6.885 \cdot 10^{-27} \left[\frac{\text{cm}^2 \text{gr}}{\text{sec}}\right]$$
$$c = c = 3.00 \cdot 10^{10} \left[\frac{\text{cm}}{\text{sec}}\right]$$
$$G = f = 6.685 \cdot 10^{-8} \left[\frac{\text{cm}^3}{\text{gr. sec}^2}\right]^1.$$

Wählt man nun die »natürlichen Einheiten« so, dass in dem neuen Maasssystem jede der vorstehenden vier Constanten den Werth 1 annimmt, so erhält man als Einheit der Länge die Grösse:

$$\sqrt{2\pi} L_{Pl} = \sqrt{\frac{bf}{c^3}} = 4.13 \cdot 10^{-33} \text{cm}, \mapsto \sqrt{2\pi}\, 1.62 \times 10^{-33} \text{ cm}$$

als Einheit der Masse:

$$\sqrt{2\pi} M_{Pl} = \sqrt{\frac{bc}{f}} = 5.56 \cdot 10^{-5} \text{gr}, \mapsto \sqrt{2\pi}\, 2.18 \times 10^{-5} \text{ g}$$

als Einheit der Zeit:

$$\sqrt{2\pi} t_{Pl} = \sqrt{\frac{bf}{c^5}} = 1.38 \cdot 10^{-43} \text{sec}, \mapsto \sqrt{2\pi}\, 5.40 \times 10^{-44} \text{ s}$$

als Einheit der Temperatur:

$$\sqrt{2\pi} T_{Pl} = a\sqrt{\frac{c^5}{bf}} = 3.50 \cdot 10^{32} {}^\circ \text{Cels.} \mapsto \sqrt{2\pi}\, 1.42 \times 10^{32} \text{ K}$$

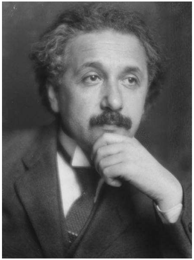
Diese Grössen behalten ihre natürliche Bedeutung so lange bei, als die Gesetze der Gravitation, der Lichtfortpflanzung im Vacuum und die beiden Hauptsätze der Wärmetheorie in Gültigkeit bleiben, sie müssen also, von den verschiedensten Intelligenzen nach den verschiedensten Methoden gemessen, sich immer wieder als die nämlichen ergeben.

“These scales retain their natural meaning as long as the law of gravitation, the velocity of light in vacuum and the central equations of thermodynamics remain valid, and therefore they must always arise, among different intelligences employing different means of measuring.” *M. Planck, “Über irreversible Strahlungsvorgänge.” Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften zu Berlin* **5**, *440-480 (1899), (last page)*

Critical $\leftrightarrow$ ‘Planck’ acceleration

In presence of high acceleration we probe connection between forces (interactions) and the structure of space-time. In that sense there is also a ‘limiting’ Planck acceleration, which to avoid misunderstanding we term ‘critical’ acceleration a_c.

Einstein’s gravity is built upon The Equivalence Principle: a relation of gravity to inertia (=the resistance to acceleration). Note that when gauge interactions are ‘geometrized’ like gravity, we are doing away with acceleration. Unified gauge theories in 10 dimensions are solving problem of acceleration by removing force, which is reintroduced by yet unknown mechanisms of symmetry breaking. This talk does not contradict this program, it ignores it focusing on physics in presence of strong fields=acceleration.



It is quantum physics that allows us to create devices that generate extended bodies, prevent free fall, expose particles to acceleration.

Critical Acceleration

Critical natural unit =1 acceleration acting on an electron:

$$a_c = \frac{m_e c^3}{\hbar} \to 2.331 \times 10^{29} \mathrm{m/s}^2$$

This critical acceleration can be imparted on an electron by the critical 'Schwinger' (Vacuum Instability) field strength of magnitude:

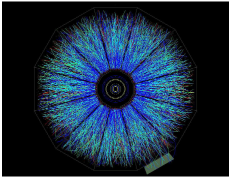
$$E_c = \frac{m_e^2 c^3}{e\hbar} = 1.323 \times 10^{18} \, V/m$$

Truly dimensionless unit acceleration arises when we introduce specific acceleration

$$\aleph = \frac{a_c}{mc^2} = \frac{c}{\hbar}$$

Specific unit acceleration arises in Newton gravity at Planck length distance: $\aleph_G \equiv G/L_p^2 = c/\hbar$ at $L_p = \sqrt{\hbar G/c}$. In the presence of sufficiently strong electric field E_c by virtue of the equivalence principle, we probe electrons subject to Planck scale force.

Critical acceleration in Relativistic Nuclear Collisions



Two nuclei smashed into each other from two sides: components ‘partons’ can be stopped in CM frame within $\Delta\tau \simeq 1$ fm/c. Tracks show multitude of particles produced, as observed at RHIC (BNL), and more extreme at LHC today.

- The acceleration a achieved to stop some/any of the components of the colliding nuclei in CM: $a \simeq \frac{\Delta y}{M_i \Delta\tau}$. Full stopping: $\Delta y_{\rm SPS} = 2.9$, and $\Delta y_{\rm RHIC} = 5.4$. Considering constituent quark masses $M_i \simeq M_N/3 \simeq 310$ MeV we need $\Delta\tau_{\rm SPS} < 1.8$ fm/c and $\Delta\tau_{\rm RHIC} < 3.4$ fm/c to exceed a_c.
- Observed unexplained soft electromagnetic radiation in hadron reactions *A. Belognni et al. [WA91 Collaboration], “Confirmation of a soft photon signal in excess of QED expectations in π–p interactions at 280-GeV/c,” Phys. Lett. B* **408**, *487 (1997)*

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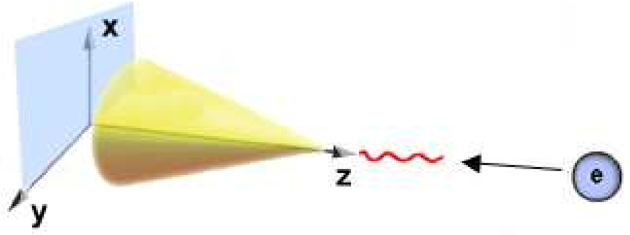
Clean path to super-critical (Planck) acceleration

$a = 1 (= m_e c^3/\hbar \to 2.331 \times 10^{29}\mathrm{m/s}^2)$

Directly accelerated electrons by ultra intense laser pulse: e at rest in lab requires Schwinger scale field

Present laser pulse intensity technology misses a few orders of magnitude. Shortcut: we can Lorentz-boost: to reach the critical acceleration scale today: we collide a counter-propagating electron with a laser pulse.



Laser pulse in electron's rest frame

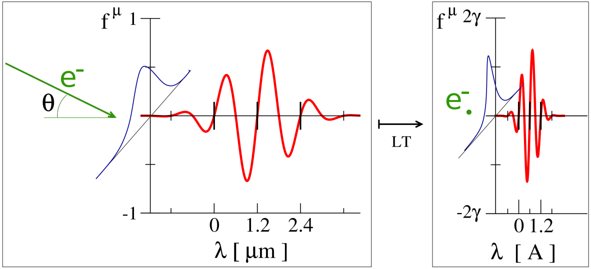


Figure shows boost (from left to right) of the force applied by a Gaussian photon pulse to an electron, on left counter propagating with $\gamma/\cos\theta = 2000$. Pulse narrowed by $(\gamma\cos\theta)^{-1}$ in the longitudinal and $(\gamma\sin\theta)^{-1}$ in the transverse direction. Corresponds to Doppler-shift:

$$\omega \to \omega' = \gamma(\omega + \vec{v}\cdot nk)$$

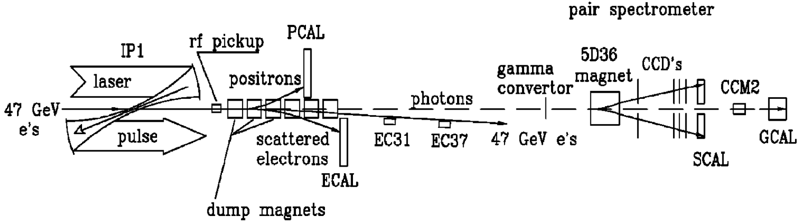
as applied to different frequencies making up the pulse.

SLAC'95 experiment below critical acceleration

$p_e^0 = 46.6$ GeV; in 1996/7 $a_0 = 0.4$, $\left|\frac{du^\alpha}{d\tau}\right| = .073[m_e]$ (Peak)

Multi-photon processes observed:

- Nonlinear Compton scattering
- Breit-Wheeler electron-positron pairs



- D. L. Burke *et al.*, "Positron production in multiphoton light-by-light scattering," Phys. Rev. Lett. **79**, 1626 (1997)
- C. Bamber *et al.*, "Studies of nonlinear QED in collisions of 46.6 GeV electrons with intense laser pulses" Phys. Rev. D **60**, 092004 (1999).

Experimental idea and initiation by our host Prof. Pisin Chen

Clean Probe of critical acceleration possible today

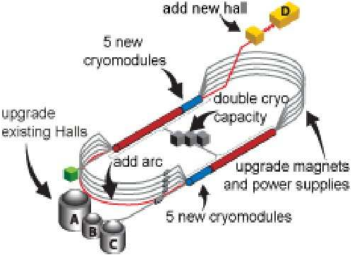
SLAC, CEBAF:

experiments possible in principle ‘today’

CEBAF: There is a 12 GeV ($\gamma = 2400$) electron beam

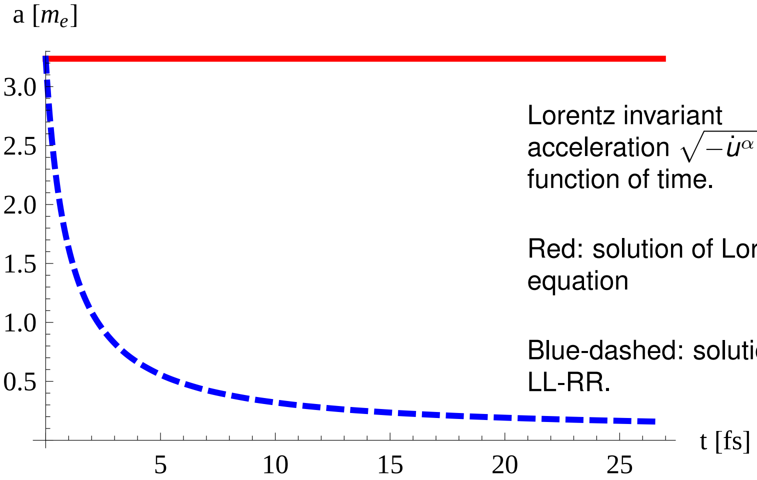
There is a laser team

There is appropriate high radiation shielded experimental hall



Electron acceleration in collision with a pulse

Collision between a circularly polarized square plane wave with $a_0 = 100$ and initial $E_e = 0.5\,\mathrm{GeV}, \gamma = 1,000$ electron. **Y. Hadad, L. Labun et al Phys.Rev.D** 82, 096012 (2010)



Lorentz invariant acceleration $\sqrt{-\dot{u}^{\alpha}\dot{u}_{\alpha}}$ as function of time.

Red: solution of Lorentz equation

Blue-dashed: solution of LL-RR.

Problem 1: Mach and Acceleration

To measure acceleration we need to refer to an inertial frame of reference. Once we know one inertial observer, the class of inertial observers is defined.

Before Einstein's relativity, Mach posited, *I paraphrase/simplify* as an alternative to Newton's absolute space, a) that inertia (resistance to acceleration) could be due to the background mass in the Universe, and b) that the reference inertial frame must be inertial with respect to the Universe mass rest frame. The latter postulate Einstein called 'Mach's principle'.

- General Relativity and GR based Cosmology motivated by Mach → Einstein's æther
- Any observer inertial wrt CMB frame qualifies – present day "Mach's fixed stars" frame of reference;
- QFT provides Mach's inertial frame: the quantum vacuum= æther
- Corollary: Inertia, the resistance to acceleration requires presence of non-geometric forces and/or extended quantum matter leading to rigid extended material body.

Sideremark: Einstein's Aether Reference Frame

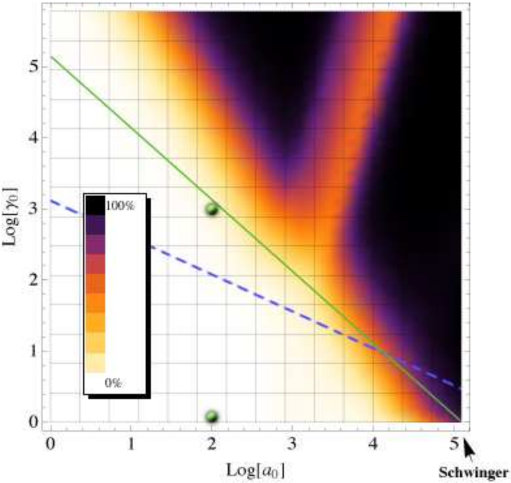
Albert Einstein at first rejected æther as unobservable when formulating special relativity, but eventually changed his initial position, re-introducing what is referred to as the ‘relativistically invariant’ æther. In a letter to H.A. Lorentz of November 15, 1919, see page 2 in *Einstein and the Æther*, L. Kostro, Apeiron, Montreal (2000). he writes:

It would have been more correct if I had limited myself, in my earlier publications, to emphasizing only the non-existence of an æther velocity, instead of arguing the total non-existence of the æther, for I can see that with the word æther we say nothing else than that space has to be viewed as a carrier of physical qualities.

In a lecture published in May 1920 (given on 27 October 1920 at Reichs-Universität zu Leiden, addressing H. Lorentz), published in Berlin by Julius Springer, 1920, also in Einstein collected works: In conclusion:

. . . space is endowed with physical qualities; in this sense, therefore, there exists an æther. . . . But this æther may not be thought of as endowed with the quality characteristic of ponderable media, as (NOT) consisting of parts which may be tracked through time. The idea of motion may not be applied to it.

Problem 2: Radiation reaction (RR) regime



Dark shaded area in $\gamma > 1, a_0 > 1$ plane, : dynamics dominated by radiation reaction force, according to solution of the LL version of radiation reaction. For $\gamma_0 \to 1$ this occurs at critical Schwinger field $E_c = m^2/e$

Problem 2: - Radiation Reaction

Maxwell, Lorentz and Inertia: ad-hoc combination

The action $\mathcal{I}$ comprises three elements:

$$\mathcal{I} = -\frac{1}{4}\int d^4x\, F^2 + q\int_{\text{path}} d\tau\, u\cdot A + \frac{mc}{2}\int_{\text{path}} d\tau (u^2 - 1).,$$

$F^{\alpha\beta} \equiv \partial^\alpha A^\beta - \partial^\beta A^\alpha, u^\alpha = ds^\alpha/d\tau$. Path is fixed at the end points assuring gauge-invariance of dynamic equations:

• The two first terms upon variation with respect to the A-field, produce **Maxwell equation**, with sources given by motion of charged particles along prescribed world lines. Note, these are allowing radiation emission in presence of accelerated charges.

• The second and third term, when varied with respect to the shape of the material particle world line, produce the **Lorentz force** equation = particle dynamics in presence of a prescribed A-field.

Consistency??

1) Maxwell Equation: obtain fields $F^{\beta\alpha}$ including radiation fields from a given source of fields $j^\alpha(x) = \sum_i \int d\tau_i u_i^\alpha q_i \delta^4(x - s_i(\tau_i))$

$$\partial_\beta F^{*\,\beta\alpha} = 0, \qquad \partial_\beta F^{\beta\alpha} = j^\alpha \quad \to F^{\beta\alpha}(x)$$

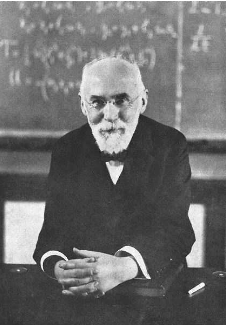
2) Inertial Force = Lorentz-force –> using fields we obtain world line of particles needed in step **1)** (Vlasov: in phase space)

$$m_e \frac{du^\alpha}{d\tau} = -eF^{\alpha\beta} u_\beta \quad \to s^\alpha(\tau),\ \frac{ds^\alpha}{d\tau} \equiv u^\alpha(\tau) \quad \to j^\alpha$$

Problem: Fields accelerate charges, accelerated charges radiate, but that alters field present in the Lorentz equation. We did it wrong, since the solution of Lorentz equation should already know of motion in the radiation field generated. The lack of consistency is recognized realizing that Lorentz equation is conservative, but radiation removes energy from particle motion.

As long as acceleration is small, radiation emitted can be incorporated as a perturbative iterative additional force.

Radiation reaction Lorentz-Abraham-Dirac (LAD) force



energy-momentum radiated:

$$\frac{dp^\alpha}{d\tau} = u_\beta q(F^{\beta\alpha} + F^{\beta\alpha}_{\rm rad}),$$

$$F^{\beta\alpha}_{\rm rad} = \frac{2q}{3}(\ddot{u}^\beta u^\alpha - \ddot{u}^\alpha u^\beta)$$

Recognized and (further) developed among others by

$\leftarrow$ Lorentz Dirac $\rightarrow$

<u>At critical acceleration</u> the radiation reaction has same magnitude as the field force.

Dirac's 1938 derivation of LAD

$$m_e\,\dot{u}^\mu \;=\; -eF^{\mu\nu}u_\nu\,, \qquad u^\mu = \dot{s}^\mu(\tau)\,, \qquad \partial^\alpha\partial_\alpha A^\mu = j^\mu$$

$$j^\mu(x) \;=\; -e\int d\tau\, u^\mu[s(\tau)]\,\delta^4[x-s(\tau)]$$

$$A^\mu_{\rm rad} \;=\; -e\int d\tau\, u^\mu[s(\tau)]\,G_+[x-s(\tau)]$$

$$-eF^{\mu\nu}_{\rm rad}\,u_\nu \;=\; e^2\int d\tau\, u_\nu(x)\,\left(u^\nu[s(\tau)]\,\partial^\mu - u^\mu[s(\tau)]\,\partial^\nu\right)\,G_+[x-x(\tau)]$$

$$G_\pm \;=\; \theta[\pm X_0]\,\delta[X^2]\,, \qquad X^\mu = x^\mu - x^{\mu\,\prime}$$

$$F^\mu_{\rm LAD} \equiv -eF^{\mu\nu}_{\rm rad}\,u_\nu \;=\; 2e^2\int d\tau\, u_\nu\,\left(u^{\nu\,\prime}X^\mu - u^{\mu\,\prime}X^\nu\right)\,\frac{\partial G_+}{\partial X^2}$$

Expansion for far zone
EM mass and LAD radiation reaction

$$X^\mu \approx \delta u^\mu - \frac{\delta^2}{2}\dot{u}^\mu + \frac{\delta^3}{6}\ddot{u}^\mu \pm \ldots, \qquad u^{\mu\,\prime} \approx u^\mu - \delta\dot{u}^\mu + \frac{\delta^2}{2}\ddot{u}^\mu \pm \ldots$$

$$\delta = t - \tau, \qquad X^2 \approx \delta^2 \to \frac{\partial}{\partial X^2} = \frac{1}{2\delta}\frac{\partial}{\partial\delta}$$

$$F^\mu_{\mathrm{LAD}} = e^2 \int d\delta\, \frac{\partial G_+}{\partial\delta}\left(\frac{\delta}{2}\dot{u}^\mu - \frac{\delta^2}{3}\left[\ddot{u}^\mu + \dot{u}^\eta \dot{u}_\eta u^\mu\right]\right)$$

With $u^2 = 1 \to u\cdot\dot{u} = 0$ and thus $\dot{u}^2 = -u\cdot\ddot{u}$ and $u_\mu F^\mu_{\mathrm{LAD}} = 0$

$$F^\mu_{\mathrm{LAD}} = \dot{u}^\mu\left(-\frac{e^2}{2}\int d\delta\, \frac{\Delta[\delta]}{|\delta|}\right) + e u_\nu F^{\nu\mu}_{\mathrm{rad}}$$

$$m_r\,\dot{u}^\mu = -e(F^{\mu\nu}_{\mathrm{ext}} + F^{\mu\nu}_{\mathrm{rad}})u_\nu \quad m_r = m_e + \frac{e^2}{2}\int d\delta\, \frac{\Delta[\delta]}{|\delta|}$$

Two Challenges

The mass problem:
The appearance of electromagnetic mass next to inertial mass. Finite EM mass can be achieved within nonlinear EM of Born-Infeld. But, given the smallness of electron mass even if all mass is of EM origin experiments are in disagreement with this theory.

The self-acceleration and the causality problem:
The appearance of a third derivative $\ddot{u}^\alpha,\ u^\alpha = \dot{x}^\alpha$ requires assumption of an additional boundary condition to arrive at a unique solution describing the motion of a particle. Only a boundary condition in the (infinite) future allows to eliminate self-accelerating charges, that is 'run-away' solutions. Such a constraint is in conflict with the principle of causality.

This LAD radiation reaction description is universally rejected. A theoretical cure is not known, a cottage industry of ad-hoc modifications of radiation-reaction dynamics arose.

Sample of proposed LAD extensions

LAD	$\mathbf{m\underline{u}}^{\alpha} = \mathbf{qF}^{\alpha\beta}\mathbf{u}_{\beta} + m\tau_0\left[\ddot{u}^{\alpha} + u^{\beta}\ddot{u}_{\beta}u^{\alpha}\right]$
Landau-Lifshitz	$\mathbf{m\underline{u}}^{\alpha} = \mathbf{qF}^{\alpha\beta}\mathbf{u}_{\beta} + q\tau_0\left\{F^{\alpha\beta}_{,\gamma}u_{\beta}u^{\gamma} + \frac{q}{m}\left[F^{\alpha\beta}F_{\beta\gamma}u^{\gamma} - (u_{\gamma}F^{\gamma\beta})(F_{\beta\delta}u^{\delta})u^{\alpha}\right]\right\}$
Caldirola	$\mathbf{0} = \mathbf{qF}^{\alpha\beta}(\tau)\,\mathbf{u}_{\beta}(\tau) + \frac{m}{2\tau_0}\left[u^{\alpha}(\tau - 2\tau_0) - u^{\alpha}(\tau)\,u_{\beta}(\tau)\,u^{\beta}(\tau - 2\tau_0)\right]$
Mo-Papas	$\mathbf{m\underline{u}}^{\alpha} = \mathbf{qF}^{\alpha\beta}\mathbf{u}_{\beta} + q\tau_0\left[F^{\alpha\beta}\dot{u}_{\beta} + F^{\beta\gamma}\dot{u}_{\beta}u_{\gamma}u^{\alpha}\right]$
Eliezer	$\mathbf{m\underline{u}}^{\alpha} = \mathbf{qF}^{\alpha\beta}\mathbf{u}_{\beta} + q\tau_0\left[F^{\alpha\beta}_{,\gamma}u_{\beta}u^{\gamma} + F^{\alpha\beta}\dot{u}_{\beta} - F^{\beta\gamma}u_{\beta}\dot{u}_{\gamma}u^{\alpha}\right]$
Caldirola-Yaghjian	$\mathbf{m\underline{u}}^{\alpha} = \mathbf{qF}^{\alpha\beta}(\tau)\,\mathbf{u}_{\beta}(\tau) + \frac{m}{\tau_0}\left[u^{\alpha}(\tau - \tau_0) - u^{\alpha}(\tau)\,u_{\beta}(\tau)\,u^{\beta}(\tau - \tau_0)\right]$

P. A. M. Dirac, “Classical theory of radiating electrons,” Proc. Roy. Soc. Lond. A **167**, 148 (1938)
L. D. Landau and E. M. Lifshitz, “The Classical theory of Fields,” *Oxford: Pergamon (1962)* 354p.
P. Caldirola, “A Relativistic Theory of the Classical Electron,” Riv. Nuovo Cim. **2N13**, 1 (1979).
T. C. Mo and C. H. Papas, “A New Equation Of Motion For Classical Charged Particles,” Izv. Akad. Nauk Arm. SSR Fiz. **5**, 402 (1970)
C. Eliezer, “On the classical theory of particles” Proc. Roy. Soc. Lond. A **194**, 543 (1948).
A. D. Yaghjian, “Relativistic Dynamics of a Charged Sphere,” *Lecture Notes in Physics, Springer-Verlag, Berlin (1992) 152p.*

Other recent references

H. Spohn, *Dynamics of charged particles and their radiation field,* (CUP, Cambridge, UK 2004, ISBN 0521836972)
F. Rohrlich, “Dynamics of a charged particle” Phys. Rev. E **77**, 046609 (2008)

Example: LAD $\rightarrow$ Caldirola

This modification assumes that particle dynamics is non-local:

This modification creates violation of Lorentz-Poincare symmetry at scales too large to accept, but solves the causality problem. All electron mass $m_{\mathrm{ed}} = 2e^2/(3d)$ can be in the field. $d \equiv c\tau_a$: a length scale, to be chosen – e.g. so that $m_{\mathrm{ed}} = m_{\mathrm{inertial}}$. Yagigan variant puts some material mass into electron.

$$
\begin{aligned}
F^{\mu}_{\mathrm{LAD}} \rightarrow F^{\mu}_{\mathrm{Cald}} &= \frac{m_{ed}}{2\tau_a}\left[u^{\mu}(\tau - 2\tau_a) - u^{\mu}(\tau)u^{\alpha}(\tau)u_{\alpha}(\tau - 2\tau_a)\right] \\
&\approx -m_{\mathrm{ed}}\dot{u}^{\mu} + m_{ed}\tau_a\left[\ddot{u}^{\mu} + \dot{u}^{\alpha}\dot{u}_{\alpha}u^{\mu}\right] + \ldots
\end{aligned}
$$

Most popular patch: LAD $\rightarrow$ Landau-Lifshitz (LL)

This modification implies that the field-particle interaction is altered, appropriate action has not been found LL has no conceptual problems and is often semi-analytically soluble!

$$m_e \dot{u}^\mu = -\frac{e}{c} F^{\mu\nu} u_\nu + F^\mu_{\mathrm{LAD}} \qquad F^\mu_{\mathrm{LAD}} = 2e^2 \left[\ddot{u}^\mu + \dot{u}^\eta \dot{u}_\eta u^\mu\right]$$

Iterate using Lorentz force and its differential in LAD:

$$\begin{aligned}
\ddot{u}^\mu \quad \rightarrow \quad & \frac{d}{d\tau}\left(-\frac{e}{m_e} F^{\mu\nu} u_\nu\right) = -\frac{e}{m_e}\left(\partial_\eta F^{\mu\nu} u_\nu u^\eta + F^{\mu\nu} \dot{u}_\nu\right) \\
= \quad & -\frac{e}{m_e}\left(\partial_\eta F^{\mu\nu} u_\nu u^\eta - \frac{e}{m_e} F^{\mu\nu} F^\eta_\nu u_\eta\right)
\end{aligned}$$

$$F^\mu_{\mathrm{LAD}} \simeq -\frac{2e^3}{3m_e}\left(\partial_\eta F^{\mu\nu} u_\nu u^\eta - \frac{e}{m_e} F^{\mu\nu} F^\eta_\nu u_\eta\right) + \frac{2e^4}{3m_e^2} F^{\eta\nu} F_{\eta\delta} u_\nu u^\delta u^\mu$$

This is equivalent to LAD only for weak acceleration. The Thompson limit of the Compton interaction is accounted for.

Outlook: EM interaction at Critical Acceleration

Maxwell and Lorentz equations which arise NEED NOT BE CONSISTENT, action respects gauge- and relativistic-invariance. Many modifications are possible:

- Born-Infeld theory introduces nonlinear field action aiming to limit the achievable field strength, and thus to limit acceleration. However, Born just intended to explain electron mass.
- Caldirola proposed discrete action generalization of Lorentz particle dynamics in an attempt to address the radiation-reaction inconsistency, and gets electron mass as well.
- I am not aware of a EM theory formulation that addresses the need to relate acceleration to a background Mach's inertial frame.
- QED is build on same ideas and beset by similar problems in the limit of strong fields = critical acceleration.

Outlook: add Gravity + quantum world

$$\mathcal{J} = \mathcal{I}_{\sqrt{-g}} + \frac{1}{8\pi G}\int d^4x\sqrt{-g}\,R$$

There are acceleration paradoxes arising combining in this way gravity and electromagnetism:

- Charged electron in orbit around the Earth will not radiate if bound by gravitational field, but it will radiate had it been bend into orbit by magnets.
- A free falling electron near BH will not radiate but an electron resting on a surface of a table should (emissions outside observer's horizon).
- A micro-BH will evaporate, but a free falling observer may not see this: Is the BH still there? (Pisin Chen et al)

One is tempted to conclude that we do not have a theory incorporating acceleration. New Physics Opportunity if we can create unit strength (critical) acceleration.

Better foundational theory not around the corner

Old idea: geometrize EM theory: 5-d Kaluza-Klein.

- EM potential part of 5-metric. To lowest order in charge, Lorentz force arises from 5-d geodetic. Hilbert-Einstein 5-d action reduces to 4-d Einstein-Maxwell action.

Pro: Any geometric EM theory has ‘æther’ and is Machian just like GR; charge is a property of the ‘æther; the missing degrees of freedom appear in 5th dimension.

Con: Lack of understandings of dynamics in 5-d extra dimension, solutions arbitrary. No experiment showing generalized equivalence principle justifying use of 5-d geodetic.

Should the generalization of Maxwell-Lorentz be geometric, critical acceleration experiments will be capable to explore this unification.

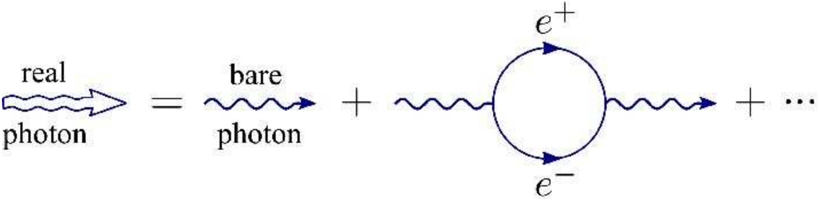
NEXT: Importance of Quantum Theory

Without quantum theory we would not have extended bodies, without extended material bodies we cannot create critical acceleration – acceleration due to interplay of quantum and EM theories.

Quantum vacuum state is providing naturally a Machian reference frame lost in classical limit. Critical acceleration in quantum theory (critical fields) leads to new particle production phenomena which have a good interpretation and no classical analog or obvious limit.

Quantum Vacuum Structure

The best known and widely accepted vacuum property is that it is a dielectric medium: a charge is screened by particle-hole (pair) excitations.



In Feynman language the real photon is decomposed into a bare photon and a photon turning into a virtual pair. The result is a renormalized electron charge smaller than bare, and slightly stronger Coulomb interaction (0.4% effect).

At any field strength the conversion of field energy into pairs possible.

Laws of Physics and Quantum Vacuum

Development of quantum physics leads to the recognition that vacuum fluctuations define laws of physics (Weinberg's effective theory picture). All this is nonperturbative property of the vacuum.

- The 'quantum æther' is polarizable: Coulomb law is modified; E.A.Uehling, 1935
- New interactions (anomalies) such as light-light scattering arise considering the electron, positron vacuum zero-point energy; Euler, Kockel, Heisenberg (1930-36);
- Casimir notices that the photon vacuum zero point energy also induces a new force, referred today as Casimir force 1949
- Non-fundamental vacuum symmetry breaking particles possible: Goldstone Bosons '60-s
- 'Fundamental electro-weak theory is effective - model of EW interactions, 'current' masses as VEV Weinberg-Salam '70-s
- Color confinement and high-T deconfinement Quark-Gluon Plasma '80-s

Acceleration and QVacuum Temperature

- W. Unruh finds that an accelerated observer records a temperature

  $$T_{\rm HU} = \frac{a}{2\pi}$$

  relation to Hawking radiation by the
  strong acceleration $=$?? strong gravity connection
- We study properties of quantum vacuum 'accelerated' by a constant EM field – Since 1977 (B. Müller et al, PLA 63, p181) it is known that the effective Euler-Heisenberg action can be cast into a heat capacity format at temperature

  $$T_{\rm EH} = \frac{a}{\pi}, \qquad a = eE/m$$

  Today we can offer a resolution of the factor 2 difference with $T_{\rm HU}$ and of the related issue of Fermi-Bose statistics of vacuum latent heat see **Talk by Lance Labun**, Thursday, at 15^{10} *Temperature of the accelerated vacuum*

Summary

New opportunity to study foundational physics involving acceleration and search for generalization of laws of physics – motivated by need for better understanding of inertia, Mach's principle, Einstein's æther= the quantum vacuum .

Critical acceleration can be greatly exceeded in electron-laser pulse collisions.
Exploration of physical laws in a new domain possible

Experiments should help resolve the old riddle of EM theory and radiation reaction
Rich field of applications and theoretical insights follows

More generally, the study of physics phenomena beyond critical acceleration opens up to experimental exploration the frontier science addressing the consistency of General Relativity, Electromagnetism and Quantum Physics.