FUNDAMENTAL PHYSICS with STRONG LASER FIELDS

Particle Production and Vacuum Structure

Johann Rafelski

Department of Physics, University of Arizona, Tucson

and visitor at MAP/MPQ/LMU-München

The beginning 1919/20: space endowed with physical qualities

Albert Einstein 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.

He continues 6 months later in a lecture published in May 1920 in Berlin by Julius Springer, in Einstein collected works (given on 27 October 1920 at Reichs-Universität zu Leiden, addressing H. Lorentz): 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.

A decade later a new beginning – the development of relativistic quantum physics, antimatter, Dirac sea and a shift in language

æther $\rightarrow$ vacuum

The Vacuum is understood as a domain empty of matter

in which quantum fluctuations exist. The vacuum state

1) defines the magnitude of the velocity of light,
2) the masses of elementary particles,
3) the contents of ‘fundamental’ interactions.

Some of this properties are understood in terms of quantum physical vacuum structure and have been under intense theoretical and experimental investigation.

These efforts have been focused in the recent past on the study of the mechanism of quark deconfinement at high temperature probing the nuclear size scale 0.1–10 fm (10^{-15}m)

Today the advent of ultra-intense laser light pulses reaching within a decade towards the critical field strength $E_0 = m^2/e = 1.3\,10^{18}$V/m should allow us to probe the Vacuum in a new way - at a "mesoscopic" nano-micrometer scale.

Creation of such electromagnetic fields is expected to be accompanied by massive particle materialization of the field energy.

STRONG gluon and quark fluctuations in vacuum

These features of QCD lead to permanent fluctuations/structure in 'space devoid of matter':

even though $\langle V|G^a_{\mu\nu}|V\rangle = 0,$ with $G^2 \equiv \sum_a G^a_{\mu\nu}G^{\mu\nu}_a = 2\sum_a[\vec{B}_a^{\,2} - \vec{E}_a^{\,2}]\,,$

we have $\langle V|\frac{\alpha_s}{\pi}G^2|V\rangle \simeq (2.3 \pm 0.3)10^{-2}\mathrm{GeV}^4 = [390(12)\,\mathrm{MeV}]^4\,,$

and $\langle V|\bar{u}u + \bar{d}d|V\rangle = -2[225(9)\,\mathrm{MeV}]^3\,.$

the QCD Vacuum structure is a key element for the understanding of quark confinement and hadron structure.

Melting the QCD vacuum structure is the objective of QGP experiments at SPS, RHIC, LHC: however, volume limited to nuclear size.

Electro-Weak Vacuum

- The Higgs mechanism: There is a field breaking the symmetry of electro-weak interactions with

$$\phi_V = \langle V|\phi|V\rangle = 248\,\text{GeV}$$

  ϕ is the Higgs field, endowed with a non vanishing vacuum expectation value everywhere. It is used to break the symmetry of electro-weak interactions giving the mass to $W^{\pm}$ and Z^0.

- Forthcoming test of dynamical nature of the Higgs field: production of Higgs particle, a fluctuation of ϕ_V
- ϕ_V provides mass for leptons e, μ, τ and quarks $d, u,\ s, c,\ b, t$.

$$m_i = g_i\langle V|\phi|V\rangle$$

  Test of this Yukawa- coupling in symmetry restoration. At high temperature we melt the ϕ_V and all particles are mass less. For quarks the volume can be small since particles interact strongly.

New way: ‘melting’ the vacuum with the light pulse

By energy consideration kJ vs. erg (factor 10^{10}) light pulses allow to create a

- Large quark-gluon plasma, with $R = 10,000$ fm, with zero baryon number and lifespan and size sufficient to truly probe the last phase transition in the early Universe in the laboratory.
- We may be able to reach Electro-Weak phase transition.

Interesting physics on the way – materialization of fields in pairs, QCD-QED interference, connection of EM plasma to hadrons,

Discussion TOPICS

1. Strong Field QED, Vacuum properties
2. Field to matter conversion: mechanism and relaxation times
3. $e\bar{e}\gamma$-plasma, Pion and muon production
4. Open problems, retrospect, conclusions

Part II: Quantum definition of the vacuum and Dirac sea

Quantum wave function in particle representation

$$\hat{\Psi} = \sum_{e} \psi_e \hat{b}_e + \sum_{\bar{e}} \psi_{\bar{e}} \hat{d}^{\dagger}_{\bar{e}},$$

Definition of vacuum: $\hat{b}_e|0\rangle = \hat{d}_{\bar{e}}|0\rangle = 0$ vacuum charge vanishes
'e': particle states and $\bar{e}$ antiparticle states.
Dirac sea charge of positrons cancels charge of electrons
(nett charge zero, distribution: vacuum polarization)

$$\hat{Q} = \int d^3x \frac{e}{2}\left[\hat{\Psi}(x)^{\dagger}, \hat{\Psi}(x)\right], \qquad \langle\hat{Q}\rangle = \frac{e}{2}\left[\sum_{e} - \sum_{\bar{e}}\right] \to 0$$

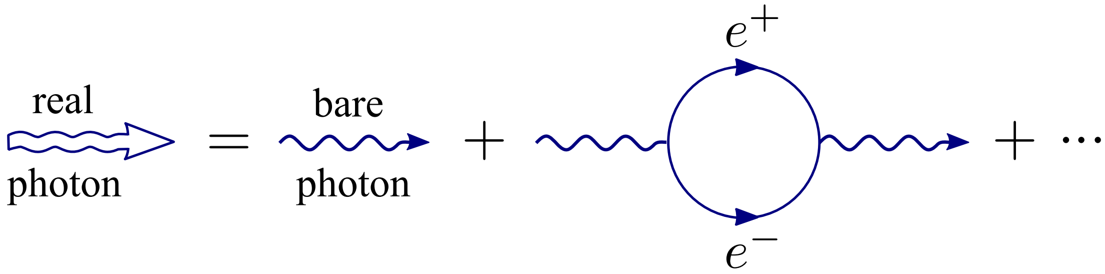
zero point energy of electrons and positrons add and diverge (the vacuum dark energy problem, super-symmetry and all that):

$$V\mathcal{E} = -\frac{1}{2}\sum_{e}\varepsilon_e - \frac{1}{2}\sum_{\bar{e}}(-\varepsilon_{\bar{e}}) \to (g_{\mathrm{Bos}} - g_{\mathrm{Ferm}})VM^4_{\mathrm{Planck}} + d_1\bar{m}^2VM^2_{\mathrm{Pl}} + \ldots$$

Vacuum Polarization - displacement charge in the Dirac Sea

It is well known that Vacuum is polarizable: $\rho_{\rm VP} = \frac{e}{2}\langle\left[\hat\Psi(x)^\dagger, \hat\Psi(x)\right]\rangle$

‘charge renormalization’ reduces the visible field/charge. As we come closer to the source of the field, the bare charge becomes more visible, and thus the vacuum polarization effect acts to increase the strength of the potential of a charge at short distances. E.A.Uehling, 1935; Atomic vac. pol. level shifts of s-states.

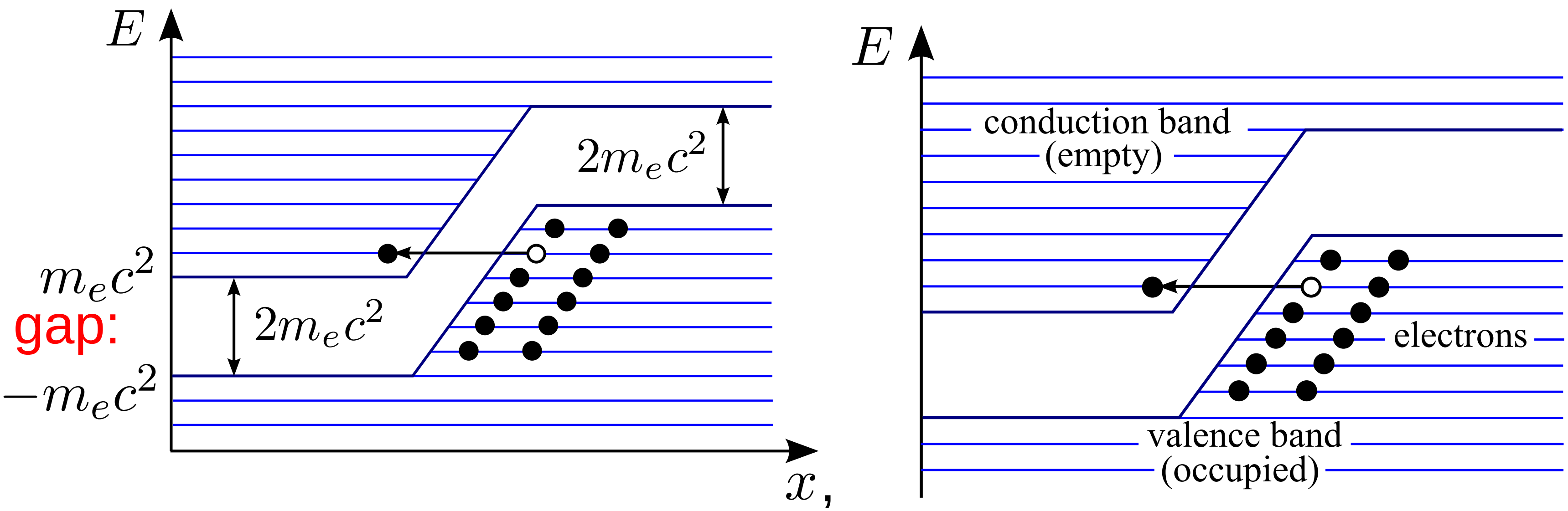


+ other diagrams

Vacuum sparking in strong fields

Vacuum is an insulator. No free charges are available.

However, when we apply sufficiently strong electric fields, with $V = |\vec{E}|x > 2mc^2$, the vacuum can SPARK. One speaks of vacuum decay. Of the particle-hole (antiparticle) pair one is retained to screen the 'supercritical' source, the mirror-particle is emitted.



Past effort: decay of the vacuum in strong ATOMIC fields

The Decay of the Vacuum

Near a superheavy atomic nucleus empty space may become unstable, with the result that matter and antimatter can be created without any input of energy. The process might soon be observed experimentally

by Lewis P. Fulcher, Johann Rafelski and Abraham Klein

Scientific American 241, pp 150-9(1979), issue 6

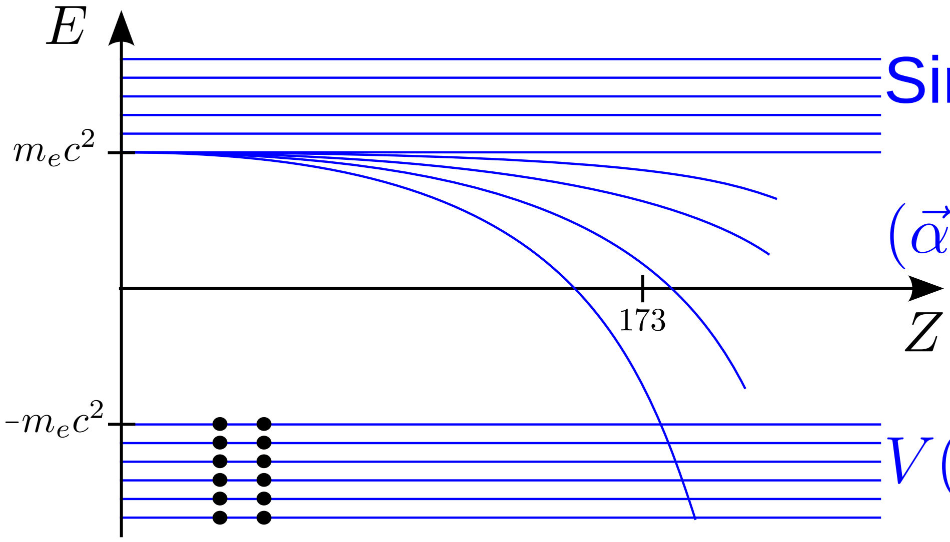
The vacuum is ordinarily defined as a state of absence: a vacuum is said to exist in a region of space if there is nothing in it. In the quantum field theories that describe the physics of elementary particles the vacuum becomes somewhat more complicated. Even in empty space matter can appear spontaneously as a result of fluctuations of the vacuum. For example, an electron and a positron, or antielectron, can be created out of the void. Particles created in this way have only a fleeting existence; they are annihilated almost as

in the space make the charge manifest. An electric field of sufficient intensity to create a charged vacuum is likely to be found in only one place: in the immediate vicinity of a superheavy atomic nucleus, one with about twice as many protons as the heaviest natural nuclei known. A nucleus that large cannot be stable, but it might be possible to assemble one for long enough to observe the decay of the neutral vacuum. Experiments that will test this possibility are now under way.

difference is carried away as energy by electromagnetic radiation.

The hydrogen binding energy of 13.6 electron volts is a small fraction of the rest mass of the electron, which is 511,000 electron volts, or about .5 MeV. (One MeV is a million electron volts.) The binding energy increases, however, along with the positive charge of the atomic nucleus. Such an increase is to be expected since a greater nuclear charge gives rise to a more intense electric field, and so the electron is bound more strongly. The nuclear charge is given by

(quasi)Atoms beyond $Z \simeq 100$



Single Particle Dirac Equation

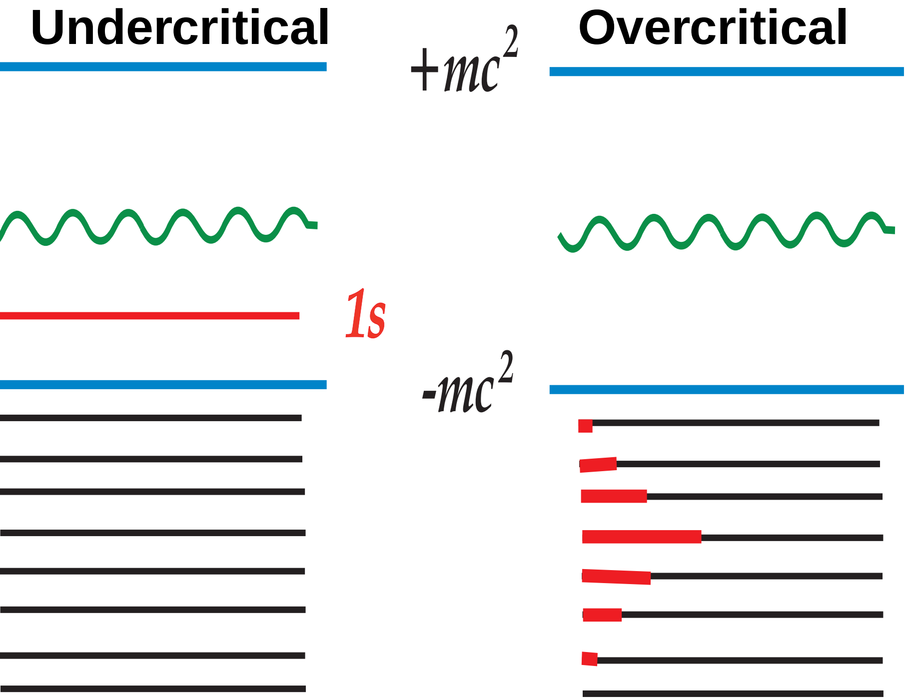
$$(\vec{\alpha}\cdot i\vec{\nabla}+\beta m+V(r))\Psi_n(\vec{r}) = E_n\Psi_n(\vec{r})$$

$$V(r) = \begin{cases} -\frac{Z\alpha}{r} & r > R_N \\ -\frac{3}{2}\frac{Z\alpha}{R_N} + \frac{r^2}{2}\frac{Z\alpha}{R_N^3} & r < R_N \end{cases}$$

The bound states drawn from one continuum move as function of Z across into the other continuum. Mix-up of particle/antiparticle states

Reference: The large volume of theoretical and initial experimental work is reviewed in
W. Greiner, B. Müller and JR
"Quantum Electrodynamics of Strong Fields,"
(Springer Texts and Monographs in Physics, 1985),
ISBN 3-540-13404-2.

Closer View of the Decay of the Vacuum

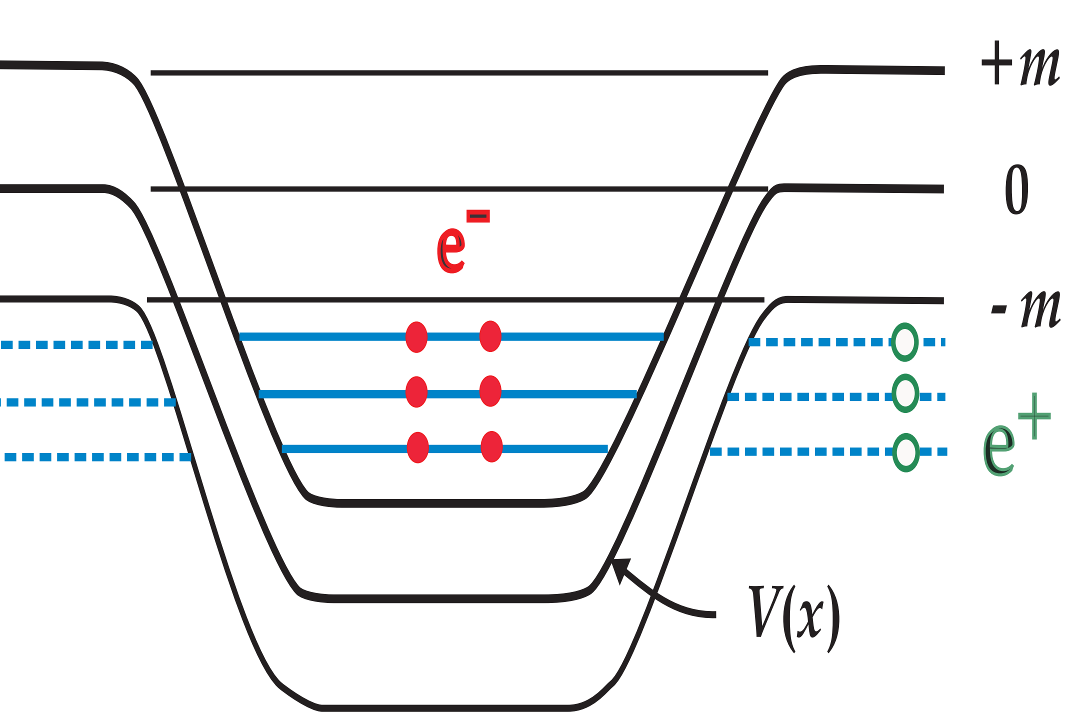


Discrete single particle Dirac states 'dive' and turn into resonances. The number of particle and antiparticle states changed.

Thus $\langle \hat{Q} \rangle \neq 0$. Charge of the vacuum discrete and equal to number of states which changed 'sides'.JR, B.Mueller, W. Greiner, Nucl. Phys. B68, 585 (1974)

In Supercritical fields If diving state 'empty' $|Q = 0\rangle \rightarrow |Q = e\rangle + e^+$
(neutral, overcritical) vacuum decays by positron production.
If diving state occupied by an electron, a 'smooth' transition, from a discrete bound particle state to a charge distribution in the proximity of field source.

New Stable Ground State: The Charged Vacuum



There is localized charge density in the vacuum, not a particle of sharp energy. Formation of the charged vacuum ground state observable by positron emission: which fills any vacancies among 'dived' states in the localized domain.

Back-reaction of real vacuum charge and screening of the external field (Müller and JR, PRL34, 349 (1975)):

$$-\vec{\nabla}^2 V = e\rho_N + \langle e\rho_e \rangle, \quad \langle e\rho_e \rangle \simeq -\frac{2_s e^2}{6\pi^2}[(E_f - V)^2 - m^2]^{3/2}\Theta(E_f - V - m)$$

Fermienergy: $E_f = -m$ for stable 'empty' vacuum

New strong field tool 2010

A new source of supercritical fields since 15 years:
femto second LASER PULSES
made possible by CPA invented by G. Mourou:

High power pulse lasers: Trident at Los Alamos is presently at the top (as measured by its E, B fields), but Mourou's ILE in Paris with objective of few kJ pulse and below 10 fs pulse length will in 1-2 years be the leader by factor 10, and the European ELI project gains yet another factor 10, already in planning.

Today: $N_\gamma = 10^{22}$ photons; considering diffraction limited focus at $(2\mu\mathrm{m})^3$ the energy density: $\epsilon \simeq 150\mathrm{J}/\mu\mathrm{m}^3 = 1\mathrm{GeV}/(10^{-10}\mathrm{m})^3$ is very high on atomic scale: pulse contains equivalent $E = mc^2$ hydrogen gas energy. However, this is low on nuclear scale. For QGP or EW transition $\rightarrow$
need relativistic focusing/energy concentration.

Note that E, B fields are on mesoscopic nano-micrometer scale.

Large nearly constant field – effective action

Euler-Heisenberg Z. Physik 98, 714 (1936) and Weisskopf, evaluate Dirac zero-point energy with (constant on scale of $\hbar/mc$) EM- fields, transform to action $\mathcal{E}(D,H) \to \mathcal{L}(E,B) = \mathcal{E} - ED$, $E \equiv \frac{\partial \mathcal{E}}{\partial D}$

$$\mathcal{L}(E,B) = -\frac{1}{8\pi^2}\int_0^\infty \frac{ds}{s^3}\mathrm{e}^{-m^2 s}\left[\frac{sE}{\tan sE}\,\frac{sB}{\tanh sB} - 1 + \frac{1}{3}(E^2 - B^2)s^2\right] .$$

E, B relativistic definition in terms of invariants, asymptotic series

$$\mathcal{L}(E,B) \to \frac{2\alpha^2}{45m^4}\left[\left(\vec{E}^{\,2} - \vec{B}^{\,2}\right)^2 + 7(\vec{E}\cdot\vec{B})^2\right] = \mathrm{light-light\ scattering}$$

Schwinger 1951 notes importance of imaginary part due to zeros of $\tan sE$: $|\langle 0_+|0_-\rangle|^2 = e^{-2\mathcal{I}m\,\mathcal{L}}$, $2\mathcal{I}m\,\mathcal{L} = \frac{\alpha^2}{\pi^2}\sum_{n=1}^{\infty} n^{-2} e^{-n\pi m^2/eE}$ is the total vacuum persistence probability in adiabatic switching on/off the E-field. For $E \to 0$ essential singularity.

This is WKB for pair tunneling.

Energy concentration needed to reach a new phases of matter

- QED plasma, $30 \geq T \geq 3$ MeV,
  at $R = 2$ nm (opaque for γ, e), $T = 10$ MeV, for $g \to g_{\rm QED} = 5.5$
  $E_{\rm QED} = V\epsilon = \frac{4\pi}{3}(RT)^3 T \frac{g\pi^2}{30} \longrightarrow E_{\rm QED} = 13$ kJ
- QGP with $T = 200$ MeV and $R = 10$ fm we have $E_{\rm QGP} = 22$ erg
  NOTE: $RT|_{\rm QED} = 10^4 RT|_{\rm QGP} \quad g \to g_{\rm QGP} = 47.5 = 8.6 g_{\rm QED}$.
  for kJ, R up by $(5\,10^8)^{1/3} = 800$, $R \simeq 10^{-11}$m =10,000 fm
- EW phase: $T > 150$ GeV Quark-Higgs masses melt:
  $E_{\rm EW} = 100^3_{RT}\, 1000_T\, 2_g\, E_{\rm QGP} = 1.4{\rm kJ}$
  for $R \to 0.1 R_{\rm QGP}$ $T = 1000 T_{\rm QGP} = 150$ GeV, $g \simeq 2 g_{\rm QGP}$

  Lepton mass melting with $R \to R_{\rm QED}$ probably unreachable
  since 10^{16} more energy needed

1 – 10 kJ energy opens new physics domains: QED Plasma, Large QGP, EW transition, successively as we improve energy focusing.

How to achieve energy concentration

- Example: for space focusing at fm-level need photons with $E_\gamma > 200$ MeV.Number of 600 MeV-ρ-energy photons needed for EW transition:
$$N_\gamma = \frac{1.4\mathrm{kJ}}{600 \cdot 1.6\, 10^{-13}\mathrm{J}} = 1.3 \cdot 10^{13}$$
About 10^{-9} of today's pulse:
- To boost a small fraction of photons from 1eV to 600 MeV: requires
  - a good moving relativistic mirror, it boosts energy by factor $4\gamma^2_{\mathrm{mirror}}$.
  - this requires a very dense cloud of electrons moving with 5GeV/particle: realization - laser acceleration.

All the above in principle achievable - even so: focusing a challenge but already demonstrated in principle;

Relativistic Mirror: elastic moving hard wall scattering

The brick wall moving at rapidity y_b. Particle momentum parallel to brick-wall motion $p_{\|} = m_\perp \sinh y$, is reflected and boosted after scattering by $2y_b$. Thus scattered energy-momentum is:

$$P^\mu_{\rm reflected} = \begin{bmatrix} m_\perp \cosh(y+2y_b) \\ -m_\perp \sinh(y+2y_b) \\ P_\perp \\ 0 \end{bmatrix} = \begin{bmatrix} E\cosh 2y_b + p_{\|}\sinh 2y_b \\ -E\sinh 2y_b - p_{\|}\cosh 2y_b \\ P_\perp \\ 0 \end{bmatrix}$$

$\cosh 2y_b = 2\cosh^2 y_b - 1 = 2\gamma_b^2 - 1, \;\sinh 2y_b = 2\cosh y_b \sinh_b = 2v_b\gamma_b^2$

$E_{\rm reflected} = (E + v_b p_{\|})2\gamma_b^2 - E, \qquad P_{\|\ \rm reflected} = -(Ev_b + p_{\|})2\gamma_b^2 + p_{\|}$

For $P_\perp = 0$ $v_b \to 1$ and $\gamma_b \gg 1$ for particles and exactly for photons $E_{\rm reflected} \to 4E\gamma_b^2$, seen in Einstein's 1905 “Electrodynamics of moving bodies” article.

Making QED Plasma: Field Materialization Relaxation Time

Direct way to high matter/energy density: E- field materialization. Use vacuum decay with tunneling. Timescale over which the field dissipates its energy into pairs is key to experimental setup.

The rate of field energy conversion into mass and source field energy are (Schwinger, Nikishov):

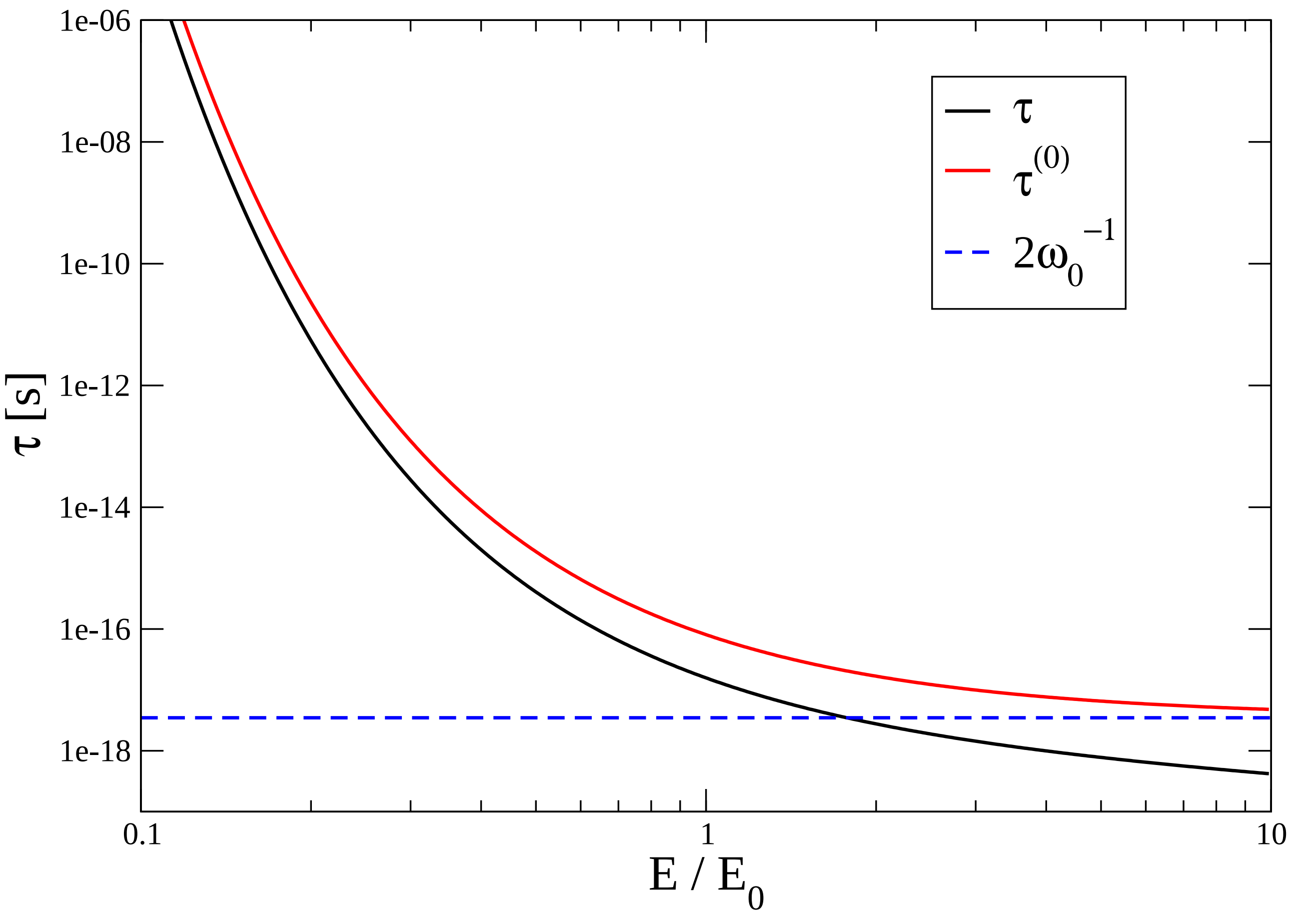
$$\frac{du_m}{dt} \simeq \omega_0 E^2 e^{-\pi E_0/E} \qquad u_{EM} \simeq \frac{E^2+B^2}{2}$$

$\omega_0 = \alpha mc^2/\pi^2\hbar = 0.574\,10^{18}\mathrm{s}^{-1}$. Relaxation time τ: time scale over which *all* field energy materializes, i.e. ratio of the rate of field energy conversion with field energy supply:

$$\frac{1}{\tau} \approx \frac{du_m/dt}{u_{EM}}$$

From Lance Labun and JR, arXiv:0808.0874

Materialization scale as function of E



$$2\omega_0^{-1} = 2\pi^2\hbar/\alpha mc^2 = 3.5\mathrm{as}$$

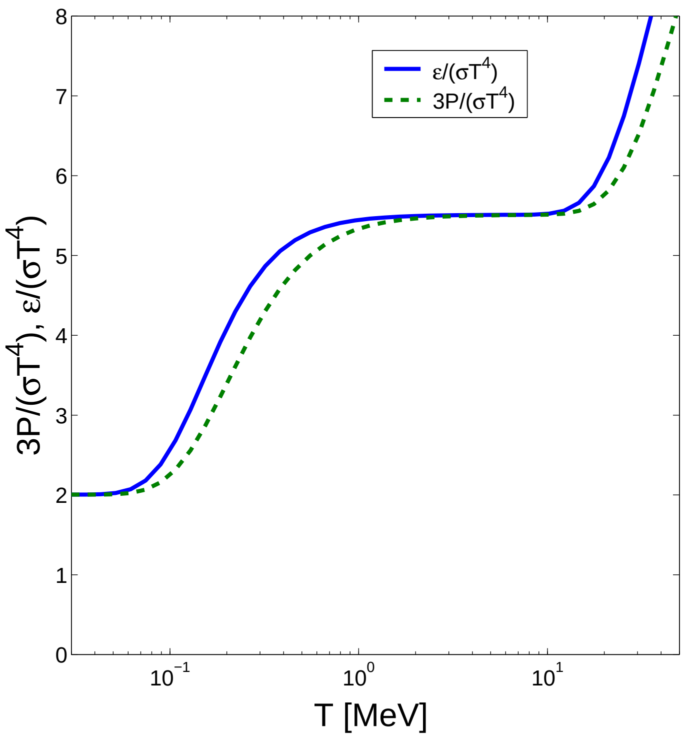
From first $e\bar{e}$-pair to QED plasma

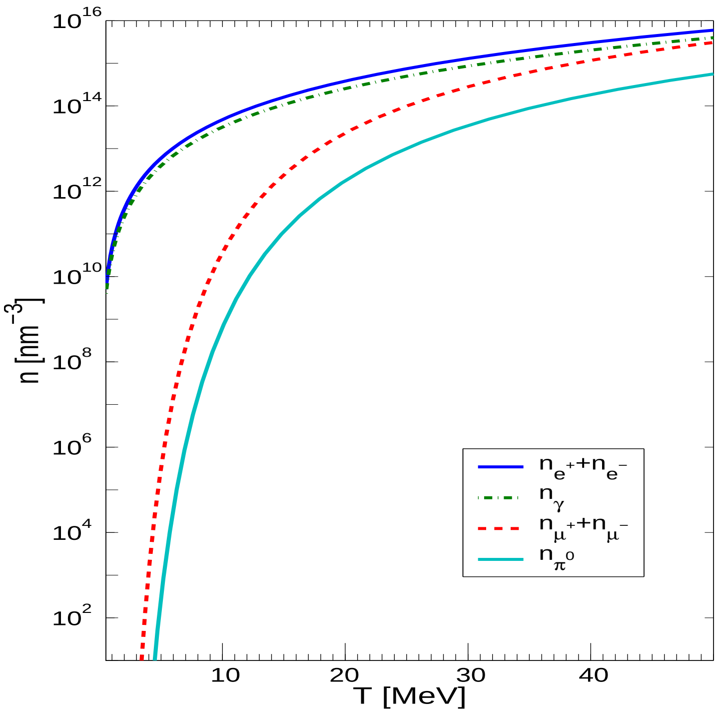
For an applied E/E_0, obtain yield rate W, and relaxation time τ with all present day bells and whistle:

E/E_0	W [$\mu\mathrm{m}^{-3}\mathrm{fs}^{-1}$]	τ [fs]
0.0628	1	4.634×10^{18}
0.1	3.102×10^{8}	3.712×10^{10}
0.2	8.234×10^{15}	5033
0.437	1.969×10^{20}	1
1	5.903×10^{22}	1.572×10^{-2}

Note that at critical field, the energy density in the field corresponds to QED plasma $T = 1.15$ MeV

Key properties of high density of e^-, e^+, γ-plasma





Plasma ball with $R = 20$ nm at $T = 1$ MeV contains 1.3 kJ energy.

Is this plasma ball opaque? The mean free paths l_i of particles ‘i’ are at sub nano-scale, shorter (including bremsstrahlung) than (Marcus Thoma, arXiv 0801.0956, PRA):

$$l_e \simeq 3.7\mathrm{nm}\left(\frac{1\,\mathrm{MeV}}{T}\right)^3\left(\frac{E}{3.1\,\mathrm{MeV}}\right)^2,\; l_\gamma \simeq 2.8\mathrm{nm}\left(\frac{1\,\mathrm{MeV}}{T}\right)^2\frac{E}{2.75\,\mathrm{MeV}}.$$

π_0 production: $\gamma + \gamma \to \pi_0$, master equation

Fugacity $\Upsilon \to 1$ describes approach to chemical equilibrium
$f_\pm(p,x) = \frac{1}{\Upsilon^{-1} e^{u\cdot p/T} \pm 1}$, $u \cdot p = E$ in rest frame.

$$\frac{1}{V}\frac{dN_{\pi^0}}{dt} = (\Upsilon_\gamma^2 - \Upsilon_{\pi^0}) R_{\pi^0} \qquad R_{\pi^0} \equiv \Upsilon_{\pi^0}^{-1}\frac{d^4 W_{\pi^0\to\gamma\gamma}}{dV\,dt} = \Upsilon_\gamma^{-2}\frac{d^4 W_{\gamma\gamma\to\pi^0}}{dV\,dt},$$

$\frac{d^4 W_{\pi^0\to\gamma\gamma}}{dV\,dt}$, $\frac{d^4 W_{\gamma\gamma\to\pi^0}}{dV\,dt}$ are Lorentz invariant decay // production rates.

$$R_{\pi^0} = \int \frac{d^3 p_\pi}{(2\pi)^3 2E_\pi} \int \frac{d^3 p_{2\,\gamma}}{(2\pi)^3 2E_{2\,\gamma}} \int \frac{d^3 p_{1\,\gamma}}{(2\pi)^3 2E_{1\,\gamma}} (2\pi)^4 \delta^4 (p_{1\,\gamma} + p_{2\,\gamma} - p_\pi) \times$$
$$\sum_{spin} |\langle p_{1\,\gamma} p_{2\,\gamma} | M | p_\pi \rangle|^2 f_\pi(p_\pi) f_\gamma(p_{1\,\gamma}) f_\gamma(p_{2\,\gamma}) \Upsilon_\gamma^{-2} \Upsilon_{\pi^0}^{-1} e^{u\cdot p_\pi/T}$$

$$R_{\pi^0} \to \left(\frac{m_\pi T}{2\pi}\right)^{3/2} \frac{e^{-m_\pi/T}}{\tau^0_{\pi^0}}.$$

Using the lifespan of the π^0 in Boltzmann limit:

Chemical equilibration time $\tau^0_{\pi^0}$

$$\tau_{\pi^0}\frac{d\Upsilon_{\pi^0}}{dt} = \Upsilon_\gamma^2 - \Upsilon_{\pi^0}, \qquad \tau_{\pi^0} = \frac{dn_{\pi^0}/d\Upsilon_{\pi^0}}{R_{\pi^0}}.$$

For $\Upsilon_{\pi^0}(t=0)=0$ and $\tau_{\pi^0}\approx$ Const. the analytical solution

$$\Upsilon_{\pi^0} = \Upsilon_\gamma^2\left(1-e^{-t/\tau_{\pi^0}}\right)$$

In the e^-, e^+, γ plasma ($T<50$ MeV) $\tau_{\pi^0}\simeq\tau^0_{\pi^0}=(84\pm6)10^{-18}\mathrm{s}$ is pion decay time in vacuum. In plasma small modifications of both relativistic and quantum τ_{π^0} origin (nearly) cancel.

Surprise: within 80–90 atto-sec the π^0 reach chemical equilibrium. I. Kuznetsova, D. Habs and JR, Phys.Rev.D78:014027,2008. arXiv:0803.1588 We have an excellent tool to diagnose formation of the QED plasma.

Sample of QED plasma particle production rates

reaction	$T{=}5$MeV τ [as]	$T = 5$MeV $W[\mathrm{nm}^{-3}\mathrm{fs}^{-1}]$	$T{=}15$MeV τ [as]	$T = 15$MeV $W[\mathrm{nm}^{-3}\mathrm{fs}^{-1}]$
$\gamma\gamma \leftrightarrow \pi_0$	88	$3.3\,10^{3}$	95	$1.2\,10^{12}$
$e^+e^- \leftrightarrow \mu^+\mu^-$	$1.2\,10^{10}$	$3.2\,10^{-3}$	$1.9\,10^{3}$	$1.5\,10^{11}$
$\gamma\gamma \leftrightarrow \mu^+\mu^-$	$1.0\,10^{10}$	$3.7\,10^{-3}$	$1.3\,10^{3}$	$2.1\,10^{11}$
$\pi^0\pi^0 \leftrightarrow \pi^+\pi^-$	$2.9\,10^{12}$	$2.1\,10^{-8}$	$4.6\,10^{2}$	$9.5\,10^{10}$
$\gamma\gamma \leftrightarrow \pi^+\pi^-$	$6.4\,10^{13}$	$9.7\,10^{-10}$	$5.1\,10^{4}$	$8.7\,10^{8}$
$e^+e^- \leftrightarrow \pi^+\pi^-$	$7.8\,10^{15}$	$7.9\,10^{-12}$	$9.5\,10^{5}$	$4.6\,10^{7}$

What next: Is the effective EH-L in strong fields correct?

The problem which we now illustrate is NOT the back-reaction issue (Emil Mottola) which describes the screening of the field by produced pairs.

The problem is that we used the idea of an unperturbed vacuum state with $\langle\overline{\psi}\psi\rangle = 0$ when evaluating non perturbative the effective Euler-Heisenberg (EH) near to Schwinger-scale fields.

Test of consistency: we assumed non-structured vacuum with vanishing condensate:

$$\langle\overline{\psi}\psi\rangle = -\frac{\partial L_{\mathrm{EH}}}{\partial m} ? = 0$$

Is this still true? Consider EHS effective action for magnetic field (which does not produce pairs the issue is not complicated by vacuum decay)

Need for self-consistent Euler–Heisenberg

$$L_{\rm EH} = \frac{1}{16\pi^2}\int_0^\infty \frac{ds}{s^3}\left(\frac{eBs\cosh eBs}{\sinh eBs} - 1\right) e^{-m^2 s} =? \frac{e^4}{360\pi^2 m^4} B^4 + \ldots .$$

clearly

$$\langle\overline{\psi}\psi\rangle_B = -\frac{\partial L_{\rm EH}}{\partial m} \neq 0$$

there is a condensate of electrons and positrons. Final result is inconsistent with the tacitly assumed vacuum structure.
Work in progress

What next: Quarks connect QED with QCD Vacuum

Another little appreciated problem is that the vacuum is full of strong electrical charge fluctuations: the quark fluctuations in the QCD vacuum $\langle\overline{\psi}_q\psi_q\rangle \simeq -(255\mathrm{MeV})^3$. The question is how strong EM fields alter this fluctuation and thus impact the properties of the vacuum. Work in progress

Epilogue: Retrospect on Virtual Matter Engineering

Development of quantum physics leads to the recognition that vacuum fluctuations alter details of laws of physics,

- The ‘quantum æther’ is polarizable: Coulomb law is not what we think. E.A.Uehling, 1935
- New interactions (anomalies) such as light-light scattering arise, Euler, Kockel, Heisenberg (1930-36)Here the electron and positron vacuum zero-point energy contains valuable information:
- Casimir notices that the photon vacuum zero point energy also induces a new force, commonly referred today as Casimir force
- Non-fundamental particles possible: Goldstone Bosons
- ‘Fundamental theory is effective - Weinberg-Salam model of EW interactions, ‘current’ masses as VEV
- Color confinement and high-T deconfinement

The End: Does mesoscopic volume size matter?

- What is the Universe manifold made of? What dimensionality (3+1) $\rightarrow (n+1)$: $n > 3$? Or a fractal dimension, even $n < 3$? What geometry it has: Lattice? (Mem)brane?
- Why is quantum physics incompatible with gravity and thus cosmology?
- What is the meaning of time?
  Rôle of the Universe expansion in defining time?
- What is the dark energy,

$$\frac{\lambda c^2}{8\pi G_N} \rightarrow \epsilon_d = \frac{(2.4\text{meV})^4}{(\hbar c)^3} = 4.3\frac{\text{keV}}{\text{cm}^3}$$

Why this fine-tuned mesoscopic value, small compared to quantum-gravity Planck mass scale:
$M_P = \sqrt{\hbar c/G_N} = 1.3\,10^{19} m_{\text{proton}}$ with $M_p^4 = 10^{125}\epsilon_d$, however, ϵ_d is big seen the emptiness, dominates the Universe today– it is 15 time the magnitude of the visible matter energy density.

Outlook

- On the way to EW symmetry restoration, we can make QED plasma, large QGP drops, make ultra intense source of pions and muons.
- Interesting strong field theoretical challenges: field materialization, unsolved QED vacuum structure, QED-QCD interference,.
- Large volume offers opportunity to question if there is a connection to other known riddles about the Universe, specifically the dark energy, cosmic strings?
- Practical challenge: how does the vacuum structure altered by ultra strong fields impact the extremely fine tuned nuclear properties??