Institutul de Fizica Atomica Magurele-Bucharest

DIASPORA la MAGURELE, September 2010

Romanian-European "EXTREME RESEARCH" PROGRAMME on LIGHT, MATTER and LASERS

M Apostol, Magurele

MEHR LICHT

Das Kind: Mein Vater, mein Vater, und horest du nicht

Wie Erlenkonig bittet mehr Licht?

Der Vater: Sei ruhig, bleibe ruhig mein Kind

In durren Blattern sauselt der Wind!

(J. W. Goethenberg, Physical Review, December 32, 2015)

O situatie grea:

Avem aparate, echipamente sofisticate, nu prea facem nimic cu ele

(LHC, ITER, Petawatt Laser, GRIDs...)

Aparatele, instalatiile se vad, Fizica mai greu

Mult prea adesea calcule numerice (simulari, modelari, ...), simple colectionari de date, simple descrieri trec drept Fizica

Mult prea adesea: “noi, administratorii, sefii, Liderii de Cercetare, am adus, facut, cumparat, etc aparate, instalatii, nu intelegem de ce Fizicienii nu lucreaza nimic la ele”

Prezint pe scurt 4 probleme de Fizica Plasmei si Laserilor, in colaborare cu M Ganciu, 2010

1 Laser Polariton

2 Theory of the Laser, Matter Polarization (2 levels), gamma laser

3 Coherent Polaritonic Compton backscattering, X- ray and gamma lasers

4 Pair Creation from Vacuum

PULSE and IMPULSE of ELI
(Extreme Light Infrastructure - Nuclear Physics (NP))
Institute of Atomic Physics, Magurele 2010

Done

1 Laser Polaritons (April 2010)

2 Plasma electrons accelerated by laser beams (M Ganciu, May 2010)

3 Gamma lasers - no chance (May 2010)

4 Cruise effect for gamma lasers (M Ganciu, July 2010)

Forthcoming

5 Coherent Compton (Thomson) backscattering by laser polaritons (M Ganciu, Oct 2010)

6 Pair creation from vacuum, vacuum refractive index (Nov 2010)

1) LASER POLARITON

Velocity and Energy

$$v \simeq c \left(1 - \frac{\omega_p^2}{2\omega_0^2}\right) \simeq c \ , \ \ \omega_p \ll \omega_0$$

$$E_{el} = \frac{mc^2}{\sqrt{1 - v^2/c^2}} \simeq \frac{\omega_0}{\omega_p} mc^2$$

$\hbar\omega_0 = 1eV$ ($\lambda_0 \simeq 1\mu$), electron density $n = 10^{18} cm^{-3}$, $\hbar\omega_p = 3 \times 10^{-2} eV$

$$E_{el} = \frac{\omega_0}{\omega_p} mc^2 \gg mc^2 \simeq 17 MeV$$

Electron flow

$$\delta N = nd^2\lambda_0 \frac{\varepsilon_p^2}{4mc^2\varepsilon_0^2}\sqrt{\pi\varepsilon_{el}W_0}$$

$I_0 = 10^{18}w/cm^2$, $d = 1mm$ (picos), ($W_0 = 10^{23}eV \simeq 10kJ$ and $\varepsilon_{el} = e^2/d = 10^{-6}eV$), $n = 10^{18}cm^{-3}$ ($\varepsilon_p = 3 \times 10^{-2}eV$), $\varepsilon_0 = 1eV$ ($\lambda_0 \simeq 1\mu$) and $mc^2 = 0.5MeV$

Get $\delta N \simeq 10^{11}$ electrons per pulse, accelerated at the energy $\simeq 17MeV$

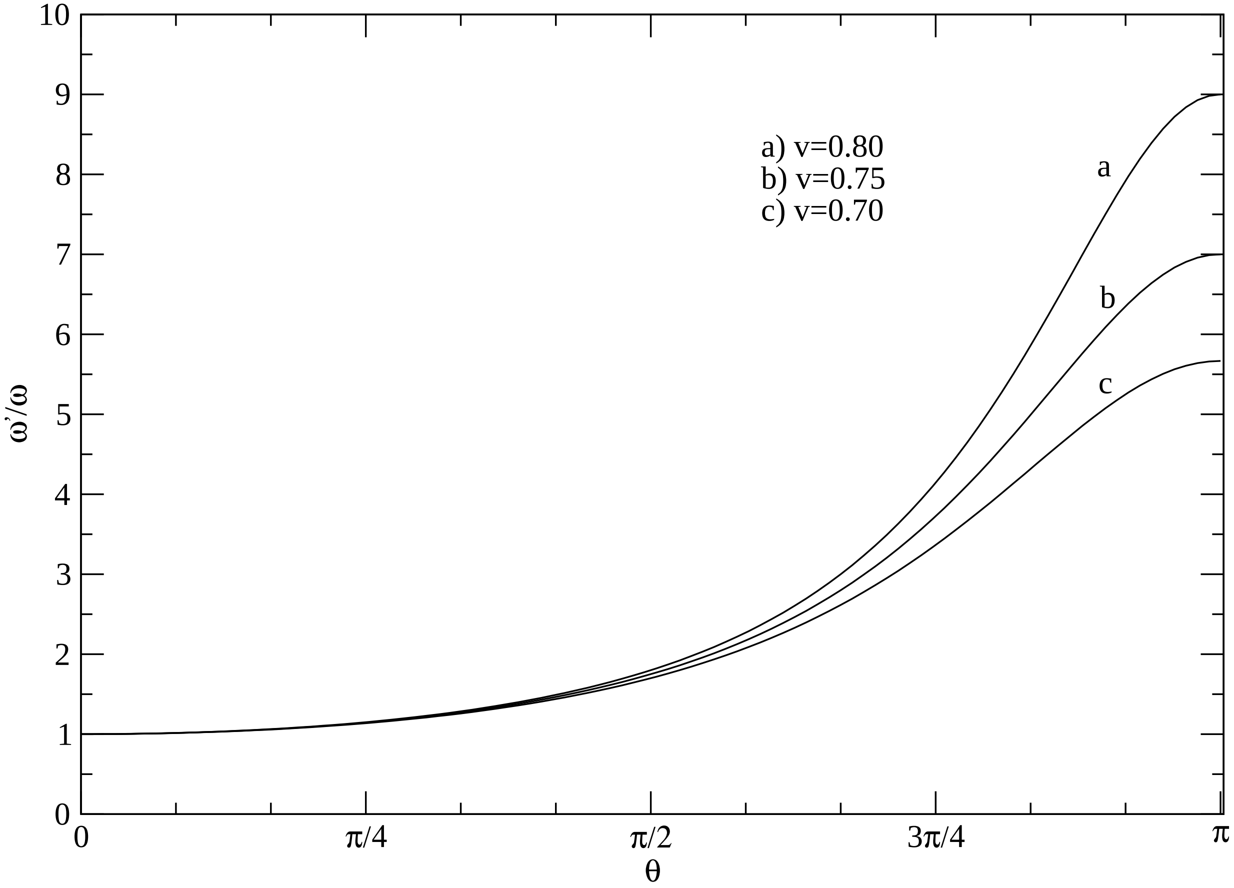
2) COHERENT COMPTON BACKSCATTERING by LASER POLARITONS

NOTE: Rigidity of the Electrons in the Polaritonic Pulse

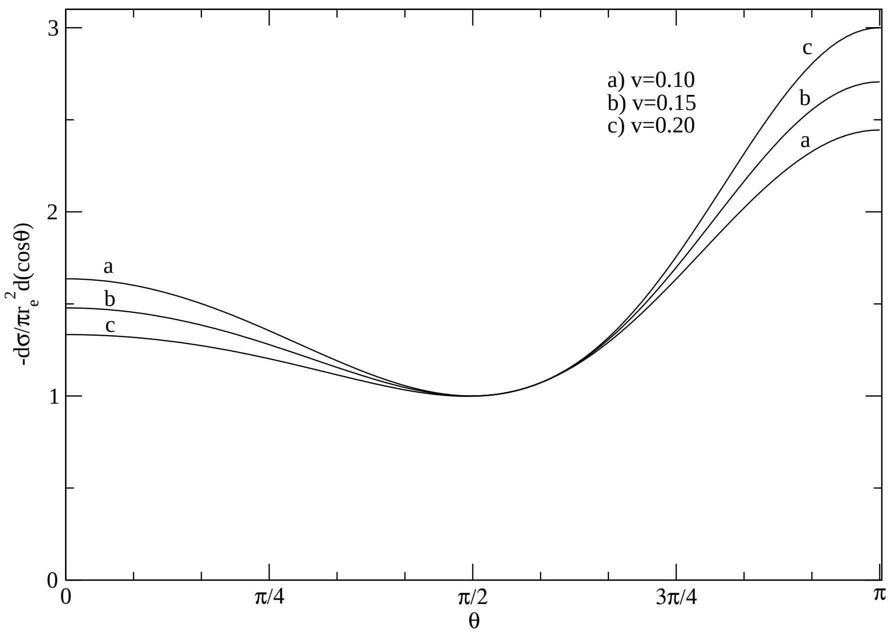
CONSEQUENCE: Coherent scattering, $\sigma \sim N^2$

$$\omega' = \omega \frac{1+v}{1 + v\cos\theta + \gamma\sqrt{1-v^2}(1-\cos\theta)} \ , \ \gamma = \omega/m \ll 1$$

$$\omega_b^{'} \simeq \omega \frac{1+v}{1-v} \simeq 10keV \ , \ 1meV$$


a) v=0.80
b) v=0.75
c) v=0.70
a
b
c
ω'/ω
θ
0
π/4
π/2
3π/4
π
0
1
2
3
4
5
6
7
8
9
10

$$d\sigma \simeq \pi r_e^2 \frac{(1-v^2)}{(1+v\cos\theta)^2}\left[\left(\frac{v+\cos\theta}{1+v\cos\theta}\right)^2+1\right]\sin\theta d\theta\ ,\ (r_e = e^2/m)\ (\gamma = 0)$$



$$dE^{coh} = \omega' dN_{ph} \Longrightarrow N^2 c n_{ph} \int \omega' d\sigma dt = -Nmd \frac{1}{\sqrt{1-v^2}}$$

$$\Delta t \simeq (\pi/2 - 1) \frac{3mc}{8\pi N \hbar \omega r_e^2 n_{ph}}$$

Incident photons $I = 10^{14} w/cm^2$ focused on $d = 1mm$ (picos)

Energy $W = Id^3/c \simeq 3J$, photon energy $\omega = 1eV$, photon density $n_{ph} \simeq 5 \times 10^{22} cm^{-3}$

For $N = 10^{11}$ (polaritonic pulse given before) we get $\Delta t \simeq 10^{-15}s$ (femtoseconds)

An estimate for the duration of the collision, duration of emission of the backscattered photons

It does not depend, practically, on the polariton energy, for high, relativistic energies

The polaritonic pulse is "stopped", and, in fact, destroyed, after the lapse of this time.

Emitted energy (per pulse) $\Delta E_b^{coh} \simeq \alpha^2 N E_0$, $\alpha \ll 1$ ($\sigma_b \simeq 5 \times 10^{-25} cm^2$, $\Delta\theta = \alpha\sqrt{2(1-v)/3v}$)

3) MATTER POLARIZATION - THEORY of the LASER - GAMMA LASER

Coherence, em field, polarizable matter; coupled, non-linear

$$\ddot{A} + \omega_0^2 A = \frac{2\omega_0 g}{\hbar\sqrt{N}} \left(\beta_0 \beta_1^* + \beta_1 \beta_0^*\right)$$

$$i\hbar\dot{\beta}_0 = \varepsilon_0 \beta_0 - \frac{g}{\sqrt{N}} \left(A + A^0\right) \beta_1$$

$$i\hbar\dot{\beta}_1 = \varepsilon_1 \beta_1 - \frac{g}{\sqrt{N}} \left(A + A^0\right) \beta_0$$

$$g = \sqrt{\pi\hbar/6a^3\omega_0} J_{01}\ ,\ \hbar\omega_1 = \varepsilon_1 - \varepsilon_0,\ A^0(t) = 2\left|\alpha^0\right| \cos\omega_0 t$$

$$\left\langle\left|\beta_{0,1}\right|^2\right\rangle = N_{0,1} \mp \lambda^2 \frac{N_0 N_1}{N} \frac{\omega_0 \omega_1}{\omega_0^2 - \omega_1^2} \mp \lambda^2 \frac{N_0 - N_1}{N} \left|\alpha^0\right|^2 \ , \ \lambda = 2g/\hbar\omega_1$$

$$\left\langle|\beta_1|^2\right\rangle = \lambda^2 \left|\alpha^0\right|^2 \ , \ E_s = \hbar\omega_1 \left\langle|\beta_1|^2\right\rangle = \frac{\omega_1}{\omega_0} \lambda^2 E_f^0 \ (N_1 = 0)$$

$N_1 = 0$. Take $\omega_0 = \omega_1$

Typical sample of atomic matter $\lambda = 0.5$ ($\hbar\omega_1 = 1eV$, $a = 3$Å, $p = 2.4 \times 10^{-18} esu$)

Reasonable values $E_f^0 = 10^3 J$, $N = 6 \times 10^{23}$ (Avogadro's number)

We get $E_s = 250J$, which may be viewed as an appreciable effect (this is the usual, optical laser; or the maser)

For atomic nuclei $\lambda = 10^{-8}$ ($\hbar\omega_1 \simeq \hbar\omega_0 = 1MeV$, $a = 3$Å, $p = 5 \times 10^{-23} esu$)

The released energy is extremely small

(Last comment: absence of the external field, $\lambda > 1$, super-radiance transition)

PAIR CREATION from VACUUM, VACUUM REFRACTIVE INDEX

"Serious" problem in QED

Critical Schwinger fields $E \simeq 10^{18} V/m$, $H \simeq 10^{13} Gs$!!!

We need 100 petawatt lasers for that!

and,

If taken seriously, our World would be for long destroyed by then!

My aim is to show that it is a trivial, common problem, interesting, perhaps, only as an exercise in QED

Dirac field interacting with radiation

$$H_{int} = -\frac{e}{c}\int d\mathbf{r}\psi^*(\mathbf{r})\mathbf{j}\psi(\mathbf{r})\mathbf{A}(\mathbf{r})$$

$$H_{int} = -ec\sum_{\mathbf{pk}}\sqrt{\tfrac{2\pi\hbar}{V\omega_k}}[A(\mathbf{p},\mathbf{p}-\mathbf{k})b^*_{\mathbf{p}}b_{\mathbf{p}-\mathbf{k}} + B(\mathbf{p},-\mathbf{p}+\mathbf{k})b^*_{\mathbf{p}}c^*_{-\mathbf{p}+\mathbf{k}} +$$

$$+B^*(-\mathbf{p}-\mathbf{k},\mathbf{p})c_{\mathbf{p}}b_{-\mathbf{p}-\mathbf{k}} + C(\mathbf{p},\mathbf{p}+\mathbf{k})c_{\mathbf{p}}c^*_{\mathbf{p}+\mathbf{k}}]\left(a_{\mathbf{k}} + a^*_{-\mathbf{k}}\right) \quad ,$$

Eqs of motion for a_k and $b_{\mathbf{p}}$, $c_{\mathbf{p}}$: formidable task!

Coherent interaction: classical fields with matter

$$b_{\mathbf{p}} \to \beta_{\mathbf{p}} \ , \ c^*_{-\mathbf{p}} \to \beta_{\mathbf{p}} \ ,$$

(particle-hole symmetry);

$$a_{\mathbf{k}} + a^*_{-\mathbf{k}} \to A_{\mathbf{k}} \ ,$$

$\beta_{\mathbf{p}}$, $A_{\mathbf{k}}$ c-numbers, classical fields

Great simplification: $g_k = 2ecb\sqrt{2\pi/V\hbar\omega_k}$

$$\ddot{A}_{\mathbf{k}} + \omega_k^2 A_{\mathbf{k}} = 2\omega_k g_k \sum_{\mathbf{p}} \beta^*_{\mathbf{p}} \beta_{\mathbf{p+k}} \ ,$$

$$i\dot{\beta}_{\mathbf{p}} = \Omega\beta_{\mathbf{p}} - \sum_{\mathbf{k}} g_k \beta_{\mathbf{p-k}} A_{\mathbf{k}} \ ,$$

(where $\Omega = \varepsilon_0/\hbar = mc^2/\hbar$)

Solution by Fourier transform

$$\beta_{\mathbf{p}} = \frac{1}{V}\int d\mathbf{r}\beta(\mathbf{r})e^{-\frac{i}{\hbar}\mathbf{pr}} \ , \ \beta(\mathbf{r}) = \sum_{\mathbf{p}} \beta_{\mathbf{p}} e^{\frac{i}{\hbar}\mathbf{pr}}$$

$(b = \frac{p_0^2}{\sqrt{35} m\varepsilon_0} \sim \hbar^2/m^2c^2d^2 \simeq (\lambda_c/d)^2)$

Electrons and positrons are created and destroyed continuously, quasi-localized over d, with a constant number N of pairs given by field energy

$$\beta(\mathbf{r}) = B(\mathbf{r})e^{-i\Omega t + i\lambda(\mathbf{r})t}$$

$$-\hbar\lambda \simeq -\frac{2e^2b^2}{\pi d}N = -\frac{12}{35}(6\pi^2)^{1/3}\frac{e^2}{d}\left(\frac{\lambda_c}{d}\right)^4 \simeq 0$$

Compton wavelength

$$\lambda_c = \hbar/mc \simeq 0.3 \times 10^{-10} cm$$

Energy (e.g., $W = 1J \Longrightarrow N \simeq 10^{13}$ pairs)

$$E_{em} + 2mc^2N = \frac{12}{35}(6\pi^2)^{1/3}\frac{e^2}{d}\left(\frac{\lambda_c}{d}\right)^4 N^2 + 2mc^2N = W$$

Introduce explicitly an external field $A_0 = 2a_0 \cos\omega_0 t$

$$\beta(\mathbf{r}) = B(\mathbf{r}) e^{-i\Omega t + i\lambda t + i\varphi(\mathbf{r},t)}$$

$$\varphi(\mathbf{r},t) = \frac{4g_0 a_0}{\omega_0} \sin\omega_0 t \cos\mathbf{k}_0\mathbf{r}$$

$$\delta\varepsilon(\mathbf{r},t) = -4\hbar g_0 a_0 \cos\omega_0 t \cos\mathbf{k}_0\mathbf{r}$$

(Stationary wave)

Refractive index

The external field induces a polarization field which is stationary (the vector potential does not depend on the time)

As a consequence of the stationary dynamics of the electrons and positrons

Therefore, the polarization electric field is vanishing, and we are left only with a static magnetic field

Under the action of an external field **the vacuum gets magnetized**

The vector potential of the polarization field $A_0^{pol} = g_0 N/2\omega_0$

This polarization field depends on the strength A_0 of the external field through the field energy W_0 which generates the number of pairs N

Consequently, we can define a static magnetic susceptibility of the polarized vacuum

$$\mu = 1 + \frac{eb}{4mc\omega_0} H_0 = 1 + \frac{(6\pi^2)^{2/3}}{4\sqrt{35}} \left(\frac{\lambda_c}{d}\right)^2 \frac{eH_0}{mc\omega_0} \ , \ n = \sqrt{\mu}$$

Extremely small deviations from unity!

In CONCLUSION

Thanks to

ELI Workshop, Februrary 2010

Institute for Lasers, Plasma and Radiation

Institute for Atomic Physics

Institute for Physics and Nuclear Engineering

all in Magurele-Bucharest

and

Thank you for your atention!