An Experimental Program on Strong-Field QED Effects in $e\gamma$, $\gamma\gamma$, and e^+e^- Collisions

K. McDonald
Princeton U.

May 14, 1991

Intense Macroscopic Electromagnetic Fields

① Terawatt Lasers

1 Joule in 1 picosecond

$\lambda \sim \frac{1}{4}\ \mu m$

$E \sim \sqrt{\frac{377 \cdot \text{Power}}{2\pi\lambda^2}}$ at diffraction-limited focus

$\sim 3\times10^{11}\ \frac{\text{Volts}}{\text{cm}}$ (300 GeV/cm !)

② Electron Bunches in Linear Colliders

NLC: $N \sim 10^{10}$

$R \sim 50\text{Å}$

$L \sim 1\ \text{psec} \sim 0.03\ \text{cm}$

$\gamma \sim 10^{6}$

At the surface of a bunch,

$E \sim B \sim \frac{2Ne}{RL} \sim 2\times10^{11}\ V/cm$

$E^* = \gamma E = 2\times10^{17}\ V/cm$ as viewed by the other beam

QED STRONG-FIELD EFFECTS

① VOLTAGE DROP OF 1 RYDBERG IN 1 BOHR RADIUS

$$E \sim \frac{13.6\,eV}{0.5\,\text{Å}} \sim 3\times10^{9}\ V/cm$$

$\Rightarrow$ ATOMS CEASE TO EXIST

② VOLTAGE DROP OF mc^2 IN 1 LASER WAVELENGTH

$$eE\frac{\lambda}{2\pi} \sim mc^2 \quad \text{OR} \quad E \sim \frac{3\times10^{10}}{\lambda \text{ IN } \mu m}\ \frac{V}{cm}$$

$\Rightarrow$ MULTIPHOTON EFFECTS DOMINATE

③ VOLTAGE DROP OF mc^2 IN 1 COMPTON WAVELENGTH

$$eE\frac{\hbar}{mc} \sim mc^2 \quad \text{OR} \quad E = \frac{m^2c^3}{e\hbar} \equiv E_{CRIT} = 1.3\times10^{16}\ V/cm$$

$\Rightarrow$ LARGE RATE OF PAIR CREATION

[PUZZLING POSITRON PEAKS OF DARMSTADT ??]

④ HAWKING FLUCTUATON ENERGY $\sim mc^2$

$$kT = \frac{\hbar a}{2\pi c} = \frac{\hbar eE}{2\pi mc} \sim mc^2 \quad \text{OR} \quad E \sim \frac{E_{CRIT}}{2\pi}$$

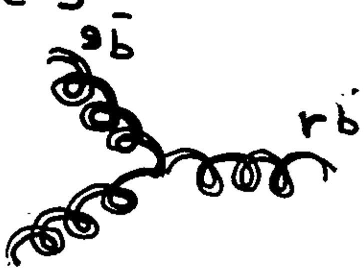
$\Rightarrow$ SYSTEM IN THERMAL EQUILIBRIUM WITH 'SEA' OF ELECTRON-POSITRON PAIRS

FUNDAMENTAL NONLINEAR FORCES

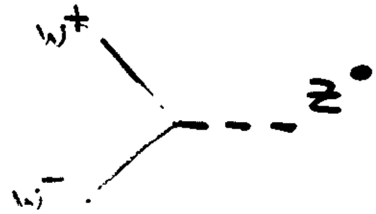
ELECTROMAGNETIC — LINEAR $\longleftrightarrow$ SUPERPOSITION OF FIELDS

STRONG, WEAK, GRAVITATIONAL } — NONLINEAR $\longleftrightarrow$ SELF-COUPLING OF GAUGE BOSONS

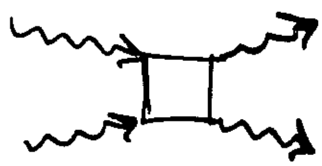
i.e.



OR



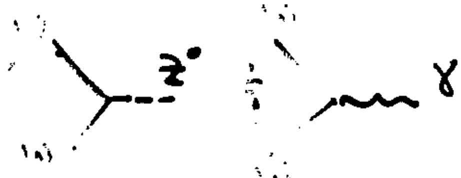
BUT, VACUUM POLARIZATION $\Rightarrow$ NONLINEARITY IN QED



LIGHT-BY-LIGHT SCATTERING (1935)

NO <u>DIRECT</u> <u>EVIDENCE</u> FOR ANY FUNDAMENTAL NONLINEAR INTERACTION!

LEP II: $50-100M TO STUDY



DOE/ER/3072-39
September 9, 1986

PROPOSAL FOR AN EXPERIMENTAL STUDY OF NONLINEAR COMPTON SCATTERING

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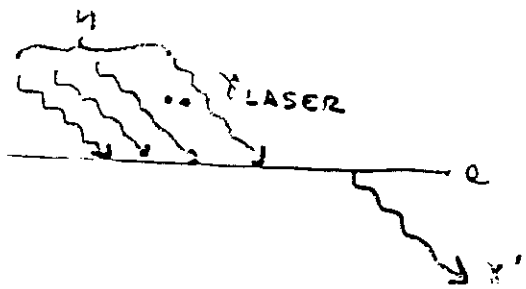
$$n\gamma_{\text{LASER}} + e \longrightarrow \gamma' + e'$$



Submitted to Brookhaven National Laboratory

† Spokesperson

FREE ELECTRONS IN A PLANE WAVE

1. TRANSVERSE VELOCITY, $V_\perp$

$$F = ma \Rightarrow eE = m\omega v_\perp \Rightarrow \frac{v_\perp}{c} = \frac{eE}{m\omega c} \equiv \eta$$

SO $v_\perp \rightarrow c$ AS $\eta \rightarrow 1$

NOTE: $\eta = \frac{1}{2\pi} \frac{eE\lambda}{mc^2} = \frac{1}{2\pi} \cdot \frac{\text{VOLTAGE DROP PER WAVELENGTH}}{\text{ELECTRON REST ENERGY}}$

2. EFFECTIVE MASS, $\bar{m}$

DUE TO THE $v_\perp$, THE ELECTRON HAS MASS

$$\gamma m = \frac{m}{\sqrt{1 - v_\perp^2/c^2}}$$

THEN REALLY $F = \gamma m a$ SO $\frac{v_\perp}{c} = \frac{\eta}{\gamma}$

$$\Rightarrow \gamma = \sqrt{1+\eta^2} \qquad \frac{v_\perp}{c} = \frac{\eta}{\sqrt{1+\eta^2}}$$

WE SAY $\bar{m} \equiv \gamma m = m\sqrt{1+\eta^2}$ = EFFECTIVE MASS OF THE ELECTRON IN THE WAVE

Higher Harmonic Radiation

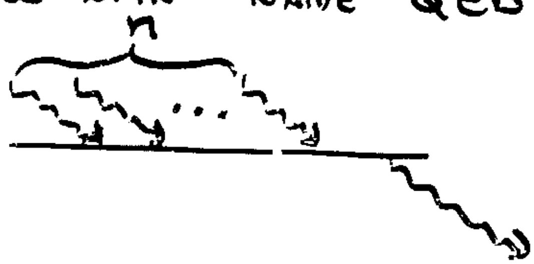
When $v \to c$, higher multipole radiation becomes important

$$\frac{dU_n}{dt} \sim \left(\frac{v}{c}\right)^{2n-2} \cdot \text{ dipole radiation}$$

$\therefore$ Cross section for scattering to final photon of frequency $n\omega$ is

$$\sigma_n \sim r_0^2 \left(\eta^2\right)^{n-1} \qquad (\eta \lesssim 1)$$

Compare with 'naive' QED analysis



$$\sigma \sim \frac{\alpha^{n+1}}{m^2} \sim r_0^2 \, \alpha^{n-1}$$

For $\eta \gg 1$ we have a kind of synchrotron radiation

$\Rightarrow$ max. intensity at harmonic

$$n\omega \sim \gamma^3 \omega \sim \eta^3 \omega$$

Close analogy to wiggler radiation:
(scattering of virtual photons of the wiggler)

– higher harmonics when $\eta = \frac{eB}{mc^2}$ [illegible] $\gtrsim 1$

SOVIET PHYSICS JETP VOLUME 20, NUMBER 3 MARCH, 1965

QUANTUM PROCESSES IN THE FIELD OF A CIRCULARLY POLARIZED ELECTROMAGNETIC WAVE

N. B. NAROZHNYĬ, A. I. NIKISHOV, and V. I. RITUS

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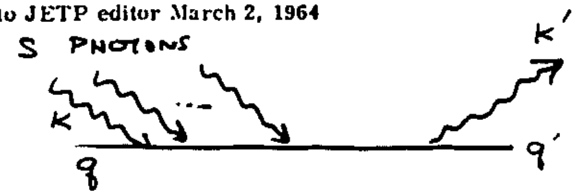
Submitted to JETP editor March 2, 1964



NON LINEAR COMPTON SCATTERING

The probability of emission of a photon by an electron evaluated per unit volume per unit time turns out to be equal to [2)]

$$W(\chi, x) = \frac{e^2 m^2 n}{16\pi q_0} \sum_{s=1}^{\infty} \int_0^{u_s} \frac{du}{(1+u)^2} \left\{ -4J_s^2(z) + x^2 \left(2 + \frac{u^2}{1+u} \right) \times (J_{s-1}^2 + J_{s+1}^2 - 2J_s^2) \right\},$$

$$u = (kk')/(kq'), \quad u_s = -2s(kq)/m_*^2 = 2s\chi/x(1+x^2),$$

$$z = (x^2 \sqrt{1+x^2}/\chi) \sqrt{u(u_s - u)}. \tag{9}$$

This probability, as well as the probability for a linearly polarized wave, depends on two invariants which we have chosen in the form

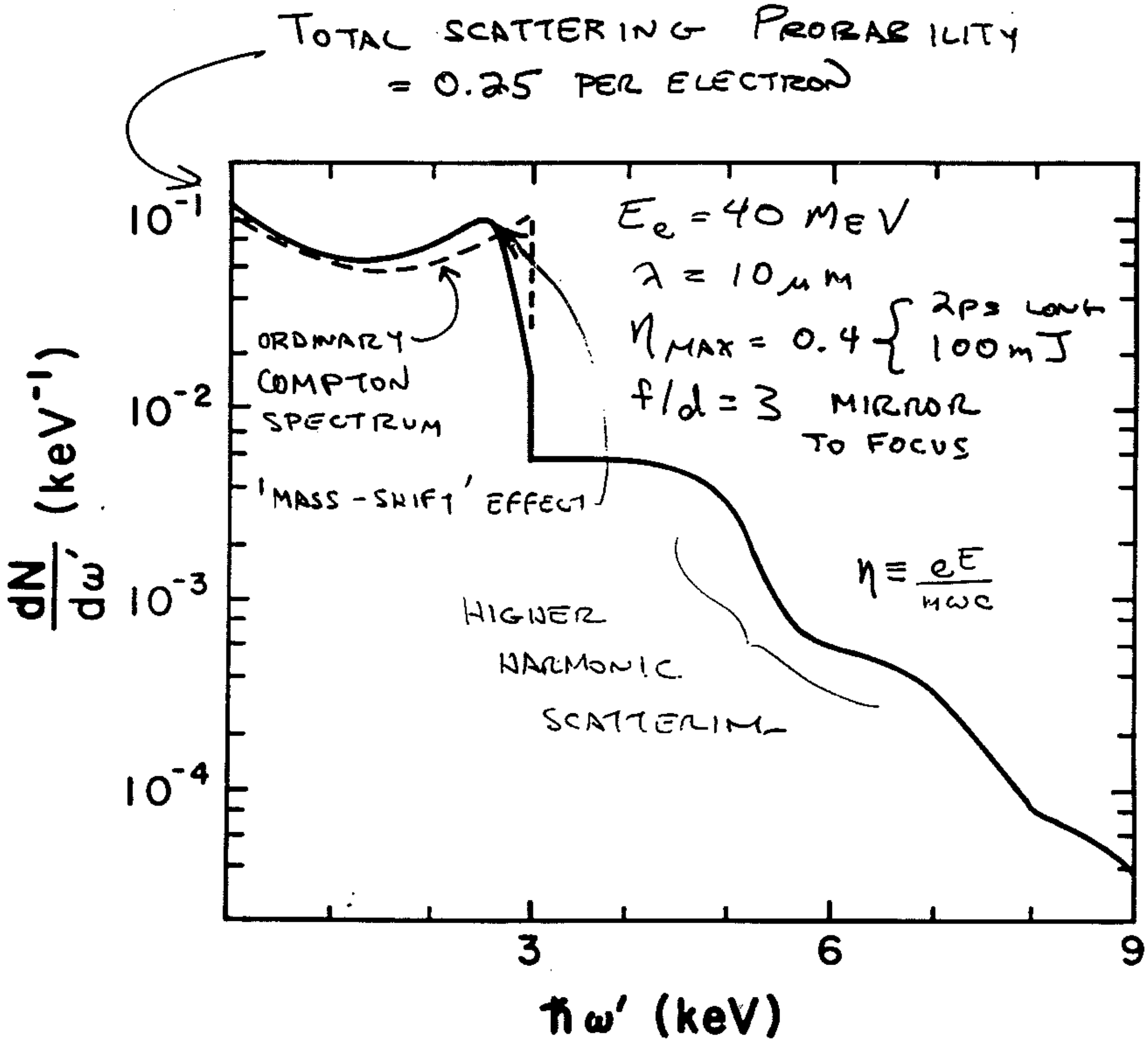
$$\eta = x = ea/m, \quad \chi = -x(kp)/m^2 = e\sqrt{(F_{\mu\nu}p_\nu)^2}/m^3,$$

where $F_{\mu\nu}$ is the amplitude of the intensity of the field.

$\eta \equiv \frac{eE}{m\omega c}$ = $\frac{\text{VOLTAGE DROP PER LASER WAVELENGTH}}{mc^2}$

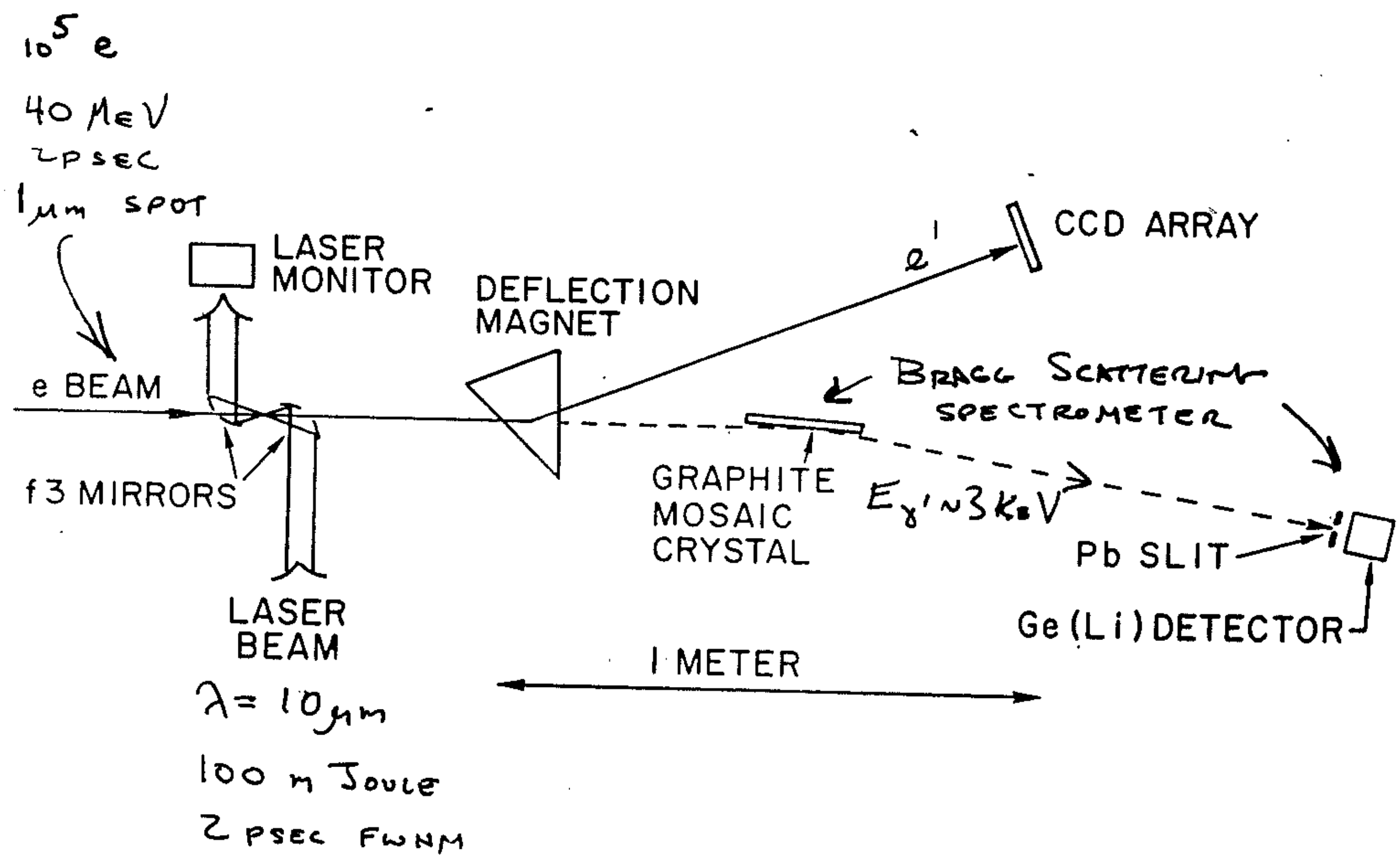
$\left(= \frac{v_{osc}}{c} \text{ IF } \eta <= 1 \right)$

NONLINEAR COMPTON SCATTERING



X-RAY PRODUCTION = BASIC TEST OF SYNCHRONIZATION OF LASER AND LINAC.

NONLINEAR COMPTON SCATTERING EXPERIMENT



BACK SCATTERED PHOTON BEAM

$E_e = 46\,GeV$
$\lambda = .308\,\mu m$ } $E_{\gamma\, MAX} = 34\,GeV$
ORDINARY COMPTON SCATTER

$\tau_e \sim 10\,ps$
$\tau_\gamma \sim .25\,ps$ } $\sim 1\%$ OF e BEAM SCATTERS
$\sigma_r \sim 1\,\mu m$

TAKE HIGHEST 5% OF SCATTERED PHOTONS
TO FORM 'MONOCHROMATIC' γ BEAM

$$I_\gamma \sim 5\times10^{-4}\, I_e$$

SLC BEAM $\Rightarrow$ $I_e \sim 5\times10^{10}$ PER PULSE

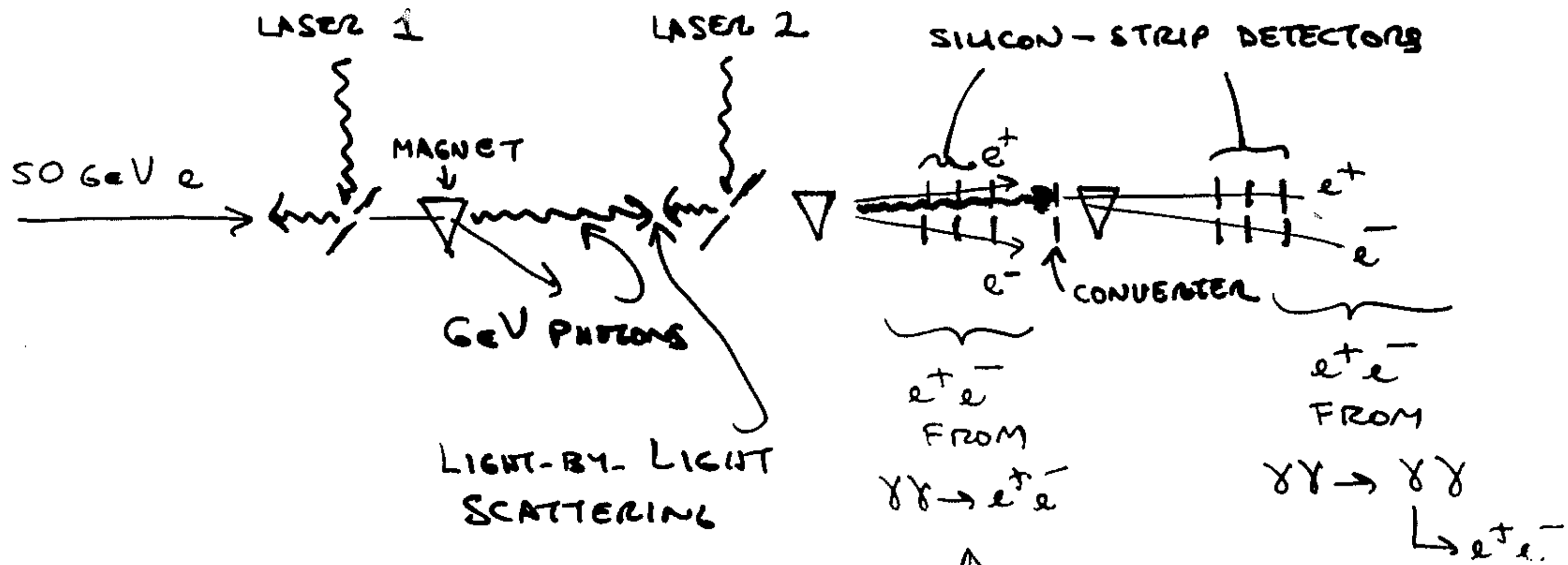
$$I_\gamma \sim 2\times10^{7}$$

CAN STUDY

$n\gamma + \gamma' \to e^+e^-$ BREIT-WHEELER EFFECT
$\sigma \sim \pi r_0^2 \sim 10^{-25}\,cm^2$

$n\gamma + \gamma' \to \gamma + \gamma$ TRUE LIGHT-BY LIGHT SCATTERING
$\sigma \sim \alpha^2 r_0^2 \sim 10^{-30}\,cm^2$

LIGHT-BY-LIGHT SCATTERING EXPERIMENTS



10 KeV RESOLUTION
ON $M_{e^+e^-}$ AT 1.8 MeV/c
USING DETECTORS
WITH 10 μm RESOLUTION

PAIR CREATION BY LIGHT

(BREIT & WHEELER, 1934)

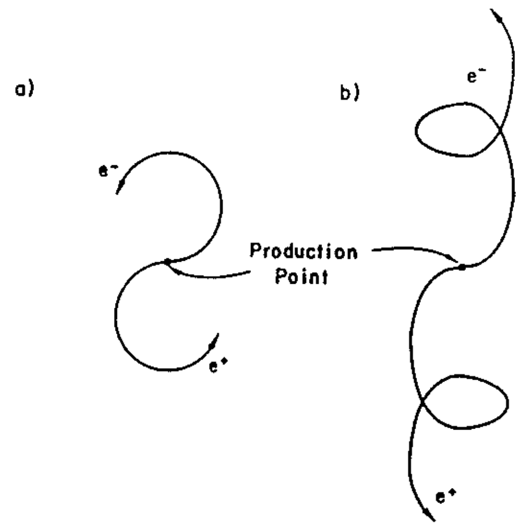
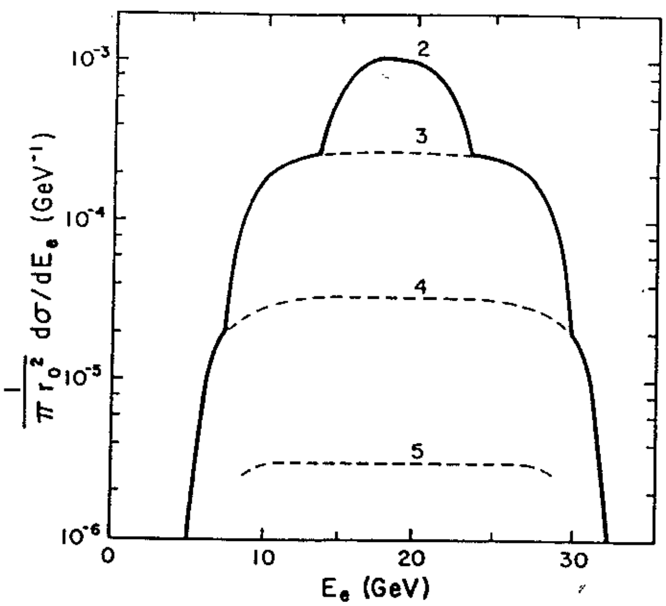


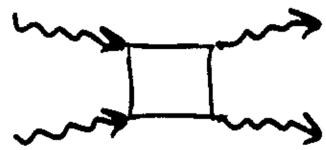
Figure 4. **a)** The trajectories of an electron-positron pair created with threshold energy in a strong wave field. The orbits are the circles discussed in section 2-1a; **b)** The trajectories for pair creation above threshold. The orbits are trochoids.



$n\, \gamma_{LASER} + \gamma' \rightarrow e^+ e^-$

Figure 5. The cross section, normalized to πr_o^2, for the multiphoton Breit-Wheeler effect. The backscattered photon beam has energy 37 GeV. The laser beam has wavelength 0.308 μm and field-strength parameter $\eta = 0.25$. The reaction is energetically forbidden to proceed with only one laser photon. The contributions to the cross section from 2 through 5 laser photons are labeled.

LIGHT-BY-LIGHT SCATTERING



A 'WEAK' ELECTROMAGNETIC INTERACTION:

AT OPTICAL FREQUENCIES, $\sigma = \frac{973}{10125\pi} \alpha^2 r_0^2 \left(\frac{\omega}{m}\right)^6$

$\sim 3 \times 10^{-61}\ \text{cm}^2$ FOR $\omega = 5\ \text{eV}$

TABLETOP LASER:

1 JOULE IN 1 PICOSECOND FOCUSED TO 1 μm

$\Downarrow$ $\qquad$ $\searrow\!\Downarrow$ $\qquad$ $\Downarrow$

$\sim 10^{18}$ PHOTONS $\qquad$ TERAWATT $\qquad$ SPOT SIZE $\sim 10^{-8}\ \text{cm}^2$

RATE/PULSE $= N_1 N_2 \dfrac{\sigma}{A} \sim 3 \times 10^{-17}$

$\Rightarrow$ NEED $> 10^6$ JOULE / PULSE FOR OPTICAL EXPERIMENT

LIGHT-BY-LIGHT SCATTERING

$n\gamma_{LASER} + \gamma' \rightarrow \gamma'' + \gamma'''$

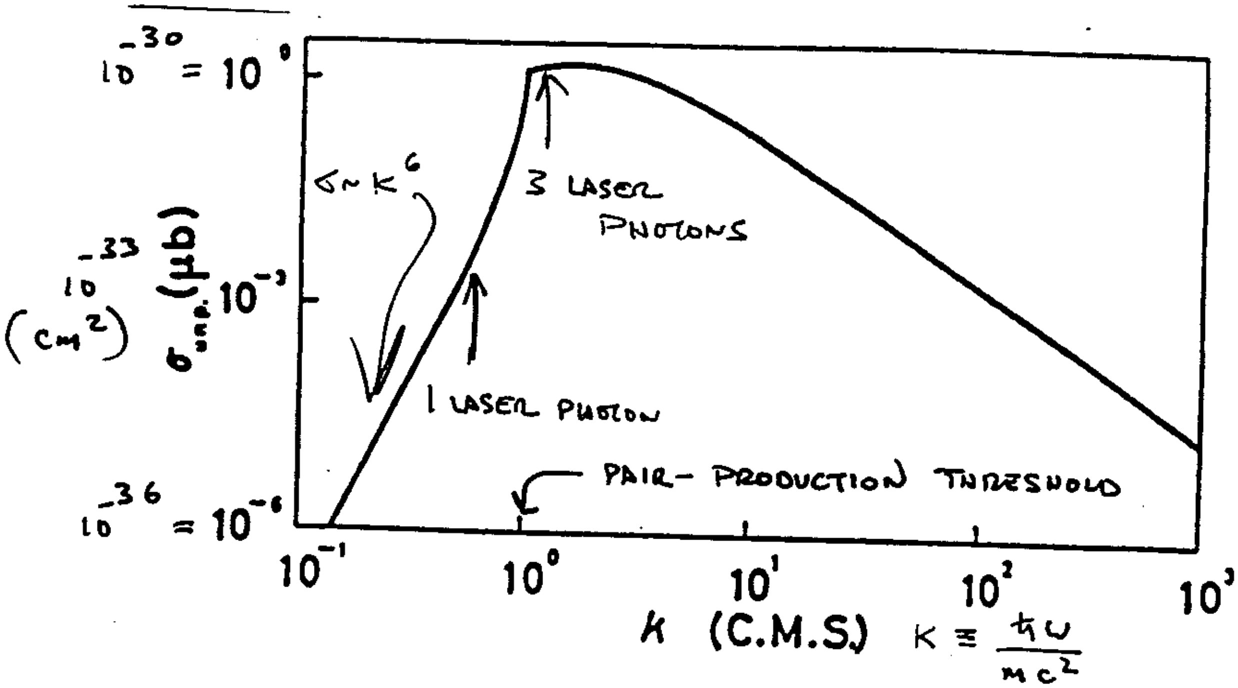


Figure 8. Total cross section of light-by-light scattering for unpolarized photons as a function of the energy k of each photon in the center-of-mass system, in units of mc^2.[63]

IN SLC EXPERIMENT, WE ARE BELOW PAIR CREATION THRESHOLD IF ONLY 1 LASER PHOTON.

NO THEORY YET FOR THE CASE OF 3 LASER PHOTONS (ABOVE PAIR-PRODUCTION THRESHOLD)

PHYSICAL REVIEW

LETTERS

VOLUME 59 | 7 SEPTEMBER 1987 | NUMBER 10

Photon Splitting in a Plane-Wave Field

Ian Affleck[a] and Leonid Kruglyak[b]

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(Received 19 June 1987)

An experiment has recently been proposed to measure the splitting of a photon into two photons in an intense plane-wave field. Coherent absorption and emission of several plane-wave photons may play an important role at these high intensities. We make an approximate calculation of these nonlinear effects which shows that they become important at intensities of 2×10^{13} V/cm, about twice the intensity in the proposed experiment.

PACS numbers 12.20.Ds

Recent proposals for experimental studies of nonlinear quantum electrodynamics have created a need for theoretical calculations of nonlinear QED effects and have pointed out a lack of such calculations in the existing literature.[1] The experiments proposed for the Stanford Linear Collider (SLC) would bring high-energy electrons and photons into collision with a high-intensity laser beam. One of the effects that may be detectable is "photon-splitting" in which an external high-energy photon enters the beam and two high-energy photons leave it. This process is accompanied by the coherent absorption and emission of some number of laser photons. The lowest-order process, involving the absorption of a single laser photon, is the "ordinary" elastic scattering of light by light. The amplitude is given by the box diagram of Fig. 1 and was calculated by Karplus and Neuman[2] and by de Tollis.[2,3] This process has never been observed experimentally.

Obtaining a high enough flux for the rate due to this process to be significant requires such an intense beam that multiple-photon processes become important. The exact calculation [up to $O(\alpha)$ corrections] can be formulated in terms of the electron propagator in a plane-wave field. The graph is shown in Fig. 2 and involves three external photon lines and three plane-wave field propagators. It is natural to regard this as a photon "decay" process. It is kinematically possible for the photon to decay because energy and momentum are only conserved modulo nk_L, in the background field, where k_L is the laser-photon four-momentum and n is an integer. Expanding the propagators in laser-photon lines gives a sum of ordinary Feynman diagrams. The rate contains a sum of terms with different numbers of *net* absorbed laser photons (number absorbed minus number emitted).

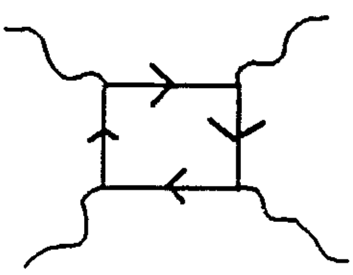


FIG. 1. Lowest-order light-by-light scattering process.

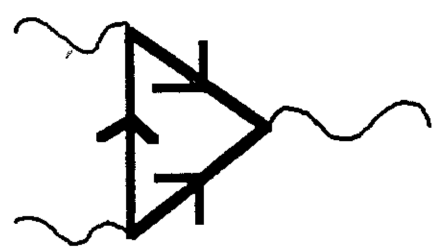


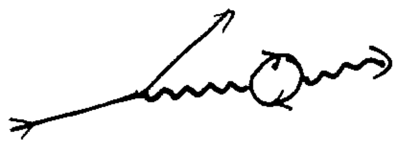
FIG. 2. Photon-splitting diagram. Heavy lines represent the exact electron propagator in a plane-wave field.

VACUUM ČERENKOV RADIATION

VACUUM POLARIZATION IN AN INTENSE LASER BEAM

$\Rightarrow$ INDEX $n \sim 1 + \frac{\alpha}{4\pi}\left(\frac{E}{m^2/e}\right)^2$ FOR $\frac{\omega}{m}\frac{E}{E_{CRIT}} \lesssim 1$

$\therefore$ ČERENKOV EFFECT WHEN $\gamma > 30 \frac{m^2/e}{E}\sqrt{1+\eta^2}$



IF TERAWATT LASER WITH $\lambda \sim \frac{1}{4}\mu m$ $(\eta \sim 1)$

NEED $\gamma > 3 \times 10^6 \Rightarrow E_e > 1.5$ TeV

[BUT DOESN'T PAY TO GO TO $\eta \gg 1$ SINCE $\frac{\sqrt{1+\eta^2}}{E} \to 1$]

EFFECT OF INDEX AT OPTICAL FREQUENCIES:

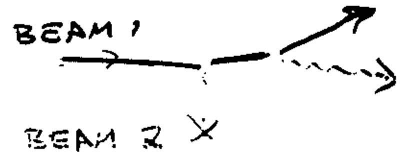
FARADAY ROTATION OF POLARIZATION IN A MAGNETIC FIELD IN VACUUM

ROTATION $\sim 10^{-12}$ FOR 1 KM PATH IN 10 KG FIELD

(MELISSINOS, ZAVATINI)

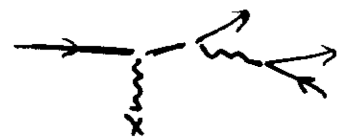
PROCESSES IN WHICH ELECTRONS LOSE ENERGY DUE TO STRONG FIELDS IN BEAM-BEAM COLLISIONS

(1) BEAMSTRAHLUNG



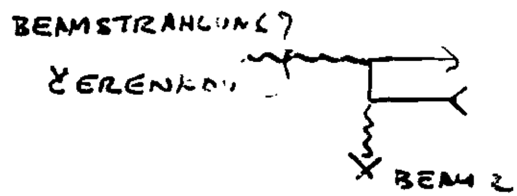
(2) VACUUM ČERENKOV RADIATION

(3) TRIDENT PRODUCTION

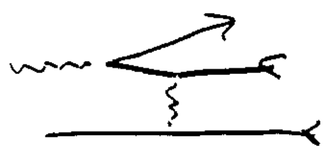


PROCESSES IN WHICH ELECTRON-POSITRON PAIRS ARE CREATED IN STRONG FIELDS IN BEAM-BEAM COLLISIONS

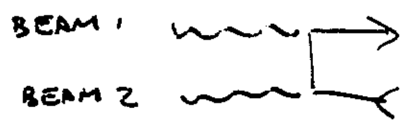
(1) REAL-PHOTON PAIR CREATION



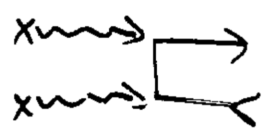
BETHE-HEITLER:



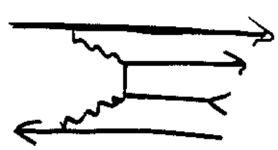
BREIT-WHEELER:



(2) 'SPONTANEOUS' PAIR CREATION



ALSO, LANDAU-LIFSHITZ:



(3) TRIDENT PRODUCTION

[THE X$\sim\sim$ IS A NON-PERTURBATIVE, MULTIPHOTON, STRONG-FIELD EFFECT.]

PHOTO PRODUCTION OF W BOSONS

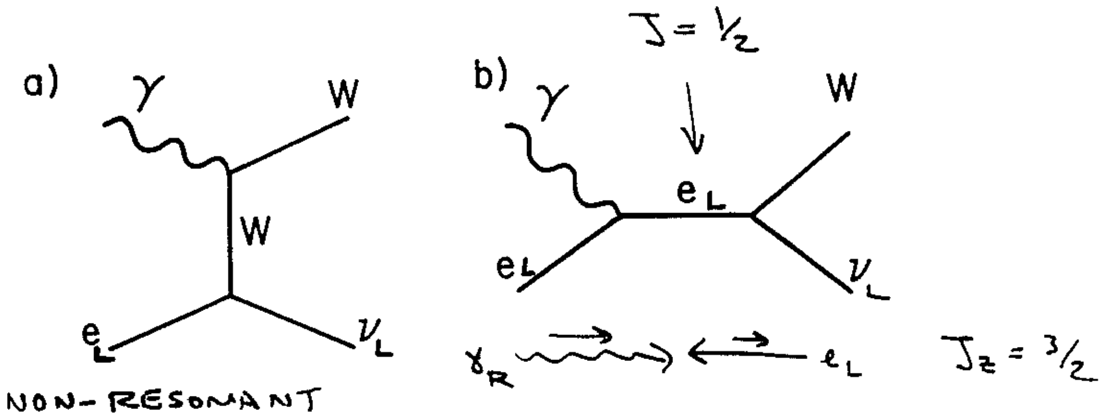


Figure 10. The two Feynman diagrams which contribute to the reaction $\gamma e \to W\nu$. Diagram b) can be suppressed by the use of right-hand circularly polarized photons.

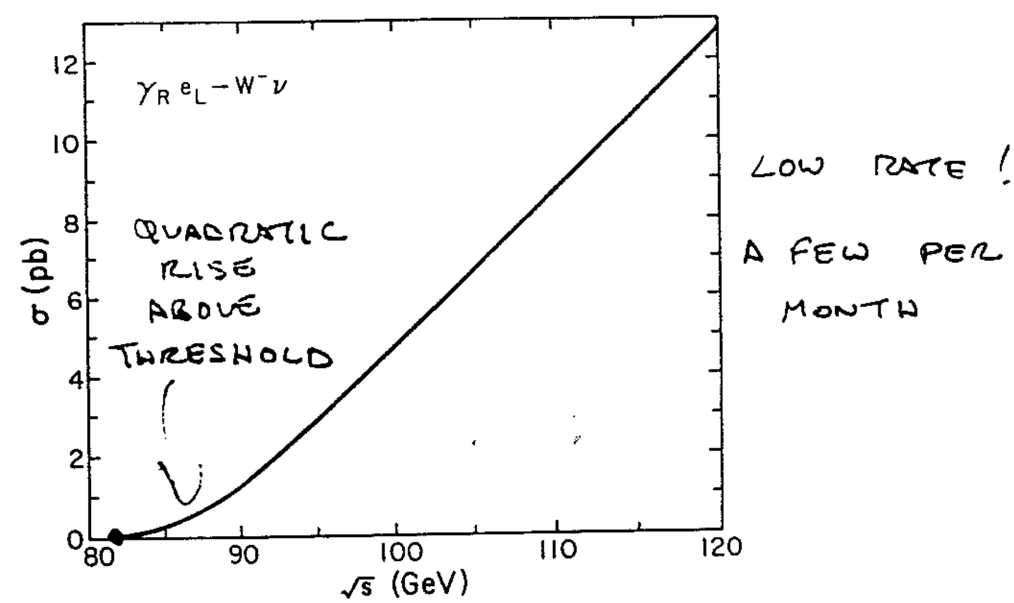
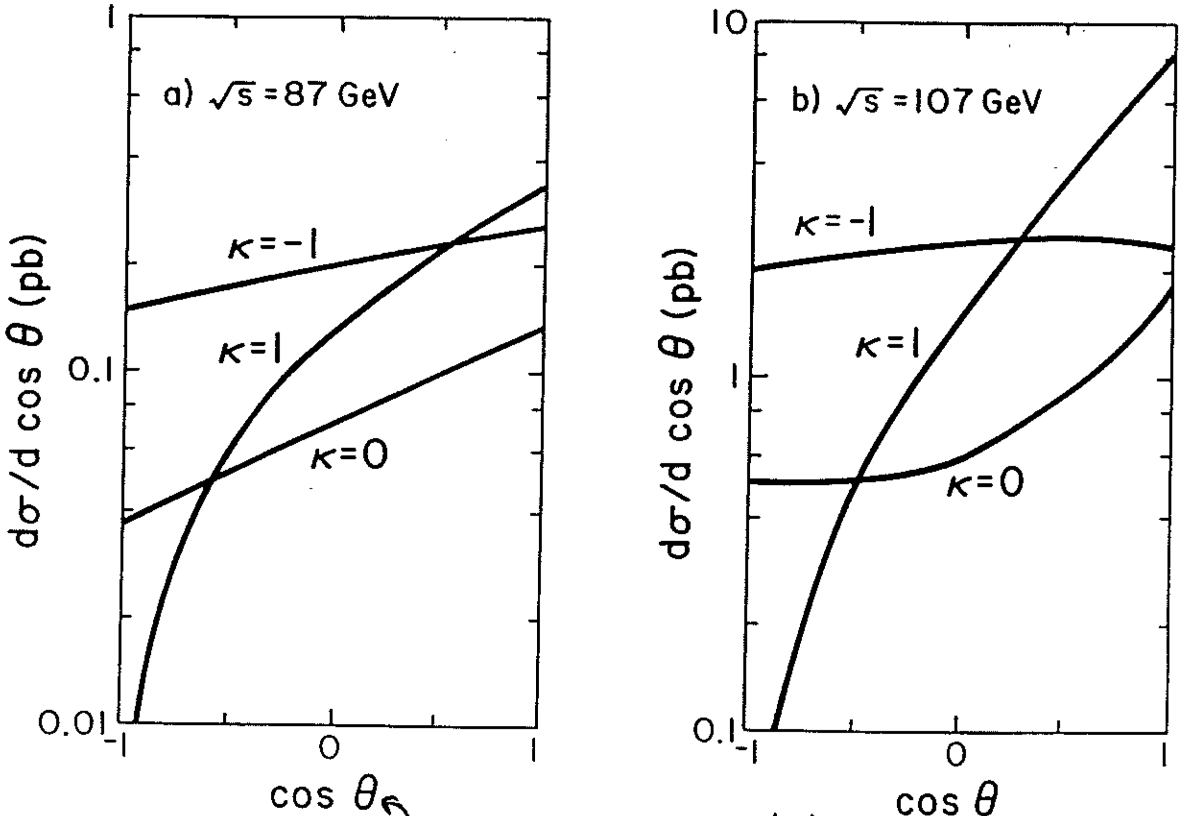


Figure 11. The dependence on center-of-mass energy of the total cross section for the reaction $\gamma_R e_L \to W\nu$.[16]

ANOMALOUS MAGNETIC MOMENT OF W

$$\mu_W \equiv \frac{e}{2M_W}(1+K)$$



ANGLE BETWEEN W AND PHOTON

K = 1 IN WEINBERG - SALAM

WHICH MAY SEEM 'ANOMALOUS' FROM AN EARLIER VIEWPOINT.

SOVIET PHYSICS – DOKLADY VOL. 8, NO. 12 JUNE, 1964

ON POLARIZATION AND SPIN EFFECTS IN THE THEORY OF SYNCHROTRON RADIATION

A. A. Sokolov and I. M. Ternov

...

For times $t \gg \tau$ the ratio n_1/n_2 tends to the limiting value

$$\frac{n_1}{n_2} = \frac{15+8\sqrt{3}}{15-8\sqrt{3}} \tag{18}$$

independently of the initial distribution of electron spin states along the field. From (18) it is clear that in this limiting case approximately 96% of the electron spins must become turned against the field, if we neglect other factors capable of inverting electron forces.

Nuclear Physics B212 (1983) 131–150

ELECTRONS AS ACCELERATED THERMOMETERS

J.S. BELL and J.M. LEINAAS

CERN, Geneva, Switzerland

Received 16 August 1982

The possibility of using accelerated electrons to exhibit the quantum field theoretic relation between acceleration and temperature is considered. In principle, the depolarization of electrons in a magnetic field could be used to give the temperature reading. The effect is examined for linearly accelerated electrons, but the result is that the relevant orders of magnitude are too small for real experiments in linear accelerators. For electrons in storage rings sufficiently large accelerations can be obtained, and the residual depolarization which has been found theoretically and experimentally is shown to be an effect closely related to the thermal effect of linearly accelerated electrons.

⇒ NEW WAY TO LOOK AT AN OLD EFFECT

THE HAWKING-UNRUH TEMPERATURE AND QUANTUM FLUCTUATIONS IN PARTICLE ACCELERATORS

K. T. McDonald
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

We wish to draw attention to a novel view of the effect of the quantum fluctuations during the radiation of accelerated particles, particularly those in storage rings. This view is inspired by the remarkable insight of Hawking[1] that the effect of the strong gravitational field of a black hole on the quantum fluctuations of the surrounding space is to cause the black hole to radiate with a temperature

$$T = \frac{\hbar g}{2\pi ck},$$

where g is the acceleration due to gravity at the surface of the black hole, c is the speed of light, and k is Boltzmann's constant. Shortly thereafter Unruh[2] argued that an accelerated observer should become excited by quantum fluctuations to a temperature

$$T = \frac{\hbar a^*}{2\pi ck},$$

where a^* is the acceleration of the observer in its instantaneous rest frame. In a series of papers Bell and coworkers[3-5] have noted that electron storage rings provide a demonstration of the utility of the Hawking-Unruh temperature, with emphasis on the question of the incomplete polarization of the electrons due to quantum fluctuations of synchrotron radiation.

Here we expand slightly on the results of Bell *et al.*, and encourage the reader to consult the literature for more detailed understanding.

Applicability of the Idea

When an accelerated charge radiates, the discrete energy and momentum of the radiated photons induce fluctuations on the motion of the charge. The insight of Unruh is that for uniform linear acceleration (in the absense of the fluctuations), the fluctuations would excite any internal degrees of freedom of the charge to the temperature stated above. His argument is very general (*i.e.*, thermodynamic) in that it does not depend on the details of the accelerating force, nor of the nature of the accelerated particle. The idea of an effective temperature is strictly applicable only for uniform linear acceleration, but should be approximately correct for other accelerations, such as that due to uniform circular motion.

A charged particle whose motion is confined by the focusing system of a particle accelerator exhibits transverse and longitudinal oscillations about its ideal path. These oscillations are excited by the quantum fluctuations of the particle's radiation, and thus provide an excellent physical example of the viewpoint of Unruh.

Further, the particles take on a thermal distribution of energies when viewed in the average rest frame of a bunch, which transforms to the observed energy spread in the laboratory. While classical synchrotron radiation would eventually polarize the spin-$\frac{1}{2}$ particles completely, the thermal fluctuations oppose this, reducing the maximum beam polarization.

It is suggestive to compare the excitation energy $U^* = kT$, as would be observed in the particle's rest frame, to the rest energy mc^2 when the acceleration is due to laboratory electromagnetic fields E and B. Noting that $a^* = eE^*/m$ we find

$$\frac{U^*}{mc^2} = \frac{\hbar e E^*}{2\pi m^2 c^3} = \frac{\left[E_\parallel + \gamma\left(E_\perp + \beta B_\perp\right)\right]}{2\pi E_{\rm crit}},$$

where the particle's laboratory momentum is $\gamma\beta mc$, and

$$E_{\rm crit} \equiv \frac{m^2c^3}{e\hbar}.$$

For an electron,

$$E_{\rm crit} = 1.3 \times 10^{16}\,\text{volts/cm} = 4.4 \times 10^{13}\,\text{gauss}.$$

($E_{\rm crit}$ is the field strength at which spontaneous pair production becomes highly probable, *i.e.*, the field whose voltage drop across a Compton wavelength is the particle's rest energy.) We might expect that the fluctuations become noticeable when $U^* \sim 0.1$ eV, and hence comparable to any other thermal effects in the system, such as the particle-source temperature.

For linear accelerators $E_\parallel \sim 10^6$ volts/cm at best, so $U^* < 10^{-5}$ eV. The effect of quantum fluctuations is of course negligible because the radiation itself is of little importance in a linear accelerator.

For an electron storage ring such as LEP, $\gamma \sim 10^5$, and $B_\perp \sim 10^3$ gauss, so that $U^* \sim 0.2$ eV. For the SSC proton storage ring, $\gamma \sim 2 \times 10^4$, while $B_\perp \sim 6 \times 10^4$ gauss, so that $U^* \sim 2$ eV. As is well known, in essentially all electron storage rings, and in future proton rings, the effect of quantum fluctuations is quite important.

The remaining discussion is restricted to beams in storage rings (= transverse particle accelerators).

Beam-Energy Spread

An immediate application of the excitation energy U^* is to the beam-energy spread. In the average rest frame of a bunch of particles, the distribution of energies is approximately thermal, with characteristic kinetic energy U^*, and momentum $p^* = \sqrt{2mU^*}$. The spread in laboratory energies is then given by

$$U_{\rm lab} \approx \gamma(mc^2 + U^* \pm \beta p^* c) \approx U_0\left(1 \pm \gamma\sqrt{\frac{\lambda_C}{\pi\rho}}\right),$$

where $U_0 = \gamma mc^2$ is the nominal beam energy, $\rho = U_0/eB_\perp$ is the radius of curvature of the central orbit, and $\lambda_C = \hbar/mc$ is the Compton wavelength. Writing this as

$$\left(\frac{\delta U}{U_0}\right)^2 \approx \frac{\gamma^2\lambda_C}{\pi\rho},$$

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