SPONTANEOUS BREAKDOWN OF THE VACUUM BY INTENSE LASERS

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We review the necessary conditions for the spontaneous production of e^+e^- pairs from the vacuum by a high intensity time dependent electric field. We then show how this was achieved by exploiting the highly relativistic motion of 50 GeV electrons from the SLAC accelerator.

1 Introduction

Soon after the discovery of the Dirac equation [?] it was noted by Klein [?], Sauter [?] and others that a strong static electric field could give rise spontaneously to the production of electron-positron pairs. The probability for pair production per unit volume and unit time was given by Schwinger in his 1951 paper [?] as

$$w = \frac{\alpha E^2}{\pi^2 \hbar} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{n\pi m^2 c^3}{e\hbar E}\right) \tag{1}$$

Here n is the number of pairs and it suffices to consider the first term in the sum. E is the electric field and m the electron mass.

The probability (1), integrated over a macroscopic space-time volume can be quite large when the exponential suppression is not extreme, that is when

$$\frac{\pi m^2 c^3}{e\hbar E} = \pi \frac{E_c}{E} = \frac{\pi}{\Upsilon} \to 1 \tag{2}$$

In Eq.(2) we have introduced the Schwinger critical field

$$E_c = \frac{m^2 c^3}{e\hbar} = 1.3 \times 10^{16}\ \text{V/cm} \tag{3}$$

and dimensionless notation for the electric field

$$\Upsilon = E/E_c \tag{4}$$

Thus, as Υ approaches or exceeds unity, pair production will be copious. We speak of the breakdown of the vacuum.

The notion of a critical field (3) and Schwinger's result (1) can be interpreted qualitatively in simple terms. A virtual e^+e^- pair from the vacuum has a "lifetime"

$$\Delta\tau = \Delta E/\hbar = mc^2/\hbar \tag{5}$$

During that time interval the virtual particles can gain energy from the electric field; should the energy gain equal or exceed their rest mass, the virtual particles can be found on the mass shell as real particles. Hence

$$eE(c\Delta\tau) = mc^2 \qquad \text{or} \qquad eE = m^2c^3/\hbar \tag{6}$$

as in Eq.(3).

Eq.(1) is often interpreted as the tunnelling of a positron from the negative energy Dirac sea to a positive energy state. In the presence of an electric field E, the width of the barrier is $\Delta x = 2mc^2/eE$. The relevant distance scale in this case is the electron's Compton wavelength $\lambda\!\!\!^{-}{}_c = \hbar/mc$ so that the tunnelling probability is proportional to

$$\exp\left(-\frac{\Delta x}{\lambda\!\!\!^{-}{}_c}\right) = \exp\left(-\frac{2m^2c^3}{\hbar eE}\right) \tag{$1'$}$$

in qualitative agreement with Eq.(1). One also sees in this model that a magnetic field cannot give rise to pair production since the field does no work on the virtual particles.

These results have fascinated theorists and experimentalists alike; not surprisingly they are also obtained as the non-perturbative limit of strong field QED. This is a rich subject that has been extensively studied [5-7]. In the laboratory, strong electric fields can be obtained, for instance, by focussing intense short pulses from a laser [?] or in heavy ion collision [?] or when electrons are channelled through crystal lattices [?]. Applications of the Schwinger mechanism to related theoretical problems can be found in refs. [11-13] while future experimental possibilities are discussed by A. Ringwald in these proceedings [?].

Since it is not possible to create static fields of critical value in the laboratory, attention has been centered on time dependent fields such as mentioned in the previous paragraph. There are however important differences between static and time dependent fields. Most importantly, a plane wave field cannot break down the vacuum because in order to generate massive particles it must hold

$$E^2 - B^2 > 0 \tag{7}$$

Instead one can consider two oppositely directed waves that interfere to produce a standing wave pattern. Then there are regions of space where the invariant condition (7) is satisfied. Other differences between static and time dependent fields have been analyzed in detail in [?].

Of course, two opposing wave fields are equivalent to photon-photon scattering which leads to pair creation when $\hbar\omega > mc^2$ [?]. But even if $\hbar\omega < m_e c^2$ pairs can be produced by <u>multiphoton</u> interactions, if the field intensity is high enough. Multiphoton processes have been extensively studied in the atomic domain [?]. They are characterized by a dimensionless (and Lorentz invariant) parameter

$$\eta = \frac{eE_{rms}}{\omega mc} \tag{8}$$

η is referred to as the normalized vector potential and ω is the frequency of the wave. By writing $\eta = eE_{rms}\lambdabar/mc^2$ we see that when $\eta = 1$ the energy gained by an electron moving across one wavelength equals its rest-mass energy, mc^2. Thus relativistic effects becomes important. Note that η is a classical parameter (it does not involve $\hbar$).

In the perturbative solution of multiphoton processes, η^2 plays the role of an expansion parameter in place of the familiar fine structure constant, α. The probability of a process involving n photons from the incident field is then proportional to η^{2n}. In particular when $\hbar\omega < mc^2$ the probability that a pair is produced by the time dependent electric field is [?]

$$w \simeq \frac{\alpha E^2}{8\hbar}\eta^{4mc^2/\hbar\omega} \tag{9}$$

Clearly, $2mc^2/\hbar\omega$ is the number of photons that must be absorbed to create the pair in agreement with the η^{2n} dependence. The probability given by Eq.(9) is valid in the limit $\Upsilon \ll 1$ and takes the form of Eq.(1) as $\Upsilon \to 1$. We note that for a static field the multiphoton parameter $\eta \to \infty$. Namely we can interpret pair production in a static field as involving the collision of an infinite number of zero energy virtual photons. The two points of view are complimentary as is so often the case.

We have seen from Eqs.(3,4) that Υ contains $\hbar$, namely it is a quantum mechanical parameter. This must be so because Υ measures the field strength for the onset of a purely quantum effect, the production of an e^+e^- pair. As written, Υ is not Lorentz invariant since the value of the electric field depends on the frame of reference from which it is viewed. Thus Eq.(4) should be expressed in terms of E^*, the electric field in the rest-frame of the produced pair

$$\Upsilon = E^*/Ec = \gamma_{cm}E^*/Ec \tag{10}$$

The above observation is crucial because it shows how one can reach critical field with existing lasers by exploiting the large γ-factors of high energy electron beams.

Existing short pulse lasers in the visible can be focussed to near the diffraction limit and have intensity (flux) in excess of

$$I = 10^{18}\ \mathrm{W/cm^2} \tag{11}$$

Improved intensities that could be possibly achieved in the future are given in [?]. The corresponding peak field

$$E_p = \sqrt{2Z_0 I} \qquad \mathrm{V/cm} \tag{12}$$

with $Z_0 = 377\ \Omega$, the impedance of free space, and I expressed in $\mathrm{W/cm^2}$ as in Eq.(9). We then find for $I = 10^{18}\ \mathrm{W/cm^2}$

$$E_p \sim 3 \times 10^{10}\ \mathrm{V/cm} \tag{13}$$

The peak field of Eq.(13) is far from the critical field of Eq.(3). Consider however the 46.6 GeV FFTB electron beam at SLAC [?] where $\gamma \sim 0.9 \times 10^5$. In the electron's rest frame

$$E^* = 2\gamma_e E \simeq 0.5 \times 10^{16}\ \mathrm{V/cm} \tag{14}$$

leading to $\Upsilon \simeq 0.3$. The interaction of the electrons with the laser field is in the strong field domain! The factor of 2 in Eq.(14) appears because we are dealing with a wave field.

To observe the breakdown of the vacuum under such conditions we collide a high energy photon ($\mathcal{E}_\gamma \sim 28$ GeV) with the laser field ($\hbar\omega = 2.34$ eV). If n photons are participating in the interaction, the cm energy is

$$\sqrt{s} = (4\mathcal{E}_\gamma n\hbar\omega)^{1/2} \tag{15}$$

Since it must hold $\sqrt{s} = 2mc^2$, the threshold for pair production for the above $\mathcal{E}_\gamma, \hbar\omega$ is $n \geq 4$. Clearly, a multiphoton process where four or more photons are absorbed from the laser field. It follows that

$$\gamma_{cm} = \frac{1}{2}\sqrt{\frac{\mathcal{E}_\gamma}{4\hbar\omega}} = 0.28 \times 10^5 \tag{16}$$

and for E_p given by Eq.(13)

$$\Upsilon = 2\gamma_{cm} E_p / E_c = 0.13 \tag{17}$$

Such an experiment [19,20,21] was completed in 1997 and will be described in the following sections.

The high energy gamma is obtained by backscattering a 46.6 GeV electron in the laser field. Because of the extremely high photon density, the gamma interacts again with the laser field leading to the production of a pair. Even though as seen in Eq.(17), Υ did not reach 1, the dependence of the data on $1/\Upsilon$, clearly verifies the Schwinger result of Eq.(1). At the same time the data are also in exact agreement with the perturbative treatment of photon-photon scattering [**?**], as they must.

2 Experimental arrangement

In it's simplest form, the experiment consists of scattering an intense laser pulse from a high energy electron beam. To study pair production, positrons are identified and detected using a magnetic spectrometer and a total absorption calorimeter. The intense flux of forward going high energy γ-rays was used mainly to monitor the interaction rate.

As already stated, the experiment was carried out at the FFTB [**?**] which delivered 5×10^9 electrons per pulse at an energy of 46.6 GeV. The repetition rate was 10 Hz. The experimental layout is shown schematically in Fig. 1. The laser crossed the electron beam at an angle of $17°$ and was focussed with $f^{\#} \simeq 6$ optics. It was returned to the laser room for diagnostic and monitoring purposes. The magnetic spectrometer consisted of a string of permanent magnets which also directed the beam to the dump. The location of the positron (PCAL) calorimeter is also indicated.

The laser was a 0.5 Hz repetition-rate, tabletop terawatt laser, that operated at 1053 nm wavelength (IR), or at 527 nm (green) after efficient ($\sim$ 45%) frequency doubling. It consisted of a mode-locked Nd:YLF oscillator, Nd:glass slab amplifier. The laser system delivered up to 2.4 J in the IR at the interaction point, but typically it was operated only up to 800 mJ of IR and 500 mJ of green. Intensities above 10^{18} W/cm^2 at the laser focus have

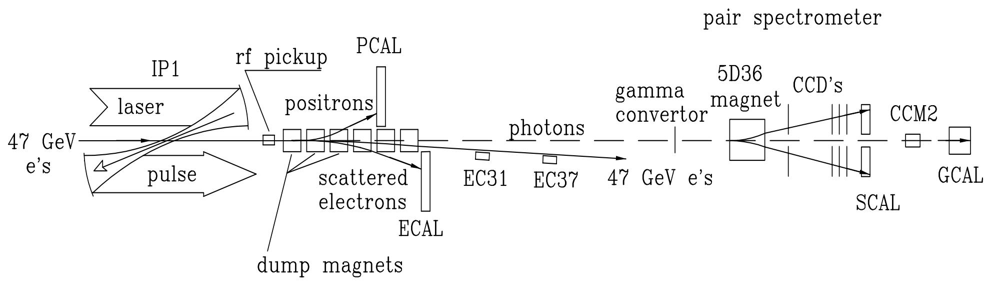

Figure 1: Schematic of the experimental setup: The laser pulses cross through the electron beam at the interaction point, IP1. The scattered electrons are deflected by the dump magnets into the electron calorimeter (ECAL). Positrons are deflected into the positron calorimeter (PCAL). The scattered photons are detected in a Čerenkov counter (not shown), or converted to e^+e^- pairs which could be detected by the pair spectrometer.

been produced.

Important issues in the experiment are the synchronization of the laser and electron beams which must hold at the level of 1 ps or better. Fig. 2 shows a timing curve where the number of forward going Compton scattered gamma rays is plotted as a function of laser delay. The spatial overlap of the electron beam with the laser focus also poses an experimental challenge because of the tight tolerances required.

The laser intensity could be determined from a measurement of the pulse energy U, area A and pulse duration τ. However for highly nonlinear processes the fluctuations inherent in these measurements were too large. Instead the experiment relied on three monitors which intercepted scattered electrons N_1, N_2, N_3 originating in one-, two-, and three-photon Compton scattering. For $\eta^2 < 1$, to a good approximation

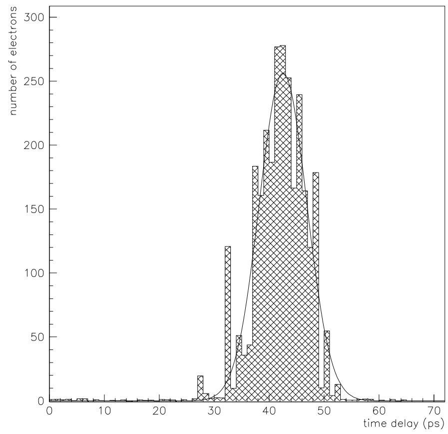

Figure 2: A "timing curve" showing the number of electrons scattered into the top row of the electron calorimeter as a function of delay of the optical pulse. The standard deviation is $\sigma = 4.3$ ps.

$$N_2 = k_2 N_1 \eta^2 \qquad\qquad N_3 = k_3 N_1 \eta^4 \tag{18}$$

where the factors $k_2,\ k_3$ depend on the acceptance and efficiency of the monitors but are the same for all events. By making an overall fit to the data η could be determined for each event with a precision of $\pm$ 11% and used for the analysis of the pair production data.

Evidence for the production of an e^+e^- pair was based on the detection of a positron in the PCAL calorimeter. The momentum p, of the positron is directly related to the location of impact on the calorimeter. The total energy, $\mathcal{E}$, deposited in the calorimeter is also recorded. Thus the ratio $\mathcal{E}/p$ should equal unity for positrons originating from the laser focal area. This was tested by placing a thin wire at the focus so that pairs were copiously produced by the Bethe-Heitler process. A plot of $\mathcal{E}/p$ as measured in the calorimeter for $p \sim 21.0$ GeV using this calibration method is shown in Fig. 3. The subsidiary peaks at $\mathcal{E}/p = 2$ and 3 correspond to cases when two or three positrons (at that given momentum) reach the calorimeter in the same pulse.

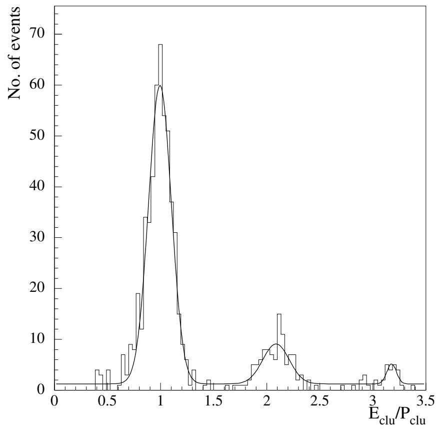

Figure 3: Distribution of the ratio $E_{\rm clu}/P_{\rm clu}$ for calibration clusters in PCAL row 7, which spans momenta from 20.3 to 21.5 GeV.

3 Results

A total of 175 positrons were identified with the laser on, and data were also taken with the laser off in order to measure the background. The number of positron candidates with the laser "on" and the laser "off" normalized to the same incident flux is shown in Fig. 4(a). The positron momentum spectrum, after subtraction of the background is given in (b) of the figure. The solid line is the prediction of the simulation.

One can also plot the number of detected positrons as a function of the laser intensity expressed by the parameter $\eta \propto \sqrt{I}$. In Fig. 5 the laser "on" events are shown by the solid circles, while the shaded area gives the background, as deduced from the laser "off" events. A power law fit to the form

$$R_{e^+} \propto \eta^{2n} \tag{19}$$

gives $n = 5.1 \ \pm 0.2$ and is indicated by the solid line. This is in agreement with the fact that near threshold five photons must be absorbed from the laser field. One photon to create the high energy γ-ray and at least four photons to create the pair as shown by Eq.(15).

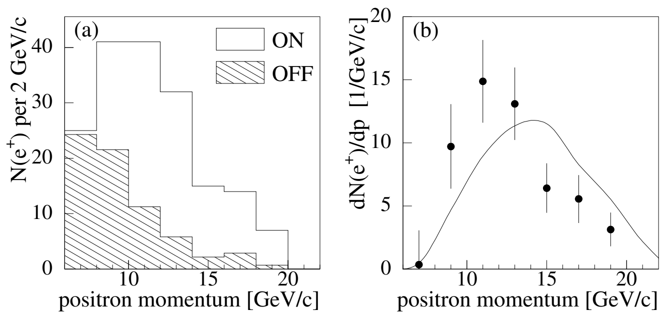

Figure 4: Number of positron candidates *vs.* momentum for laser-on (ON) and laser-off (OFF) electron pulses. (b) Spectrum of signal positrons obtained by subtracting the laser-off from the laser-on distribution. The curve shows the expected momentum spectrum from the model calculation.

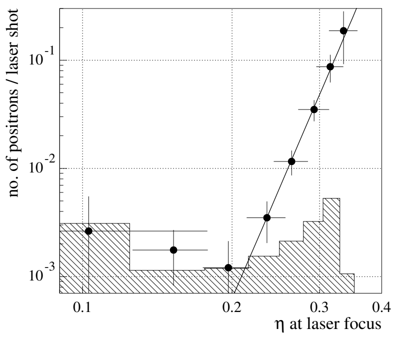

Figure 5: The dependence of the positron rate per laser shot on the laser field-strength parameter η. The line shows a power law fit to the data. The shaded distribution is the 95% confidence limit on the residual background from showers of lost beam particles after subtracting the laser-off positron rate.

The data are compared with the simulation in Fig. 6. The yield is normalized to the total number of Compton scatters which is directly inferred from the monitors while the simulation is shown by the solid line. The prediction of the simulation has not been normalized and is in excellent agreement with the data. This would not have been possible without an accurate knowledge of the laser intensity for each event as discussed in Eq.(18).

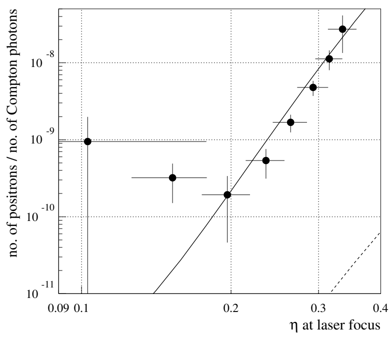

Figure 6: The dependence of the positron rate on the laser field-strength parameter η when the rate is divided by the number of Compton scatters inferred from the EC37 monitor. The solid line is the prediction per Compton photon based on the simulation for photon-multiphoton scattering. The dashed line represents the simulation for the one-step trident process.

It is of interest, of course, to consider the positron yield as a function of the parameter Υ defined by Eq. (17). We would then expect in the limit $\eta \gtrsim 1$ a dependence such as given by the Schwinger result of Eq.(1). This is confirmed by the data which are plotted in Fig. 7 as a function of $1/\Upsilon$. A fit to the form

$$R_{e^+} \propto e^{-A/\Upsilon_\gamma} \tag{20}$$

yields $A = 1.27 \pm 0.08 \pm 0.25$, the first error being statistical and the second systematic. Naively one would expect $A = \pi$. However the fact that $\eta < 1$ introduces corrections in the case of a wave field [?] which lead to the prediction $A = 1.1$ in excellent agreement with the observed slope. Data from two different electron energies are combined in the plot of Fig. 7.

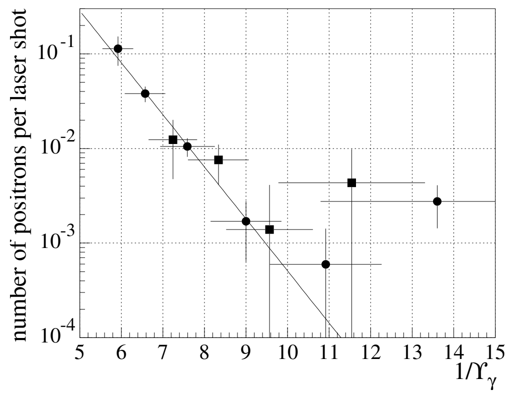

Figure 7: Number of positrons per laser shot as a function of $1/\Upsilon_\gamma$. The circles are the 46.6 GeV data whereas the squares are the 49.1 GeV data. The solid line is a fit to the data.

We conclude that indeed the wave field breaks down the vacuum, albeit in the fast moving rest frame of the pair. In a complimentary fashion we can argue that multiphoton-photon scattering created an electron positron pair as excepted from strong QED calculations.

4 Discussion

It has been suggested that a strong field could also create a pair of neutral particles because of its coupling to virtual charged particles present in loop diagrams [23,24]. As an example we consider $E \to \nu\bar{\nu}$ where the effective coupling has strength

$$g = eG_F m_e^2/(\hbar c)^3 = 3 \times 10^{-12} e \tag{21}$$

The critical field is given as in Eq.(3) but the question arises as to whether one should use the mass of the neutral particles produced (as in [?]) or the mass of the lightest intermediate particle in the loop (as in [?]). In the former case

$$E_c(\nu) = \frac{m_\nu^2 c^3}{g\hbar} \tag{22}$$

and for $m_\nu = 1$ eV, $E_c(\nu) = E_c$ opening up the possibility of an experiment.

Of course, because of the smallness of g in Eq.(21), the overall production rate is highly suppressed even when the exponential is saturated. Furthermore the low efficiency for neutrino detection reduces the observable rate. It is nevertheless interesting that this rate is extremely sensitive to the neutrino mass depending on it exponentially. A word of caution however: Mikheev points out that one should use m_e^2 instead of m_ν^2 [?].

The breakdown of the vacuum by a strong gravitational field can also be invoked as an alternate interpretation of Hawking radiation [?]. Since the gravitational field couples to energy, all particles are produced and the spectrum is dominated by the particles of lowest mass, photons. They are emitted with a Planck spectrum and for a spherical star of mass M, the temperature is

$$T_H = \frac{\hbar c}{8\pi k} \frac{c^2}{MG} \tag{23}$$

where k is Boltzmann's and G the gravitational constants. Thus production of neutrinos of mass m_ν will be suppressed with respect to photon radiation by an exponential factor

$$R_\nu / R_\gamma - e^{-m_\nu c^2/kT_H} \tag{24}$$

Since for a solar mass $kT_H \sim 10^{-11}$ eV the ratio of Eq.(24) is vanishingly small, unless neutrinos are massless.

References

[1] P.A.M. Dirac, Proc. Roy. Soc. (London) A17, 610 (1928).

[2] O. Klein, Zeits f. Phys. 53, 157 (1929).

[3] F. Sauter, Zeits. f. Phys. 69, 742 (1931).

[4] J. Schwinger, Phys. Rev. 82, 664 (1951).

[5] A.I. Nikishov and V.I. Ritus, Sov. Phys. JETP 19, 1191 (1964); 20, 757 (1965).

[6] L.S. Brown and T.W.B. Kibble, Phys. Rev. 133A, 705 (1964); H.R. Reiss, J. Math. Phys. 3, 59 (1962); Phys. Rev. Lett. 26, 1072 (1971).

[7] R. Bonvincini et al, Phys. Rev. Lett. 62, 2381 (1989).

[8] C. Bamber *et al.*, Laser Physics 7, 135 (1997).

[9] R. Ganz *et al.*, Phys. Lett. B389, 4, (1996) and references therein.

[10] A. Belkacem *et al.*, Phys. Lett. B177, 211 (1986); B206, 561 (1988); R. Medenwalt *et al.*, Phys. Lett. B227, 483 (1989).

[11] H.M. Fried *et al.*, Phys. Rev. D63, 125001 (2001).

[12] E.A. Paschos, Phys. Lett. B389, 383 (1996).

[13] P. Chen and V. Telnov, Phys. Rev. Lett. 63, 1796 (1989).

[14] A.Ringwald "Fundamental Physics at an X-ray Free Electron Laser", these proceedings; Phys. Lett. B510, 107 (2001).

[15] E. Brezin and C. Itzykson, Phys. Rev. D2, 1191 (1970).

[16] G. Breit and J.A. Wheeler, Phys. Rev. 46, 1087 (1934).

[17] E. Sarachik and G. Shappert, Phys. Rev. D10, 2378 (1970).

[18] V. Balakin *et al.*, Phys. Rev. Lett. 74, 2479 (1995).

[19] C. Bula *et al.*, Phys. Rev. Lett. 76, 3116 (1996).

[20] D.L. Burke *et al.*, Phys. Rev. Lett. 79, 1626 (1997).

[21] C. Bamber *et al.*, Phys. Rev. D60, 092004 (1999).

[22] N.B. Narozhny *et al.*, Sov. Phys. JETP 20, 622 (1965).

[23] J.A. Grifols, E. Masso, S. Mohanty and K. Shajesh, Phys. Rev. D60, 097701 (1999).

[24] A.C. Melissinos, Nuclear Physics B (Proc. Suppl.) 72, 195 (1999).

[25] N.V. Mikheev, private communication and A.A. Gvozdev, *et al.*, Phys. Rev. D54, 5674 (1996).

[26] T.Damour and R. Ruffini, Phys. Rev. D14, 332 (1976).