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Laser Acceleration up to Black Hole Values and B-Meson Decay

H. Hora, R. Castillo, T. Stait-Gardner, D.H.H. Hoffmann, G.H. Miley & P. Lalousis

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This paper is dedicated to Professor Chiyoe Yamanaka, Osaka University, for his 88th birthday.

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Abstract: Studies of laser produced pair production are followed up from early stages. Pair production by vacuum polarization was discussed with laser produced acceleration up to values similar to those at the surface of black holes leading to the discovery of a difference between Hawking and Unruh radiation. It was found that production of anti-hydrogen by this method is at least a million times more efficient than by present day accelerator technology. Another application of ultrahigh laser fields is to focus them into the collision area of the LHC (Large Hadron Collider) to study the details of the B-meson decay. This also may allow us to detect more details about CP violation of B_s mesons and possible signs of new particles on the horizon. Lasers with picosecond pulses and exawatts of power are now becoming available which will be interesting for studying ultra-intense shock waves in astrophysics and resulting nuclear reactions.

INTRODUCTION AND INITIAL RESULTS

Using very high intensity laser radiation, with the electric and magnetic fields **E** and **H** far above any values applied before, has led to many new physics phenomena and to the realisation that the nonlinear physics involved opens a new dimension of exploration. It has also shown that the linear physics needs to be based on higher accuracy data than previously thought (Hora 2000a).

Examples have appeared where results in linear physics were completely wrong compared to results in nonlinear physics in contrast to earlier instances where there were only gradual differences or approximations. This was discovered not only through using techniques to produce higher and higher laser intensities, mostly realised by chirped pulse amplification CPA (Mourou et al. 2001), but also from considering relativistic effects. The first calculations on how to produce relativistic conditions for pair production of electrons was done by Bunkin (Bunkin et al. 1969) and these calculations were extended to determine the conditions for laser fields to produce quiver motion of electrons with energies above mc^2 (Hora 1973a).

Calculation of the conditions for producing anti-protons (Hora 1973a, Hora 1973b, Shearer et al. 1973) and experiments by Shearer (Shearer et al. 1974) were the very first to show indications of the generation of laser produced positrons. With respect to the quiver motion and drift for proton pair production, the advantages of long wave length laser pulses was found to be of considerable interest (Christopoulos et al. 1988). After interest in antihydrogen for space research became more widely known, the use of lasers for fusion also was found to be of interest because the efficiency was more than one million times higher with lasers due to the available particle density was much higher than with accelerator techniques. It was calculated that a mission to the next star within a reasonable time of 50 years can only be done with laser produced anti-hydrogen fuel (Hora et al. 1986). Thanks to the CPA technique, sub-picosecond laser pulses of 2 PW produced for the first time a considerable number of positrons

(Cowan et al. 1999) finally achieving record-level positon beams with intensities above any other method (Chen et al. 2009).

PAIR PRODUCTION BY VACUUM POLARIZATION

Pair production in vacuum was from the beginning considered (Bunkin et al. 1969, Hora 1973a and 1973b) where a laser intensity above 10^{28} W/cm^2 was needed (Heisenberg 1934, Heisenberg et al. 1936). A correction to an about ten times higher value followed later (Hora et al. 2002). At these intensities the acceleration of the electrons by the electric field of the laser is close to the values of Hawking radiation and Unruh radiation at the surface of black holes. This was studied in and compared to black body radiation in which fields are of the same order and where the electrons at thermal equilibrium were not longer following Fermi-Dirac statistics (Hora et al. 1961, Eliezer at al. 2002, Stait-Gardner et al. 2006). Further studies clarified that there was a difference between the Hawking and the Unruh radiation (Hawking 1975) with a relation to the Casimir effect (Unruh 1976, Unruh et al. 1989). These results were based on the theory of electron acceleration in vacuum (Hora 1988, Wang et al. 1998, Hora et al. 2000b) as a basically nonlinear effect (Hora 2000a). The essential aspects of these studies are as follows.

The Unruh effect is a phenomenon whereby an accelerated observer travelling through a true vacuum state – that is the ground state |0> which will be referred to here as the Minkowski vacuum – will experience themselves to be immersed in a thermal blackbody distribution of particles (Hawking 1975). Before comparing the thermal radiation experienced by an accelerated observer to the Hawking radiation of a black hole a brief digression into the physical nature of the vacuum is appropriate.

The Minkowski vacuum is a physical vacuum with pairs of virtual particles manifesting for short durations continuously and, unlike the pre-quantum field theory of vacuum, has observable effects on physical systems (e.g. the fine structure of the atomic hydrogen spectrum and the Casimir effect). Taking the Casimir effect as an example, two parallel mirrors placed in a vacuum will experience an attractive force inversely proportional to the forth power of the distance separating them as a result of the quantum fluctuations of the vacuum. Essentially long wavelength virtual particles cannot manifest between the conducting mirrors resulting in a decreased energy density between the mirrors compared with the vacuum surrounding them where there is no such restriction. The Casimir effect is symbolic of the physical nature of the quantum vacuum.

The quantum field is best decomposed for an accelerated observer using a different basis than the standard momentum basis used in quantum field theory; this basis being related to the standard basis by the Bogoliubov transformations. These transformations play an integral part in analyses of the Unruh effect. The particle number operator differs too and does not give zero when applied to the Minkowski vacuum state (which is not identical to the Rindler vacuum state). The result is, as stated above, that accelerated observers in a pure vacuum will experience themselves in a heat bath with a blackbody distribution.

Thus a state without particles to an inertial observer will be seen to contain particles by an accelerated observer. The dependence of temperature upon acceleration is $T = 2\pi ck_B a/\hbar$, where c is the velocity of light, and a is the acceleration. If a is interpreted as the acceleration at the event horizon of a black hole then the same equation describes the temperature of the thermal radiation emitted from a black hole via the process of Hawking radiation. The similarity of the equations and the equivalence principle of general relativity hint that the mechanisms for the radiation may be the same but this is not the case. Consider the following.

Hawking radiation is sometimes described as resulting from pair production near the horizon of a black hole with one of the virtual particles escaping and becoming real and the other disappearing into the black hole (Hawking 1975). All observers experience Hawking radiation while only accelerated observers experience the Unruh effect. Furthermore, an observer on Earth is effectively in an accelerated coordinate system via the equivalence principle and hence should observe the surrounding vacuum to have a temperature due to the Unruh effect. However, the Earth does not emit Hawking radiation and neither do other gravitational bodies without event horizons. The Unruh effect results from a different mechanism to that of Hawking radiation; it is local, being experienced only by accelerated observers (Stait-Gardner 2006).

PETAWATT LASER PULSES FOR B-MESON DIAGNOSTICS

The present day available PW laser pulses of sub-picosecond duration and the next higher powers can be used for important studies of the details of B-meson diagnostics because their lifetimes are on the same time scale. The use of lasers with as a diagnostic tool for collider beam interactions was studied previously (Hora 1992) for the conditions of the Large Electron Positron (LEP) collider. This can now be extended for the conditions of B-mesons, e.g. at the Large Hadron Collider LHC or similar B-meson factories (Hora et al. 2008).

A prototype of this technique was given by the interaction of 10^{16} W/cm^2 laser intensities in low density helium (Boreham et al. 1979). It was expected from theory that a radial emission of electrons from the focus should convert half of the quiver energy of the electrons into energy of translative motion. The measured energy of radially emitted keV electrons corresponded exactly to the theory predictions. The conservation of the momentum of the photons leads to a slightly forward direction parallel to the laser axis. This was measured (Meyerhofer et al. 1996) and found to be in agreement with the earlier prediction (Hora et al. 1983). Similarly, charged particles generated in the focus of the collider when in the focus of the laser beam, will get an upshift of energy and a change of direction. Petawatt or even the higher exawatt (EW) laser pulses of a few fs duration (Azechi 2011) can then follow up the timing of generating or annihilating processes of the B-meson generation and the decay processes. The importance of this is that further analyzing the different types of B-mesons e.g. with respect to $B_s^0 - \bar{B}_s^0$ oscillations (Abdullenia et al. 2006) where the time resolution can be measured in subsequent steps with the later (Hora et al. 2006). It was mentioned that this open the way to find "possible new particles on the horizon" (Stokstad 2010).

The theory is based on electro-dynamic interaction of the laser radiation with the particles as known from plasma interaction as the nonlinear force given by (Hora 1969, 1985, 1991):

$$\begin{aligned} f_{NL} = \nabla \cdot [&\mathbf{EE} + \mathbf{HH} - 0.5(\mathbf{E}^2 + \mathbf{H}^2)\mathbf{1} \\ &+(1 + (\partial/\partial t)/\omega)(n^2 - 1)\mathbf{EE}]/4\pi \\ &-(\partial/\partial t)\mathbf{E} \times \mathbf{H}/4\pi c \end{aligned} \qquad (1)$$

where $\mathbf{1}$ is the unity tensor and c is the vacuum speed of light (see Eq. 8.88 of Hora 1991). The value n is the (complex) refractive index determined by the laser frequency ω and the electron-ion collision frequency ν of a plasma:

$$n = 1 - (n_e/n_{ec})/(1 + i\nu/\omega) \qquad (2)$$

where n_e is the electron density, n_{ec} is the critical electron density and where the plasma frequency ω_p is equal to the laser frequency ω. The dielectric properties of the vacuum polarization are to be included appropriately for pair production in a vacuum. The derivation of this force with inclusion of the dielectric plasma properties for the non-transient case (Hora 1969) was based on momentum conservation. The final complete transient case, Eq. (1), was derived later (Hora 1985) and is based on symmetry where it was proved that this, and only this, is the Lorentz and gauge invariant description of the nonlinear force.

For the simplified one-dimensional geometry and perpendicular laser irradiation, the force (1) can be reduced to the time averaged value:

$$\begin{aligned} f_{NL} &= -(\partial/\partial x)(\mathbf{E}^2 + \mathbf{H}^2)/8\pi \\ &= -(\omega_p/\omega)^2(\partial/\partial x)(\mathbf{E}_v^2/n)/16\pi \end{aligned} \qquad (3)$$

where E_v is the amplitude of the electric field in vacuum. The last expression is reminiscent of the formulation of the ponderomotive force in electrostatics and is sometimes called "radiation pressure acceleration".

The relativistic limits for the emission of the charged particles from the collider area with a laser focus are given for laser intensities of neodymium glass lasers (Hora et al. 2008):

(1) charged B-mesons;
$I_{rel} = 1.2\times10^{25}$ W/cm^2 $\Delta\varepsilon = 2.41\,\mathrm{keV}$

(2) protons or antiprotons from the B-decay;
$I_{rel} = 3.9\times10^{26}$ W/cm^2 $\Delta\varepsilon = 424\,\mathrm{eV}$

(3) charged π-mesons from B-mesons decay;
$I_{rel} = 2.73\times10^{23}$ W/cm^2 $\Delta\varepsilon = 31.5\,\mathrm{keV}$

The size of the lasers for PW-fs pulses are comparably compact such that the diagnostics with an additional laser focus may not be a too difficult problem. The signals from the detectors for comparable cases with and without the laser will then be done by functional analytical folding of the information about the time dependence of creation, decay and annihilation processes of the numerous types of charged particles.

EXAWATT LASER PULSES FOR SHOCK WAVES AND NUCLEAR REACTIONS

Studies with advanced PW to EW laser pulses are also important for exotic conditions of shock waves in astrophysics (Hora et al. 2011), ultrahigh acceleration and for related interactions, including nuclear mechanisms. The essential difference from the usual thermal pressure generation processes in plasmas is the direct conversion of laser energy into particle motion. This can be seen from the nonlinear forces including the optical response since 1969 (Hora 1969) expressed in Eq. (1). The then predicted ultrahigh accelerations were first measured by Sauerbrey by the Doppler effect at target interaction with above TW-ps laser pulses. The nonlinear force driven accelerations were 10^{20} cm/s^2 (Sauerbrey 1996) in contrast to comparable accelerations with thermal-pressures of 10^{15} cm/s^2 (Park et al. 2011). The high acceleration was in full agreement with the theory (Hora et al. 2007) and could then be used to ignite solid state density fusion fuel deuterium tritium DT (Hora 2009). This is a rather simplified scheme of igniting hydrogen-^{11}boron that produces less radiation per megawatt of generated energy than burning coal (Hora et al. 2010).

Figure 1 shows the computations of the ion density of the fusion flame in frozen DT at ps laser irradiation of 10^{20} W/cm^2. This demonstrates the expected velocity of the reaction front. In addition this reaction front, propagating through the solid DT, can generate compressions up to four times the solid state value within the moving short-depth shock wave. This numerical result agrees with the factor four of the Rankine-Hugoniot shock wave theory. The shock velocity of 1550 km/s is in the range known for this type of interaction.

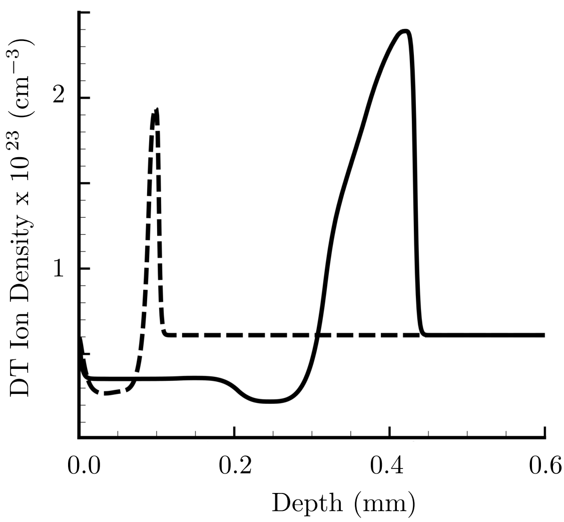

Figure 1. Genuine two fluid hydrodynamic computations (Lalousis et al. 1983, Hora et al. 1984) of the ion density in solid DT after irradiation of a laser pulse of 10^{20} W/cm^2 of ps duration at the times 22 ps (dashed) and 225 ps after the initiation.

For later times the fusion flame shows an increasing deviation of the density profile from the simplified shock wave theory. This is evident from measuring the velocity of the generated alpha particles as the flame moves into the untouched solid DT. The velocities will change as the conditions of densities and temperatures within the DT gradually change. Remarkably, the velocity of the entire flame is unchanged. More properties are given in the references, however, the genuine two-fluid computations arrive at many more details than known from the one-fluid computation (Hora 2009, Hora et al. 2010). It is important to note that these studies model ps laser pulses in the range of 30 PW up to nearly EW.

Generalizing the preceding computations, the genuine two-fluid hydrodynamics (Lalousis et al. 1983, Hora et al. 1984) is used in order to follow up the details of the generated very high electric fields in the shock fronts and to confirm most of the other results calculated before with the usual one fluid hydrodynamics. The results are interesting for astrophysical cases and for shock ignition of fusion (Betti et al. 2007) where in contrast to the thermal pressure process, the new research now is generalized to non-thermal nonlinear force direct conversion of laser energy into plasma motion to reach ultra-high accelerations.

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H. Hora, Dept. Theor. Phys. UNSW Sydney, Australia. Email: h.hora@unsw.edu.au *

R. Castillo, T. Stait-Gardner, BMSci. Univ. Western Sydney, Campbelltown, Australia

D.H.H. Hoffmann, Dept. Nucl. Phys. TU Darmstadt, Germany

G.H. Miley, Dept. Nucl. Plasma & Radiolog. Engin. Univ. Illinois USA

P. Lalousis, IESL/FORTH, Heraklion, Greece

* Author for correspondence.

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