DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 87-168
December 1987

A NEW PHASE OF QED?

by

R. D. Peccei, J. Solà, C. Wetterich

Deutsches Elektronen-Synchrotron DESY, Hamburg

ISSN 0418-9833

NOTKESTRASSE 85 · 2 HAMBURG 52

To be sure that your preprints are promptly included in the
HIGH ENERGY PHYSICS INDEX ,
send them to the following address (if possible by air mail) :

DESY
Bibliothek
Notkestrasse 85
2 Hamburg 52
Germany

DESY 87-168
December 1987

ISSN 0418-9833

A NEW PHASE OF QED?

R.D. Peccei, J. Solà*and C. Wetterich
Deutsches Elektronen Synchrotron, DESY
D-2000 Hamburg, Fed. Rep. Germany

December 18, 1987

Abstract

We discuss the speculation that the sharp positron lines and correlated e^+e^- and $\gamma\gamma$ signals seen in heavy ion collisions may be evidence for a new phase of QED. We examine several characteristics of the data which argue for this interpretation and point out further experimental observations which would favour this hypothesis. However, we detail also theoretical difficulties and experimental contradictions which considerably weaken the basis for this speculation. In particular, we argue that for the formation of a new phase or a soliton like structure in QED it is necessary that non linear effects in electrodynamics become important. Even though $Z\alpha$ is large, these effects always entail a suppression factor of α, which is difficult to overcome.

In the collision of very heavy ions, at energies close to the Coulomb barrier, one produces sufficiently strong electromagnetic fields that positron emission can be induced. In addition, for sufficiently high ionic charges $Z_1 + Z_2 \geq 173$, since the lowest bound state of the combined system dips below -2m, one expects that it should be possible for spontaneous positron creation to occur [1]. Experimentally, quasiatomic positron production [2] was observed soon after the beginning of UNILAC operation at GSI [3]. However, some evidence for an anomalous line structure in the positron spectrum was reported early on [4], which was subsequently confirmed by detailed investigations by the ORANGE [5] and EPOS [6] collaborations.

The presence of this ununderstood line structure has spurred additional measurements, which have revealed even more puzzling phenomena. The EPOS collaboration, using a double solenoid spectrometer, recently presented evidence for a peak structure in the spectrum of correlated positrons and electrons with the same energy, emitted oppositely to each other [7]. In fact, more detailed investigations appear to show three correlated e^+e^- structures, at sum energies of approximately 1630 Kev, 1780 Kev and 1830 Kev [8]. Multiple peak structures in the single positron spectrum have also been reported recently by the ORANGE collaboration [9], at positron kinetic energies around 250 Kev, 340 Kev and 410 Kev. Finally, a very recent experiment in the super HILAC at LBL, looking at U + Th. collisions at the Coulomb barrier, has reported a correlated back to back $\gamma\gamma$ signal, at a sum energy of 1060 Kev [10].

*On leave from Departament de Fisica, Universidad Autónoma de Barcelona, 8193 Bellaterra (Barcelona), Cataloña, Spain

The energy distribution of the quasiatomic induced positrons is rather broad, with a width of order 500 Kev. In contrast, the peak structure observed and, particularly, the correlated e^+e^- and $\gamma\gamma$ signals are very narrow. Typically, for the positron lines $\Gamma_{e^+} \simeq 50 - 80KeV$ [9], while the sum energy e^+e^- peaks have widths of the order of $\Gamma_{e^+e^-} \simeq 25 - 40KeV$[8]. The $\gamma\gamma$ correlated peak is extremely sharp, with $\Gamma_{\gamma\gamma} \simeq 2.5KeV$ [10]. Furthermore, both the location of the positron lines, as well as their width, seem to be largely independent of the total charge $Z = Z_1 + Z_2$ of the colliding ions, although the strength of the lines has some dependence on the precise parameters of the scattering process [8] [9]. Since the peak phenomena is seen for both $Z > 173$ as well as $Z < 173$ [9], there appears to be no direct correlation between these observations and the possibility of spontaneous positron creation.

A great many theoretical explanations have been put forward concerning the origin of the positron lines and correlated e^+e^- signals [11]. It is fair to say, however, that no wholly satisfactory solution is yet in sight. A particularly intriguing early suggestion associated the positron signal with the production and subsequent decay of a real elementary particle - an axion [12]. However, this explanation was rendered moot by the observation of the multiple peak structures and was eliminated altogether by experiments which showed that, in electron beam dumps, no such elementary excitation was produced [13].

A much more conventional possibility is that the positron peaks are the result of some interference among different amplitudes contributing to the positron production [14] [15]. This possibility is difficult to rule out out of hand, since the actual production mechanism is very complex [2]. Thus to calculate the emitted positron spectrum one necessarily must resort to truncations and extensive numerical evaluations of the time evolution operator [15]. This said, however, it is difficult to see where another time scale, besides the Rutherford scattering time, enters into the problem. Furthermore, although interference effects could modulate the positron spectrum, it is unclear how they could produce the correlated e^+e^- signals. Obviously this explanation would have no bearing in the $\gamma\gamma$ correlations, which would have to be accidental.

Perhaps the most intriguing - and bold - explanation for the puzzling heavy ion data so far, has been suggested recently by three different groups [1] [16] [17] [18]. These authors argued that the strong electromagnetic fields in the collision cause the formation of a new phase of QED. The correlated e^+e^- and $\gamma\gamma$ signals are then associated with the decay of a set of discrete bound states produced in this new QED phase. Although this idea is very interesting, only some phenomenological arguments, but little theoretical evidence, supporting it is presented by its proponents. The purpose of this note is to examine this suggestion in some detail. In particular, we want to see if it is at all possible for the strong fields present in the heavy ion collisions to cause a breakdown of ordinary QED. Furthermore, if a new phase really obtains, it is important to ascertain what further signals of its existence can manifest themselves experimentally.

The original observation of Landau [19] and Gell Mann and Low [20] that in QED the renormalized charge blows up at sufficiently short distances suggests that perhaps this theory may possess another phase for strong coupling. This matter has been the subject of considerable theoretical interest and has been studied with a variety of techniques [21],

[1]This speculation was also entertained by one of us (CW) more than two years ago, but he was convinced by another one of us (RDP) not to pursue it!

including, recently, lattice gauge theory simulations [22]. The lattice calculations appear to show a transition to a strong coupling phase, with confined charges and spontaneously broken chiral symmetry. It is not clear, however, what relevance these calculations have for the problem at hand, since for all practical purposes α remains equal to $\frac{1}{137}$ in the heavy ion collisions. What one needs to imagine is that, as a function of an order parameter related to the strong external electromagnetic fields provided by the heavy ions, the phase transition point in QED - if it exists - moves down from $\alpha_c \sim 0(1)$ to $\alpha \simeq \frac{1}{137}$. To our knowledge, however, no theoretical evidence exists suggesting that, in the presence of an external electromagnetic field, the possible phase transition point of QED moves to weak coupling.

There are several aspects of the heavy ion data which fit very well with the idea that some phase transition phenomena has occurred [17] [18]:

- The peaks seem to be peculiar to heavy ion collisions and so are naturally connected to the presence of the strong electromagnetic fields.
- If in the new phase extended objects are formed [16], these will naturally have various excitation modes. Thus multiple peak structures are expected [17] [18].
- The energy sharpness of the signals can be understood if the strong fields trigger the formation of a new phase, which then persists as a false vacuum [17]. This would explain why the peaks appear to originate from the decay of a neutral object, produced essentially at rest in the CM system. The lifetime and mass of the various modes excited is then independent of the precise formation characteristics.

It is useful to elaborate somewhat on the last point above, which is particularly important. In Rutherford collisions of heavy ions at the Coulomb barrier, the heavy ions experience substantial acceleration only for a limited time, as shown in Fig 1. This characteristic time is of the order of a few electron's Compton times:

$$t_R \simeq 10\frac{Z_1 Z_2 \alpha(M_1 + M_2)}{\beta_0^3 M_1 M_2} \simeq \frac{3}{m} \simeq 2 \times 10^{-21} sec \qquad (1)$$

where $\beta_0 \simeq 0.11$ is the typical relative velocity of the heavy ions in the experiments. A signal of intrinsic width less than 2.5 Kev, as is the $\gamma\gamma$ correlation peak observed in Ref [10], by the uncertainty principle is associated to very much larger time scales, $t_{\gamma\gamma} \geq 2.5 \times 10^{-19} sec$. At $t_{\gamma\gamma}$ the ions themselves are separated by almost 10^4 fm and the residual fields in the interaction region are very small. Although the strong electromagnetic fields during the Rutherford time t_R may trigger the formation of a new phase of QED in a volume of order $(\frac{1}{m})^3$, these fields diminish rapidly as the heavy ions move away and are totally negligible by $t_{\gamma\gamma}$. This behaviour is illustrated in Fig 2, where the dimensionless electric field $\hat{E} = \frac{eE}{m^2}$ at $r = \frac{1}{m}$ and $r = \frac{1}{2m}$, at a given angle, is plotted as a function of time.

The above considerations make it obvious that to associate the $\gamma\gamma$ signals with the decay of a new phase of QED requires that this phase be self sustained for a considerable time, after the strong fields of the ions have ceased to be important. The only sensible picture is that an extended bubble of the new QED phase is formed and that this soliton like structure survives way after the triggering fields are gone. The decay time argument is different for

the positron peaks and correlated e^+e^- signals since at $t_{e^-e^-} \simeq 20m^{-1} \simeq 10^{-20} sec$ the electromagnetic fields in the central region are still substantial. If electrons and positrons would be produced at $t_{e^+e^-}$ from the decay of a neutral "particle" at rest, they would feel the strong potential of the nearby ions (typically $V \sim m$ at $t_{e^+e^-}$) and therefore experience different accelerations. It is difficult to imagine that sharp peaks in the correlated energy spectrum are produced unless the ions are already much further away at the time of decay. The sharpness of the peaks suggests that at the decay time the electric potential from the ions, in the central region, is $\leq \Gamma_{e^+e^-}$. The true intrinsic width is therefore expected in the order of at most a few KeV.

The different masses of the correlated signals are associated with excitations within this new phase. The spatial extent of the new QED phase cannot be substantially greater than a Compton length m^{-1}, since the electromagnetic fields decrease rapidly outside a central volume of this size. The Compton length is also the characteristic size of possible bound states in a new QED phase. Thus one should visualize the various distinct peaks as solitons with different quantum numbers [16], rather than as local excitations propagating in an extended new QED phase.

Two significant conclusions can be drawn from these considerations, which have experimental importance:

- The formation of a bubble of the new QED phase is triggered by some order parameter, connected with the strong electromagnetic fields. Thus one can expect that the production cross section for the observed signals be sensitive to the detailed characteristics of the heavy ion reactions, including the total charge $Z = Z_1 + Z_2$, the ion's scattering angle Θ_{CM} and the ion's relative velocity β_0. However, variations in the signal induced by changing some parameter, like Z, are correlated with similar variations produced by changing another parameter, say Θ_{CM}.
- Since the soliton bubbles must survive to times when the external fields are insignificant, $\hat{E} << 1$, the masses and widths of these excitations should be independent of detailed characteristics of the heavy ion reactions: Z, Θ_{CM} and β_0. Once the soliton emerges from some specific initial configuration, its intrinsic properties are governed by the asymptotic (quasi stationary) behaviour, which should be independent of how it was formed.

As we shall see, broadly speaking, the heavy ion data appears to have these properties. However, in detail there are numerous contradictions, which considerably weaken the phenomenological support for the hypothesis of the formation of bubbles of a new QED phase.

It is conceivable that the soliton production sets in only if the electromagnetic fields have passed some critical value. Then the peaks should appear only for $Z > Z_c$ and we would expect a strong Z dependence of the production cross section for total charges in the "threshold region" just above Z_c. For $Z >> Z_c$, however, the production should only depend weakly on Z. However, the characteristics of the electromagnetic field during the collision depend not only on Z, but also on the distance of closest approach of the ions, which is connected with Θ_{CM} and β_0. If there is threshold behaviour in Z, one expects a similar threshold in Θ_{CM} and β_0. On the other hand, if the dependence on Θ_{CM} is weak, one also expects a correlated weak dependence on Z. Unfortunately, the experimental situation is somewhat obscured, since the scattered ions are not identified and a threshold for small Θ_{CM} may be difficult to detect.

We do not know what a suitable order parameter for the triggering of the new phase should be. As an example, which we feel should be sensible beyond the threshold region, we focus on the interaction energy of the heavy ions, in a sphere of radius $r = \frac{1}{m}$, around the interaction region:

$$W_{int} = \frac{Z_1 Z_2 \alpha}{2R(t)} \begin{cases} \frac{r_0 R(t)}{r_0^2 + R(t)^2} - arctan\frac{r_0}{R(t)} & r_0 \leq R(t) \\ 1 - \frac{\pi}{2} - \frac{r_0 R(t)}{r_0^2+R(t)^2} + arctan\frac{r_0}{R(t)} & r_0 \geq R(t) \end{cases} \tag{2}$$

Here $2R(t)$ is the distance between the two ions. As is shown in Fig 3, in the Rutherford time interval when the heavy ions suffer considerable acceleration, this interaction energy is of order $10^2 m$. Let us investigate the hypothesis that the probability of producing a soliton of mass M^* is simply related to the Fourier transform of W_{int}

$$P = A(M^*)|\int_{-\infty}^{\infty} dt e^{iM^* t} W_{int}(t)|^2 \tag{3}$$

Because W_{int} is only significant for $R(t) << \frac{1}{m}$, it should suffice in (3) to approximate W_{int} by the term outside the curly bracket in Eq(2). Using the explicit form of the Rutherford trajectory, one then easily deduces that

$$P = A\frac{Z_1^2 Z_2^2 \alpha^2}{\beta_0^2} e^{-\pi\mu} K_{i\mu}^2\left(\frac{\mu}{sin\frac{\Theta_{CM}}{2}}\right) \tag{4}$$

where

$$\mu = \frac{Z_1 Z_2 \alpha (M_1 + M_2)}{\beta_0^3 M_1 M_2} M^* \tag{5}$$

and $K_\nu(x)$ is the modified Bessel function.

Although Eq(4) is ad hoc, it serves to emphasize the important point made earlier. The probability of producing the new phase is a function of Z, Θ_{CM} and β_0, and the dependence on these variables is necessarily correlated. It turns out that (4) gives an adequate description of how the strength of the positron peaks measured by the ORANGE collaboration, in U + U and U + Th reactions, vary with the heavy ion scattering angle [23]. Since it is not possible to distinguish between ejectiles and recoils in the experiment, what is measured is the symmetrized convolution of P with the Rutherford cross section

$$\frac{d\sigma}{d\Omega_{CM}} = P(\Theta_{CM})\left(\frac{d\sigma}{d\Omega_{CM}}\right)^{Ruth}(\Theta_{CM}) + P(\pi - \Theta_{CM})\left(\frac{d\sigma}{d\Omega_{CM}}\right)^{Ruth}(\pi - \Theta_{CM}) \tag{6}$$

The experimental data in the range measured, from $\Theta_{CM} \sim 30^0$ to $\Theta_{CM} \sim 90^0$, is approximately independent of Θ_{CM}. The prediction of Eq(4) nicely reproduces this behaviour, as is seen in Fig 4. Note that $P(\Theta_{CM})$ decreases for smaller ion scattering angles. However this behaviour is compensated by the increase in the Rutherford scattering cross section. A formula quite similar to Eq(4) was proposed independently earlier by Bang Hansteen and Kocbach [24], who also were trying to relate the formation of the positron lines with the time varying Coulomb fields of the heavy ion reaction.

If W_{int} is the correct order parameter to consider, then the Z and β_0 dependence of the cross section for producing the lines is fixed by Eq(4). It is not difficult to convince oneself

that the quantity $\frac{d\sigma}{d\Omega_{CM}}$, with P given by Eq(4), is also not terribly strongly dependent on Z or β_0. Indeed, the weak Z dependence can be directly seen in Fig 3, where we plot W_{int} for both U + U and Pb + Pb collisions, at two different angles Θ_{CM}, for the heavy ion scattering. Unfortunately, these expectations do not seem to be in agreement with data obtained rather recently by the EPOS and ORANGE collaborations. However, to add to the confusion, these experiments also do not seem to agree with each other in these very important details!

To be more precise, the ORANGE collaboration [25] sees an increase of about an order of magnitude in the strength of the positron lines between the measurements done in Pb + Pb and in U + U ($\frac{d\sigma}{d\Omega_{CM}} = 0.46\pm0.1\frac{\mu b}{st}$ vs $\frac{d\sigma}{d\Omega_{CM}} = 3.5\pm1\frac{\mu b}{st}$, for the 340 Kev line). Our simple formula, for the angular range studied, predicts only a small change. On the other hand, the EPOS collaboration [26] seems to see very little Z dependence in their data, and gives a value of $\frac{d\sigma}{d\Omega_{CM}} \sim 10\frac{\mu b}{st}$ for all the systems studied. The situation is reversed, with regards to the β_0 dependence. The ORANGE collaboration, studying U + U collisions, have purposely varied the bombarding energy from $5.6\frac{Mev}{nucleon}$ to $5.9\frac{Mev}{nucleon}$ [27]. Their results show little change in the single positron peak intensity. This is in agreement with our expectations, but in contradiction to what has been reported by the EPOS collaboration [8]. The strenght of the correlated e^+e^- peaks observed in this experiment apparently is very sensitively dependent on the initial bombarding energy, with variations of a few hundredths of an Mev/nucleon being important!

Clearly it is very important to resolve the above experimental discrepancies before reaching premature conclusions regarding the possible existence or not of a new phase of QED. The rapid Z variation of the ORANGE collaboration data and the rapid β_0 variation of the EPOS collaboration data, if confirmed, could indicate a threshold behaviour which should also appear in the angular dependence. However, an irregular dependence on the collision parameters Θ_{CM}, Z, β_0 is much more likely to obtain through detailed atomic processes, so that a lack of correlations in these parameters would favour some interference origin for the positron lines [2] [14] [15].

The most distinct experimental characteristic of the soliton interpretation is the predicted independence of mass and width from the production parameters Z, Θ_{CM} and β_0. In contrast, an interference type or other atomic or nuclear explanation would lead to dependence of the invariant mass of the peaks on Z, Θ_{CM} or β_0, even if this dependence is only weak. Experimentally, there is a disquieting drift in time of the location of the positron peaks. Although these peaks are essentially Z independent within a given set of experiments, the data of different runs do not seem to always reproduce the same structures! Also there does not seem to be a strict one to one correspondence between the ORANGE spectrometer positron peaks and the EPOS correlated peaks. A glance at the summary table of all the observations to date [Table IV in [25]], could very well lead one to conclude that the peaks are randomly scattered in an energy interval between 230 and 400 Kev. We do not want to be too critical, but we do feel that the data needs urgent clarification.

Purely theoretically, of course, it is even harder to answer the question if a new phase

[2]There is another experimental distinction between a "soliton" and an "interference" explanation: whereas interference predicts fluctuations around the "background" with "peaks" and "valleys" separated by about the width of the "peaks", the decay of solitons should lead to well separated peaks above background. The experimental situation is not very clear in this respect.

of QED could obtain in the heavy ion reactions. It is often stated that since the electric fields are strong ($Z\alpha > 1$), this obviously signals a breakdown of the perturbative regime of QED. However, nonlinear effects in QED arise only indirectly. The external fields can couple to the photon field strenghts only via electron loops and these necessarily involve α. In fact, as we shall demonstrate below, just having strong homogenous fields $\hat{E} = \frac{eE}{m^2} >> 1$ in no sense causes profound modifications to QED.

For any "new phase" or "soliton" state in QED, it is crucial that Coulomb's law for the interaction between charged particles gets qualitatively modified. The effective action for strong electromagnetic fields must deviate substantially from the Maxwell form. In all regions of space where the (linear) Maxwell equations have only small corrections the only stable or quasistable state in the absence of external charges is the standard vacuum and no soliton like structures are expected. For weak fields we can expand the effective electromagnetic action in terms of three sorts of small parameters: α, $\frac{eE}{m^2}$ or $\frac{eB}{m^2}$ and higher derivative corrections like $\frac{\nabla^2 E}{Em^2}$. The lowest order correction, for slowly varying fields, gives the well known Euler-Heisenberg [28] action

$$\mathcal{L}_{EH} = \frac{2\alpha^2}{45m^4}\{[\vec{E}^2 - \vec{B}^2]^2 + 7[\vec{E}\cdot\vec{B}]^2\} \tag{7}$$

Naively, one could think that strong nonlinearities arise for $\frac{eE}{m^2} \sim \frac{1}{\alpha}$, which happens in a volume with radius ~ 40 fm during the heavy ion collision. These nonlinearities, are, however, an artifact of an invalid expansion. If we neglect for a moment the higher derivative corrections, we can use the exact one loop effective action for arbitrary strong fields, calculated by Schwinger [29]. Schwinger's formula is valid to all orders in the external fields, but only to lowest order in α.

$$\mathcal{L}_{Schwinger} = -\frac{2}{(4\pi)^2}\int_0^\infty \frac{ds}{s^3}e^{-m^2 s}\{(es)^2 G\frac{Re(cosH^{\frac{1}{2}}es)}{Im(cosH^{\frac{1}{2}}es)} - 1 + \frac{2}{3}(es)^2 F\} \tag{8}$$

where

$$\begin{aligned} F &= -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} = \frac{1}{2}(\vec{E}^2 - \vec{B}^2) \\ G &= -\frac{1}{4}F^{\mu\nu}\tilde{F}_{\mu\nu} = \vec{E}\cdot\vec{B} \\ H &= 2(F - iG) = (\vec{E} - i\vec{B})^2 \end{aligned} \tag{9}$$

This Lagrangian has both a dispersive and an absorptive part, with the later arising from singularities along the real s axis in Eq(8). We discuss these in turn.

The real part of (8) describes the nonlinear modifications of Maxwell's equations, which in lowest order in G and H reproduces Eq(7). We have evaluated the integral for three cases: $\vec{B} = 0$, $\vec{E} = 0$, $\vec{E} = \vec{B}$. The results for the deviation $\delta\hat{\mathcal{L}}$ from Maxwell's action are shown in Fig 5. [$\mathcal{L} = \frac{1}{2}\vec{E}^2(1 + \delta\hat{\mathcal{L}})$ for the first case and similarly for the other two cases.] We find that even for very strong fields $\hat{E} = \frac{eE}{m^2}$ or $\hat{B} = \frac{eB}{m^2}$, the nonlinear correction $\delta\hat{\mathcal{L}}$ remain very small ($\delta\hat{\mathcal{L}} \sim \alpha ln\hat{E}$ for $\hat{E} \to \infty$). Although the expansion in $\hat{E}$ and $\hat{B}$ breaks down, this does not lead to a breakdown of the expansion in α, which would be needed for strong nonlinear effects. We suspect that this feature remains true for higher loops in strong fields which are supressed by further powers of α. We conclude that an extended new QED phase with weakly varying strong electromagnetic fields seems very unlikely. The situation here is qualitatively different from the case of strong electromagnetic coupling for which nonlinearities indeed become important.

During the collision of the heavy ions the expansion in $\frac{\nabla^2 E}{Em^2}$ breaks down at a distance $\simeq \frac{1}{m}$ from the center of mass. The same will be true for a possible "soliton configuration" with size m^{-1}. Thus the real problem of the peaks in heavy ion collisions cannot be treated with the constant field approximation. In particular, the formula (8) gives only information on the photon propagator for $q^2 \to 0$ whereas we need the behaviour for $|q^2| \geq m^2$. We therefore cannot exclude a soliton interpretation of the GSI peaks on theoretical grounds, so far. However, we can point to a serious difficulty already encountered above: the breakdown in the derivative approximation must be so strong that it overrides the factors of α necessarily appearing in all modifications of Maxwell's equations!

The absorptive part of $\mathcal{L}$ gives the number n_c of e^+e^- pairs produced per Compton volume $\frac{4\pi}{3m^3}$ and per Compton time m^{-1} as a result of having a constant electric field. For $\vec{B} = 0$, one finds [29]

$$n_c = \frac{8\pi}{3m^4}Im\mathcal{L} = \frac{\hat{E}^2}{3\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}e^{-\frac{n\pi}{\hat{E}}} \tag{10}$$

Clearly n_c becomes large when $\hat{E} >> \pi$, since then the non perturbative exponential factor in (12) is ineffective. Naively, $n_c >> 1$ appears to be a manifestation of a breakdown of QED. If one imagines that the e^+e^- pairs are produced nearly at rest, then it is not possible to pack many such pairs in a Compton volume, per Compton time, so that $n_c >> 1$ would be contradictory. However, in the case at hand, as $\hat{E}$ grows so does the energy of the pairs and many more pairs "fit" in a Compton volume. So n_c can be much greater than unity, without signifying anything amiss in perturbative QED.

The approximation of constant $\hat{E}$ does not apply in our case. One is interested to know n_c for the rapidly varying Coulomb field with charge $Z_1 + Z_2$ and also the kinetic energy distribution of the produced pairs. A large number of pairs produced with small kinetic energy could indicate an instability or breakdown of standard QED. For example, the system could respond to this abnormality by forming a chiral condensate. Unfortunately, we do not know how to compute n_c for this realistic situation. A little example shows that n_c does not only depend on the value of $\hat{E}$ (averaged in some region of space) but also in a crucial way on the spatial distribution of $\hat{E}$. The pair production in static fields can be understood qualitatively as a quantum mechanical tunneling phenomenon [30]. (This is quite different from pair production by time varying electromagnetic fields.) A positron bound in a deep well, $V_0 = -2m$, when an external constant field E is applied, can tunnel through the potential barrier. The tunneling probability, computed with the usual WKB approximation, provides the damping factor $e^{-\frac{\pi}{\hat{E}}}$ in Eq. (10). By applying the same sort of reasoning to the Coulomb potential, one may get a rough guess for the exponential factor in a more realistic situation. The problem is analogous to α disintegration in nuclear physics and the probability of tunneling through a Coulomb barrier between a_0 and a_1 is $exp - W$, where

$$W = (2mZ\alpha a_1)^{\frac{1}{2}}\{arccos(\frac{a_0}{a_1})^{\frac{1}{2}} - [(1 - \frac{a_0}{a_1})\frac{a_0}{a_1}]^{\frac{1}{2}}\} \tag{11}$$

In our problem the height of the barrier, $\frac{Z\alpha}{a_0} - \frac{Z\alpha}{a_1}$, should be $2m$. Defining $Z_c = \frac{2ma_0}{\alpha}$ one finds a nonvanishing probability only for $Z > Z_c$ and a typical threshold behaviour with strong Z dependence near Z_c and e^{-W} near one, for Z beyond the threshold region.

$$W = \frac{\alpha(ZZ_c)^{\frac{1}{2}}}{X}[arccos X - X(1-X^2)^{\frac{1}{2}}] \tag{12}$$

with $X = (\frac{Z-Z_c}{Z})^{\frac{1}{2}}$. If Z is not too far from Z_c, the positron kinetic energy is small. Although this threshold behaviour is interesting, there is no way to estimate Z_c in this simple approach. In addition, the disappearance of the supression factor ($e^{-W} \sim 1$) does not tell us the value of n_c in this regime and a breakdown of standard QED for $Z >> Z_c$ cannot be inferred. Also this approach completely neglects any time dependent effects.

In conclusion, we have found so far no clear theoretical indication that Maxwell's laws and the Coulomb potential get substantially modified and that the perturbative expansion in the fine structure constant breaks down for strong electromagnetic fields. An extended new QED phase caused by strong, but weakly varying, electromagnetic fields is unlikely to exist. The correlated peaks can therefore not be explained by the decay of local excitations (bound states) within such an extended phase, which would survive the heavy ion collision. It remains to be seen if the breakdown of perturbation theory necessary for any "new phase" or "soliton" interpretation of the GSI peaks becomes realized for strongly varying electromagnetic fields. If the different observed structures are connected to non-linear effects in QED at all, they should originate from the decay of neutral soliton-like objects of radius of order m^{-1}

Acknowledgements

We would like to thank E. Dagotto, M. Lüscher and T.T. Wu for useful conversations. One of us (RDP) is also grateful to H. Bokemeyer for helpful information on the experimental data.

References

[1] S.S. Gershstein and Y.B. Zeldovich, Sov. Phys. J.E.T.P. 30 (1970) 358; W. Pieper and W. Greiner, Z. Phys. 218 (1969) 126; Y.B. Zeldovich and V.S. Popov, Sov. Phys. Usp. 14 (1972) 673

[2] J. Reinhardt, B. Müller and W. Greiner, Phys. Rev. A24 (1981) 103; see also Quantum Electrodynamics of Strong Fields, ed. W. Greiner (Plenum, New York 1983)

[3] H. Backe et al, Phys. Rev. Lett. 42 (1979) 376

[4] P. Kienle in Proc. Seventh Int. Conf. on Atomic Physics (MIT 1980), Atomic Physics 7, eds. D. Kleppner and F.M. Pipkin (Plenum, New York)

[5] M. Clemente et al, Phys. Lett. B137 (1984) 41; M. Tsertos et al, Phys. Lett. B162 (1985) 273

[6] J. Schweppe et al, Phys. Rev. Lett. 51 (1983) 2261; T. Cowan et al, Phys. Rev. Lett. 54 (1985) 1761

[7] T. Cowan et al, Phys. Rev. Lett. 56 (1986) 444

[8] H. Bokemeyer, GSI preprints 87-1, (Jan 1987) and 37-35, (June 1987)

[9] H. Tsertos et al, Z. Phys. A326 (1987) 235; W. Koenig et al, GSI preprint 87-39 (July 1987), Z. Phys. A in press

[10] K. Danzmann et al, Phys. Rev. Lett. 59 (1987) 1885

[11] For a recent review see G. Soff et al, to appear in the Proceedings of the International Symposium on Modern Developments in Nuclear Physics, Novosibirsk 1987

[12] R.D. Peccei, T.T. Wu and T. Yanagida, Phys. Lett. B172 (1986) 435; L.M. Krauss and F. Wilczek, Phys. Lett. B173 (1986) 189

[13] For a review, see M. Davier in Proceedings of the XXIII International Conference on High Energy Physics, Berkeley, Calif. 1986

[14] W. Lichten and A. Robatini. Phys. Rev. Lett. 54 (1985) 781; 55 (1985) 135; see, however, J. Reinhardt, B. Müller and W. Greiner, Phys. Rev. Lett. 55 (1985) 134

[15] G. Scharf and D. Twerenbold, Phys. Lett. B198 (1987) 389

[16] L.S. Celenza, V.K. Mishra, C.M. Shakin and K.F. Liu, Phys. Rev. Lett. 57 (1986) 55; L.S. Celenza, C.R. Ji and C.M. Shakin, Brooklyn College preprint BCCNT 87/041/165

[17] D.G. Caldi and A. Chodos, Yale preprint YTP 87-10(1987)

[18] Y.J. Ng and Y. Kikuchi, North Carolina preprint, IFP-289 UNC (1987)

[19] L. Landau in Niels Bohr and the Development of Physics, ed. by W. Pauli (Pergamon Press, London, 1955)

[20] M. Gell Mann and F. Low, Phys. Rev. 95 (1954) 1300

[21] See for example, P. Fomin, V. Gusymin, V. Miransky and Yu. Sitenko, Riv. Nuov. Cim. 6 (1983) 1

[22] E. Dagotto and J. Kogut, Phys. Rev. Lett. 59 (1987) 617; Illinois preprints, Ill-Th-87-45; Ill-Th-87-54

[23] H. Tsertos et al, GSI preprint, 1987

[24] J.M. Bang, J.M. Hansteen and L. Kocbach, NORDITA preprint 181 (1987)

[25] W. Koenig et al, GSI preprint 87-39 (July 1987), Z. Phys. A in press

[26] T. Cowan et al, Phys. Rev. Lett. 54 (1985) 1761

[27] H. Tsertos et al, Z. Phys. A326 (1987) 235

[28] W. Heisenberg and M. Euler, Z. Phys. 98 (1936) 714

[29] J. Schwinger, Phys. Rev. 82 (1951) 664. For more details, see also J. Schwinger Particles Sources and Fields Vol II (Addison Wesley, Reading 1973)

[30] C. Itzykson and J.B. Zuber, Quantum Field Theory (Mc Graw Hill, New York 1980)

Figure captions

Fig 1: Center of mass velocity and acceleration of heavy ion in Rutherford scattering ($\beta_0 = 2\beta(t \to \infty)$) for $Z_1 = Z_2 = 92, \Theta_{CM} = \frac{\pi}{2}$.
Fig 2: Electric field strength $\hat{E} = \frac{e|E|}{m^2}$ at distance r from center of mass (at given angle $\theta = \frac{\pi}{4}$), during heavy ion scattering ($Z_1 = Z_2 = 92, \theta_{CM} = \frac{\pi}{2}, \beta_0 \sim 0.11$).
Fig 3: Electrostatic interaction energy W_{int}, in the central Compton volume, during heavy ion scattering
Fig 4: Production cross section of "solitons" by the mechanism explained in text
Fig 5: Nonlinear corrections to effective action of QED, for static homogenous fields $\hat{E} = \frac{e|E|}{m^2}$ and $\hat{B} = \frac{e|B|}{m^2}$.

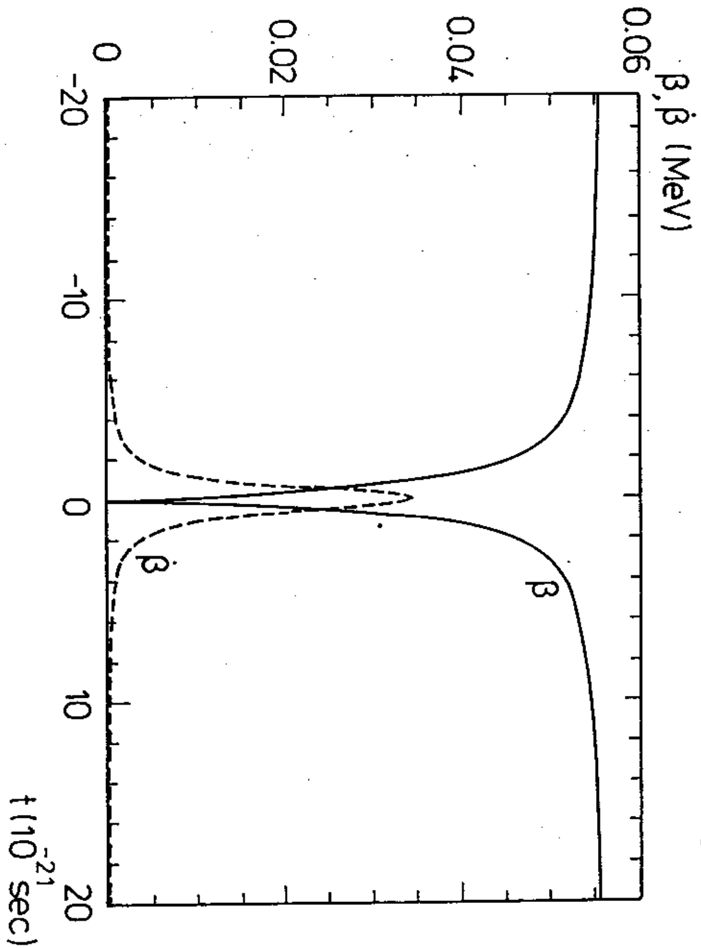


Fig. 1

Fig. 2

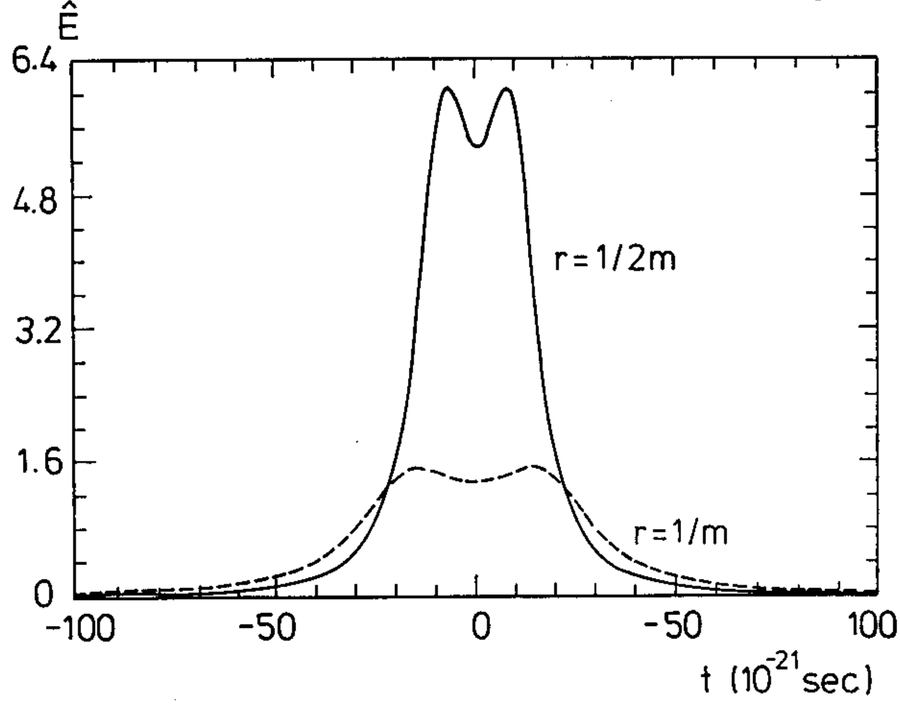

Ê
6.4
4.8
3.2
1.6
0
r=1/2m
r=1/m
-100
-50
0
-50
100
t (10^-21 sec)

Fig. 3

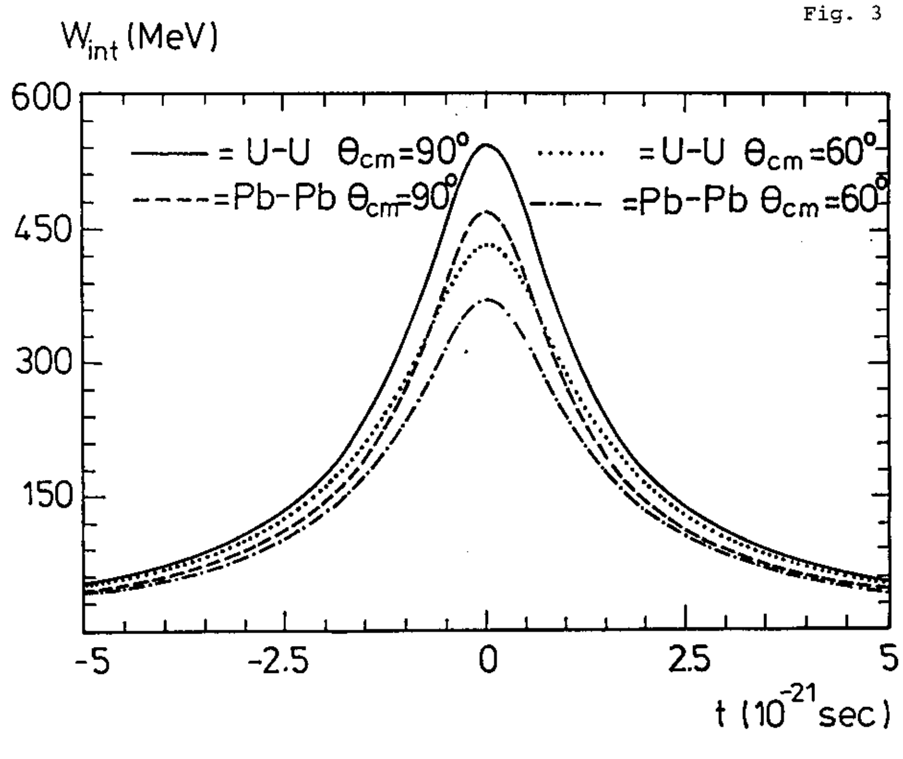
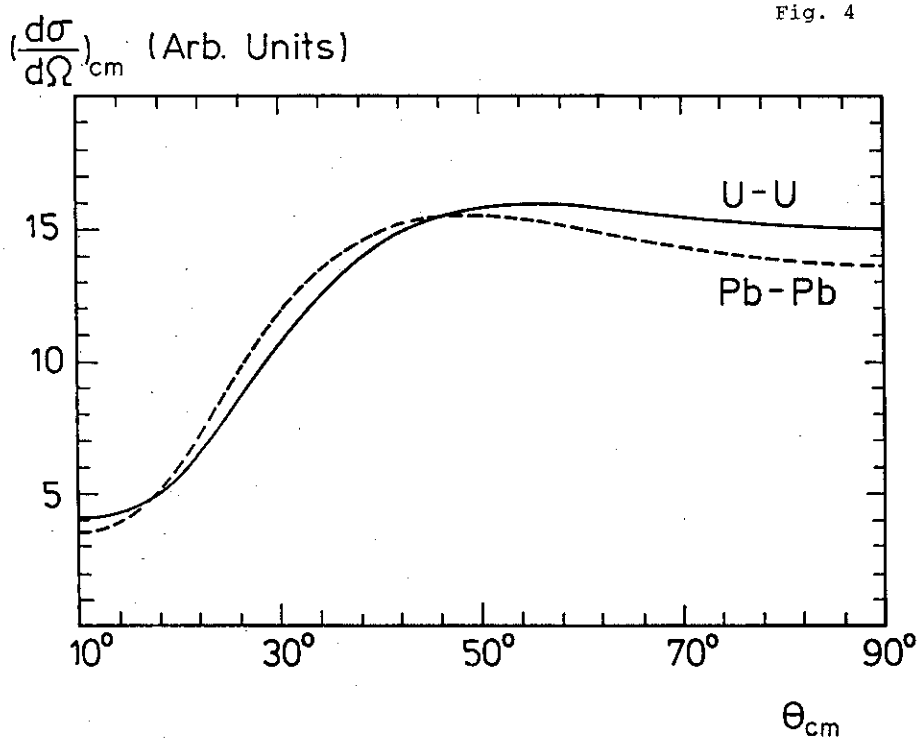
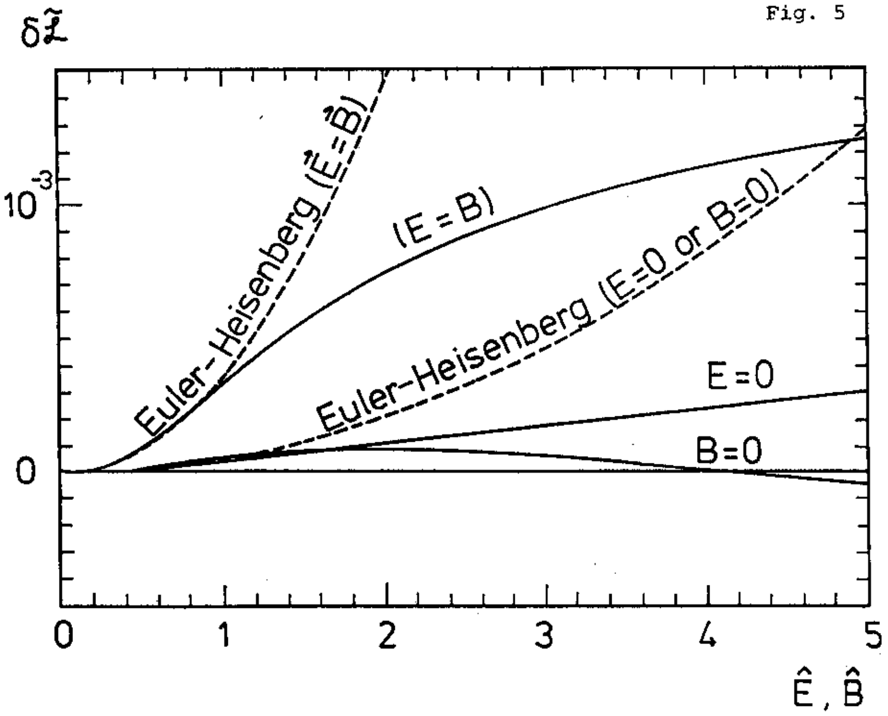

W_int (MeV)
600
450
300
150
= U-U θcm=90°
= U-U θcm=60°
=Pb-Pb θcm=90°
=Pb-Pb θcm=60°
-5
-2.5
0
2.5
5
t (10^-21 sec)

Fig. 4



$(\frac{d\sigma}{d\Omega})_{cm}$ (Arb. Units)
U-U
Pb-Pb
15
10
5
10°
30°
50°
70°
90°
Θ_{cm}

Fig. 5



$\delta\tilde{\mathcal{L}}$
Euler-Heisenberg ($\vec{E} = \vec{B}$)
(E = B)
Euler-Heisenberg (E=0 or B=0)
E=0
B=0
10^{-3}
0
0
1
2
3
4
5
$\hat{E}, \hat{B}$