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Narrow e^+e^- peaks in heavy-ion collisions and a possible new phase of QED

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Motivated by the otherwise inexplicable e^+e^- peaks observed in heavy-ion collisions at GSI, we postulate the existence of a new phase of QED. The transition to this new phase is induced by the presence of unusual background electromagnetic field environments. Strong-coupling calculations of the spectrum of confined QED are reported, and the masses fit well with the observed peaks.

Heavy-ion scattering experiments conducted at GSI over the last few years[1-6] have generated increasingly puzzling results. The measured quantities are the kinetic energy of the emitted positrons and electrons. In this paper we shall concentrate on the more recent e^+e^- data taken by the EPOS group.[5,6]

The feature that has excited wide interest is the presence of very narrow lines. The peaks have a natural width of not more than about 30 keV and the energies of the electron and positron are equal. The data suggest the interpretation[5,6] that the e^+e^- are emitted back-to-back by a system whose mass is approximately 1.7 or 1.8 MeV at rest (or very nearly so) in the center of mass of the colliding-ion system. Recent data reveal two such peaks in the uranium-on-thorium system, split by about 200 keV in the sum of the e^+ and e^- energies, in addition to the peak observed in previous data.

Many explanations have been advanced,[7,8] but we feel that none is compelling. In particular, attention has been given to the idea of a new elementary particle. However, there are at least three difficulties with the particle interpretation. (i) It is very hard to construct a model in which the particle is produced predominantly at rest.[8] (ii) There is no corroborating evidence from other experiments for a new particle in this mass range.[9] (iii) If the evidence for more than one line in a single colliding-ion system continues to hold up, one is forced to postulate the existence of several new particles.

We wish to examine a different hypothesis, motivated in large part by the same factors that militate against a conventional particle interpretation. The heavy ions in the GSI experiments induce significant background electromagnetic fields, and these unusual field environments may give rise to a new phase of QED. This new phase should possess a set of e^+e^- bound states analogous to positronium in the normal phase of QED. But the energy levels should be quite different. For example, the spectrum would necessarily be very different if the new phase is a confining one. Let us suppose that these levels are in the mass range of 1.6 to 1.8 MeV. After the heavy ions have scattered, the unusual background fields disappear, and the new phase becomes a "false vacuum." The system then tunnels to the familiar vacuum of perturbative QED. The "false positronium," now no longer bound, appears as the e^+e^- pair in the EPOS detectors. Here we assume that the decay of the false vacuum,[10] which liberates the e^+ and e^- with a considerable kinetic energy, proceeds more rapidly than the annihilation process that governs standard positronium decay.

Whatever the *a priori* likelihood of this scenario, it does have some built-in advantages in confronting the data. In the first place, the phase transition is triggered by the presence of the background fields generated by the heavy ions, so that one can understand why the peaks appear specifically in these experiments and not in others designed to snare a more conventional particle. Second, since the peaks are due to the decay of a composite object, several levels should be seen, as now seems to be the case experimentally.

One possibility is that the phase transition is analogous to the chiral phase transition of QCD, although in the QED case the normal vacuum is symmetric and the new phase is the spontaneously broken one. In the QCD case, there is evidence, based both on theoretical arguments[11] and on lattice gauge calculations,[12] of a close connection between the chiral transition and the deconfining one. If this persists in the Abelian case, as the theoretical arguments suggest, then it is possible that the new phase is a confining one.

There is further evidence from lattice gauge theory (LGT) for a confining phase of QED which occurs for strong coupling, as is in general true for LGT's based on compact groups.[13] For the U(1) case it has been rigorously established,[14] as well as numerically demonstrated,[15] that there is a phase transition which separates the strong-coupling confining phase from a Coulomb phase. For lattice coupling g less than the critical coupling g_c one can take the continuum limit of the theory and so obtain the usual perturbative QED, since for $g<g_c$ there is actually a line of critical points.

But for $g=g_c$, the continuum limit may be taken from the strong-coupling phase, assuming that the transition is second order, for which there is much numerical evidence.[15] The continuum limit of this confining phase would not look like the standard QED. But standard QED is not a well-defined theory until one regulates it, and the only nonperturbative, gauge-invariant regularization is the lattice. Hence, the continuum limit of the confining phase of U(1) LGT would be an acceptable nonperturbative QED.

To apply the confining phase obtained from U(1) LGT to the heavy-ion experiments one must relate the effect of strong coupling [actually just $g=g_c=O(1)$] to the unusual background-field environment discussed above. Incorporating background-field configurations into the U(1) LGT is an interesting question that we are continuing to study.

In lattice QED one can do spectrum calculations. We have done a strong-coupling calculation[16] of the low-lying "meson" spectrum using the Hamiltonian formulation with Kogut-Susskind fermions.[17] The latter are represented by a one-component field $\chi(\mathbf{r})$, where $\mathbf{r}$ is a three-dimensional spatial lattice site $\mathbf{r}=(x,y,z)$.

The rescaled Hamiltonian is, following the notation of Ref. 17, $W=(2a/g^2)H$, with a = lattice spacing and

$$H=H_{\text{elec}}+H_{\text{mag}}+H_e \;. \tag{1}$$

In particular, H_{elec} and H_{mag} are the standard gauge-field terms, and

$$H_e=(1/2a)\sum_{\mathbf{r},\hat{\mathbf{n}}}\chi^\dagger(\mathbf{r})U(\mathbf{r},\hat{\mathbf{n}})\chi(\mathbf{r}+\hat{\mathbf{n}})\eta(\hat{\mathbf{n}}) \;, \tag{2}$$

where $\eta(\hat{\mathbf{z}})=(-1)^y$, $\eta(\hat{\mathbf{x}})=(-1)^z$, $\eta(\hat{\mathbf{y}})=(-1)^x$, $\eta(-\hat{\mathbf{n}})=\eta(\hat{\mathbf{n}})$. The gauge field $\mathbf{A}(\mathbf{r})$ is incorporated into the compact U(1) link variable $U(\mathbf{r},\hat{\mathbf{n}})$ at site $\mathbf{r}$ in the $\hat{\mathbf{n}}$ direction: $U(\mathbf{r},\hat{\mathbf{n}})=\exp[igaA^i(\mathbf{r})\hat{n}^i)]$.

The lattice is divided into odd and even sites ($x+y+z$ = even or odd), and the vacuum, which spontaneously breaks the remaining discrete chiral symmetry, has positive charges on all odd sites, and negative ones on all even sites. This is implemented through the operator

$$\rho(\mathbf{r})=[\chi^\dagger(\mathbf{r}),\chi(\mathbf{r})] \;, \tag{3}$$

with the charge above being the eigenvalue of ρ in a state. It is useful[17] as well as possibly desirable[18] to include into the unperturbed Hamiltonian a four-fermion operator,

$$W_A=A\sum_{\mathbf{r},\hat{\mathbf{n}}}[\rho(\mathbf{r})\rho(\mathbf{r}+\hat{\mathbf{n}})+1] \;, \tag{4}$$

where A is a dimensionless parameter. W_A is generated in any case by higher-order processes. We may also add an explicit chiral-symmetry-breaking mass term, but it turns out that its effects can be included by readjusting the parameter A. The unperturbed Hamiltonian is now

$$W_0=W_{\text{elec}}+W_A \;. \tag{5}$$

We then consider perturbations by W_e (and in higher order by W_{mag}). Here we report on calculations only to second order[16] (i.e., to order $1/g^4$). The results are summarized in the following series for the mass energy of the "mesons" named in analogy with the comparable hadronic states, i.e., π, ρ or ω (Ref. 19), σ, B, A_1, and f:

$$m_\pi=(g^2/2a)\left[(1+20A)+\left(\frac{54}{1+20A}-\frac{36}{1+16A}-\frac{8}{1+12A}\right)x^2\right] , \tag{6a}$$

$$m_\rho=(g^2/2a)\left[(1+20A)+\left(\frac{58}{1+20A}-\frac{44}{1+16A}-\frac{4}{1+12A}\right)x^2\right] , \tag{6b}$$

$$m_\omega=(g^2/2a)\left[(1+20A)+\left(\frac{62}{1+20A}-\frac{52}{1+16A}\right)x^2\right] , \tag{6c}$$

$$m_\sigma=(g^2/2a)\left[(1+20A)+\left(\frac{71}{1+20A}-\frac{52}{1+16A}-\frac{8}{1+12A}\right)x^2\right] , \tag{6d}$$

$$m_B=(g^2/2a)\left[(1+20A)+\left(\frac{58}{1+20A}-\frac{36}{1+16A}\right)x^2\right] , \tag{6e}$$

$$m_{A_1}=(g^2/2a)\left[(1+20A)+\left(\frac{-13}{1+20A}+\frac{8}{1+16A}+\frac{4}{1+12A}\right)x^2\right] , \tag{6f}$$

$$m_f=(g^2/2a)\left[(1+20A)+\left(\frac{64.5}{1+20A}-\frac{44}{1+16A}-\frac{4}{1+12A}\right)x^2\right] , \tag{6g}$$

where $x = 1/g^2$.

Significant results are obtained by forming mass ratios and taking the continuum limit, here $g \approx 1$ (presumably near or at the radius of convergence of the strong-coupling expansion). The results are summarized in Table I, where the parameter A has been adjusted to give a good fit to the data, taking the lowest state, the σ-type meson, to have mass $= 1.60$ MeV.

We see that the three peaks observed in the experiments, at roughly 1.6, 1.7, and 1.8 MeV, are in reasonable correspondence with the calculated masses in the confined phases of QED. We note also that the calculated spectrum predicts additional peaks in this mass range which the experiments have not yet resolved. These mass values will be better determined when higher-order corrections are included.[16] Furthermore, the problem with the π-type meson, an e^+e^- "pion" or what we may call an electropion, may also improve with higher-order corrections. We expect it to be much lower in mass than the other mesons, due to its pseudo-Goldstone nature. However, in low orders of strong-coupling expansions it is hard to get the pion mass right,[17] due to the problems of fully implementing chiral symmetry on the lattice. Nevertheless, a clear prediction of confined QED is that the lowest-lying state should be the electropion, and if the scenario advocated here is the explanation for the heavy-ion data, then a peak considerably lower than the three so far observed should be found. The region below 1.6 MeV has not yet been carefully explored, so that the position of the ground state of this system remains to be determined. (But see note added.)

Whether or not one actually has a confined phase, it is also independently possible that chiral symmetry is spontaneously broken and that this alone is responsible for the phase transition. There is some evidence both in the continuum[20] and from the lattice[21] that QED has a chiral phase transition. We want to see if this can occur due to unusual background-field configurations. For simplicity, we ignore the dynamical electromagnetic degrees of freedom, and consider the problem of electrons and positrons interacting with a fixed background.

We employ the proper-time formalism of Fock, Nambu, and Schwinger.[22] The electron propagator $S(x,x';A)$ is

$$S(x,x';A) = (i\gamma D + m)(-i)\int_0^\infty ds \exp(-im^2 s) \times \langle x | \exp(-iHs) | x' \rangle \;, \tag{7}$$

where

$$H = -(\gamma \cdot \Pi)^2, \text{ with } \Pi_\mu = iD_\mu = p_\mu - eA_\mu \;, \tag{8}$$

TABLE I. Spectrum of the low-lying mesons in confined QED.

	$A = 0.5$		
m_π	1.64 MeV	m_{A_1}	1.71 MeV
m_σ	1.60 MeV	m_f	1.73 MeV
m_ω	1.65 MeV	m_B	1.86 MeV

and p and x are canonically conjugate. Thus the propagator may be thought of as the transform of a quantum-mechanical transition amplitude governed by the Hamiltonian H. Note that this amplitude carries spinor indices, which we have suppressed, as well as the labels x and x'.

The crucial object is the matrix element $\langle x | \exp(-iHs) | x' \rangle$. If we set $x = x'$ and trace over Dirac indices, it is related via Eq. (7) to the vacuum expectation value of $\bar{\psi}\psi$. In the unbroken phase, as $\tau = -is \to \infty$, for a free particle the matrix element behaves as τ^{-2}. As shown in Ref. 11, for chiral symmetry to be spontaneously broken, it must fall off as $\tau^{-1/2}$. We are studying[23] this behavior for a variety of background fields using a path-integral representation evaluated by Monte Carlo techniques.

It is also interesting to note that the Hamiltonian of Eq. (8) is supersymmetric.[24] Define

$$Q_\pm = \tfrac{1}{2}(1 \pm \gamma_5)\gamma \cdot \Pi \;. \tag{9}$$

Then

$$Q_+^2 = Q_-^2 = 0, \; \{Q_+, Q_-\} = H \;. \tag{10}$$

This is the algebra of quantum-mechanical supersymmetry.[25] The existence of supersymmetry in this system has been noted by a variety of other authors.[26]

It may be possible that instead of chiral-symmetry breaking one can have spontaneous supersymmetry breaking.[27] If so, the matrix element will behave, for large τ, as $\exp(-E_0\tau)$ where $E_0 > 0$ is the lowest eigenvalue of H. For constant $F_{\mu\nu}$ one can solve for the matrix element in Eq. (7) exactly, and one finds that supersymmetry is unbroken.

A description of roughly the sort of phase transition in QED that we have been discussing has appeared in the literature.[28] This model, involving a scalar condensate, is flexible enough to accommodate the kind of structure observed in the EPOS experiments.

In summary, a new phase of QED is the only explanation so far which provides a cogent and consistent interpretation of the data. A composite system of e^+e^- in a new phase explains why there are many peaks, why they are seen in heavy-ion collisions, why the states decay into e^+e^-, and also predicts an electropion. Given both the experimental and especially the theoretical uncertainties, it is not clear whether the specific mechanisms we have been considering will turn out to be the relevant ones. Be that as it may, we wish, most importantly, to stress the broader possibility that these data may well represent the first laboratory example of a phase transition in a gauge theory, and that a window may have been unexpectedly opened on a new regime in what had been believed to be the best understood theory in all of physics.

Note added. We have become aware of a recent Stanford-Berkeley-Livermore experiment[29] that measures the γ-γ spectrum in U-Th collisions, and sees some evidence for a peak at 1.062 MeV with a width < 1 keV. If this is confirmed, it would be a natural candidate for the electropion, decaying into two γ's due to annihilation via the triangle anomaly.

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