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Narrow e^+e^- peaks in heavy-ion collisions as possible evidence of a confining phase of QED

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We suggest that the correlated narrow-peak structures in e^+e^- spectra observed in heavy-ion collisions at GSI are due to the decay of a bound e^+e^- system formed in a new phase of QED. We discuss the mass spectrum for this confined positronium system. Observation of correlated photons of energy $\lesssim 150$ keV in the center-of-mass frame at GSI will be further evidence of this new phase, the existence of which has strong support from studies of lattice QED.

Quantum electrodynamics of strong fields has been a fascinating subject for quite some time.[1] Detailed QED calculations have predicted spontaneous positron emissions from "supercritical" nuclear systems; and it was suggested by Greiner, Müller, and collaborators (among others) that the effect of a "supercritical" nucleus can be simulated in collisions of large-Z nuclei. These theoretical ideas have motivated an active experimental search for such phenomena culminating in the recent observation of correlated narrow-peak structures in positron and electron spectra at the Gesellschaft für Schwerionenforschung (GSI) in Darmstadt.[2-4] These peaks have been seen in U+Th, Th+Th, and Th+Cm collisions and are relatively Z independent. The mean energies and widths of the positron and electron peaks are equal within experimental errors. Furthermore, at least two pairs of back-to-back e^+e^- lines at sum energies of ~620 and ~810 keV have been reported in the U+Th collision system. The data suggest that the e^+e^- spectra are due to the decay of a system produced essentially at rest in the c.m. frame with a mass ~1.6 to 1.8 MeV.[4,5] Theorists have been hard pressed in search for explanations.[4] One popular explanation is the possible existence of a new neutral particle, such as the axion.[6] But this proposal also appears to have been ruled out by experiments.

In this paper we conjecture that the correlated e^+e^- peaks observed in the heavy-ion collision experiments are due to the decay of a bound e^+e^- system formed in a new confining phase of QED. We conjecture that this phase is induced by the intense and rapidly varying electromagnetic fields of the large-Z ions. A similar idea has already been put forth by Celenza, Mishra, Shakin, and Liu.[7] These authors suggest that the peaks result from the decay of a nontopological soliton consisting of a quasielectron and quasipositron formed in a new vacuum phase. (They also introduce a scalar condensate field χ with the potential term of the form $\frac{1}{2}m_\chi{}^2\chi^2$.) Unlike the other proposals involving new particles, this scheme can easily accommodate a rich e^+e^- spectrum (which now appears to be the case). Our proposal shares with theirs the existence of a new vacuum phase but differs from theirs in other respects. Let us first motivate our conjecture.

Many years ago Schwinger observed that massive gauge fields need not violate gauge invariance.[8] He illustrated the general ideas in the (1+1)-dimensional quantum-electrodynamics theory now called the Schwinger model. In this model, vacuum polarization totally screens the electrical charges giving the "photon" a mass. Schwinger went on to suggest that the same effect might occur in a four-dimensional theory if the coupling is large enough. According to his conjecture the photon is massless for any coupling e less than a critical coupling e_c. For $e > e_c$ the photon becomes massive and its mass varies with e. Thus, according to this scenario four-dimensional QED undergoes a phase transition at $e = e_c$ from a weak-coupling regime $e < e_c$ to a strong-coupling regime $e > e_c$.

This investigation was picked up by Wilson some twelve years later. In his study of quark confinement[9] Wilson suggested that the strong-coupling regime of QCD must be connected smoothly to the scaling (asymptotically free) regime of weak coupling. There is no intervening phase transition in QCD. But there must be such a transition in QED since QED does not confine electrons. Subsequent Monte Carlo simulations in lattice gauge theories have supported Wilson's speculation and have shown that in the strong-coupling regimes of both QCD and QED the (massless) gauge fields are essentially squeezed into a flux tube, giving rise to a linear potential between (heavy) charged particles.[10]

Therefore, the proposal that QED has a new (strong-coupling) confining phase is a natural one. We will henceforth assume its existence. We believe that the narrow e^+e^- peaks in large-Z heavy-ion collisions at GSI are evidence of such a phase. The correlated e^+e^- emissions originate in the decay of a new type of positronium system. This proposal is an attractive and economic one: (1) It dispenses with the need to postulate any new particles or fields and it makes use of a new phase of QED, the existence of which has strong support from the studies of lattice gauge theories. (2) This positronium system in the confining phase is expected to possess a rich spectrum; a multiple e^+e^- peak structure in heavy-ion collisions is predicted. (3) The relative Z independence of the e^+e^- peaks is automatic. (4) That the system producing the e^+e^- peaks is at rest in the center-of-mass frame of the heavy ions presents no problem with this proposal. (5) It is natural that the system has a mass (~1.6–1.8 MeV) about (but more than) twice the electron mass. That the spectrum of this new type of positronium is different from the conventional positronium system is expected since the two systems are in two different phases of QED. (6) Since the new positronium is composed of an electron and a positron it seems natural that it decays primarily into the observed e^+e^- pair. (More on this point later.)

Let us now discuss the spectrum of the confined positronium system. Since the region below 1.6 MeV has not been carefully explored in the heavy-ion experiments and there is a lack of sufficient experimental data for comparisons, the bound-state spectrum presented below should be taken only as indicative of the structure of the strongly coupled positronium. For conciseness we will take the mass of the 1*S* state to be 1650 keV and the 2*S*-1*S* splitting to be 200 keV. To calculate the spectrum we will (1) use ($r=|\mathbf{r}|$ with $\mathbf{r}$ being the relative coordinate)

$$V(\mathbf{r})=\lambda r \ , \tag{1}$$

the linear potential between two heavy charged particles obtained in the strong-coupling regime of lattice QED, and (2) apply the nonrelativistic Schrödinger equation to the novel positronium system with reduced mass (in units $c=1$) $\mu=\frac{1}{2}\times m_e=\frac{1}{2}\times 511$ keV. Now, from the known energy levels we know that the positronium under consideration is a rather relativistic system. To minimize the relativistic corrections we will first apply the potential (1) to the 2*S*-1*S* splitting to determine the string tension λ; then we will calculate the other *S*-state splittings and finally obtain the mass spectrum assuming that the ground-state mass is 1650 keV.

The energy eigenvalues of the Schrödinger equation (in units $\hbar=1$)

$$-\frac{1}{2\mu}\nabla^2\psi(\mathbf{r})+(\lambda r-E)\psi(\mathbf{r})=0 \ , \tag{2}$$

are specified by the zeros of Airy functions, and are well approximated in the semiclassical method by[11]

$$E_n=\left[\frac{\lambda}{\sqrt{2\mu}}\frac{3\pi}{2}\left(n-\tfrac{1}{4}\right)\right]^{2/3} . \tag{3}$$

In fact Eq. (3) can be generalized to all partial waves by the replacement $n\rightarrow n+(l/2)$. With the 2*S*-1*S* splitting being 200 keV, Eq. (3) gives

$$\lambda^{1/2}\simeq 166 \text{ keV} \ . \tag{4}$$

(If the 2*S*-1*S* splitting is smaller than 200 keV, say there are more states found in the mass range 1.65 to 1.85 MeV, then $\lambda^{1/2}$has a smaller value.) The energy levels for the first few *S* states are shown in Table I.[12] Although we cannot trust the absolute energy levels as given in Table I (e.g., the ground-state level may well be below 1650 keV) the relative splittings are probably more reliable. However, one should keep in mind that the lightest particle in the spectrum may be considerably lighter than the other particles due to possible chiral-symmetry breaking (the existence of which is quite likely,[13] based on our experience with confining QCD).

TABLE I. Splittings of *S* states. The constant *C* stands for $\lambda^{2/3}(2\mu)^{-1/3}$. For the last column we have used $\lambda^{1/2}=166$ keV and assumed the 2*S*-1*S* splitting to be 200 keV. With the assumption that the 1*S* and 2*S* energy levels are 1650 and 1850 keV, the next three *S* states are given by 2013, 2158, and 2289 keV, respectively.

$(n+1)S$-nS	Splittings	Splittings with $C=114$ keV
2*S*-1*S*	1.75*C*	200 keV
3*S*-2*S*	1.43*C*	163 keV
4*S*-3*S*	1.27*C*	145 keV
5*S*-4*S*	1.15*C*	131 keV

Although we do not know how to reliably calculate the decay rate of the new positronium system into two photons (assuming it is in a parastate), the upper limit from Delbrück scattering on the two-photon decay width of any neutral state in this mass range is about 0.005 eV (Ref. 14) which is much smaller than the e^+e^- sum-energy peak width ($\lesssim 40$ keV).[4] Thus, it is likely that the new positronium system decays considerably more rapidly via another mechanism (not into photons but) into the observed e^+e^- pairs. Conceivably, shortly after the scattering of the heavy ions, in the absence of the strong electromagnetic fields the positronium system is left in a metastable vacuum; hence, it decays to the normal weak-coupling phase via the Coleman-Frampton tunneling mechanism[15] into the observed e^+e^- pairs.

In this work we have speculated that there is a connection between strong dynamical electromagnetic fields in heavy-ion collisions and strong-coupling QED. At this point we have not yet succeeded in proving this connection. But as mentioned above, our proposal that the correlated narrow e^+e^- peaks observed in heavy-ion collisions are due to the decay of a bound e^+e^- system formed in a (new) confining phase of QED is a very natural and economic one. In any case, this idea can be experimentally checked. One can use Table I as a rough guide to find more structure in the heavy-ion experiments. Two additional predictions which follow from our proposal can also be checked.

(1) Although we still do not understand the detailed mechanism causing the purported transition to the confining phase in the heavy-ion collision experiments, we know there is no evidence of such a phase transition in other experiments. So we speculate that its creation in the GSI experiments must be due to the intense electromagnetic fields of the large-*Z* heavy ions. It follows that those e^+e^- peaks detected at GSI are not expected in the e^+e^- elastic-scattering experiments now in progress at Brookhaven National Laboratory.[16]

(2) Our discussion hinges heavily on the new (strong-coupling) confining phase of QED. So far its existence has been rigorously demonstrated only in lattice gauge theory. But if we take lattice gauge theory seriously we expect that in the spectrum of the strong-coupling phase of QED, in addition to the states of the confined positronium system, there are states consisting of strongly bound photons only,[17,18] the QED counterpart of glueballs in QCD. From our experience with glueballs it is likely[17] that these states have a mass several times the square root

of the string tension ($\lambda^{1/2}$):

$$M \sim 2 \times 166 \text{ keV} . \tag{5}$$

But this mass is less than twice the electron mass, so we expect these states to decay only into back-to-back photons of energy ~150 keV (in the center-of-mass frame). (A smaller value of the string tension, given by say a smaller $2S$-$1S$ splitting, yields photons with smaller energy.) Observation of such correlated photons at GSI would constitute unmistakable evidence of the new phase of QED that we have been discussing throughout this paper.

To summarize, we have proposed the existence of a positronium system in the confining phase of QED to explain the correlated narrow e^+e^- peaks observed in large-Z heavy-ion collisions. We have calculated a (representative) mass spectrum for this confined positronium system and we have proposed other ways to experimentally check our idea. Obviously much work remains to be done. But it is exciting to contemplate that QED, far from being a closed field of research, may yet pose challenging questions for experimentalists and theorists alike.

We have received a paper by D. G. Caldi and A. Chodos [Phys. Rev. D **36**, 2876 (1987)] in which a similar explanation of heavy-ion collision data is proposed.

Note added in proof. A narrow line at 1062 ± 1 keV in U+Th collisions has been found in a recent Stanford-Berkeley-Livermore experiment [K. Danzmann *et al.*, Phys. Rev. Lett. (to be published)].

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[12] The readers may be interested to compare the spectrum of the linear potential case with that of a logarithmic potential which interpolates between the Coulombic potential and the linear potential. Consult Ref. 11.

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[16] We thank J. Greenberg for raising this question to us.

[17] We thank T. DeGrand for a very useful discussion on this point.

[18] Recall that in the lattice QED Lagrangian there is a term $\cos\theta_P$ where θ_P is proportional to $|F_{\mu\nu}|$. Hence photons are coupled to themselves. See, e.g., Refs. 9 and 10.