QED Meson Description of the X17 and Other Anomalous Particles

Cheuk-Yin Wong

Physics Division, Oak Ridge National Laboratory*, Oak Ridge, Tennessee 37831, USA

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Abstract. The X17 particle, the E38 particle, and the anomalous soft photons are anomalous particles because they do not appear to belong to any known Standard Model families. We propose a QED meson description of the anomalous particles as composite systems of a light quark and a light antiquark bound and confined by the compact QED interaction, by combining Polyakov’s transverse confinement of opposite electric charges in compact QED in (2+1)D and Schwinger’s longitudinal confinement for massless opposite electric charges in QED in (1+1)D. With predicted QED meson masses close to the observed X17 and E38 masses, QED mesons may be good candidates for the description of the anomalous particles.

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1 Introduction

The observed X17 particle [12], the E38 particle [34], and the anomalous soft photons [56789] are anomalous particles because their masses of many tens of MeV do not lie in the mass region of any known family of particles of the Standard Model. Many different interpretations have been presented and their theoretical implications discussed [10]. We focus our attention on the description of the X17 particle and other anomalous particles as composite particles of a light quark and a light antiquark bound and confined by their mutual QED interaction [1112131415]. We shall call such a composite particle a QED meson (compactly written as a “qedmeson”), in analogy with the QCD meson.

Previously, in many exclusive experiments in high-energy hadron-hadron collisions and $e^+e^-$ annihilations, it has been consistently observed that whenever hadrons are produced, anomalous soft photons in the form of $e^+e^-$ pairs about 4 to 8 times in excess of the bremsstrahlung expectations are produced, and when hadrons are not produced, these anomalous soft photons are also not produced [56789]. The transverse momenta of the excess $e^+e^-$ pairs lie in the range of a few MeV/c to many tens of MeV/c, corresponding to masses from a few MeV to many tens of MeV. Owing to its correlated and simultaneous production alongside with hadrons, a parent particle of an anomalous soft photon is likely to contain elements of the hadrons, such as a pair of light quark and light antiquark. According to the Schwinger’s $m^2=g^2/\pi$ relationship between the coupling constant $g$ and the boson mass $m$ of the composite fermion-antifermion pair interacting in a gauge interaction in (1+1)D [1617], the QED gauge interaction will bring the quantized mass $m$ of a $q\bar{q}$ pair to the mass range of the anomalous soft photons, when we consider the QCD and QED coupling constants and the mass scale of a QCD meson. It was therefore proposed in [1112] that a quark and an antiquark in a $q\bar{q}$ system interacting in the QED gauge interaction may lead to new open-string bound and confined qedmesons with a mass of many tens of MeV. These qedmesons may be produced simultaneously along with mesons in high-energy collisions [56789], and the excess $e^+e^-$ pairs may arise from the decays of the qedmesons [1112]. The predicted masses of the isoscalar $I(J^\pi)=0(0^+)$ and $I(J^\pi)=1(0^+)$ qedmesons are about 13-17 and 36-38 MeV respectively [1112], which agree approximately with the masses of the X17 [112] and the E38 particles [34] subsequently observed. The tentative agreement lends support to the possible qedmeson interpretation of the anomalous particles of the X17, the E38, and anomalous soft photons.

2 Can a $q$ interact with a $\bar{q}$ in QED alone?

A serious question arises whether a light quark and a light antiquark can ever be produced and interact in the QED interaction alone, without the QCD interaction. Actually, there are circumstances in the decays from highly excited nuclear states with the possible production of a light $q\bar{q}$...
pair as in Fig. 1(a), the hadron+nucleus reaction as in Fig. 1(b), and the $e^+e^-\rightarrow\gamma\rightarrow q\bar{q}\rightarrow(q\bar{q})^n$ reaction as in Fig. 1(c), when the CM energy, $\sqrt{s(q\bar{q})}$, of the produced $q\bar{q}$ pair lies in the range $(m_\pi+m_\pi)\sqrt{s(q\bar{q})}<m_\pi$. In order to bring the produced $q\bar{q}$ pair in this CM energy range to a possible stable state, the produced $q$ and $\bar{q}$ can only interact with the QED interaction alone, because the QCD interaction will otherwise endow the $q\bar{q}$ pair with a CM energy beyond the range, in a contradictory manner.

For the production of X17 in $^4$He and $^8$Be decays at ATOMKI [12], we envisage the scenario that the excited states of $^4$He(0+ 20.02 MeV) and $^8$Be(1+ 18.15 MeV) are formed by pulling a proton out of one of $n$ alpha-particles of the $(\alpha)^n$-nucleus and by placing the proton on an orbital that is considerably outside the corresponding tritium core as shown in Fig. 1(a). The stretched string-like strong interaction between the proton and the tritium core polarizes the vacuum so much that the strong interaction may lead to the production of a $q\bar{q}$ pair. At the appropriate $\sqrt{s(q\bar{q})}$ eigenenergy, the QED interaction between the $q$ and the $\bar{q}$ may result in the formation of the $q\bar{q}$ bound state X17 [11,12], which is subsequently emitted as the proton drops down to fill the hole in the tritium core to reach the $(\alpha)^n$-nucleus ground state. Such a production mechanism strongly suggests that X17 may also be produced from the excited states of other $(\alpha)^n$-nuclei in which a proton is pulled out from one of its alpha particles. In this respect, the $^{12}$C(1+ 18.16 MeV) state with a width of $\Gamma=240$ keV may be an interesting analog of the $^8$Be*(1+ 18.15 MeV) state with a width of $\Gamma=138$ keV and may likewise decay with the emission of an X17 particle.

In other processes as illustrated in Figs. 1(b) and 1(c), many $q\bar{q}$ pairs may also be produced in high-energy nuclear collisions at Dubna [3,4], in high-energy hadron collisions in anomalous soft photon production experiments [5,6,7,8], and in high-energy $e^+e^-$ annihilations in DELPHI experiments [9,10]. The $q\bar{q}$ pairs may also be produced in high-energy heavy-ion collisions at RHIC and LHC in two ways: either through the production of $q\bar{q}$ pairs in the multiple collision process similar to Fig. 1(b), or through the coalescence of quarks in the deconfinement-to-confinement phase transition of the quark gluon plasma. While most produced $q\bar{q}$ pairs will lead to hadron production, there may be $q\bar{q}$ pairs with $(m_\pi+m_\pi)\sqrt{s(q\bar{q})}<m_\pi$ for which the QED interaction between the quark and the antiquark may lead to the production of the X17 and E88 particles at the appropriate energies. The observation of the E88 particle at Dubna suggests that along with E88, the X17 particle with a mass of 17 MeV may also be produced in the same reaction at Dubna with an even greater probability because of its lower mass.

### 3 How can $q\bar{q}$ be produced and confined in QED?

To answer the question how a $q\bar{q}$ pair can be produced and confined in a QED meson, we note first of all that there are two different types of QED U(1) gauge interactions possessing different confinement properties [13,19,20]. There is the compact QED U(1) gauge theory in which the gauge fields $A^\mu$ are angular variables with a periodic gauge field action that allows transverse photons to self-interact among themselves. Defined on a lattice, the compact QED U(1) gauge theory has the gauge field action [13,19,20]

$$S = \frac{1}{2g^2} \sum_{x,\alpha,\beta} (1 - \cos F_{x,\alpha,\beta}),$$

where $g$ is the coupling constant and the gauge fields are

$$F_{x,\alpha,\beta} = A_{x,\alpha} + A_{x,\beta} - A_{x,\alpha} - A_{x,\beta},$$

with $-\pi \leq A_{x,\alpha} \leq \pi$.

There is also the non-compact QED U(1) gauge theory with the gauge field action [18,19,20]

$$S = \frac{1}{2g^2} \sum_{x,\alpha,\beta} F_{x,\alpha,\beta}^2,$$

with $-\infty \leq A_{x,\alpha} \leq +\infty$.

In non-compact QED gauge theories, the transverse photons do not interact with other transverse photons. Even though the compact and the non-compact QED gauge theories have the same continuum limit, they have different confinement properties. A pair of opposite electric charges are confined in compact QED in (2+1)D and strong coupling (3+1)D, but they are unconfined in weak coupling (3+1)D [18,19,20]. They are unconfined in non-compact QED in (3+1)D [18,19,20].

Which type of the QED U(1) gauge interaction does a quark interact with an antiquark? As pointed out by Yang [21], the quantization and the commensurability properties of the electric charges of the interacting particles imply the compact property of the underlying QED gauge theory. Because (i) quark and antiquark electric charges are quantized and commensurate, (ii) quarks and antiquarks are confined, and (iii) there are experimental evidences for possible occurrence of confined $q\bar{q}$ qedmeson states as we mentioned in the Introduction, it is therefore reasonable to propose that quarks and antiquarks interact with the compact QED U(1) interaction.

In compact QED, Polyakov [18,19,20] showed previously that a pair of opposite electric charges in (2+1)D, $(x^1, x^2, x^0)$, space-time are confined, and that the confinement persists for all non-vanishing coupling constants, no matter how weak. As explained by Drell and collaborators [20], such a
confinement in \((2+1)D\) arises from the angular variable property of \(A_{\phi}\) and the periodicity of the gauge field action as indicated in Eqs. (1) and (2). Such gauge periodicity in the neighborhood of the produced opposite electric charges leads to self-interacting transverse gauge photons. These transverse gauge photons interact among themselves, they do not radiate away, and they join the two opposite electric charges by a confining linear interaction.

(a) Electric and magnetic lines of force of a QED meson

(b) Lattice description of the above QED meson

We can use the above Polyakov’s result in compact QED in \((2+1)D\) as the starting point to construct a model of a quark and an antiquark produced and confined in a QED meson. We envisage the production of the \(\bar{q}q\) pair at the eigenenergy \(\sqrt{s}(qq)\) of the QED meson and take the quark charge to be positive, which can be easily generalized to other cases. We consider the production of the \(\bar{q}q\) charge pair at \((x^1, x^2, x^3)=0\) with the antiquark separated initially from the antiquark along a direction chosen to be the longitudinal \(x^3\) direction at an incipient separation \(\Delta x^3\). The creation of the \(\bar{q}q\) charge pair is accompanied by the creation of the gauge fields \(A, E\), and \(B=\nabla \times A\). We can apply Polyakov’s result to infer that the produced charges and the QED gauge fields are confined in \((2+1)D\) transversely at the \(x^3=0\) plane. We can now stretch the antiquark longitudinally along \(x^3\) away from the quark at \(x^3=0\) to execute the 3D yo-yo motion for the bound state, reaching a momentary snapshot of the flux tube in the stretch \((2+1)D\) configuration shown in Fig. 2(a). We can transcribe Fig. 2(a) in terms of the lattice link and plaquette variables in Fig. 2(b), by following the Hamiltonian formulation and the notations of Drell et al. [24]. Specifically, in the \(A^\lambda=0\) gauge we specify the canonical conjugate gauge fields \(A, E\) at the links in Fig. 2(b), where we display only the \(A^1, A^2\) and \(E^3\) values of the conjugate gauge fields. The magnetic field \(B\) associated with the plaquettes can be determined as the curl of \(A\) and is directed along \(x^3\) in Figs. 2(a) and 2(b). The magnetic field \(B\) sends the quark and antiquark charges into the appropriate Landau orbitals to execute transverse zero-mode harmonic oscillator zero-point motions on their \(\{x^1, x^2\}\) planes. At the qedmeson eigenenergy, the electric field \(E\) and the magnetic field \(B\) along the longitudinal \(x^3\) direction send the quark and the antiquark in longitudinal 3D yo-yo motion. The positive electric quark charge fractions (solid circles in Fig. 2(b)) reside at the \(x^3=0\) plaquette vertices and the negative electric antiquark charge fractions (open circles in Fig. 2(b)) at the antiquark plaquette vertices at the \(x^3\) plane. The transverse gauge fields \(A\) on the transverse links are copies of those on the quark and the antiquark plaquettes, and they are unchanged in the stretching, while the longitudinal links are all \(E^3=|E|/4\). Consequently, the self-interactions of the transverse gauge fields that initially confine the charges and the gauge field transversely will be retained and the cloud of gauge fields will continue to interact with each other to maintain the transverse confinement.

With transverse confinement and \(E\) and \(B\) aligned along the \(x^3\) direction, it remains necessary to study longitudinal confinement, dynamical quark effects, and spontaneous chiral symmetry breaking. Therefore, we idealize the flux tube in stretch \((2+1)D\) as a longitudinal string in \((1+1)D\) and approximate the quarks to be massless. With massless quarks in QED in \((1+1)D\), there is a gauge-invariant relation between the quark current \(j^\mu\) and the gauge field \(A^\mu\) as given by [16,17,23]

\[
j^\mu = -\frac{g}{\pi} (A^\mu - \partial^\mu \frac{1}{\partial_3} \partial_3 A^3), \quad \mu, \lambda, \nu = 0, 3. \tag{4}
\]

On the other hand, the gauge field \(A^\nu\) depends on the quark current \(j^\nu\) through the Maxwell equation,

\[
\partial_\nu (\partial^\mu A^\nu - \partial^\nu A^\mu) = -g j^\nu, \quad \nu = 0, 3. \tag{5}
\]

Equations (4) and (5) lead to \(-\Box A^\mu = (g^2/\pi)A^\mu\) and \(-\Box j^\mu = (g^2/\pi)j^\mu\), with \(j^\mu\) and \(A^\nu\) self-interacting among themselves and building a longitudinal confining interaction between the quark and the antiquark in \((1+1)D\). As a consequence, in accordance with Schwinger’s exact solution for massless fermions in QED in \((1+1)D\), the light quark and the light antiquark interacting in QED will be longitudinally confined just as well and will form a stable QED quark-antiquark system. Possessing both transverse and longitudinal confinements as in an open-string, such a stable QED state may be experimentally observed as a qedmeson. By using the method of bosonization, we obtain the masses of the lowest-energy states of the open-string QED mesons which adequately match those of X17 and E38 [11,12] to support its approximate validity.

4 How can QED mesons be detected?

The qedmesons can be detected by the invariant masses of their decay products. In a qedmeson, the quark and the antiquark can annihilate, leading to the emission of two real photons (\(\gamma_1\gamma_2\)) as in Fig. 3(a), two virtual photons (\(\gamma_1^*\gamma_2^*\)) or two dilepton (\(e^+e^-\)) pairs as in Fig. 3(b), or a
single ($e^+e^-$) pair as in Fig. 3(c). We can make an order of magnitude estimate on the decay width of X17 into two photons as depicted in Fig. 3(a). From Eq. (89.3) of [22], we have for $X_{17} \rightarrow \gamma \gamma$,

$$\Gamma(X_{17} \rightarrow \gamma \gamma) = \frac{1}{2} \left[ \left( \frac{1}{3} \right)^2 + \left( \frac{2}{3} \right)^2 \right]^2 \frac{4\pi \alpha_{\text{QED}}^2}{M^2} |\psi(0)|^2/\pi R^2$$

where $\psi(0)$ is the wave function at the origin. The wave function at the origin can be estimated from the size of the quark-antiquark model, $|\psi(0)|^2 \sim 1/\pi R^2 L_z$, where $R_T \sim 0.4$ fm [12] and the longitudinal length $L_z \sim 7.5$ fm as estimated from Table 2 for the lowest qedmeson state in Ref. [13]. The X17 with a mass of 17 MeV, $\Gamma(X_{17} \rightarrow \gamma \gamma) \sim 0.4$ MeV.

From the total width and the branching ratio into $e^+e^-$ in ATOMKI measurements [12], the X17 width $\Gamma(X_{17} \rightarrow e^+e^-)$ can be estimated to be 4.2 eV from $^4$He decay and 0.828 eV from $^8$Be decay. The knowledge of the approximate widths will make possible future searches for the qedmesons.

In high-energy heavy-ion collisions at RHIC and LHC, one expects copious production of $q\bar{q}$ pairs either from the multiple collision process or from the coalescence of quarks and antiquarks in the confinement-to-deconfinement phase transitions. Among the produced $q\bar{q}$ pairs, there will be some pairs whose invariant masses match the qedmeson eigenenergies to lead to the production of qedmesons. For these produced qedmesons, the decay into two virtual photons via Fig. 3(b) offers an interesting tool for the search of the anomalous particles. Specifically, a decay into two virtual photons involves the measurement of the momenta of four final leptons which requires a high degree of correlation. As a consequence, the experimental noises of chance coincidences may be significantly reduced.

One can construct the sum and the difference of the invariant momenta square of the virtual photon 4-momenta, $P = \sqrt{(p_{\gamma_1} + p_{\gamma_2})^2}$, and $Q = \sqrt{-(p_{\gamma_1} - p_{\gamma_2})^2}$. The virtual diphoton pair distribution $dN(P,Q)/dP dQ$ at RHIC and LHC will provide useful information to search for the qedmesons.

5 Conclusions and Discussions

The observations of the X17 particle, the E38 particle, and the anomalous soft photons raise many interesting questions on the nature of these anomalous particles. While most theoretical discussions center on the elementary particle possibilities [10], we examine here the description of these anomalous particles as composite states of a quark and an antiquark interacting in compact QED. We propose a model of the production and the confinement of a quark and an antiquark in a QED meson by combining Polyakov’s transverse confinement of opposite electric charges in compact QED in (2+1)D and Schwinger’s longitudinal confinement in QED in (1+1)D. The important ingredients are (i) the self-interactions of the transverse photons in compact QED that confine the gauge fields and the opposite electric charges transversely in (2+1)D [13], (ii) the stretching of the (2+1)D with incipient longitudinal separation to come to the longitudinal flux tube configuration in a 3D yo-yo motion, (iii) the idealization of the longitudinal flux tube of the stretch (2+1)D configuration as a string in (1+1)D and the light quarks as massless, and finally (iv) Schwinger’s solution of longitudinal confinement of massless quarks in QED (1+1)D, resulting in a bound and confined $qq$ as a composite qedmeson state. The quark and the antiquark in a qedmeson are essentially electric charge monopoles and Polyakov’s magnetic monopoles in dynamical motion. If this picture of a $q$ and a $\bar{q}$ interacting in compact QED interactions is correct, it will imply that a quark and an antiquark obey QED laws that differ from those for an electron and a positron.

It will be of great interest to study in future lattice gauge calculations the problem of quark confinement and $qq$ bound states in compact QED for quarks with different color and flavors in the stretch (2+1)D configuration with the proper quantization and dynamical light quarks.

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