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COLOR-SINGLET AND COLOR-OCTET $q\bar{q}$ QUARK MATTERS [1,2]

*Quarks and antiquarks carry color and electric charges and belong to the color-triplet **3** group and the color-antitriplet $\bar{\mathbf{3}}$ group respectively. The product groups of **3** and $\bar{\mathbf{3}}$ consist of the color-singlet **1** and the color-octet **8** subgroups. Therefore, quarks and antiquarks combine to form color-singlet $[q\bar{q}]^1$ quark matter and color-octet $[q\bar{q}]^8$ quark matter. The color-octet quark matter corresponds to the conventional understanding of $q\bar{q}$ quark matter whereas the color-singlet quark matter remains largely unexplored and is proposed here for investigation. The color-singlet quark matter with two flavors can be separated into charged and neutral color-singlet quark matters. In the neutral color-singlet quark matter, the quark and the antiquark interacting only via the QED interaction may form stable and confined colorless QED mesons non-perturbatively at about 17 MeV and 38 MeV (PRC81,064903(2010) and JHEP(2020(8), 165)). It is proposed that the possible existence of such QED mesons may be a signature of the neutral color-singlet quark matter at $T = 0$. The observations of the anomalous soft photons at CERN, and the anomalous bosons with masses of about 17 at ATOMKI, DUBNA, and HUS, and about 38 MeV at DUBNA, provide promising experimental indications for the existence of such QED mesons, pending further confirmations.*

Keywords: QED mesons, color-singlet and color-octet $q\bar{q}$ quark matter.

1. Introduction

It is fitting that we dedicate the Proceedings of this conference to the memory of Prof. Vászló Jenkovszky, not only because he was one of the founders of this series of conferences, but also because of his many important contributions to high energy physics and his promotion of friendship among physicists of all nations. He firmly believed that contacts and collaborations among physicists of different nations would lead to better understanding among peoples of all countries, and would promote the development of peace as well as science and technology. He will be well remembered by all those who knew him.

In the current state of knowledge, the material and the interaction in the conventional "quark matter" are generally considered to consist of quarks interacting predominantly via the non-Abelian SU(3) QCD interaction, with the Abelian U(1) QED interaction as a small perturbation. As a function of temperature T, the manifestation of the quark matter in different phases has been well studied [1–3]. The extension of the study of quark matter to other unexplored color degrees of freedom in conjunction with the nonperturbative inclusion of the U(1) QED interaction will bring us to previously uncharted frontiers.

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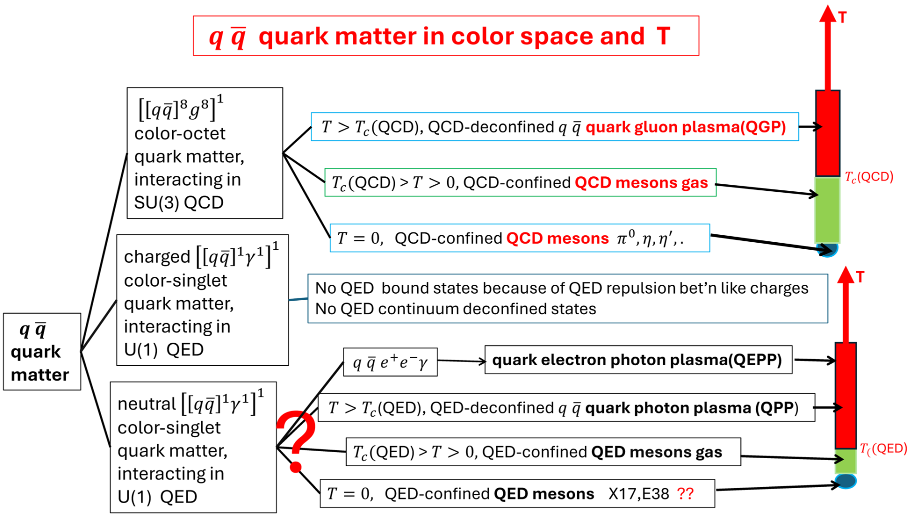

Fig. 1. The classification of the $q\bar{q}$ quark matter with two light flavors in color space, temperature T, and possible phases. The large question mark points to new and unexplored physics frontiers worthy of further exploration

the color-antitriplet $\bar{\mathbf{3}}$ group respectively. From the group theoretical considerations, we have $\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$. That is, the direct product of the $\mathbf{3}$ group and the $\bar{\mathbf{3}}$ group consists of the color-singlet subgroup $\mathbf{1}$ and the color-octet subgroup $\mathbf{8}$. Therefore, quarks and antiquarks combine to form the color-singlet $[q\bar{q}]^1$ quark matter and the color-octet $[q\bar{q}]^8$ quark matter, where the superscripts denote color-multiplet indeces.

By the principle of the colorless nature of observable entities, observable $q\bar{q}$ quark matter complexes must be colorless color-singlet entities. Consequently, to form color-singlet states of these complexes in their lowest-energy regions at $T = 0$, the color-octet quark matter must first interact via the color-octet SU(3) QCD interaction non-perturbatively to form QCD-confined colorless $[[q\bar{q}]^8 g^8]^1$ complexes. Additional QED interaction in the complexes can then be included either perturbatively or nonperturbatively, and such an additive inclusion does not change the colorless nature nor the confinement property of these colorless complexes. We therefore recognize the $q\bar{q}$ color-octet quark matter as corresponding to the $q\bar{q}$ quark matter conventionally envisaged in the current state of knowledge.

On the other hand, the color-singlet quark matter remains unexplored. We wish to study theoretically colorless physical complexes composed of such interacting quark matter at $T = 0$ as the doorway states for future exploration of the different phases of the neutral color-singlet quark matter at higher temperatures. To form color-singlet complexes of such quark matter in the lowest-energy region at $T = 0$, the color-singlet quark matter must interact exclusively via the color-singlet U(1) QED interaction. Inclusion of the QCD interaction in the color-singlet quark matter would change the colorless nature of these color-singlet complexes, or place them to much higher-energy excited states such as the $[[q\bar{q}]^1[gg]^1]^1$ states and the glueball states. The color-singlet quark matter interacting only via the Abelian U(1) QED interaction brings us to a new sector of the $q\bar{q}$ quark matter in uncharted territories.

We focus our attention mainly on $q\bar{q}$ quark matter with two light flavors. We assume isospin symmetry so that I and I_z are good quantum numbers. In this sector, the color-singlet $q\bar{q}$ quark matter can be separated into charged color-singlet quark matter with $I = 1$ and $I_z = \pm 1$ and neutral color-singlet quark matter with $I_z = 0$ and $I = 0,\ 1$ as depicted in Fig. 1. We shall also examine the qqq quark matter, including baryons and the QED neutron in Section 5.

Charged color-singlet quark matter with $I = 1$ and $I_z = \pm 1$ involves $|u\bar{d}\rangle$ and $|d\bar{u}\rangle$ states with the quark and the antiquark possessing electric charges of the same sign. It does not possess stable $q\bar{q}$ bound states in the U(1) QED interaction because of the repulsion between the quark and the antiquark with electric charges of the same sign. Furthermore, as isolated quarks do not exist, the charged color-singlet quark matter does not possess QED continuum unbound $q\bar{q}$ states. Consequently, below the pion mass threshold, charged color-singlet quark matter does not leave remarkable signatures of its existence at $T = 0$. Above the pion mass threshold, the strongly attractive QCD interaction in the quark matter dominates the confinement dynamics leading to charged QCD meson states in which the weaker repulsive QED interaction provides only a perturbative correction to the QCD meson energy levels.

On the other hand, neutral color-singlet quark matter with $I_z = 0, I = 0, 1$ involves a linear combination of $|u\bar{u}\rangle$ and $|d\bar{d}\rangle$ states with the quark and the antiquark possessing electric charges of opposite signs and may form stable and confined states at $T = 0$ because of the attractive QED interaction between the quark and the antiquark and the Schwinger confinement mechanism. The QED-confined $q\bar{q}$ composite particles in neutral color-singlet quark matter at $T = 0$ can be called the QED mesons, in analogy with the QCD mesons arising from the attractive color-octet SU(3) interaction between a quark and an antiquark in QCD at $T = 0$. If QED mesons exist at $T = 0$, then, by further analogy with QCD, there will likely be a critical temperature T_c(QED) below which an assembly of neutral color-singlet $q\bar{q}$ quark matter would exist as a QED meson gas. Above T_c(QED), the color-singlet quark matter would likely consist of deconfined quarks, antiquarks, and photons in a quark photon plasma. At a higher temperature, when the photons split into electron-positron pairs, the neutral color-singlet quark matter may exist as a quark electron photon plasma. The classification of quark matter in color space, temperature T, and possible phases is depicted in Fig. 1.

Previously, QED mesons consisting of q and $\bar{q}$ interacting non-perturbatively only in QED were predicted to have masses of about 17 and 38 MeV [4, 5]. They were proposed as the parent particles of the anomalous soft photons observed at CERN [6–15]. Anomalous neutral bosons with masses at about 17 and about 38 MeV observed at ATOMKI [16–24], Dubna [25–28], and HUS [29] and were called the hypothetical X17 and E38 particles respectively. These observations provide promising experimental indications for the existence of QED mesons and support the possible existence of neutral color-singlet quark matter at $T = 0$, pending further theoretical and experimental confirmations.

We review here the theoretical and experimental evidence for QED mesons and color-singlet quark matter. We also study qqq quark matter and discuss the implications should the existence of these objects be established.

2. Confined $q\bar{q}$ States in Neutral Color-Singlet and Color-Octet Quark Matters at $T = 0$

As we explain in the Introduction, a quark and an antiquark in the neutral color-singlet quark matter must interact only via the color-singlet U(1) QED interaction in order to form stable colorless $[[q\bar{q}]^1\gamma^1]^1$ complexes at $T = 0$. We note that the Schwinger confinement mechanism [30, 31] stipulates that a massless fermion and its antiparticle interacting via the Abelian QED interaction in $(1+1)$D with a coupling constant $g_{2\text{D}}^{\text{QED}}$ will be confined as a massive boson with a mass m^{QED},

$$(m^{\text{QED}})^2 = \frac{(g_{2\text{D}}^{\text{QED}})^2}{\pi}, \tag{1}$$

for a fermion system with a single flavor.

The neutral color-singlet quark matter with two flavors possesses colorless complexes characterized by $I_z = 0, I = 0, 1$ involving a linear combination of $|u\bar{u}\rangle$ and $|d\bar{d}\rangle$ states with unlike-sign charged quarks. Upon approximating the quarks as massless, the Schwinger confinement mechanism can be applied to the color-singlet quark matter to give the masses of the $I_z = 0$, $I = 0$, 1 QED mesons in $(1+1)$D as [4, 5]

$$(m_I^{\text{QED}})^2 = \frac{(g_{2\text{D}}^{\text{QED}})^2[Q_u^{\text{QED}} + (-1)^I Q_d^{\text{QED}}]^2}{2\pi}, \tag{2}$$

where $Q_u^{\text{QED}} = 2/3$ and $Q_d^{\text{QED}} = -1/3$ are the electric charge numbers of the u and d quarks respectively.

A $q\bar{q}$ QED meson in $(1+1)$D as an open-string may represent a physical QED meson in $(3+1)$D as a flux tube if the $q\bar{q}$ open-string is the approximate compactification of a physical $q\bar{q}$ flux tube in $(3+1)$D. The central question is whether the $q\bar{q}$ QED open-string in $(1+1)$D is indeed the approximate compactification of a physical QED flux tube in $(3+1)$D. While an e^+e^- system is confined as an open-string in $(1+1)$D string, the e^+e^- system is not confined in $(3+1)$D because an electron and a positron can be isolated. Howe ver, for a $q\bar{q}$ system, a $q\bar{q}$ open-string $(1+1)$D may be an approximate representation of a $q\bar{q}$ flux tube in $(3+1)$D because an isolated quark or antiquark have never been observed in $(3+1)$D, and the principle of colorless observable entities may be at work for a quark and an antiquark in $(3+1)$D. Whatever theoretical debates there may be, the answer to the question will eventually be settled by experiments. On that score, the existence of $q\bar{q}$ QED mesons in $(3+1)$D may explain many experimental anomalies: 1) the soft photon anomaly that whenever hadrons are produced, soft photons in the form of excess e^+e^- pairs are always produced, as described in Section 3, and 2) the neutral boson anomaly at ∼17 MeV and ∼38 MeV observed at ATOMKI, Dubna, and HUS, as described in Section 4. It is therefore useful to propose the hypothesis that the $q\bar{q}$ open-string in $(1+1)$D QED for quarks and antiquarks may be the approximate compactification of a $q\bar{q}$ QED flux tube in $(3+1)$D.

A light quark and a light antiquark interacting via the QCD SU(3) interaction can be approximated within the quasi-Abelian approximation [4, 5, 33–36] as quarks interacting in the Abelian U(1) interaction with the coupling constants of QCD in $(1+1)$D, as in the Lund model description of hadrons [38]. Under the additional massless quark approximation, the Schwinger confinement mechanism can be applied to quarks in QCD to infer the mass of the QCD meson for quarks in $(1+1)$D as

$$(m^{\rm QCD})^2 = \frac{(g_{\rm 2D}^{\rm QCD})^2}{\pi}. \tag{3}$$

For massless quarks with two flavors and the assumed isospin symmetry, the masses of the $I_z = 0$, $I = 0$, 1 QED and QCD mesons in $(1+1)$D are given in Refs. [4, 5]

$$(m_I^\lambda)^2 = \frac{(g_{\rm 2D}^\lambda)^2[Q_u^\lambda + (-1)^I Q_d^\lambda]^2}{2\pi}, \ \lambda = \begin{cases} 0 \text{ for QED}, \\ 1 \text{ for QCD}, \end{cases} \tag{4}$$

where Q_q^0 and Q_q^1 are the electric and color charge numbers of the q quark, respectively.

Previously, when we compactifying a flux tube system in $(3+1)$D with cylindrical symmetry into an open string in $(1+1)$D, it was found that the longitudinal equation in $(1+1)$D contains a coupling constant $g_{\rm 2D}$ that encodes the information regarding the flux tube transverse radius R_T and the coupling constant $g_{\rm 4D}$ in $(3+1)$D as reported in Refs. [5, 32, 33, 35–37]

$$(g_{\rm 2D})^2 = \frac{1}{\pi R_T^2}(g_{\rm 4D})^2 = \frac{4\alpha_{\rm 4D}}{R_T^2}. \tag{5}$$

Thus, in $(3+1)$D, the masses of the QCD and QED $I_z = 0$, $I = 0$, 1 mesons are

$$(m_I^\lambda)^2 = \frac{4\alpha_{\rm 4D}^\lambda}{\pi R_T^2} \frac{[Q_u^\lambda + (-1)^I Q_d^\lambda]^2}{2}. \tag{6}$$

Due to the lack of quantitative information, we adopt the working hypothesis that the flux tube radius R_T is an intrinsic property of the quarks so that it is the same for both QED and QCD where $R_T \sim 0.4$ fm [39]. This hypothesis is also justified *a posteriori* as it yields anomalous soft photons and QED mesons with masses in the relevant energy region. In the QED case with $Q_u^{\rm QED} = 2/3$, $Q_d^{\rm QED} = -1/3$, and $g_{\rm 4D}^{\rm QED} = = 1/137$, we obtain from Eq. (4) $m_{I=0}^{\rm QED} = 11.4$ MeV, and $m_{I=1}^{\rm QED} = 33.6$ MeV, see Refs. [4, 5].

For QCD mesons, the mass of π^0 is zero from the Schwinger confinement mechanism and the π^0 mass receives contributions only from the quark condensate. According to the Gell–Mann–Oakes–Renner relation [40], the QCD quark condensate, $\langle\bar{\psi}\psi\rangle_{\rm QCD}$, contributes to the square of the pion quark mass. For QED mesons, there should be likewise a QED quark condensate, $\langle\bar{\psi}\psi\rangle_{\rm QED}$, contribution to the square of the QED meson mass. Since the quark condensate arises from the quark-antiquark interaction [41] and the interaction between a quark and an antiquark depends on the strength of the coupling constant $\alpha_{\rm 4D}$, it is therefore expected that the QCD and QED quark condensate contributions to the squared composite mass Δm^2 are proportional to the square of their respective coupling constants $(g_{\rm 4D}^\lambda)^2$, or $\Delta m_{\rm QED}^2/\Delta m_{\rm QCD}^2 \sim \langle\bar{\psi}\psi\rangle_{\rm QED}/\langle\bar{\psi}\psi\rangle_{\rm QCD} \sim \alpha_{\rm 4D}^{\rm QED}/\alpha_{\rm 4D}^{\rm QCD}$. The mass formula for QED mesons with two flavors and the quark condensate can be estimated to be [5]

$$(m_I^{\rm QED})^2 = = \frac{4\alpha_{\rm 4D}^{\rm QED}}{\pi R_T^2} \frac{[Q_u^{\rm QED} + (-1)^I Q_d^{\rm QED}]^2}{2} + m_\pi^2 \frac{\alpha_{\rm 4D}^{\rm QED}}{\alpha_{\rm 4D}^{\rm QCD}}, \tag{7}$$

which gives $m_{I=0}^{\rm QED} = 17.9$ MeV, $m_{I=1}^{\rm QED} = 36.4$ MeV.

In the case of QCD mesons, it is necessary to generalize the mass formula to three flavors with the inclusion of the strange quark yielding

$$m_i^2 = \frac{4\alpha_{\rm 4D}^{\rm QCD}}{\pi R_T^2} \left(\sum_{f=1}^{3} D_{if} Q_f^{\rm QCD} \right)^2 + m_\pi^2 \sum_{f=1}^{3} \frac{m_f}{m_{ud}} (D_{if})^2, \tag{8}$$

where $m_{ud} = (m_u + m_d)/2$, and the physical meson is $\Phi_i = \sum_{f=1}^{3} D_{if}\phi_f$, $\phi_1 = |u\bar{u}\rangle, \phi_2 = |d\bar{d}\rangle, \phi_3 = |s\bar{s}\rangle$. With $Q_u^{\rm QCD} = Q_d^{\rm QCD} = 1$, and $g_{\rm 4D}^{\rm QCD} = 0.68$ MeV, the above mass formula yields $m_\eta = 498.4$ MeV, and $m_{\eta'} = 948.2$ MeV, which are in approximate agreement with experimental values [5].

To search for the signature of the neutral color-singlet quark matter at $T = 0$, the objective is to find the QED meson states with these masses in hadron collisions and $e^+ - e^-$ annihilations where $q\bar{q}$ pairs may be produced. These bosons are expected to decay into $e^+ - e^-$ or $\gamma\gamma$ pairs [5, 33, 35–37].

3. Observations of Anomalous Soft Photons at CERN and the DELPHI Anomaly

Experimentally, there have been numerous observations of excess e^+e^- pairs at CERN, referred to as "anomalous soft photons", whenever hadrons were produced in high-energy K^+p [7, 8], π^+p [8], π^-p [9–11], pp collisions [12], and e^+e^- annihilations [6, 13–15]. Specifically, in the DELPHI exclusive measurements in the decay of Z^0 in e^+e^- annihilations, the excess e^+e^- pairs were observed to be produced proportionally to the production of hadrons (mostly mesons) [6, 15] (see Fig. 2, *b*), whereas they were not produced in the absence of hadrons [14]. The transverse momenta of the excess e^+e^- pairs lay in the range from a few MeV/c to many tens of MeV/c, corresponding to a mass scale of the anomalous soft photons in the range from a few MeV to several tens of MeV.

Owing to the simultaneous and correlated production alongside hadrons, a parent particle of the anomalous soft photons is likely to contain elements of the hadron sector, such as a light quark and a light antiquark. In comparison with the QCD interaction, the Schwinger mechanism for massless quarks in $(1+1)$D QED interactions will bring the quantized mass of a $q\bar{q}$ pair in Eq. (1) to the mass range of the anomalous soft photons of several tens of MeV. It was therefore proposed in [4] that a quark and an antiquark in a $q\bar{q}$ system interacting via the QED interaction might lead to new open string bound states (QED-meson states) with a mass of many tens of MeV. These QED mesons might be produced simultaneously with the QCD mesons in the string fragmentation process in high-energy collisions [6–15], and the excess e^+e^- pairs might arise from the decays of these QED mesons. Theoretical calculations based on

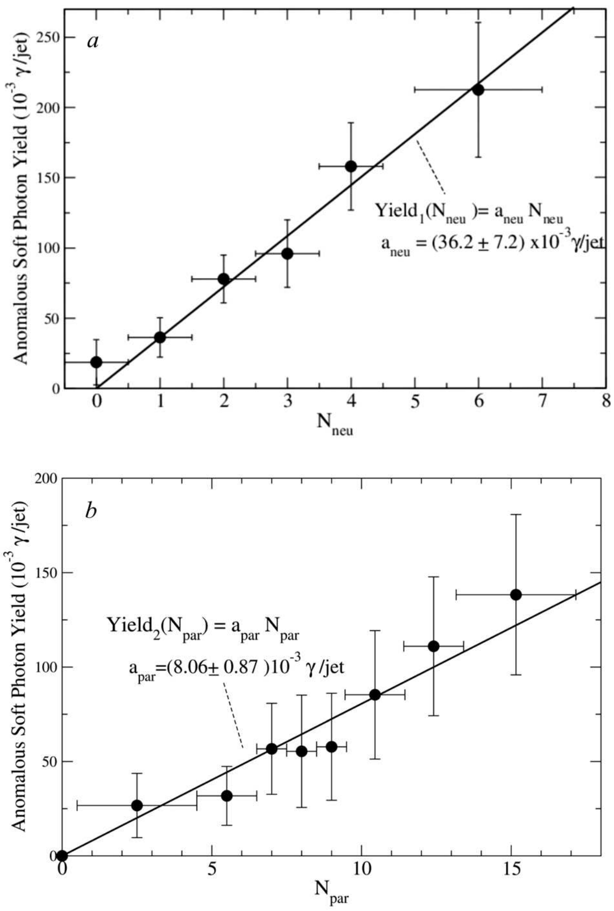

Fig. 2. The anomalous soft photon yield in the e^+e^- annihilation at Z^0 energy in DELPHI measurements at CERN [15]. In Fig. 2, *a*, (Yield$_1$) is the yield as a function of the number of neutral particles, $N_{\rm neu}$, inclusive of different number of charged particles, $N_{\rm ch}$. In Fig. 2, *b*, (Yield$_2$) is the yield as a function of $N_{\rm par} = N_{\rm neu} + N_{\rm ch}$, the total number of neutral and charged particles

such an open-string model provided a good description of the p_T distribution and the mass region of the anomalous soft photons [4, 5].

There is a perplexing DELPHI anomalous soft photon anomaly that warrants special attention. In the e^+e^- annihilation at the Z^0 energy, the production of the anomalous soft photons was found to be more probable in conjunction with the production of neutral hadrons than with charged hadrons, in contrast to the common intuitive notion that electromagnetic radiation (such as photons) is more likely to be associated with charged particle production than with neutral particle production. The yield $y_{\rm asp}$ of the anomalous soft photons is found to be related to the number of produced charged hadrons $N_{\rm ch}$ and the number of produced neutral hadrons $N_{\rm neu}$ by [15]

$$y_{\rm asp} = a_1 N_{\rm ch} + a_2 N_{\rm neu}, \quad (9)$$

where $a_1 = dy_{\rm asp}/dN_{\rm ch} = (6.9{\pm}1.8{\pm}1.8){\times}10^{-3}\ \gamma/{\rm jet}$ and $a_2 = dy_{\rm asp}/dN_{\rm neu} = (37.7{\pm}3.0{\pm}3.6){\times}10^{-3}\ \gamma/{\rm jet}$, and $dy_{\rm asp}/dN_{\rm neu} \gg dy_{\rm asp}/dN_{\rm ch}$ [15]. Similarly, Fig. 2, *a* gives $dy_{\rm asp}/dN_{\rm neu} = (36.2{\pm}7.2){\times}10^{-3}\ \gamma/{\rm jet}$ and Fig. 2, *b* gives $dy_{\rm asp}/dN_{\rm par} = (10.0 \pm 0.87)\times \times 10^{-3}\ \gamma/{\rm jet}$. The Schwinger pair production mechanism [4] and dipole radiation [15] were suggested as possible explanations for such an unusual DELPHI anomaly. However, in view of the different properties of the neutral and charged color-singlet quark matter as presented in Eq. (9) and the Introduction, a better alternative explanation may be more appropriate.

We envisage that the dynamics of the quark matter at $T = 0$ can be described as the space-time variation of the quark current and the gauge field at each space-time arena as in a quantum fluid. The dynamics of the mesons are characterized by stable, localized, collective, and periodic space-time variations of the quark current $j^\mu(x,t)$ and the gauge field $A^\mu(x,t)$ [4,5,35–37]. The QCD mesons π^0, η^0,... are excitation quanta of the color-octet quark fluid at $T = 0$. The neutral color-singlet quark matter at $T = 0$ is distinguished by having localized stable and confined excitation quanta of the fluid in the form of QED $q\bar q$ mesons, whereas the charged color-singlet quark matter does not possess stable QED excitation quanta at $T = 0$.

Hence, in situations in which the quark fluid is excited by an external disturbance such as the production of a neutral or a charged $q\bar q$ pair in string fragmentation process, both the neutral color-octet and neutral color-singlet quark matter can be excited, leading to the production of QCD and/or QED $q\bar q$ mesons when a neutral $q\bar q$ pair is produced. When a charged $q\bar q$ pair is produced in the string fragmentation process, the charged color-octet quark matter excitation can lead to the production of stable QCD $q\bar q$ mesons but the charged color-singlet quark matter neither possesses nor produces stable excitation quanta at $T = 0$. However, at higher temperatures, $T \neq 0$, the charged color-singlet quark matter may contain a small amount of neutral QED meson gas in a thermal environment. Neutral QED mesons in thermal equilibrium may be produced in conjunction with the production of charged QCD mesons at $T \neq 0$. Consequently, neutral QED mesons, the precursors of the anomalous soft photons, are more likely to be produced in association with neutral QCD mesons than with charged QCD mesons. It will be of great interest to study further whether the anomalous soft photon production preference for neutral QCD mesons in the DELPHI anomaly may be used to differentiate between the properties of neutral and charged color-singlet quark matters at different temperatures.

4. Observations of Anomalous Bosons with Masses of About 17 and 38 MeV

4.1. ATOMKI observations of X17

Since 2016, the ATOMKI Collaboration has been observing the occurrence of a neutral boson, the hypothetical X17, with a mass of about 17 MeV, by studying the e^+e^- spectrum in the de-excitation of the excited alpha-conjugate nuclei ^{4}He*, ^{8}Be*, ^{12}C* at various energies in low energy proton-fusion experiments [16, 19, 23, 24]. A summary and update of the ATOMKI results were presented [20, 24] and the confirmation of the ATOMKI data for the $p + {}^7$Be reaction by Hanoi University of Science (HUS) was reported [29]. The signature for the X17 particle consists of a resonance structure in the invariant mass of the emitted e^+e^- pair. Such a signature provides a unique identification of a particle. Because e^+e^- pairs are also produced in the internal pair conversion of the photon from the radiative decay of the compound nucleus, it is necessary to subtract contributions from such a process and from random and cosmic-ray backgrounds.

The ATOMKI experiments consist of low-energy proton fusion of nucleus A (the proton) and nucleus B (the target nucleus) to produce an α-conjugate nucleus C^* with the subsequent e^+e^- de-excitation of the C^* nucleus to the ground state $C_{\rm gs}$ or an excited state $C_{\rm f}$ in the reaction

$$A + B \to C^* \xrightarrow{\gamma} C_{\rm gs} \text{ or } C_{\rm f}, \quad (10)$$

which is followed by

$$\begin{aligned} &\gamma \xrightarrow{\text{internal conversion}} e^+ + e^-, \\ &\text{and if } C^* \xrightarrow{\gamma} C_{\rm f}, \text{ then } C_{\rm f} \to C_{\rm gs} + \gamma_{\rm f}. \end{aligned} \quad (11)$$

The internal pair conversion process has a characteristic $dN/d\Omega_{\theta_{e^+e^-}}$ distribution of the opening angle between e^+ and e^- that depends on the multipolarity of the $C^* \xrightarrow{\gamma} C_{\rm gs}$ or $C_{\rm f}$ transition [42]. It is a relatively smooth $dN/d\Omega_{\theta_{e^+e^-}}$ distribution in the CM system in which C^* is at rest.

In the presence of such an e^+e^- internal pair conversion background, the ATOMKI Collaboration searches for an unknown neutral boson X that may be emitted by C^* in its de-excitation,

$$A + B \to C^* \xrightarrow{X} C_{\rm gs} \text{ or } C_{\rm f}, \tag{12}$$

which is followed by

$$X \to e^+ + e^-,$$
$$\text{and if } \; C^* \xrightarrow{X} C_{\rm f}, \text{ then } C_{\rm f} \to C_{\rm gs} + \gamma_{\rm f}. \tag{13}$$

The decay of the X particle into e^+ and e^- gives rise to an e^+e^- excess above the internal pair conversion e^+e^- background, which serves as the signal for the neutral X boson.

In the C^* center-of-mass system, the decay of an unknown X particle with a mass m_X into e^+ and e^- will lead to an e^+-e^- energy sum $E_{e^+e^-}$ distribution,

$$dN/dE_{e^+e^-} = \delta(E_{e^+e^-} - K - m_X), \tag{14}$$

and an e^+-e^- opening angle $\theta_{e^+e^-}$ distribution

$$\frac{dP}{d\Omega_{\theta_{e^+e^-}}} = \frac{1}{4\pi}\frac{1}{\gamma^2\beta(1-\cos\theta_{e^+e^-})^{3/2}} \times$$
$$\times \frac{1}{\sqrt{-1+2\beta^2-\cos\theta_{e^+e^-}}}, \tag{15}$$

as obtained by McDonald [43] in a similar case for the π^0 decay into two photons. The minimum opening angle $\theta_{e^+e^-}(\text{min})$ in the observer's system is given by

$$\cos[\theta_{e^+e^-}(\text{min})] = -1 + 2\beta^2, \tag{16}$$

as was obtained earlier by McDonald [43], Barducci and Toni [44].

The quantity K in Eq. (14) is the sum of the kinetic energy of the X boson and the kinetic energy of its emission partner $C_{\rm f}$ in the CM system, given explicitly by

$$K = E_x - [M(C_{\rm f}) - M(C_{\rm gs})] - m_X, \tag{17}$$

$$E_x = \frac{AB}{A+B}E_A^{\rm lab} + Q_{\rm gs}, \tag{18}$$

$$Q_{\rm gs} = M(A) + M(B) - M(C_{\rm gs}), \tag{19}$$

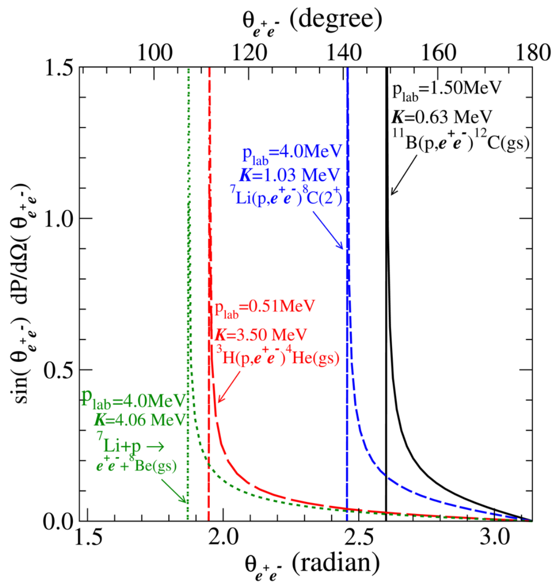

Fig. 3. The e^+e^- opening angle distribution, $\sin(\theta_{e^+e^-}) \times \times dP/d\Omega_{\theta_{e^+e^-}}$, for different proton $E_p^{\rm lab}$, different kinetic energies K of the X17 boson, and different reaction initial participants and final compound nucleus states, for $m_{X17} = 16.7$ MeV

where E_x is the excitation energy of the compound nucleus C^* relative to its ground state $C_{\rm gs}$, $M(A)$, $M(B)$, $M(C)$, and $M(C_{\rm f})$ are the masses of A, B, C, and $C_{\rm f}$, respectively, m_X is the mass of the X boson, and $Q_{\rm gs}$ is the Q value for $AB \to C_{\rm gs}$. As $M(C_{\rm f}) \gg \gg m_X$, K is essentially the kinetic energy of X in the C^* CM system. The quantity β^2 is related to K by

$$\beta^2 = 1 - \frac{1}{(1+K/m_X)^2} =$$
$$= \left(\frac{2K}{m_X} + \frac{K^2}{m_X^2}\right)\bigg/\left(1 + \frac{2K}{m_X} + \frac{K^2}{m_X^2}\right). \tag{20}$$

The opening angle distribution for a few cases in the ATOMKI experiment for the emission of the X particle is shown in Fig. 3.

At the minimum opening angle $\theta_{e^+e^-}(\text{min})$, the denominator on the right-hand side of Eq. (15) goes to zero, and the opening angle distribution $dP/d\Omega_{\theta_{e^+e^-}}$ diverges to infinity and gives rise to the so-called "Jacobian peak" [3] in Fig. 3.

For an optimal detection of the X17 signals, the ATOMKI Collaboration found it necessary to focus

[3] The author is indebted to Dr. T. Awes for pointing out the "Jacobian Peak" name for such a peak.

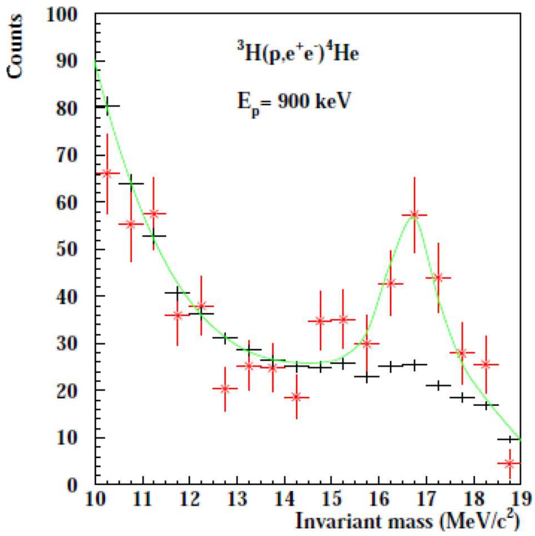

Fig. 4. The invariant mass distribution of the emitted e^+ and e^- in the de-excitation of the compound nucleus ^{4}He* state at 20.49 MeV in the ^{3}H$(p, e^+e^-)^4$He$_{gs}$ reaction at $E_p^{\rm lab} =$ = 0.9 MeV as given in [17]. Red data points correspond to the data in the signal region, $19.5 < E_{e^+e^-} < 22.0$ MeV, and black points correspond to the data in the background region, $5 < E_{e^+e^-} < 19.0$ MeV

on certain regions of the phase space with strong signals so as to enhance the observation probability. For example, in the collision of p with ^{3}H at 0.9 MeV, the ATOMKI Collaboration found that the correlation angle $\theta_{e^+e^-}$ of 120° was optimal for a large signal (see Fig. 3). At such an angle, the energy sum of the e^+ and e^-, $E_{e^+e^-}(\text{sum}) = E_{e^+} + E_{e^-}$, showed a peak structure at around 20.6 MeV as shown in Fig. 1 of [19]. Two spectra were constructed for the energy sum $E_{e^+e^-}(\text{sum})$, one at $\theta_{e^+e^-} = 120°$ and another at 60° where no X17 signal was expected. The energy sum spectrum in the lower panel of Fig. 1 of [19] was obtained by subtracting the latter from the former, after proper normalization. In the signal region of $19.5 \le E_{e^+e^-} \le 22.0$ MeV and the background region of $5 \le E_{e+e^-} < 19$ MeV, the invariant mass spectrum of the emitted e^+ and e^- showed a resonance structure at ~ 17 MeV as shown in Fig. 4.

In the ATOMKI X17 emission model, the nature of the X17 and the coupling between the emitting excited alpha conjugate nucleus and the emitted X17 particle are left unspecified. Among many possibilities, the X17 was suggested as a possible carrier of a fifth force [45–47] and has generated a great deal of interest [21]. It could also be the isoscalar QED meson, which has a predicted mass of ∼17 MeV and can decay into e^+ and e^- [4, 5]. The nature of the particle can be determined only by future experiments.

Among many proposed models for the X17 particle, there is one that involves a QED explanation presented by Varró [48] who suggests that the X17 particle may be a dressed radiation excitations of photons that gain a non-zero rest mass through their own A^μ-field self-interaction and their interaction with a proton while the E38 may be a similar dressed radiation excitations of photons that gain a non-zero rest mass through their interaction with a neutron. It will be of interest to study in future work whether the dressed self-interacting photon of Ref. [48] may be related to the $A^\mu \to j^\mu \to A^\mu \to j^\mu$... loop (the AjA nonlinearity) that will lead to photon A^μ self-interaction and QED mesons involving massless quarks of the Schwinger confinement mechanism, see Refs. [1, 4, 5, 33, 35].

4.2. $\theta_{e^+e^-}$ (min) systematics

The successful analysis of the total e^+e^- opening angle distribution is subject to uncertainties in the e^+e^- background contributions from internal pair conversion [49, 50]. It is useful to make a supplementary test of the X17 signals from another robust perspective. Specifically, because of the large difference in the shapes of the smooth opening angle distribution from the internal pair conversion background and the sharp Jacobian peak opening angle distribution from the X17 decay products, the onset of the additional X17 decay product contributions can be obtained with a lower degree of uncertainty. As shown in Fig. 3, the occurrence of the X17 particle is signaled by a sudden rise in the opening angle distribution as a function of the opening angle because of the occurrence of the Jacobian peak, and correspondingly by a sudden change in the slope of the total opening angle distribution at $\theta_{e^+e^-}(\text{min})$.

From each of the experimental ATOMKI reactions in [16–24], and the HUS reaction in [29], we extract the $\theta_{e^+e^-}(\text{min})$ value as the midpoint between a sudden jump in the first derivative of the angular distribution of $\theta_{e^+e^-}$ at the onset of the anomaly.

We compare in Fig. 5 the experimental $\theta_{e^+e^-}(\text{min})$ data as a function of K with the theoretical predictions of the X17 emission model, obtained from Eqs. (16) and (20). All final nucleus states $C_{\rm f}$ are implicitly ground states, unless specified explicitly for the case of the ^{7}Li$(p, e^+e^-)^8$Be(2^+) reaction at $E_p^{\rm lab} = 4$ MeV. One observes that there is reasonable agreement between the theoretical curve and the data points in Fig. 5 for all cases of collision energies, initial colliding nuclei, and final compound nucleus states, indicating the approximate validity of the ATOMKI X17 emission model [16]. Previous analyses of the X17 decay by Feng *et al.* [47] and by Barducci and Toni [44] using earlier experimental data also support the validity of the ATOMKI X17 emission model [16].

Recently, ATOMKI reported the observation of the emission of the X17 particle in the de-excitation of the compound nucleus ^{8}Be* to the excited ^{8}Be$(2^+$, 3.03 MeV) state [24]. We can test the extended ATOMKI X17 emission model [24] which proposes the emission of the X17 particle not only in the de-excitation of the produced compound nucleus to the ground state, but also to an excited state of the compound nucleus [16]. In Fig. 5, the experimental minimum opening angle $\theta_{e^+e^-}$(min) for this de-excitation to the excited 2^+ state is shown as the solid square data point. This data point follows the same systematics as other reaction data points for de-excitation down to the ground states. The ATOMKI X17 emission model is therefore shown to be valid also for the de-excitation of the compound nucleus C^* to an excited state $C_{\rm f}$ of the compound nucleus.

We would like to remark that, although the systematics of the experimental minimum opening angle $\theta_{e^+e^-}$(min) are in general agreement with the X17 emission model, there is nevertheless a notable but small difference between the data points for ^{4}He and those following the systematics for ^{8}Be and ^{12}C in Fig. 5. It is well known that ^{4}He is a spherical nucleus, while ^{8}Be and ^{12}C are strongly deformed prolate and oblate nuclei, respectively. It will be of great interest to investigate theoretically whether minor difference in $\theta_{e^+e^-}$(min) systematics may arise from the final state interaction of very deformed ^{8}Be and ^{12}C nuclei that modify the opening angles between e^+ and e^-.

4.3. The HUS observation of X17 with a new e^+e^- spectrometer

The ATOMKI e^+e^- spectrometer had five arms in 2016 [16]. The spectrometer was subsequently improved to acquire an additional sixth arm. Taking advantage of the occurrence of the optimal opening angles in the decay of the hypothetical X17 par-

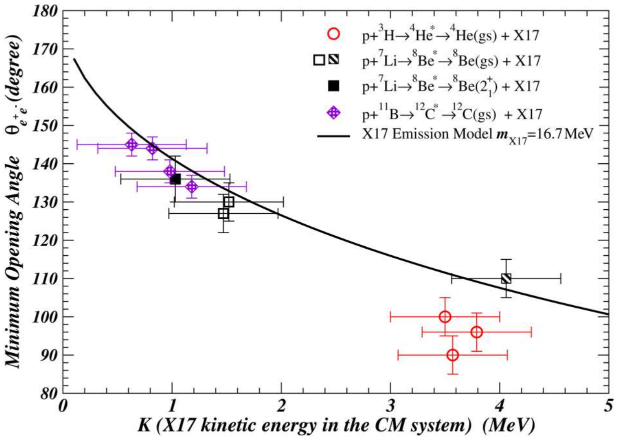

Fig. 5. Comparison of the experimental data for the minimum opening angle $\theta_{e^+e^-}$(min) as a function of the X17 kinetic energy K from ATOMKI [16,19,23,24] and HUS [29] for different collision energies, targets, and final states. The X17 emission model envisages the fusion of the incident proton p with the target nucleus B forming a compound nucleus C^*, which subsequently de-excites to the final state $C_{\rm f}$ with the simultaneous emission of the X17 particle. The subsequent decay of the X17 particle into e^+ and e^- then gives the angle $\theta_{e^+e^-}$ between e^+ and e^-. The curves give the theoretical predictions of $\theta_{e^+e^-}$(min) as a function of the X17 kinetic energy K

ticle, Tran *et al.* [29], at Hanoi University of Science, in collaboration with ATOMKI experimentalists, built a new two-arm e^+e^- spectrometer to check the ATOMKI ^{8}Be anomaly. The HUS spectrometer consists of only two arms making an angle of 140^o with respect to each other. It bases its design on the theoretical and experimental estimates that when the proton beam is at $E_{\rm lab}$ =1.04 MeV, the opening angle $\theta_{e^+e^-}$ at 140^o will be optimal for the detection of both e^+ and e^-.

In the HUS measurement, the experimental opening angle distribution data points are shown as solid circles in Fig. 6. The background distribution arising from the sum of E1 and M1 internal pair conversion transitions is shown as the solid curve in Fig. 6. There is an e^+e^- excess of event counts as the experimental opening angle distribution exhibits a deviation above the solid curve of the internal pair conversion background. The difference between the experimental e^+e^- data counts and the background distributions are the X17 signals which are shown as solid square data point in Fig. 6. The experimental X17 signal can be described adequately by the opening angle distribution arising from the decay of the X17

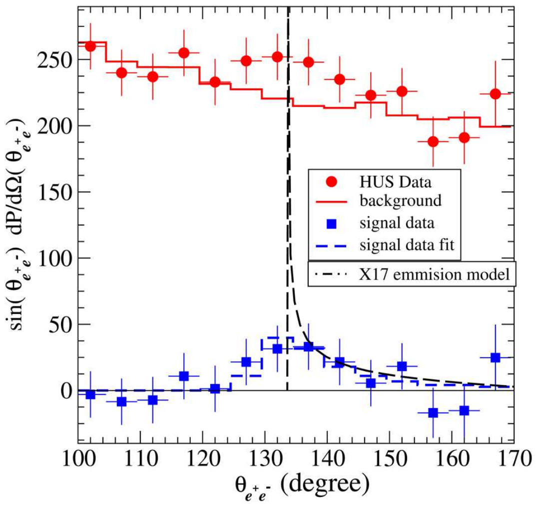

Fig. 6. Experimental $\sin(\theta_{e^+e^-})dN/d\Omega_{\theta_{e^+e^-}}$ data from Hanoi University of Science (HUS) in ^{7}Li$(p, e^+e^-)^8$Be$_{\rm gs}$ reactions at $E_p = 1.04$ MeV as given in [29]. The solid circles give the opening angle distribution data for e^+ and e^- and the solid curve gives the background opening angle distribution. The data–background difference is given by the solid square data points and the dashed curve is the HUS fit to the signal data [29]. The dash-dot curve with a Jacobian peak is the theoretical opening angle distribution from the X17 emission model calculated with Eq. (15)

particle with a mass of 16.7 MeV, when the uncertainties in the event number fluctuations and in the opening angle measurements are taken into account, as presented by HUS and shown as the dashed curve in Fig. 6 [29].

The successful observation of the X17 signal with an optimally-designed e^+e^- spectrometer with only two arms (in lieu of ATOMKI's five or six arms) by Tran *et al.* [29] is a notable indication of the validity of the X17 emission model and the possible existence of the X17 particle. The statistics of the observed opening angle distribution could be improved with a longer experimental running period to provide stronger support for the existence of the X17 particle.

There are other searches for the X17 particle using different methods [21]. Recently, the PADME Collaboration searched for the X17 particle by scattering e^+ and e^- at around the resonance energy, using a positron beam to collide with electrons in a diamond target. They obtained a resonance signal at the expected energy with a statistical measure of about 2σ magnitude [51], which is not yet significant enough for a definitive confirmation. A measurement with a greater statistical significance is needed. Another MEG II experiment, originally designed to search for the $\mu^+ \to e^+\gamma$ decay, was adapted to investigate the X17 by studying the $p(^7\mathrm{Li}, e^+e^-)^8$Be reaction, with a proton beam at an energy of 1.080 MeV colliding with the ^{7}Li target, resulting in the excitation of two different resonances [52]. The sensitivity of the measurement has not yet reached the level to observe a significant signal, and limits on the branching ratios of the two resonances to X17 were set.

4.4. The Dubna observation of diphoton decays of X17 and E38

Abraamyan and collaborators at Dubna have been investigating the two-photon decay of particles to study the resonance structure of the lightest hadrons and $q\bar{q}$ states, using d and p beams of a few GeV with fixed internal C and Cu targets at the JINR Nuclotron [25–28]. Their PHONTON2 detector consists of two arms placed at 26 and 28 degrees from the beam direction, with each arm equipped with 32 lead-glass photon detectors. The photon detectors measure the energies and the emission angles of the photons, from which the invariant masses of the photon pairs can be measured. By selecting photon pairs from the same arm with small opening angles, it is possible to study neutral bosons with small invariant masses, such as those below the pion mass gap m_π. Upon the suggestion of van Beveren and Rupp [53], they search for a neutral boson resonance with a mass of 38 MeV, they reported earlier the observation of a resonance structure at a mass of ∼38 MeV [26, 27]. In a recent analysis of the diphoton spectrum (see Fig. 7) extended down to the lower invariant mass region, the Dubna Collaboration reported the observation of resonance-like structures both at ∼17 and ∼38 MeV in the same experimental set-up in which the decay of the π^0 particle into two photons was also observed, supporting earlier ATOMKI observation of the hypothetical X17 particle [25].

The observation of X17 and E38 at Dubna completes an important piece of the anomalous particle puzzle, as the isoscalar X17 and the isovector E38 come in a pair, and they are orthogonal linear combinations of the $|u\bar{u}\rangle$ and $|d\bar{d}\rangle$ components. The signals for the E38 particle are, however, quite weak. Further measurements need to be carried out to ensure that the E38 signals are genuine and not experimental artifacts.

It is worth noting that, if the two-photon decay of the X17 particle observed at Dubna is confirmed, then the two-photon decay mode will impose a constraint on the spin of the X17 particle on account of the Landau–Yang theorem [54, 55], which states that a massive boson with spin 1 cannot decay into two photons.

The agreement of the X17 and E38 masses with those from the phenomenological open-string model of $q\bar{q}$ QED mesons [4, 5] lends support to the description that a quark and an antiquark may be confined and bound as stable QED mesons interacting in the Abelian U(1) QED interaction. The confirmation of the X17 and E38 particles will therefore be of great interest.

5. The *qqq* Color-Singlet and Color-Multiplet Quark Matter

We have up to now considered only $q\bar{q}$ quark matter. Our consideration can be extended to qqq quark matter in color space. Quarks belong to the color-triplet **3** group. From group theoretical considerations, we have

$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{1} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{10}. \qquad (21)$$

That is, the direct triple product of the triplet **3** group consists of the color-singlet **1** subgroup, two color-octet **8** subgroups, and one color-decuplet **10** subgroup. Therefore, three quarks combine to form the color-singlet $[qqq]^1$ quark matter, two color-octet $[qqq]^8$ quark matter, and the color-decuplet $[qqq]^{10}$ quark matter.

By the principle of the colorless nature of observable entities, observable quark matter complexes must be colorless color-singlet entities. Consequently, the color-octet and the color-decuplet qqq quark matter must interact non-perturbatively first with the color-octet SU(3) QCD interactions to form QCD-confined colorless $[[qqq]^8 g^8]^1$ or $[[qqq]^{10} g^8]^1$ complexes. Additional QED interaction in the color-multiplet qqq quark matter can then be included either perturbatively or nonperturbatively, and such an additive inclusion does not change the colorless nature or the confinement property of these colorless complexes. We therefore recognize the qqq color-octet and color-decuplet quark matter as corresponding to the qqq quark matter as conventionally envisaged in the realm of our present knowledge.

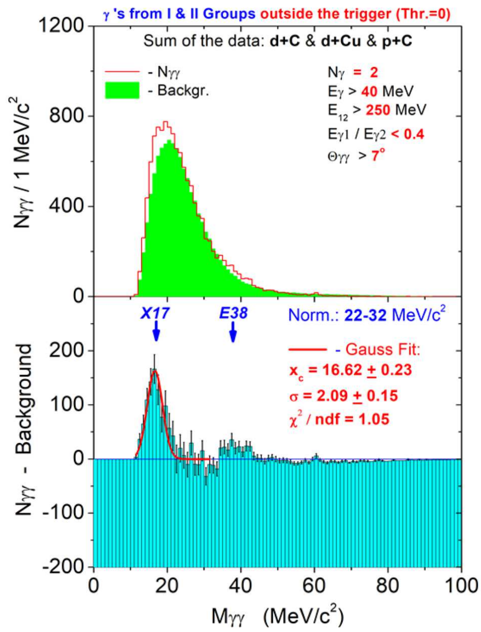

Fig. 7. The diphoton invariant mass spectra from d and p collisions with C and Cu targets at a few GeV per nucleon at the JINR Nuclotron, Dubna, as given in [25]. The solid curve in the upper panel shows the invariant mass distribution obtained by combining two photons from the same event, and the green shaded region shows the invariant mass distribution obtained by combining two photons from mixed events. Subtracting the mixed-event background from the correlated-photon signal yields the signal in the lower panel where the resonance-like structures at $\sim$17 and $\sim$38 MeV appear

On the other hand, the color-singlet qqq quark matter is unexplored and is now submitted for exploration. Quarks in the color-singlet qqq quark matter must interact only with the color-singlet U(1) QED interaction to form colorless color-singlet $[[qqq]^1\gamma]^1$ complexes in the lowest-energy region at $T = 0$. The inclusion of the SU(3) color-octet QCD interaction in the color-singlet $[qqq]^1$ quark matter will change the colorless nature of these color-singlet complexes, or would place them at much higher energy excited states, such as the $[[qqq]^1[gg]^1]^1$ states and the glueball states.

Of particular interest in the qqq color-singlet quark matter is the QED neutron composed of d, u, and d quarks [33–35]. In such a color-singlet d-u-d system with three quarks of different colors, the attractive QED interaction between the u quark and the two d quarks may overwhelm the repulsion between the two d quarks and may stabilize the QED neutron. Upon examining the QED neutron in a phenomenological three-body problem in $1 + 1$ dimensions with an effective interaction extracted from Schwinger's exact QED solution in $1 + 1$ dimensions, a phenomenological model using a variational calculation yields a stable QED neutron at 44.5 MeV [33–35]. The analogous $u{-}d{-}u$ QED proton has been found to be theoretically unstable because of the stronger QED repulsion between the two u quarks, and it does not provide either a bound state or a continuum state for the QED neutron to decay onto, by way of the weak interaction. Hence, the QED neutron may be a dark neutron and may be stable against the weak interaction. It may have a very long lifetime and may be a good candidate for dark matter. Because QED mesons and QED neutrons may arise from the coalescence of deconfined quarks during the deconfinement-to-confinement phase transition in different environments, such as in high-energy heavy-ion collisions, neutron star mergers [56], and neutron star cores [57], the search for QED bound states in various environments will be of great interest.

It is interesting to explore the possibility of a QED neutron star as a large assembly of QED neutrons. The interaction between a QED neutron and another QED neutron is through an attractive electromagnetic polarization potential at large separations and a repulsive Pauli-exclusion-type interaction at small separations. The electromagnetic interactions are quite weak. A collection of a large number of QED neutrons under their own gravitational field can be stabilized by the attractive gravitational pressure and the repulsive pressure of the degenerate QED neutron gas. If a QCD neutron star and a QED neutron star can be approximated as a polytropic gas spheres of index $n = 3$, as in the early consideration of Landau for a gravitating and degenerate fermion gas [59, 60], then, from the mathematical results of Landau, the maximum mass of a QCD or QED neutron star is inversely proportional to the square of its constituent mass. One can thus estimate the maximum mass of the QED neutron star and the maximum mass of the QCD neutron star to be approximately given by

$$\frac{M_{\max}(\text{QED neutron star})}{M_{\max}(\text{QCD neutron star})} \sim \frac{(m_{\text{neutron}}^{\text{QCD}})^2}{(m_{\text{neutron}}^{\text{QED}})^2}. \tag{22}$$

Thus, for $M_{\max}(\text{QCD neutron star}) \sim 1.6\text{–}2\ M_\odot$ [61] and $m_{\text{QED}} \sim 44.5$ MeV [33], we have

$$M_{\max}(\text{QED neutron star}) \sim 712\text{–}890\, M_\odot. \tag{23}$$

Beyond such a maximum mass, an assembly of QED neutrons will collapse into a black hole. It will be of great interest to explore whether such a QED neutron star or a black hole may exist in the Universe.

6. Implications for the Possible Existence of the QED Mesons

While the confirmation of the observations is pending, it is of interest to examine the implications of the existence of the QED mesons. If the observations of the QED mesons are indeed confirmed under further scrutiny, we expect an expansion of our present knowledge into new territories, including but not limited to the following:

1. Color-singlet quark matter may exist, with possible neutral QED mesons at $T = 0$. There may then be the QED meson gas phase at $T < T_c(\text{QED})$, quark photon plasma above $T_c(\text{QED})$, and quark electron photon plasma at still higher temperatures.

2. There may be a new family of QED-confined $q\bar{q}$ particles at $T = 0$ that are composite in nature, with additional degrees of freedom in spin-spin, spin-orbit, collective vibrations, collective rotations, molecular states, ...

3. Confinement occurs for q and $\bar{q}$ not only in QCD but also in neutral color-singlet quark matter in QED. The group of quark-antiquark gauge interaction may be a broken U(3) group with U(3) = U(1) ⊕ ⊕ SU(3).

4. Confinement may be an intrinsic property of the quarks such that quarks and antiquarks may interact with other different interactions, including weak and gravitational interactions, to form confined $q\bar{q}$ composite particles.

5. The QED interaction between a quark and an antiquark may be predominantly linear. In such a case, there may be a stable $d - u - d$ QED neutron, whereas the corresponding $u - d - u$ QED proton is unstable. The QED neutron may be a good candidate for dark matter, as discussed in Section 5.

6. The confining QED interaction between a quark and an antiquark may differ from the non-confining QED interaction between an electron and a positron because of the additional color degrees of freedom of quarks. The QED U(1) interaction between a quark and an antiquark is part of the larger, but broken, U(3) group of interactions in which U(3) = = U(1) ⊕ SU(3), whereas the QED interaction be-

tween an electron and a positron is purely a U(1) interaction. There is the question of whether the QED interaction between an electron and a positron may belong to the non-compact non-confining QED theory while the QED interaction between a quark and an antiquark belong to the confining compact QED theory.

7. Astrophysical objects consisting of a large assembly of the isoscalar QED mesons will be electron–positron emitters, gamma ray emitters, or dark black holes with no emission depending on the mass of the assembly. Such assemblies of QED mesons present themselves as good candidates for e^+e^- emitters, gamma-ray emitters, or the primordial dark matter [5].

7. Summary and Discussions

If the experimental QED mesons are confirmed, it would suggest that the proposal of quarks interacting only in QED under appropriate conditions would be a reasonable concept. While we first presented such an unusual and unfamiliar possibility as a phenomenological idea, stimulated by the Schwinger QED confinement mechanism and the observation of the anomalous soft photons [4], we may now realize that it may have a firmer and stronger foundation in the group theory and the principle of colorless observable entities. In the process, we may expand our knowledge of quark matter into the uncharted frontiers in color space.

Quarks carry color and electric charges. The direct product of the quark color-triplet group and the antiquark color-antitriplet group consists of the color-singlet subgroup and the color-octet subgroup. Therefore, quarks and antiquarks combine to form the color-singlet $q\bar{q}$ quark matter and the color-octet $q\bar{q}$ quark matter. While the color-octet $q\bar{q}$ quark matter corresponds to the $q\bar{q}$ quark matter commonly envisaged, the color-singlet $q\bar{q}$ quark matter has been unexplored until now.

In order for the color-singlet quark matter to form color-singlet, colorless complexes at $T \sim 0$, the color-singlet quark matter must interact only via the Abelian U(1) QED interaction while the color-octet quark matter must interact in the non-Abelian SU(3) QCD interaction.

Applying the Schwinger confinement mechanism to quarks with two light flavors interacting only in QED, we find stable and confined $q\bar{q}$ isoscalar state at around 12 MeV and an isovector state around 33 MeV. Including corrections due to the small quark masses with the associated quark condensates leads to the isoscalar QED meson mass at about 17 MeV and the isovector meson mass at about 38 MeV.

The observations of the anomalous soft photons, the X17 particle, and the E38 particle provide promising evidence for the possible existence of the QED mesons confined and bound non-perturbatively by the QED interaction. Their masses at ∼17 and ∼38 MeV are close to the theoretically predicted masses of isoscalar and isovector QED mesons. The occurrence of the isoscalar and isovector doublet reflects properly the two-flavor nature of the light quarks. Their decays into $\gamma\gamma$ and e^+e^- indicate their composite nature and their connection to the QED interaction. Their modes of production by low-energy proton fusion and by high-energy nuclear collisions can also be understood in terms of the production of quark–antiquark pairs by soft gluon fusion or the $(q\bar{q})$ production by string fragmentation in high-energy hadron–hadron collisions [5, 33, 37].

There remain many important questions that need to be experimentally tested and resolved. It has been conjectured all along that the precursors of the anomalous soft photons may be the QED mesons with masses of about 17 and 38 MeV [4, 5]. A direct experimental confirmation of such a conjecture for anomalous soft photons remains lacking. It will be of great interest in new studies of the anomalous soft photons [58] to search for the QED mesons. The X17 and E38 particles have been uncovered at Dubna, and a confirmation of these particles will be necessary to indicate the two-flavor nature of the light quarks. Experiments of the ATOMKI type using the p^3+H and $n+^3$He reactions may lead to stronger $X17$ signals and may lessen the strong deformation effects present in the internal pair conversion in the ^{8}Be and ^{12}C compound nuclei. New experimental measurements in search of the QED mesons will bring us forward toward the new physics frontier.

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КОЛЬОРОВО-СИНГЛЕТНА
ТА КОЛЬОРОВО-ОКТЕТНА $q\bar{q}$ КВАРКОВА МАТЕРІЯ

Кварки і антикварки несуть кольорові та електричні заряди й належать до груп колірного триплету **3** та колірного антитриплету $\bar{\mathbf{3}}$, відповідно. Добутки груп **3** та $\bar{\mathbf{3}}$ складаються з підгруп колірного синглету **1** та колірного октету **8**. Отже, кварки та антикварки об'єднуються, утворюючи кваркову матерію колірного синглету $[q\bar{q}]^1$ та кваркову матерію колірного октетну $[q\bar{q}]^8$. Кваркова матерія колірного октету відповідає загальноприйнятому розумінню кваркової матерії $q\bar{q}$ тоді як кваркова матерія колірного синглету залишається ще значною мірою недослідженою, і в даній роботі пропонується її дослідження. Кваркову матерія колірного синглету можна розділити на заряджену та нейтральну. У нейтральній кварковій матерії колірного синглету кварк і антикварк, взаємодіючи лише через КЕД-взаємодію, можуть утворювати стабільні та обмежені безколірні КЕД-мезони з масами приблизно 17 МеВ і 38 МеВ (PRC81,064903(2010) та JHEP(2020(8),165)). Висловлюється припущення, що існування таких КЕД-мезонів може бути ознакою нейтральної кваркової матерії колірного синглету при $T = 0$. Спостереження аномальних м'яких фотонів у CERN та аномальних бозонів з масою близько 17 в ATOMKI, Дубні та HUS, а також масою близько 38 МеВ у Дубні дають багатообіцяючі експериментальні докази існування таких КЕД-мезонів, що потребує подальших підтверджень.

Ключові слова: КЕД-мезони, кольорово-синглетна та кольорово-октетна $q\bar{q}$ кваркова матерія.