On the observability of free quarks near their production thresholds

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Abstract

It is proposed to search for free quarks near their production thresholds. If the current-quark masses for u, d quarks are smaller than the pion mass, \( u\bar{u} \) and \( d\bar{d} \) pairs produced below the pion pair threshold, would not have sufficient energy to hadronize and could be observable. In the case of large u,d quark masses and also for the heavy quarks, production near threshold may show hadronization probability < 1, and lead to free quarks. Searches for fractional charges in stable matter could be more promising, through irradiation of samples at energies near the quark pair production thresholds.

Keywords: deconfinement, free quark observability, near threshold,fractional charges, small quark mass.
1 Introduction

Numerous free quark searches have been conducted up to now [1],[2],[3],[4]. The results have been negative, with the exception of one experiment [3] which claimed to have observed fractional charges in stable matter, but which was contradicted by other experiments. A commonly accepted explanation for the non-observation of free quarks, is that the quarks are confined within hadrons. Evidence that this confinement conjecture is valid, was given from numerical calculations in the framework of lattice QCD [5], but these calculations allow deconfinement under certain conditions, and since a rigorous analytic proof does not exist, the question of the existence of free quarks is still open and the search for free quarks is going on [4].

The non-observation of free quarks could also be explained, if the cross-section of the quark interaction with matter is very high as has been suggested in [6]. In fact only few of the quark search experiments have used little material (< 1% inter length) between the interaction region and the detection apparatus [2]. These experiments further improved the experimental upper limits for the production of free quarks to \( R = \frac{\sigma(qq)}{\sigma(\mu^+\mu^-)} = 10^{-4} \), and it is now believed that any produced quarks hadronize with probability 1.

It was expected that with increasing accelerator energies, an energy could be reached where free quarks may exist. Increasing of the energy though, may simply result in further increasing the hadron multiplicity according to the relation \( < n > = A + B \times \ln s + C \times (\ln s)^2 \) measured up to existing energies.

2 Implications of small quark-masses

A possibility for free quark observation may exist, especially for the light quarks, provided that their masses are small. Mass calculations from different sources, as the QCD sum rules, SU(4) symmetry and grand unified theories, give few MeV/c\(^2\) masses for the u and d ”current quarks” as is discussed in the review paper [7] and also later [8]. Calculations in the framework of lattice QCD [9], are consistent with the above mentioned values. Models based on extended Technicolor produce u and d quark masses in the region 35 to 70 MeV/c\(^2\) [10], whereas calculations in a six-dimentional SO(12) theory [11] argues that \( m_{mu} \gg m_u, m_d, m_e \). In QCD, the used masses are the running masses, defined at energy scale \( \mu = 1GeV \) and they are expected to grow with smaller scales in a way similar to the running of the QCD coupling constant. However, in some cases (see for example [12]), the masses are considered as electromagnetic self energies and the color force is not expected to contribute substantially to them. In such a case the growing of the running masses with smaller scales would be limited.

Therefore, and despite the fact that according to nonrelativistic potential models the masses of the u and d quarks bound in hadrons (constituent quarks, considered to contain a valence quark and many qq pairs and gluons), are about 300 MeV/c\(^2\); we accept the existence of evidence from a variety of theoretical calculations, that the masses of the u and d quarks -if they would exist as free particles- should be considerably smaller than the pion mass. A mass of the u or d quarks smaller than the pion mass, could allow deconfinement of these quarks at low energies:
In $e^+e^-$ collisions at C.M. energies below the pion pair production threshold, $u\bar{u}$ or $d\bar{d}$ pairs produced electromagnetically according to the diagram shown on Figure 1, would lack energy to produce the lowest hadrons i.e they could not hadronize (unless hadrons less heavy than pions would exist), and could be observable.

Along the same line of thinking, if the masses of the u and d quarks are larger than the pion mass, the small available energy for hadronization (in the case of production near threshold) may lead to a hadronization probability smaller than 1, which has been observed up to now at high energies. Therefore free quarks may be observable near their production thresholds.

### 3 Free quark observability

To estimate the expected $q\bar{q}$ rates and compare with possible backgrounds, we use the following expression for the cross-section [13] calculated exactly in the one photon annihilation of QED, which describes the production of fermion-antifermion pairs in $e^+e^-$ interactions

$$\sigma = e_f^2 N_c \frac{\pi \alpha^2 (hc)^2}{3 E_b^2} \sqrt{1 - m^2/E_b^2(1 + m^2/2E_b^2)}$$

where $e_f$ is the quark charge, $N_c$ is a factor for the quark color and $E_b$, is the beam energy. This expression is obtained by integrating the corresponding differential cross section:

$$\frac{d\sigma}{d\Omega} = e_f^2 \frac{\alpha^2 N_c (hc)^2}{4s} \beta(1 + \cos^2\theta + (1 - \beta^2)\sin^2\theta)$$
Fig. 2 shows the cross section for the production of $u\bar{u}$ and $d\bar{d}$ pairs in $e^+e^-$ collisions, calculated using (1), with masses $m_u = 50$ and 100 MeV/$c^2$ and $m_d=100$ MeV/$c^2$.

The $u$ and $d$ quarks produced in $e^+e^-$ collisions as described above, could be detected and their charge and mass could be calculated from the measured momenta, using the energy conservation criterion, provided that the Bhabha scattering background would not be too large. Additional measurements (time of flight, dE/dx) will help quark identification. To check if the background is not too large, we have calculated $d\sigma/d\Omega$ for $e^+e^- \rightarrow u\bar{u}$ and $d\bar{d}$ using relation (2), for $\beta = l$. The results are plotted on Fig. 3. Together with a $e^+e^- \rightarrow e^+e^-$ calculation using the expression:
\[
\frac{d\sigma}{d\Omega} = \frac{\alpha^2(hc)^2 (3 + \cos^2\theta)^2}{4 (1 - \cos\theta)^2}
\]  

It is clear that for \(\cos(\theta) < 0\), \(u\bar{u}\) and \(d\bar{d}\) production rates are not too far below Bhabha scattering rates. If no free \(u,d\) quarks would be observed under these conditions, lower limits can be set on their masses. It is interesting to note that no free quark search has been conducted up to now in this energy region.

Figure 3: Calculated differential cross section for the production of quark pairs in low energy \(e^+e^-\) collisions compared to the Bhabha cross section.

In an analogous way, free \(s\) quarks may be observed at C.M. energies below the kaon threshold, because \(130 < m_s < 230MeV/c^2\) [7]. Below this threshold the produced strange quarks would lack energy to hadronize to Kaons (unless hadrons with strange quark content and less heavy than Kaons existed). Similar arguments are valid for the heavy quarks.

The detection of free quarks may be also possible in other reactions -as for example in photoproduction- below the appropriate thresholds. In photoproduction, the ratio
\[ \frac{\sigma(q\bar{q})}{\sigma(e^+e^-)} \sim 10^{-4} \text{ for } m_u = 10\text{MeV and } 10^{-6} \text{ for } m_u = 100\text{MeV because of the dependence of the cross section on } (e_f)^4/m^2. \] Therefore the electron-positron background would be large. It is possible to discriminate against \( e^+e^- \) at large production angles, because \( e^+e^- \) are produced mainly in the beam direction. In a magnetic spectrometer, quarks produced at large angles to the beam can be separated from \( e^+e^- \) pairs through the energy conservation requirement plus \( dE/dx \) and time of flight cuts. In this case too, the alleged large quark interaction cross section with matter may dictate the use of thin targets and evacuated spectrometers. Free quark searches carried out in photoproduction so far, gave negative results but have been performed at energies > 6 GeV [14] and used large amounts of material in front of the detectors.

For similar reasons, free quark search in stable matter, may be more promising than up to now, if the samples under investigation for fractional charges would be previously irradiated at energies near the quark pair production thresholds.

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