# A Novel Scheme to Search for Fractional Charge Particles in Low Energy Accelerator Experiments

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## Abstract

In the Standard Model of particle physics, the quarks have fractional charge equal to ±1/3 or ±2/3 of the electron's charge. There have been a large number of experiments in searching for fractional charge, isolatable, elementary particles using a variety of methods, including $e^+e^-$ collisions using dE/dx ionization energy loss measurements, but no evidence is found to confirm existence of the free fractional charge particles, which leads to the quark confinement theory. In this paper, The design of a novel scheme to search for this kind particles is presented, which is based on the conservation law of four-momentum. Thanks to CLEOc and BESIII detectors' large coverage, precision measurement and their collected large data samples, these features make the scheme feasible in practice. The advantage of the scheme is independence of any theoretical models and high sensitivity even if there are a small fraction of quarks transitting to unconfinement phase.

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In the Standard Model (SM) of particle physics, the mesons comprise of two quarks and the baryons comprise of three quarks, while the quarks carry fractional charge $\pm 1/3e$ or $\pm 2/3e$, $e$ being the magnitude of the electron charge[1]. The successes of SM in the fields of the spectroscopy and the high energy interaction of the hadrons have motivated a lot of experimental searches for fractional charge, isolatable lepton-like particles. There have been a large of experiments in searching for free fractional charge particles using a variety of methods and no evidence up to date is found to convince their existence. There are three kinds of experiments in searching for fractional charge particles, which use accelerators to produce fractional charge particles[3−6], exploit cosmic rays as the source of fractional charges[7] and search in bulk matters[8] respectively. No observation of fractional charge particles results in the confinement concept that the quarks are permanently confined within the hadrons. The questions are whether there is a small fraction of the quarks transitting to the unconfinement phase from the confinement phase and whether there is new sensitive methods to search for them.

It is noted that dE/dx ionization energy loss measurements are used to identify charged particle species for $e^+e^-$[3,4] (or proton anti-proton[5] or heavy ions[6]) collisions in the accelerator experiments. The energy loss fluctuation is predominated by the Landau's theory[11]. One wonders if the theory remains to apply to the quarks which take part in both of the electroweak interaction and strong interaction and sensitive enough to distinguish the quarks from the five stable particles such as the electron, muon ,pion, kaon and proton if there is a small fraction of the quarks which are unconfined. However it is no doubt that the conservation law of momentum and energy (four-momentum) applys to all kinds of the interactions, which can be used to search for the fractional charge particles in combination with the Lorents force law for low energy accelerator experiments, in which a detector is required to possess large coverage (to prevent forward quarks from undetection), good particle identification, precise momentum resolution of charged tracks and energy resolution of neutral tracks (to satisfy the conservation law) and collect large data samples (to increase statistics). For instance, recently upgraded CLEOc[9] and BESIII[10] detectors can search for fractional charge particles based on the laws. The center masses energy of $e^+e^-$ collisions in CLEOc and BESIII cover the energy range of the charmonium production. Therefore fractional charge particles with the mass range of (0,2) GeV can be conceived to appear in the products of the collisions if they are physical reality, which have been searched for in the experiments[3].

The momentum measurement of a track with charge $qe$ produced in every event of $e^+e^-$ collisions is based its movement radius $R$ in the magnetic field $B$ along $z$ direction in the tracking chamber according to the Lorentz force law,

$$P_{xy} = qeB/R,$$

there $P_{xy}$ is the transverse component of the track momentum. The longitudinal component is measured by considering the polar angle $\theta$ of the track with respect to the $e^+$ beam direction,

$$P_z = P_{xy} ctg(\theta).$$

In other words, the radius is a measured value while the momentum is a derived value and dependent of assuming of its charge $q$. In CELOc and BESIII experiments[9,10] as well as the others[3−6] $q$ is a priori set to be 1 no matter how large charge it has. The momentum $\vec{P}_n$ measured in this way, we call it the nominal momentum, for the track equals to its real momentum $\vec{P}_r$ if $q$ is 1. If $q$ is not 1, its nominal momentum increases by a factor of $1/q$ compared with its real momentum, i.e. $\vec{P}_n = 1/q\vec{P}_r$.

Assuming there is a pair of quarks $f$ and $\overline{f}$ with opposite charge $qe$ such as $u\overline{u}$, $d\overline{d}$ and $s\overline{s}$ in the event, which is required to have even number of charged tracks, the total nominal momentum and energy

$$\vec{P}_n(tot) = \vec{P}_n(f) + \vec{P}_n(\overline{f}) \ + \ \textit{other particle contributions}$$
$$= 1/q\vec{P}_r(f) + 1/q\vec{P}_r(\overline{f}) \ + \ \textit{other particle contributions},$$
$$E_n(tot) = \sqrt{P_n^2(f) + m_f^2} + \sqrt{P_n^2(\overline{f}) + m_f^2} \ + \ \textit{other particle contributions}$$
$$= \sqrt{(1/qP_r)^2(f) + m_f^2} + \sqrt{(1/qP_r)^2(\overline{f}) + m_f^2} \ + \ \textit{other particle contributions}.$$

If $\vec{P}_n(tot) \neq 0$, there are two reasons. One is some tracks in the event are undetected for they are neutrinos or go beyond the coverage of the detector. Another is that $q$ is not 1. For the latter case, $q$ can be adjusted so that the real total momentum

$$\vec{P}_r(tot) = q\vec{P}_n(f) + q\vec{P}_n(\overline{f}) \ + \ \textit{other particle contributions} = 0.$$

Then the mass $m_f$ of the quark (anti-quark) can be calculated by requiring the real total energy

$$E_r(tot) = \sqrt{(qP_n)^2(f) + m_f^2} + \sqrt{(qP_n)^2(\overline{f}) + m_f^2} \ + \ \textit{other particle contributions} = \sqrt{s},$$

there $\sqrt{s}$ is the mass center energy of the $e^+e^-$ collisions. In practical measurement and calculation, one does not know which pair of particles with opposite charge have fractional charge. So the momenta and mass of any one pair of particles with opposite charge are adjusted so that the event satisfies the conservation law of momentum and energy. It should be noted that $\vec{P}_r(tot)$ is a vector of three components, one can be used to derive $q$, the two others can be used to suppress events from the first case because they can not satisfy the conservation law of three components simultaneously while events with fractional charge particles can. The procedure is repeated for all events in data samples and the parameter set of $(q,\ m_f)$ is obtained. Then the parameter set is plotted into a two dimension distribution. For the first case, $(q,\ m_f)$ are a set of random numbers, but for the latter case, they should concentrate at one or more points if there are one or more fractional charge particles in the data samples.

To suppress the contribution to $(q,\ m_f)$ from the first case, the velocity $v_m$ of each of the pair of particles, which is measured by the detector, can be compared with the derived velocity $v_r = qP_n/\sqrt{m_f^2 + (qP_n/c)^2}$ and they should be consistent, i.e. $v_r - v_m = 0$ if it is a real fractional charge particle. If the parameter set of $(q,\ v_r - v_m)$ is plotted into two dimension distribution, the points corresponding to fractional charge particles should concentrate along q axis.

To search for events containing a pair of quarks $f1$ and $\overline{f}2$ with opposite charge $qe$ and different masses $m_{f1}$ and $m_{\overline{f}2}$ such $d\overline{s}$, the events are required to have even number of charged tracks and

$$\vec{P}_r(tot) = q\vec{P}_n(f1) + q\vec{P}_n(\overline{f}2)\ +\ other\ particle\ contributions = 0,$$

$$E_r(tot) = \sqrt{(qP_n)^2(f1) + m_{f1}^2} + \sqrt{(qP_n)^2(\overline{f}2) + m_{\overline{f}2}^2}\ +\ other\ particle\ contributions = \sqrt{s},$$

$$v_r(f1) = qP_n/\sqrt{m_{f1}^2 + (qP_n/c)^2(f1)} = v_m(f1)$$

are used to derive $q$, $m_{f1}$ and $m_{\overline{f}_2}$. $v_r(\overline{f}2) = qP_n/\sqrt{m_{\overline{f}2}^2 + (qP_n/c)^2(\overline{f}2)} = v_m(\overline{f}2)$ is used to suppress the contribution from the first case.

To search for events containing a pair of quarks $f1$ and $f2$ with same sign charge $qe$ and $(1-q)e$ and different masses $m_{f1}$ and $m_{f2}$ such as $u\overline{d}$ and $u\overline{s}$, the events are required to have add number of charged tracks and

$$\vec{P}_r(tot) = q\vec{P}_n(f1) + (1-q)\vec{P}_n(f2)\ +\ other\ particle\ contributions = 0,$$

$$E_r(tot) = \sqrt{(qP_n)^2(f1) + m_{f1}^2} + \sqrt{((1-q)P_n)^2(f2) + m_{f2}^2} + other\ particle\ contributions = \sqrt{s},$$

$$v_r(f1) = qP_n/\sqrt{m_{f1}^2 + (qP_n/c)^2(f1)} = v_m(f1)$$

are used to derive $q$, $m_{f1}$ and $m_{f_2}$. $v_r(f2) = (1-q)P_n/\sqrt{m_{f2}^2 + ((1-q)P_n/c)^2(f2)} = v_m(f2)$ is used to suppress the contribution from the first case.

In summary, the dE/dx ionization energy loss measurement combined with the Landau theory for a charged track can be used to identify its species, including its charge, but it is not sensitive[3−6]. For a particle with fractional charge $q$, its nominal momentum, derived by assuming its charge equal to 1 when it is reconstructed, increases by a factor $1/q$ compared with its real momentum. Then the nominal total momentum and energy for the event containing a pair of this kind of tracks will not satisfy the conservation law, which can help find fractional charge particles described by the two parameters ($q$, $m_f$). Between the two parameters, $q$ is more sensitive than $m_f$. Whether the distribution of $m_f$ concentrates at one or more points very well depends on the momentum resolution for charged tracks and the energy resolution for neutral tracks, while $q$ depends little. The effect of $\mid 1/q - 1 \mid$ on the momentum for charged tracks is much larger than the resolutions. Let $q = 2/3$, then $\mid 1/q - 1 \mid$ is 50%, while the momentum resolution is 0.5% for charged tracks and 2.5% for neutral tracks for BESIII[10]. The larger $\mid 1/q - 1 \mid$ is, the more sensitive the method is to search for the fractional charge particles, especially for the type of $f\overline{f}$. Another advantage of the method is independence of any theory models. How to search for events containing three free quarks is not mentioned here, in principle, it can be done in the similar way. The two simplest examples are $\Delta^{++}\overline{uuu}\ +\ others$ and $\Delta^{-}\overline{ddd}\ +\ others$ and their charge conjugation, where $\Delta$ decays to $N\pi$.

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