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SEARCH FOR FRACTIONALLY CHARGED PARTICLES PRODUCED IN $e^+ e^-$ ANNIHILATION.

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ABSTRACT

A search has been made for particles with charge $Q = \frac{1}{3}$, $Q = \frac{2}{3}$ and $Q = \frac{4}{3}$ produced in e^+e^- annihilation using the ARGUS detector at the e^+e^- storage ring DORIS, operating at a centre of mass energy around 10 GeV. No candidate events were found in 84.5 pb^{-1} of collected data. Upper limits are established for the cross section for the production of fractionally charged particles with masses up to 4 GeV/c^2, improving on previously obtained limits.

Since the formulation of the quark model[1], searches for free quarks have been made by many experiments[2–6], generally without success. It is therefore a common belief that the strong interaction, as formulated by Quantum Chromodynamics, causes quarks to be confined in hadrons. In the absence of a rigorous proof for this supposition, whenever improved tools become available, a search for fractionally charged particles should be performed. Electron-positron annihilation, having no hadrons in the initial state, would seem to be a reaction where one might favourably expect the production of free quarks.

We report here on a search for fractionally charged particles with charges $Q = \frac{1}{3}$, $Q = \frac{2}{3}$ and $Q = \frac{4}{3}$, using the ARGUS detector at the e^+e^- storage ring DORIS. Recently, quark searches in e^+e^- collisions have been performed by the JADE[3], Mark II[4], PEP4[5], PEP14[6] and OLYA[7] collaborations. We have achieved an increased sensitivity by exploiting the capability of the ARGUS detector to precisely measure dE/dx energy loss of particle tracks with good pattern recognition, and because of the higher cross section for e^+e^- annihilation at DORIS, operating at centre of mass energies around 10 GeV. An important feature of our detector is that particles traverse only 1.2% of a nuclear interaction length from the vertex before being detected. This is less matter than in other detectors, due to the absence of a pressure vessel, reducing the probability of quark absorption before detection. We also want to note that our data do not only originate from continuum e^+e^- reactions, but also from decays of the various Υ-states.

A description of the ARGUS detector has been previously published[8,9], so that only relevant features are summarized here. Charged particle tracks are measured by a cylindrical drift chamber in an 0.8 T magnetic field. The drift chamber is operated with a gas mixture consisting of 97% propane and 3% methylal at atmospheric pressure. A particle track is measured by 36 concentric cylindrical layers of 18 mm thickness. In each layer the track coordinate and energy loss are measured. The truncated average dE/dx for a track is calculated by discarding the highest lying 30% and lowest lying 10% of the energy loss measurements. The dE/dx measurement thus obtained corresponds to the most probable energy loss. Bhabha scattering events are used for calibration. The resulting resolutions are for the track momentum:

$$\sigma_p/p = \sqrt{0.01^2 + 0.01^2\left(\frac{p}{\mathrm{GeV/c}}\right)^2}$$

and for the dE/dx energy loss, in longterm average:

$$\sigma(dE/dx)/\,(dE/dx) = 0.05$$

The dE/dx resolution function is closely approximated by a Gaussian distribution over more than 3 orders of magnitude.

The search for fractionally charged particles with charge Q was made using the following relation for the energy loss:

$$\frac{dE}{dx} = \frac{Q^2}{\beta^2} f(\beta)$$

The function $f(\beta)$ contains only constants, except for the particle velocity β, which depends on the particle mass, m_q:

$$\beta = p/\sqrt{p^2 + m_q^2}$$

The momentum measurement gives only the apparent momentum, p_a, which is related to the true momentum by:

$$p = Qp_a$$

Thus, the quark charge Q is determined by a measurement of p_a and dE/dx, if the quark mass m_q is known or assumed. Furthermore, an observation of a dE/dx value smaller than that for minimum ionizing tracks can only result from quarks. The most probable energy loss for minimum ionizing Q=1 particles is 2.5 keV/cm in the gas mixture used.

The quark search was performed in two regions of energy loss and apparent momentum which are not populated by the known Q=1 particles. These regions are shown in Figure 1. They are defined as:

$$\text{Lower region}:\ 0.875\ \mathrm{keV/cm} \le \frac{dE}{dx} \le 1.5\ \mathrm{keV/cm}$$

$$\text{Upper region}:\ 4.0\ \mathrm{keV/cm} \le \frac{dE}{dx} \le 27.5\ \mathrm{keV/cm}$$

The upper region was further bounded by requiring that, for any apparent momentum, dE/dx be larger than that for a Q=1 particle with mass 1.41 GeV/c^2.

The quark search in the upper region was made in inclusive multihadron events, $e^+e^- \to qX$, as well as in exclusive two body events, $e^+e^- \to q\bar{q}$. However, only negatively charged tracks were examined, in order to exclude contamination by fragments from beam gas or beam wall interactions. The number of dE/dx samples was required to be larger than 15 after truncation, to insure good dE/dx resolution. Tracks were rejected where $\sigma(dE/dx)$ exceeded 7%, or the track fit probability was less than 1%. These last two requirements eliminate most overlapping and fake tracks.

In the lower region, both charge signs were admitted, but only multihadron events were used, because the trigger efficiency of the detector for the two-body quark channel is small and not precisely known. Here at least 7 dE/dx samples and a dE/dx resolution of better than 18% were required to accept a track. For both regions, only tracks with a polar angle θ such that $|\cos\theta| \leq 0.7$ were considered.

Data taken at various centre of mass energies on and off Υ resonances have been used for this search. The corresponding integrated luminosities and numbers of events obtained are listed in Table 1. Multihadron events were selected according to the standard ARGUS procedure[8]. They represent a complete and unbiased inclusive data set for events with 3 or more detected tracks.

The two-prong events consist mainly of muon pairs, tau pairs and events from $\gamma\gamma$ reactions. Events are accepted if they contain just 2 oppositely charged tracks whose origin deviates from the interaction point by less than 6 cm in the beam direction, and less than 1.5 cm radially. If at least one track has momentum less than 2 GeV/c or the event has less than 0.6 GeV energy in the shower counters, no further requirements are made. Failing this, in order to suppress Bhabha scattering events, the remaining two-prong events were required to have at least one track with a polar angle such that $|\cos\theta| < 0.866$, and to satisfy, in addition, at least one of the following: (1) at least one track with shower energy $E_s < 1.5$ GeV, (2) at least one track with momentum $p < 3$ GeV/c and $E_s < 4$ GeV, (3) acollinearity between the two tracks larger than 15°, or (4) energy loss incompatible with an electron assignment, that is $dE/dx < 2$ keV/cm or $dE/dx > 4.4$ keV/cm.

Using the events thus obtained, and applying the quark track search criteria discussed above, no quark candidate was found in the lower search region with small dE/dx. In the upper dE/dx region, 25 candidates were observed. Of these, 6 were clearly identified as the production of antideuterons in e^+e^-[10].

A further 18 events, we attribute to overlapping tracks of electrons in Bhabha scattering events with a bremstrahlung photon, which converts into an electon-positron pair: that is $e^+e^- \to e^+e^-\gamma$ followed by $\gamma \to e^+e^-$. This interpretation is supported by the following observations. The events apparently have 3-prongs: charge conservation demands an additional track with the same charge as the candidate track. The energy loss of the candidates is twice that expected for an electron. The time-of-flight measurement is consistent with $\beta = 1$ for the candidate tracks. The energy deposited in the shower counters corresponds to twice the momentum of the candidate track. Momentum balance demands another track with approximately the same momentum as the candidate track. Thus, by using all detector information available, these tracks can confidently be identified as overlapping electrons.

The remaining one event contains a track which can be explained as the overlap of two hadron tracks. Again, charge conservation demands one more track of the same charge as the candidate track. Also, the energy loss is twice that for that of a pion, the time-of-flight measurement is consistent with a fast pion track and the energy deposited in the shower counters is consistent with two overlapping hadrons. The transverse momentum balance, using photons and charged tracks, requires an additional particle with $p_T = 1.27$ Gev/c at an azimuth of $\phi = 2.47$ radians. The candidate track has $p_T = 1.03$ GeV/c at $\phi = 2.51$ radians, corresponding well, within errors, to the missing p_T. Therefore this track can also be rejected as an overlap. We conclude that no free quarks have been observed.

In order to convert this result into an upper limit for the cross section for quark production, $\sigma_q(e^+e^- \to qX)$, we use the definition for the 90% confidence level from Poisson statistics:

$$\sum_i L_i \sigma_q^{vis} = 2.3$$

The sum is extended over the various beam energies, where the integrated luminosities, L_i, were accumulated. The visible cross section, σ_q^{vis} is related to the true cross section by

$$\frac{\sigma_q^{vis}}{\sigma_q} = \frac{\int^R \frac{d\sigma_q}{dp}\epsilon(p, Q, m_q)dp}{\int^R \frac{d\sigma_q}{dp}dp}$$

The integral is performed in the dE/dx-p_a plane with the assumed quark mass and charge kept constant. Only those momenta p_a for which dE/dx lies inside one of the regions R of search contribute to the integral. The finite dE/dx resolution has been taken into account at the boundaries of the regions. Two extreme forms were taken for the momentum distribution, $d\sigma_q/dp$, of the produced quarks:

$$\frac{d\sigma_q}{dp} \propto \frac{p^2}{E} \qquad \text{(I)}$$

and

$$\frac{d\sigma_q}{dp} \propto \frac{p^2}{E} e^{-3.5E/\mathrm{GeV}} \qquad \text{(II)}$$

as previously suggested by the JADE collaboration[3]. The function $\epsilon(p, Q, m_q)$ represents the detection efficiency for a free quark as a function of its momentum, charge and mass. This efficiency is composed of many factors: the trigger efficiency, the geometrical acceptance, the track reconstruction efficiency and the efficiency for the applied selection cuts. All of these factors were carefully determined by an analysis of data events supplemented by Monte Carlo studies. In particular, the track reconstruction efficiency in the lower region of dE/dx was determined by running the drift chamber with reduced high voltage.

Finally, we relate the quark production cross section to the cross section for muon pair production and quote our result as a limit on:

$$R_q = \frac{\sigma\,(e^+e^- \to qX)}{\sigma\,(e^+e^- \to \mu^+\mu^-)}$$

The result is shown in Figure 2, together with previously reported limits[3-6]. In the case $Q = \frac{2}{3}$ or $Q = \frac{4}{3}$ particles, the limits can be extended to quark masses below those shown in the figure. At $m_q = 1\,\mathrm{MeV}/c^2$, the limits on R_q are respectively 1.1×10^{-4} and 0.65×10^{-4} for model I, and 0.50×10^{-4} and 1.1×10^{-3} for model II.

We conclude that we have obtained a significantly improved sensitivity for the observation of free quarks which reaches the level of 10^{-4} in R_q. Cross section limits are presented for free quark production with quark masses less than 4 GeV/c^2. No free quarks were observed.

TABLE 1

	L [pb^{-1}]	Selected Multihadron Events ($\times 10^3$)	Selected Two-prong Events ($\times 10^3$)
Υ(1S)	23.6	321	278
Υ(2S)	38.6	309	440
Υ(4S)	10.0	53	65
Continuum	12.3	46	98
Total	84.5	729	881

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FIGURE CAPTIONS

Figure 1 : Regions in the dE/dx-p_a plane used in the free quark search are shown in the hatched areas. The dE/dx measurements from a sample of positively and negatively charged tracks representing about 1% of the data set illustrate the separation of the various particle types.

Figure 2 : Upper limits at the 90% confidence level for the production of particles with charge $Q = \frac{1}{3}$, $Q = \frac{2}{3}$ and $Q = \frac{4}{3}$ in e^+e^- annihilation are shown for two different assumptions concerning their momentum spectrum. Also shown are previously reported limits from other e^+e^- experiments[3-6].

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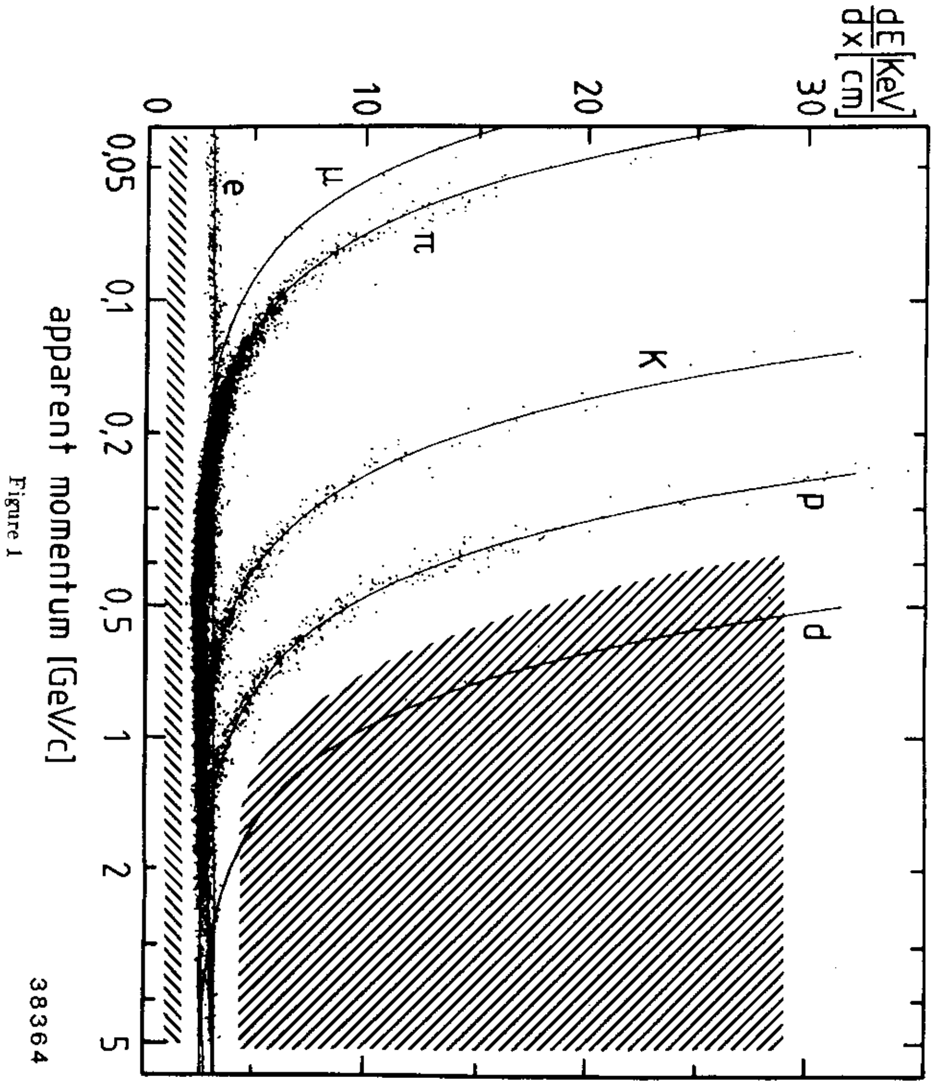
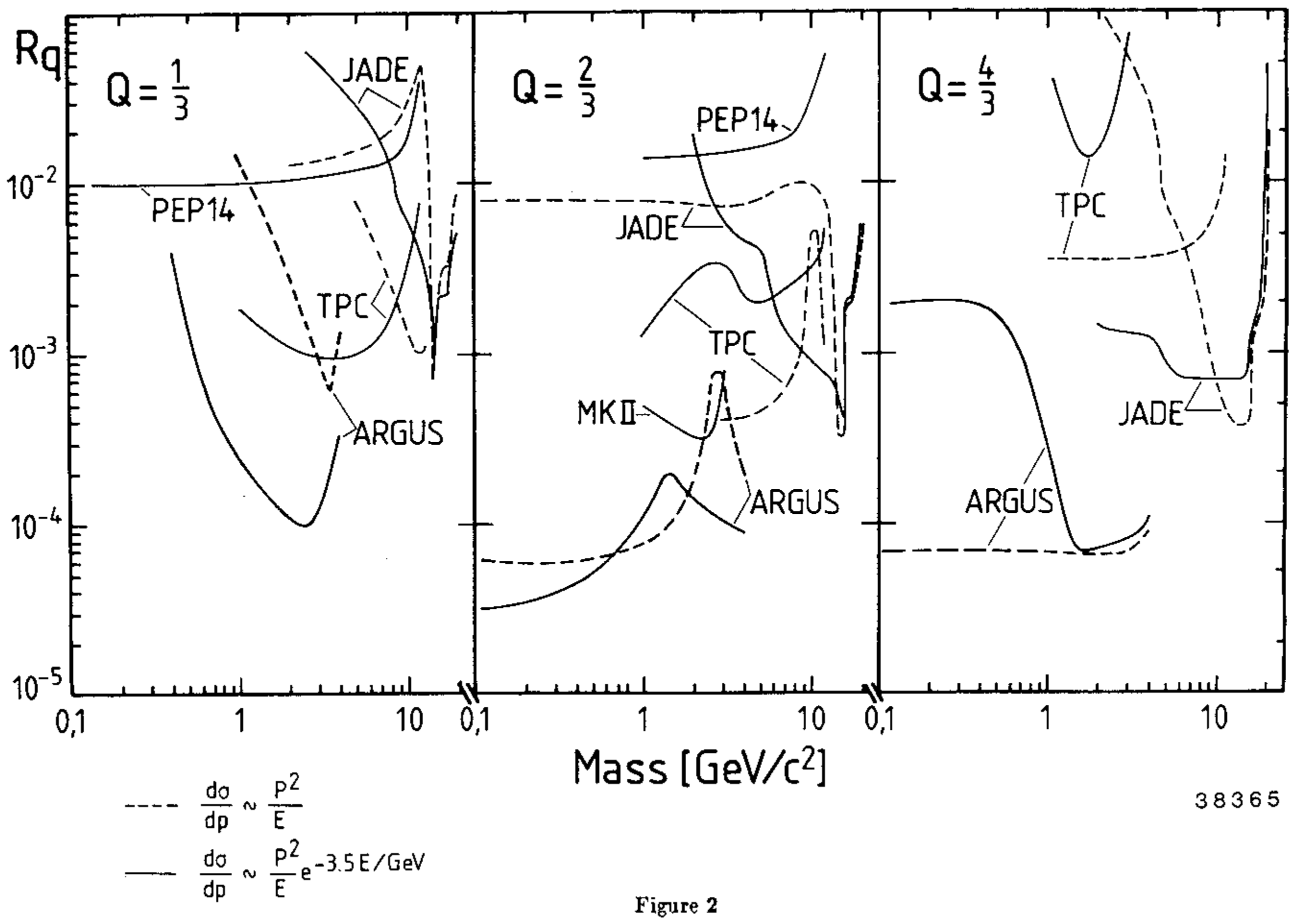


Figure 1



Rq
Q = 1/3
Q = 2/3
Q = 4/3
JADE
PEP14
TPC
ARGUS
MKII
10^-2
10^-3
10^-4
10^-5
0,1
1
10
Mass [GeV/c^2]
38365

Figure 2