DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 80/42
May 1980

QUARKS AND MONOPOLES AT LEP

ECFA/LEP Specialized Study Group 9 "Exotic Particles"

G. Barbiellini	-	*INFN, Frascati and CERN*
G. Bonneaud	-	*Strasbourg and CERN*
R. J. Cashmore	-	*Dept. of Nuclear Physics, Oxford*
G. Coignet	-	*LAPP, Annecy-le-vieux*
J. Ellis	-	*CERN*
M. K. Gaillard	-	*LAPP, Annecy-le-vieux*
J. F. Grivaz	-	*LAL, Orsay*
C. Matteuzzi	-	*CERN*
R. D. Peccei	-	*Max-Planck-Institut, München*
B. H. Wiik	-	*DESY*

NOTKESTRASSE 85 · 2 HAMBURG 52

QUARKS AND MONOPOLES AT LEP

G.Barbiellini	-	INFN, Frascati and CERN
G.Bonneaud	-	Strasbourg and CERN
R.J.Cashmore	-	Dept. of Nuclear Physics, Oxford
G.Coignet	-	LAPP, Annecy-le-vieux
J.Ellis	-	CERN
M.K.Gaillard		LAPP, Annecy-le-vieux
J.F.Grivaz	-	LAL, Orsay
C.Matteuzzi	-	CERN
R.D.Peccei	-	Max-Planck-Institut, München
B.H.Wiik	-	DESY

Contents

1) Introduction

The two types of particle discussed in this report have exercised a special fascination for many years. Ever since the quark hypothesis[1] was formulated in 1964, the aesthetic structure of the quark model and the growing indirect evidence for the reality of quarks have fed the urge to find them. For a much longer time, people offended that the symmetry of Maxwell's equations should be marred by the existence of free electric charges but the absence of magnetic charges have looked[2] to monopoles for the restoration of lost elegance. Monopoles have recently acquired enhanced status through the realization[3] that they and other topological structures appear in a wide class of gauge theories. Experimental searches for quarks[4] and monopoles[5] have been the obsession of a dedicated minority for many years, and always feature in the experimental programme of any new particle accelerator. It is clear that LEP will be no exception to this rule, particularly since the high energies and large momentum transfers provided by e^+e^- collisions at LEP yield extreme kinematical conditions and may provide the optimal conditions for liberating quarks or fabricating monopoles[6]. This report reviews the previous searches for quarks and monopoles, discusses the different varieties in which they may occur, and examines some possible ways to look for them at LEP.

Hadrons are believed to be made out of quarks[1] which are held together by gluons. Indirect evidence for the reality of quarks comes from hadron spectroscopy, deep inelastic scattering experiments and e^+e^- annihilation. Particularly impressive are the spectroscopy of charmonium[7], the ratio between neutrino- and electroproduction cross-sections[8], and the dominance of two-jet events in e^+e^- annihilation[9]. On the basis of these results it is generally accepted that quarks are fractionally charged point-like spin 1/2 objects which may either be relatively light ($m_{u,d,s} << 1$ GeV) or heavy ($m_{c,b,t} > 1$ GeV). The evidence for gluons is less striking but increasingly persuasive. Important indications come from hyperfine spectroscopic splittings[10], the deep inelastic momentum sum rule[11] and scaling violations[12], and jet broadening and three-jet events in e^+e^- annihilation[13]. Gluons are probably uncharged and point-like with spin 1 [10,12-14]. The search for free, physical quarks as a new level of the structure of matter is clearly of fundamental importance, but one should also remember the possible existence of free gluons and the interest of searching for them also.

It is not clear what the properties of a free physical quark might be. Perhaps they will have fractional charge, as bound quarks appear to have, or perhaps their charge will be modified by the absorption of charged hadrons[15], or perhaps quarks actually have integer charges[16]. Perhaps free quarks are heavy, perhaps they are light but difficult to liberate, or perhaps their masses are even indeterminate[17]. Presumably free quarks are coloured, but some of them may have unusual non-triplet colour[18], and it is not clear whether or not colour is an exact symmetry[16]. It has often been assumed that free quarks may have smaller interaction cross-sections than conventional hadrons[4], but their cross-sections might in fact be considerably larger because of their non-zero colour[15]. The form factors for their weak and electromagnetic interactions may well not be pointlike[19], and it is quite possible that quarks may possess a detectable substructure. These are some of the many possibilities to be born in mind when one is considering the design of quark search experiments.

Some of the properties of monopoles are relatively well-defined. They should have strong electromagnetic interactions because their couplings to the electromagnetic field are $O(1/\alpha)$. Therefore monopoles should make distinctively large "splashes" of ionization and energy deposition in a particle detector. Furthermore they are accelerated, rather than deflected, by a magnetic field. The experimental signatures for monopoles are therefore no mystery[5]: the problem is to know whether they should exist, and if so what their masses might be. As previously remarked, some gauge theories of weak and electromagnetic interactions possess[3] monopoles as topological excitations with masses $O(10^3$ to $10^4)$ GeV. Such objects do not exist in the currently popular Glashow-Weinberg-Salam (GWS) model[20], but it has been conjectured that other lighter monopoles may exist[21]. Even in the GWS model there may be other topological exitations with masses in the TeV range[22,23]. In any case, one's experimental urges should not be restained by the paucity of theoretical imagination.

The structure of this report is as follows. Section 2 looks at quarks, starting with a review of previous experimental searches[4] and continuing with the phenomenology of the different varieties of quark which are mentioned above. We study the direct production and detection of conventional fractionally charged quarks, of strongly interacting coloured quarks with appetite[15], and of quarks with indeterminate mass[17] or integer charge[16]. We also examine the

search for indirect manifestations of quarks with non-standard colour[18], or with substructure[19]. Section 3 deals with monopoles, starting with a summary of motivations for their existence, and their expected properties, as well as a review of the previous searches[5]. It continues with a survey of the different ways of looking for conventional magnetic monopoles and other possible topological exitations in gauge theories.

Our conclusions may be briefly stated: they are that most types of quarks and monopoles can be readily detected at LEP if they exist and are produced in any quantity.

2) QUARKS

2.1 Previous experimental searches

There exists quite a rich variety of "theoretical quarks" (integer charge, fractional charge, stable, unstable, light, massive, etc.) Experiments have generally been based (in the hope of reducing the problem of experimental detection) on the hypotheses that:

i) the charge of the quark is fractional
ii) the quark mass is bigger than the nucleon mass
iii) a quark can be produced by breaking up a hadron, or in pairs $q\bar{q}$.

One can group quark searches according to the different places in which they could be found, namely:

1) cosmic rays
2) accelerators
3) stable matter

There is a very exhaustive review of all experimental results up to 1977 in Ref. 4. We have taken from there the synthesis of results prior to 1977 and have completed the review with what has been happening more recently.

Below, Table 1 summarizes all the different types of techniques employed to look for quarks from different possible sources.

Table 1 - Summary of previous quark search method

Subsection	Type of experiment	Experimental methods
2.1.1	Cosmic rays	single particle searches air shower studies time delay technique
2.1.2	Accelerators	photon interactions ν interactions (SPS) e.m. interactions — electron beam on fixed target (SLAC, DESY, CEA); e^+e^- colliding beams (PETRA)
2.1.3	Stable matter	rocks, sea water, lunar rocks Niobium or iron balls suspended in a magnetic field

2.1.1 Searches in cosmic rays

A quark can be searched for in cosmic rays, either by just looking for a single particle among the cosmic flux with special characteristics such as very low ionization, or among the products of big showers of particles generated by interactions of very highly energetic particles in the high atmosphere (one can reach $E = 10^7$ GeV). To detect a single particle of fractional charge the most usual technique is that of measuring anomalous ionization, using for example scintillation counters.

The typical cosmic ray flux of nucleons and nuclei (essentially He) is given by

$$\frac{d\phi(E)}{dE} = 2.35\ E^{-2.67}\ \text{nucleons/GeV cm}^2\ \text{sr sec} \qquad (2.1)$$

The limit on quark flux this kind of experiment can give is determined by the geometrical acceptance of the apparatus and the time of exposure. Table 2, taken from ref. 4, gives an review of all the existing results. Combining them, it was concluded in ref. 4 that the flux of quarks ϕ_q is

$$\phi_{1/3} \leq 1.1 \times 10^{-11}\ (\text{cm}^2\ \text{sr sec})^{-1} \quad \text{at 90\% C.L.}$$
$$\phi_{1/3} \leq 2.4 \times 10^{-11}\ (\text{cm}^2\ \text{sr sec})^{-1} \quad \text{at 90\% C.L.} \qquad (2.2)$$

Table 2 - Cosmic ray searches for single quarks (from L.W.Jones, ref. 4)

Group	Reference	Detectors	Elevation above sea level (m)	Admittance (m^2 sr)	Data Collection time (hr)	Quark flux limits (90% C.L.) $\phi \times 10^{-10} (cm^2 sr\ sec)^{-1}$ ±1/3e	±2/3e	±4/3e
BNL	Sunyar, 1964	7 scint.	S	0.0011	720	2000		
Arizona	Bowen, 1964	5 liquid scint.	2750	0.033	237	160		
CERN	Massam, 1965		S	0.0054			500	
Arizona	Delise, 1965	6 liquid scint.	2750	0.024	1100	87	180	
Yale-BNL	Kasha, 1966	3 plastic scint. 3 liquid scint.	S	0.065	2500 900	26	21	
CERN	Buhler-Brohlin, 1966	6 plastic scint. 2 spk. chamber	S	0.11	850	15	14	
Argonne	Lamb,1966	2 gas counters 2 plastic scint. 4 liquid scint.	S	0.40	1750	4.5	16	
Cal.Tech	Gomez, 1967	8 plastic scint. 2 spk.chamber	S	0.15	3300	1.7	3.4	
CERN	Buhler-Brohlin, 1967a	6 plastic scint. 2 spk.chamber	S	0.11	2605	4.5	1.7	
Yale-BNL	Kasha, 1967	7 scint.	S	0.060	2000		20	
Yale-BNL	Kasha, 1968a	8 layer hodoscope each of 6 scint.	S	1.0	1100		1.2	
Yale-BNL	Kasha, 1968b		S	1.0	1000			1.3
Osaka	Hanayama,1968	5 plastic scint. 16 spk. chamber	S	0.52	800	3.1		
Tokyo	Fukushima,1969	12 scint. 1 streamer chamber	S	0.20	3500	0.5	7.5	
Arizona	Krider,1970	6 scint. 4 spk.chambers 1 shower detector 1 range chamber	750	0.95	1160	0.98	1.6	
Aachen	Faissner,1970	6 gas counter layers	S	0.428	1580	1.9		

Table 2 - continued

Osaka	Chin,1971	6 scint. 16 spk.chamber	S 2770	0.38	2050 5500	1.3 0.57		
Arizona	Cox, 1972	6 liquid scint. 2 wide gap spk.cham.	2750	0.63	1500	0.83	0.96	
Arizona	Beauchamp,1972	6 liquid scint. 2 wide gap spk.cham.	2750	0.63	1500			4.1
Case	Crouch,1972	5 liquid scint. 2 flash tube trays	S	0.51	1159		2.2	
Tokyo	Kifune,1974	6 layer hodoscope each of 4 scint.	S	0.65	556	3.0		
London	Barton, 1966	1 scint.	220 000	1.0	1840		1.4	
London	Barton, 1967	6 liquid scint.	6 000	0.51	1600		1.4	
CERN	Buhler-Brohlin, 1967 b	6 plastic scint. 2 spk.chamber	790	0.11	12			1600
M.I.T.	Garmire,1968	2 plastic scint. 1 liquid scint. 2 prop. counters	∿300 b	0.52	...	0.66 c	0.89 c	
Torino-CERN	Briatore,1968	6 scint.	6300	0.010	4170 770	1.8	1.8	110 a)

a) Not 90% C.L.,uncertain by ± 180.

b) One meter concrete

c) 95% Confidence level.

Details of the experimental references can be found in Ref. 4

Experiments done at surface level are indicated by S.

Another method of looking for quarks in cosmic rays is to study the air showers generated in the atmosphere by very high energy particles. If the primary interaction takes place in the atmosphere at a typical altitude of $\sim 3 \times 10^4$ m, at sea level the quark will be found at a distance from the core of the shower which depends on its mass and on the transverse momentum with which it is produced. The experimental arrangement of McCusker[24], who initiated this kind of search, consisted of 3 arrays of Geiger counters each of 110 cm^2 effective area arranged in a horizontal equilateral triangle of 2 m on a side. This apparatus is efficient for triggering on air showers corresponding to energies $\geq 10^5$ GeV. Four cloud chambers placed between and below the trigger counters completed the apparatus. With it, 5500 shower events were analyzed, and 5 quark candidates were retained among 60000 tracks. This result, which gave

$$\phi_{2/3} = 5.5 \times 10^{-10} \, (cm^2 \; sr \; sec)^{-1} \qquad (2.3)$$

was never reproduced in the following experiment with the same detector or in any other experiment of the same kind.

Table 3 taken from ref. 4 gives a resumé of air shower experiment results.

The combined result on the quark flux is:

$$\phi_{1/3} < 0.75 \times 10^{-11} \, (cm^2 \; sr \; sec)^{-1} \text{ at 90\% C.L.}$$
$$\phi_{2/3} < 1.4 \times 10^{-11} \, (cm^2 \; sr \; sec)^{-1} \text{ at 90\% C.L.} \qquad (2.4)$$

Finally, another technique, useful for detecting particles of any charge which are very massive, is a time delay technique. If a massive particle is among the components of an air shower produced at an attitude of 10 km, it would arrive at the detector with a certain delay (e.g. 160 nsec if it has a mass of 10 GeV and an energy of 100 GeV. These detectors usually contain a device to measure ionization (cloud chambers, scintillators, etc).

Table 4 contains the results of time delay experiments.

One may assess the significance of these searches by observing that the limits (2.2), (2.4) on the quark flux ϕ_q are about 10^{-11} of the integrated flux (2.1) of cosmic ray nucleons with energies above 1 GeV. However, the integrated flux of cosmic ray nucleons with $E > 2 \times 10^7$ GeV, which would give rise to nucleon-nucleon collisions with centre-of-mass energies $\sqrt{s}$ of 200 GeV comparable to those available with LEP, is itself less than 10^{-11} $(cm^2 \; sr \; sec)^{-1}$. Furthermore, the vast majority of nucleon-nucleon collisions at $\sqrt{s}$ = 200 GeV are not "hard" with large momentum transfers, unlike all the e^+e^- annihilation

Table 4 - Time delay experiments (from L.W.Jones, ref. 4)

Group	Reference	Detector	Location	Showers studied	Candidates	upper limit[a] quark flux ϕ x 10^{-10} $(cm^2$ sr sec$)^{-1}$
Copenhagen	Bjorneboe, 1968	1.6 ton liquid scintillator	Sea level plus $3.6x10^3$ g cm^{-2}		Background of accidential events	1-3[d]
Echo Lake	Jones,1967	Ionization calorimeter	715 g cm^{-2}	$3x10^5$	1	0.23 0.90[c]
Calgary	White,1970	Scintillator counters	Sea level plus 274 g cm^{-2} Pb			4
Tata	Tonwar,1972	Ionization calorimeter	800 g cm^{-2}	$1.4x10^4$	42	10-20 [b]
Tata	Tonwar,1976	Cloud chamber	800 g cm^{-2}		2	1 [b]
Torino	Dardo,1972	Scintillator counters	Sea level plus $7x10^3$ g cm^2			300 [b]
Torino	Briatore,1975	Counters and spark chambers	Sea level plus $7x10^3$ g cm^{-2}	719		12.5 [d]

a) 90% confidence level

b) positive result reported (see text)

c) one event observed, not claimed as evidence for quark

d) delayed events detected compatible with background

Table 3 : Quark searches in air showers (from L.W.Jones, ref. 4).

Group	References	Detector and area	Absorber	Shower energy	Shower density (particles m^{-2})	Number triggers	Number of tracks studied	Upper limit[a] quark flux Qx10^{-10} $(cm^2$sr sec$)^{-1}$ 1/3e	2/3e	other
Sydney	Cairns,1969;	3 cloud chambers, each 120 cm^2	15 cm Pb	$\sim 4x10^6$GeV	$100-5x10^4$	5500	55000		5.5[c]	
	McCusker,1969	1 cloud chamber 120 cm^2	unshielded			~12000			2.4[c]	
Ohio	Chu,1970	1 m diam.bubble chamber	$1200cm^{-2}$ Fe and Cu			10000[d]			1000[c]	
Edinburgh	Evans, 1971	High pressure, cloud chamber 140 cm^2		$>10^5$GeV		1200	12000	40[b]		
Michigan	Hazen, 1971	Cloud chamber 0.15 m^2	10 cm concrete 1.25 cm Al plate in chamber	$>10^6$GeV		3200	~100000		1	
Aachen	Bohm,1972	1 m^2 proportional counters	15 cm Pb	10^5-10^6GeV	≤ 600	523724	107500	1	1	
Durham	Ashton,1973a Ashton,1973b Ashton,1975	Neon flash tube-hododcope array	15 cm Pb		>250 > 80 > 20	1217 4516 12057		0.43 0.55 0.80		
Livermore	Clark, 1974	11 cloud chambers, each 44 cm diam. x 9 cm deep	half under 10 cm Pb	$\geq 10^6$GeV	$\leq$ 86 ≤ 5000	20000 (200000 chamber photo-graphs)	1000000	0.8	0.2	7(1/4e) 1000(1/6e) 100(4/9e)
Leeds	Hazen, 1975	Cloud chamber 3 m^2 (horizontal)	20g cm^{-2} 250 g cm^{-2}	$\sim 5x10^6$GeV	≤ 500	5000 2250		0.12		

a) 90% confidence level; b) 95% confidence level upper limit; c) Quark candidates reported (see text)
d) 10000 bubble chamber photographs studied with no a priori requirement of coincident cosmic ray.

Accelerator	Reference	Detector system	Proton beam momentum (GeV/c)	Beam angle (mrad)	Quark beam momentum (GeV/c)	Charge	Upper limit quark flux $\frac{d}{d\Omega\,dp}$ $\left(\frac{cm^2}{sr\ GeV/c}\right)$	Quarks per pion	Quark mass range (GeV/c^2)	Quark mass at maximum sensitivity (GeV/c^2)	Quark production cross section (cm^2)
CERN PS	Morrison, 1964	30 cm hydrogen bubble chamber	24.8	70	5.3	-1/3	4.8×10^{-34}	10^{-5}	0.5 - 2.40	2.0	4×10^{-34}
					10.7	-2/3				2.0	8×10^{-34}
CERN PS	Bingham, 1964	1 m freon bubble chamber	24.8	77	5.3	-1/3	1×10^{-36}	10^{-8}	0.5 - 2.46	1.6	3×10^{-35}
					10.7	-2/3	2×10^{-36}			1.6	6×10^{-35}
BNL AGS	Hagopian, 1964	2 m hydrogen bubble chamber	31	120	2.83	+1/3					
					5.67	+2/3		10^{-5}	0.5 - 2.5	2	8×10^{-34}
CERN PS	Blum, 1964	81 m hydrogen bubble chamber	27.5	77	6.7	-1/3			0.5 - 3		10^{-33}
					13.3	-2/3	9.5×10^{-36}	6×10^{-6}	0.5 - 2.5	2	2×10^{-35}
BNL AGS	Leipuner, 1964	7 pulse height scintilation counters	29	~0	...	±1/3		3×10^{-8}			2×10^{-35}
				314	1.5	-1/3		5×10^{-10}			1×10^{-34}
BNL AGS	Franzini, 1965	Electrostatic mass separator, time-of-flight	31	120	4.7	-2/3		2×10^{-8}	2 - 3	2.8	2×10^{-35}
BNL AGS	Dorfan, 1965b	Time-of-flight momentum	31	76	6.0	-2/3	1.5×10^{-36}	2.5×10^{-11}	< 3.0		10^{-36}
CERN PS	Allaby, 1969	6 pulse ht.scint. ctrs.6 triggers ctrs. 2 threshold Cerenkov ctrs 1.1 liter isotropic spark chm.	27.2	0	10.9	-1/3	7.2×10^{-36}			2.7	3.2×10^{-31}
			26.4	0 6.5 6.5	21.4) 14.7) 13.3)	-2/3	5.2×10^{-36}			2.4	5.5×10^{-38}
				44	6.7	+1/3	2.6×10^{-35}			2.5	1.8×10^{-35}
				44	13.3	+2/3	1.3×10^{-35}			2.5	1.0×10^{-35}
SERPUKOV	Antipov, 1969a	10 pulse ht.scint. ctrs. 2 threshold Cerenkov ctrs., time-of-flight, wide gap spark chamber-magnetic spectrometer	70	0	13.3) 16.7)	-1/3	4.9×10^{-36}) 1.4×10^{-36})		2 - 5	4.7	1×10^{-38}
					21.5) 26.7) 26.6) 33) 43) 53.3)	-2/3	3.6×10^{-37}) 7.1×10^{-38}) 2.8×10^{-36}) 7.7×10^{-36}) 2.1×10^{-37}) 4.1×10^{-38})		2 - 5	4.9	2×10^{-37}
FNAL	Leipuner, 1973	6 pulse ht.scint. ctrs.	300	6.5	...	±1/3	10^{-35}	7×10^{-10}	1-12	11	1×10^{-35}
					...	±2/3			1-12	11	1×10^{-35}
		2 threshold Cerenkov ctrs		6.5	80	-4/3		10^{-5}	2-12	11	5×10^{-31}
FNAL	Nash, 1974	8 pulse ht. scint. ctrs. 2 Cerenkov ctrs., muon idenfifier	200	1	90	-1/3	5×10^{-36})				
					69	-1/3	5×10^{-35})				
					50	-1/3	8.0×10^{-35})				
			300		90 69 50	-1/3 -1/3 +1/3	5.1×10^{-34}) 1.0×10^{-34}) 4.8×10^{-35})		2-10	8.8	6×10^{-31} 10^{-35}
			200		180 138 100	-2/3 -2/3 +2/3	2.8×10^{-36}) 2.8×10^{-35}) 4.0×10^{-35})		2-12	11	2×10^{-37}
			300		180 138 100	-2/3 -2/3 +2/3	2.5×10^{-34}) 5.0×10^{-35}) 2.4×10^{-33})				3.5×10^{-35}

Details of the experimental references may be found in Ref. 4.

events. We conclude that LEP can probe kinematic conditions not accessible with cosmic ray searches.

2.1.2 Quark searches at accelerators

A) Proton interactions

Many experiments have given a limit on quark production by protons, usually assuming the reaction

$$p\ p \rightarrow q\bar{q}\ ppX$$

These experiments are listed in Table 5: most of them give quite poor limits. The most significant limits are given by an experiment at fixed p_T performed at FNAL[25] with the Chicago-Princeton spectrometer, and two experiments[26,27] at CERN-ISR with a $\langle p_T \rangle$ = 0.400 GeV/c.

The properties of the three experiments and the results are summarized in Table 6.

The limits on the ratio of quark flux to charged single particle flux are also shown in Fig.1. All are at 90% C.L. - Fig. 2 shows the corresponding limits on cross sections but they are strongly model dependent.

We should emphasize that none of these experiments has reached the centre-of-mass energy range accessible to LEP, and that a relatively small fraction of hadron-hadron scattering events are "hard". It seems intuitively reasonable that it might be easier to liberate a quark by "breaking a bag" in a collision with a large momentum kick as provided by LEP.

It may be useful to compare the capabilities of LEP in this respect with those of a high energy, high luminosity hadron-hadron colliding ring machine such as Isabelle. For such a device with $\lesssim$ 1 TeV in the centre-of-mass we guess that the effective cross-section for events with a momentum kick of order 10^4 GeV^2 might be $O(10^{-32}$ cm$^2)$. With a luminosity of 10^{33} cm^{-2}sec^{-1} this implies a rate for large Q^2 events slightly higher than that at LEP operated at the Z^0 peak. However, the background problems at Isabelle are probably more severe, bearing in mind the large number of spectator particles in the interesting hard interactions, and the large number of uninteresting soft interactions from which the interesting events should be separated. We feel that LEP is not obviously inferior to such a machine as far as free quark hunting is concerned.

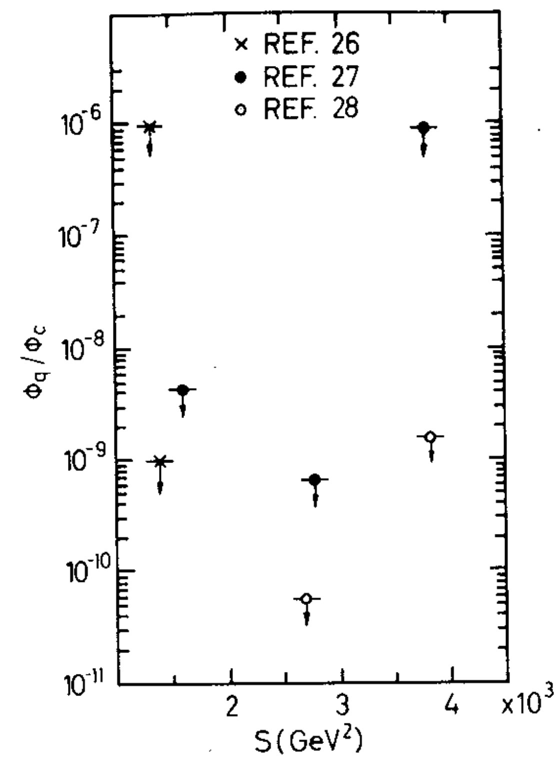


Fig.1

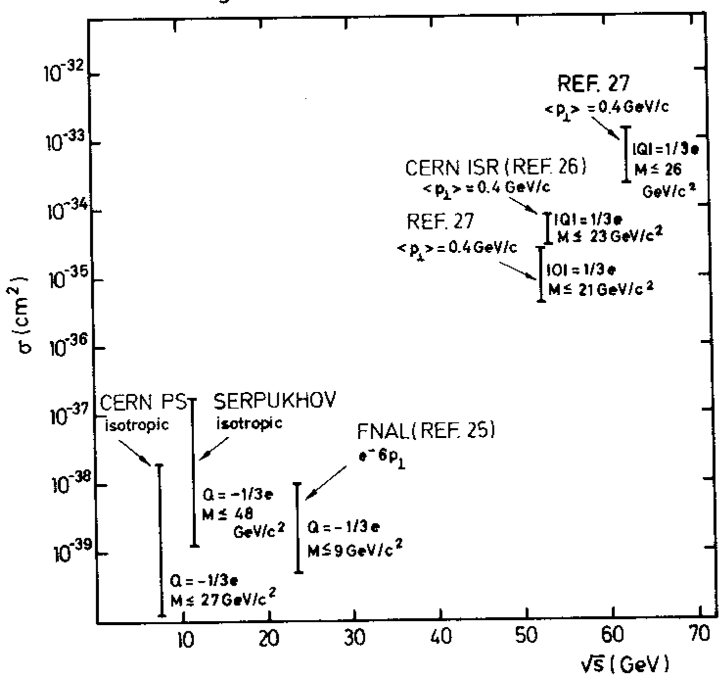


Fig. 2

Table 6 - Quark searches in proton collisions

Accelerator	Reaction	Energy in c.m. (GeV)	p_T^{π} (GeV)	Limit $\phi_{1/3,2/3}/\phi_1$	Detectors	Limit on quark mass	Ref.
FNAL	$pCu \rightarrow NN q\bar{q} X$	27.4	6.15	10^{-3} for 1/3 10^{-6} for 2/3	Chicago-Princeton spectrom. Ionization measurements with plastic scintillation counters. Sensitive to 1/20 of the average pulse height of a charge one track	6.3 for 1/3 8.0 for 2/3	25
CERN ISR	$pp \rightarrow pp q\bar{q} X$	5.3	$<p_T>=0.4$	7×10^{-10} 4×10^{-8} 1×10^{-6}	9 pulse height scintillation counters: 3 MWPC, time-of-flight measurement	20	26
CERN ISR	$pp \rightarrow pp q\bar{q} X$	52.5 62.	$<p_T>=0.4$	5.1×10^{-11} 1.8×10^{-9}(1/3) 1×10^{-9} (-1/3)	Hodoscopes measuring eD/dx, time-of-flight.of damped seconds, MPWC allowing re-construction of tracks	21 26	27

B) ν interactions

Quarks have been sought in ν interactions with the ν SPS wide-band beam. There exists a published result [29] and a major experiment is now running at CERN[30]. The technique consists of measuring dE/dx in 3 scintillation counters, and the time of flight of the particles which is needed to determine β. A muon detector triggers the ν event, synchronized with the ν beam spill. The test reported in ref. 29 collected 4700 ν interactions among which there is one event falling in the region of ionization expected for a -1/3e charged quark , determined by two counters. However, the limit on ν production of quarks is calculated on the basis of 0 candidates supposing that quarks are produced as μ's and that their absorption length is $270 g/cm^2$. The result is

$$\sigma_q < (5 \pm 1.7) \times 10^{-3} \text{ per } \nu \text{ interaction} \qquad (2.5)$$

at an average momentum transfer of a few GeV^2.

The ongoing experiment[30] in the ν line at the SPS, which uses a streamer chamber to look at very low ionization, expects to lower this limit to 10^{-6} in 50 days of data taking.

c) Electromagnetic interactions

Dedicated experiments with electron beams of 6 to 12 GeV, to look for quarks were made at SLAC, DESY, and CEA (Cambridge Electron Accelerator). They set limits[4] on quarks masses less than of the order of 1 GeV for charge 2/3 and 700 - 800 MeV for charge 1/3.

A CERN experiment using the SPS muon beam line has just been completed by the E.M.C. group. The first FODO system (600 m long) is used to transport a mixed muon-pion beam, produced on the internal target on to the Beryllium target (= 1 m long); the second FODO (300 m long) is used as a spectrometer to analyse for produced quarks. Six "Q" (12 cm x 12 cm, 2 cm thick) and six "p" (15 cm x 15 cm, 2 cm thick) scintillation counters are evenly distributed on the last 60 m of the second FODO. If the trigger, requiring a coincidence of the six "Q" scintillation counters and a sum of the pulse hights smaller than a predetermined value fires, then the pulse heights of the six "p" scintillation counters are read out. Data were taken for the three following conditions

1st FODO	2nd FODO	quark charge
+ 200 (GeV/c)	+ 250 (GeV/c)	+ 2/3
+ 200 "	- 250 ")	- 1/3
+ 200 "	- 50 ")	

Analysis of the data is now underway and the sensitivity of the experiment is as yet unknwon.

In e^+e^- collisions, the JADE experiment at PETRA has recently quoted[31] an upper limit of 0.1 for the cross-section for free quarks relative to $\mu^+\mu^-$, for a wide range of quark masses and Q = 1/3 or 2/3.

A promising future development seems to be the experiment proposed at PEP[32]. The reaction looked for is $e^+e^- \to q\bar{q}$ and the technique of measuring dE/dx and the time of flight in 8 layers of scintillation counters should allow the determination of the charge over a wide range of velocities. PEP 14 uses MWPC for track reconstruction. Each counter covers an angular region of $\Delta\Omega = (1/3)\ 4\pi$, so that the quark could be detected also if accompanied by a jet of hadrons. Taking:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 Q^2}{16E^2_{beam}} \beta \ (1 + \cos^2\theta_{prod} + (1 - \beta^2) \sin^2\theta_{prod} \qquad (2.6)$$

E_{beam} = 15 GeV and L = luminosity = $10^{31} cm^{-2} sec^{-1}$

PEP-14 would expect to have ∿ 6 events/day of charge 1/3 and ∿ 23 events/day of charge 2/3 up to masses of 8 GeV. Fig. 3 shows how the limits set by an e^+e^- machine like PEP or PETRA can be better than those from hadronic interactions. For comparison, one could imagine that a 100% efficient quark detection experiment at LEP could push the limit on R_Q to 10^{-7} for $m_Q \lesssim 45$ GeV using the Z^0 pole, and to 10^{-4} for $m_Q \lesssim 100$ GeV at the highest available LEP energies.

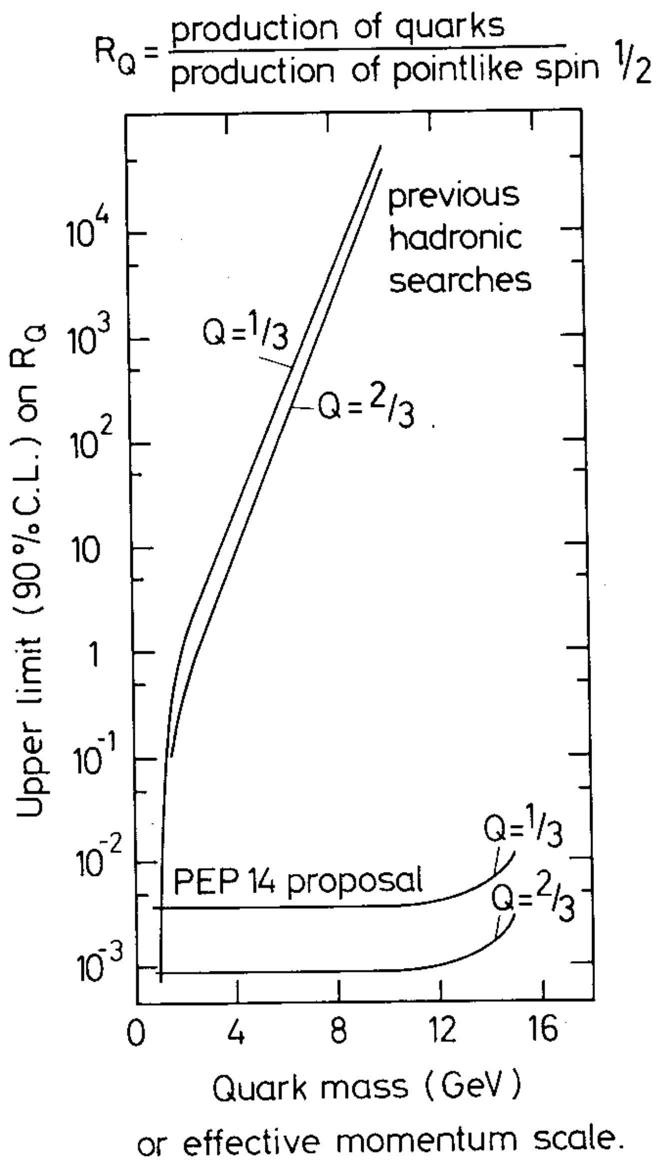


Fig. 3

2.1.3 Searches in stable matter

Quarks have been sought in meteorites, rocks at least 1 million years old, in the sea, and in lunar rocks. One method consists of heating the material, extracting the negative particles with an electric potential, and concentrating them on a filament used as source for a mass spectrometer. No quarks were found in such experiments.

Another method is to measure the charge of a droplet analogous to the classic Millikan experiment. In ref. 33 niobium balls of $\sim 9 \times 10^{-5}$ g are suspended in a magnetic field between two horizontal capacitor plates. In ref. 34 iron is used instead of niobium. The most recent results of these two experiments, which have been continuing for a long time, are: a negative result from the experiment of ref 34, which gives a limit on quark density:

$$\rho < 3 \times 10^{-21} \text{ quarks/nucleon} \qquad (2.7a)$$

and a positive result from experiment of ref. 33, in which 5 candidates are found with an average charge of $(0.325 \pm 0.008)e$. This implies that

$$\rho \gtrsim 1 \times 10^{-20} \text{ quarks/nucleon} \qquad (2.7b)$$

According to recent theoretical calculations[35], this may correspond to a quark mass of around 20 GeV. However, the positive signal[33] (2.7b) remains to be confirmed, though it does give hope that the previous cosmic ray and accelerator searches may not be the end of the story.

2.2 Fractionally Charged Quarks

In this subsection we consider the production and detection of "traditional" free quarks which have $Q = -1/3$ or $2/3$ and interaction cross-sections with matter which are smaller than those for conventional hadrons - motivated by the additive quark rule for calculating total cross-sections:

$$\sigma(h_1 + h_2) = \sum_{q \epsilon h_1} \sigma(q + h_2) \qquad (2.8)$$

In the next section we will consider an alternative[15] to this assumption which yields additional quark signatures. The two main techniques for detecting fractionally charged quarks are

A - Ionization Measurements
B - "Super-energy" measurements.

The first of these may be done in several different ways. One possibility, used in the PEP-14 experiment[32] mentioned earlier, is to measure the ionization with several scintillation counters. In order to determine β and reject background from lightly ionizing hadronic particles one should incorporate time-of-flight counters. A dedicated quark search experiment constructed along these lines and hence analogous to PEP 14[32] may work at LEP, through the relatively large granularity of scintillation counters may lead to problems when searching within high multiplicity final states. Another technique for measuring ionization would be to use a chamber (e.g. drift or streamer) which might already be installed for doing more conventional LEP-experiments. JADE, one of the general-purpose detectors at PETRA, has already reported[31] some preliminary results ($\sigma(e^+e^- \to Q\bar{Q}X)/\ \sigma(e^+e^- \to \mu^+\mu^-) \leq 0.1$) using their high pressure drift chamber. The main desiderata for a chamber to detect lightly ionizing particles are clearly a high density gas, and the possibility of frequent sampling of the tracks. These requirements conflict somewhat with the desiderata for a detector of strongly interacting quarks (see the next section), but are fine for the relatively weakly interacting quarks we discuss here. An important problem for these ionization-measurement detectors to contend with is the high probability that the quark emerges in a jet of hadrons. JADE has had no problem resolving jets at PETRA energies, while the fact that the average multiplicity is higher than anticipated from a naive logarithmic extrapolation of SPEAR results may cause disquiet for the PEP 14 experiment. One expects jets at LEP to be more collimated than at PETRA, particularly the faster particles among which one might expect to find the quarks.

The second type of quark search relies on a magnetic field and tracking for charged particles, together with a calorimeter to collect neutral particles. The idea is that quarks having fractional charge would be less bent magnetically than integer-charge particles and hence would appear to have a higher momentum. Adding together the magnetically "measured" momenta of the charged particles together with the energies of the neutrals one could then have events with "super-energy" where the total apparent energy exceeded the beam energy[36]. Shown in table 7 are approximate reconstructed final-state energies for different hadronic final states with and without quarks. The quarks are assumed to be leading particles with mass 5 GeV, and the centre-of-mass energy is taken to be 200 GeV.

Table 7 - Super-energy estimates (Taken from K.Winter, ref. 6)

Reaction	Reconstructed final-state energy (GeV)
$e^+e^- \to$ (hadrons) jet 1 + (hadrons) jet 2	200
$e^+e^- \to$ (u + hadrons) jet 1 + ($\bar{u}$ + hadrons) jet 2	230
$e^+e^- \to$ (d + hadrons) jet 1 + ($\bar{d}$ + hadrons) jet 2	340
$e^+e^- \to$ (hadrons) jet 1 + u + $\bar{u}$ + hadrons) jet 2	230
$e^+e^- \to$ (hadrons) jet 1 + (d + $\bar{d}$ + hadrons) jet 2	310

It is clear that events with final state neutrinos coming from weak decays would possess "sub-energy" rather than "super-energy". We can immediately read off from Table 7 the resolution in reconstructed energy necessary for such a "super-energy" detector. For comparison, present general-purpose detectors at PETRA report[37] an achieved energy resolution σ of about 5 GeV at $\sqrt{s}$ = 30 GeV, which would correspond to < 15 GeV at $\sqrt{s}$ = 200 GeV if one scaled the resolution as $E_{beam}^{1/2}$. Despise the probable existence of a non-Gaussian tail in the energy resolution, it therefore seems that the super-energy technique might be feasible, at least for final states with pairs of free quarks of charge 1/3.

2.3 Quarks with Appetite

It may well be that the additive quark model (2.9) argument for small interaction cross-sections of free quarks on ordinary matter is too naive. A counter-argument is that the electromagnetic interaction cross-section of a charged particle is known to be generally larger than that for a comparable neutral bound state, and that one might expect a free coloured particle to have a cross-section correspondingly larger than that for a conventional hadron with hidden colour.

A semi-quantitative model along these lines has been developed by de Rújula, Giles and Jaffe[15]. In their model colour is an exact global SU(3) symmetry, but the elementary gluons acquire a finite mass μ which causes the conventional confinement mechanism to break down. They then calculate[15] the properties of free physical quarks and gluons using a bag model[38]. The free quark Q is then a large lump of hadronic matter with

radius $$\rho_q \gtrsim O(\mu^{-1/3}) \tag{2.9}$$

and mass $$M_Q = \frac{1}{2\pi\alpha'\mu} + O(\mu^{1/3}) \tag{2.10}$$

where α' = 0.88 GeV^{-2} is the slope of conventional hadronic Regge trajectories. Free physical gluons G also form their own hadronic bags with

masses $$M_Q = 3/2\ M_Q + O(\mu^{1/3}) \tag{2.11}$$

The large physical quark and gluon bags can be regarded as cavities which can absorb ("eat") hadrons until the exclusion principle disfavours this process energetically. The number of nucleons which can be absorbed (eaten) by a physical quark is called its "appetite" A and has been estimated to be of order

$$A_Q \gtrsim M_Q / m_N \tag{2.12}$$

The large size (2.9) of a free quark and its non-zero colour lead one to expect[15] a large interaction cross-section with nucleons

$$\frac{\sigma_{tot}(QN)}{\sigma_{tot}(NN)} \gtrsim \frac{1}{4}\left(1 + \left(\frac{2m_Q}{m_N}\right)^{1/3}\right)^2 \tag{2.13}$$

At low quark energies E_Q where the centre-of-mass energy is comparable with the mass of the free quark:

$$E_Q \lesssim \left(\frac{2m_Q^2}{m_N}\right) \tag{2.14}$$

one would expect[15] a substantial part of the total cross-section (2.13) to involve the absorption by the quark of the nucleon which it hits as in Fig. 4a. At quark energies higher than (2.14) the bulk of the total cross-section (2.13) is probably inelastic. However, in a substantial fraction of the events the quark may eat some of the hadrons (mainly pions) produced in the collision, as illustrated in Fig. 4b, thereby altering its charge and mass.

An important consequence of the large size (2.9) of physical free quarks is that one expects them to have form-factors which are not pointlike. If one regards the quarks as having a uniform charge distribution over a sphere of radius

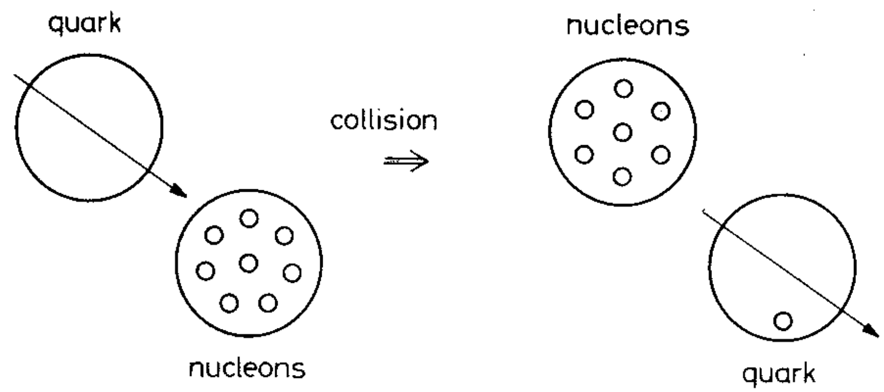


Fig. 4a

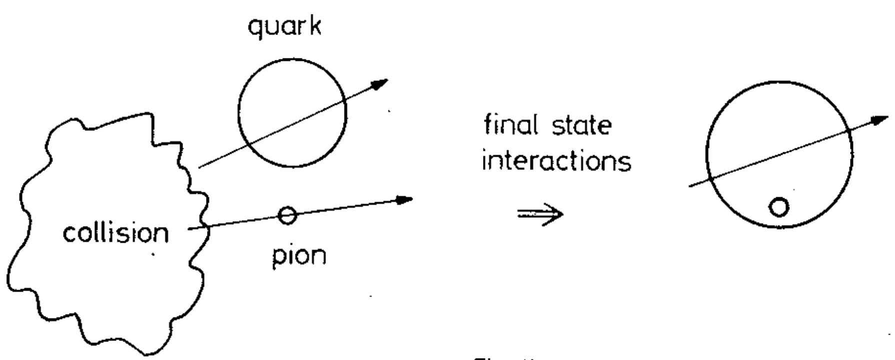


Fig. 4b

R_Q, then one might guess a form factor

$$F_Q\,(q^2) \sim \frac{1}{(1 + q^2R_Q^2/10)^p} \qquad (2.15)$$

where the power p depends on dynamics which we do not yet understand. If we have p = 1 (a monopole form factor) then we get the predictions[15] of Fig. 5 for the exclusive production of free quark-antiquark pairs:

$$R_Q^{exc.} \equiv \frac{\sigma(e^+e^- \to Q\bar{Q})}{\sigma(e^+e^- \to \mu^+\mu^-)} \gtrsim e_Q^2\,(1 - \frac{4m_Q^2}{q^2})^{1/2}\,(1 + q^2R_Q^2/10)^{-2p} \qquad (2.16)$$

which leads to unobservable cross-sections at LEP energies even if m_Q = 1 GeV. However, one might guess a much larger cross-section for the inclusive production of free quarks with extra hadrons. Perhaps it is

$$R_Q^{inc.} \equiv \frac{\sigma(e^+e^- \to Q\bar{Q}X)}{\sigma(e^+e^- \to \mu^+\mu^-)} \gtrsim e_Q^2\,(1 - \frac{4\,m_Q^2}{q^2})^{1/2}\,(1 + \frac{4m_Q^2\,R_Q^2}{10})^{-2p} \qquad (2.17)$$

which yields the inclusive cross-section predictions of Fig. 6. In this inclusive model, quarks with masses $\leq$ 5 GeV should be visible at the Z^0 peak. They would also of course be kinematically accessible in lower energy experiments such as those at PETRA. But the rate of production, even for quarks of mass 1 GeV, is seen from Fig. 6 to be far below the present experimental limits from JADE[31] and other PETRA experiments. However, this conclusion rests on the ansatz that p = 1 in the form factor (2.15), which may well be too pessimistic. The prediction for m_Q = 1 GeV is comparable with the limits (Fig. 3) which the PEP 14 experiment[32] hopes to establish, and much below the limits from previous hadronic searches[4]. One should of course not take seriously the details of the cross-section estimates (2.16, 2.17), but they do emphasize the possibility that the quarks to be seen at LEP may have masses relatively low. But even such low-mass quarks may not have been excluded previously by previous lower energy experiments.

How would one detect quarks with appetite ? For quarks with masses $\geq$ 3 GeV, the criterion (2.14) suggests that the bulk of them will eat nucleons when they make nuclear collisions. This is because at the Z^0 peak one expects that leading particles in jets should have a mean energy $\lesssim$ 20 GeV while non-leading particles should have still lower energies, and the formulae (2.16, 2.17) suggest that the bulk of free quarks will be produced in inelastic collisions. Lighter- or very

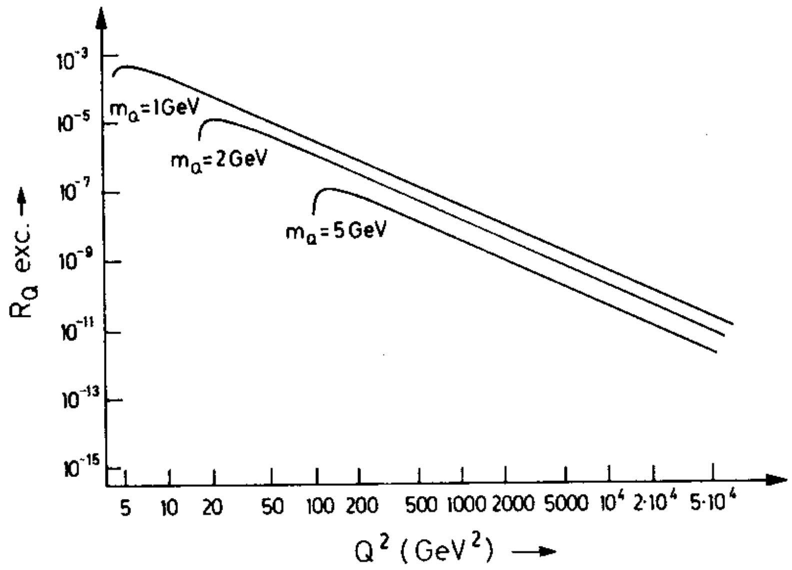


Fig. 5

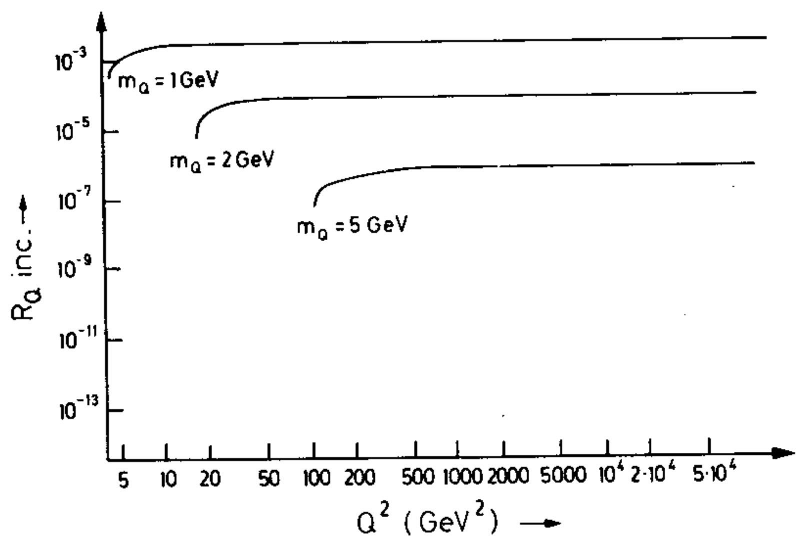


Fig. 6

energetic-quarks not respecting the condition (2.14) may also change charge and mass in collisions, as discussed above. Therefore a very distinctive signature for quarks with appetite would be a change in charge and mass during an inelastic collision in the apparatus (see Fig. 4). One should also be alert to the possibility that the free quark is not produced with charge $\pm$ 1/3 or $\pm$ 2/3. It may eat charged pions or other hadrons during the initial production process and have larger charge ($\pm$ 4/3, $\pm$ 5/3, ...). A conceptual sketch of a detector "Copernicus" for quarks with appetite is shown in Fig. 7: it would also be able to detect traditional fractional charged quarks. After an initial measurement of its ionization and mass, one allows the quark to interact (formula (2.13) suggests a cross-section of order 100 mb for a quark of mass 5 GeV) and then remeasures it. This procedure may be repeated several times, if possible. It would seem possible to try this procedure within a conventional general-purpose LEP detector through a dedicated experiment might do somewhat better.

One should also bear in mind the possibility that the quark mass is very large, or that formula (2.13) is wrong, so that the QN cross-section is so large that a significant fraction of the quarks produced may get trapped in the beam-pipe. It would be desirable to be able to investigate this possibility by removing the portion of the beam-pipe close to the interaction region and searching for free quarks by traditional chemical methods, as used during the searches in stable matter described in subsection 2.1.3.

We should make some final remarks about free physical gluons with appetite. They should be rather heavier (2.11) than free quarks, and probably have a larger hadronic interaction-cross-section. On the other hand their production rate is presumably smaller than that for quarks except in the decays of very heavy onia - if they exist. Free gluons would possess the same charge- and mass-changing signatures as quarks. They would of course lack the fractional charge signature, but the other signatures should be enough to permit their detection, for example in the scheme of Fig. 7.

2.4 Indeterminate Mass Quarks

Many models have been studied in attempts to understand confinement and its possible breakdown. If quarks are confined they do not appear as asymptotic states of the theory, and the quark propagator therefore cannot have an isolated pole. It may then either be an entire function, or just have cuts in the complex momentum plane, such as

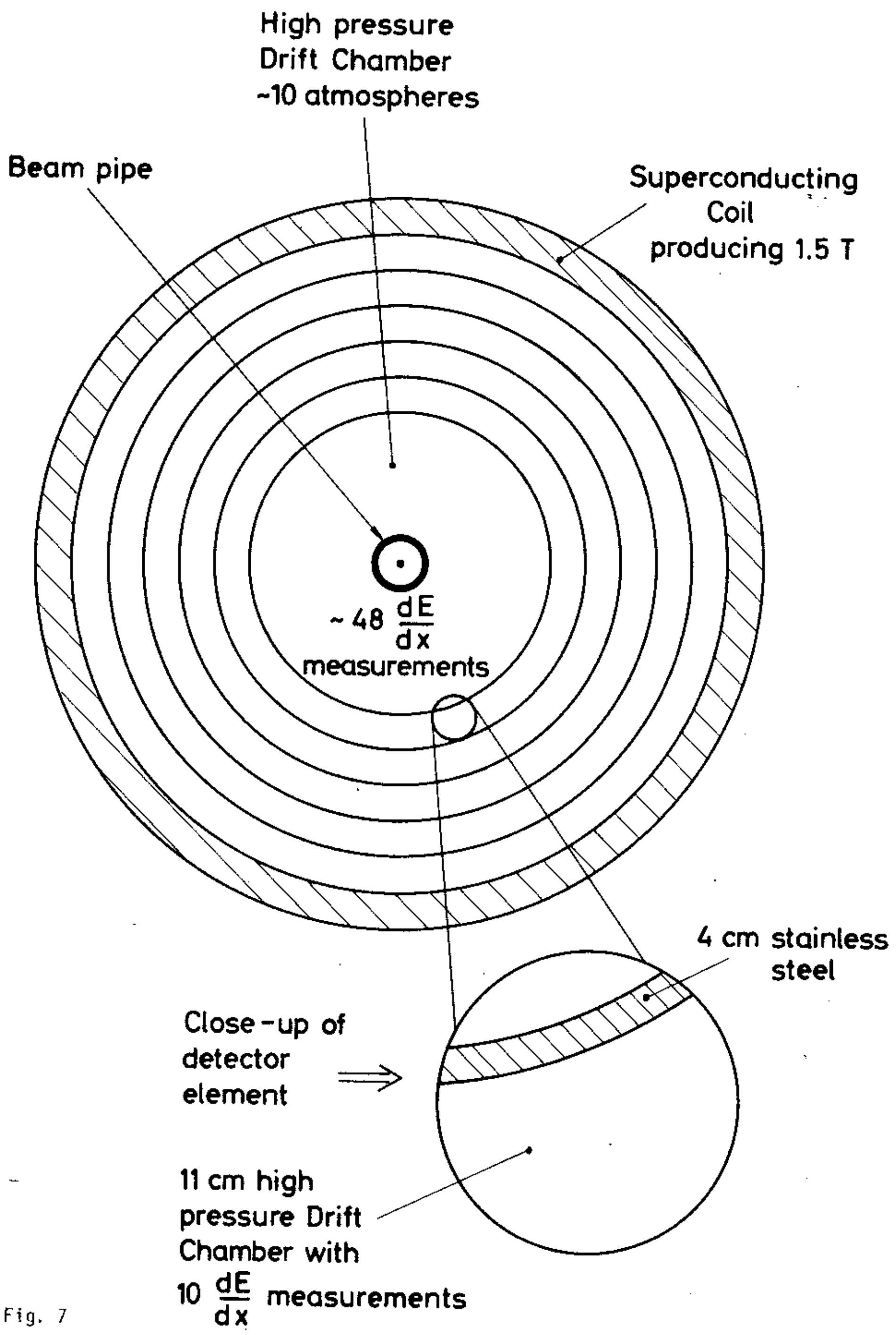


Fig. 7

$$\frac{1}{k^2 - m^2} \rightarrow \ln(k^2/\mu^2) \quad \text{or} \ (k^2 - m^2)^{1/2} \ \text{or} \ \ldots \tag{2.18}$$

Examples of this type of behaviour have been found in some two-dimensional field theories[39]. What are the phenomenological properties of such indeterminate mass particles[17] (IMPs) ?

Since such an object may be regarded as the superposition of an infinite number of infinitely closely spaced energy levels, its wave function will spread out as a function of time

$$\psi(x,t) = \int d\sigma\{\exp i\ (E_\sigma t - p\ x)\}\ f(\sigma); \quad E_\sigma^2 = p^2 + \sigma^2 \tag{2.19}$$

and its size will grow without limit. This certainly guarantees the absence of asymptotic states. In the absence of any detailed and realistic model we have no clear idea how rapid the expansion velocity v of an IMP might be, but no good reason is seen[17] why v should differ substantially from the velocity of light. For the purposes of general orientation, we consider an IMP which expands at a velocity $v \sim 1/10$ c. If its expansion rate were substantially higher than this it is difficult for us to see how it could even be recognized as a particle. If the quark is produced with a highly relativistic velocity $\sim$ c, then it will appear as a Lorentz-contracted disc which grows geometrically like the base of a cone as one progresses further and further from the vertex point at the e^+e^- interaction region, as illustrated in Fig. 8.

The phenomenology of IMP's then depends crucially on a question of interpretation of the literature[17] which does not seem to us to be perfectly clear. Is an IMP like a jelly (interpretation J) with no granularity in the distribution of strong, weak and electromagnetic charge within the expanding space it occupies (as in Fig.9a)? Or is an IMP like a dust cloud (interpretation D), with one or more small scattering centres moving around in the large and expanding volume of space (as in Fig. 9b)? One could even envisage mixed possibilities, with the charges of some interactions distributed, and the charges of others localized. Here we just consider interpretation J which seems to be that advocated by McCoy and Wu[17], and interpretation D which seems to us more physical and has been advocated to us by ourselves and by J.S.Bell[40].

According to interpretation J, when the IMP expands to a size somewhat larger than a typical atomic size r_A it will no longer be able to ionize

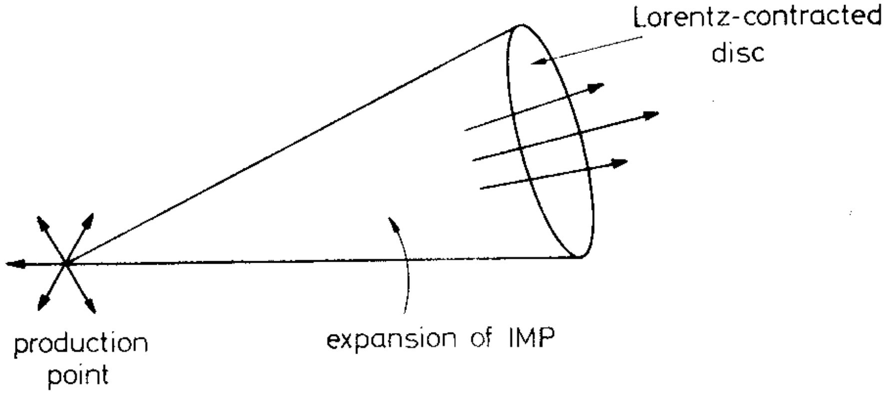


Fig.8

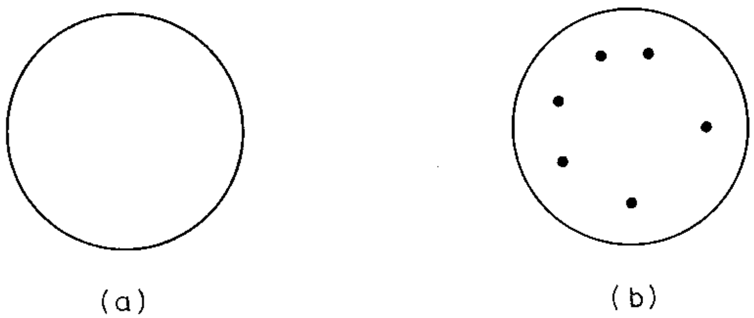


Fig. 9

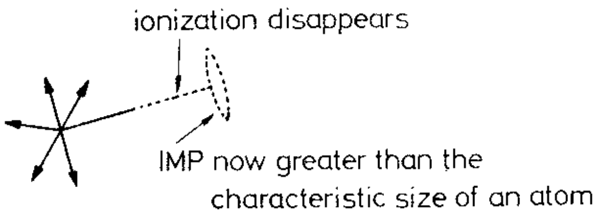


Fig. 10

because the electric field intensity at any point within the region occupied by the IMP will be smaller than that due to the atom itself, so that electrons will not be kicked out. If produced highly relativistically the IMP will have expanded to a size >> r_A when at a distance

$$d \gg \frac{r_A}{v} \qquad (2.20)$$

from the interaction point. An IMP signature would therefore be a track which ionizes close to the interaction point and then fizzles out[17]. Unfortunately, for realistic ($v \gtrsim 1/10\ c$?) expansion velocities this fizzling out is likely to occur a fraction of a millimetre away from the interaction point. Discussions with machine physicists[41] indicate that since the LEP beam width is very small in the vertical direction ($\sigma \approx 20\ \mu$), it might in principle be possible from a machine point of view to bring "Roman pot" devices to within a few σ of the interaction point as in Fig. 11. Unfortunately, it is unclear that any sort of ionization detector could function in the very hostile electromagnetic invironment so close to the interaction point (see Fig. 11). Getting a detector closer to the interaction point than the exterior of the beam-pipe might be interesting for other reasons (looking for finite track lengths due to weak decays of heavy fermions, for example), but it seems very unlikely to be a competitive way of searching for IMPs according to interpretation J. Similar remarks apply to the detection of IMPs by Cerenkov radiation which relies on a molecular polarization effect which has an intrinsic scale not very different from r_A (2.20). This is unfortunate because an IMP would have a distinctive Cerenkov disc or annulus image rather than the ring (Fig. 12a) produced by a particle of definite mass and β:

$$\cos\theta = \frac{1}{\beta \cdot n} \quad : \quad n \equiv \text{index of refraction} \qquad (2.21)$$

We see that according to interpretation J, it would be much better to use ionization or Cerenkov radiation effects to look for IMPs in experiments at accelerators where one can observe the interaction vertex directly, e.g. in emulsion experiments at fixed target hadron accelerators.

Even after a J-IMP has expanded beyond atomic or molecular size and looks superficially electrically neutral, it may still have some interactions with matter in the experimental apparatus. For example, if a J-IMP passes through a magnetic field, it will experience a force acting coherently on all the jelly-like distribution of charge within it, and so be bent just like an ordinary particle[17] as in Fig. 13. The back-reaction of the J-IMP on the magnetic field is of course undetectably small, so the only question is whether one could detect the J-IMP after deflection. One could either look for it in places geometrically

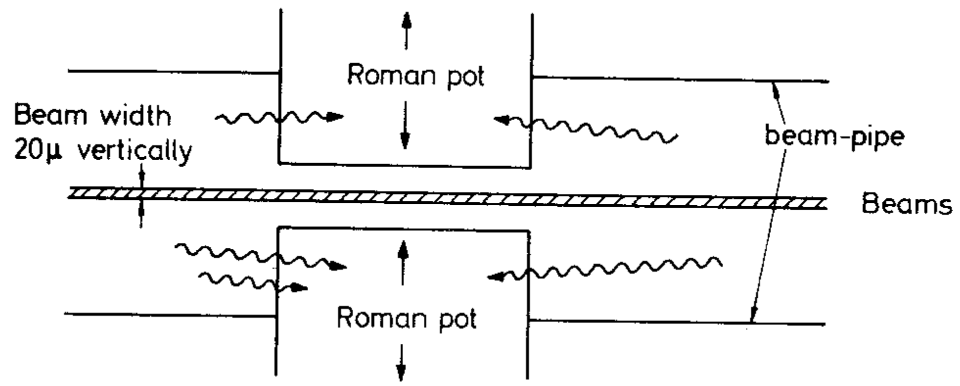


Fig. 11

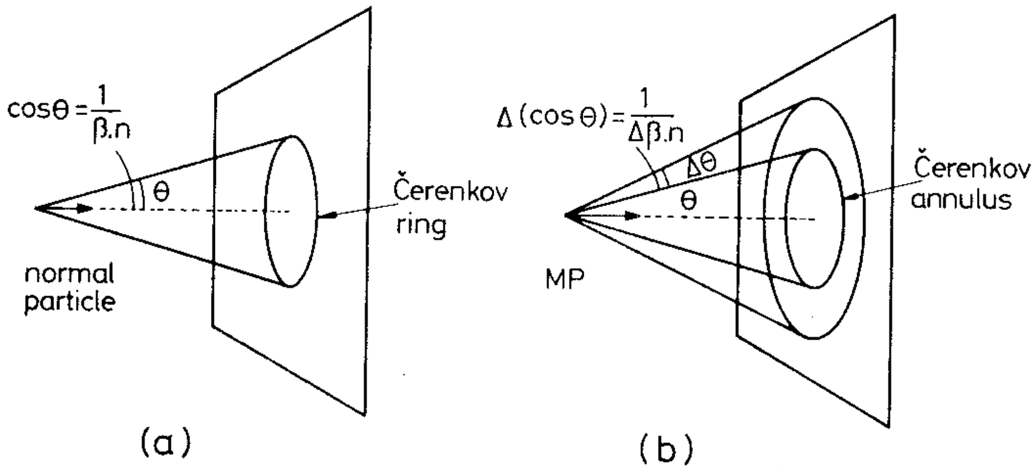


Fig. 12

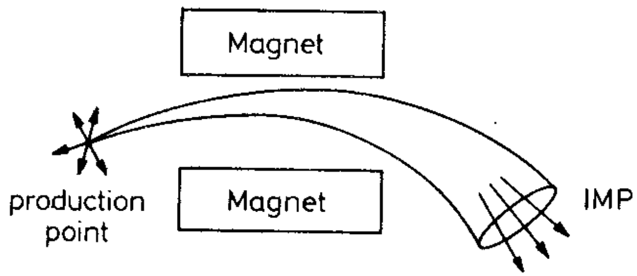


Fig. 13

inaccessible to neutral particles (IMP traps - see Fig. 14a) or set up a directional calorimeter (c.f. the CERN CHARM experiment) to look for showers which do not point back to the e^+e^- interaction point as in Fig. 14b. The feasible angular resolution in such a detector seems to be

$$\Delta_R\theta(\text{radians}) \sim \frac{1}{10\sqrt{E\,(\text{GeV})}} \qquad (2.22a)$$

whereas the bending angle for a particle of charge 1/3 passing through a magnet is

$$\Delta_M\theta(\text{radians}) \sim \frac{0.1}{E(\text{GeV})}\int Bdl \quad (\text{Tesla-metres}) \qquad (2.22b)$$

In order for the deflection (2.22b) to be detected, we would need it to be larger than $\Delta_R\theta$ (2.22a) and hence for an IMP energy of 25 GeV

$$\int Bdl \quad > \quad 5 \text{ Tesla-metres} \qquad (2.23)$$

which seems feasible for a detector magnet. It is not clear to us whether such a directional calorimeter would be interesting for any other experiments at LEP. Moreover, it seems to us quite likely that a J-IMP would not deposit all its energy in a calorimeter in the usual way. The hadronic matter in a region of radius r_N of an expanded disc of radius r_I of jelly would only be a fraction

$$f \gtrsim (r_N/r_I)^2 \qquad (2.24)$$

of the total. Thus on the one hand we would expect (See Fig. 15) the scattering cross-section on an individual nucleus to be much smaller than that for a concentrated blob of hadronic matter - e.g. an IMP shortly after production. On the other hand the J-IMP's large radius exposes it to interactions with a large number of nuclei as potential scattering centres as in Fig. 15. On yet another hand, each time the J-IMP has a collision, the small fraction f (2.24) of it which actually interacts will only contain a similar fraction f (2.24) of the total IMP energy, which will typically be too small to exite single pion emission, or as we saw before, even to ionize an atom. We therefore expect the J-IMP to scatter elastically and lose almost none of its energy in any plausible calorimeter[42].

We should mention one other idea that has been suggested[17] for an IMP search, namely looking for weak decays of heavy quark IMP's, e.g. $s_{IMP} \to u_{IMP}$ + hadrons. Because of the large size of the IMP its resultant absence of ionization would cause the hadrons to appear to spring out of the vacuum. The problem with this idea is that the valence part of a J-IMP has such a large extent that the form factor $F(q^2)$: $q \gtrsim m_\pi$ for weak emission of hadrons can be expected to be very

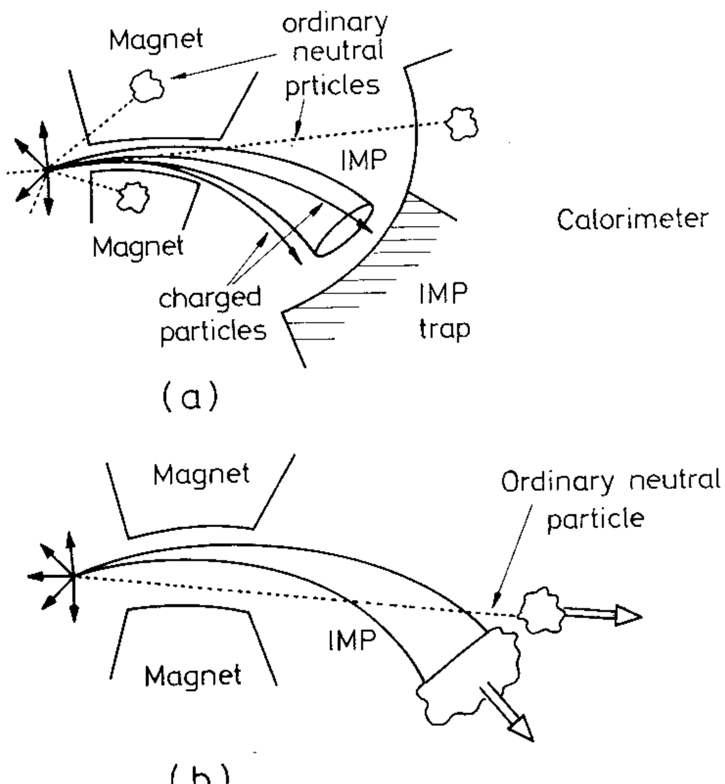


Fig. 14

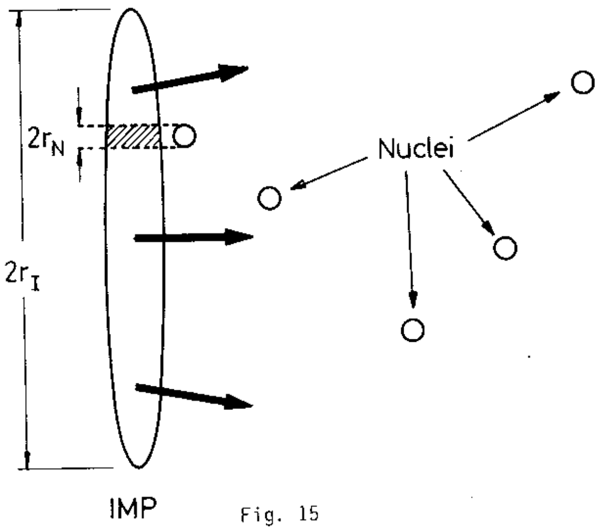


Fig. 15

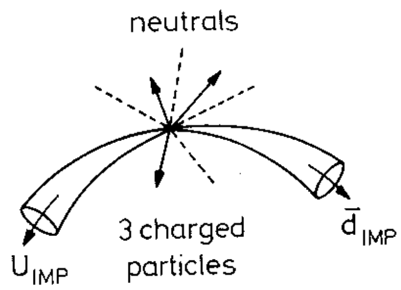


Fig. 16

strongly suppressed by some negative power of $(q^2 r_I^2)$. Thus one expects J-IMPs to live for a very long time, and one can even argue that their lifetime will in fact be infinite[43]. This does not therefore seem to be a promising way of detecting J-IMPs.

Is there any way of detecting a J-IMP at LEP ? The only possibility we can think of consists to look for events which do not appear to conserve charge, as well as energy and momentum. These could arise from events of the type illustrated in Fig. 16:

$$e^+e^- \to u_{IMP} + \bar{d}_{IMP} + (\text{hadrons})^- \quad \text{or} \quad \bar{u}_{IMP} + d_{IMP} + (\text{hadrons})^+ \tag{2.25}$$

The charges of the u_{IMP} and $\bar{d}_{IMP}$ would not be detectable, by the previous chain of arguments. The only question is whether a non-zero hadronic charge of the type (2.25) could be detected at all. To remove beam-gas background one could select on the longitudinal momentum imbalance. The main background is likely to be $e^+e^- \to (\text{hadrons})^0$ events where some particles go down the beam-pipe and one or more of them are undetected. This seems inevitable, and it is difficult to see how to design a LEP experiment which could establish significant upper limits on charge non-conserving events.

The prospects for detecting dust-cloud D-IMPs (Fig. 9b) seem rather brighter. The more-or-less point-like flecks of dust moving about inside them would produce the conventional anomalously low ionization signature of a fractionally charged particle. A distinctive signature would be that because of the variable velocities of flecks within the dust cloud, one could expect to see a Cerenkov disc or annulus rather than a ring, as in Fig. 12. A D-IMP would presumably be re-flected by a magnet in a perfectly normal way as in Fig. 13, however, the de-flection of the D-IMP would be

$$\sim \Big(\sum_{\text{flecks}} e_{\text{flecks}}\Big)^2 \tag{2.26a}$$

whereas the ionization would be

$$\sim \sum_{\text{flecks}} (e_{\text{fleck}})^2 \tag{2.26b}$$

and the possible difference between (2.26a) and (2.26b) might be another useful signature. Assuming that the total number of flecks is at most a few, one would expect each one of them to carry a substantial fraction of the total D-IMP momentum, and that each fleck would have more or less normal hadronic cross-section with nuclear matter in a calorimeter. One would therefore expect D-IMP's to be detectable in calorimeters in the normal way as in Fig. 14. There is also no reason to expect any anomalously long lifetime for weakly decaying D-IMP's. However, we have seen that there are two possible signatures (a Cerenkov annulus or disc, and anomalous electromagnetic properties (2.26)) which might serve to distinguish a D-IMP from a conventional fractionally charged quark.

2.5 Integer charged quarks

While most theorists believe that the local SU(3) colour symmetry is exact, it has often been stressed[16] that a viable alternative is to have SU(3) broken in such a way that all the quarks are not identical. It is generally felt that in the former case quarks would be confined - through this has not been proved definitively at the time of writing - and that quarks would not be confined if SU(3) were a broken symmetry. In section 2.3 we discussed the possibility that while SU(3) was locally broken, it was globally unbroken with all the quarks having identical weak and electromagnetic charges and the gluons acquiring an identical mass. Historically, a prior suggestion was that SU(3) colour was globally broken by the weak and electromagnetic interactions, so that quarks of different colours but the same conventional "flavour" have, for example, different electromagnetic charges[16].

The most natural possibility is that the quarks have integer charges which give the standard fractional charges when averaged over all the colours. It is generally felt that such quarks would be unconfined, as would be the charged and coloured gluons of such a theory.

Gauge theory models with integer-charged quarks have been proposed[16], and in this section we discuss the phenomenology of such theories[44]. In the favoured model the octet of gluons have masses in the range 1 to 10 GeV, and baryon and lepton numbers are violated, so that quarks can decay into leptons. One expects decay modes such as

$$q \to \nu + \text{mesons} \qquad (2.27a)$$

with lifetimes

$$\tau_q \gtrsim \frac{10^{-10} \text{ to } 10^{-11}}{(m_q(\text{GeV}))^3} \text{ seconds} \qquad (2.27b)$$

at least for lighter quarks where conventional baryon number conserving decays such as $q' \to q + (q + \bar{q})$ or $q + (\ell + \nu)$ are kinematically forbidden or suppressed. It is suggested[44] that theories with integer-charge quarks provide a natural explanation of the observation of jet structures in e^+e^- annihilation[9] and elsewhere: it is clear from (2.27a) that quark jets from such a source would have large amounts of missing neutral energy. It has been pointed out that there are essentially two alternative patterns for quark decays.

Either

a) All quarks decay into neutrinos and mesons as in (2.27a), without emitting charged leptons, or

b) two colours of quarks (called yellow and blue) and the neutral red quark (u_R^o, c_R^o, t_R^o, ...) decay as in (2.27a), while the charged red quark (d_R^-, s_R^-, b_R^-, ...) decays into charged gluons and neutrinos, and the charged gluons subsequently decay into ($\ell^- \nu$) or into hadrons:

$$(d_R^-, s_R^-, b_R^-, \ldots) \rightarrow V^- + \nu \qquad (2.28)$$
$$\quad\quad\quad\quad \llcorner\!\!\rightarrow (e\nu), (\mu\nu), (\tau\nu), \text{hadrons}$$

This latter decay pattern holds if the charged red quarks are heavier than the charged gluons. For some time it seemed possible that the eμ events[45] generally associated with the τ lepton[46] might be interpretable as charged u and d quark production and subsequent decay according to (2.27a) or (2.28). This interpretation now seems unlikely in view of the discovery of the b quark (to restore quark-lepton symmetry) and the point-like behaviour of the τ lepton on momentum scales up to a cut-off greater than 50 GeV[47]. It is difficult to see how a strongly interacting quark could have an elastic form factor of essentially unity all the way up to Q = 30 GeV. However, the possibility that an integer-charge quark might mimic many of the signatures of a heavy lepton should be borne in mind during heavy lepton searches at LEP.

A more detailed breakdown[44] of the likely decay pattern if quark decays in the presence of conservation of fermion number F = B + L is shown in Table 8. We would expect that since the bulk of the decays in Table 8 are basically 3-body, as the mesonic systems spring from primordial $q\bar{q}$ origins. We would also expect that above the quark liberation threshold the fraction of the total energy carried off by neutrinos would be approximately

$$FE(\nu) \quad \gtrsim \quad 1/3 \; (F_q(Q^2))^2 \qquad (2.29)$$

where the quark electromagnetic form factor appears as $F_q(Q^2)$ in equation (2.29). If $F_q(Q^2)$ is not too small, a signature for the quark liberation threshold might be a jump in the unobserved neutral energy fraction. It should also be noted that in a liberated integer-charge quark model both jets should individually have large missing energy unlike the case of pair production of heavy quark-antiquark pairs, where usually only one at a time decays semileptonically emitting unseen neutrinos. Notice that

in the event that $m(q_p^-) > m(V^-)$ so that decays of d_R^- and s_R^- into charged vector gluons occur (see Table 8) then neutral energy fractions even larger than (2.29) are possible because the gluons may also decay into neutrinos, interaction. One may also look for the direct production of charged vector gluons:

$$\frac{\sigma(e^+e^- \rightarrow V^+V^-)}{\sigma(e^+e^- \rightarrow \gamma \rightarrow \mu^+\mu^-)} = \frac{1}{8} \; (F_V(Q^2)^2$$

where $F_V(Q^2)$ is the gluon electromagnetic form factor. A distinctive signature for charged vector gluon production is of course a bump in a dijet invariant mass distribution form $V \rightarrow q\bar{q}$. One can also imagine signatures for $e^+e^- \rightarrow V^+V^-$, $V^- \rightarrow e\nu$ or $\mu\nu$. If the other V decays into hadrons, it defines on jet axis for the event as in Fig. 17. Now measure the p_T of the lepton transverse to the projection of the jet axis into the opposite hemisphere as in Fig. 17. In an idealized world it would exhibit a Jacobian peak because of the two-body $V \rightarrow \ell\,\nu$ phase space as in Fig. 18. In practice, this signature will be obscured by the possible production of extra associated hadrons, and by the finite angular resolution of the jet axis of the other V. One would expect the energy spectrum of the lepton to be peaked at $m_V/2$ if the associated production of hadrons is small. One would of course expect the dijets from the decay of the other V to exhibit an invariant mass peak.

It is clear from this discussion that the prime consideration for detecting inter-charge quarks and gluons is calorimetry, with the ability to pinpoint the energy and angle of outgoing unobserved neutrinos, with lepton idenfification to pick up V decays. While it would be nice to check and refute or confirm the more detailed predictions of Table 8 for the quantum numbers of outgoing mesonic systems, this could presumably be left for a second generation of integer-charge quark studies after the initial discovery!

Table 8 - Possible[44] decays of integer-charge quarks *)

u^+, $d^0_{Y,B}$	→	ν_e + (non strange meson systems) ν_μ + (strange meson systsms)
$s^0_{Y,B}$	→	ν_μ + (ss meson systems) ν_e + (strange meson systems)
$c^+_{Y,B}$	→ → →	ν_e + (charmed meson systems) ν_μ + ($c\bar{s}$ meson systems) $s^0_{Y,B}$ + (charged meson system, dominantly non strange)$^+$ └→ ν_e or ν_μ + (mesons)
$d^0_{Y,B}$	→	$u^0_R + \gamma$ (dominant if $m(u^0_{y,B}) > m(u^0_e)$)
u^0_R	→ →	$d^0_{Y,B} + \gamma$ (dominant if $m(u^0_e) > m(d^0_{y,B})$) ν_μ + (non strange meson systems)
c^0_R	→	$s^0_{Y,B} + \gamma$ └→ ν + (mesons)

and if $m_R - m_Y < m_\pi$:

$(d^-, s^-)_R$	→	$V^- + \nu$ (if $m(q^-_R) > m(V^-)$) └→ $e\nu$, $\nu\mu$, $\tau\nu$, hadrons
d^-_R	→	ν_μ + (non strange mesons)
s^-_R	→	ν_μ + (strange mesons)

while if $m_R - m_Y > m_\pi$:

q^-_R	→	$q^0_{Y,B}$ + (mesons)$^-$ └→ ν + (mesons)

*) For all except the lightest quarks of a given colour, Baryon number conserving decays such as $q' \to q + (q + \bar{q})$ or $q + (\ell + \nu)$ might be dominant.

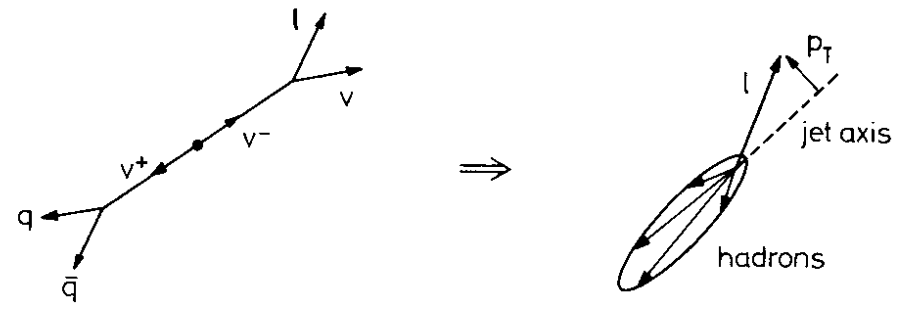


Fig. 17

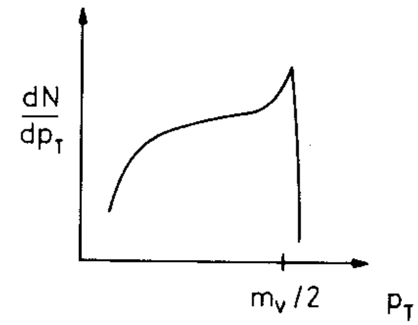
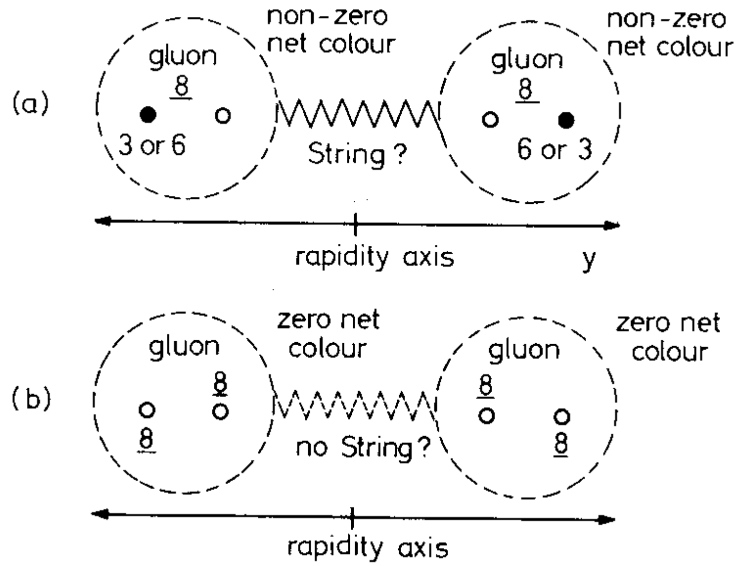


Fig. 18



2.6 Quarks with non-standard colour

While most of this report is concerned with the detection of free, physical quarks, it also seems an appropriate place to review the properties of confined quarks which have unusual, i.e. non-triplet, colour. Examples which have been proposed include colour sextets and octets[18]. The aspects which we will discuss are the e^+e^- continuum above threshold, onium spectroscopy and decays, and the weak decays of quarks with non-standard colour.

The total cross-section for colour triplet $q\bar{q}$ production is expected to be

$$R \equiv \frac{(e^+e^- \to \gamma^* \to q\bar{q})}{(e^+e^- \to \gamma^* \to \mu^+\mu^-)} = 3 \sum_q e_q^2 \qquad (2.31)$$

where the 3 is the number of quarks in each colour representation. Correspondingly we expect

$$R = (6 \text{ or } 8) \sum_q e_q^2 \qquad (2.32)$$

for colour sextet or octet fermions, respectively. Thus the first signal for non-triplet $q\bar{q}$ production would be an anomalously large threshold rise. The final state might exhibit some unusual features, depending on one's picture of hadronization. In a naive string or bremsstrahlung picture it has been suggested[48] that one might expect the multiplicities in gluon and colour triplet quark jets to be the ratio of two colour casimirs

$$\frac{\langle N_G \rangle}{\langle N_3 \rangle} = 3/(4/3) = \frac{9}{4} \qquad (2.33)$$

The corresponding statements for jets from colour sextet or colour octet fermions would be

$$\frac{\langle N_6 \rangle}{\langle N_3 \rangle} = (10/3)\,/\,(4/3) = \frac{5}{2} \qquad (2.34a)$$

$$\frac{\langle N_8 \rangle}{\langle N_3 \rangle} = 3\,/\,(4/3) = \frac{9}{4} \qquad (2.34b)$$

It would be interesting to see whether the naive ideas (2.33, 2.34) are correct. However, doubts have been expressed, particularly with regard to the string picture for final states generated by heavy colour octet quarks. It has been

argued[49] that the octet colour in contrast to triplet and sextet colour as in Fig. 19a, can be "bleached" by the appearance of a gluon close in rapidity to the colour source as in Fig. 19b. This has the effect of removing the colour flux normally regarded as polarizing the vacuum in between the primordial fermion-antifermion pair and creating a string, so that the multiplicity in the final state of octet production might be very small. However, it is not at all clear that the hadronic final state really evolves according to a string picture at all, even in the case of primordial $e^+e^- \to q(\underline{3})\,\bar{q}(\bar{\underline{3}})$. Recent ideas[50] suggest that the gross features of the hadronic final state are determined by perturbative phenomena at large momentum transfers, and that the nonperturbative phenomena described by the string picture only affect the final stage of hadronization. In this view they should not affect the general behaviour of the multiplicity, at least that of the heavy quarks which have been discussed reasonably rigorously[51]. Because of these different competing viewpoints, measurements of the multiplicities in jets generated by primordial quanta belonging to different colour representations ($\underline{3}$, $\underline{6}$, $\underline{8}$, ...) would be very interesting.

It seems that clear and definite tests of the colour content of a fermion can be made using the spectroscopy, decay rates and branching ratios of the associated heavy onia. It is generally believed that the fermion-antifermion potential in QCD has a Coulombic piece at short distances and a linear rise at large distances:

$$V(\underline{r}) = -\frac{4}{3}\frac{\alpha_s(\underline{r})}{|\underline{r}|} + L\,|\underline{r}| \qquad \text{for } \underline{3}\cdot\bar{\underline{3}} \qquad (2.35)$$

Simple colour Clebsch-Gordon coefficients then suggest

$$V(\underline{r}) = -\frac{10}{3}\frac{\alpha_s(|\underline{r}|)}{|\underline{r}|} + \sqrt{2}\cdot s\ L|\underline{r}| \qquad \text{for } \underline{6}\cdot\bar{\underline{6}} \qquad (2.36)$$

and

$$V(\underline{r}) = -3\,\frac{\alpha_s(|\underline{r}|)}{|\underline{r}|} + (?)\,L\,|\underline{r}| \qquad \text{for } \underline{8}\cdot\bar{\underline{8}} \qquad (2.37)$$

with the (?) in (2.37) reflecting the possibility of the linear string-like potential being bleached. One then has simple predictions[18] for the ratios of mass differences in $\underline{6}\cdot\bar{\underline{6}}$ and $\underline{3}\cdot\bar{\underline{3}}$ spectroscopy:

$$(V \equiv {}^3S_1) \qquad \frac{m(V_6') - m(V_6)}{m(V_3') - m(V_3)} = \left(\frac{m_6}{m_3}\right) \left(\frac{\alpha_s(m_6)}{\alpha_s(m_3)} \times \frac{10/3}{4/3} \right)^2 \tag{2.38}$$

$$\rightarrow \quad 6.25 \text{ if } \quad m_3 = m_6$$

if the states lie in the Coulomb region of the potential (2.36), and

$$\frac{m(V_6') - m(V_6)}{m(V'_3) - m(V_3)} = \left(2.5 \frac{m_3}{m_6} \right)^3 \tag{2.39}$$

$$\rightarrow \quad 1.36 \text{ if } m_3 = m_6$$

if the states lie in the linear region of the potential (2.36). The corresponding predictions for 8 - $\bar{8}$ bound states can be seen immediately from (2.37). It would be particularly interesting to investigate higher excited states of the 8 - $\bar{8}$ spectroscopy to see whether the string-like part of the potential - normally associated with "Regge recurrences" - is indeed absent. There are also predictions[18] for other mass differences:

$$(P \equiv {}^1S_0) \qquad \frac{M(V_6) - m(P_6)}{m(V_2) - m(P_3)} = 2.5 \; \frac{\alpha_s(m_6)}{\alpha_s(m_3)} \; \frac{m_3^2}{m_6^2} \; \left| \frac{\phi_6^2(0)}{\phi_3^2(0)} \right|^2 \tag{2.40}$$

$$\rightarrow \quad 2.5 \quad |\phi_6(0)|^2/|\phi_3(0)|^2 \text{ if } m_3 = m_6$$

where the $\phi_n(0)$ are the values of the wave-functions at the origin. We expect these to be sensitive to details of the potential (2.35, 2.36, 2.37). If the $\phi_n(0)$ are determined by the Coulombic part of the potential, then we expect[18]:

$$|\phi_6(0)|^2 \; / \; |\phi_3(0)|^2 = \left(\frac{10}{4} \right)^3 = \frac{125}{8} \tag{2.41a}$$

$$|\phi_8(0)|^2 \; / \; |\phi_3(0)|^2 = \left(3/\frac{4}{3} \right)^3 = \frac{729}{64} \tag{2.41b}$$

for comparable masses of quarks. In addition to the implications (2.40) for spectroscopy, the results (2.41) also have implications for the decay rates of heavy onia. For example, they suggest[18]

$$\Gamma(V_3 \rightarrow \mu^+\mu^-) : \Gamma(V_6 \rightarrow \mu^+\mu^-) : \Gamma(V_8 \rightarrow \mu^+\mu^-) = 1 : \frac{125}{4} : \frac{243}{8} \tag{2.42}$$

For ratios of transitions, which are independent of the values of the wave functions at the origin, one has

$$\left.\begin{array}{l} \dfrac{\Gamma(V_8 \rightarrow 2g + \gamma)}{\Gamma(V_8 \rightarrow \mu^+\mu^-)} \Big/ \dfrac{\Gamma(V_3 \rightarrow 2g + \gamma)}{\Gamma(V_3 \rightarrow \mu^+\mu^-)} = 5.06 \\ \dfrac{\Gamma(V_6 \rightarrow 2g + \gamma)}{\Gamma(V_6 \rightarrow \mu^+\mu^-)} \Big/ \dfrac{\Gamma(V_3 \rightarrow 2g + \gamma)}{\Gamma(V_3 \rightarrow \mu^+\mu^-)} = 6.25 \end{array}\right\} \tag{2.43}$$

$$\left.\begin{array}{l} \dfrac{\Gamma(V_8 \rightarrow 3g)}{\Gamma(V_8 \rightarrow \mu^+\mu^-)} \Big/ \dfrac{\Gamma(V_3 \rightarrow 3g)}{\Gamma(V_3 \rightarrow \mu^+\mu^-)} = 0 \\ \dfrac{\Gamma(V_6 \rightarrow 3g)}{\Gamma(V_6 \rightarrow \mu^+\mu^-)} \Big/ \dfrac{\Gamma(V_3 \rightarrow 3g)}{\Gamma(V_3 \rightarrow \mu^+\mu^-)} = 12.25 \end{array}\right\} \tag{2.44}$$

Looking at the different results (2.38) to (2.44) it seems that studies of the associated onia should be able to tell us quite quickly about the colour assignments of any future, massive fermions. As an example the experimental data[52] on the leptonic and hadronic decay widths of the Υ, and to a lesser extent the Υ - Υ' mass difference, suggested very early that the Υ system was not made up out of 6 or 8 quarks.

A final remark concerns the possible decay modes of 6 and 8 quarks. Conventional colour excludes such standard decay modes as

$$\left.\begin{array}{llll} q_6 \not\rightarrow q_3 q_3 \bar{q}_3 & & \text{or } q_8 \not\rightarrow & q_3 q_3 \bar{q}_3 \\ \;\;\; \not\rightarrow q_3 \, \ell \, \nu & & \;\;\; \not\rightarrow & q_3 \, \ell \, \nu \end{array}\right\} \tag{2.45}$$

Instead one must appeal to more exotic possibilities such as

$$\left.\begin{array}{llll} p_6 \rightarrow q_3 q_3 \, \ell & \text{or} & q_8 \rightarrow & q_3 \bar{q}_3 \, \ell \\ & & \;\;\; \rightarrow & g_8 \, \ell \end{array}\right\} \tag{2.46}$$

These decay modes would have obvious implications for bizarre final states due to primordial $e^+e^- \rightarrow 6\bar{6}$ or $8\;\bar{8}$ production. They would clearly need to be mediated by some new form of weak interaction which is likely to be weaker than the conventional G_F. It is very possible that the lowest-lying hadrons made out of such non-triplet quarks might even be stable - if so, they must be rather massive[53], but could still lie within the mass-range accessible to LEP.

2.7 Quarks with substructure

The main reason to build LEP may well be the hope of revealing a new level of matter underlying quarks and lpetons. Through speculative, it has frequently happened in the past that investigations of a new energy scale have revealed previously unsuspected levels of structure. Precision measurements of (g-2) for the muon and electron give strong limits on at least certain types of lepton substructure, but there are no comparable limits on quark substructure. How might this be manifested ? Several years ago it was suggested that possible structure in the quark be parametrized[19] by modifying the electric form factor:

$$1 \rightarrow 1 / (1-Q^2/m_V^2) \qquad (2.47)$$

where m_V is the mass of a vector gluon assumed to be much heavier than the quark mass m_Q. From (2.47) one has

$$\sigma(e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q}) = 3\sigma(e^+e^- \rightarrow \gamma^* \rightarrow \mu^+\mu^-)e_e^2 \left(\frac{1}{1 - Q^2/m_V^2}\right)^2 \qquad (2.48)$$

and hence

$$R \quad \frac{\sigma(e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q})}{\sigma(e^+e^- \rightarrow \gamma^* \rightarrow \mu^+\mu^-)} \simeq 3e_Q^2 \left(1 + \frac{2Q^2}{m_V^2} + \ldots \right) \qquad (2.49)$$

at centre-of-mass energies $Q << m_V$ as in Fig. 20. We see from (2.49) that if one measures R with a precision of 10% at Q = 240 GeV, a feasible experiment, one has a sensitivity to

$$m_V \lesssim 1 \text{ TeV} \qquad (2.50)$$

Hence one would be able to detect any quark substructure on a distance scale $\gtrsim 10^{-17}$ cm. In principle, in addition to the modification (2.47) of the electric form factor one could also anticipate the generation of a non-trivial magnetic form factor, and hence a deviation from the naive $(1 + \cos^2\theta)$ angular distribution expected for $e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q}$. For comparison with (2.49) and (2.50) we might consider the possible effects visible in deep inelastic ep scattering. In the limit of momentum transfers $Q << m_V$ one would have

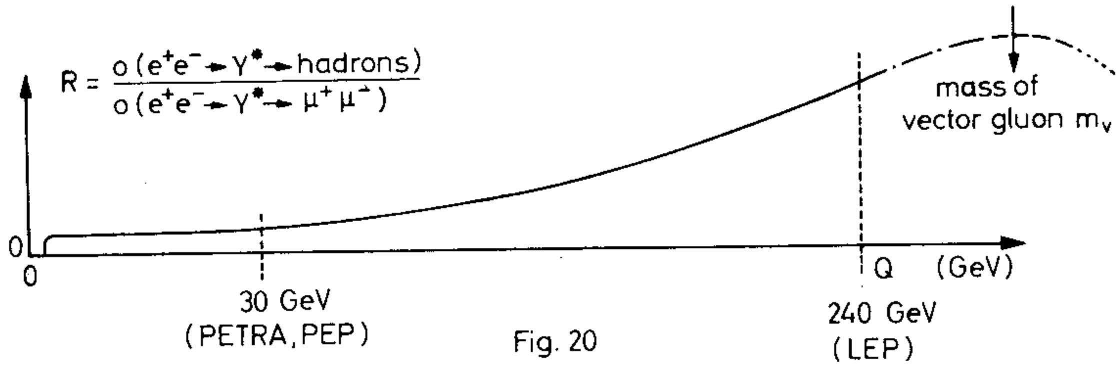


Fig. 20

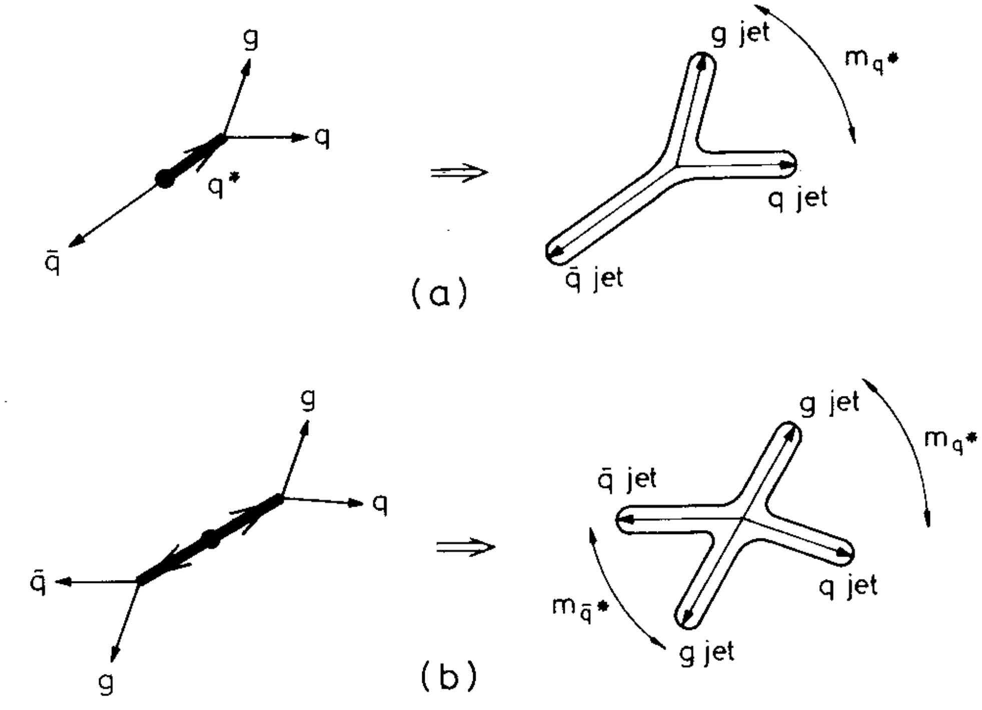


Fig. 21

$$\nu W_2(\text{substructure}) = \nu W_2(\text{point-like})\ (1 - \frac{2Q^2}{m_V^2} + \ldots) \qquad (2.51)$$

It would be distinguishable from the trivial modifications to νW_2 due to QCD corrections by its universal behaviour in x, to be contrasted with general expectation in strong interaction field theories of an accelerating decrease in the structure function at large x compensated by a growth at small x. If one assumes a 5% measurement of νW_2 at a $Q^2 \approx 3 \cdot 10^4\ GeV^2$, which might be obtainable with the proposed HERA machine[54], one would also be sensitive to m up to 1 TeV.

Other manifestations of quark substructure are possible in addition to the naive form factor effect (2.47). One might expect to see excited states of quarks q^*, whose energy of excitation might be much less than the vector gluon mass m_V: recall that

$$m_{D^*} - m_D,\ m_{F^*} - m_F \ll m_\rho,\ m_{J/\psi} \qquad (2.52)$$

One could then expect to get events of the type $e^+e^- \to q^*\bar{q}$ and $q^*\bar{q}^*$ in addition to the usual $e^+e^- \to q\bar{q}$. These events would increase the hadronic R value and alter the expected angular distributions of hadronic jets. Presumably one would expect excited q^* to decay down into q, and likely decay modes would seem to be

$$q^* \to q + g,\ q + \gamma,\ q + Z^0,\ q + W \qquad (2.52)$$

The gluonic decay mode would yield, for example, 3 jet final states as in Fig. 21a from $e^+e^- \to \bar{q}(q^* \to q + g)$ where the invariant mass of two jets would be

$$m_{q+g} = Q^2(1 - X_{\bar{q}}) \ :\ X_{\bar{q}} = \frac{2Q}{E_{\bar{q}}} \qquad (2.53)$$

Future studies of $e^+e^- \to 3$ jet events[13] should look for bumps in the invariant mass distributions of dijet combinations. Events of the type $e^+e^- \to q^*\bar{q}^*$ would give 4 jet events as in Fig. 21b, which QCD expects to be relatively rare in the normal hadronic continuum[55].

Eventually one would expect above the thresholds for producting many combinations of pairs of q^* and $\bar{q}^*$, the total $e^+e^- \to$ hadrons cross-section to reflect the number and charges of the subconstituents of quarks:

$$R = 3 \sum_q e_q^2 \to N_{sq} \sum_{sq} e_{sq}^2 \qquad (2.54)$$

One can imagine scenarios in which R goes either up or down - e.g. each charge -1/3 quark made up of N_{sq} identical subquarks of charge $- 1/3N_{sq}$ implies a contribution to R of $1/3\ N_{sq}$ as in Fig. 22. Quark substructure seems to be the only way of getting a negative threshold in $e^+e^- \to$ hadrons. All in all, it seems that any quark substructure in the energy range accessible to LEP should be visible in a distinctive manner.

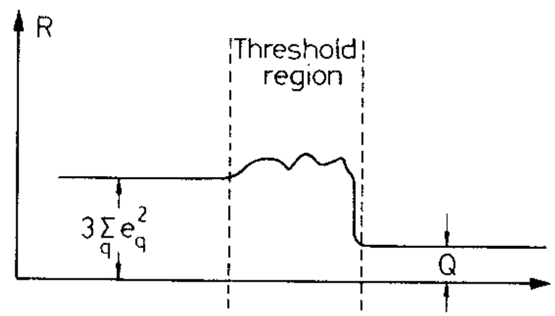


Fig. 22

3) Monopoles

3.1 Motivations

In the original approach of Dirac[2], based on the observation that the five Maxwell equations are symmetric under reciprocal transformations of electric into magnetic quantities, monopoles are introduced in the theory of electromagnetism for aesthetic reasons. This inclusion of external sources as new singularities of the electromagnetic field has immediate implications. In particular there is the magnetic charge quantization condition of Dirac[2]:

$$g \cdot e = 4\pi\,(n/2) \qquad (3.1)$$

$$(n \text{ integer} = 1, 2, \ldots.)$$

If monopoles with magnetic strength g exist, the elastic charge e is then quantized and similarly, the existence of a charge unit e requires all monopole charges to be quantized. This relation (3.1) shows also that the unit (n = 1) of magnetic charge deduced from the known unit of elastic charge is quite large

$$g_1^2 / 4\pi = 137 / 4 \approx 34 \qquad (3.2)$$

to compare with $e^2/4\pi = 1/137$ (3.3)

The value (3.2) is further increased by a factor of 9 if one takes the unit to be e/3 instead of e, as motivated by fractionally charged quarks.

Divergent integrals appear in Dirac's theory, arising from the reaction of a magnetic particle on the field that it produces itself. A solution to this problem was proposed by Cabibbo and Ferrari[56], who make a extention of quantum electrodynamics to the case of two vector potentials: one electric and one magnetic. They argue that it is possible to describe, with no non-physical singularities, the electromagnetic field produced by classical electric and magnetic sources. In their approach, while the strength of the magnetic charge is not arbitrary, the mass of such objects is a free parameter which can be adjusted to accomodate any experimental lower limit.

More recently, new theoretical progress, due particularly to Wu and Yang[57], has been made along the lines of Dirac's concept. The mathematical structure of this theory is that of fibre bundles. Their introduction in the theory of magnetic monopoles has the advantage of removing the string singularity of Fig. 23 introduced by Dirac[2], which long impeded progress in this field. This approach has furthermore the advantage of being deeply connected with gauge theories.

The unified gauge theories of weak and electromagnetic interactions provide an alternative explanation of the universality of electric charge, and introduce a new variety of magnetic monopoles: the so-called 't Hooft-Polyakov Monopoles[3]. In these theories particles carrying magnetic charge appear as soliton solutions to the classical field equations. There is no introduction of external sources and the existence of these 't Hooft-Polyakov magnetic monopoles is compelling on basically topological grounds. The masses of magnetic states, given by the finite energy of the classical solution, is calculable and estimated to be

$$m_M \sim O(m_W/\alpha) \sim O\,(10^4)\ \text{GeV} \qquad (3.4)$$

It is obvious that this large value would account for the failure of past searches in accelerator experiments and would predict a similar situation for the foreseeable future.

However, in view of the present success of these unified gauge theories, it is clear that if such models contain topologically stable solitons carrying magnetic charges, it is necessary to search experimentally for such objects. This argument becomes stronger as long as it is not completely clear that they have masses of the order of the scale $\gtrsim m_W$ of the weak symmetry breakdown. Troost and Vinciarelli[21] have argued that monopoles exist as solitons in a wider class of field theories when, in particular, the vector mesons possess an arbitrary positive anomalous magnetic moment. They find solutions of finite energy and predict the existence of a monopole of mass smaller than

$$m_M < (\sqrt{2}\,\pi/\alpha^2)\, m_e \simeq 43\ \text{GeV} \qquad (3.5)$$

Pairs of such monopoles should be produced in collisions of conventional particles with a rate typical of an interaction of strength 1. Furthermore,

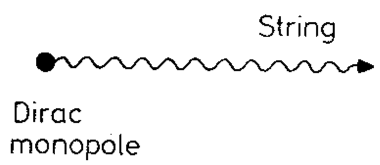


Fig. 23

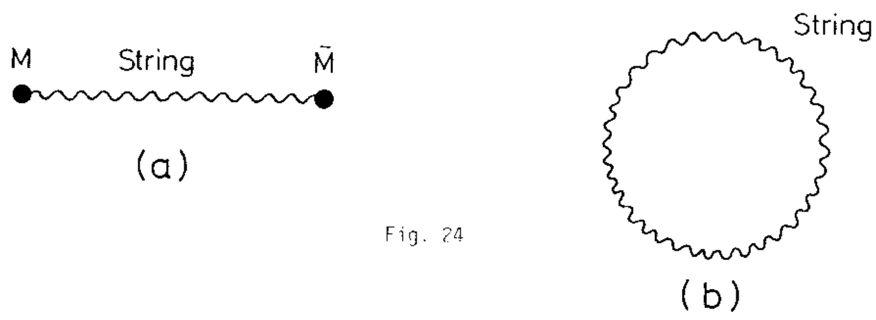


Fig. 24

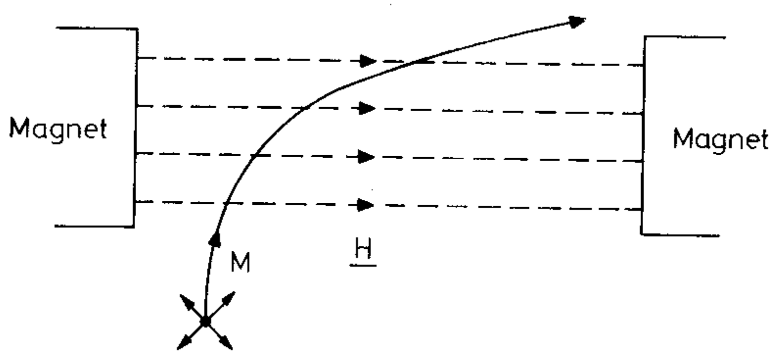


Fig. 25

it seems that even below threshold, the excitation of virtual pairs could produce a multitude of photons, electrons and positrons.

According to Schwinger[58], the great strength of magnetic attraction violates the formal symmetry in nature between electric and magnetic quantities. This fact led him to suggest that ordinary matter which is magnetically natural, is in fact a composition of magnetically charged particles carrying fractional electric charges: the dyons. On this basis, Zwanziger and Schwinger[59] have generalized Dirac's quantization condition to allow for the possibility of such particles

$$\frac{g \cdot e}{4\pi} = n \tag{3.6}$$

The lowest magnetic charge ($n = 1$, $g = 4\pi/e$) is then the value of the lowest Dirac magnetic charge, while the hypothesis of the existence of particles with fractional electric charge (1/3, 2/3 ...) would entail a further increase.

It should be emphasized that while monopoles and dyons exist in many gauge theories, they do not exist in the SU(2) x U(1) Glashow-Weinberg-Salam model[20], or in other models where the U(1) group of electromagnetism is not embedded in a simple group. However, it is quite possible to embed the Glashow-Weinberg-Salam model in a larger simple group, such as SU(3) or SU(5)[60], in which case m_W in (3.4) is replaced by the heavier gauge vector bosons. In the extreme case of a grand unified theory such as SU(5) or SU(10), the monopoles would have masses[61] in excess of 10^{16} GeV. However, it has been suggested that even the spectrum of the Weinberg-Salam model may contain "topological" particles at relatively low masses $O(10^3$ to $10^4)$ GeV. These might include monopole-antimonopole-like solutions connected by a piece of string analogous to that in Dirac's original theory[22] as in Fig. 24a. Alternatively, there may be state which are like loops of string[23] as in Fig. 24 b. None of these states is expected on topological grounds to be strictly stable, but it is possible that at least some of them might have lifetimes much longer than their masses would suggest: $\tau \gg 1/m$. In this case they might be detectable as reasonably well-defined particles.

3.2 Properties of magnetic monopoles

It is usual to suppose that, except for annihilation with a pole of opposite magnetic charge, the lightest monopole should be a stable particle. Concerning the mass, the Dirac theory[2] makes no definite prediction. It is conventional, though not very well motivated, to take as references the masses corresponding to the classical radius of the monopoles being equal to that of the electron. Expressed then in terms of the proton mass m_p and of the Dirac magnetic charge unit number n, we have

$$m_M \sim 2.56 . n^2 . m_p \qquad (3.7)$$

One finds from (3.7) that

$$m_M = \begin{cases} 2.4 \text{ GeV} & \text{for } n = 1 \\ 10 \text{ GeV} & \text{for } n = 2 \\ 150 \text{ GeV} & \text{for } n = 8 \\ 10^4 \text{ GeV} & \text{for } n = 64 \quad \ldots \end{cases} \qquad (3.8)$$

In the 't Hooft-Polyakov approach[3], on the other hand, the mass is calculable. One finds so from equation (3.4) that

$$m_M = 1 \text{ to } 10 \text{ TeV} \qquad (3.9)$$

As mentioned in section 3.1, more recently Troost and Vinciarelli[21] have predicted the existence of a monopole of mass smaller than 43 GeV (see equ.3.5). The spin of a monopole does not seem to be completely certain. It has often been thought to have spin 0, though recent arguments suggest it may have spin 1[62]. It appears likely that at least some dyons may be fermions of spin 1/2[58].

Three dynamical properties are particularly interesting in the search for magnetic monopoles. The first is that a magnetic field H accelerates (see Fig. 25) a monopole of charge g with the force

$$F_g = g H \qquad (3.10)$$

which results in a gain of energy at a rate of roughly

$$\Delta E \sim 2n \text{ GeV/kG.m} \qquad (3.11)$$

where n is the number of Dirac magnetic charge units. Since monopoles acquire so much energy in a magnetic field, this can be used to distinguish them from any possible background due to heavy ions, which would also ionize strongly.

A moving monopole induces an electric field and thus produces in matter ionization and energy losses. It seems that this ionization should be roughly uniform though slightly decreasing for slower monopoles. Due to the fact that this ionization should be the same for all velocities β and Dirac magnetic charge unit numbers n, one has a simple relation to the ionization of an electrically charged particle with the same β and charge Z:

$$Z/\beta = n \, (1/2\,\alpha) \qquad (3.12)$$

It is therefore obvious that monopoles are heavily ionizing particles

$$dE/dx \Big|_{\substack{\text{magnetic} \\ \text{monopole}}} = \beta^2 n^2 \, (1/2\alpha)^2 \, dE/dx \Big|_{\substack{\text{minimum} \\ \text{ionization}}} \qquad (3.13)$$

This very large anomalous ionization can be then used for monopole searches using emulsions, scintillation counters or etched plastic detectors. The rate of ionization (3.13) corresponds too to an energy loss of

$$\Delta E \simeq 8 \, n^2 \quad \text{GeV/g/cm}^2 \qquad (3.14)$$

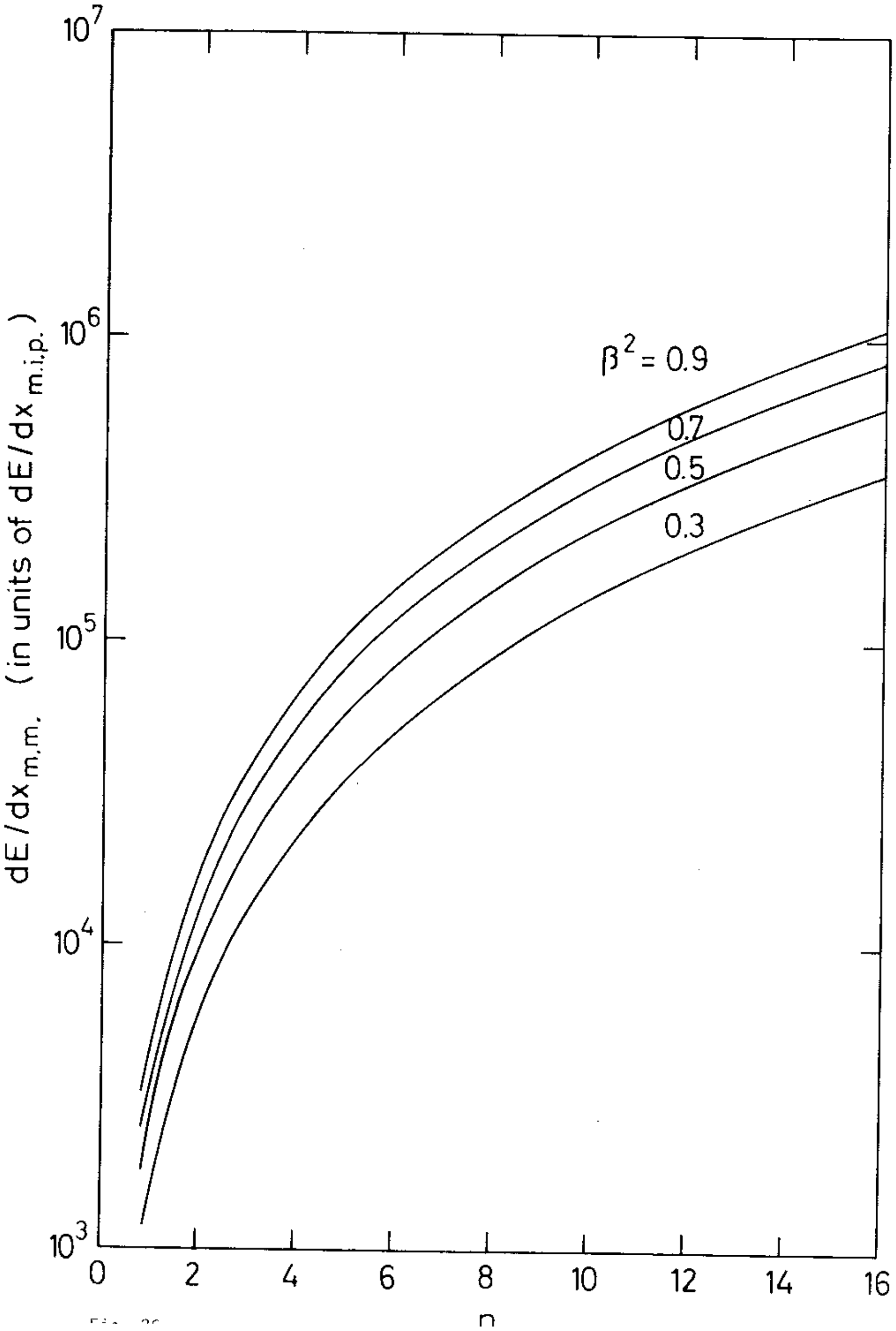
Hence the large R of a magnetic monopole of kinetic energy T can be approximated by

$$R \simeq T / 10 \, n^2 \quad \text{g/cm}^2 \text{ GeV} \qquad (3.15)$$

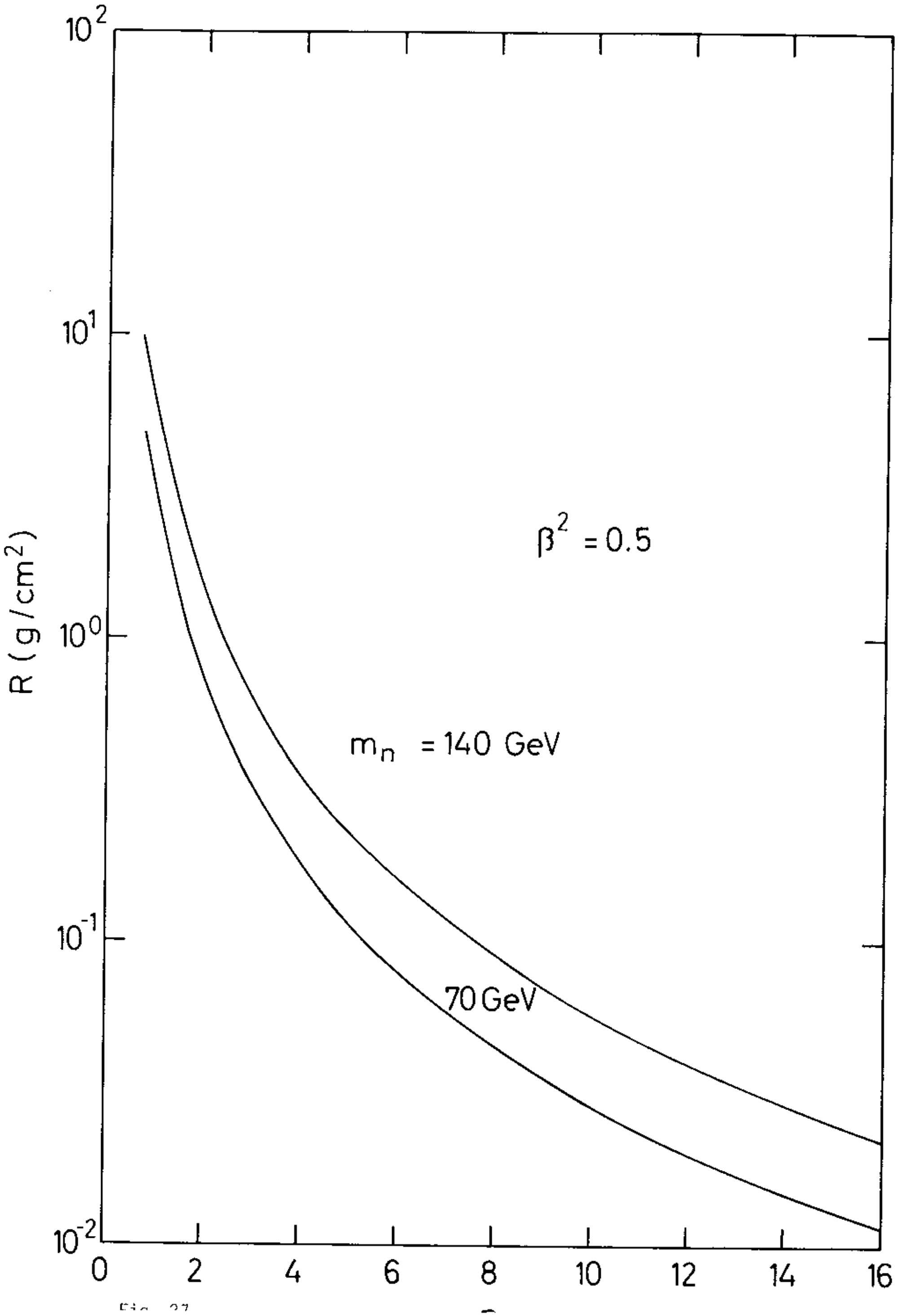
To summarize: magnetic charges should gain energy in a magnetic field in direct proportion to their magnetic charge, while they should lose energy in matter proportionally to their charge squared.

Figs. 26 and Figs. 27 show the variations respectively of energy loss (in unity of minimum ionization) and of the charge (in g/cm^2) as functions of the Dirac magnetic charge unit number n. As is easy to see, since the ionization rates are expected to be very high, the monopole range is expected to be very short.

The third property of monopoles concerns their possible behaviour in matter. It has been suggested that magnetic monopoles may bind with molecules or nuclei. We can suppose that, by analogy to the attraction of an electrical charge to a dielectric material, a magnetic charge may be magnetostatically bound to ferromagnetic or paramagnetic materials[63]. Models of magnetic pole binding thus suggest that monopoles will bind on soft iron. This permits one to store them for indirect searches, although recombination mechanisms could possibly occur.



dE/dx m.m. (in units of dE/dx m.i.p.)
β² = 0.9
0.7
0.5
0.3
n



R (g/cm²)
β² = 0.5
m_n = 140 GeV
70 GeV

3.3 Previous Searches

Searches for magnetic monopoles have been performed at particle accelerators, in cosmic rays, and using bulk matter.

3.3.1 Searches at accelerators

The general distinguishing features of searches for magnetic monopoles at accelerators are that, while the range of possible masses is greatly limited compared to cosmic ray searches, the high flux of primary particles permit low values to be obtained for the upper limit of the monopole production cross section and there are less ambiguities in the interpretation of results. Furthermore, experiments at accelerators permit one to search for magnetic monopoles directly after their production. In all of these experiments until now, monopoles are supposed to be produced in nucleon-nucleon collisions.

Table 9 gives, for different experiments, the upper limits on monpole production cross-sections and the corresponding mass and charge ranges searched for magnetic monopoles.

Fidecaro et al[65] at the CERN-PS and Giacomelli et al.[74] at the CERN-ISR have attempted to detect monopoles immediately after their production in high energy collisions. In the last experiment, this is done by placing stacks of plastic detectors around the interaction region. This type of search is now improved by placing plastic detectors directly inside the beam pipe[77].

Fig. 28 taken from Ref. 73 and 78 illustrates the cross section limits as a function of the magnetic charge, for different experiments.

3.3.2 Searches in Cosmic-Rays

Because of the extremely high energies available, the interactions of the primary cosmic range is seen as a natural place to look for monopole production. Once created in the atmosphere, an initially energetic monopole could reach a low thermal velocity in the earth's magnetic field because of its large ionization loss (see equ. 3.14 and 3.15).

Two types of experiment are then possible: direct searches by observing the effects of such monopoles as they arrive on the earth, and indirect searches where one takes advantage of geological collecting times by extracting monopoles trapped in matter.

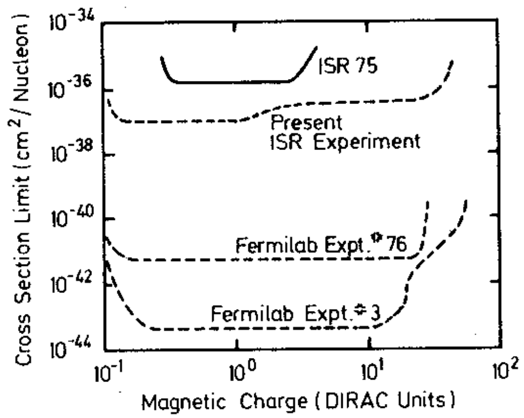


Fig. 28

Table 9 - Accelerator Searches

Ref.	Accelerator	Beam Momentum (GeV/c)	charge range (ħc/2e)	mass range (m_p)	upper limit on monopole production cross section (cm^2/nucleon) (95% C.L.)
64	Bevatron	6. - 6.3	1	≤ 1	< 10^{-40} - 2×10^{-35}
65	CERN-PS	19.	0.6 - 4	< 2.2	10^{-37} (a)
		27.5	0.3 - 4	< 2.8	10^{-39} (a)
		27.5			10^{-36} - 10^{-35}
66	CERN-PS	25.-27.2	1	≤ 3.4	0.5×10^{-40}
67	A.G.S.	30.	1	2. - 2.9	1.4×10^{-40} (a)
			1	1. - 2.	$3. \times 10^{-40}$ (a)
68	IPHE	70.	1	≤ 7	1.5×10^{-41} (b)
69	IPHE	70.			1.4×10^{-43}
70	IPHE	70.	> 1/2	≤ 5.15	2.1×10^{-43}
71	F.N.A.L.	300.	1/6-24	≤ 12.	6×10^{-42}
72	F.N.A.L.	400.	1/30-24	≤ 14.	5.1×10^{-42}
73	F.N.A.L.	300.	1 - 7	≤ 11.	5.0×10^{-44}
		400.	1 - 7	≤ 13.	2.0×10^{-42}
74	CERN-ISR	$45.-62.8^{(c)}$	0.4-2.5	< 20	2.0×10^{-36} (a)
75	CERN	neutrinos P.S.			< 10^{-39} (a)
76	CERN-ISR	$11.7-31.6^{(c)}$	0.2-1.2	< 20	1.3×10^{-37}
			1.2-24	< 20	4.0×10^{-37}

(a) Direct search, (b) 90% confidence level, (c) centre of mass energy

In 1951, Malkus[79] was the pioneer of the direct type of search. He thought of drawing monopoles, moving at thermal velocity along the earth's field lines, through a long solenoid. The monopoles were then accelerated and passed through a window to strike a photographic emulsion. The negative result of this experiment permitted him to put an upper limit on the monopole arrival rate of less than $10^{-10}/cm^2 sec$. This corresponds to a cross section for monopole production by primary cosmic radiation of less than 3×10^{-35} cm^2.

Later, Carithers et al.[80] have repeated the Malkus experiment with a solenoid covering an effective area of 1600 m^2. The detection system consisted of 3 scintillation counters, a spark chamber and a rack of nuclear emulsions. Only n = 1 or 2 monopoles (n is Dirac's magnetic charge in unit of ħc/2e) would have been detected reliable. The negative result put a new upper limit on the flux of north monopoles in the atmosphere of $3.34 \times 10^{-14}/cm^2 sec$, at the 90% confidence level. Carithers et al. estimated then an upper limit for the cross section for monopole production in nucleon-nucleon collisions of 8.1×10^{-41} $E_T^{1.67} cm^2$ (90% C.L.), where E_T is the threshold energy to produce a pair of monopoles expressed in GeV. This result showed that the cross section limit varies with the monopole mass M approximately as $M^{3.4}$.

From the results of studies concerning extensive air shower on the Tyan' - Shan' mountain, Erlykin et al.[81] estimated, in 1969, the flux of relativistic Dirac monopoles of various energies. They conclude that

for $E \gtrsim 10^{13}$ eV the flux is less than $2.5 \times 10^{-12}/cm^2 sec\ \Delta\Omega$

for $E \gtrsim 3 \times 10^{13}$ eV this flux is less than $7.0 \times 10^{-13}/cm^2\ sec\ \Delta\Omega$

Carrigan and Nezrick[82] reexamined, in 1971, the existing magnetic monopole search in terms of monopole production by cosmic-ray neutrinos. They concluded that an upper limit for the cross section of direct production is 1.0×10^{-39} E_T^2 cm^2.

From the data of Price et al.[83], Fleischer et al.[83] calculated the limits on monopole flux from cosmic-rays near the top of the atmosphere. The results are given in Table 10. In the same paper[83], Fleischer et al. reported the result of an experiment at sea level where monopoles of masses bigger than 20 m_p

and charges between $2\pi/e$ and $4\pi/e$ should mostly penetrate if they are incident at energies above around 5.0×10^{13} eV. The equipment consisted of panels of size 1.22m by 2.44 m, each covered with one thickness of 254μm Lexan polycarbonate sheets. The total exposure amounted to 8.76×10^{12} cm^2sec. From the negative result they placed the limits on the flux of heavily ionizing particles at sea level reported in Table 10.

In 1975, Price et al.[84] announced that an experiment to study ultraheavy cosmic rays ($Z \geq 60$), with ballon flights, had detected a magnetic monopole of strength $n = 2$ and velocity $\beta \sim 0.5$. The mass of this object was larger than 200 proton masses. They found then for the flux of monopoles of strength $n = 2$, near the top of the atmosphere, around $10^{-13}/cm^2 sec\ A\Omega$ in conflict with previous searches. More recently however, Price et al.[85] have given a detailed account of the experiment showing that several other hypotheses are compatible with the data and the monopole explanation is not necessary.

Table 10 - See Ref. 83

Situation	Magnetic charge ($\hbar c/2e$)	Flux (95% C.L.) $(cm^2 sec\ A\Omega)^{-1}$	Maximum cosmic-ray energy tested (eV)
on top of the atmosphere	1	$< 7.1 \times 10^{-11}$	2×10^{15}
	≥ 2	$< 1.2 \times 10^{-11}$	5×10^{15}
sea level	1	$< 1.52 \times 10^{-13}$	3×10^{16}
	≥ 2	$< 1.25 \times 10^{-13}$	4×10^{16}

3.3.3 Searches in Matter

The ability to search for cosmic monopoles in matter relies on their properties of being thermalized in the atmosphere and the ocean, and then drifting slowly in the earth's magnetic field to be trapped by ferromagnetic materials. This type of experiment has thus the advantage of geological collecting times, but their interpretation is strongly correlated with arguments concerning the binding properties of monopoles in matter.

In the most of these experiments, the monopoles should be extracted from samples with powerful magnetic fields and identified by their typical ionization in nucleon-emulsions or scintillation counters. The magnetic charge of the sample can also be measured by the current charge induced in a closed superconducting circuit contraining a solenoid, when the sample is in motion along the axis of the solenoid. However, it is reasonable to think that not all conceivable monopoles are stopped and trapped by materials on the earth's surface or on the floors of oceans. Thus, in this case it is only possible to search for their passage, since moving monopoles are highly ionizing particles whole tracks might be decorded in natural samples of materials such as mica and obsidian.

Goto et al[86] have tried to extract magnetic monopoles from a magnetite outcrop on the earth's surface and from fragments of a stony-iron meteorite. No candidate was found in the nuclear emulsions used for detection. Later, Fleischer et al.[87], by magnetic extraction from manganese modules, obtained a much lower limit for the integral flux of cosmic monopoles of mass less than 130 m_p and charge less than $60(4\pi/e)$. These results are given in Table 11, together with those of a second publication of Fleischer et al.[88] in which the area x time product of the experiment was improved to give, for monopole masses smaller or equal to 3 m_p a pair production cross section upper limit of $4.5 \times 10^{-42} cm^2$ for 90% confidence level. The conclusion was that, below 10^{19} eV, the cosmic rays are not dominantly monopoles.

In 1969, Fleischer et al.[89] also published the results of an attempt to detect the passage of monopoles in natural samples. Samples of mica and obsidian were scanned and in none of those were any tracks detected which could be attributed to magnetic monopoles. The maximum cross section for monopole pair production by neclear interactions in the upper atmosphere are given in Table 11, corresponding to primary cosmic ray energies of about 7×10^{18} eV for mica and about 10^{15} eV for obsidian.

Later, Fleischer et al.[90] extended the study of Ref. 88 to the search for magnetic monopoles of charge up to 120 times the Dirac magnetic charge unit. The conclusions are identical to those of the producing works, except that the cross section for the production of free monopoles by nuclear interactions lies below $10^{-40} cm^2$ for monopole masses between 1 and 3 proton masses.

Kolm et al.[91] have attempted to extract, from sediments, magnetic monopoles with masses up to 1.4×10^4 proton masses and charges between 0.16 and 27 times the Dirac charge unit. Eberhard et al.[92] and Ross et al.[93] published in 1971 and 1973 the results of studies of lunar material. The detection principle adopted was to measure the current change in a superconducting circuit traversed by a magnetically charged object. The results are given in Table 11 and Ross et al.[93] deduced an upper limit of 1.7×10^{-4} monopole/g for the density of isolated monopoles in the lunar surface.

The Fig. 29 from Ref. 73 and 78 illustrates the results of these experiments.

It is difficult to compare these various limits with those obtainable in principle from LEP. However, we note that all these experiments are primarily sensitive to monopole production in "soft" nucleon-nucleon collisions in contrast to the "hard" collisions at $Q^2 \sim 10^4$ GeV^2 available with LEP. Furthermore, even the limits on monopole production in "soft" collisions at centre-of-mass energies $\geq$ 100 GeV are not comparable with those obtainable from LEP.

Table 11 - Searches in matter

Ref.	Maximum cosmic ray energy tested (90% C.L.) (eV)	upper limit flux (90% C.L.) $(cm^2\ sec.)^{-1}$	monopole mass (x mp)	upper limit on the monopole production cross section (90% C.L.) (cm^2)
86	8×10^{12}	10^{-13}	1	10^{-37}
			10^2	10^{-32}
87	2×10^{17}	8.4×10^{-15}	1	10^{-39}
			10^2	10^{-34}
88	10^{19}	4×10^{-18}	1	10^{-42}
			10^2	10^{-37}
89 (mica)	3×10^{19}	3.27×10^{-19} (a)	10^5	10^{-28}
89 (obsidian)	2×10^{18}	2.92×10^{-17} (a)	10^3	10^{-33}
90			≤ 3	10^{-40}
91	4×10^{15}	1.25×10^{-17}	10	10^{-40}
	2×10^{14}	1.7×10^{-1}'	10^3	10^{-33}
92	10^{13} (c)	10^{-18} (b)	$< 10^2$	10^{-38} (b)
93			1	10^{-37} (b)
			10^2	10^{-32} (b)

(a) differential flux upper limit $(cm^2 sec. \Delta\Omega)^{-1}$ (b) 95% confidence level
(c) monopole kinetic energy

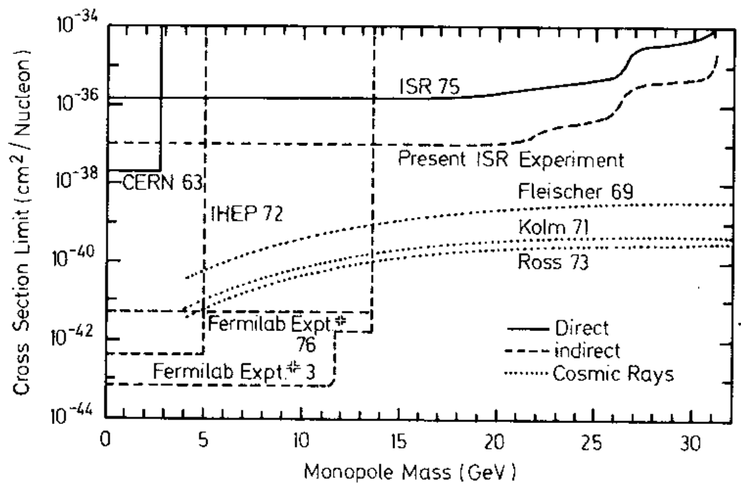


Fig. 29

However, extremely low limits on cross sections, less than 10^{-40} cm^2, have been set in previous searches for monopole production and for this point of view LEP is not better than other accelerator experiments.

3.4 Production of Monopoles

Experiments at accelerators do not permit one to search for monopole mass values as high as are possible with cosmic ray searches, for example, but they offer much more controlled conditions and for this reason appear to be competitive with other techniques. It appears that production by two photons as in Fig. 30 may be the most convenient for producing Dirac monopoles in e^+e^- collisions if they exist.

However, because of the strong coupling (3.2) of the monopole to the electromagnetic field, it is not clear that perturbation theory is of any use for discussing production cross sections, which are probably essentially non-perturbative[94].

For this reason, up to now there are no reliable estimates of possible monopole production cross sections. Furthermore, it is possible that strong final state interactions between the produced pairs of monopoles, like those proposed by Ruderman and Zwanziger[95], could supress the direct observation of magnetic monopoles. General kinematic arguments can be used to say that, if high-mass objects are to be produced with appreciable kinetic energy, the interaction must be principally central, resulting in large production angles in the center of mass.

Extremely low limits on cross sections, less than 10^{-40} cm^2, have been set in previous searches for monopole production[5]. From this point of view LEP is not better than other accelerator experiments. However, LEP permits us to search in a new range of masses of monopoles above 20 GeV and below about 100 - 140 GeV. It is true that other techniques, principally indirect searches, have given some limits at much more higher masses than these values, but it is not unreasonable to hope that recombination mechanisms might have impeded them from observing magnetic monopoles.

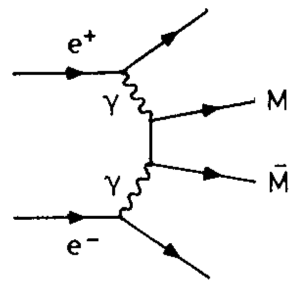


Fig. 30

3.5 Detection of Monopoles

At an accelerator like LEP, the direct search for magnetic monopoles should take into account the following points.

Due to the very high value of the coupling constant of magnetic monopoles to the electromagnetic field (3.2), it seems crucial to detect them immediately after their production, avoiding matter between the region of collision and the detector. This can be done by a system where materials sensitive only to highly ionizing particles are put into the beam-pipe itself. Tracks in these solid-state detectors (Lexan foils for example) should then be a totally distinctive and identifiable feature[96].

The very high energy loss of magnetic poles is a unique signature for an inner detector and one does not need to have very good energy resolution, but rather a large dynamic range. Such a system could be a lead-liquid calorimeter.

Due to the property of conservation of the overall magnetic charge, production of monopoles always occurs in pairs, and a clean signature would be the simultaneous detection of both north and south monopoles.

Since magnetic monopoles are accelerated by magnetic fields, the presence of a magnet would enable one to separate monopole candidates from backgrounds such as heavy ions produced by beam-gas interactions. Moreover, then utilisation of a magnetic field can increase the efficiency of the detector and move the mass range to higher values by giving kinetic energy to the produced monopoles.

It seems to us that experiments at LEP should be able to detect any magnetic monopoles produced if they exist, with a mass up to about 100 - 140 GeV.

References:

1. M.Gell-Mann, Phys.Lett. 8, 214 (1964)
   G.Zweig, CERN preprints TH 401, 412 (1964)

2. P.A.M.Dirac, Proc.Roy.Soc. A 133, 60 (1931), Phys.Rev. 74, 817 (1948)

3. A.M.Polyakov, J.E.T.P.Letters 20, 194 (1974)
   G.'t Hooft, Nucl.Phys. B 79, 276 (1974)

4. For a recent review see
   L.W.Jones, Rev.Mod.Phys. 49, 717 (1977)

5. For a recent review, see R.A.Carrigan, Jr., Magnetic Monopole Bibliography 1973-76, Fermilab Report 77/42, January 1977

6. For previous work on quarks at LEP, see
   F.Palmomari, ECFA/LEP note 11 (1978)
   M.Hagenauer, ECFA/LEP note 12 (1978)
   G.Barbiellini, H.Grote and K.Winter, ECFA/LEP note 13 (1978)
   G.Barbiellini, P.O.Hulth, D.Treille and T.T.Wu, ECFA/LEP note 41 (1978)
   and the review by K.Winter, Proceedings of the LEP Summer Study at Les Houches, 1978, CERN Yellow report 79-01 (1979) p. 93

7. For a recent review, see E.Bloom, Proceedings of the 1979 Lepton-Photon Symposium (FNAL, Batavia, 1980)

8. H.Deden et al., Nucl.Phys. B 85, 269 (1975)

9. G.Hanson et al., Phys.Rev.Lett. 35, 1489 (1975)

10. A.De Rújula, H.Georgi and S.L.Glashow, Phys.Rev. D12, 147 (1975)
    for a review see:
    N.Isgur, Oxford University preprint OUTP 78-67 (1978

11. D.H.Perkins, Proceedings of the XVIth Int.Conf. on High Energy Physics, Chicago-Batavia 1972 (NAL, Batavia, 1972), p. 189

12. P.C.Bosetti et al., Nucl.Phys. B 142, 1 (1978)
    J.G.H. De Groot et al., Z.Phys. C1, 143 (1979), Phys.Lett. 82B, 292, 456 (1979)
    H.L.Anderson et al., Fermilab preprint PUB-79/30-EXP(1979)

13. TASSO Collaboration, R.Brandelik et al., Phys.Lett. 86B, 243 (1979)
MARK J Collaboration, D.P.Barber et al., Phys.Rev.Lett. 43, 830 (1979)
PLUTO Collaboration, C.L.Berger et al., Phys.Lett. 86B, 418 (1979)

14. K.Koller and H.Krasemann, Phys.Lett. 88B, 119 (1979)
TASSO Collaboration, private communication (1979)

15. A.De Rújula, R.C.Giles and R.L.Jaffe, Phys.Rev. D17, 285 (1978)

16. M.Han and Y.Nambu, Phys.Rev. 139B, 1006 (1965)
Y.Nambu and Y.Han, Phys.Rev. D10, 674 (1974)
J.C.Pati and A.Salam, Phys.Rev.Lett. 31, 661 (1973)
Phys.Rev. D10, 275 (1974), Phys.Lett. 58B, 333 (1975)

17. B.M.McCoy and T.T.Wu, Phys.Lett. 72B, 219 (1977),
CERN preprint TM 2487 (1978)

18. Y.J.Ng and S.-H.H.Tye, Phys.Rev.Lett. 41, 6 (1978)
H.Fritzsch, Phys.Lett. 78B, 611 (1978)

19. M.S.Chanowitz and S.D.Drell, Phys.Rev.Lett. 30, 807 (1973)
and Phys.Rev. D9, 2078 (1977)

20. S.L.Glashow, Nucl.Phys. 22, 579 (1961)
S.Weinberg, Phys.Rev.Lett. 19, 1264 (1967)
A.Salam, Proc. of 8th Nobel Symposium, ed.N.Svartholen (Almquist and Wiksell, Stockholm, 1968), p. 367

21. W.Troost and P.Vinciarelli, CERN preprint TH 2195 (1976)

22. Y.Nambu, Nucl.Phys. B 130, 505 (1977)

23. M.B.Einhorn and R.S.Savit, Phys.Lett. 77B, 295 (1978)

24. C.B.A.McCusker and I.Cairns, Phys.Rev.Lett. 23, 658 (1969)

25. D.Antreasyan et al., Phys.Rev.Lett. 39, 513 (1977

26. U.Bott-Bodenhausen et al., Phys.Lett. 40B, 693 (1972),
B.Alper et al., Phys.Lett. 46B, 265 (1973)

27. C.Fabjan et al., Nucl.Phys. B 101, 349 (1975)

28. M.Basile et al., Nuov.Cim. 40A, 41 (1977), Nuov.CimLett.18, 529 (1977)
Nuov.Cim. 45 A, 171 (1978)

29. M.Basile et al., Nuov.Cim. 45A, 281 (1978)

30. CERN experiment WA 44: for details of the proposal, see the documents CERN/SPCS/77-10, 73 (1977)

31. S.Orito, DESY preprint 79-77, to appear in the Proceedings of the 1979 Lepton-Photon Int. Symp. FNAL, Batavia, 1980

32. PEP-14 proposal: A.Litke et al.

33. G.S.LaRue, W.M.Fairbank and A.F.Hebard, Phys.Rev.Lett. 38, 1011 (1977)
G.S.LaRue, W.M.Fairbank and J.D.Phillips, Phys.Rev.Lett. 42, 142 (1979)

34. G.Gallinaro et al., Phys.Rev.Lett. 38, 1255 (1977)

35. R.Wagoner and G.Steigman, Phys.Rev. D20, 825 (1979)

36. See the third and fith papers listed in Ref. 6

37. Contributions from the PETRA experiments to the e^+e^- Symposium at Vanderbilt Univ., Nashville, May 1-3, 1980

38. A.Chodos, R.L.Jaffe, K.Johnson, C.B.Thorn and V.F.Weisskopf, Phys.Rev.D9, 3471 (1974)

39. T.T.Wu, B.M.McCoy, C.A.Tracy and E.Barouch, Phys.Rev. B13, 316 (1976)
T.T.Wu, Phys.Lett. 71B, 142 (1977)
A.Luther, private communication to B.McCoy and T.T.Wu, cited in ref. 17

40. J.S.Bell, private communication. We have had fun discussing IMPs with J.S.Bell and T.T.Wu as well as amongst ourselves

41. W.Schnell and K.Potter - private communications

42. On this point we differ with the opinion expressed in ref. 17, see also ref. 40

43. R.D.Peccei - ECFA-LEP working group specialized study report SSG/9/9 (1980)

44. J.C.Pati and A.Salam, Nucl.Phys. B 144, 445 (1978)

45. M.L.Perl et al., Phys.Rev.Lett. 35, 1489 (1975)

46. For a review see: G.J.Feldman, Comments Nucl.Part.Phys. 9, 23 (1979)

47. D.P.Barber et al., Phys. Rev.Lett. 43, 1915 (1979)

48. S.J.Brodsky and J.F.Gunion, Phys.Rev.Lett. 37, 402 (1976)

49. H.Fritzsch, private communication

50. D.Amati and G.Veneziano, Phys.Lett. 83B, 87 (1979) and references therein

51. W.Furmański, R.Petronzio and S.Pokorski, Nucl.Phys. B 199, 253 (1979)

52. H.Meyer, DESY preprint 79/81, to appear in the Proceedings of the 1979 Lepton-Photon Symp., FNAL, Batavia.

53. S.Wolfram - Phys.Lett. 82B, 55 (1979)
C.B.Dover, T.K.Gaisser and G.Steigman Phys.Rev.Lett. 42, 117 (1979)
R.Middleton, R.W.Zurmühle, J.Klein and R.V.Kallavits Phys.Rev.Lett. 43, 429 (197)

54. HERA - ECFA 80/42
DESY HERA 80/01 - 17 March 1980

55. A.Ali et al., Phys.Lett. 82B, 285 (1979)

56. N.Cabibbo and E.Ferrari Nuov.Cim. 23, 1147 (1962)

57. T.T.Wu and C.N.Yang, Phys.Rev. D14, 437 (1976)

58. J.Schwinger, Phys.Rev. 144, 1087 (1966); Phys.Rev. 173, 1536 (1968) and Science 169, 797 (1969)

59. J.Schwinger, see ref. 58
D.Zwanziger, Phys.Rev. 176 (1968) 1480 and 1489

60. H.Georgi and S.L.Glashow, Phys.Rev.Lett. 32, 438 (1974)

61. The existence of such magnetic monopoles raises problems in the conventional big-bang cosmology - see J.P.Preskill, Phys.Rev. Lett. 43, 1365 (1979) who argues that they may be produced in observationally unacceptably large amounts in the very early universe.
See also: Y.B.Zeldovich and M.Y.Khlopov, Phys.Lett. 79B, 239 (1978)

62. P.Goddard, H.Nuyts and D.Olive, Nucl.Phys. B 125, 1 (1977)

63. C.Kittel and A.Manolin, Phys.Rev. B15, 333 (1977)

64. H.Bradner et al., Phys.Rev. 114 (1959) 603

65. M.Fidecaro et al., Nuovo Cim. 22 (1961) 657

66. E.Amaldi et al., Nuovo Cim. 28 (1963) 773

67. E.M.Purcell et al., Phys.Rev. 129 (1963) 2326

68. I.I.Garevitch et al., Phys.Lett. 31B (1970) 394

69. I.I.Garevitch et al., Phys.Lett. 38B (1972) 569

70. L.M.Barkov et al., JETP 34 (1972) 917

71. R.A.Carrigan et al., Phys.Rev. D8 (1973) 3717

72. R.A.Carrigan et al., Phys.Rev. D 10 (1974) 3867

73. P.H.Eberhard et al., Phys.Rev. D 11 (1975) 3099

74. G.Giacomelli et al., Nuovo Cimento A 21 (1975) 21

75. R.A.Carrigan et al., Nucl.Phys. B 91 (1975) 279

76. R.A.Carrigan et al., Phys.Rev. D 17 (1978) 1754

77. B.Anlost et al., Search for Magnetic Monpoles, CERN-EXPT-R501

78. G.Giacomelli Proceed. of the 1978 Int.Meeting on Frontier of Physics, Singapore (1978) p. 565

79. W.V.R.Malkus, Phys.Rev. 83, 899 (1951)

80. W.C.Carithers et al., Phys.Rev. 149, 1070 (1966)

81. A.M.Erlykin et al., Soviet Phys. JETP 29 (1969) 992

82. R.A.Carrigan et al., Phys.Rev. D3 (1971) 56

83. R.L.Fleischer et al., Phys.Rev. D 4(1971) 24
P.B.Price et al., Phys.Rev. D 3 (1971) 815

84. P.B. Price et al., Phys.Rev. Lett. 35 (1975) 687

85. P.B.Price et al., Phys.Rev. D 18 (1978) 1382

86. E.Goto et al., Phys.Rev. 132 (1963) 387

87. R.L.Fleischer et al., Phys.Rev. 177 (1969) 2029

88. R.L.Fleischer et al., Phys.Rev. 184 (1969) 1393

89. R.L.Fleischer et al., Phys.Rev. 184 (1969) 1398

90. R.L.Fleischer et al., Forum of Appl.Phys. 41 (1970) 958

91. H.H.Kolm et al., Phys.Rev. D 4 (1971) 1285

92. P.H.Eberhard et al., Phys.Rev. D 4 (1971) 3260)
and L.Alvarez et al., Science 167, 701 (1970)

93. R.R.Ross et al., Phys.Rev. D 8 (1973) 698

94. E.Witten, Nucl.Phys. B 160 (1979) 57

95. M.A.Ruderman and D.Zwanziger, Phys.Rev.Lett. 22 (1965) 146

96. This technique is currently being used or considered at several colliding ring machines.

D.Fryberger and P.B.Price
A proposal to search for highly ionizing particles at PEP.
Proposal PEP-2. SLAC November 1976.

B.Aubert, P.Musset, M.Price and J.P.Vialle,
Search for Magnetic Monopoles, CERN/SPSC/78-15/p.96

G.Flügge, E.Lohrmann, P.Musset, M.Price
Sarch for heavily ionizing particles at PETRA - PRC 79/10

<u>Figure Captions</u>:

1. Accelerator limits[4] on the ratio of quark fluxes to charged hadron fluxes ϕ_q/ϕ_c

2. Accelerator limits[4] on the production cross-sections for free quarks

3. Possible limits on free quark production ratios obtainable with PEP and PETRA

4. Ways in which a quark with appetite may (a) change its charge and mass by absorbing a nucleon in a collision with matter, or (b) be produced with unusual charge and mass by absorbing a pion during production

5. The exclusive production cross section $e^+e^- \to q\bar{q}$ as estimated in ref. 15

6. The inclusive production cross section $e^+e^- \to q\bar{q}X$ as estimated in ref. 15

7. A conceptual design of a detector for quarks with appetite

8. An IMP moving away from its production point, Lorentz-contracted but expanding laterally

9. Two possible interpretations of IMPs: (a) a Jelly-like IMP (J-IMP), and (b) a dust-like IMP (D-IMP)

10. A possible signature for a J-IMP: the ionization in its track fizzles out as it expands away from the production vertex, ef. fig. 8

11. A possible "Roman pot" system to make observations very close to the e^+e^- beam crossing region

12. (a) Cerenkov ring imaging for a particle of definite β, and (b) Cerenkov disc or annulus imaging for an IMP

13. The bending of an IMP by a magnetic field

14. (a) An IMP trap, they are the only non-ionizing particles which can impact in the shaded region of the calorimeter
    (b) IMP detection with a directional calorimeter. The direction vectors of the energy flows from ordinary neutral particles and IMPs are different

15. Artistic impression of the interaction of a J-IMP with hadronic matter

16. Apparent charge non-conservation in an e^+e^- collision because of the production of a u_{IMP} and a $\bar{d}_{IMP}$

17. The pair-production and decay of unconfined vector gluons: $e^+e^- \to V^+V^- \to (q\bar{q}) + (\ell\nu)$

18. The possible Jacobian peak in the p_T of the lepton relative to the jet axis defined by the hadrons in fig. 17

19. In the string picture of hadronic final states (a) a $\underset{\sim}{3}$ or $\underset{\sim}{6}$ of colour <u>cannot</u> be "bleached" by a gluon, whereas (b) an $\underset{\sim}{8}$ of colour <u>can</u> be "bleached" by a gluon, with the possible result that there is no string

20. A massive vector gluon could cause R to rise at LEP energies

21. The possible production of (a) 3-jet events from $e^+e^- \to q^*\bar{q}$, and (b) 4-jet events from $e^+e^- \to q^*\bar{q}^*$

22. A signature exclusive to quark substructure ? an abrupt reduction in R

23. A Dirac monopole has a string which can only terminate at infinity or at an anti-monopole

24. Possible "topological" structures in the Glashow-Weinberg-Salam theory: (a) a monopole M antimonopole $\bar{M}$ pair connected by a piece of string[22], and (b) a closed loop of string[23]

25. A magnetic monopole is bent and accelerated parallel to a magnetic field

26. The energy loss dE/dx of a magnetic monopole of Dirac charge n

27. The range of a magnetic monopole of Dirac charge n

28. Cross section limits as a function of magnetic charge (Ref. 73 and 78)

29. Cross section limit as a function of monopole mass (ref. 73 and 78)

30. The possibly dominant $\gamma\gamma$-production mechanism for $M\bar{M}$ production