Free Quark Searches

FREE QUARK SEARCHES

The basis for much of the theory of particle scattering and hadron spectroscopy is the construction of the hadrons from a set of fractionally charged constituents (quarks). A central but unproven hypothesis of this theory, Quantum Chromodynamics, is that quarks cannot be observed as free particles but are confined to mesons and baryons.

Experiments show that it is at best difficult to "unglue" quarks. Accelerator searches at increasing energies have produced no evidence for free quarks, while only a few cosmic-ray and matter searches have produced uncorroborated events.

This compilation is only a guide to the literature, since the quoted experimental limits are often only indicative. Reviews can be found in Refs. 1–3.

References

1. P.F. Smith, Ann. Rev. Nucl. and Part. Sci. **39**, 73 (1989).
2. L. Lyons, Phys. Reports **129**, 225 (1985).
3. M. Marinelli and G. Morpurgo, Phys. Reports **85**, 161 (1982).

Quark Production Cross Section — Accelerator Searches

X-SECT (cm^2)	CHG (e/3)	MASS (GeV)	ENERGY (GeV)	BEAM	EVTS	DOCUMENT ID		TECN
$<1.3E-36$	± 2	45–84	130–172	$e^+ e^-$	0	ABREU	97D	DLPH
$<2.E-35$	$+2$	250	1800	$p\overline{p}$	0	[1] ABE	92J	CDF
$<1.E-35$	$+4$	250	1800	$p\overline{p}$	0	[1] ABE	92J	CDF
$<3.8E-28$			14.5A	^{28}Si–Pb	0	[2] HE	91	PLAS
$<3.2E-28$			14.5A	^{28}Si–Cu	0	[2] HE	91	PLAS
$<1.E-40$	$\pm 1,2$	<10		$p,\nu,\overline{\nu}$	0	BERGSMA	84B	CHRM
$<1.E-36$	$\pm 1,2$	<9	200	μ	0	AUBERT	83C	SPEC
$<2.E-10$	$\pm 2,4$	1–3	200	p	0	[3] BUSSIERE	80	CNTR
$<5.E-38$	$+1,2$	>5	300	p	0	[4,5] STEVENSON	79	CNTR
$<1.E-33$	± 1	<20	52	$p p$	0	BASILE	78	SPEC
$<9.E-39$	$\pm 1,2$	<6	400	p	0	[4] ANTREASYAN	77	SPEC
$<8.E-35$	$+1,2$	<20	52	$p p$	0	[6] FABJAN	75	CNTR

<5.E−38	−1,2	4–9	200	p	0	NASH	74	CNTR
<1.E−32	+2,4	4–24	52	pp	0	ALPER	73	SPEC
<5.E−31	+1,2,4	<12	300	p	0	LEIPUNER	73	CNTR
<6.E−34	±1,2	<13	52	pp	0	BOTT	72	CNTR
<1.E−36	−4	4	70	p	0	ANTIPOV	71	CNTR
<1.E−35	±1,2	2	28	p	0	[7] ALLABY	69B	CNTR
<4.E−37	−2	<5	70	p	0	[3] ANTIPOV	69	CNTR
<3.E−37	−1,2	2–5	70	p	0	[7] ANTIPOV	69B	CNTR
<1.E−35	+1,2	<7	30	p	0	DORFAN	65	CNTR
<2.E−35	−2	< 2.5–5	30	p	0	[8] FRANZINI	65B	CNTR
<5.E−35	+1,2	<2.2	21	p	0	BINGHAM	64	HLBC
<1.E−32	+1,2	<4.0	28	p	0	BLUM	64	HBC
<1.E−35	+1,2	<2.5	31	p	0	[8] HAGOPIAN	64	HBC
<1.E−34	+1	<2	28	p	0	LEIPUNER	64	CNTR
<1.E−33	+1,2	<2.4	24	p	0	MORRISON	64	HBC

[1] ABE 92J flux limits decrease as the mass increases from 50 to 500 GeV.
[2] HE 91 limits are for charges of the form $N \pm 1/3$ from 23/3 to 38/3.
[3] Hadronic or leptonic quarks.
[4] Cross section cm^2/GeV^2.
[5] 3×10^{-5} <lifetime $< 1 \times 10^{-3}$ s.
[6] Includes BOTT 72 results.
[7] Assumes isotropic cm production.
[8] Cross section inferred from flux.

Quark Differential Production Cross Section — Accelerator Searches

X-SECT (cm^{2}sr^{-1}GeV^{-1})	*CHG* *e*/3	*MASS* (GeV)	*ENERGY* (GeV)	*BEAM*	*EVTS*	*DOCUMENT ID*		*TECN*
<4.E−36	−2,4	1.5–6	70	p	0	BALDIN	76	CNTR
<2.E−33	±4	5–20	52	pp	0	ALBROW	75	SPEC
<5.E−34	<7	7–15	44	pp	0	JOVANOV...	75	CNTR
<5.E−35			20	γ	0	[9] GALIK	74	CNTR
<9.E−35	−1,2		200	p	0	NASH	74	CNTR
<4.E−36	−4	2.3–2.7	70	p	0	ANTIPOV	71	CNTR
<3.E−35	±1,2	<2.7	27	p	0	ALLABY	69B	CNTR
<7.E−38	−1,2	<2.5	70	p	0	ANTIPOV	69B	CNTR

[9] Cross section in cm^2/sr/equivalent quanta.

Quark Flux — Accelerator Searches

The definition of FLUX depends on the experiment

(a) is the ratio of measured free quarks to predicted free quarks if there is no "confinement."
(b) is the probability of fractional charge on nuclear fragments. Energy is in GeV/nucleon.
(c) is the 90%CL upper limit on fractionally-charged particles produced per interaction.
(d) is quarks per collision.
(e) is inclusive quark-production cross-section ratio to $\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)$.
(f) is quark flux per charged particle.
(g) is the flux per ν-event.

(h) is quark yield per π^- yield.

(i) is 2-body exclusive quark-production cross-section ratio to $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$.

FLUX		CHG (e/3)	MASS (GeV)	ENRGY (GeV)	BEAM	EVTS	DOCUMENT ID		TECN
<1.6E−3	b	see note		200	^{32}S–Pb	0	[10] HUENTRUP	96	PLAS
<6.2E−4	b	see note		10.6	^{32}S–Pb	0	[10] HUENTRUP	96	PLAS
<0.94E−4	e	±2	2–30	88–94	e^+e^-	0	AKERS	95R	OPAL
<1.7E−4	e	±2	30–40	88–94	e^+e^-	0	AKERS	95R	OPAL
<3.6E−4	e	±4	5–30	88–94	e^+e^-	0	AKERS	95R	OPAL
<1.9E−4	e	±4	30–45	88–94	e^+e^-	0	AKERS	95R	OPAL
<2.E−3	e	+1	5–40	88–94	e^+e^-	0	[11] BUSKULIC	93C	ALEP
<6.E−4	e	+2	5–30	88–94	e^+e^-	0	[11] BUSKULIC	93C	ALEP
<1.2E−3	e	+4	15–40	88–94	e^+e^-	0	[11] BUSKULIC	93C	ALEP
<3.6E−4	i	+4	5.0–10.2	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<3.6E−4	i	+4	16.5–26.0	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<6.9E−4	i	+4	26.0–33.3	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<9.1E−4	i	+4	33.3–38.6	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<1.1E−3	i	+4	38.6–44.9	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<1.6E−4	b	see note		see note		0	[12] CECCHINI	93	PLAS
	b	4,5,7,8		2.1A	^{16}O	0,2,0,6	[13] GHOSH	92	EMUL
<6.4E−5	g	1			$\nu,\overline{\nu}$	1	[14] BASILE	91	CNTR
<3.7E−5	g	2			$\nu,\overline{\nu}$	0	[14] BASILE	91	CNTR
<3.9E−5	g	1			$\nu,\overline{\nu}$	1	[15] BASILE	91	CNTR
<2.8E−5	g	2			$\nu,\overline{\nu}$	0	[15] BASILE	91	CNTR
<1.9E−4	c			14.5A	^{28}Si–Pb	0	[16] HE	91	PLAS
<3.9E−4	c			14.5A	^{28}Si–Cu	0	[16] HE	91	PLAS
<1.E−9	c	±1,2,4		14.5A	^{16}O–Ar	0	MATIS	91	MDRP
<5.1E−10	c	±1,2,4		14.5A	^{16}O–Hg	0	MATIS	91	MDRP
<8.1E−9	c	±1,2,4		14.5A	Si–Hg	0	MATIS	91	MDRP
<1.7E−6	c	±1,2,4		60A	^{16}O–Hg	0	MATIS	91	MDRP
<3.5E−7	c	±1,2,4		200A	^{16}O–Hg	0	MATIS	91	MDRP
<1.3E−6	c	±1,2,4		200A	S–Hg	0	MATIS	91	MDRP
<5E−2	e	2	19–27	52–60	e^+e^-	0	ADACHI	90C	TOPZ
<5E−2	e	4	<24	52–60	e^+e^-	0	ADACHI	90C	TOPZ
<1.E−4	e	+2	<3.5	10	e^+e^-	0	BOWCOCK	89B	CLEO
<1.E−6	d	±1,2		60	^{16}O–Hg	0	CALLOWAY	89	MDRP
<3.5E−7	d	±1,2		200	^{16}O–Hg	0	CALLOWAY	89	MDRP
<1.3E−6	d	±1,2		200	S–Hg	0	CALLOWAY	89	MDRP
<1.2E−10	d	±1	1	800	p–Hg	0	MATIS	89	MDRP
<1.1E−10	d	±2	1	800	p–Hg	0	MATIS	89	MDRP
<1.2E−10	d	±1	1	800	p–N_2	0	MATIS	89	MDRP
<7.7E−11	d	±2	1	800	p–N_2	0	MATIS	89	MDRP
<6.E−9	h	−5	0.9–2.3	12	p	0	NAKAMURA	89	SPEC
<5.E−5	g	1,2	<0.5		$\nu,\overline{\nu}d$	0	ALLASIA	88	BEBC
<3.E−4	b	See note		14.5	^{16}O–Pb	0	[17] HOFFMANN	88	PLAS
<2.E−4	b	See note		200	^{16}O–Pb	0	[18] HOFFMANN	88	PLAS
<8E−5	b	19,20,22,23		200*A*			GERBIER	87	PLAS
<2.E−4	a	±1,2	<300	320	$\overline{p}p$	0	LYONS	87	MLEV

<1.E−9	c	±1,2,4,5		14.5	^{16}O–Hg	0		SHAW	87	MDRP
<3.E−3	d	−1,2,3,4,6	<5	2	Si–Si	0	[19]	ABACHI	86C	CNTR
<1.E−4	e	±1,2,4	<4	10	e^+e^-	0		ALBRECHT	85G	ARG
<6.E−5	b	±1,2	1	540	$p\overline{p}$	0		BANNER	85	UA2
<5.E−3	e	−4	1–8	29	e^+e^-	0		AIHARA	84	TPC
<1.E−2	e	±1,2	1–13	29	e^+e^-	0		AIHARA	84B	TPC
<2.E−4	b	±1		72	^{40}Ar	0	[20]	BARWICK	84	CNTR
<1.E−4	e	±2	<0.4	1.4	e^+e^-	0		BONDAR	84	OLYA
<5.E−1	e	±1,2	<13	29	e^+e^-	0		GURYN	84	CNTR
<3.E−3	b	±1,2	<2	540	$p\overline{p}$	0		BANNER	83	CNTR
<1.E−4	b	±1,2		106	^{56}Fe	0		LINDGREN	83	CNTR
<3.E−3	b	$>\|\pm 0.1\|$		74	^{40}Ar	0	[20]	PRICE	83	PLAS
<1.E−2	e	±1,2	<14	29	e^+e^-	0		MARINI	82B	CNTR
<8.E−2	e	±1,2	<12	29	e^+e^-	0		ROSS	82	CNTR
<3.E−4	e	±2	1.8–2	7	e^+e^-	0		WEISS	81	MRK2
<5.E−2	e	+1,2,4,5	2–12	27	e^+e^-	0		BARTEL	80	JADE
<2.E−5	g	1,2			ν	0	[14,15]	BASILE	80	CNTR
<3.E−10	f	±2,4	1–3	200	p	0	[21]	BOZZOLI	79	CNTR
<6.E−11	f	±1	<21	52	pp	0		BASILE	78	SPEC
<5.E−3	g				ν_μ	0		BASILE	78B	CNTR
<2.E−9	f	±1	<26	62	pp	0		BASILE	77	SPEC
<7.E−10	f	+1,2	<20	52	p	0	[22]	FABJAN	75	CNTR
		+1,2	>4.5		γ	0	[14,15]	GALIK	74	CNTR
		+1,2	>1.5	12	e^-	0	[14,15]	BELLAMY	68	CNTR
		+1,2	>0.9		γ	0	[15]	BATHOW	67	CNTR
		+1,2	>0.9	6	γ	0	[15]	FOSS	67	CNTR

[10] HUENTRUP 96 quote 95% CL limits for production of fragments with charge differing by as much as ±1/3 (in units of e) for charge 6 ≤ Z ≤ 10.

[11] BUSKULIC 93C limits for inclusive quark production are more conservative if the ALEPH hadronic fragmentation function is assumed.

[12] CECCHINI 93 limit at 90%CL for 23/3 ≤ Z ≤ 40/3, for 16*A* GeV O, 14.5*A* Si, and 200*A* S incident on Cu target. Other limits are 2.3×10^{-4} for 17/3 ≤ Z ≤ 20/3 and 1.2×10^{-4} for 20/3 ≤ Z ≤ 23/3.

[13] GHOSH 92 reports measurement of spallation fragment charge based on ionization in emulsion. Out of 650 measured tracks, 2 were consistent with charge $5e/3$, and 4 with $7e/3$.

[14] Hadronic quark.

[15] Leptonic quark.

[16] HE 91 limits are for charges of the form $N \pm 1/3$ from 23/3 to 38/3, and correspond to cross-section limits of 380μb (Pb) and 320μb (Cu).

[17] The limits apply to projectile fragment charges of 17, 19, 20, 22, 23 in units of $e/3$.

[18] The limits apply to projectile fragment charges of 16, 17, 19, 20, 22, 23 in units of $e/3$.

[19] Flux limits and mass range depend on charge.

[20] Bound to nuclei.

[21] Quark lifetimes $> 1 \times 10^{-8}$ s.

[22] One candidate m <0.17 GeV.

Quark Flux — Cosmic Ray Searches

Shielding values followed with an asterisk indicate altitude in km. Shielding values not followed with an asterisk indicate sea level in kg/cm^2.

FLUX ($cm^{-2}sr^{-1}s^{-1}$)	*CHG* (e/3)	*MASS* (GeV)	*SHIELDING*	*EVTS*	*DOCUMENT ID*		*TECN*
$< 9.2E-15$	±1		3800	0	[23] AMBROSIO	00C	MCRO
$<2.1E-15$	±1			0	MORI	91	KAM2
$<2.3E-15$	±2			0	MORI	91	KAM2
$<2.E-10$	$\pm1,2$		0.3	0	WADA	88	CNTR
	±4		0.3	12	[24] WADA	88	CNTR
	±4		0.3	9	[25] WADA	86	CNTR
$<1.E-12$	$\pm2,3/2$		$-70.$	0	[26] KAWAGOE	84B	PLAS
$<9.E-10$	$\pm1,2$		0.3	0	WADA	84B	CNTR
$<4.E-9$	±4		0.3	7	WADA	84B	CNTR
$<2.E-12$	$\pm1,2,3$		-0.3 *	0	MASHIMO	83	CNTR
$<3.E-10$	$\pm1,2$		0.3	0	MARINI	82	CNTR
$<2.E-11$	$\pm1,2$			0	MASHIMO	82	CNTR
$<8.E-10$	$\pm1,2$		0.3	0	[26] NAPOLITANO	82	CNTR
				3	[27] YOCK	78	CNTR
$<1.E-9$				0	[28] BRIATORE	76	ELEC
$<2.E-11$	$+1$			0	[29] HAZEN	75	CC
$<2.E-10$	$+1,2$			0	KRISOR	75	CNTR
$<1.E-7$	$+1,2$			0	[29,30] CLARK	74B	CC
$<3.E-10$	$+1$	>20		0	KIFUNE	74	CNTR
$<8.E-11$	$+1$			0	[29] ASHTON	73	CNTR
$<2.E-8$	$+1,2$			0	HICKS	73B	CNTR
$<5.E-10$	$+4$		2.8 *	0	BEAUCHAMP	72	CNTR
$<1.E-10$	$+1,2$			0	[29] BOHM	72B	CNTR
$<1.E-10$	$+1,2$		2.8 *	0	COX	72	ELEC
$<3.E-10$	$+2$			0	CROUCH	72	CNTR
$<3.E-8$			7	0	[28] DARDO	72	CNTR
$<4.E-9$	$+1$			0	[29] EVANS	72	CC
$<2.E-9$		>10		0	[28] TONWAR	72	CNTR
$<2.E-10$	$+1$		2.8 *	0	CHIN	71	CNTR
$<3.E-10$	$+1,2$			0	[29] CLARK	71B	CC
$<1.E-10$	$+1,2$			0	[29] HAZEN	71	CC
$<5.E-10$	$+1,2$		3.5 *	0	BOSIA	70	CNTR
	$+1,2$	<6.5		1	[29] CHU	70	HLBC
$<2.E-9$	$+1$			0	FAISSNER	70B	CNTR
$<2.E-10$	$+1,2$		0.8 *	0	KRIDER	70	CNTR
$<5.E-11$	$+2$			4	CAIRNS	69	CC
$<8.E-10$	$+1,2$	<10		0	FUKUSHIMA	69	CNTR
	$+2$			1	[29,31] MCCUSKER	69	CC
$<1.E-10$		>5	1.7,3.6	0	[28] BJORNBOE	68	CNTR
$<1.E-8$	$\pm1,2,4$		6.3,.2 *	0	[26] BRIATORE	68	CNTR
$<3.E-8$		>2		0	FRANZINI	68	CNTR
$<9.E-11$	$\pm1,2$			0	GARMIRE	68	CNTR
$<4.E-10$	±1			0	HANAYAMA	68	CNTR
$<3.E-8$		>15		0	KASHA	68	OSPK
$<2.E-10$	$+2$			0	KASHA	68B	CNTR
$<2.E-10$	$+4$			0	KASHA	68C	CNTR
$<2.E-10$	$+2$		6	0	BARTON	67	CNTR

<2.E−7	+4		0.008,0.5 ∗	0	BUHLER	67	CNTR
<5.E−10	1,2		0.008,0.5 ∗	0	BUHLER	67B	CNTR
<4.E−10	+1,2			0	GOMEZ	67	CNTR
<2.E−9	+2			0	KASHA	67	CNTR
<2.E−10	+2		220	0	BARTON	66	CNTR
<2.E−9	+1,2		0.5 ∗	0	BUHLER	66	CNTR
<3.E−9	+1,2			0	KASHA	66	CNTR
<2.E−9	+1,2			0	LAMB	66	CNTR
<2.E−8	+1,2	>7	2.8 ∗	0	DELISE	65	CNTR
<5.E−8	+2	>2.5	0.5 ∗	0	MASSAM	65	CNTR
<2.E−8	+1		2.5 ∗	0	BOWEN	64	CNTR
<2.E−7	+1		0.8	0	SUNYAR	64	CNTR

[23] AMBROSIO 00C limit is below 11×10^{-15} for $0.25 < q/e < 0.5$, and is changing rapidly near $q/e=2/3$, where it is 2×10^{-14}.
[24] Distribution in celestial sphere was described as anisotropic.
[25] With telescope axis at zenith angle 40° to the south.
[26] Leptonic quarks.
[27] Lifetime $> 10^{-8}$ s; charge ±0.70, 0.68, 0.42; and mass >4.4, 4.8, and 20 GeV, respectively.
[28] Time delayed air shower search.
[29] Prompt air shower search.
[30] Also $e/4$ and $e/6$ charges.
[31] No events in subsequent experiments.

Quark Density — Matter Searches

For a review, see SMITH 89.

QUARKS/ NUCLEON	*CHG* (e/3)	*MASS* (GeV)	*MATERIAL/METHOD*	*EVTS*	*DOCUMENT ID*	
<4.7E−21	±1,2		silicone oil drops	0	MAR	96
<8.E−22	+2		Si/infrared photoionization	0	PERERA	93
<5.E−27	±1,2		sea water/levitation	0	HOMER	92
<4.E−20	±1,2		meteorites/mag. levitation	0	JONES	89
<1.E−19	±1,2		various/spectrometer	0	MILNER	87
<5.E−22	±1,2		W/levitation	0	SMITH	87
<3.E−20	+1,2		org liq/droplet tower	0	VANPOLEN	87
<6.E−20	−1,2		org liq/droplet tower	0	VANPOLEN	87
<3.E−21	±1		Hg drops-untreated	0	SAVAGE	86
<3.E−22	±1,2		levitated niobium	0	SMITH	86
<2.E−26	±1,2		^{4}He/levitation	0	SMITH	86B
<2.E−20	>±1	0.2–250	niobium+tungs/ion	0	MILNER	85
<1.E−21	±1		levitated niobium	0	SMITH	85
	+1,2	<100	niobium/mass spec	0	KUTSCHERA	84
<5.E−22			levitated steel	0	MARINELLI	84
<9.E−20	± <13		water/oil drop	0	JOYCE	83
<2.E−21	> | ± 1/2|		levitated steel	0	LIEBOWITZ	83
<1.E−19	±1,2		photo ion spec	0	VANDESTEEG	83
<2.E−20			mercury/oil drop	0	[32] HODGES	81
1.E−20	+1		levitated niobium	4	[33] LARUE	81
1.E−20	−1		levitated niobium	4	[33] LARUE	81
<1.E−21			levitated steel	0	MARINELLI	80B
<6.E−16			helium/mass spec	0	BOYD	79

1.E−20	+1		levitated niobium	2	[33] LARUE	79
<4.E−28			earth+/ion beam	0	OGOROD...	79
<5.E−15	+1		tungs./mass spec	0	BOYD	78
<5.E−16	+3	<1.7	hydrogen/mass spec	0	BOYD	78B
<1.E−21	±2,4		water/ion beam	0	LUND	78
<6.E−15	>1/2		levitated tungsten	0	PUTT	78
<1.E−22			metals/mass spec	0	SCHIFFER	78
<5.E−15			levitated tungsten ox	0	BLAND	77
<3.E−21			levitated iron	0	GALLINARO	77
2.E−21	−1		levitated niobium	1	[33] LARUE	77
4.E−21	+1		levitated niobium	2	[33] LARUE	77
<1.E−13	+3	<7.7	hydrogen/mass spec	0	MULLER	77
<5.E−27			water+/ion beam	0	OGOROD...	77
<1.E−21			lunar+/ion spec	0	STEVENS	76
<1.E−15	+1	<60	oxygen+/ion spec	0	ELBERT	70
<5.E−19			levitated graphite	0	MORPURGO	70
<5.E−23			water+/atom beam	0	COOK	69
<1.E−17	±1,2		levitated graphite	0	BRAGINSK	68
<1.E−17			water+/uv spec	0	RANK	68
<3.E−19	±1		levitated iron	0	STOVER	67
<1.E−10			sun/uv spec	0	[34] BENNETT	66
<1.E−17	+1,2		meteorites+/ion beam	0	CHUPKA	66
<1.E−16	±1		levitated graphite	0	GALLINARO	66
<1.E−22			argon/electrometer	0	HILLAS	59
	−2		levitated oil	0	MILLIKAN	10

[32] Also set limits for $Q = \pm e/6$.
[33] Note that in PHILLIPS 88 these authors report a subtle magnetic effect which could account for the apparent fractional charges.
[34] Limit inferred by JONES 77B.

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