

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	$p\bar{p}$	0	¹ ABE	92J CDF
<1.E-35	+4	250	1800	$p\bar{p}$	0	¹ ABE	92J CDF
<3.8E-28			14.5A	$^{28}\text{Si-Pb}$	0	² HE	91 PLAS
<3.2E-28			14.5A	$^{28}\text{Si-Cu}$	0	² HE	91 PLAS
<1.E-40	$\pm 1,2$	<10		$p, \nu, \bar{\nu}$	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 BUSSIÈRE	80 CNTR
<5.E-38	+1,2	>5	300	p	0	^{4,5} STEVENSON	79 CNTR
<1.E-33	± 1	<20	52	pp	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	pp	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	<i>pp</i>	0	ALPER	73	SPEC
<5.E-31	+1,2,4	<12	300	<i>p</i>	0	LEIPUNER	73	CNTR
<6.E-34	±1,2	<13	52	<i>pp</i>	0	BOTT	72	CNTR
<1.E-36	-4	4	70	<i>p</i>	0	ANTIPOV	71	CNTR
<1.E-35	±1,2	2	28	<i>p</i>	0	⁷ ALLABY	69B	CNTR
<4.E-37	-2	<5	70	<i>p</i>	0	³ ANTIPOV	69	CNTR
<3.E-37	-1,2	2-5	70	<i>p</i>	0	⁷ ANTIPOV	69B	CNTR
<1.E-35	+1,2	<7	30	<i>p</i>	0	DORFAN	65	CNTR
<2.E-35	-2	<2.5-5	30	<i>p</i>	0	⁸ FRANZINI	65B	CNTR
<5.E-35	+1,2	<2.2	21	<i>p</i>	0	BINGHAM	64	HLBC
<1.E-32	+1,2	<4.0	28	<i>p</i>	0	BLUM	64	HBC
<1.E-35	+1,2	<2.5	31	<i>p</i>	0	⁸ HAGOPIAN	64	HBC
<1.E-34	+1	<2	28	<i>p</i>	0	LEIPUNER	64	CNTR
<1.E-33	+1,2	<2.4	24	<i>p</i>	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 $3 \times 10^{-5} < \text{lifetime} < 1 \times 10^{-3} \text{ s}$.

⁶ Includes BOTT 72 results.

⁷ Assumes isotropic cm production.

⁸ Cross section inferred from flux.

Quark Differential Production Cross Section — Accelerator Searches

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

<u>FLUX</u>		<u>CHG</u> (e/3)	<u>MASS</u> (GeV)	<u>ENRGY</u> (GeV)	<u>BEAM</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>
<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			$\nu, \bar{\nu}$	1	¹⁴ BASILE	91 CNTR
<3.7E-5	g	2			$\nu, \bar{\nu}$	0	¹⁴ BASILE	91 CNTR
<3.9E-5	g	1			$\nu, \bar{\nu}$	1	¹⁵ BASILE	91 CNTR
<2.8E-5	g	2			$\nu, \bar{\nu}$	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		$\nu, \bar{\nu} d$	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		200A			GERBIER	87 PLAS

<2.E-4	a	$\pm 1,2$	<300	320	$\bar{p}p$	0	LYONS	87	MLEV
<1.E-9	c	$\pm 1,2,4,5$		14.5	$^{16}\text{O-Hg}$	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	$\pm 1,2,4$	<4	10	e^+e^-	0	ALBRECHT	85G	ARG
<6.E-5	b	$\pm 1,2$	1	540	$p\bar{p}$	0	BANNER	85	UA2
<5.E-3	e	-4	1-8	29	e^+e^-	0	AIHARA	84	TPC
<1.E-2	e	$\pm 1,2$	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	$\pm 1,2$	<13	29	e^+e^-	0	GURYN	84	CNTR
<3.E-3	b	$\pm 1,2$	<2	540	$p\bar{p}$	0	BANNER	83	CNTR
<1.E-4	b	$\pm 1,2$		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	$\pm 1,2$	<14	29	e^+e^-	0	MARINI	82B	CNTR
<8.E-2	e	$\pm 1,2$	<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	$\pm 2,4$	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 $\pm 1/3$ (in units of e) for charge $6 \leq Z \leq 10$.

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 $23/3 \leq Z \leq 40/3$, for 16A GeV O, 14.5A Si, and 200A S incident on Cu target. Other limits are 2.3×10^{-4} for $17/3 \leq Z \leq 20/3$ and 1.2×10^{-4} for $20/3 \leq Z \leq 23/3$.

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 $380\mu\text{b}$ (Pb) and $320\mu\text{b}$ (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/cm².

<i>FLUX</i> (cm ⁻² sr ⁻¹ s ⁻¹)	<i>CHG</i> (e/3)	<i>MASS</i> (GeV)	<i>SHIELDING</i>	<i>EVTS</i>	<i>DOCUMENT ID</i>	<i>TECN</i>
<2.1E-15	±1			0	MORI	91 KAM2
<2.3E-15	±2			0	MORI	91 KAM2
<2.E-10	±1,2		0.3	0	WADA	88 CNTR
	±4		0.3	12	23 WADA	88 CNTR
	±4		0.3	9	24 WADA	86 CNTR
<1.E-12	±2,3/2		-70.	0	25 KAWAGOE	84B PLAS
<9.E-10	±1,2		0.3	0	WADA	84B CNTR
<4.E-9	±4		0.3	7	WADA	84B CNTR
<2.E-12	±1,2,3		-0.3 *	0	MASHIMO	83 CNTR
<3.E-10	±1,2		0.3	0	MARINI	82 CNTR
<2.E-11	±1,2			0	MASHIMO	82 CNTR
<8.E-10	±1,2		0.3	0	25 NAPOLITANO	82 CNTR
				3	26 YOCK	78 CNTR
<1.E-9				0	27 BRIATORE	76 ELEC
<2.E-11	+1			0	28 HAZEN	75 CC
<2.E-10	+1,2			0	KRISOR	75 CNTR
<1.E-7	+1,2			0	28,29 CLARK	74B CC
<3.E-10	+1	>20		0	KIFUNE	74 CNTR
<8.E-11	+1			0	28 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	28 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	27 DARDO	72 CNTR
<4.E-9	+1			0	28 EVANS	72 CC
<2.E-9		>10		0	27 TONWAR	72 CNTR
<2.E-10	+1		2.8 *	0	CHIN	71 CNTR
<3.E-10	+1,2			0	28 CLARK	71B CC
<1.E-10	+1,2			0	28 HAZEN	71 CC
<5.E-10	+1,2		3.5 *	0	BOSIA	70 CNTR
	+1,2	<6.5		1	28 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	28,30 MCCUSKER	69 CC
<1.E-10		>5	1.7,3.6	0	27 BJORNBOE	68 CNTR
<1.E-8	±1,2,4		6.3,.2 *	0	25 BRIATORE	68 CNTR
<3.E-8		>2		0	FRANZINI	68 CNTR
<9.E-11	±1,2			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 *	DELISE	65	CNTR
<5.E-8	+2	>2.5	0.5 *	MASSAM	65	CNTR
<2.E-8	+1		2.5 *	BOWEN	64	CNTR
<2.E-7	+1		0.8	SUNYAR	64	CNTR

²³ Distribution in celestial sphere was described as anisotropic.

²⁴ With telescope axis at zenith angle 40° to the south.

²⁵ Leptonic quarks.

²⁶ Lifetime > 10⁻⁸ s; charge ±0.70, 0.68, 0.42; and mass >4.4, 4.8, and 20 GeV, respectively.

²⁷ Time delayed air shower search.

²⁸ Prompt air shower search.

²⁹ Also e/4 and e/6 charges.

³⁰ No events in subsequent experiments.

Quark Density — Matter Searches

For a review, see SMITH 89.

<u>QUARKS/ NUCLEON</u>	<u>CHG (e/3)</u>	<u>MASS (GeV)</u>	<u>MATERIAL/METHOD</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>
<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	³¹ HODGES 81
1.E-20	+1		levitated niobium	4	³² LARUE 81
1.E-20	-1		levitated niobium	4	³² 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	³² 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	³² LARUE	77
4.E-21	+1		levitated niobium	2	³² 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	³³ 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

³¹ Also set limits for $Q = \pm e/6$.

³² Note that in PHILLIPS 88 these authors report a subtle magnetic effect which could account for the apparent fractional charges.

³³ Limit inferred by JONES 77B.

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