# 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).


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**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 | ±1,2 | <10 | | $p,\nu,\overline{\nu}$ | 0 | BERGSMA | 84B | CHRM |
| <1.E−36 | ±1,2 | <9 | 200 | $\mu$ | 0 | AUBERT | 83C | SPEC |
| <2.E−10 | ±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 | $pp$ | 0 | BASILE | 78 | SPEC |
| <9.E−39 | ±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 | *p p* | 0 | ALPER | 73 | SPEC |
| <5.E−31 | +1,2,4 | <12 | 300 | *p* | 0 | LEIPUNER | 73 | CNTR |
| <6.E−34 | ±1,2 | <13 | 52 | *p p* | 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 $N\pm1/3$ from 23/3 to 38/3.
[3] Hadronic or leptonic quarks.
[4] Cross section $cm^2/GeV^2$.
[5] $3\times10^{-5}$ <lifetime $< 1\times10^{-3}$ 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* ($cm^2sr^{-1}GeV^{-1}$) | *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 | *p p* | 0 | ALBROW | 75 | SPEC |
| <5.E−34 | <7 | 7–15 | 44 | *p p* | 0 | JOVANOV... | 75 | CNTR |
| <5.E−35 | | | 20 | $\gamma$ | 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 $\nu$-event.

(h) is quark yield per $\pi^-$ 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 |
| <1.7E−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 | $>\lvert\pm 0.1\rvert$ | | 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 | | | $\nu$ | 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 | | | | $\nu_\mu$ | 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 | | $\gamma$ | 0 | [14,15] | GALIK | 74 | CNTR |
| | | +1,2 | >1.5 | 12 | $e^-$ | 0 | [14,15] | BELLAMY | 68 | CNTR |
| | | +1,2 | >0.9 | | $\gamma$ | 0 | [15] | BATHOW | 67 | CNTR |
| | | +1,2 | >0.9 | 6 | $\gamma$ | 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 $6 \leq Z \leq 10$.

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

[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$\mu$b (Pb) and 320$\mu$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/cm$^2$.

| *FLUX* (cm$^{-2}$sr$^{-1}$s$^{-1}$) | *CHG* (e/3) | *MASS* (GeV) | *SHIELDING* | *EVTS* | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|---|---|---|---|
| <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 * | 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] Distribution in celestial sphere was described as anisotropic.
[24] With telescope axis at zenith angle $40^{o}$ to the south.
[25] Leptonic quarks.
[26] Lifetime $> 10^{-8}$ s; charge $\pm 0.70$, 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.

| 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 | [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.

## REFERENCES FOR Free Quark Searches


| | | | |
|---|---|---|---|
| ABREU | 97D | PL B396 315 | P. Abreu+ (DELPHI Collab.) |
| HUENTRUP | 96 | PR C53 358 | +Weidmann, Hirzebruch, Winkel, Heinrich (SIEG) |
| MAR | 96 | PR D53 6017 | +Lee, Fleming, Case+ (SLAC, SCHAF, LANL, UCI) |
| AKERS | 95R | ZPHY C67 203 | +Alexander, Allison, Ametewee, Anderson+ (OPAL Collab.) |
| BUSKULIC | 93C | PL B303 198 | +Decamp, Goy, Lees, Minard+ (ALEPH Collab.) |
| CECCHINI | 93 | ASP 1 369 | S. Cecchini+ |
| PERERA | 93 | PRL 70 1053 | +Betarbet, Byungsung, Coon (PITT) |
| ABE | 92J | PR D46 R1889 | +Amidei, Anway-Weiss+ (CDF Collab.) |
| GHOSH | 92 | NC 105A 99 | +Roy, Ghosh, Ghosh, Basu (JADA, BANGB) |
| HOMER | 92 | ZPHY C55 549 | +Smith, Lewin, Robertson+ (RAL, SHMP, LOQM) |
| BASILE | 91 | NC 104A 405 | +Berbiers, Cara Romeo+ (BGNA, INFN, CERN, PLRM+) |
| HE | 91 | PR C44 1672 | +Price (UCB) |
| MATIS | 91 | NP A525 513c | +Pugh, Alba, Bland, Calloway+ (LBL, SFSU, UCI, LANL) |
| MORI | 91 | PR D43 2843 | +Oyama, Suzuki, Takahashi+ (Kamiokande II Collab.) |
| ADACHI | 90C | PL B244 352 | +Aihara, Doser, Enomoto+ (TOPAZ Collab.) |
| BOWCOCK | 89B | PR D40 263 | +Kinoshita, Mauskopf, Pipkin+ (CLEO Collab.) |
| CALLOWAY | 89 | PL B232 549 | +Alba, Bland, Dickson, Hodges+ (SFSU, UCI, LBL, LANL) |
| JONES | 89 | ZPHY C43 349 | +Smith, Homer, Lewin, Walford (LOIC, RAL) |
| MATIS | 89 | PR D39 1851 | +Pugh, Bland, Calloway+ (LBL, SFSU, UCI, FNAL, LANL) |
| NAKAMURA | 89 | PR D39 1261 | +Kobayashi, Konaka, Imai, Masaike+ (KYOT, TMTC) |
| SMITH | 89 | ARNPS 39 73 | (RAL) |
| ALLASIA | 88 | PR D37 219 | +Angelini, Baldini+ (WA25 Collab.) |
| HOFFMANN | 88 | PL B200 583 | +Brechtmann, Heinrich, Benton (SIEG, USF) |
| PHILLIPS | 88 | NIM A264 125 | +Fairbank, Navarro (STAN) |
| WADA | 88 | NC 11C 229 | +Yamashita, Yamamoto (OKAY) |
| GERBIER | 87 | PRL 59 2535 | G. Gerbier+ (UCB, CERN) |
| LYONS | 87 | ZPHY C36 363 | +Smith, Homer, Lewin, Walford+ (OXF, RAL, LOIC) |

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| SHAW | 87 | PR D36 3533 | +Matis, Pugh, Slansky+ | (UCI, LBL, LANL, SFSU) |
| SMITH | 87 | PL B197 447 | +Homer, Lewin, Walford, Jones | (RAL, LOIC) |
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| SMITH | 86 | PL B171 129 | +Homer, Lewin, Walford, Jones | (RAL, LOIC) |
| SMITH | 86B | PL B181 407 | +Homer, Lewin, Walford, Jones | (RAL, LOIC) |
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| BANNER | 85 | PL 156B 129 | +Bloch, Borer, Borghini+ | (UA2 Collab.) |
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| AIHARA | 84B | PRL 52 2332 | +Alston-Garnjost, Badtke, Bakker+ | (TPC Collab.) |
| BARWICK | 84 | PR D30 691 | +Musser, Stevenson | (UCB) |
| BERGSMA | 84B | ZPHY C24 217 | +Allaby, Abt, Gemanov+ | (CHARM Collab.) |
| BONDAR | 84 | JETPL 40 1265 | +Kurdadze, Lelchuk, Panin, Sidorov+ | (NOVO) |
| | | Translated from ZETFP 40 440. | | |
| GURYN | 84 | PL 139B 313 | +Parker, Fries+ | (FRAS, LBL, NWES, STAN, HAWA) |
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| AUBERT | 83C | PL 133B 461 | +Bassompierre, Becks, Best+ | (EMC Collab.) |
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| LINDGREN | 83 | PRL 51 1621 | +Joyce+ | (SFSU, UCR, UCI, SLAC, LBL, LANL) |
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| LARUE | 81 | PRL 46 967 | +Phillips, Fairbank | (STAN) |
| WEISS | 81 | PL 101B 439 | +Abrams, Alam, Blocker+ | (SLAC, LBL, UCB) |
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| Also | 80 | PL 94B 427 | Marinelli, Morpurgo | (GENO) |
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| Also | 79B | PRL 42 1019 | Larue, Fairbank, Phillips | |
| OGOROD... | 79 | JETP 49 953 | Ogorodnikov, Samoilov, Solntsev | (KIAE) |
| | | Translated from ZETF 76 1881. | | |
| STEVENSON | 79 | PR D20 82 | | (LBL) |
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| BASILE | 78B | NC 45A 281 | +Cara-Romeo, Cifarelli, Contin+ | (CERN, BGNA) |
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| BOYD | 78B | PL 72B 484 | +Elmore, Nitz, Olsen, Sugarbaker, Warren+ | (ROCH) |
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| BASILE | 77 | NC 40A 41 | +Romeo, Cifarelli, Giusti+ | (CERN, BGNA) |
| BLAND | 77 | PRL 39 369 | +Bocobo, Eubank, Royer | (SFSU) |
| GALLINARO | 77 | PRL 38 1255 | +Marinelli, Morpurgo | (GENO) |
| JONES | 77B | RMP 69 717 | | |
| LARUE | 77 | PRL 38 1011 | +Fairbank, Hebard | (STAN) |
| MULLER | 77 | Science 521 | +Alvarez, Holley, Stephenson | (LBL) |
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