

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. 1–4.

References

1. M.L. Perl, E.R. Lee, and D. Lomba, *Mod. Phys. Lett.* **A19**, 2595 (2004).
2. P.F. Smith, *Ann. Rev. Nucl. and Part. Sci.* **39**, 73 (1989).
3. L. Lyons, *Phys. Reports* **129**, 225 (1985).
4. M. Marinelli and G. Morpurgo, *Phys. Reports* **85**, 161 (1982).

Quark Production Cross Section — Accelerator Searches

| <i>X-SECT</i> (cm ²) | <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> |
|-------------------------------------|------------------------------|----------------------|------------------------|---|-------------|--------------------------|-------------|
| <1.3E-36 | ±2 | 45-84 | 130-172 | <i>e</i> ⁺ <i>e</i> ⁻ | 0 | ABREU | 97D DLPH |
| <2.E-35 | +2 | 250 | 1800 | <i>p</i> \bar{p} | 0 | ¹ ABE | 92J CDF |
| <1.E-35 | +4 | 250 | 1800 | <i>p</i> \bar{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 | | <i>p, ν, ν̄</i> | 0 | BERGSMA | 84B CHRM |
| <1.E-36 | ±1,2 | <9 | 200 | <i>μ</i> | 0 | AUBERT | 83C SPEC |
| <2.E-10 | ±2,4 | 1-3 | 200 | <i>p</i> | 0 | ³ BUSSIERE | 80 CNTR |
| <5.E-38 | +1,2 | >5 | 300 | <i>p</i> | 0 | ^{4,5} STEVENSON | 79 CNTR |

| | | | | | | | | |
|---------|--------|---------|-----|-----------|---|-------------------------|-----|------|
| <1.E-33 | ±1 | <20 | 52 | <i>pp</i> | 0 | BASILE | 78 | SPEC |
| <9.E-39 | ±1,2 | <6 | 400 | <i>p</i> | 0 | ⁴ ANTREASYAN | 77 | SPEC |
| <8.E-35 | +1,2 | <20 | 52 | <i>pp</i> | 0 | ⁶ FABJAN | 75 | CNTR |
| <5.E-38 | -1,2 | 4-9 | 200 | <i>p</i> | 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

| $X\text{-SECT}$ ($\text{cm}^2\text{sr}^{-1}\text{GeV}^{-1}$) | CHG $e/3$ | $MASS$ (GeV) | $ENERGY$ (GeV) | $BEAM$ | $EVTS$ | $DOCUMENT ID$ | $TECN$ |
|---|----------------|-----------------|-------------------|-----------|--------|--------------------|----------|
| <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 $\text{cm}^2/\text{sr}/\text{equivalent quanta}$.

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 | 32S-Pb | 0 | 10 HUENTRUP | 96 PLAS |
| <6.2E-4 | b | see note | 10.6 | 32S-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 | 16O | 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 | 28Si-Pb | 0 | 16 HE | 91 PLAS |
| <3.9E-4 | c | | 14.5A | 28Si-Cu | 0 | 16 HE | 91 PLAS |
| <1.E-9 | c | ±1,2,4 | 14.5A | 16O-Ar | 0 | MATIS | 91 MDRP |
| <5.1E-10 | c | ±1,2,4 | 14.5A | 16O-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 | 16O-Hg | 0 | MATIS | 91 MDRP |
| <3.5E-7 | c | ±1,2,4 | 200A | 16O-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 | 16O-Hg | 0 | CALLOWAY | 89 MDRP |
| <3.5E-7 | d | ±1,2 | 200 | 16O-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 | 16O-Pb | 0 | 17 HOFFMANN | 88 PLAS |

| | | | | | | | | | |
|---------|---|---------------|-------|--------------------|--------------------|------------------------|--------------------------|------|------|
| <2.E-4 | b | See note | 200 | $^{16}\text{O-Pb}$ | 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> |
|---|---------------------|----------------------|------------------|-------------|--------------------|-------------|
| < 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 | ±1,2 | | 0.3 | 0 | WADA | 88 CNTR |
| | ±4 | | 0.3 | 12 | WADA | 88 CNTR |
| | ±4 | | 0.3 | 9 | 25 WADA | 86 CNTR |
| <1.E-12 | ±2,3/2 | | -70. | 0 | 26 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 | 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 | ±1,2,4 | | 6.3,.2 * | 0 | 26 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 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 $\pm 0.70, 0.68, 0.42$; and mass $> 4.4, 4.8, \text{ and } 20$ 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

| <u>QUARKS/ NUCLEON</u> | <u>CHG (e/3)</u> | <u>MASS (GeV)</u> | <u>MATERIAL/METHOD</u> | <u>EVTS</u> | <u>DOCUMENT ID</u> |
|----------------------------|----------------------|-----------------------|-----------------------------|-------------|-------------------------|
| <1.17E-22 | | | silicone oil drops | 0 | ³² LEE 02 |
| <4.71E-22 | | | silicone oil drops | 1 | ³³ HALYO 00 |
| <4.7E-21 | $\pm 1,2$ | | silicone oil drops | 0 | MAR 96 |
| <8.E-22 | +2 | | Si/infrared photoionization | 0 | PERERA 93 |
| <5.E-27 | $\pm 1,2$ | | sea water/levitation | 0 | HOMER 92 |
| <4.E-20 | $\pm 1,2$ | | meteorites/mag. levitation | 0 | JONES 89 |
| <1.E-19 | $\pm 1,2$ | | various/spectrometer | 0 | MILNER 87 |
| <5.E-22 | $\pm 1,2$ | | 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 | $\pm 1,2$ | | levitated niobium | 0 | SMITH 86 |
| <2.E-26 | $\pm 1,2$ | | ⁴ He/levitation | 0 | SMITH 86B |
| <2.E-20 | $> \pm 1$ | 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 | $\pm < 13$ | | water/oil drop | 0 | JOYCE 83 |
| <2.E-21 | $> \pm 1/2 $ | | levitated steel | 0 | LIEBOWITZ 83 |
| <1.E-19 | $\pm 1,2$ | | photo ion spec | 0 | VANDESTEEG 83 |
| <2.E-20 | | | mercury/oil drop | 0 | ³⁴ HODGES 81 |
| 1.E-20 | +1 | | levitated niobium | 4 | ³⁵ LARUE 81 |
| 1.E-20 | -1 | | levitated niobium | 4 | ³⁵ 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 | ³⁵ 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 | ³⁵ LARUE | 77 |
| 4.E-21 | +1 | levitated niobium | 2 | ³⁵ 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 | ³⁶ 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 95% CL limit for fractional charge particles with $0.18e \leq |Q_{residual}| \leq 0.82e$ in total of 70.1 mg of silicone oil.

³³ 95% CL limit for particles with fractional charge $|Q_{residual}| > 0.16e$ in total of 17.4 mg of silicone oil.

³⁴ Also set limits for $Q = \pm e/6$.

³⁵ Note that in PHILLIPS 88 these authors report a subtle magnetic effect which could account for the apparent fractional charges.

³⁶ Limit inferred by JONES 77B.

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