

Free Quark Searches

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Quark Production Cross Section — Accelerator Searches

<u>X-SECT</u> (cm ²)	<u>CHG</u> (e/3)	<u>MASS</u> (GeV)	<u>ENERGY</u> (GeV)	<u>BEAM</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>
<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 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,ν, $\bar{\nu}$	0	BERGSMA 84B	CHRM
<1.E–36	±1,2	<9	200	μ	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	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 cm²/GeV².

⁵ $3 \times 10^{-5} < \text{lifetime} < 1 \times 10^{-3}$ s.

⁶ Includes BOTT 72 results.

⁷ Assumes isotropic cm production.

⁸ Cross section inferred from flux.

Quark Differential Production Cross Section — Accelerator Searches

<u>X-SECT</u> (cm ² sr ^{–1} GeV ^{–1})	<u>CHG</u> e/3	<u>MASS</u> (GeV)	<u>ENERGY</u> (GeV)	<u>BEAM</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>
<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	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 cm²/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> (<i>e</i> /3)	<u>MASS</u> (GeV)	<u>ENERGY</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	<i>e</i> ⁺ <i>e</i> ⁻	0	AKERS	95R OPAL
<1.7E-4	e	±2	30-40	88-94	<i>e</i> ⁺ <i>e</i> ⁻	0	AKERS	95R OPAL
<3.6E-4	e	±4	5-30	88-94	<i>e</i> ⁺ <i>e</i> ⁻	0	AKERS	95R OPAL
<1.9E-4	e	±4	30-45	88-94	<i>e</i> ⁺ <i>e</i> ⁻	0	AKERS	95R OPAL
<2.E-3	e	+1	5-40	88-94	<i>e</i> ⁺ <i>e</i> ⁻	0	11 BUSKULIC	93C ALEP
<6.E-4	e	+2	5-30	88-94	<i>e</i> ⁺ <i>e</i> ⁻	0	11 BUSKULIC	93C ALEP
<1.2E-3	e	+4	15-40	88-94	<i>e</i> ⁺ <i>e</i> ⁻	0	11 BUSKULIC	93C ALEP
<3.6E-4	i	+4	5.0-10.2	88-94	<i>e</i> ⁺ <i>e</i> ⁻	0	BUSKULIC	93C ALEP
<3.6E-4	i	+4	16.5-26.0	88-94	<i>e</i> ⁺ <i>e</i> ⁻	0	BUSKULIC	93C ALEP
<6.9E-4	i	+4	26.0-33.3	88-94	<i>e</i> ⁺ <i>e</i> ⁻	0	BUSKULIC	93C ALEP
<9.1E-4	i	+4	33.3-38.6	88-94	<i>e</i> ⁺ <i>e</i> ⁻	0	BUSKULIC	93C ALEP
<1.1E-3	i	+4	38.6-44.9	88-94	<i>e</i> ⁺ <i>e</i> ⁻	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		ν,ν̄d	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	±1,2	<300	320	p̄p	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	p̄p̄	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	p̄p̄	0		BANNER	83	CNTR
<1.E-4	b	±1,2		106	⁵⁶ Fe	0		LINDGREN	83	CNTR
<3.E-3	b	> ±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				νμ	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 $23/3 \leq Z \leq 40/3$, 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/cm^2 .

$FLUX$ ($\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$)	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
$< 2.E-10$	$\pm 1, 2$		0.3	0	WADA 88	CNTR
	± 4		0.3	12	²⁴ WADA 88	CNTR
	± 4		0.3	9	²⁵ WADA 86	CNTR
$< 1.E-12$	$\pm 2, 3/2$		-70.	0	²⁶ KAWAGOE 84B	PLAS
$< 9.E-10$	$\pm 1, 2$		0.3	0	WADA 84B	CNTR
$< 4.E-9$	± 4		0.3	7	WADA 84B	CNTR
$< 2.E-12$	$\pm 1, 2, 3$		-0.3 *	0	MASHIMO 83	CNTR
$< 3.E-10$	$\pm 1, 2$		0.3	0	MARINI 82	CNTR
$< 2.E-11$	$\pm 1, 2$			0	MASHIMO 82	CNTR
$< 8.E-10$	$\pm 1, 2$		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	±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	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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