Heavy Particle Flux in Cosmic Rays

VALUE ($cm^{-2}sr^{-1}s^{-1}$)	CL%	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$< 1.8 \times 10^{-12}$	90		[44] ASTONE 93	CNTR		$m \geq 1.5 \times 10^{-13}$gram
$< 1.1 \times 10^{-14}$	90		[45] AHLEN 92	MCRO		$10^{-10} < m <$ 0.1 gram
$\sim 6 \times 10^{-9}$		2	[46] SAITO 90			$Q \simeq 14$, $m \simeq 370 m_p$
$< 1.4 \times 10^{-12}$	90	0	[47] MINCER 85	CALO		$m \geq 1$ TeV
$< 3.2 \times 10^{-11}$	90	0	[48] NAKAMURA 85	CNTR		$m > 1.5 \times 10^{-13}$gram
			[49] SAKUYAMA 83B	PLAS		$m \sim 1$ TeV
$< 1.7 \times 10^{-11}$	99	0	[50] BHAT 82	CC		
$< 1. \times 10^{-9}$	90	0	[51] MARINI 82	CNTR	$\pm$	$Q = 1$, $m \sim 4.5 m_p$
$< 3.5 \times 10^{-11}$	90	0	[52] ULLMAN 81	CNTR		Planck-mass 10^{19}GeV
$< 7. \times 10^{-11}$	90	0	[52] ULLMAN 81	CNTR		$m = 1. \times 10^{-16}$ GeV or less
$2. \times 10^{-9}$		3	[53] YOCK 81	SPRK	$\pm$	$Q = 1$, $m \sim 4.5 m_p$
		3	[53] YOCK 81	SPRK		Fractionally charged
3.0×10^{-9}		3	[54] YOCK 80	SPRK		$m \sim 4.5\ m_p$
$(4 \pm 1) \times 10^{-11}$		3	GOODMAN 79	ELEC		$m \geq 5$ GeV
$< 1.3 \times 10^{-9}$	90		[55] BHAT 78	CNTR	$\pm$	$m > 1$ GeV
$< 1.0 \times 10^{-9}$		0	BRIATORE 76	ELEC		
$< 7. \times 10^{-10}$	90	0	YOCK 75	ELEC	$\pm$	$Q > 7e$ or $< -7e$
$> 6. \times 10^{-9}$		5	[56] YOCK 74	CNTR		$m > 6$ GeV
$< 3.0 \times 10^{-8}$		0	DARDO 72	CNTR		
$< 1.5 \times 10^{-9}$		0	TONWAR 72	CNTR		$m > 10$ GeV
$< 3.0 \times 10^{-10}$		0	BJORNBOE 68	CNTR		$m > 5$ GeV
$< 5.0 \times 10^{-11}$	90	0	JONES 67	ELEC		m=5–15 GeV

[44] ASTONE 93 searched for quark matter ("nuclearites") in the velocity/c range $= 10^{-3}$–1. Their Table 1 gives a compilation of searches for nuclearites.

[45] AHLEN 92 searched for quark matter ("nuclearites"). The bound applies to velocity/c $< 2.5 \times 10^{-3}$. See their Fig. 3 for other velocity/c and heavier mass range.

[46] SAITO 90 candidates carry about 450 MeV/nucleon. Cannot be accounted for by conventional backgrounds. Consistent with strange quark matter hypothesis.

[47] MINCER 85 is high statistics study of calorimeter signals delayed by 20–200 ns. Calibration with AGS beam shows they can be accounted for by rare fluctuations in signals from low-energy hadrons in the shower. Claim that previous delayed signals including BJORNBOE 68, DARDO 72, BHAT 82, SAKUYAMA 83B below may be due to this fake effect.

[48] NAKAMURA 85 at KEK searched for quark-matter. These might be lumps of strange quark matter with roughly equal numbers of u, d, s quarks. These lumps or nuclearites were assumed to have velocity/c of 10^{-4}–10^{-3}.

[49] SAKUYAMA 83B analyzed 6000 extended air shower events. Increase of delayed particles and change of lateral distribution above 10^{17} eV may indicate production of very heavy parent at top of atmosphere.

[50] BHAT 82 observed 12 events with delay $> 2. \times 10^{-8}$ s and with more than 40 particles. 1 eV has good hadron shower. However all events are delayed in only one of two detectors in cloud chamber, and could not be due to strongly interacting massive particle.

[51] MARINI 82 applied PEP-counter for TOF. Above limit is for velocity $= 0.54$ of light. Limit is inconsistent with YOCK 80 YOCK 81 events if isotropic dependence on zenith angle is assumed.

[52] ULLMAN 81 is sensitive for heavy slow singly charge particle reaching earth with vertical velocity 100–350 km/s.

[53] YOCK 81 saw another 3 events with $Q = \pm 1$ and m about $4.5 m_p$ as well as 2 events with $m > 5.3 m_p$, $Q = \pm 0.75 \pm 0.05$ and $m > 2.8 m_p$, $Q = \pm 0.70 \pm 0.05$ and 1 event with $m = (9.3 \pm 3.) m_p$, $Q = \pm 0.89 \pm 0.06$ as possible heavy candidates.

[54] YOCK 80 events are with charge exactly or approximately equal to unity.

[55] BHAT 78 is at Kolar gold fields. Limit is for $\tau > 10^{-6}$ s.

[56] YOCK 74 events could be tritons.

Concentration of Heavy (Charge +1) Stable Particles in Matter

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$< 4 \times 10^{-17}$	95	[57] YAMAGATA 93	SPEC	Deep sea water, m=5–1600m_p
$< 6 \times 10^{-15}$	95	[58] VERKERK 92	SPEC	Water, $m = 10^5$ to 3×10^7 GeV
$< 7 \times 10^{-15}$	95	[58] VERKERK 92	SPEC	Water, $m = 10^4$, 6×10^7 GeV
$< 9 \times 10^{-15}$	95	[58] VERKERK 92	SPEC	Water, $m = 10^8$ GeV
$< 3 \times 10^{-23}$	90	[59] HEMMICK 90	SPEC	Water, $m = 1000 m_p$
$< 2 \times 10^{-21}$	90	[59] HEMMICK 90	SPEC	Water, $m = 5000 m_p$
$< 3 \times 10^{-20}$	90	[59] HEMMICK 90	SPEC	Water, $m = 10000 m_p$
$< 1. \times 10^{-29}$		SMITH 82B	SPEC	Water, m=30–400m_p
$< 2. \times 10^{-28}$		SMITH 82B	SPEC	Water, m=12–1000m_p
$< 1. \times 10^{-14}$		SMITH 82B	SPEC	Water, $m > 1000\ m_p$
$< (0.2–1.) \times 10^{-21}$		SMITH 79	SPEC	Water, m=6–350 m_p

[57] YAMAGATA 93 used deep sea water at 4000 m since the concentration is enhanced in deep sea due to gravity.

[58] VERKERK 92 looked for heavy isotopes in sea water and put a bound on concentration of stable charged massive particle in sea water. The above bound can be translated into into a bound on charged dark matter particle (5×10^6 GeV), assuming the local density, ρ=0.3 GeV/cm^3, and the mean velocity $\langle v \rangle$=300 km/s.

[59] See HEMMICK 90 Fig. 7 for other masses 100–10000 m_p.

Concentration of Heavy (Charge −1) Stable Particles

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$< 4 \times 10^{-20}$	90	[60] HEMMICK 90	SPEC	C, $M = 100 m_p$
$< 8 \times 10^{-20}$	90	[60] HEMMICK 90	SPEC	C, $M = 1000 m_p$
$< 2 \times 10^{-16}$	90	[60] HEMMICK 90	SPEC	C, $M = 10000 m_p$
$< 6 \times 10^{-13}$	90	[60] HEMMICK 90	SPEC	Li, $M = 1000 m_p$
$< 1 \times 10^{-11}$	90	[60] HEMMICK 90	SPEC	Be, $M = 1000 m_p$
$< 6 \times 10^{-14}$	90	[60] HEMMICK 90	SPEC	B, $M = 1000 m_p$
$< 4 \times 10^{-17}$	90	[60] HEMMICK 90	SPEC	O, $M = 1000 m_p$
$< 4 \times 10^{-15}$	90	[60] HEMMICK 90	SPEC	F, $M = 1000 m_p$
$< 1.5 \times 10^{-13}$/nucleon	68	[61] NORMAN 89	SPEC	^{206}PbX^-
$< 1.2 \times 10^{-12}$/nucleon	68	[61] NORMAN 87	SPEC	^{56,58}FeX^-

[60] See HEMMICK 90 Fig. 7 for other masses 100–10000 m_p.

[61] Bound valid up to $m_{X^-} \sim 100$ TeV.

Long-Lived Particle Search at Hadron Collisions

Limits are for cross section times branching ratio.

VALUE (pb/nucleon)	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2	90	0	[62] BADIER 86	BDMP	$\tau = (0.05–1.) \times 10^{-8}$s

[62] BADIER 86 looked for long-lived particles at 300 GeV π^- beam dump. The limit applies for nonstrongly interaction neutral or charged particles with mass >2 GeV. The limit applies for particle modes, $\mu^+\pi^-$, $\mu^+\mu^-$, $\pi^+\pi^-$X, $\pi^+\pi^-\pi^\pm$ etc. See their figure 5 for the contours of limits in the mass-τ plane for each mode.

REFERENCES FOR Other Stable Particle Searches

ABE	93G	PRL 71 2542	+Albrow, Akimoto, Amidei, Anway-Wiese+	(CDF Collab.)
ASTONE	93	PR D47 4770	+Bassan, Bonifazi, Coccia+	(ROMA, ROMAI, CATA, FRAS)
BUSKULIC	93C	PL B303 198	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
YAMAGATA	93	PR D47 1231	+Takamori, Utsunomiya	(KONAN)
ABE	92J	PR D46 R1889	+Amidei, Anway-Weiss+	(CDF Collab.)
AHLEN	92	PRL 69 1860	+Ambrosio, Antolini, Auriemma, Baker+	(MACRO Collab.)
VERKERK	92	PRL 68 1116	+Grynberg, Pichard, Spiro, Zylberajch+	(ENSP, SACL, PAST)
AKESSON	91	ZPHY C52 219	+Almehed, Angelis, Atherton, Aubry+	(HELIOS Collab.)
ADACHI	90C	PL B244 352	+Aihara, Doser, Enomoto+	(TOPAZ Collab.)
ADACHI	90E	PL B249 336	+Anazawa, Doser, Enomoto, Fujii+	(TOPAZ Collab.)
AKRAWY	90O	PL B252 290	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
HEMMICK	90	PR D41 2074	+Elmore+	(ROCH, MICH, OHIO, RAL, LANL, STON)
SAITO	90	PRL 65 2094	+Hatano, Fukada, Oda	(ICRR, KOBE)
NAKAMURA	89	PR D39 1261	+Kobayashi, Konaka, Imai, Masaike+	(KYOT, TMTC)
NORMAN	89	PR D39 2499	+Chadwick, Lesko, Larimer, Hoffman	(LBL)
BERNSTEIN	88	PR D37 3103	+Shea, Winstein, Cousins, Greenhalgh+	(STAN, WISC)
REN	88	PR D38 1417	+Huo, Lu, Su+	(China-Japan Collab., Mt. Fuji Collab.)
BORISOV	87	PL B190 226	+Cherdyntseva+	(Pamir-Chacaltaya Collab.)
NORMAN	87	PRL 58 1403	+Gazes, Bennett	(LBL)
ALNER	86	PL B180 415	+Ansorge, Asman, Booth, Burow+	(UA5 Collab.)
BADIER	86	ZPHY C31 21	+Bemporad, Boucrot, Callot+	(NA3 Collab.)
MINCER	85	PR D32 541	+Freudenreich, Goodman+	(UMD, GMAS, NSF)
NAKAMURA	85	PL 161B 417	+Horie, Takahashi, Tanimori	(KEK, INUS)
THRON	85	PR D31 451	+Cardello, Cooper, Teig+	(YALE, FNAL, IOWA)
ARNISON	83B	PL 122B 189	+Astbury, Aubert, Bacci+	(UA1 Collab.)
SAKUYAMA	83B	LNC 37 17	+Nuzuki	(MEIS)
Also	83	LNC 36 389	Sakuyama, Watanabe	(MEIS)
Also	83D	NC 78A 147	Sakuyama, Watanabe	(MEIS)
Also	83C	NC 6C 371	Sakuyama, Watanabe	(MEIS)
ALPGARD	82	PL 115B 71	+Ansorge, Asman, Berglund+	(UA5 Collab.)
BHAT	82	PR D25 2820	+Gupta, Murthy, Sreekantan+	(TATA)
KINOSHITA	82	PRL 48 77	+Price, Fryberger	(UCB, SLAC)
MARINI	82	PR D26 1777	+Peruzzi, Piccolo+	(FRAS, LBL, NWES, STAN, HAWA)
SMITH	82B	NP B206 333	+Bennett, Homer, Lewin, Walford, Smith	(RAL)
BAYBURINA	81	NP B191 1	+Borisov+	(LEBD, MOSU, INRM, GEOR, TAJK+)
KINOSHITA	81B	PR D24 1707	+Price	(UCB)
LOSECCO	81	PL 102B 209	+Sulak, Galik, Horstkotte+	(MICH, PENN, BNL)
ULLMAN	81	PRL 47 289		(LEHM, BNL)
YOCK	81	PR D23 1207		(AUCK)
BARTEL	80	ZPHY C6 295	+Canzler, Lords, Drumm+	(JADE Collab.)
BUSSIERE	80	NP B174 1	+Giacomelli, Lesquoy+	(BGNA, SACL, LAPP)
LATTES	80	PRPL 65 151	+Fujimoto, Hasegawa	(CAMP, WASU)
YOCK	80	PR D22 61		(AUCK)
ARMITAGE	79	NP B150 87	+Benz, Bobbink+	(CERN, DARE, FOM, MCHS, UTRE)
BHAT	79	JPG 5 L13	+Gopalakrishnan, Gupta, Tonwar	(TATA)
BOZZOLI	79	NP B159 363	+Bussiere, Giacomelli+	(BGNA, LAPP, SACL, CERN)
GOODMAN	79	PR D19 2572	+Ellsworth, Ito, Macfall, Siohan+	(UMD)
SMITH	79	NP B149 525	+Bennett	(RHEL)
BHAT	78	Pramana 10 115	+Murthy	(TATA)
CARROLL	78	PRL 41 777	+Chiang, Johnson, Kycia, Ki+	(BNL, PRIN)
CUTTS	78	PRL 41 363	+Dulude+	(BROW, FNAL, ILL, BARI, MIT, WARS)
VIDAL	78	PL 77B 344	+Herb, Lederman+	(COLU, FNAL, STON, UCB)
VIERTEL	78	LNC 22 235	+Hahn, Schacher	(BERN)
PEREPELITSA	77	PL 67B 471		(ITEP)
SMITH	77	CJP 55 1280	+Standil	(MANI)
ALEKSEEV	76	SJNP 22 531 (Translated from YAF 22 1021.)	+Zaitsev, Kalinina, Kruglov+	(JINR)
ALEKSEEV	76B	SJNP 23 633 (Translated from YAF 23 1190.)	+Zaitsev, Kalinina, Kruglov+	(JINR)
BALDIN	76	SJNP 22 264 (Translated from YAF 22 512.)	+Vertogradov, Vishnevsky, Grishkevich+	(JINR)
BRIATORE	76	NC 31A 553	+Dardo, Piazzoli, Mannocchi+	(LCGT, FRAS, FREIB)
GUSTAFSON	76	PRL 37 474	+Ayre, Jones, Longo, Murthy	(MICH)
PRESCOTT	76	JPG 2 261		(ADLD)
ALBROW	75	NP B97 189	+Barber+	(CERN, DARE, FOM, LANC, MCHS, UTRE)
BLAGOV	75	SJNP 21 158 (Translated from YAF 21 300.)	+Komar, Murashova, Syreishchikova+	(LEBD)