Searches for WIMPs and Other Particles

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GALACTIC WIMP SEARCHES

Cross-Section Limits for Dark Matter Particles (X^0) on Nuclei

These limits are for weakly-interacting stable particles that may constitute the invisible mass in the galaxy. Unless otherwise noted, a local mass density of 0.3 GeV/cm^3 is assumed; see each paper for velocity distribution assumptions. In the papers the limit is given as a function of the X^0 mass. Here we list limits only for typical mass values of 20 GeV, 100 GeV, and 1 TeV. Specific limits on supersymmetric dark matter particles may be found in the Supersymmetry section.

For $m_{X^0} = 20$ GeV

VALUE (nb)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[1] BENOIT	00	EDEL	Ge
		[2] BERNABEI	00	DAMA	NaI
		[3] COLLAR	00	SMPL	F
		[4] MORALES	00	IGEX	^{76}Ge
		[5] SPOONER	00	UKDM	NaI
		[6] BAUDIS	99	CNTR	^{76}Ge
	90	[7] BELLI	99C	CNTR	F
		[2] BERNABEI	99	CNTR	NaI
		[8] OOTANI	99	BOLO	LiF
		[2] BERNABEI	98	CNTR	NaI
		[9] BERNABEI	98C	CNTR	^{129}Xe
$<$ 0.04	95	[10] KLIMENKO	98	CNTR	^{73}Ge, inel.
		[11] BERNABEI	97	CNTR	F
$<$ 0.8		ALESSAND...	96	CNTR	O
$<$ 6		ALESSAND...	96	CNTR	Te
$<$ 0.02	90	[12] BELLI	96	CNTR	^{129}Xe, inel.
		[13] BELLI	96C	CNTR	^{129}Xe
$<$ 0.004	90	[14] BERNABEI	96	CNTR	Na
$<$ 0.3	90	[14] BERNABEI	96	CNTR	I
$<$ 0.2	95	[15] SARSA	96	CNTR	Na
$<$ 0.015	90	[16] SMITH	96	CNTR	Na
$<$ 0.05	95	[17] GARCIA	95	CNTR	Natural Ge
$<$ 0.1	95	QUENBY	95	CNTR	Na
$<$90	90	[18] SNOWDEN-...	95	MICA	^{16}O
$< 4 \times 10^3$	90	[18] SNOWDEN-...	95	MICA	^{39}K
$<$ 0.7	90	BACCI	92	CNTR	Na
$<$ 0.12	90	[19] REUSSER	91	CNTR	Natural Ge
$<$ 0.06	95	CALDWELL	88	CNTR	Natural Ge

[1] BENOIT 00 find four event categories in Ge detectors and suggest that low-energy surface nuclear recoils can explain anomalous events reported by UKDMC and Saclay NaI experiments.

[2] See the following subsection for claim of a possible signal.

[3] COLLAR 00 give $\sigma < 1 \times 10^1$ pb for spin-dependent X^0-proton cross section.

[4] MORALES 00 give $\sigma < 7 \times 10^{-5}$ pb for spin-independent X^0-nucleon cross section.

[5] SPOONER 00 reanalyze SMITH 96 data with recent form-factor estimates and give $\sigma < 3 \times 10^{-4}$ pb for spin-independent higgsino X^0-nucleon cross section and $\sigma < 1$ pb for spin-dependent higgsino X^0-proton cross section.

[6] BAUDIS 99 give the limit $\sigma < 1 \times 10^{-4}$ pb for scalar X^0-nucleon cross section.

[7] BELLI 99C give $\sigma < 10$ pb for the spin-dependent X^0-proton cross section.

[8] OOTANI 99 give $\sigma < 40$ pb for the spin-dependent neutralino-proton cross section. The cross-section limit extends to lower masses compared to other experiments.

[9] BERNABEI 98C use pulse shape discrimination to enhance a possible signal. The limits $\sigma < 3 \times 10^{-4}$ pb (90%CL) for spin-independent X^0-nucleon cross section (assuming isoscalar), and $\sigma < 20$ pb (90%CL) for spin-dependent (assuming Z^0 exchange) are given.

[10] KLIMENKO 98 limit is for inelastic scattering $X^0\ {}^{73}\text{Ge} \rightarrow X^0\ {}^{73}\text{Ge}^*$ (13.26 keV).

[11] BERNABEI 97 give $\sigma < 12$ pb (90%CL) for the spin-dependent X^0-proton cross section.

[12] BELLI 96 limit for inelastic scattering $X^0\ {}^{129}\text{Xe} \rightarrow X^0\ {}^{129}\text{Xe}^*$(39.58 keV).

[13] BELLI 96C use background subtraction and obtain $\sigma < 150$ pb (< 1.5 fb) (90%CL) for spin-dependent (independent) X^0-proton cross section. The confidence level is from R. Bernabei, private communication, May 20, 1999.

[14] BERNABEI 96 use pulse shape discrimination to enhance the possible signal. The limit here is from R. Bernabei, private communication, September 19, 1997.

[15] SARSA 96 search for annual modulation of WIMP signal. See SARSA 97 for details of the analysis. The limit here is from M.L. Sarsa, private communication, May 26, 1997.

[16] SMITH 96 use pulse shape discrimination to enhance the possible signal. A dark matter density of 0.4 GeV cm^{-3} is assumed.

[17] GARCIA 95 limit is from the event rate. A weaker limit is obtained from searches for diurnal and annual modulation.

[18] SNOWDEN-IFFT 95 look for recoil tracks in an ancient mica crystal. Similar limits are also given for ^{27}Al and ^{28}Si. See COLLAR 96 and SNOWDEN-IFFT 96 for discussion on potential backgrounds.

[19] REUSSER 91 limit here is changed from published (0.04) after reanalysis by authors. J.L. Vuilleumier, private communication, March 29, 1996.

For $m_{X^0} = 100$ GeV

VALUE (nb)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[20] BAUDIS	01	HDMS	Ge
		[21] ABUSAIDI	00	CDMS	Ge, Si
		[22] BELLI	00	RVUE	
		[23] BENOIT	00	EDEL	Ge
		[24] BERNABEI	00	DAMA	NaI
		[25] COLLAR	00	SMPL	F
		[26] MORALES	00	IGEX	^{76}Ge

		[27] SPOONER	00	UKDM	NaI
		[28] AMBROSIO	99	MCRO	
		[29] BAUDIS	99	CNTR	^{76}Ge
	90	[30] BELLI	99C	CNTR	F
		[31] BERNABEI	99	CNTR	NaI
		[32] BRHLIK	99	RVUE	
		[33] OOTANI	99	BOLO	LiF
		[34] BERNABEI	98	CNTR	NaI
		[35] BERNABEI	98C	CNTR	^{129}Xe
< 0.008	95	[36] KLIMENKO	98	CNTR	^{73}Ge, inel.
< 0.08	95	[37] KLIMENKO	98	CNTR	^{73}Ge, inel.
		[38] BERNABEI	97	CNTR	F
< 4		ALESSAND...	96	CNTR	O
<25		ALESSAND...	96	CNTR	Te
< 0.006	90	[39] BELLI	96	CNTR	^{129}Xe, inel.
		[40] BELLI	96C	CNTR	^{129}Xe
< 0.001	90	[41] BERNABEI	96	CNTR	Na
< 0.3	90	[41] BERNABEI	96	CNTR	I
< 0.7	95	[42] SARSA	96	CNTR	Na
< 0.03	90	[43] SMITH	96	CNTR	Na
< 0.8	90	[43] SMITH	96	CNTR	I
< 0.35	95	[44] GARCIA	95	CNTR	Natural Ge
< 0.6	95	QUENBY	95	CNTR	Na
< 3	95	QUENBY	95	CNTR	I
$< 1.5 \times 10^2$	90	[45] SNOWDEN-...	95	MICA	^{16}O
$< 4 \times 10^2$	90	[45] SNOWDEN-...	95	MICA	^{39}K
< 0.08	90	[46] BECK	94	CNTR	^{76}Ge
< 2.5	90	BACCI	92	CNTR	Na
< 3	90	BACCI	92	CNTR	I
< 0.9	90	[47] REUSSER	91	CNTR	Natural Ge
< 0.7	95	CALDWELL	88	CNTR	Natural Ge

[20] BAUDIS 01 give $\sigma < 3 \times 10^{-5}$ pb for spin-independent X^0-nucleon cross section.

[21] ABUSAIDI 00 give $\sigma < 3 \times 10^{-6}$ pb for spin-independent X^0-nucleon cross section. The 3σ signal region observed by the DAMA experiment is excluded at 75%CL, assuming a spin-independent X^0-nucleon coupling.

[22] BELLI 00 discuss the effect of astrophysical uncertainties on the WIMP interpretation of the BERNABEI 99 signal.

[23] BENOIT 00 find four event categories in Ge detectors and suggest that low-energy surface nuclear recoils can explain anomalous events reported by UKDMC and Saclay NaI experiments.

[24] BERNABEI 00 search for annual modulation of the WIMP signal. The data favor the hypothesis of annual modulation at 4σ and are consistent with $m_{X^0}=52^{+10}_{-\ 3}$ GeV and a spin-independent X^0-proton cross section of $(7.2^{+0.4}_{-0.9}) \times 10^{-6}$ pb.

[25] COLLAR 00 give $\sigma < 1.5 \times 10^{1}$ pb for spin-dependent X^0-proton cross section.

[26] MORALES 00 give $\sigma < 1.5 \times 10^{-5}$ pb for spin-independent X^0-nucleon cross section.

[27] SPOONER 00 reanalyze SMITH 96 data with recent form-factor estimates and give $\sigma < 4 \times 10^{-5}$ pb for spin-independent higgsino X^0-nucleon cross section and $\sigma < 0.8$ pb for spin-dependent higgsino X^0-proton cross section.

[28] AMBROSIO 99 search for upgoing muon events induced by neutrinos originating from WIMP annihilations in the Sun and Earth.

[29] BAUDIS 99 give the limit $\sigma < 7 \times 10^{-6}$ pb for scalar X^0-nucleon cross section.

[30] BELLI 99C give $\sigma < 4.8$ pb for the spin-dependent X^0-proton cross section.

[31] BERNABEI 99 search for annual modulation of the WIMP signal. The data favor the hypothesis of annual modulation at 99.6%CL and are consistent with $m_{X^0}=59^{+17}_{-14}$ GeV and spin-independent X^0-proton cross section of $(7.0^{+0.4}_{-1.2}) \times 10^{-6}$ pb ($1\,\sigma$ errors).

[32] BRHLIK 99 discuss the effect of astrophysical uncertainties on the WIMP interpretation of the BERNABEI 99 signal.

[33] OOTANI 99 give $\sigma < 0.1$ nb for the spin-dependent neutralino-proton cross section.

[34] BERNABEI 98 search for annual modulation of the WIMP signal. The data is consistent with $m_{X^0}=59^{+36}_{-19}$ GeV and spin-independent X^0-proton cross section of $(1.0^{+0.1}_{-0.4}) \times 10^{-5}$ pb ($1\,\sigma$ errors).

[35] BERNABEI 98C use pulse shape discrimination to enhance a possible signal. The limits $\sigma < 7 \times 10^{-6}$ pb (90%CL) for spin-independent X^0-nucleon cross section (assuming isoscalar), and $\sigma < 0.6$ pb (90%CL) for spin-dependent (assuming Z^0 exchange) are given.

[36] KLIMENKO 98 limit is for inelastic scattering $X^0\,{}^{73}\text{Ge} \rightarrow X^0\,{}^{73}\text{Ge}^*$ (13.26 keV).

[37] KLIMENKO 98 limit is for inelastic scattering $X^0\,{}^{73}\text{Ge} \rightarrow X^0\,{}^{73}\text{Ge}^*$ (66.73 keV).

[38] BERNABEI 97 give $\sigma < 5$ pb (90%CL) for the spin-dependent X^0-proton cross section.

[39] BELLI 96 limit for inelastic scattering $X^0\,{}^{129}\text{Xe} \rightarrow X^0\,{}^{129}\text{Xe}^*$(39.58 keV).

[40] BELLI 96C use background subtraction and obtain $\sigma < 0.35$ pb (< 0.15 fb) (90%CL) for spin-dependent (independent) X^0-proton cross section. The confidence level is from R. Bernabei, private communication, May 20, 1999.

[41] BERNABEI 96 use pulse shape discrimination to enhance the possible signal. The limit here is from R. Bernabei, private communication, September 19, 1997.

[42] SARSA 96 search for annual modulation of WIMP signal. See SARSA 97 for details of the analysis. The limit here is from M.L. Sarsa, private communication, May 26, 1997.

[43] SMITH 96 use pulse shape discrimination to enhance the possible signal. A dark matter density of 0.4 GeV cm^{-3} is assumed.

[44] GARCIA 95 limit is from the event rate. A weaker limit is obtained from searches for diurnal and annual modulation.

[45] SNOWDEN-IFFT 95 look for recoil tracks in an ancient mica crystal. Similar limits are also given for ^{27}Al and ^{28}Si. See COLLAR 96 and SNOWDEN-IFFT 96 for discussion on potential backgrounds.

[46] BECK 94 uses enriched ^{76}Ge (86% purity).

[47] REUSSER 91 limit here is changed from published (0.3) after reanalysis by authors. J.L. Vuilleumier, private communication, March 29, 1996.

For m_{X^0} = 1 TeV

VALUE (nb)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[48] ABUSAIDI	00	CDMS	Ge, Si
		[49] BENOIT	00	EDEL	Ge
		[50] BERNABEI	00	DAMA	NaI
		[51] COLLAR	00	SMPL	F
		[52] MORALES	00	IGEX	^{76}Ge

		[53] SPOONER 00	UKDM	NaI
	90	[54] BELLI 99C	CNTR	F
		[50] BERNABEI 99	CNTR	NaI
		[55] BERNABEI 99D	CNTR	SIMP
		[56] DERBIN 99	CNTR	SIMP
		[57] OOTANI 99	BOLO	LiF
		[50] BERNABEI 98	CNTR	NaI
		[58] BERNABEI 98C	CNTR	^{129}Xe
$<$ 0.06	95	[59] KLIMENKO 98	CNTR	^{73}Ge, inel.
$<$ 0.4	95	[60] KLIMENKO 98	CNTR	^{73}Ge, inel.
		[61] BERNABEI 97	CNTR	F
$<$ 40		ALESSAND... 96	CNTR	O
$<$700		ALESSAND... 96	CNTR	Te
$<$ 0.05	90	[62] BELLI 96	CNTR	^{129}Xe, inel.
$<$ 1.5	90	[63] BELLI 96	CNTR	^{129}Xe, inel.
		[64] BELLI 96C	CNTR	^{129}Xe
$<$ 0.01	90	[65] BERNABEI 96	CNTR	Na
$<$ 9	90	[65] BERNABEI 96	CNTR	I
$<$ 7	95	[66] SARSA 96	CNTR	Na
$<$ 0.3	90	[67] SMITH 96	CNTR	Na
$<$ 6	90	[67] SMITH 96	CNTR	I
$<$ 6	95	[68] GARCIA 95	CNTR	Natural Ge
$<$ 8	95	QUENBY 95	CNTR	Na
$<$ 50	95	QUENBY 95	CNTR	I
$< 7 \times 10^2$	90	[69] SNOWDEN-... 95	MICA	^{16}O
$< 1 \times 10^3$	90	[69] SNOWDEN-... 95	MICA	^{39}K
$<$ 0.8	90	[70] BECK 94	CNTR	^{76}Ge
$<$ 30	90	BACCI 92	CNTR	Na
$<$ 30	90	BACCI 92	CNTR	I
$<$ 15	90	[71] REUSSER 91	CNTR	Natural Ge
$<$ 6	95	CALDWELL 88	CNTR	Natural Ge

[48] ABUSAIDI 00 give $\sigma < 2 \times 10^{-5}$ pb for spin-independent X^0-nucleon cross section.

[49] BENOIT 00 find four event categories in Ge detectors and suggest that low-energy surface nuclear recoils can explain anomalous events reported by UKDMC and Saclay NaI experiments.

[50] See the previous subsection for claim of a possible signal.

[51] COLLAR 00 give $\sigma < 1 \times 10^2$ pb for spin-dependent X^0-proton cross section.

[52] MORALES 00 give $\sigma < 8 \times 10^{-5}$ pb for spin-independent X^0-nucleon cross section.

[53] SPOONER 00 reanalyze SMITH 96 data with recent form-factor estimates and give $\sigma < 2 \times 10^{-4}$ pb for spin-independent higgsino X^0-nucleon cross section and $\sigma < 4$ pb for spin-dependent higgsino X^0-proton cross section.

[54] BELLI 99C give $\sigma < 28$ pb for the spin-dependent X^0-proton cross section.

[55] BERNABEI 99D search for SIMPs (Strongly Interacting Massive Particles) in the mass range 10^3–10^{16} GeV. See their Fig. 3 for cross-section limits.

[56] DERBIN 99 search for SIMPs (Strongly Interacting Massive Particles) in the mass range 10^2–10^{14} GeV. See their Fig. 3 for cross-section limits.

[57] OOTANI 99 give $\sigma < 1$ nb for the spin-dependent neutralino-proton cross section.

[58] BERNABEI 98C use pulse shape discrimination to enhance a possible signal. The limits $\sigma < 4 \times 10^{-5}$ pb (90%CL) for spin-independent X^0-nucleon cross section (assuming isoscalar), and $\sigma < 4$ pb (90%CL) for spin-dependent (assuming Z^0 exchange) are given.

[59] KLIMENKO 98 limit is for inelastic scattering $X^0\ {}^{73}\text{Ge} \rightarrow X^0\ {}^{73}\text{Ge}^*$ (13.26 keV).

[60] KLIMENKO 98 limit is for inelastic scattering $X^0\ {}^{73}\text{Ge} \rightarrow X^0\ {}^{73}\text{Ge}^*$ (66.73 keV).

[61] BERNABEI 97 give $\sigma < 32$ pb (90%CL) for the spin-dependent X^0-proton cross section.

[62] BELLI 96 limit for inelastic scattering $X^0\ {}^{129}\text{Xe} \rightarrow X^0\ {}^{129}\text{Xe}^*$(39.58 keV).

[63] BELLI 96 limit for inelastic scattering $X^0\ {}^{129}\text{Xe} \rightarrow X^0\ {}^{129}\text{Xe}^*$(236.14 keV).

[64] BELLI 96C use background subtraction and obtain $\sigma < 0.7$ pb (< 0.7 fb) (90%CL) for spin-dependent (independent) X^0-proton cross section. The confidence level is from R. Bernabei, private communication, May 20, 1999.

[65] BERNABEI 96 use pulse shape discrimination to enhance the possible signal. The limit here is from R. Bernabei, private communication, September 19, 1997.

[66] SARSA 96 search for annual modulation of WIMP signal. See SARSA 97 for details of the analysis. The limit here is from M.L. Sarsa, private communication, May 26, 1997.

[67] SMITH 96 use pulse shape discrimination to enhance the possible signal. A dark matter density of 0.4 GeV cm^{-3} is assumed.

[68] GARCIA 95 limit is from the event rate. A weaker limit is obtained from searches for diurnal and annual modulation.

[69] SNOWDEN-IFFT 95 look for recoil tracks in an ancient mica crystal. Similar limits are also given for ^{27}Al and ^{28}Si. See COLLAR 96 and SNOWDEN-IFFT 96 for discussion on potential backgrounds.

[70] BECK 94 uses enriched ^{76}Ge (86% purity).

[71] REUSSER 91 limit here is changed from published (5) after reanalysis by authors. J.L. Vuilleumier, private communication, March 29, 1996.

CONCENTRATION OF STABLE PARTICLES IN MATTER

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	[72] YAMAGATA 93	SPEC	Deep sea water, m=5–1600m_p
$<6 \times 10^{-15}$	95	[73] VERKERK 92	SPEC	Water, $m= 10^5$ to 3×10^7 GeV
$<7 \times 10^{-15}$	95	[73] VERKERK 92	SPEC	Water, $m= 10^4$, 6×10^7 GeV
$<9 \times 10^{-15}$	95	[73] VERKERK 92	SPEC	Water, $m= 10^8$ GeV
$<3 \times 10^{-23}$	90	[74] HEMMICK 90	SPEC	Water, $m = 1000m_p$
$<2 \times 10^{-21}$	90	[74] HEMMICK 90	SPEC	Water, $m = 5000m_p$
$<3 \times 10^{-20}$	90	[74] HEMMICK 90	SPEC	Water, $m = 10000m_p$
$<1. \times 10^{-29}$		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

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

[73] 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.

[74] 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	[75] HEMMICK	90	SPEC	C, $M = 100 m_p$
$<8 \times 10^{-20}$	90	[75] HEMMICK	90	SPEC	C, $M = 1000 m_p$
$<2 \times 10^{-16}$	90	[75] HEMMICK	90	SPEC	C, $M = 10000 m_p$
$<6 \times 10^{-13}$	90	[75] HEMMICK	90	SPEC	Li, $M = 1000 m_p$
$<1 \times 10^{-11}$	90	[75] HEMMICK	90	SPEC	Be, $M = 1000 m_p$
$<6 \times 10^{-14}$	90	[75] HEMMICK	90	SPEC	B, $M = 1000 m_p$
$<4 \times 10^{-17}$	90	[75] HEMMICK	90	SPEC	O, $M = 1000 m_p$
$<4 \times 10^{-15}$	90	[75] HEMMICK	90	SPEC	F, $M = 1000 m_p$
$< 1.5 \times 10^{-13}$/nucleon	68	[76] NORMAN	89	SPEC	$^{206}\mathrm{Pb}X^-$
$< 1.2 \times 10^{-12}$/nucleon	68	[76] NORMAN	87	SPEC	$^{56,58}\mathrm{Fe}X^-$

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

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

LIMITS ON NEUTRAL PARTICLE PRODUCTION

Production Cross Section of Radiatively-Decaying Neutral Particle

VALUE (pb)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<(2.5–0.5)	95	[77] ACKERSTAFF	97B	OPAL	$e^+ e^- \rightarrow X^0 Y^0$, $X^0 \rightarrow Y^0 \gamma$
<(1.6–0.9)	95	[78] ACKERSTAFF	97B	OPAL	$e^+ e^- \rightarrow X^0 X^0$, $X^0 \rightarrow Y^0 \gamma$

[77] ACKERSTAFF 97B associated production limit is for $m_{X^0} = 80$–160 GeV, m_{Y^0}=0 from 10.0 pb^{-1} at $\sqrt{s} = 161$ GeV. See their Fig. 3(a).

[78] ACKERSTAFF 97B pair production limit is for $m_{X^0} = 40$–80 GeV, m_{Y^0}=0 from 10.0 pb^{-1} at $\sqrt{s} = 161$ GeV. See their Fig. 3(b).

Heavy Particle Production Cross Section

VALUE (cm^2/*N*)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
			[79] ADAMS	97B	KTEV	m= 1.2–5 GeV
$< 10^{-36}$–10^{-33}	90		[80] GALLAS	95	TOF	m= 0.5–20 GeV
$<(4$–$0.3) \times 10^{-31}$	95		[81] AKESSON	91	CNTR	$m = 0$–5 GeV
$<2 \times 10^{-36}$	90	0	[82] BADIER	86	BDMP	$\tau = (0.05$–$1.) \times 10^{-8}$s
$<2.5 \times 10^{-35}$		0	[83] GUSTAFSON	76	CNTR	$\tau > 10^{-7}$ s

[79] ADAMS 97B search for a hadron-like neutral particle produced in pN interactions, which decays into a ρ^0 and a weakly interacting massive particle. Upper limits are given for the ratio to K_L production for the mass range 1.2–5 GeV and lifetime 10^{-9}–10^{-4} s. See also our Light Gluino Section.

[80] GALLAS 95 limit is for a weakly interacting neutral particle produced in 800 GeV/c pN interactions decaying with a lifetime of 10^{-4}–10^{-8} s. See their Figs. 8 and 9. Similar limits are obtained for a stable particle with interaction cross section 10^{-29}–10^{-33} cm^2. See Fig. 10.

[81] AKESSON 91 limit is from weakly interacting neutral long-lived particles produced in pN reaction at 450 GeV/c performed at CERN SPS. Bourquin-Gaillard formula is used as the production model. The above limit is for $\tau > 10^{-7}$ s. For $\tau > 10^{-9}$ s, $\sigma < 10^{-30}$ cm^{-2}/nucleon is obtained.

[82] BADIER 86 looked for long-lived particles at 300 GeV π^- beam dump. The limit applies for nonstrongly interacting 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.

[83] GUSTAFSON 76 is a 300 GeV FNAL experiment looking for heavy (m >2 GeV) long-lived neutral hadrons in the M4 neutral beam. The above typical value is for $m = 3$ GeV and assumes an interaction cross section of 1 mb. Values as a function of mass and interaction cross section are given in figure 2.

Production of New Penetrating Non-ν Like States in Beam Dump

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[84] LOSECCO	81	CALO	28 GeV protons

[84] No excess neutral-current events leads to σ(production) × σ(interaction)×acceptance $< 2.26 \times 10^{-71}$ cm^4/nucleon^2 (CL = 90%) for light neutrals. Acceptance depends on models (0.1 to 4. × 10^{-4}).

LIMITS ON JET-JET RESONANCES

Heavy Particle Production Cross Section in $p\overline{p}$

Limits are for a particle decaying to two hadronic jets.

Units(pb)	*CL%*	*Mass*(GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
			[85] ABE	99F	CDF	1.8 TeV $p\overline{p} \rightarrow b\overline{b}+$ anything
			[86] ABE	97G	CDF	1.8 TeV $p\overline{p} \rightarrow$ 2 jets
<2603	95	200	[87] ABE	93G	CDF	1.8 TeV $p\overline{p} \rightarrow$ 2jets
< 44	95	400	[87] ABE	93G	CDF	1.8 TeV $p\overline{p} \rightarrow$ 2jets
< 7	95	600	[87] ABE	93G	CDF	1.8 TeV $p\overline{p} \rightarrow$ 2jets

[85] ABE 99F search for narrow $b\overline{b}$ resonances in $p\overline{p}$ collisions at E_{cm}=1.8 TeV. Limits on $\sigma(p\overline{p} \rightarrow X+$ anything$)\times$B$(X \rightarrow b\overline{b})$ in the range 3–10^3 pb (95%CL) are given for m_X=200–750 GeV. See their Table I.

[86] ABE 97G search for narrow dijet resonances in $p\overline{p}$ collisions with 106 pb^{-1} of data at $E_{\mathrm{cm}} = 1.8$ TeV. Limits on $\sigma(p\overline{p} \rightarrow X+$ anything$)\cdot$B$(X \rightarrow jj)$ in the range 10^4–10^{-1} pb (95%CL) are given for dijet mass m=200–1150 GeV with both jets having $|\eta| < 2.0$ and the dijet system having $|\cos\theta^*| < 0.67$. See their Table I for the list of limits. Supersedes ABE 93G.

[87] ABE 93G gives cross section times branching ratio into light (d, u, s, c, b) quarks for $\Gamma = 0.02\,M$. Their Table II gives limits for M = 200–900 GeV and Γ = (0.02–0.2) M.

LIMITS ON CHARGED PARTICLES IN $e^+ e^-$

Heavy Particle Production Cross Section in $e^+ e^-$

Ratio to $\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)$ unless noted. See also entries in Free Quark Search and Magnetic Monopole Searches.

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
			[88] ACKERSTAFF	98P	OPAL	Q=1,2/3, m=45–89.5 GeV
			[89] ABREU	97D	DLPH	Q=1,2/3, m=45–84 GeV
			[90] BARATE	97K	ALEP	Q=1, m=45–85 GeV
$<2 \times 10^{-5}$	95		[91] AKERS	95R	OPAL	Q=1, m= 5–45 GeV
$<1 \times 10^{-5}$	95		[91] AKERS	95R	OPAL	Q=2, m= 5–45 GeV
$<2 \times 10^{-3}$	90		[92] BUSKULIC	93C	ALEP	Q=1, m=32–72 GeV
$<(10^{-2}$–1)	95		[93] ADACHI	90C	TOPZ	Q = 1, m = 1–16, 18–27 GeV
$<7 \times 10^{-2}$	90		[94] ADACHI	90E	TOPZ	Q = 1, m = 5–25 GeV
$<1.6 \times 10^{-2}$	95	0	[95] KINOSHITA	82	PLAS	Q=3–180, m <14.5 GeV
$<5.0 \times 10^{-2}$	90	0	[96] BARTEL	80	JADE	Q=(3,4,5)/3 2–12 GeV

[88] ACKERSTAFF 98P search for pair production of long-lived charged particles at $\sqrt{s}$ between 130 and 183 GeV and give limits $\sigma <$(0.05–0.2) pb (95%CL) for spin-0 and spin-1/2 particles with m=45–89.5 GeV, charge 1 and 2/3. The limit is translated to the cross section at $\sqrt{s}$=183 GeV with the s dependence described in the paper. See their Figs. 2–4.

[89] ABREU 97D search for pair production of long-lived particles and give limits $\sigma <$(0.4–2.3) pb (95%CL) for various center-of-mass energies $\sqrt{s}$=130–136, 161, and 172 GeV, assuming an almost flat production distribution in cosθ.

[90] BARATE 97K search for pair production of long-lived charged particles at $\sqrt{s}$ = 130, 136, 161, and 172 GeV and give limits $\sigma <$(0.2–0.4) pb (95%CL) for spin-0 and spin-1/2 particles with m=45–85 GeV. The limit is translated to the cross section at $\sqrt{s}$=172 GeV with the $\sqrt{s}$ dependence described in the paper. See their Figs. 2 and 3 for limits on J = 1/2 and J = 0 cases.

[91] AKERS 95R is a CERN-LEP experiment with $W_{cm} \sim m_Z$. The limit is for the production of a stable particle in multihadron events normalized to $\sigma(e^+ e^- \rightarrow \text{hadrons})$. Constant phase space distribution is assumed. See their Fig. 3 for bounds for $Q = \pm 2/3$, $\pm 4/3$.

[92] BUSKULIC 93C is a CERN-LEP experiment with $W_{cm} = m_Z$. The limit is for a pair or single production of heavy particles with unusual ionization loss in TPC. See their Fig. 5 and Table 1.

[93] ADACHI 90C is a KEK-TRISTAN experiment with W_{cm} = 52–60 GeV. The limit is for pair production of a scalar or spin-1/2 particle. See Figs. 3 and 4.

[94] ADACHI 90E is KEK-TRISTAN experiment with W_{cm} = 52–61.4 GeV. The above limit is for inclusive production cross section normalized to $\sigma(e^+ e^- \rightarrow \mu^+ \mu^-) \cdot \beta(3 - \beta^2)/2$, where $\beta = (1 - 4m^2/W_{cm}^2)^{1/2}$. See the paper for the assumption about the production mechanism.

[95] KINOSHITA 82 is SLAC PEP experiment at W_{cm} = 29 GeV using lexan and ^{39}Cr plastic sheets sensitive to highly ionizing particles.

[96] BARTEL 80 is DESY-PETRA experiment with W_{cm} = 27–35 GeV. Above limit is for inclusive pair production and ranges between $1. \times 10^{-1}$ and $1. \times 10^{-2}$ depending on mass and production momentum distributions. (See their figures 9, 10, 11).

Branching Fraction of Z^0 to a Pair of Stable Charged Heavy Fermions

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<5 \times 10^{-6}$	95	[97] AKERS 95R	OPAL	m= 40.4–45.6 GeV
$<1 \times 10^{-3}$	95	AKRAWY 90O	OPAL	m = 29–40 GeV

[97] AKERS 95R give the 95% CL limit $\sigma(X\overline{X})/\sigma(\mu\mu) < 1.8\times10^{-4}$ for the pair production of singly- or doubly-charged stable particles. The limit applies for the mass range 40.4–45.6 GeV for $X^{\pm}$ and $<$ 45.6 GeV for $X^{\pm\pm}$. See the paper for bounds for $Q = \pm2/3$, $\pm4/3$.

LIMITS ON CHARGED PARTICLES IN HADRONIC REACTIONS

Heavy Particle Production Cross Section

VALUE (nb)	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	95		[98] ABE 92J	CDF	m=50–200 GeV
<30–130			[99] CARROLL 78	SPEC	m=2–2.5 GeV
<100		0	[100] LEIPUNER 73	CNTR	m=3–11 GeV

[98] ABE 92J look for pair production of unit-charged particles which leave detector before decaying. Limit shown here is for m=50 GeV. See their Fig. 5 for different charges and stronger limits for higher mass.

[99] CARROLL 78 look for neutral, $S = -2$ dihyperon resonance in $pp \rightarrow\ 2K^{+}X$. Cross section varies within above limits over mass range and p_{lab} = 5.1–5.9 GeV/c.

[100] LEIPUNER 73 is an NAL 300 GeV p experiment. Would have detected particles with lifetime greater than 200 ns.

Heavy Particle Production Differential Cross Section

VALUE ($\text{cm}^2\text{sr}^{-1}\text{GeV}^{-1}$)	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<2.6 \times 10^{-36}$	90	0	[101] BALDIN 76	CNTR	−	Q= 1, m=2.1–9.4 GeV
$<2.2 \times 10^{-33}$	90	0	[102] ALBROW 75	SPEC	±	Q= ±1, m=4–15 GeV
$<1.1 \times 10^{-33}$	90	0	[102] ALBROW 75	SPEC	±	Q= ±2, m=6–27 GeV
$<8.\ \times 10^{-35}$	90	0	[103] JOVANOV... 75	CNTR	±	m=15–26 GeV
$<1.5 \times 10^{-34}$	90	0	[103] JOVANOV... 75	CNTR	±	Q= ±2, m=3–10 GeV
$<6.\ \times 10^{-35}$	90	0	[103] JOVANOV... 75	CNTR	±	Q= ±2, m=10–26 GeV
$<1.\ \times 10^{-31}$	90	0	[104] APPEL 74	CNTR	±	m=3.2–7.2 GeV
$<5.8 \times 10^{-34}$	90	0	[105] ALPER 73	SPEC	±	m=1.5–24 GeV
$<1.2 \times 10^{-35}$	90	0	[106] ANTIPOV 71B	CNTR	−	Q=−, m=2.2–2.8
$<2.4 \times 10^{-35}$	90	0	[107] ANTIPOV 71C	CNTR	−	Q=−, m=1.2–1.7, 2.1–4
$<2.4 \times 10^{-35}$	90	0	BINON 69	CNTR	−	Q=−, m=1–1.8 GeV
$<1.5 \times 10^{-36}$		0	[108] DORFAN 65	CNTR		Be target m=3–7 GeV
$<3.0 \times 10^{-36}$		0	[108] DORFAN 65	CNTR		Fe target m=3–7 GeV

[101] BALDIN 76 is a 70 GeV Serpukhov experiment. Value is per Al nucleus at $\theta = 0$. For other charges in range -0.5 to -3.0, CL = 90% limit is $(2.6 \times 10^{-36})/|(\text{charge})|$ for

mass range (2.1–9.4 GeV) × $|(\text{charge})|$. Assumes stable particle interacting with matter as do antiprotons.

[102] ALBROW 75 is a CERN ISR experiment with $E_{\text{cm}} = 53$ GeV. $\theta = 40$ mr. See figure 5 for mass ranges up to 35 GeV.

[103] JOVANOVICH 75 is a CERN ISR 26+26 and 15+15 GeV pp experiment. Figure 4 covers ranges $Q = 1/3$ to 2 and $m = 3$ to 26 GeV. Value is per GeV momentum.

[104] APPEL 74 is NAL 300 GeV pW experiment. Studies forward production of heavy (up to 24 GeV) charged particles with momenta 24–200 GeV (−charge) and 40–150 GeV (+charge). Above typical value is for 75 GeV and is per GeV momentum per nucleon.

[105] ALPER 73 is CERN ISR 26+26 GeV pp experiment. $p > 0.9$ GeV, $0.2 < \beta < 0.65$.

[106] ANTIPOV 71B is from same 70 GeV p experiment as ANTIPOV 71C and BINON 69.

[107] ANTIPOV 71C limit inferred from flux ratio. 70 GeV p experiment.

[108] DORFAN 65 is a 30 GeV/c p experiment at BNL. Units are per GeV momentum per nucleus.

Long-Lived Heavy Particle Invariant Cross Section

VALUE (cm^2/GeV^2/N)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$< 5 \times 10^{-35}$–7×10^{-33}	90	0	[109] BERNSTEIN	88	CNTR		
$< 5 \times 10^{-37}$–7×10^{-35}	90	0	[109] BERNSTEIN	88	CNTR		
$< 2.5 \times 10^{-36}$	90	0	[110] THRON	85	CNTR	−	$Q = 1$, m=4–12 GeV
$< 1. \times 10^{-35}$	90	1	[110] THRON	85	CNTR	+	$Q = 1$, m=4–12 GeV
$< 6. \times 10^{-33}$	90	0	[111] ARMITAGE	79	SPEC		m=1.87 GeV
$< 1.5 \times 10^{-33}$	90	0	[111] ARMITAGE	79	SPEC		m=1.5–3.0 GeV
		0	[112] BOZZOLI	79	CNTR	±	$Q = (2/3, 1, 4/3, 2)$
$< 1.1 \times 10^{-37}$	90	0	[113] CUTTS	78	CNTR		m=4–10 GeV
$< 3.0 \times 10^{-37}$	90	0	[114] VIDAL	78	CNTR		m=4.5–6 GeV

[109] BERNSTEIN 88 limits apply at $x = 0.2$ and $p_T = 0$. Mass and lifetime dependence of limits are shown in the regions: $m = 1.5$–7.5 GeV and $\tau = 10^{-8}$–2×10^{-6} s. First number is for hadrons; second is for weakly interacting particles.

[110] THRON 85 is FNAL 400 GeV proton experiment. Mass determined from measured velocity and momentum. Limits are for $\tau > 3 \times 10^{-9}$ s.

[111] ARMITAGE 79 is CERN-ISR experiment at $E_{\text{cm}} = 53$ GeV. Value is for $x = 0.1$ and $p_T = 0.15$. Observed particles at $m = 1.87$ GeV are found all consistent with being antideuterons.

[112] BOZZOLI 79 is CERN-SPS 200 GeV pN experiment. Looks for particle with τ larger than 10^{-8} s. See their figure 11–18 for production cross-section upper limits vs mass.

[113] CUTTS 78 is pBe experiment at FNAL sensitive to particles of $\tau > 5 \times 10^{-8}$ s. Value is for $-0.3 < x < 0$ and $p_T = 0.175$.

[114] VIDAL 78 is FNAL 400 GeV proton experiment. Value is for $x = 0$ and $p_T = 0$. Puts lifetime limit of $< 5 \times 10^{-8}$ s on particle in this mass range.

Long-Lived Heavy Particle Production (σ(Heavy Particle) / $\sigma(\pi)$)

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<10^{-8}$		[115] NAKAMURA	89	SPEC	±	$Q = (-5/3, \pm 2)$
	0	[116] BUSSIERE	80	CNTR	±	$Q = (2/3, 1, 4/3, 2)$

[115] NAKAMURA 89 is KEK experiment with 12 GeV protons on Pt target. The limit applies for mass $\lesssim$ 1.6 GeV and lifetime $\gtrsim 10^{-7}$ s.

[116] BUSSIERE 80 is CERN-SPS experiment with 200–240 GeV protons on Be and Al target. See their figures 6 and 7 for cross-section ratio vs mass.

Production and Capture of Long-Lived Massive Particles

VALUE (10^{-36} cm^2)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<20 to 800	0	[117] ALEKSEEV	76	ELEC	τ=5 ms to 1 day
<200 to 2000	0	[117] ALEKSEEV	76B	ELEC	τ=100 ms to 1 day
<1.4 to 9	0	[118] FRANKEL	75	CNTR	τ=50 ms to 10 hours
<0.1 to 9	0	[119] FRANKEL	74	CNTR	τ=1 to 1000 hours

[117] ALEKSEEV 76 and ALEKSEEV 76B are 61–70 GeV *p* Serpukhov experiment. Cross section is per Pb nucleus.

[118] FRANKEL 75 is extension of FRANKEL 74.

[119] FRANKEL 74 looks for particles produced in thick Al targets by 300–400 GeV/*c* protons.

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	[120] BADIER	86	BDMP	$\tau = (0.05\text{–}1.) \times 10^{-8}$s

[120] BADIER 86 looked for long-lived particles at 300 GeV π^- beam dump. The limit applies for nonstrongly interacting 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.

Long-Lived Heavy Particle Cross Section

VALUE (pb/sr)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<34	95	[121] RAM	94	SPEC	$1015 < m_{X^{++}} < 1085$ MeV
<75	95	[121] RAM	94	SPEC	$920 < m_{X^{++}} < 1025$ MeV

[121] RAM 94 search for a long-lived doubly-charged fermion X^{++} with mass between m_N and $m_N + m_\pi$ and baryon number +1 in the reaction $p p \rightarrow X^{++} n$. No candidate is found. The limit is for the cross section at 15° scattering angle at 460 MeV incident energy and applies for $\tau(X^{++}) \gg 0.1\,\mu$s.

LIMITS ON CHARGED PARTICLES IN COSMIC RAYS

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. • • •							
$\sim 6 \times 10^{-9}$		2	[122] SAITO	90			$Q \simeq 14$, $m \simeq 370 m_p$
$< 1.4 \times 10^{-12}$	90	0	[123] MINCER	85	CALO		$m \geq 1$ TeV
			[124] SAKUYAMA	83B	PLAS		$m \sim 1$ TeV
$< 1.7 \times 10^{-11}$	99	0	[125] BHAT	82	CC		
$< 1. \times 10^{-9}$	90	0	[126] MARINI	82	CNTR	±	$Q= 1$, $m \sim 4.5 m_p$
$2. \times 10^{-9}$		3	[127] YOCK	81	SPRK	±	$Q= 1$, $m \sim 4.5 m_p$
		3	[127] YOCK	81	SPRK		Fractionally charged
3.0×10^{-9}		3	[128] 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		[129] BHAT	78	CNTR	±	$m >1$ GeV
$< 1.0 \times 10^{-9}$		0	BRIATORE	76	ELEC		
$< 7. \times 10^{-10}$	90	0	YOCK	75	ELEC	±	$Q >7e$ or $< -7e$
$> 6. \times 10^{-9}$		5	[130] 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

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

[123] 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.

[124] 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.

[125] 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.

[126] 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.

[127] 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.

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

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

[130] YOCK 74 events could be tritons.

Superheavy Particle (Quark Matter) Flux in Cosmic Rays

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE ($\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$)	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<5 \times 10^{-16}$	90		[131] AMBROSIO 00B	MCRO	$m > 5 \times 10^{14}$ GeV
$<1.8 \times 10^{-12}$	90		[132] ASTONE 93	CNTR	$m \geq 1.5 \times 10^{-13}$gram
$<1.1 \times 10^{-14}$	90		[133] AHLEN 92	MCRO	$10^{-10} < m < 0.1$ gram
$<2.2 \times 10^{-14}$	90	0	[134] NAKAMURA 91	PLAS	$m > 10^{11}$ GeV
$<6.4 \times 10^{-16}$	90	0	[135] ORITO 91	PLAS	$m > 10^{12}$ GeV
$<3.2 \times 10^{-11}$	90	0	[136] NAKAMURA 85	CNTR	$m > 1.5 \times 10^{-13}$gram
$<3.5 \times 10^{-11}$	90	0	[137] ULLMAN 81	CNTR	Planck-mass 10^{19}GeV
$<7. \times 10^{-11}$	90	0	[137] ULLMAN 81	CNTR	$m \leq 10^{16}$ GeV

[131] AMBROSIO 00B searched for quark matter ("nuclearites") in the velocity range $(10^{-5}–1)\,c$. The listed limit is for $2 \times 10^{-3}\,c$.

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

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

[134] NAKAMURA 91 searched for quark matter in the velocity range $(4 \times 10^{-5}–1)\,c$.

[135] ORITO 91 searched for quark matter. The limit is for the velocity range $(10^{-4}–10^{-3})\,c$.

[136] 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 of $(10^{-4}–10^{-3})\,c$.

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

Highly Ionizing Particle Flux

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE ($\mathrm{m}^{-2}\mathrm{yr}^{-1}$)	*CL%*	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
<0.4	95	0	KINOSHITA 81B	PLAS	Z/β 30–100

SEARCH FOR LOW-SCALE GRAVITY EFFECTS

This section contains experimental papers searching for effects of real or virtual gravitons (massless and massive, denoted by *G*) with observable coupling strength. This is expected if there are extra spacetime dimensions with a size larger than the electroweak scale, in which case the fundamental gravity scale can be around TeV, not 10^{19} GeV.

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	*DOCUMENT ID*	*TECN*
	[138] ABBIENDI 00R	OPAL
	[139] ABREU 00A	DLPH
	[140] ABREU 00S	DLPH
	[141] ABREU 00Z	DLPH
	[142] ACCIARRI 00P	L3
	[143] ADLOFF 00	H1
	[144] ABBIENDI 99P	OPAL
	[145] ACCIARRI 99M	L3
	[146] ACCIARRI 99R	L3
	[147] ACCIARRI 99S	L3

[138] ABBIENDI 00R search for s-channel graviton exchange effects in $e^+e^- \rightarrow \mu^+\mu^-$ and $\tau^+\tau^-$ at E_{cm}=189 GeV. The limits $M_s > 0.68$ (0.61) TeV for λ=+1 (-1) are obtained, where M_s is a string mass scale.

[139] ABREU 00A search for s-channel graviton exchange effects in $e^+e^- \rightarrow \gamma\gamma$ at E_{cm}= 189–202 GeV. The limits $M_s > 713$ (691) GeV for λ=+1 (-1) are obtained, where M_s is a string mass scale.

[140] ABREU 00S search for s-channel graviton exchange effects in $e^+e^- \rightarrow \mu^+\mu^-$ and $\tau^+\tau^-$ at E_{cm}=183–189 GeV. The limits $M_s > 680$ (542) GeV for λ=+1 (-1) are obtained, where M_s is a string mass scale.

[141] ABREU 00Z search for the reaction $e^+e^- \rightarrow \gamma G$ at E_{cm}= 183–189 GeV. The limits $M_D >$(1.10, 0.68, 0.51) TeV are obtained for the number of extra dimensions n = (2,4,6), where M_D is a fundamental gravity scale.

[142] ACCIARRI 00P search for TeV string effects in $e^+e^- \rightarrow e^+e^-$ at E_{cm}= 183–189 GeV. The limit $M_s > 0.49$ TeV is obtained, where M_s is a string mass scale.

[143] ADLOFF 00 search for t-channel graviton exchange effects in deep inelastic scattering ($eq \rightarrow eq$ and $eg \rightarrow eg$) at E_{cm}=300 GeV. The limits $M_s > 0.48$ (0.72) TeV for λ=+1 (-1) are obtained, where M_s is a string mass scale.

[144] ABBIENDI 99P search for s-channel graviton exchange effects in $e^+e^- \rightarrow \gamma\gamma$ at E_{cm}=189 GeV. The limits $G_+ > 660$ GeV and $G_- > 634$ GeV are obtained from combined E_{cm}=183 and 189 GeV data, where $G_\pm$ is a scale related to the fundamental gravity scale.

[145] ACCIARRI 99M search for the reaction $e^+e^- \rightarrow \gamma G$ and s-channel graviton exchange effects in $e^+e^- \rightarrow \gamma\gamma$, W^+W^-, ZZ, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\overline{q}$ at E_{cm}=183 GeV. Limits on the gravity scale are listed in their Tables 1 and 2.

[146] ACCIARRI 99R search for the reaction $e^+e^- \rightarrow \gamma G$ at E_{cm}=189 GeV. Limits on the gravity scale are listed in their Table 4.

[147] ACCIARRI 99S search for the reaction $e^+e^- \rightarrow ZG$ and s-channel graviton exchange effects in $e^+e^- \rightarrow \gamma\gamma$, W^+W^-, ZZ, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\overline{q}$ at E_{cm}=189 GeV. Limits on the gravity scale are listed in their Tables 1 and 2.

REFERENCES FOR Searches for WIMPs and Other Particles

BAUDIS	01	PR D63 022001	L. Baudis *et al.*	(Heidelberg-Moscow Collab.)
ABBIENDI	00R	EPJ C13 553	G. Abbiendi *et al.*	(OPAL Collab.)
ABREU	00A	PL B491 67	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	00S	PL B485 45	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	00Z	EPJ C17 53	P. Abreu *et al.*	(DELPHI Collab.)
ABUSAIDI	00	PRL 84 5699	R. Abusaidi *et al.*	(CDMS Collab.)
ACCIARRI	00P	PL B489 81	M. Acciarri *et al.*	(L3 Collab.)
ADLOFF	00	PL B479 358	C. Adloff *et al.*	(H1 Collab.)
AMBROSIO	00B	EPJ C13 453	M. Ambrosio *et al.*	(MACRO Collab.)
BELLI	00	PR D61 023512	P. Belli *et al.*	(DAMA Collab.)
BENOIT	00	PL B479 8	A. Benoit *et al.*	(EDELWEISS Collab.)
BERNABEI	00	PL B480 23	R. Bernabei *et al.*	(DAMA Collab.)
COLLAR	00	PRL 85 3083	J.I. Collar *et al.*	(SIMPLE Collab.)
MORALES	00	PL B489 268	A. Morales *et al.*	(IGEX Collab.)
SPOONER	00	PL B473 330	N.J.C. Spooner *et al.*	(UK Dark Matter Col.)
ABBIENDI	99P	PL B465 303	G. Abbiendi *et al.*	(OPAL Collab.)
ABE	99F	PRL 82 2038	F. Abe *et al.*	(CDF Collab.)
ACCIARRI	99M	PL B464 135	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	99R	PL B470 268	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	99S	PL B470 281	M. Acciarri *et al.*	(L3 Collab.)
AMBROSIO	99	PR D60 082002	M. Ambrosio *et al.*	(Macro Collab.)
BAUDIS	99	PR D59 022001	L. Baudis *et al.*	(Heidelberg-Moscow Collab.)
BELLI	99C	NP B563 97	P. Belli *et al.*	(DAMA Collab.)
BERNABEI	99	PL B450 448	R. Bernabei *et al.*	(DAMA Collab.)
BERNABEI	99D	PRL 83 4918	R. Bernabei *et al.*	(DAMA Collab.)
BRHLIK	99	PL B464 303	M. Brhlik, L. Roszkowski	
DERBIN	99	PAN 62 1886 Translated from YAF 62 2034.	A.V. Derbin *et al.*	

OOTANI	99	PL B461 371	W. Ootani *et al.*	
ACKERSTAFF	98P	PL B433 195	K. Ackerstaff *et al.*	(OPAL Collab.)
BERNABEI	98	PL B424 195	R. Bernabei *et al.*	(DAMA Collab.)
BERNABEI	98C	PL B436 379	R. Bernabei *et al.*	(DAMA Collab.)
KLIMENKO	98	JETPL 67 875 Translated from ZETFP 67 835.	A.A. Klimenko *et al.*	
ABE	97G	PR D55 R5263	F. Abe *et al.*	(CDF Collab.)
ABREU	97D	PL B396 315	P. Abreu *et al.*	(DELPHI Collab.)
ACKERSTAFF	97B	PL B391 210	K. Ackerstaff *et al.*	(OPAL Collab.)
ADAMS	97B	PRL 79 4083	J. Adams *et al.*	(KTeV Collab.)
BARATE	97K	PL B405 379	R. Barate *et al.*	(ALEPH Collab.)
BERNABEI	97	ASP 7 73	R. Bernabei *et al.*	(DAMA Collab.)
SARSA	97	PR D56 1856	M.L. Sarsa *et al.*	(ZARA)
ALESSAND...	96	PL B384 316	A. Alessandrello *et al.*	(MILA, MILAI, SASSO)
BELLI	96	PL B387 222	P. Belli *et al.*	(DAMA Collab.)
Also	96B	PL B389 783 (erratum)	P. Belli *et al.*	(DAMA Collab.)
BELLI	96C	NC 19C 537	P. Belli *et al.*	(DAMA Collab.)
BERNABEI	96	PL B389 757	R. Bernabei *et al.*	(DAMA Collab.)
COLLAR	96	PRL 76 331	J.I. Collar	(SCUC)
SARSA	96	PL B386 458	M.L. Sarsa *et al.*	(ZARA)
Also	97	PR D56 1856	M.L. Sarsa *et al.*	(ZARA)
SMITH	96	PL B379 299	P.F. Smith *et al.*	(RAL, SHEF, LOIC+)
SNOWDEN-...	96	PRL 76 332	D.P. Snowden-Ifft, E.S. Freeman, P.B. Price	(UCB)
AKERS	95R	ZPHY C67 203	R. Akers *et al.*	(OPAL Collab.)
GALLAS	95	PR D52 6	E. Gallas *et al.*	(MSU, FNAL, MIT, FLOR)
GARCIA	95	PR D51 1458	E. Garcia *et al.*	(ZARA, SCUC, PNL)
QUENBY	95	PL B351 70	J.J. Quenby *et al.*	(LOIC, RAL, SHEF+)
SNOWDEN-...	95	PRL 74 4133	D.P. Snowden-Ifft, E.S. Freeman, P.B. Price	(UCB)
Also	96	PRL 76 331	J.I. Collar	(SCUC)
Also	96	PRL 76 332	D.P. Snowden-Ifft, E.S. Freeman, P.B. Price	(UCB)
BECK	94	PL B336 141	M. Beck *et al.*	(MPIH, KIAE, SASSO)
RAM	94	PR D49 3120	S. Ram *et al.*	(TELA, TRIU)
ABE	93G	PRL 71 2542	F. Abe *et al.*	(CDF Collab.)
ASTONE	93	PR D47 4770	P. Astone *et al.*	(ROMA, ROMAI, CATA, FRAS)
BUSKULIC	93C	PL B303 198	D. Buskulic *et al.*	(ALEPH Collab.)
YAMAGATA	93	PR D47 1231	T. Yamagata, Y. Takamori, H. Utsunomiya	(KONAN)
ABE	92J	PR D46 R1889	F. Abe *et al.*	(CDF Collab.)
AHLEN	92	PRL 69 1860	S.P. Ahlen *et al.*	(MACRO Collab.)
BACCI	92	PL B293 460	C. Bacci *et al.*	(Beijing-Roma-Saclay Collab.)
VERKERK	92	PRL 68 1116	P. Verkerk *et al.*	(ENSP, SACL, PAST)
AKESSON	91	ZPHY C52 219	T. Akesson *et al.*	(HELIOS Collab.)
NAKAMURA	91	PL B263 529	S. Nakamura *et al.*	
ORITO	91	PRL 66 1951	S. Orito *et al.*	(ICEPP, WASCR, NIHO, ICRR)
REUSSER	91	PL B255 143	D. Reusser *et al.*	(NEUC, CIT, PSI)
ADACHI	90C	PL B244 352	I. Adachi *et al.*	(TOPAZ Collab.)
ADACHI	90E	PL B249 336	I. Adachi *et al.*	(TOPAZ Collab.)
AKRAWY	90O	PL B252 290	M.Z. Akrawy *et al.*	(OPAL Collab.)
HEMMICK	90	PR D41 2074	T.K. Hemmick *et al.*	(ROCH, MICH, OHIO+)
SAITO	90	PRL 65 2094	T. Saito *et al.*	(ICRR, KOBE)
NAKAMURA	89	PR D39 1261	T.T. Nakamura *et al.*	(KYOT, TMTC)
NORMAN	89	PR D39 2499	E.B. Norman *et al.*	(LBL)
BERNSTEIN	88	PR D37 3103	R.M. Bernstein *et al.*	(STAN, WISC)
CALDWELL	88	PRL 61 510	D.O. Caldwell *et al.*	(UCSB, UCB, LBL)
NORMAN	87	PRL 58 1403	E.B. Norman, S.B. Gazes, D.A. Bennett	(LBL)
BADIER	86	ZPHY C31 21	J. Badier *et al.*	(NA3 Collab.)
MINCER	85	PR D32 541	A. Mincer *et al.*	(UMD, GMAS, NSF)
NAKAMURA	85	PL 161B 417	K. Nakamura *et al.*	(KEK, INUS)
THRON	85	PR D31 451	J.L. Thron *et al.*	(YALE, FNAL, IOWA)
SAKUYAMA	83B	LNC 37 17	H. Sakuyama, N. Suzuki	(MEIS)
Also	83	LNC 36 389	H. Sakuyama, K. Watanabe	(MEIS)
Also	83D	NC 78A 147	H. Sakuyama, K. Watanabe	(MEIS)
Also	83C	NC 6C 371	H. Sakuyama, K. Watanabe	(MEIS)
BHAT	82	PR D25 2820	P.N. Bhat *et al.*	(TATA)
KINOSHITA	82	PRL 48 77	K. Kinoshita, P.B. Price, D. Fryberger	(UCB+)
MARINI	82	PR D26 1777	A. Marini *et al.*	(FRAS, LBL, NWES, STAN+)
SMITH	82B	NP B206 333	P.F. Smith *et al.*	(RAL)
KINOSHITA	81B	PR D24 1707	K. Kinoshita, P.B. Price	(UCB)
LOSECCO	81	PL 102B 209	J.M. LoSecco *et al.*	(MICH, PENN, BNL)

ULLMAN	81	PRL 47 289	J.D. Ullman	(LEHM, BNL)
YOCK	81	PR D23 1207	P.C.M. Yock	(AUCK)
BARTEL	80	ZPHY C6 295	W. Bartel *et al.*	(JADE Collab.)
BUSSIERE	80	NP B174 1	A. Bussiere *et al.*	(BGNA, SACL, LAPP)
YOCK	80	PR D22 61	P.C.M. Yock	(AUCK)
ARMITAGE	79	NP B150 87	J.C.M. Armitage *et al.*	(CERN, DARE, FOM+)
BOZZOLI	79	NP B159 363	W. Bozzoli *et al.*	(BGNA, LAPP, SACL+)
GOODMAN	79	PR D19 2572	J.A. Goodman *et al.*	(UMD)
SMITH	79	NP B149 525	P.F. Smith, J.R.J. Bennett	(RHEL)
BHAT	78	Pramana 10 115	P.N. Bhat, P.V. Ramana Murthy	(TATA)
CARROLL	78	PRL 41 777	A.S. Carroll *et al.*	(BNL, PRIN)
CUTTS	78	PRL 41 363	D. Cutts *et al.*	(BROW, FNAL, ILL, BARI+)
VIDAL	78	PL 77B 344	R.A. Vidal *et al.*	(COLU, FNAL, STON+)
ALEKSEEV	76	SJNP 22 531 Translated from YAF 22 1021.	G.D. Alekseev *et al.*	(JINR)
ALEKSEEV	76B	SJNP 23 633 Translated from YAF 23 1190.	G.D. Alekseev *et al.*	(JINR)
BALDIN	76	SJNP 22 264 Translated from YAF 22 512.	B.Y. Baldin *et al.*	(JINR)
BRIATORE	76	NC 31A 553	L. Briatore *et al.*	(LCGT, FRAS, FREIB)
GUSTAFSON	76	PRL 37 474	H.R. Gustafson *et al.*	(MICH)
ALBROW	75	NP B97 189	M.G. Albrow *et al.*	(CERN, DARE, FOM+)
FRANKEL	75	PR D12 2561	S. Frankel *et al.*	(PENN, FNAL)
JOVANOV...	75	PL 56B 105	J.V. Jovanovich *et al.*	(MANI, AACH, CERN+)
YOCK	75	NP B86 216	P.C.M. Yock	(AUCK, SLAC)
APPEL	74	PRL 32 428	J.A. Appel *et al.*	(COLU, FNAL)
FRANKEL	74	PR D9 1932	S. Frankel *et al.*	(PENN, FNAL)
YOCK	74	NP B76 175	P.C.M. Yock	(AUCK)
ALPER	73	PL 46B 265	B. Alper *et al.*	(CERN, LIVP, LUND, BOHR+)
LEIPUNER	73	PRL 31 1226	L.B. Leipuner *et al.*	(BNL, YALE)
DARDO	72	NC 9A 319	M. Dardo *et al.*	(TORI)
TONWAR	72	JPA 5 569	S.C. Tonwar, S. Naranan, B.V. Sreekantan	(TATA)
ANTIPOV	71B	NP B31 235	Y.M. Antipov *et al.*	(SERP)
ANTIPOV	71C	PL 34B 164	Y.M. Antipov *et al.*	(SERP)
BINON	69	PL 30B 510	F.G. Binon *et al.*	(SERP)
BJORNBOE	68	NC B53 241	J. Bjornboe *et al.*	(BOHR, TATA, BERN+)
JONES	67	PR 164 1584	L.W. Jones	(MICH, WISC, LBL, UCLA, MINN+)
DORFAN	65	PRL 14 999	D.E. Dorfan *et al.*	(COLU)