# Magnetic Monopole Searches

## See the related review(s):

Magnetic Monopoles

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### Monopole Production Cross Section — Accelerator Searches

| *X-SECT* (cm$^2$) | *MASS* (GeV) | *CHG* ($g$) | *ENERGY* (GeV) | *BEAM* | *DOCUMENT ID* | *TECN* |
|---|---|---|---|---|---|---|
| <4 E-41 | 200–4000 | 1–2 | 13000 | $p p$ | [1] AAD 23CO | ATLS |
| <4 E-38 | 590–1000 | 1–4 | 8000 | $p p$ | [2] ACHARYA 22A | INDU |
| <2 E-29 | 0–70 | 1–3 | 5020 | PbPb | [3] ACHARYA 22B | INDU |
| <3 E-38 | 750–1910 | 1–5 | 13000 | $p p$ | [4] ACHARYA 21 | INDU |
| <1.3E−40 | 200–4000 | 1 | 13000 | $p p$ | [5] AAD 20G | ATLS |
| <5.6E−40 | 500–4000 | 2 | 13000 | $p p$ | [5] AAD 20G | ATLS |
|  | 200–5000 | 2 | 13000 | $p p$ | [6] ACHARYA 19B | INDU |
|  | 200–5000 | 1 | 13000 | $p p$ | [7] ACHARYA 18A | INDU |
| <2.5E−37 | 200–6000 | 1 | 13000 | $p p$ | [8] ACHARYA 17 | INDU |
| <2E−37 | 200–6000 | 2 | 13000 | $p p$ | [8] ACHARYA 17 | INDU |
| <4E−37 | 200–5000 | 3 | 13000 | $p p$ | [8] ACHARYA 17 | INDU |
| <1.5E−36 | 400–4000 | 4 | 13000 | $p p$ | [8] ACHARYA 17 | INDU |
| <7E−36 | 1000–3000 | 5 | 13000 | $p p$ | [8] ACHARYA 17 | INDU |
| <5E−40 | 200–2500 | 0.5–2.0 | 8000 | $p p$ | [9] AAD 16AB | ATLS |
| <2E−37 | 100–3500 | 1 | 8000 | $p p$ | [10] ACHARYA 16 | INDU |
| <2E−37 | 100–3500 | 2 | 8000 | $p p$ | [10] ACHARYA 16 | INDU |
| <6E−37 | 500–3000 | 3 | 8000 | $p p$ | [10] ACHARYA 16 | INDU |
| <7E−36 | 1000–2000 | 4 | 8000 | $p p$ | [10] ACHARYA 16 | INDU |
| <1.6E−38 | 200–1200 | 1 | 7000 | $p p$ | [11] AAD 12CS | ATLS |
| <5E−38 | 45–102 | 1 | 206 | $e^+ e^-$ | [12] ABBIENDI 08 | OPAL |
| <0.2E−36 | 200–700 | 1 | 1960 | $p \overline{p}$ | [13] ABULENCIA 06K | CNTR |
| < 2.E−36 |  | 1 | 300 | $e^+ p$ | [14,15] AKTAS 05A | INDU |
| < 0.2 E−36 |  | 2 | 300 | $e^+ p$ | [14,15] AKTAS 05A | INDU |
| < 0.09E−36 |  | 3 | 300 | $e^+ p$ | [14,15] AKTAS 05A | INDU |
| < 0.05E−36 |  | $\geq 6$ | 300 | $e^+ p$ | [14,15] AKTAS 05A | INDU |
| < 2.E−36 |  | 1 | 300 | $e^+ p$ | [14,16] AKTAS 05A | INDU |
| < 0.2E−36 |  | 2 | 300 | $e^+ p$ | [14,16] AKTAS 05A | INDU |
| < 0.07E−36 |  | 3 | 300 | $e^+ p$ | [14,16] AKTAS 05A | INDU |
| < 0.06E−36 |  | $\geq 6$ | 300 | $e^+ p$ | [14,16] AKTAS 05A | INDU |
| < 0.6E−36 | >265 | 1 | 1800 | $p \overline{p}$ | [17] KALBFLEISCH 04 | INDU |
| < 0.2E−36 | >355 | 2 | 1800 | $p \overline{p}$ | [17] KALBFLEISCH 04 | INDU |
| < 0.07E−36 | >410 | 3 | 1800 | $p \overline{p}$ | [17] KALBFLEISCH 04 | INDU |
| < 0.2E−36 | >375 | 6 | 1800 | $p \overline{p}$ | [17] KALBFLEISCH 04 | INDU |
| < 0.7E−36 | >295 | 1 | 1800 | $p \overline{p}$ | [18,19] KALBFLEISCH 00 | INDU |
| < 7.8E−36 | >260 | 2 | 1800 | $p \overline{p}$ | [18,19] KALBFLEISCH 00 | INDU |
| < 2.3E−36 | >325 | 3 | 1800 | $p \overline{p}$ | [18,20] KALBFLEISCH 00 | INDU |
| < 0.11E−36 | >420 | 6 | 1800 | $p \overline{p}$ | [18,20] KALBFLEISCH 00 | INDU |
| <0.65E−33 | <3.3 | $\geq 2$ | 11$A$ | $^{197}$Au | [21,22] HE 97 |  |
| <1.90E−33 | <8.1 | $\geq 2$ | 160$A$ | $^{208}$Pb | [21,22] HE 97 |  |
| <3.E−37 | <45.0 | 1.0 | 88–94 | $e^+ e^-$ | PINFOLD 93 | PLAS |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| <3.E−37 | <41.6 | 2.0 | 88–94 | $e^+e^-$ | PINFOLD | 93 | PLAS |
| <7.E−35 | <44.9 | 0.2–1.0 | 89–93 | $e^+e^-$ | KINOSHITA | 92 | PLAS |
| <2.E−34 | <850 | $\geq 0.5$ | 1800 | $p\overline{p}$ | BERTANI | 90 | PLAS |
| <1.2E−33 | <800 | $\geq 1$ | 1800 | $p\overline{p}$ | PRICE | 90 | PLAS |
| <1.E−37 | <29 | 1 | 50–61 | $e^+e^-$ | KINOSHITA | 89 | PLAS |
| <1.E−37 | <18 | 2 | 50–61 | $e^+e^-$ | KINOSHITA | 89 | PLAS |
| <1.E−38 | <17 | <1 | 35 | $e^+e^-$ | BRAUNSCH... | 88B | CNTR |
| <8.E−37 | <24 | 1 | 50–52 | $e^+e^-$ | KINOSHITA | 88 | PLAS |
| <1.3E−35 | <22 | 2 | 50–52 | $e^+e^-$ | KINOSHITA | 88 | PLAS |
| <9.E−37 | <4 | <0.15 | 10.6 | $e^+e^-$ | GENTILE | 87 | CLEO |
| <3.E−32 | <800 | $\geq 1$ | 1800 | $p\overline{p}$ | PRICE | 87 | PLAS |
| <3.E−38 | | <3 | 29 | $e^+e^-$ | FRYBERGER | 84 | PLAS |
| <1.E−31 | | 1,3 | 540 | $p\overline{p}$ | AUBERT | 83B | PLAS |
| <4.E−38 | <10 | <6 | 34 | $e^+e^-$ | MUSSET | 83 | PLAS |
| <8.E−36 | <20 | | 52 | $pp$ | [23] DELL | 82 | CNTR |
| <9.E−37 | <30 | <3 | 29 | $e^+e^-$ | KINOSHITA | 82 | PLAS |
| <1.E−37 | <20 | <24 | 63 | $pp$ | CARRIGAN | 78 | CNTR |
| <1.E−37 | <30 | <3 | 56 | $pp$ | HOFFMANN | 78 | PLAS |
| | | | 62 | $pp$ | [23] DELL | 76 | SPRK |
| <4.E−33 | | | 300 | $p$ | [23] STEVENS | 76B | SPRK |
| <1.E−40 | <5 | <2 | 70 | $p$ | [24] ZRELOV | 76 | CNTR |
| <2.E−30 | | | 300 | $n$ | [23] BURKE | 75 | OSPK |
| <1.E−38 | | | 8 | $\nu$ | [25] CARRIGAN | 75 | HLBC |
| <5.E−43 | <12 | <10 | 400 | $p$ | EBERHARD | 75B | INDU |
| <2.E−36 | <30 | <3 | 60 | $pp$ | GIACOMELLI | 75 | PLAS |
| <5.E−42 | <13 | <24 | 400 | $p$ | CARRIGAN | 74 | CNTR |
| <6.E−42 | <12 | <24 | 300 | $p$ | CARRIGAN | 73 | CNTR |
| <2.E−36 | | 1 | 0.001 | $\gamma$ | [24] BARTLETT | 72 | CNTR |
| <1.E−41 | <5 | | 70 | $p$ | GUREVICH | 72 | EMUL |
| <1.E−40 | <3 | <2 | 28 | $p$ | AMALDI | 63 | EMUL |
| <2.E−40 | <3 | <2 | 30 | $p$ | PURCELL | 63 | CNTR |
| <1.E−35 | <3 | <4 | 28 | $p$ | FIDECARO | 61 | CNTR |
| <2.E−35 | <1 | 1 | 6 | $p$ | BRADNER | 59 | EMUL |

[1] AAD 23CO limits given for monopoles pair produced via a Drell-Yan or photon-fusion mechanism. Spins 1/2 and 0 are considered. The quoted limit is representative of the lowest values that were achieved.

[2] ACHARYA 22A give limits for monopoles pair-produced via a Drell-Yan production. Spins 0, 1/2, and 1 are considered. The cross section limit is representative of the lowest values that were achieved. The experiment used a combination of nuclear track detectors to look evidence of passing monopoles and a SQUID magnetometer to look for stopped monopoles.

[3] ACHARYA 22B achieved limits on monopole (point-like included) production via the Schwinger mechanism in Pb-Pb collisions at 5.02 TeV centre-of-mass energy per nucleon pair. The upper cross section limit value quoted here is representative of the lowest values achieved.

[4] ACHARYA 21 search for dyons at LHC. Using a production model limits (we report the lowest) are set for dyons with magnetic charge up to 5 gD, electric charges up to 200 e and spins 0, 1/2, 1. The corresponding mass limits for magnetic monopoles are in the range 870–2040 GeV for magnetic charges in the same range.

[5] AAD 20G give limits for Drell-Yan production with spin-0 and spin-1/2 monopoles. The above limit is for spin = 0 at mass = 3 TeV.

[6] ACHARYA 19B limits both $\beta$-dependent and $\beta$-independent on monopoles with spins 0, 1/2, and 1 and with magnetic charges ranging from one to five times the Dirac charge in mass ranges between 200 GeV and 5000 GeV.

[7] ACHARYA 18A provide limits on monopoles with spins 0, 1/2, and 1 and with magnetic charges ranging from two to five times the Dirac charge.

[8] The search was sensitive to monopoles which had stopped in aluminium trapping volumes. Monopoles with spins 0 and 1/2 were considered; mass-dependent spin 1/2 monopole limits are quoted here.

[9] AAD 16AB model-independent 95% CL limits estimated using a fiducial region of approximately constant acceptance. Limits are mass-dependent.

[10] ACHARYA 16 limits at 95% CL estimated using a Drell-Yan-like production mechanism for scalar monopoles.

[11] AAD 12CS searched for monopoles as highly ionising objects. The cross section limits are based on an assumed Drell Yan-like production process for spin 1/2 monopoles. The limits are mass- and scenario-dependent.

[12] ABBIENDI 08 assume production of spin 1/2 monopoles with effective charge $g\beta$ (n=1), via $e^+ e^- \rightarrow \gamma^* \rightarrow M\overline{M}$, so that the cross section is proportional to $(1 + \cos^2\theta)$. There is no $z$ information for such highly saturated tracks, so a parabolic track in the jet chamber is projected onto the $xy$ plane. Charge per hit in the chamber produces a clean separation of signal and background.

[13] ABULENCIA 06K searches for high-ionizing signals in CDF central outer tracker and time-of-flight detector. For Drell-Yan $M\overline{M}$ production, the cross section limit implies $M > 360$ GeV at 95% CL.

[14] AKTAS 05A model-dependent limits as a function of monopole mass shown for arbitrary mass of 60 GeV. Based on search for stopped monopoles in the H1 Al beam pipe.

[15] AKTAS 05A limits with assumed elastic spin 0 monopole pair production.

[16] AKTAS 05A limits with assumed inelastic spin 1/2 monopole pair production.

[17] KALBFLEISCH 04 reports searches for stopped magnetic monopoles in Be, Al, and Pb samples obtained from discarded material from the upgrading of DØ and CDF. A large-aperture warm-bore cryogenic detector was used. The approach was an extension of the methods of KALBFLEISCH 00. Cross section results moderately model dependent; interpretation as a mass lower limit depends on possibly invalid perturbation expansion.

[18] KALBFLEISCH 00 used an induction method to search for stopped monopoles in pieces of the DØ (FNAL) beryllium beam pipe and in extensions to the drift chamber aluminum support cylinder. Results are model dependent.

[19] KALBFLEISCH 00 result is for aluminum.

[20] KALBFLEISCH 00 result is for beryllium.

[21] HE 97 used a lead target and barium phosphate glass detectors. Cross-section limits are well below those predicted via the Drell-Yan mechanism.

[22] This work has also been reinterpreted in the framework of monopole production via the thermal Schwinger process (GOULD 17); this gives rise to lower mass limits.

[23] Multiphoton events.

[24] Cherenkov radiation polarization.

[25] Re-examines CERN neutrino experiments.

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## Monopole Production — Other Accelerator Searches

| *MASS* (GeV) | *CHG* ($g$) | *SPIN* | *ENERGY* (GeV) | *BEAM* | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|---|---|---|---|
| $>$ 610 | $\geq 1$ | 0 | 1800 | $p\overline{p}$ | [1] ABBOTT | 98K | D0 |
| $>$ 870 | $\geq 1$ | 1/2 | 1800 | $p\overline{p}$ | [1] ABBOTT | 98K | D0 |
| $>$1580 | $\geq 1$ | 1 | 1800 | $p\overline{p}$ | [1] ABBOTT | 98K | D0 |
| $>$ 510 | | | 88–94 | $e^+ e^-$ | [2] ACCIARRI | 95C | L3 |

[1] ABBOTT 98K search for heavy pointlike Dirac monopoles via central production of a pair of photons with high transverse energies.

[2] ACCIARRI 95C finds a limit B($Z \rightarrow \gamma\gamma\gamma$) $< 0.8 \times 10^{-5}$ (which is possible via a monopole loop) at 95% CL and sets the mass limit via a cross section model.

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## Monopole Flux — Cosmic Ray Searches

"Caty" in the charge column indicates a search for monopole-catalyzed nucleon decay.

| *FLUX* (cm$^{-2}$sr$^{-1}$s$^{-1}$) | *MASS* (GeV) | *CHG* ($g$) | *COMMENTS* ($\beta = v/c$) | *DOCUMENT ID* | *TECN* |
|---|---|---|---|---|---|
| <2E-19 | | 1 | $0.86 < \beta < 0.995$ | [1] ABBASI 22 | ICCB |
| <2E-14 | >5E8 | | $6E-4 < \beta < 5E-3$ | [2] ACERO 21 | NOVA |
| <1E-17 | | Caty | $1E-5 < \beta < 1E-3$ | [3] GAPONENKO 21 | BAIK |
| <1.5E−18 | | 1 | $\beta > 0.6$ | [4] ALBERT 17 | ANTR |
| <2.5E−21 | | 1 | $1E8 < \gamma < 1E13$ | [5] AAB 16 | AUGE |
| <1.55E-18 | | | $\beta > 0.51$ | [6] AARTSEN 16B | ICCB |
| <1E-17 | | Caty | $1E-3 < \beta < 1E-2$ | [7] AARTSEN 14 | ICCB |
| <3E-18 | | 1 | $\beta > 0.8$ | [8] ABBASI 13 | ICCB |
| <1.3E-17 | | 1 | $\beta > 0.625$ | [9] ADRIAN-MAR.. 12A | ANTR |
| <6E-28 | <1E17 | Caty | $1E-5 < \beta < 0.04$ | [10] UENO 12 | SKAM |
| **<1E-19** | | **1** | **$\gamma > 1E10$** | [11] DETRIXHE 11 | ANIT |
| <3.8E-17 | | 1 | $\beta > 0.76$ | [8] ABBASI 10A | ICCB |
| <1.3E−15 | 1E4<M<5E13 | 1 | $\beta > 0.05$ | [12] BALESTRA 08 | PLAS |
| <0.65E−15 | >5E13 | 1 | $\beta > 0.05$ | [12] BALESTRA 08 | PLAS |
| **<1E−18** | | **1** | **$\gamma > 1$ E8** | [11] HOGAN 08 | RICE |
| **<1.4E−16** | | **1** | **$1.1E-4 < \beta < 1$** | [13] AMBROSIO 02B | MCRO |
| <3E−16 | | Caty | $1.1E-4 < \beta < 5E-3$ | [14] AMBROSIO 02C | MCRO |
| <1.5E−15 | | 1 | $5E-3 < \beta < 0.99$ | [15] AMBROSIO 02D | MCRO |
| <1E−15 | | 1 | $1.1 \times 10^{-4}$–0.1 | [16] AMBROSIO 97 | MCRO |
| <5.6E−15 | | 1 | (0.18–3.0)E−3 | [17] AHLEN 94 | MCRO |
| <2.7E−15 | | Caty | $\beta \sim 1 \times 10^{-3}$ | [18] BECKER-SZ... 94 | IMB |
| <8.7E−15 | | 1 | >2.E−3 | THRON 92 | SOUD |
| <4.4E−12 | | 1 | all $\beta$ | GARDNER 91 | INDU |
| <7.2E−13 | | 1 | all $\beta$ | HUBER 91 | INDU |
| <3.7E−15 | >E12 | 1 | $\beta$=1.E−4 | [19] ORITO 91 | PLAS |
| <3.2E−16 | >E10 | 1 | $\beta > 0.05$ | [19] ORITO 91 | PLAS |
| <3.2E−16 | >E10–E12 | 2, 3 | | [19] ORITO 91 | PLAS |
| <3.8E−13 | | 1 | all $\beta$ | BERMON 90 | INDU |
| <5.E−16 | | Caty | $\beta < 1.E-3$ | [18] BEZRUKOV 90 | CHER |
| <1.8E−14 | | 1 | $\beta > 1.1E-4$ | [20] BUCKLAND 90 | HEPT |
| <1E−18 | | | $3.E-4 < \beta < 1.5E-3$ | [21] GHOSH 90 | MICA |
| <7.2E−13 | | 1 | all $\beta$ | HUBER 90 | INDU |
| <5.E−12 | >E7 | 1 | $3.E-4 < \beta < 5.E-3$ | BARISH 87 | CNTR |
| <1.E−13 | | Caty | $1.E-5 < \beta < 1$ | [18] BARTELT 87 | SOUD |
| <1.E−10 | | 1 | all $\beta$ | EBISU 87 | INDU |
| <2.E−13 | | | $1.E-4 < \beta < 6.E-4$ | MASEK 87 | HEPT |
| <2.E−14 | | | $4.E-5 < \beta < 2.E-4$ | NAKAMURA 87 | PLAS |
| <2.E−14 | | | $1.E-3 < \beta < 1$ | NAKAMURA 87 | PLAS |
| <5.E−14 | | | $9.E-4 < \beta < 1.E-2$ | SHEPKO 87 | CNTR |
| <2.E−13 | | | $4.E-4 < \beta < 1$ | TSUKAMOTO 87 | CNTR |
| <5.E−14 | | 1 | all $\beta$ | [22] CAPLIN 86 | INDU |
| <5.E−12 | | 1 | | CROMAR 86 | INDU |
| <1.E−13 | | 1 | $7.E-4 < \beta$ | HARA 86 | CNTR |

| | | | | | | |
|---|---|---|---|---|---|---|
| <7.E−11 | | 1 | all $\beta$ | INCANDELA | 86 | INDU |
| <1.E−18 | | | 4.E−4 < $\beta$ <1.E−3 | [21] PRICE | 86 | MICA |
| <5.E−12 | | 1 | | BERMON | 85 | INDU |
| <6.E−12 | | 1 | | CAPLIN | 85 | INDU |
| <6.E−10 | | 1 | | EBISU | 85 | INDU |
| <3.E−15 | | Caty | 5.E−5 ≤ $\beta$ ≤ 1.E−3 | [18] KAJITA | 85 | KAMI |
| <2.E−21 | | Caty | $\beta$ <1.E−3 | [18,23] KAJITA | 85 | KAMI |
| <3.E−15 | | Caty | 1.E−3 < $\beta$ <1.E−1 | [18] PARK | 85B | CNTR |
| <5.E−12 | | 1 | 1.E−4 < $\beta$ <1 | BATTISTONI | 84 | NUSX |
| <7.E−12 | | 1 | | INCANDELA | 84 | INDU |
| <7.E−13 | | 1 | 3.E−4 < $\beta$ | [20] KAJINO | 84 | CNTR |
| <2.E−12 | | 1 | 3.E−4 < $\beta$ <1.E−1 | KAJINO | 84B | CNTR |
| <6.E−13 | | 1 | 5.E−4 < $\beta$ <1 | KAWAGOE | 84 | CNTR |
| <2.E−14 | | | 1.E−3 < $\beta$ | [18] KRISHNA... | 84 | CNTR |
| <4.E−13 | | 1 | 6.E−4 < $\beta$ <2.E−3 | LISS | 84 | CNTR |
| <1.E−16 | | | 3.E−4 < $\beta$ <1.E−3 | [21] PRICE | 84 | MICA |
| <1.E−13 | | 1 | 1.E−4 < $\beta$ | PRICE | 84B | PLAS |
| <4.E−13 | | 1 | 6.E−4 < $\beta$ <2.E−3 | TARLE | 84 | CNTR |
| | | | | [24] ANDERSON | 83 | EMUL |
| <4.E−13 | | 1 | 1.E−2 < $\beta$ <1.E−3 | BARTELT | 83B | CNTR |
| <1.E−12 | | 1 | 7.E−3 < $\beta$ <1 | BARWICK | 83 | PLAS |
| <3.E−13 | | 1 | 1.E−3 < $\beta$ <4.E−1 | BONARELLI | 83 | CNTR |
| <3.E−12 | | Caty | 5.E−4 < $\beta$ <5.E−2 | [18] BOSETTI | 83 | CNTR |
| <4.E−11 | | 1 | | CABRERA | 83 | INDU |
| <5.E−15 | | 1 | 1.E−2 < $\beta$ <1 | DOKE | 83 | PLAS |
| <8.E−15 | | Caty | 1.E−4 < $\beta$ <1.E−1 | [18] ERREDE | 83 | IMB |
| <5.E−12 | | 1 | 1.E−4 < $\beta$ <3.E−2 | GROOM | 83 | CNTR |
| <2.E−12 | | | 6.E−4 < $\beta$ <1 | MASHIMO | 83 | CNTR |
| <1.E−13 | | 1 | $\beta$=3.E−3 | ALEXEYEV | 82 | CNTR |
| <2.E−12 | | 1 | 7.E−3 < $\beta$ <6.E−1 | BONARELLI | 82 | CNTR |
| 6.E−10 | | 1 | all $\beta$ | [25] CABRERA | 82 | INDU |
| <2.E−11 | | | 1.E−2 < $\beta$ <1.E−1 | MASHIMO | 82 | CNTR |
| <2.E−15 | | | concentrator | BARTLETT | 81 | PLAS |
| <1.E−13 | >1 | | 1.E−3 < $\beta$ | KINOSHITA | 81B | PLAS |
| <5.E−11 | <E17 | | 3.E−4 < $\beta$ <1.E−3 | ULLMAN | 81 | CNTR |
| <2.E−11 | | | concentrator | BARTLETT | 78 | PLAS |
| 1.E−1 | >200 | 2 | | [26] PRICE | 75 | PLAS |
| <2.E−13 | | >2 | | FLEISCHER | 71 | PLAS |
| <1.E−19 | | >2 | obsidian, mica | FLEISCHER | 69C | PLAS |
| <5.E−15 | <15 | <3 | concentrator | CARITHERS | 66 | ELEC |
| <2.E−11 | | <1–3 | concentrator | MALKUS | 51 | EMUL |

[1] ABBASI 22 search was based on Cherenkov light detection in an array of optical modules in the Antarctic ice cap. Limits are speed-dependent.

[2] ACERO 21 employ NOvA experiment to set reported 90% CL upper limit on the cosmic monopoles flux for velocity $6 \times 10^{-4} < \beta < 5 \times 10^{-3}$ and mass $> 5 \times 10^{8}$ GeV.

[3] GAPONENKO 21 use data of NT200 two-year operation at Baikal to give speed-dependent limits for different assumed catalysis cross sections. Reported limit is for $\sigma = 10$ mb.

[4] ALBERT 17 limits were estimated using a Cherenkov light in an array of optical modules under the Mediterranean Sea. The limits are for MM masses between $10^{10}$ and $10^{14}$ GeV. The limits are speed-dependent.

[5] AAB 16 search was made with a set of telescopes sampling the longitudinal profile of fluorescence light emitted by extensive air showers. Limits are speed dependent.

[6] AARTSEN 16B was based on a Cherenkov signature in an array of optical modules which were sunk in the Antarctic ice cap. Limits are speed-dependent.

[7] Beyond the monopole speed, the limits of AARTSEN 14 depend on the catalysis cross section ($\sigma$) which corresponds to the monopole radiating $\hat{l}$ times the light per track length compared to the Cherenkov light from a single electrically charged, relativistic particle. The values quoted here correspond to $\sigma = 1$ barn or $\hat{l} = 30$.

[8] ABBASI 13 and ABBASI 10A were based on a Cherenkov signature in an array of optical modules which were sunk in the Antarctic ice cap. Limits are speed-dependent.

[9] ADRIAN-MARTINEZ 12A measurements were based on a Cherenkov signature in an underwater telescope in the Western Mediterranean Sea. Limits are speed-dependent.

[10] The limits from UENO 12 depend on the monopole speed and are also sensitive to assumed values of monopole mass and the catalysis cross section.

[11] HOGAN 08 and DETRIXHE 11 limits on relativistic monopoles are based on nonobservation of radio Cherenkov signals at the South Pole. Limits are speed-dependent.

[12] BALESTRA 08 exposed of nuclear track detector modules totaling 400 $\text{m}^2$ for 4 years at the Chacaltaya Laboratory (5230 m) in search for intermediate-mass monopoles with $\beta >$ 0.05. The analysis is mainly based on three CR39 modules. For $\text{M} > 5 \times 10^{13}$ GeV there can be upward-going monopoles as well, hence the flux limit is half that obtained for less massive monopoles. Previous experiments (e.g. MACRO and OHYA (ORITO 91)) had set limits only for $\text{M} > 1 \times 10^9$ GeV.

[13] AMBROSIO 02B direct search final result for $m \geq 10^{17}$ GeV, based upon 4.2 to 9.5 years of running, depending upon the subsystem. Limit with CR39 track-etch detector extends the limit from $\beta$=4 $\times$ $10^{-5}$ ($3.1 \times 10^{-16}\,\text{cm}^{-2}\,\text{sr}^{-1}\,\text{s}^{-1}$) to $\beta$= 1 $\times$ $10^{-4}$ ($2.1 \times 10^{-16}\,\text{cm}^{-2}\,\text{sr}^{-1}\,\text{s}^{-1}$). Limit curve in paper is piecewise continuous due to different detection techniques for different $\beta$ ranges.

[14] AMBROSIO 02C limit for catalysis of nucleon decay with catalysis cross section of $\approx$ 1 mb. The flux limit increases by $\sim$ 3 at the higher $\beta$ limit, and increases to $1 \times 10^{-14}\,\text{cm}^{-2}\,\text{sr}^{-1}\,\text{s}^{-1}$ if the catalysis cross section is 0.01 mb. Based upon 71193 hr of data with the streamer detector, with an acceptance of 4250 $\text{m}^2$ sr.

[15] AMBROSIO 02D result for "more than two years of data." Ionization search using several subsystems. Limit curve as a function of $\beta$ not given. Included in AMBROSIO 02B.

[16] AMBROSIO 97 global MACRO 90%CL is $0.78 \times 10^{-15}$ at $\beta$=$1.1 \times 10^{-4}$, goes through a minimum at $0.61 \times 10^{-15}$ near $\beta$=(1.1–2.7) $\times$ $10^{-3}$, then rises to $0.84 \times 10^{-15}$ at $\beta$=0.1. The global limit in this region is below the Parker bound at $10^{-15}$. Less stringent limits are established for $4 \times 10^{-5} < \beta < 1 \times 10^{-4}$. Limits set by various triggers and different subdetectors are given in the paper. All limits assume a catalysis cross section smaller than a few mb.

[17] AHLEN 94 limit for dyons extends down to $\beta$=0.9E−4 and a limit of 1.3E−14 extends to $\beta$ = 0.8E−4. Also see comment by PRICE 94 and reply of BARISH 94. One loophole in the AHLEN 94 result is that in the case of monopoles catalyzing nucleon decay, relativistic particles could veto the events. See AMBROSIO 97 for additional results.

[18] Catalysis of nucleon decay; sensitive to assumed catalysis cross section.

[19] ORITO 91 limits are functions of velocity. Lowest limits are given here.

[20] Used DKMPR mechanism and Penning effect.

[21] Assumes monopole attaches fermion nucleus.

[22] Limit from combining data of CAPLIN 86, BERMON 85, INCANDELA 84, and CABRERA 83. For a discussion of controversy about CAPLIN 86 observed event, see GUY 87. Also see SCHOUTEN 87.

[23] Based on lack of high- energy solar neutrinos from catalysis in the sun.

[24] Anomalous long-range $\alpha$ ($^4$He) tracks.

[25] CABRERA 82 candidate event has single Dirac charge within ±5%.

[26] ALVAREZ 75, FLEISCHER 75, and FRIEDLANDER 75 explain as fragmenting nucleus. EBERHARD 75 and ROSS 76 discuss conflict with other experiments. HAGSTROM 77 reinterprets as antinucleus. PRICE 78 reassesses.

## Monopole Flux — Astrophysics

| *FLUX* ($\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$) | *MASS* (GeV) | *CHG* ($g$) | *COMMENTS* ($\beta = v/c$) | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|---|---|---|
| $< 1.2 \times 10^{-21}$ | $> 10^{4}$ | 1 | Parker | [1] KOBAYASHI | 23A | COSM |
| $< 1.3 \times 10^{-20}$ | | | faint white dwarf | [2] FREESE | 99 | ASTR |
| $< 1 \times 10^{-16}$ | $10^{17}$ | 1 | galactic field | [3] ADAMS | 93 | COSM |
| $< 1 \times 10^{-23}$ | | | Jovian planets | [2] ARAFUNE | 85 | ASTR |
| $< 1 \times 10^{-16}$ | $10^{15}$ | | solar trapping | BRACCI | 85B | ASTR |
| $< 1 \times 10^{-18}$ | | 1 | | [2] HARVEY | 84 | COSM |
| $< 3 \times 10^{-23}$ | | | neutron stars | KOLB | 84 | ASTR |
| $< 7 \times 10^{-22}$ | | | pulsars | [2] FREESE | 83B | ASTR |
| $< 1 \times 10^{-18}$ | $< 10^{18}$ | 1 | intergalactic field | [2] REPHAELI | 83 | COSM |
| $< 1 \times 10^{-23}$ | | | neutron stars | [2] DIMOPOUL... | 82 | COSM |
| $< 5 \times 10^{-22}$ | | | neutron stars | [2] KOLB | 82 | COSM |
| $< 5 \times 10^{-15}$ | $> 10^{21}$ | | galactic halo | SALPETER | 82 | COSM |
| $< 1 \times 10^{-12}$ | $10^{19}$ | 1 | $\beta = 3 \times 10^{-3}$ | [4] TURNER | 82 | COSM |
| $< 1 \times 10^{-16}$ | | 1 | galactic field | PARKER | 70 | COSM |

[1] KOBAYASHI 23A found Parker-type bounds on magnetic monopoles with arbitrary magnetic charge based on the survival of galactic, seed, and primordial magnetic fields. Bounds are between $10^{-21}$ and $10^{-5}$ $\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$ for masses between $10^{4}$ and $10^{18}$ GeV. Reported bound is the most stringent one.

[2] Catalysis of nucleon decay.

[3] ADAMS 93 limit based on "survival and growth of a small galactic seed field" is $10^{-16}$ ($m/10^{17}$ GeV) $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. Above $10^{17}$ GeV, limit $10^{-16}$ ($10^{17}$ GeV$/m$) $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ (from requirement that monopole density does not overclose the universe) is more stringent.

[4] Re-evaluates PARKER 70 limit for GUT monopoles.

## Monopole Density — Matter Searches

| *DENSITY* | *CHG* ($g$) | *MATERIAL* | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|---|---|
| <9.8E−5/gram | ≥ 1 | Polar rock | BENDTZ | 13 | INDU |
| <6.9E−6/gram | >1/3 | Meteorites and other | JEON | 95 | INDU |
| <2.E−7/gram | >0.6 | Fe ore | [1] EBISU | 87 | INDU |
| <4.6E−6/gram | > 0.5 | deep schist | KOVALIK | 86 | INDU |
| <1.6E−6/gram | > 0.5 | manganese nodules | [2] KOVALIK | 86 | INDU |
| <1.3E−6/gram | > 0.5 | seawater | KOVALIK | 86 | INDU |
| >1.E+14/gram | >1/3 | iron aerosols | MIKHAILOV | 83 | SPEC |
| <6.E−4/gram | | air, seawater | CARRIGAN | 76 | CNTR |
| <5.E−1/gram | >0.04 | 11 materials | CABRERA | 75 | INDU |
| <2.E−4/gram | >0.05 | moon rock | ROSS | 73 | INDU |
| <6.E−7/gram | <140 | seawater | KOLM | 71 | CNTR |
| <1.E−2/gram | <120 | manganese nodules | FLEISCHER | 69 | PLAS |
| <1.E−4/gram | >0 | manganese | FLEISCHER | 69B | PLAS |
| <2.E−3/gram | <1–3 | magnetite, meteor | GOTO | 63 | EMUL |
| <2.E−2/gram | | meteorite | PETUKHOV | 63 | CNTR |

[1] Mass $1 \times 10^{14}$–$1 \times 10^{17}$ GeV.

[2] KOVALIK 86 examined 498 kg of schist from two sites which exhibited clear mineralogical evidence of having been buried at least 20 km deep and held below the Curie temperature.

## Monopole Density — Astrophysics

| *DENSITY* | *CHG (g)* | *MATERIAL* | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|---|---|
| $<1.E-9$/gram | 1 | sun, catalysis | [1] ARAFUNE | 83 | COSM |
| $<6.E-33$/nucl | 1 | moon wake | SCHATTEN | 83 | ELEC |
| $<2.E-28$/nucl | | earth heat | CARRIGAN | 80 | COSM |
| $<2.E-4$/prot | | 42cm absorption | BRODERICK | 79 | COSM |
| $<2.E-13/m^3$ | | moon wake | SCHATTEN | 70 | ELEC |

[1] Catalysis of nucleon decay.

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