

# Magnetic Monopole Searches

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## Monopole Production Cross Section — Accelerator Searches

<i>X-SECT</i> (cm <sup>2</sup> )	<i>MASS</i> (GeV)	<i>CHG</i> (g)	<i>ENERGY</i> (GeV)	<i>BEAM</i>	<i>DOCUMENT ID</i>	<i>TECN</i>
<1.3E-40	200-4000	1	13000	<i>pp</i>	<sup>1</sup> AAD	20G ATLS
<5.6E-40	500-4000	2	13000	<i>pp</i>	<sup>1</sup> AAD	20G ATLS
	200-5000	2	13000	<i>pp</i>	<sup>2</sup> ACHARYA	19B INDU
	200-5000	1	13000	<i>pp</i>	<sup>3</sup> ACHARYA	18A INDU
<2.5E-37	200-6000	1	13000	<i>pp</i>	<sup>4</sup> ACHARYA	17 INDU
<2E-37	200-6000	2	13000	<i>pp</i>	<sup>4</sup> ACHARYA	17 INDU
<4E-37	200-5000	3	13000	<i>pp</i>	<sup>4</sup> ACHARYA	17 INDU
<1.5E-36	400-4000	4	13000	<i>pp</i>	<sup>4</sup> ACHARYA	17 INDU
<7E-36	1000-3000	5	13000	<i>pp</i>	<sup>4</sup> ACHARYA	17 INDU
<5E-40	200-2500	0.5-2.0	8000	<i>pp</i>	<sup>5</sup> AAD	16AB ATLS
<2E-37	100-3500	1	8000	<i>pp</i>	<sup>6</sup> ACHARYA	16 INDU
<2E-37	100-3500	2	8000	<i>pp</i>	<sup>6</sup> ACHARYA	16 INDU
<6E-37	500-3000	3	8000	<i>pp</i>	<sup>6</sup> ACHARYA	16 INDU
<7E-36	1000-2000	4	8000	<i>pp</i>	<sup>6</sup> ACHARYA	16 INDU
<1.6E-38	200-1200	1	7000	<i>pp</i>	<sup>7</sup> AAD	12CS ATLS
<5E-38	45-102	1	206	<i>e<sup>+</sup>e<sup>-</sup></i>	<sup>8</sup> ABBIENDI	08 OPAL
<0.2E-36	200-700	1	1960	<i>p<math>\bar{p}</math></i>	<sup>9</sup> ABULENCIA	06K CNTR
< 2.E-36		1	300	<i>e<sup>+</sup>p</i>	<sup>10,11</sup> AKTAS	05A INDU
< 0.2 E-36		2	300	<i>e<sup>+</sup>p</i>	<sup>10,11</sup> AKTAS	05A INDU
< 0.09E-36		3	300	<i>e<sup>+</sup>p</i>	<sup>10,11</sup> AKTAS	05A INDU
< 0.05E-36		≥ 6	300	<i>e<sup>+</sup>p</i>	<sup>10,11</sup> AKTAS	05A INDU
< 2.E-36		1	300	<i>e<sup>+</sup>p</i>	<sup>10,12</sup> AKTAS	05A INDU
< 0.2E-36		2	300	<i>e<sup>+</sup>p</i>	<sup>10,12</sup> AKTAS	05A INDU
< 0.07E-36		3	300	<i>e<sup>+</sup>p</i>	<sup>10,12</sup> AKTAS	05A INDU
< 0.06E-36		≥ 6	300	<i>e<sup>+</sup>p</i>	<sup>10,12</sup> AKTAS	05A INDU
< 0.6E-36	>265	1	1800	<i>p<math>\bar{p}</math></i>	<sup>13</sup> KALBFLEISCH 04	INDU
< 0.2E-36	>355	2	1800	<i>p<math>\bar{p}</math></i>	<sup>13</sup> KALBFLEISCH 04	INDU
< 0.07E-36	>410	3	1800	<i>p<math>\bar{p}</math></i>	<sup>13</sup> KALBFLEISCH 04	INDU
< 0.2E-36	>375	6	1800	<i>p<math>\bar{p}</math></i>	<sup>13</sup> KALBFLEISCH 04	INDU
< 0.7E-36	>295	1	1800	<i>p<math>\bar{p}</math></i>	<sup>14,15</sup> KALBFLEISCH 00	INDU
< 7.8E-36	>260	2	1800	<i>p<math>\bar{p}</math></i>	<sup>14,15</sup> KALBFLEISCH 00	INDU
< 2.3E-36	>325	3	1800	<i>p<math>\bar{p}</math></i>	<sup>14,16</sup> KALBFLEISCH 00	INDU
< 0.11E-36	>420	6	1800	<i>p<math>\bar{p}</math></i>	<sup>14,16</sup> KALBFLEISCH 00	INDU
<0.65E-33	<3.3	≥ 2	11A	<sup>197</sup> Au	<sup>17,18</sup> HE	97
<1.90E-33	<8.1	≥ 2	160A	<sup>208</sup> Pb	<sup>17,18</sup> HE	97
<3.E-37	<45.0	1.0	88-94	<i>e<sup>+</sup>e<sup>-</sup></i>	PINFOLD	93 PLAS
<3.E-37	<41.6	2.0	88-94	<i>e<sup>+</sup>e<sup>-</sup></i>	PINFOLD	93 PLAS
<7.E-35	<44.9	0.2-1.0	89-93	<i>e<sup>+</sup>e<sup>-</sup></i>	KINOSHITA	92 PLAS
<2.E-34	<850	≥ 0.5	1800	<i>p<math>\bar{p}</math></i>	BERTANI	90 PLAS
<1.2E-33	<800	≥ 1	1800	<i>p<math>\bar{p}</math></i>	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	$p\bar{p}$	PRICE	87	PLAS
<3.E-38		<3	29	$e^+e^-$	FRYBERGER	84	PLAS
<1.E-31		1,3	540	$p\bar{p}$	AUBERT	83B	PLAS
<4.E-38	<10	<6	34	$e^+e^-$	MUSSET	83	PLAS
<8.E-36	<20		52	$pp$	<sup>19</sup> 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	$pp$	<sup>19</sup> DELL	76	SPRK
<4.E-33			300	$p$	<sup>19</sup> STEVENS	76B	SPRK
<1.E-40	<5	<2	70	$p$	<sup>20</sup> ZRELOV	76	CNTR
<2.E-30			300	$n$	<sup>19</sup> BURKE	75	OSPK
<1.E-38			8	$\nu$	<sup>21</sup> 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	$\gamma$	<sup>20</sup> 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

<sup>1</sup> 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.

<sup>2</sup> 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.

<sup>3</sup> 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.

<sup>4</sup> 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.

<sup>5</sup> AAD 16AB model-independent 95% CL limits estimated using a fiducial region of approximately constant acceptance. Limits are mass-dependent.

<sup>6</sup> ACHARYA 16 limits at 95% CL estimated using a Drell-Yan-like production mechanism for scalar monopoles.

<sup>7</sup> 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.

<sup>8</sup> ABBIENDI 08 assume production of spin 1/2 monopoles with effective charge  $g\beta$  ( $n=1$ ), via  $e^+e^- \rightarrow \gamma^* \rightarrow M\bar{M}$ , 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.

- <sup>9</sup> ABULENCIA 06K searches for high-ionizing signals in CDF central outer tracker and time-of-flight detector. For Drell-Yan  $M\bar{M}$  production, the cross section limit implies  $M > 360$  GeV at 95% CL.
- <sup>10</sup> 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.
- <sup>11</sup> AKTAS 05A limits with assumed elastic spin 0 monopole pair production.
- <sup>12</sup> AKTAS 05A limits with assumed inelastic spin 1/2 monopole pair production.
- <sup>13</sup> 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.
- <sup>14</sup> 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.
- <sup>15</sup> KALBFLEISCH 00 result is for aluminum.
- <sup>16</sup> KALBFLEISCH 00 result is for beryllium.
- <sup>17</sup> HE 97 used a lead target and barium phosphate glass detectors. Cross-section limits are well below those predicted via the Drell-Yan mechanism.
- <sup>18</sup> 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.
- <sup>19</sup> Multiphoton events.
- <sup>20</sup> Cherenkov radiation polarization.
- <sup>21</sup> Re-examines CERN neutrino experiments.

### Monopole Production — Other Accelerator Searches

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

<sup>1</sup> ABBOTT 98K search for heavy pointlike Dirac monopoles via central production of a pair of photons with high transverse energies.

<sup>2</sup> 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.

### Monopole Flux — Cosmic Ray Searches

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

FLUX ( $\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$ )	MASS (GeV)	CHG (g)	COMMENTS ( $\beta = v/c$ )	EVTS	DOCUMENT ID	TECN
<2E-14	>5E8		$6 \times 10^{-4} < \beta < 5 \times 10^{-3}$	<sup>1</sup> ACERO 21	NOVA	
<1.5E-18		1	$\beta > 0.6$	0	<sup>2</sup> ALBERT 17	ANTR
<2.5E-21		1	$1E8 < \gamma < 1E13$	0	<sup>3</sup> AAB 16	AUGE
<1.55E-18			$\beta > 0.51$	0	<sup>4</sup> AARTSEN 16B	ICCB
<1E-17		Caty	$1E-3 < \beta < 1E-2$	0	<sup>5</sup> AARTSEN 14	ICCB
<3E-18		1	$\beta > 0.8$	0	<sup>6</sup> ABBASI 13	ICCB
<1.3E-17		1	$\beta > 0.625$	0	<sup>7</sup> ADRIAN-MAR..12A	ANTR
<6E-28	<1E17	Caty	$1E-5 < \beta < 0.04$	0	<sup>8</sup> UENO 12	SKAM
<b>&lt;1E-19</b>		<b>1</b>	<b><math>\gamma &gt; 1E10</math></b>	0	<sup>9</sup> DETRIXHE 11	ANIT
<3.8E-17		1	$\beta > 0.76$	0	<sup>6</sup> ABBASI 10A	ICCB

<1.3E-15	1E4<M<5E13	1	$\beta > 0.05$	0	10	BALESTRA	08	PLAS
<0.65E-15	>5E13	1	$\beta > 0.05$	0	10	BALESTRA	08	PLAS
<b>&lt;1E-18</b>		<b>1</b>	<b><math>\gamma &gt; 1 \text{ E8}</math></b>	0	9	HOGAN	08	RICE
<b>&lt;1.4E-16</b>		<b>1</b>	<b><math>1.1\text{E}-4 &lt; \beta &lt; 1</math></b>	0	11	AMBROSIO	02B	MCRO
<3E-16		Caty	$1.1\text{E}-4 < \beta < 5\text{E}-3$	0	12	AMBROSIO	02C	MCRO
<1.5E-15		1	$5\text{E}-3 < \beta < 0.99$	0	13	AMBROSIO	02D	MCRO
<1E-15		1	$1.1 \times 10^{-4} - 0.1$	0	14	AMBROSIO	97	MCRO
<5.6E-15		1	$(0.18-3.0)\text{E}-3$	0	15	AHLEN	94	MCRO
<2.7E-15		Caty	$\beta \sim 1 \times 10^{-3}$	0	16	BECKER-SZ...	94	IMB
<8.7E-15		1	$>2.\text{E}-3$	0		THRON	92	SOUD
<4.4E-12		1	all $\beta$	0		GARDNER	91	INDU
<7.2E-13		1	all $\beta$	0		HUBER	91	INDU
<3.7E-15	>E12	1	$\beta = 1.\text{E}-4$	0	17	ORITO	91	PLAS
<3.2E-16	>E10	1	$\beta > 0.05$	0	17	ORITO	91	PLAS
<3.2E-16	>E10-E12	2,3		0	17	ORITO	91	PLAS
<3.8E-13		1	all $\beta$	0		BERMON	90	INDU
<5.E-16		Caty	$\beta < 1.\text{E}-3$	0	16	BEZRUKOV	90	CHER
<1.8E-14		1	$\beta > 1.1\text{E}-4$	0	18	BUCKLAND	90	HEPT
<1E-18			$3.\text{E}-4 < \beta < 1.5\text{E}-3$	0	19	GHOSH	90	MICA
<7.2E-13		1	all $\beta$	0		HUBER	90	INDU
<5.E-12	>E7	1	$3.\text{E}-4 < \beta < 5.\text{E}-3$	0		BARISH	87	CNTR
<1.E-13		Caty	$1.\text{E}-5 < \beta < 1$	0	16	BARTELT	87	SOUD
<1.E-10		1	all $\beta$	0		EBISU	87	INDU
<2.E-13			$1.\text{E}-4 < \beta < 6.\text{E}-4$	0		MASEK	87	HEPT
<2.E-14			$4.\text{E}-5 < \beta < 2.\text{E}-4$	0		NAKAMURA	87	PLAS
<2.E-14			$1.\text{E}-3 < \beta < 1$	0		NAKAMURA	87	PLAS
<5.E-14			$9.\text{E}-4 < \beta < 1.\text{E}-2$	0		SHEPKO	87	CNTR
<2.E-13			$4.\text{E}-4 < \beta < 1$	0		TSUKAMOTO	87	CNTR
<5.E-14		1	all $\beta$	1	20	CAPLIN	86	INDU
<5.E-12		1		0		CROMAR	86	INDU
<1.E-13		1	$7.\text{E}-4 < \beta$	0		HARA	86	CNTR
<7.E-11		1	all $\beta$	0		INCANDELA	86	INDU
<1.E-18			$4.\text{E}-4 < \beta < 1.\text{E}-3$	0	19	PRICE	86	MICA
<5.E-12		1		0		BERMON	85	INDU
<6.E-12		1		0		CAPLIN	85	INDU
<6.E-10		1		0		EBISU	85	INDU
<3.E-15		Caty	$5.\text{E}-5 \leq \beta \leq 1.\text{E}-3$	0	16	KAJITA	85	KAMI
<2.E-21		Caty	$\beta < 1.\text{E}-3$	0	16,21	KAJITA	85	KAMI
<3.E-15		Caty	$1.\text{E}-3 < \beta < 1.\text{E}-1$	0	16	PARK	85B	CNTR
<5.E-12		1	$1.\text{E}-4 < \beta < 1$	0		BATTISTONI	84	NUSX
<7.E-12		1		0		INCANDELA	84	INDU
<7.E-13		1	$3.\text{E}-4 < \beta$	0	18	KAJINO	84	CNTR
<2.E-12		1	$3.\text{E}-4 < \beta < 1.\text{E}-1$	0		KAJINO	84B	CNTR
<6.E-13		1	$5.\text{E}-4 < \beta < 1$	0		KAWAGOE	84	CNTR
<2.E-14			$1.\text{E}-3 < \beta$	0	16	KRISHNA...	84	CNTR
<4.E-13		1	$6.\text{E}-4 < \beta < 2.\text{E}-3$	0		LISS	84	CNTR
<1.E-16			$3.\text{E}-4 < \beta < 1.\text{E}-3$	0	19	PRICE	84	MICA
<1.E-13		1	$1.\text{E}-4 < \beta$	0		PRICE	84B	PLAS
<4.E-13		1	$6.\text{E}-4 < \beta < 2.\text{E}-3$	0		TARLE	84	CNTR
				7	22	ANDERSON	83	EMUL
<4.E-13		1	$1.\text{E}-2 < \beta < 1.\text{E}-3$	0		BARTELT	83B	CNTR

<1.E−12		1	$7.E−3 < \beta < 1$	0	BARWICK	83	PLAS
<3.E−13		1	$1.E−3 < \beta < 4.E−1$	0	BONARELLI	83	CNTR
<3.E−12		Caty	$5.E−4 < \beta < 5.E−2$	0	<sup>16</sup> BOSETTI	83	CNTR
<4.E−11		1		0	CABRERA	83	INDU
<5.E−15		1	$1.E−2 < \beta < 1$	0	DOKE	83	PLAS
<8.E−15		Caty	$1.E−4 < \beta < 1.E−1$	0	<sup>16</sup> ERREDE	83	IMB
<5.E−12		1	$1.E−4 < \beta < 3.E−2$	0	GROOM	83	CNTR
<2.E−12			$6.E−4 < \beta < 1$	0	MASHIMO	83	CNTR
<1.E−13		1	$\beta = 3.E−3$	0	ALEXEYEV	82	CNTR
<2.E−12		1	$7.E−3 < \beta < 6.E−1$	0	BONARELLI	82	CNTR
6.E−10		1	all $\beta$	1	<sup>23</sup> CABRERA	82	INDU
<2.E−11			$1.E−2 < \beta < 1.E−1$	0	MASHIMO	82	CNTR
<2.E−15			concentrator	0	BARTLETT	81	PLAS
<1.E−13	>1		$1.E−3 < \beta$	0	KINOSHITA	81B	PLAS
<5.E−11	<E17		$3.E−4 < \beta < 1.E−3$	0	ULLMAN	81	CNTR
<2.E−11			concentrator	0	BARTLETT	78	PLAS
1.E−1	>200	2		1	<sup>24</sup> PRICE	75	PLAS
<2.E−13		>2		0	FLEISCHER	71	PLAS
<1.E−19		>2	obsidian, mica	0	FLEISCHER	69C	PLAS
<5.E−15	<15	<3	concentrator	0	CARITHERS	66	ELEC
<2.E−11		<1−3	concentrator	0	MALKUS	51	EMUL

<sup>1</sup> 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.

<sup>2</sup> 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.

<sup>3</sup> 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.

<sup>4</sup> 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.

<sup>5</sup> Beyond the monopole speed, the limits of AARTSEN 14 depend on the catalysis cross section ( $\sigma$ ) which corresponds to the monopole radiating  $\hat{\Gamma}$  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  $\hat{\Gamma} = 30$ .

<sup>6</sup> 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.

<sup>7</sup> ADRIAN-MARTINEZ 12A measurements were based on a Cherenkov signature in an underwater telescope in the Western Mediterranean Sea. Limits are speed-dependent.

<sup>8</sup> 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.

<sup>9</sup> 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.

<sup>10</sup> 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  $M > 5 \times 10^{13}$  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  $M > 1 \times 10^9$  GeV.

<sup>11</sup> 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.

- <sup>12</sup> 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  $4250 \text{ m}^2 \text{ sr}$ .
- <sup>13</sup> 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.
- <sup>14</sup> 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.
- <sup>15</sup> AHLEN 94 limit for dyons extends down to  $\beta=0.9\text{E}-4$  and a limit of  $1.3\text{E}-14$  extends to  $\beta = 0.8\text{E}-4$ . 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.
- <sup>16</sup> Catalysis of nucleon decay; sensitive to assumed catalysis cross section.
- <sup>17</sup> ORITO 91 limits are functions of velocity. Lowest limits are given here.
- <sup>18</sup> Used DKMPR mechanism and Penning effect.
- <sup>19</sup> Assumes monopole attaches fermion nucleus.
- <sup>20</sup> 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.
- <sup>21</sup> Based on lack of high-energy solar neutrinos from catalysis in the sun.
- <sup>22</sup> Anomalous long-range  $\alpha$  ( $^4\text{He}$ ) tracks.
- <sup>23</sup> CABRERA 82 candidate event has single Dirac charge within  $\pm 5\%$ .
- <sup>24</sup> 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

<i>FLUX</i> ( $\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$ )	<i>MASS</i> (GeV)	<i>CHG</i> (g)	<i>COMMENTS</i> ( $\beta = v/c$ )	<i>DOCUMENT ID</i>	<i>TECN</i>
<1.3E-20			faint white dwarf	<sup>1</sup> FREESE 99	ASTR
<1.E-16	E17	1	galactic field	<sup>2</sup> ADAMS 93	COSM
<1.E-23			Jovian planets	<sup>1</sup> ARAFUNE 85	ASTR
<1.E-16	E15		solar trapping	BRACCI 85B	ASTR
<1.E-18		1		<sup>1</sup> HARVEY 84	COSM
<3.E-23			neutron stars	KOLB 84	ASTR
<7.E-22			pulsars	<sup>1</sup> FREESE 83B	ASTR
<1.E-18	<E18	1	intergalactic field	<sup>1</sup> REPHAELI 83	COSM
<1.E-23			neutron stars	<sup>1</sup> DIMOPOUL... 82	COSM
<5.E-22			neutron stars	<sup>1</sup> KOLB 82	COSM
<5.E-15	>E21		galactic halo	SALPETER 82	COSM
<1.E-12	E19	1	$\beta=3.E-3$	<sup>3</sup> TURNER 82	COSM
<1.E-16		1	galactic field	PARKER 70	COSM

<sup>1</sup> Catalysis of nucleon decay.

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

<sup>3</sup> Re-evaluates PARKER 70 limit for GUT monopoles.

**Monopole Density — Matter Searches**

<u>DENSITY</u>	<u>CHG (g)</u>	<u>MATERIAL</u>	<u>DOCUMENT ID</u>	<u>TECN</u>
<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	<sup>1</sup> EBISU 87	INDU
<4.6E−6/gram	> 0.5	deep schist	KOVALIK 86	INDU
<1.6E−6/gram	> 0.5	manganese nodules	<sup>2</sup> 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

<sup>1</sup> Mass  $1 \times 10^{14}$ – $1 \times 10^{17}$  GeV.<sup>2</sup> 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**

<u>DENSITY</u>	<u>CHG (g)</u>	<u>MATERIAL</u>	<u>DOCUMENT ID</u>	<u>TECN</u>
<1.E−9/gram	1	sun, catalysis	<sup>1</sup> 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 <sup>3</sup>		moon wake	SCHATTEN 70	ELEC

<sup>1</sup> Catalysis of nucleon decay.**REFERENCES FOR Magnetic Monopole Searches**

ACERO 21	PR D103 012007	M.A. Acero <i>et al.</i>	(NOvA Collab.)
AAD 20G	PRL 124 031802	G. Aad <i>et al.</i>	(ATLAS Collab.)
ACHARYA 19B	PRL 123 021802	B. Acharya <i>et al.</i>	(MoEDAL Collab.)
ACHARYA 18A	PL B782 510	B. Acharya <i>et al.</i>	(MoEDAL Collab.)
ACHARYA 17	PRL 118 061801	B. Acharya <i>et al.</i>	(MoEDAL Collab.)
ALBERT 17	JHEP 1707 054	A. Albert <i>et al.</i>	(ANTARES Collab.)
GOULD 17	PRL 119 241601	O. Gould, A. Rajantie	
AAB 16	PR D94 082002	A. Aab <i>et al.</i>	(Pierre Auger Collab.)
AAD 16AB	PR D93 052009	G. Aad <i>et al.</i>	(ATLAS Collab.)
AARTSEN 16B	EPJ C76 133	M.G. Aartsen <i>et al.</i>	(IceCube Collab.)
ACHARYA 16	JHEP 1608 067	B. Acharya <i>et al.</i>	(MoEDAL Collab.)
AARTSEN 14	EPJ C74 2938	M.G. Aartsen <i>et al.</i>	(IceCube Collab.)
Also	EPJ C79 124 (errat.)	M.G. Aartsen <i>et al.</i>	(IceCube Collab.)
ABBASI 13	PR D87 022001	R. Abbasi <i>et al.</i>	(IceCube Collab.)
BENDTZ 13	PRL 110 121803	K. Bendtz <i>et al.</i>	
AAD 12CS	PRL 109 261803	G. Aad <i>et al.</i>	(ATLAS Collab.)
ADRIAN-MAR...12A	ASP 35 634	S. Adrian-Martinez <i>et al.</i>	(ANTARES Collab.)
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DETRIXHE 11	PR D83 023513	M. Detrixhe <i>et al.</i>	(ANITA Collab.)
ABBASI 10A	EPJ C69 361	R. Abbasi <i>et al.</i>	(IceCube Collab.)
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BALESTRA 08	EPJ C55 57	S. Balestra <i>et al.</i>	(SLIM Collab.)
HOGAN 08	PR D78 075031	D.P. Hogan <i>et al.</i>	(KANS, NEBR, DELA)

ABULENCIA	06K	PRL 96 201801	A. Abulencia <i>et al.</i>	(CDF Collab.)
AKTAS	05A	EPJ C41 133	A. Aktas <i>et al.</i>	(H1 Collab.)
KALBFLEISCH	04	PR D69 052002	G.R. Kalbfleisch <i>et al.</i>	(OKLA)
AMBROSIO	02B	EPJ C25 511	M. Ambrosio <i>et al.</i>	(MACRO Collab.)
AMBROSIO	02C	EPJ C26 163	M. Ambrosio <i>et al.</i>	(MACRO Collab.)
AMBROSIO	02D	ASP 18 27	M. Ambrosio <i>et al.</i>	(MACRO Collab.)
KALBFLEISCH	00	PRL 85 5292	G.R. Kalbfleisch <i>et al.</i>	
FREESE	99	PR D59 063007	K. Freese, E. Krasteva	
ABBOTT	98K	PRL 81 524	B. Abbott <i>et al.</i>	(D0 Collab.)
AMBROSIO	97	PL B406 249	M. Ambrosio <i>et al.</i>	(MACRO Collab.)
HE	97	PRL 79 3134	Y.D. He	(UCB)
ACCIARRI	95C	PL B345 609	M. Acciarri <i>et al.</i>	(L3 Collab.)
JEON	95	PRL 75 1443	H. Jeon, M.J. Longo	(MICH)
Also		PRL 76 159 (erratum)	H. Jeon, M.J. Longo	
AHLEN	94	PRL 72 608	S.P. Ahlen <i>et al.</i>	(MACRO Collab.)
BARISH	94	PRL 73 1306	B.C. Barish, G. Giacomelli, J.T. Hong	(CIT+)
BECKER-SZ...	94	PR D49 2169	R.A. Becker-Szendy <i>et al.</i>	(IMB Collab.)
PRICE	94	PRL 73 1305	P.B. Price	(UCB)
ADAMS	93	PRL 70 2511	F.C. Adams <i>et al.</i>	(MICH, FNAL)
PINFOLD	93	PL B316 407	J.L. Pinfold <i>et al.</i>	(ALBE, HARV, MONT+)
KINOSHITA	92	PR D46 881	K. Kinoshita <i>et al.</i>	(HARV, BGNA, REHO)
THRON	92	PR D46 4846	J.L. Thron <i>et al.</i>	(SOUDAN-2 Collab.)
GARDNER	91	PR D44 622	R.D. Gardner <i>et al.</i>	(STAN)
HUBER	91	PR D44 636	M.E. Huber <i>et al.</i>	(STAN)
ORITO	91	PRL 66 1951	S. Orito <i>et al.</i>	(ICEPP, WASCR, NIHO, ICRR)
BERMON	90	PRL 64 839	S. Bermon <i>et al.</i>	(IBM, BNL)
BERTANI	90	EPL 12 613	M. Bertani <i>et al.</i>	(BGNA, INFN)
BEZRUKOV	90	SJNP 52 54	L.B. Bezrukov <i>et al.</i>	(INRM)
		Translated from YAF 52 86.		
BUCKLAND	90	PR D41 2726	K.N. Buckland <i>et al.</i>	(UCSD)
GHOSH	90	EPL 12 25	D.C. Ghosh, S. Chatterjea	(JADA)
HUBER	90	PRL 64 835	M.E. Huber <i>et al.</i>	(STAN)
PRICE	90	PRL 65 149	P.B. Price, J. Guiru, K. Kinoshita	(UCB, HARV)
KINOSHITA	89	PL B228 543	K. Kinoshita <i>et al.</i>	(HARV, TISA, KEK+)
BRAUNSCH...	88B	ZPHY C38 543	R. Braunschweig <i>et al.</i>	(TASSO Collab.)
KINOSHITA	88	PRL 60 1610	K. Kinoshita <i>et al.</i>	(HARV, TISA, KEK+)
BARISH	87	PR D36 2641	B.C. Barish, G. Liu, C. Lane	(CIT)
BARTELT	87	PR D36 1990	J.E. Bartelt <i>et al.</i>	(Soudan Collab.)
Also		PR D40 1701 (erratum)	J.E. Bartelt <i>et al.</i>	(Soudan Collab.)
EBISU	87	PR D36 3359	T. Ebisu, T. Watanabe	(KOBE)
Also		JP G11 883	T. Ebisu, T. Watanabe	(KOBE)
GENTILE	87	PR D35 1081	T. Gentile <i>et al.</i>	(CLEO Collab.)
GUY	87	NAT 325 463	J. Guy	(LOIC)
MASEK	87	PR D35 2758	G.E. Masek <i>et al.</i>	(UCSD)
NAKAMURA	87	PL B183 395	S. Nakamura <i>et al.</i>	(INUS, WASCR, NIHO)
PRICE	87	PRL 59 2523	P.B. Price, R. Guoxiao, K. Kinoshita	(UCB, HARV)
SCHOUTEN	87	JP E20 850	J.C. Schouten <i>et al.</i>	(LOIC)
SHEPKO	87	PR D35 2917	M.J. Shepko <i>et al.</i>	(TAMU)
TSUKAMOTO	87	EPL 3 39	T. Tsukamoto <i>et al.</i>	(ICRR)
CAPLIN	86	NAT 321 402	A.D. Caplin <i>et al.</i>	(LOIC)
Also		JP E20 850	J.C. Schouten <i>et al.</i>	(LOIC)
Also		NAT 325 463	J. Guy	(LOIC)
CROMAR	86	PRL 56 2561	M.W. Cromar, A.F. Clark, F.R. Fickett	(NBSB)
HARA	86	PRL 56 553	T. Hara <i>et al.</i>	(ICRR, KYOT, KEK, KOBE+)
INCANDELA	86	PR D34 2637	J. Incandela <i>et al.</i>	(CHIC, FNAL, MICH)
KOVALIK	86	PR A33 1183	J.M. Kovalik, J.L. Kirschvink	(CIT)
PRICE	86	PRL 56 1226	P.B. Price, M.H. Salamon	(UCB)
ARAFUNE	85	PR D32 2586	J. Arafune, M. Fukugita, S. Yanagita	(ICRR, KYOTU+)
BERMON	85	PRL 55 1850	S. Bermon <i>et al.</i>	(IBM)
BRACCI	85B	NP B258 726	L. Bracci, G. Fiorentini, G. Mezzorani	(PISA+)
Also		LNC 42 123	L. Bracci, G. Fiorentini	(PISA)
CAPLIN	85	NAT 317 234	A.D. Caplin <i>et al.</i>	(LOIC)
EBISU	85	JP G11 883	T. Ebisu, T. Watanabe	(KOBE)
KAJITA	85	JPSJ 54 4065	T. Kajita <i>et al.</i>	(ICRR, KEK, NIIG)
PARK	85B	NP B252 261	H.S. Park <i>et al.</i>	(IMB Collab.)
BATTISTONI	84	PL 133B 454	G. Battistoni <i>et al.</i>	(NUSEX Collab.)
FRYBERGER	84	PR D29 1524	D. Fryberger <i>et al.</i>	(SLAC, UCB)
HARVEY	84	NP B236 255	J.A. Harvey	(PRIN)
INCANDELA	84	PRL 53 2067	J. Incandela <i>et al.</i>	(CHIC, FNAL, MICH)
KAJINO	84	PRL 52 1373	F. Kajino <i>et al.</i>	(ICRR)
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KAWAGOE	84	LNC 41 315	K. Kawagoe <i>et al.</i>	(TOKY)
KOLB	84	APJ 286 702	E.W. Kolb, M.S. Turner	(FNAL, CHIC)
KRISHNA...	84	PL 142B 99	M.R. Krishnaswamy <i>et al.</i>	(TATA, OSKC+)
LISS	84	PR D30 884	T.M. Liss, S.P. Ahlen, G. Tarle	(UCB, IND+)
PRICE	84	PRL 52 1265	P.B. Price <i>et al.</i>	(ROMA, UCB, IND+)
PRICE	84B	PL 140B 112	P.B. Price	(CERN)
TARLE	84	PRL 52 90	G. Tarle, S.P. Ahlen, T.M. Liss	(UCB, MICH+)
ANDERSON	83	PR D28 2308	S.N. Anderson <i>et al.</i>	(WASH)
ARAFUNE	83	PL 133B 380	J. Arafune, M. Fukugita	(ICRR, KYOTU)
AUBERT	83B	PL 120B 465	B. Aubert <i>et al.</i>	(CERN, LAPP)
BARTELT	83B	PRL 50 655	J.E. Bartelt <i>et al.</i>	(MINN, ANL)
BARWICK	83	PR D28 2338	S.W. Barwick, K. Kinoshita, P.B. Price	(UCB)
BONARELLI	83	PL 126B 137	R. Bonarelli, P. Capiluppi, I. d'Antone	(BGNA)
BOSETTI	83	PL 133B 265	P.C. Bosetti <i>et al.</i>	(AACH3, HAWA, TOKY)
CABRERA	83	PRL 51 1933	B. Cabrera <i>et al.</i>	(STAN)
DOKE	83	PL 129B 370	T. Doke <i>et al.</i>	(WASU, RIKK, TTAM, RIKEN)
ERREDE	83	PRL 51 245	S.M. Errede <i>et al.</i>	(IMB Collab.)
FREESE	83B	PRL 51 1625	K. Freese, M.S. Turner, D.N. Schramm	(CHIC)
GROOM	83	PRL 50 573	D.E. Groom <i>et al.</i>	(UTAH, STAN)
MASHIMO	83	PL 128B 327	T. Mashimo <i>et al.</i>	(ICEPP)
MIKHAILOV	83	PL 130B 331	V.F. Mikhailov	(KAZA)
MUSSET	83	PL 128B 333	P. Musset, M. Price, E. Lohrmann	(CERN, HAMB)
REPHAELI	83	PL 121B 115	Y. Rephaeli, M.S. Turner	(CHIC)
SCHATTEN	83	PR D27 1525	K.H. Schatten	(NASA)
ALEXEYEV	82	LNC 35 413	E.N. Alekseev <i>et al.</i>	(INRM)
BONARELLI	82	PL 112B 100	R. Bonarelli <i>et al.</i>	(BGNA)
CABRERA	82	PRL 48 1378	B. Cabrera	(STAN)
DELL	82	NP B209 45	G.F. Dell <i>et al.</i>	(BNL, ADEL, ROMA)
DIMOPOUL...	82	PL 119B 320	S. Dimopoulos, J. Preskill, F. Wilczek	(HARV+)
KINOSHITA	82	PRL 48 77	K. Kinoshita, P.B. Price, D. Fryberger	(UCB+)
KOLB	82	PRL 49 1373	E.W. Kolb, S.A. Colgate, J.A. Harvey	(LASL, PRIN)
MASHIMO	82	JPSJ 51 3067	T. Mashimo, K. Kawagoe, M. Koshiba	(INUS)
SALPETER	82	PRL 49 1114	E.E. Salpeter, S.L. Shapiro, I. Wasserman	(CORN)
TURNER	82	PR D26 1296	M.S. Turner, E.N. Parker, T.J. Bogdan	(CHIC)
BARTLETT	81	PR D24 612	D.F. Bartlett <i>et al.</i>	(COLO, GESC)
KINOSHITA	81B	PR D24 1707	K. Kinoshita, P.B. Price	(UCB)
ULLMAN	81	PRL 47 289	J.D. Ullman	(LEHM, BNL)
CARRIGAN	80	NAT 288 348	R.A. Carrigan	(FNAL)
BRODERICK	79	PR D19 1046	J.J. Broderick <i>et al.</i>	(VPI)
BARTLETT	78	PR D18 2253	D.F. Bartlett, D. Soo, M.G. White	(COLO, PRIN)
CARRIGAN	78	PR D17 1754	R.A. Carrigan, B.P. Strauss, G. Giacomelli	(FNAL+)
HOFFMANN	78	LNC 23 357	H. Hoffmann <i>et al.</i>	(CERN, ROMA)
PRICE	78	PR D18 1382	P.B. Price <i>et al.</i>	(UCB, HOUS)
HAGSTROM	77	PRL 38 729	R. Hagstrom	(LBL)
CARRIGAN	76	PR D13 1823	R.A. Carrigan, F.A. Nezrick, B.P. Strauss	(FNAL)
DELL	76	LNC 15 269	G.F. Dell <i>et al.</i>	(CERN, BNL, ROMA, ADEL)
ROSS	76	LBL-4665	R.R. Ross	(LBL)
STEVENS	76B	PR D14 2207	D.M. Stevens <i>et al.</i>	(VPI, BNL)
ZRELOV	76	CZJP B26 1306	V.P. Zrelov <i>et al.</i>	(JINR)
ALVAREZ	75	LBL-4260	L.W. Alvarez	(LBL)
BURKE	75	PL 60B 113	D.L. Burke <i>et al.</i>	(MICH)
CABRERA	75	Thesis	B. Cabrera	(STAN)
CARRIGAN	75	NP B91 279	R.A. Carrigan, F.A. Nezrick	(FNAL)
Also		PR D3 56	R.A. Carrigan, F.A. Nezrick	(FNAL)
EBERHARD	75	PR D11 3099	P.H. Eberhard <i>et al.</i>	(LBL, MPIM)
EBERHARD	75B	LBL-4289	P.H. Eberhard	(LBL)
FLEISCHER	75	PRL 35 1412	R.L. Fleischer, R.N.F. Walker	(GESC, WUSL)
FRIEDLANDER	75	PRL 35 1167	M.W. Friedlander	(WUSL)
GIACOMELLI	75	NC 28A 21	G. Giacomelli <i>et al.</i>	(BGNA, CERN, SACL+)
PRICE	75	PRL 35 487	P.B. Price <i>et al.</i>	(UCB, HOUS)
CARRIGAN	74	PR D10 3867	R.A. Carrigan, F.A. Nezrick, B.P. Strauss	(FNAL)
CARRIGAN	73	PR D8 3717	R.A. Carrigan, F.A. Nezrick, B.P. Strauss	(FNAL)
ROSS	73	PR D8 698	R.R. Ross <i>et al.</i>	(LBL, SLAC)
Also		PR D4 3260	P.H. Eberhard <i>et al.</i>	(LBL, SLAC)
Also		SCI 167 701	L.W. Alvarez <i>et al.</i>	(LBL, SLAC)
BARTLETT	72	PR D6 1817	D.F. Bartlett, M.D. Lahana	(COLO)
GUREVICH	72	PL 38B 549	I.I. Gurevich <i>et al.</i>	(KIAE, NOVO, SERP)
Also		JETP 34 917	L.M. Barkov, I.I. Gurevich, M.S. Zolotorev	(KIAE+)
Also		Translated from ZETF 61	1721.	
Also		PL 31B 394	I.I. Gurevich <i>et al.</i>	(KIAE, NOVO, SERP)
FLEISCHER	71	PR D4 24	R.L. Fleischer <i>et al.</i>	(GESC)

KOLM	71	PR D4 1285	H.H. Kolm, F. Villa, A. Odian	(MIT, SLAC)
PARKER	70	APJ 160 383	E.N. Parker	(CHIC)
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