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SEARCH FOR MAGNETIC MONOPOLES IN LUNAR MATERIAL USING AN ELECTROMAGNETIC DETECTOR*

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ABSTRACT

Our search for magnetic monopoles in lunar materials has been concluded with the exploration in April 1971 of an additional 11.5 kg of material returned by the Apollo 11, 12, and 14 missions, using a modified version of our electromagnetic detector. Again, no magnetic monopole was detected. Combining these results with the results of our previous experiment, we set an upper limit of $1.7\ 10^{-4}$ monopoles/g for the density of isolated monopoles in the lunar surface and update our upper limits set for the monopole flux in cosmic rays and for monopole pair production cross section.

INTRODUCTION

Our search for magnetic monopoles in 8 kg of lunar material has been reported.[1] The search has been continued in more lunar material returned by the Apollo 11, 12, and 14 missions. The result is still negative and the new experiment permits improvement of the upper limits derived in Ref. 1 for the monopole density in the lunar sample, for the monopole flux in cosmic rays, and for cross sections of pair production by incident cosmic-ray protons.

THE EXPERIMENT

The search technique was the same as the one used in Ref. 1. The lunar material was divided into 46 samples and the magnetic charge $\underline{g}$ of each sample was measured independently. The detector used to measure the magnetic charge has been modified in an attempt to save on liquid helium consumption but its principle is still the same, relying on the current change ΔI induced in a superconducting circuit traversed by a magnetically charged object. The circuit is represented schematically in Fig. 1 and described in more detail in a separate report.[2] A very sensitive magnetometer consisting of a SQUID[3] coupled to a 1000-turn coil is used now to measure the current change in the circuit.

Certain values of ΔI cannot be detected because of the noise in the magnetometer signal and because its response is a periodic function of ΔI. Therefore, to minimize the domain of undetected charges, several tests with different numbers of passes N_p were needed. We used a series $N_p = 1, 2, 4, 8$, and 16. However, there are two distinct regions of magnetic charge that would have escaped detection and hence this fact restricts the range of magnetic charge to which our search applies.

Restriction(a): Magnetic charges that are too small to give a signal larger than the noise. Using an arbitrary criterion of five standard deviations of signal above noise, this amounts to a charge range of $g < 0.4\, g_0$, where g_0 is the minimum Dirac monopole charge:

$$g_0 = \frac{\hbar c}{2e} \qquad (1)$$

in Gaussian units.

Restriction(b): Magnetic charges that have just the right size to cause the magnetometer to show no change due to its periodic response. For our equipment this restriction amounts to $g \approx n \times 36.0 \times g_0$, where n is an integer and 36.0 is a property of our equipment.

Those restrictions are explained in more detail in Ref. 2. They do not appreciably affect the validity of our search, since any monopole compatible with Dirac's theory escapes restriction(a) and since restriction(b) applies only to magnetic charges of a considerable magnitude.

RESULTS

In Fig. 2, we plot the measured value, g_{meas}, of the magnetic charges g of each sample, determined by a least-squares technique using all measurements on a given sample. Within the error due to the magnetometer noise, it represents the value of the real magnetic charge modulo $36.0\, g_0$. Tables I to III list each sample with its NASA identification number, weight, nature, and magnetic charge as we have measured it.

From Fig. 2 one sees that we found no magnetic charges g_{meas} significantly different from zero in the samples. We conclude that there are no magnetic monopoles consistent with Dirac's theory [except possibly for restriction (b) above], or at least that the number of south and north poles are such that they cancel in each sample.

A small portion of the lunar material was also searched for monopoles of charge $36\, g_0$, using the detector in a desensitized mode as described in Ref. 2. This portion comprised samples 2, 17, and 19. The result was also compatible with a zero magnetic charge for each of the three samples. Here restriction(a) still applies but, combining the result of of the normal test procedure and the one due to the desensitized mode, we reduce restriction(b) to charges near multiples of $36\, g_0$ and $305\, g_0$ at the same time. That less-restrictive condition of our search applies to samples 2, 17, and 19 only.

INTERPRETATION

Combining these results and those reported in Ref. 1, we compute an upper limit for the density of monopoles in the lunar surface material. It is less than $1.7\ 10^{-4}$ monopoles/g for a 95% confidence level, using the same computation as in Ref. 1; i.e., including the correction for equal north- and south-pole charges in a sample.

From the upper limit of the density, we compute the upper limit for the flux of monopoles in cosmic rays as a function of energy for different values of N, the effective magnetic charge in units of g_0 as defined in Ref. 1. Also, the computation is described in Ref. 1. Adjustment for varying exposure ages of the samples has been made and all samples have been taken to have a mixing depth of 1000 g/cm^2.[4] Our upper limits for the monopole flux in cosmic rays together with comparable limits set by other experiments[7,8] using different techniques are shown on Fig. 3.

Because of the correlation between north- and south-pole density distributions when pairs of them are produced (as explained in Ref. 1), we compute the new limit for the monopole density due to pair production by incident cosmic ray protons, using only the 6.81 kg of fines from Apollo 14 materials, the 2.02 kg from Apollo 12, and the 7.9 kg from Apollo 11 analyzed in Ref. 1. That selection corresponds to an arbitrary size limit of less than 1 mm for particles in the samples used. The maximum density is then 2.0×10^{-4} monopoles for a 95% confidence level. Our upper limits for the cross section of pair production along with comparable limits set by other recent experiments[7-9] using different techniques are shown in Fig. 4.

In Ref. 1 (Table IV) we listed the properties assumed for the monopoles that condition their detection by our search; they are still valid here. In addition, there are the restrictions(a) and (b) mentioned above.

CONCLUSION

The lunar soil was a highly desirable place to search for magnetic monopoles, as evidenced by the limits placed on their production cross section in Fig. 4 from the analysis of about 20 kg of material. The search was carried out in such a way that even a single isolated monopole of the minimum charge compatible with the Dirac theory would have been unambiguously detected by its magnetic charge. The accumulated evidence against the existence of isolated magnetic monopoles is by now very great, and the hope to detect them can be heldout only in experiments even more sensitive than this one.

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Footnotes and References

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4. The exposure ages used were 500 (Ref. 1), 360 (Ref. 5), and 425 m.y. (Ref. 6) for Apollo 11, 12, and 14 samples respectively. (The estimated mixing depths using the published ages of crystalization were 1000 g/cm^2, 1260 g/cm^2, and 1275 g/cm^2 for Apollo 11, 12, and 14 respectively, so using 1000 g/cm^2 for the cutoff will make only a small change of our flux limits for high energy, and the reliability of the mixing depths is not certain enough to warrant their inclusion.)
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Table I. Apollo 14.

Sample Number	NASA Number	Weight (g)	Type[a]	g_{meas}[b]
1	14163.0	259.4	F	-.05
2	14163.0	230.9	F	.09
3	14163.0	299.5	F	.01
4	14163.0	142.9	F	-.02
5	14163.0	268.2	F	.01
6	14163.0	269.6	F	.02
7	14163.0	223.8	F	.00
8	14163.0	259.2	F	.00
9	14259.0	198.5	F	-.09
10	14259.0	215.1	F	.08
11	14259.0	199.0	F	.06
12	14259.0	224.6	F	.00
13	14163.0	250.6	F	-.02
14	14003.15	301.0	F	.04
15	14163.0	206.5	F	-.01
16	14259.0	198.1	F	-.06
17	14163.0	288.0	F	.07
18	14259.8	301.5	F	.05
19	14163.0	286.4	F	.01
20	14163.1	34.3	F	-.13
21	14259.0	207.3	F	-.10
22	14163.0	248.6	F	-.02
23	14163.0	232.3	F	-.02
24	14321.60	261.0	R	-.00
25	14259.0	196.1	F	.06
26	14003.16	301.0	F	.07
27	14259.0	192.5	F	-.01
28	14321.61	104.0	R	.04
29	14163.0	243.0	F	-.01
30	14163.0	238.8	F	.06
31	14163.0	263.2	F	.06

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[a] F stands for fine material of grain size less than 1 mm, R stands for rocks and chips.

[b] The units of g_{meas} are g_0 [see Eq. (1)].

Table II. Apollo 11.

Sample Number	NASA Number	Weight (g)	Type[a]	g^{b}_{meas}
32	10072.19	40.26	R	
	10017.74	107.52	R	
	10021.36	29.98	R	
	10061.2	32.89	R	
	10017.81	98.98	R	
	10085.105	28.13	R	
		337.76		.06
33	10019.31	29.66	R	
	10058.3	173.29	R	
	10085.101	26.03	R	
	10061.48	27.00	R	
	10044.15	39.74	R	
	10082.1	49.13	R	
		344.76		-.02
34	10057	35.50	R	
	10045.18	21.02	R	
	10002.22	46.05	R	
	10059.1	53.96	R	
	10100.2	22.98	R	
	10020.16	128.65	R	
		308.16		.12

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[a] F stands for fine material of grain size less than 1 mm, R stands for rocks and chips.

[b] The units of g_{meas} are g_0 [see Eq. (1)].

Table III. Apollo 12.

Sample Number	NASA Number	Weight (g)	Type[a]	g_{meas}[b]
35	12065.89	49.82	R	
	12001.98	32.90	F	
	12079.10	168.14	F	
	12021.151	.04	R	
	12021.152	7.32	R	
	12021.153	1.70	R	
	12021.159	.01	R	
	12033.1B	7.60	R	
	12059.0	58.35	F	
		325.88		.04
36	12021.75	3.40	R	
	12033.1D	3.50	R	
	12036.1	42.75	R	
	12021,123	106.21	R	
	12001.3	85.54	F	
	12044.0	70.11	F	
	12021.107	2.89	R	
	12077.0	21.25	R	
		335.65		.05
37	12021.158	.80	R	
	12033.1F	10.13	R	
	12037.4	36.36	F	
	1372	239.55	F	
		286.84		
38	12032.1	26.62	R	
	12021.110	4.04	R	
	12034.38	21.83	R	
	12035.7	21.61	R	
		74.10		-.06
39	12021.113	2.34	R	
	12053.74	35.76	R	
	12002.179	42.40	R	
	12051.21	26.22	R	
	12022.108	31.94	R	
	12021.100	2.46	R	
	1373 C	235.10	F	
		376.22		.14
40	12063.74	41.32	R	
	12021.128	3.50	R	
	12021.76	2.14	R	
	12076.4	28.80	R	
	12033.1A	2.42	R	
	12042.4	57.70	F	
	12021.74	3.92	R	
	1373 A	239.35	F	
		379.15		.13
41	12021.101	3.91	R	
	12033.3	23.00	R	
	12070.150	181.16	F	
	12033.2	22.40	R	
	12064.44	22.65	R	
	12060.0	22.18	R	
	12021.117	2.65	R	
		277.95		.05
42	12021.96	9.92	R	
	12021.127	4.01	R	
	12020.46	25.14	R	
	12038.76	36.43	R	
	12070.165	39.95	F	
	12070.138	156.40	F	
	12079.2	78.35	R	
		350.20		.10
43	12070.150	150.00	F	
	12008.2	30.30	R	
	12065.55	40.61	R	
	12022.91	88.82	R	
	12002.92	36.40	R	
	12002.183	26.33	R	
	12021.131	2.12	R	
		374.58		.00
44	12002.25	77.92	R	
	12021.15	23.75	R	
	12022.103	41.11	R	
	1373 B	227.08	F	
	12018.65	24.88	R	
	12063.118	27.06	R	
	12021.119	3.40	R	
		425.20		.08
45	12021.115	1.83	R	
	12003.29	46.28	F	
	12021.54	29.96	R	
	12021.121	2.40	R	
	12051.63	28.78	R	
	12021.35	2.77	R	
	1377	32.57	R	
		144.59		.07
46	12021.64	39.58	R	.05

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[a] F stands for fine material of grain size less than 1 mm, R stands for rocks and chips.

[b] The units of g_{meas} are g_0 [see Eq.(1)].

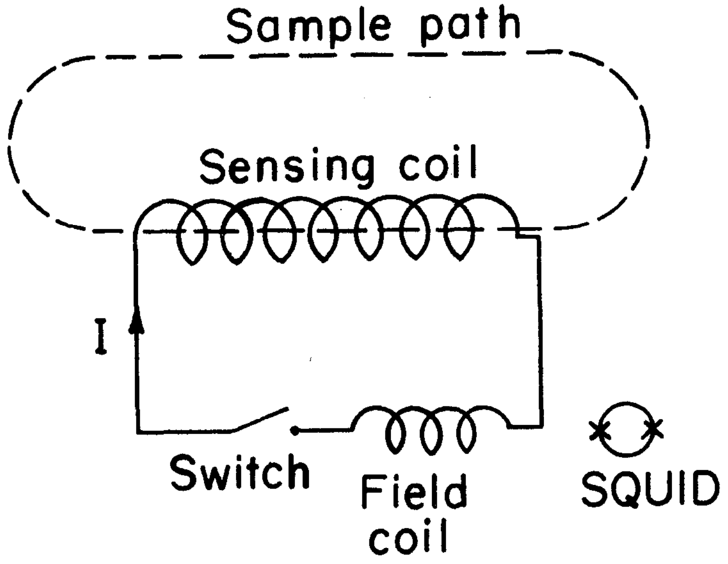
Figure Captions

Fig. 1. Sample path through the superconducting loop used for magnetic charge measurement. Current change is measured by the coupling of a 1000-turn field coil to the SQUID.[2]

Fig. 2. Magnetic-charge measurements of samples 1 through 46 of Tables I through III.

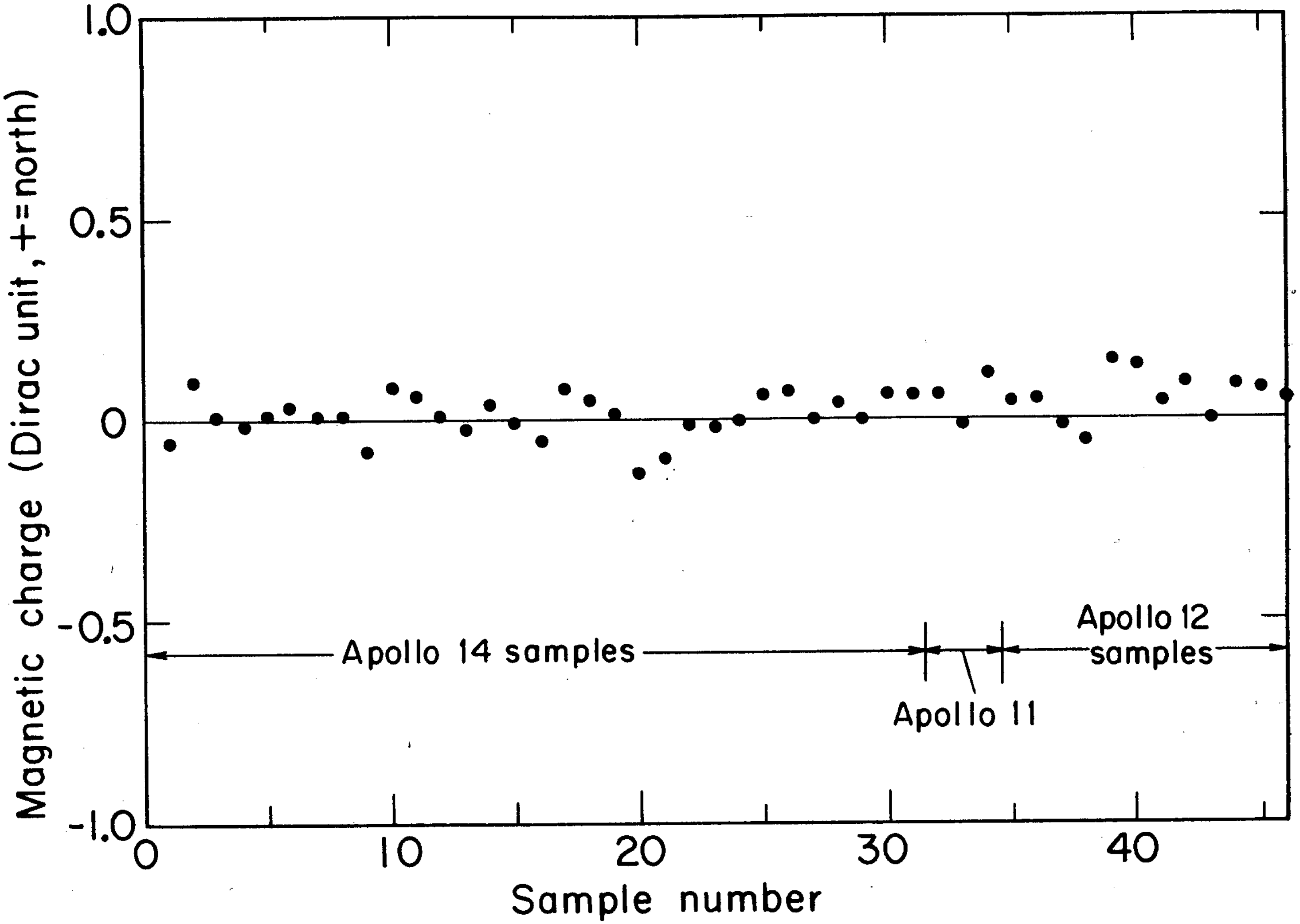
Fig. 3. Upper limit (95% confidence level) on the flux of cosmic monopoles as determined in recent monopole searches. A from this work, B from Ref. 7, C from Ref. 8.

Fig. 4. Upper limit (95% confidence level) on monopole pair-production cross section in proton-nucleon collisions as determined in recent monopole searches. A from this work, B from Ref. 7, C from Ref. 8, D from Ref. 9.



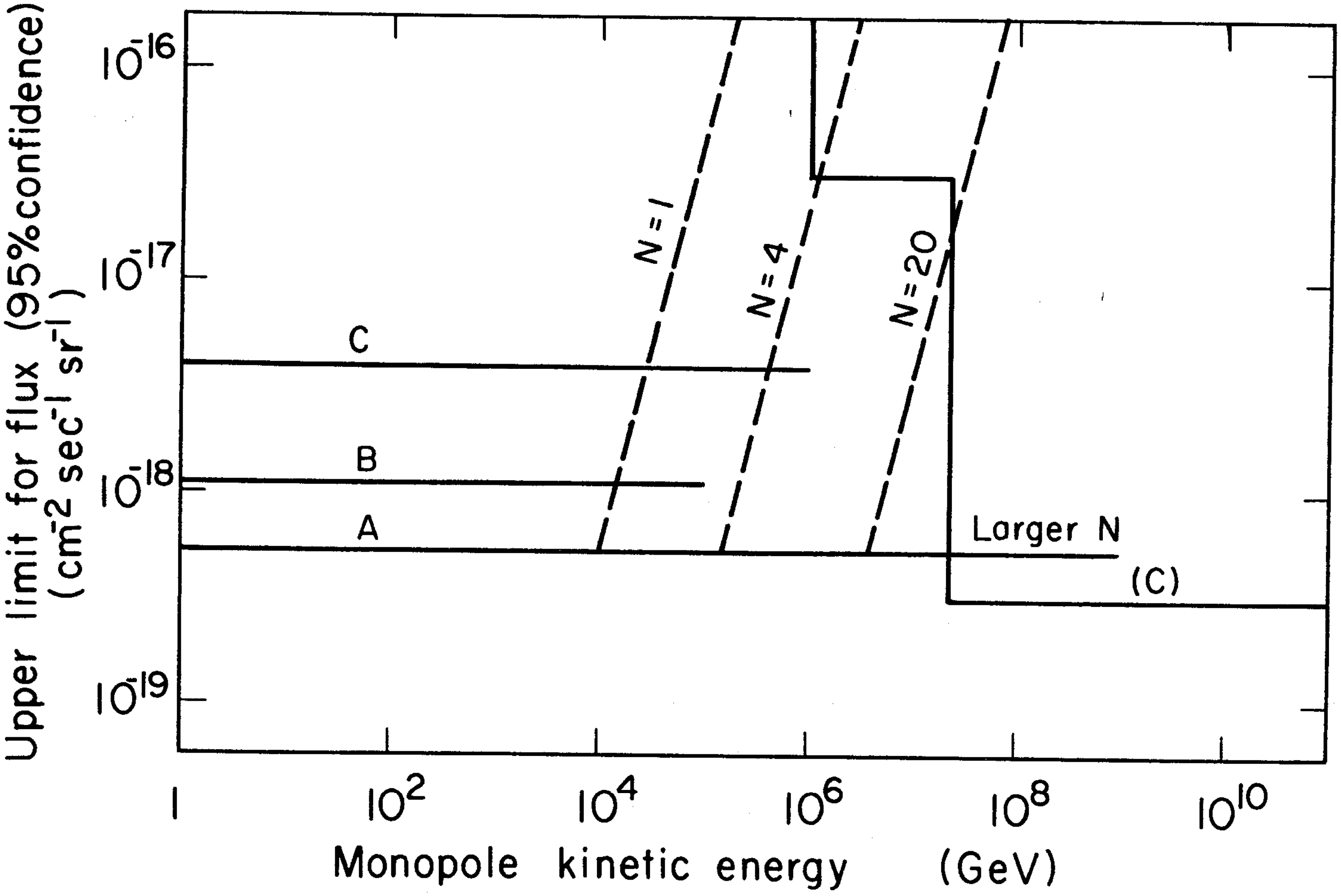
XBL733-2557

Fig. 1



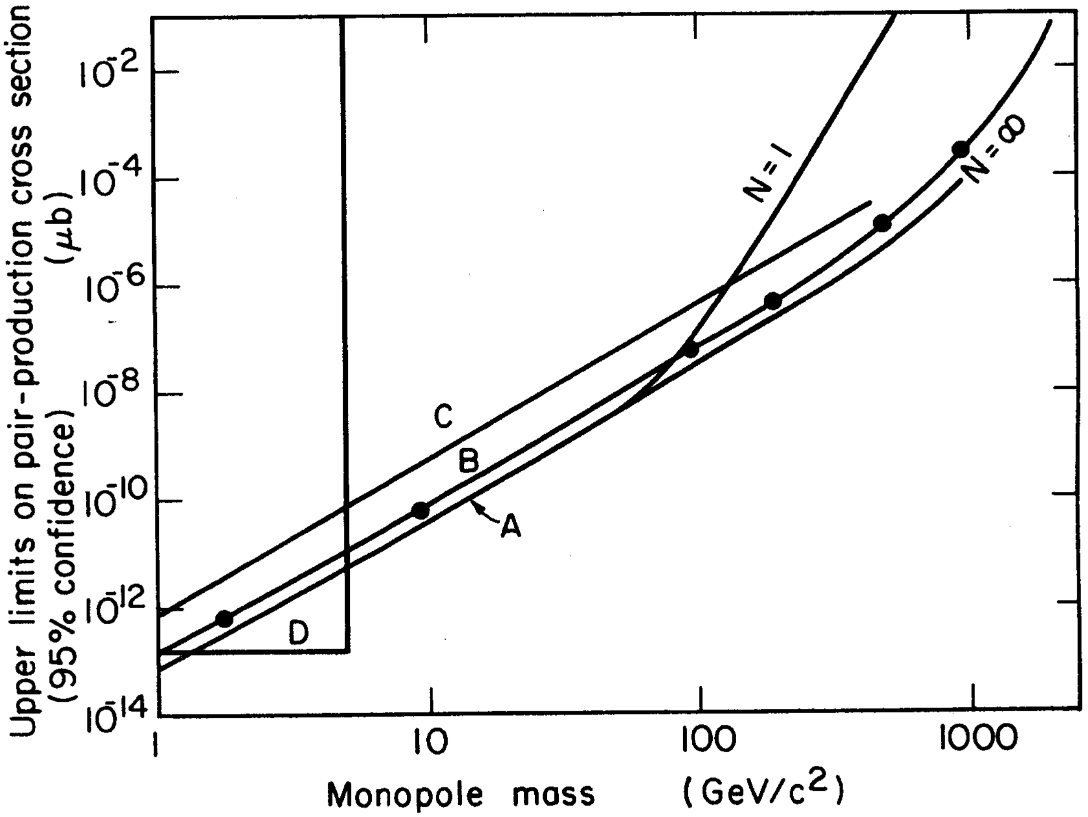
XBL733-2558

Fig. 2



XBL733-2559

Fig. 3



XBL733-2560

Fig. 4