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Limits on Monopole Production in *pp* and Heavy Ion Collisions Derived from Cosmic Ray Flux Limits

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Abstract

Limits on monopole production in *pp* and heavier ion collisions are derived from the results of searches for naturally occuring monopoles. The monopoles would be produced by high energy cosmic rays interacting with the upper atmosphere, and detected by track etch detectors on the surface. By combining the limits from these track etch detectors with the known flux and composition of cosmic rays, it is possible to derive limits on monopole production in *pp* and heavy ion collisions.

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Over the past decade, monopole searches have been done at each new accelerator commissioned. Most recently, at the Fermilab collider, Price and collaborators set a limit $\sigma(M) < 1.2 \times 10^{-33}\text{cm}^{-2}$ in $p\bar{p}$ collisions at 1.8 TeV.[1]

However, it is also possible to find cross section limits using the naturally occuring cosmic ray flux. Because cosmic rays extend up to extremely high energies, and because passive experiments can be left exposed for long periods of time, these limits extend to energies currently inaccessible at accelerators, despite the relatively low cosmic ray flux.

A number of early experiments considered this possibility. Carithers and collaborators[2] set limits on monopole production in cosmic rays. Their experiment was designed to search for monopoles weighing a few GeV/c^2, that would thermalize by dE/dx while still in the atmosphere, and could be collected by a magnetic field. The heavier monopoles considered here will not thermalize in the atmosphere. E. Goto and collaborators[3] searched for monopoles on the surface of an exposed iron outcropping and in meteorites. This search was also optimized for lighter monopoles; monopoles above 50 GeV/c^2 mass would penetrate deeper into the rock, or through the meteorite and out the other side.

Fleischer and collaborators[4] searched for monopoles in manganese crust from the sea floor. They targeted primoridial or cosmic ray produced monopoles that could have thermalized in the atmosphere or the ocean, sunk and been magnetically captured by the manganese. Any monopoles should be extracted from the pulverized nodules with a magnetic field, pulling the monopoles out of the sample and into a track etch detector. While they obtained excellent limits, these limits are subject to a number of assumptions and systematic uncertainties regarding monopole capture by the nodules and extraction from the crushed nodules. There are also a number of more recent results which cast some uncertainty on the detection of short tracks and tracks from low velocity monopoles in track etch detectors.[5]

Ross *et al.* made a similar search in moon rocks,[6] passing rock samples through

a superconducting loop. Although their detection method was very clean, the experiment was subject to similar assumptions about monopole penetration and capture in the moon rock. All of these experimenters assumed that cosmic rays were composed mainly of protons, and used fluxes that differ in varying amounts from currently accepted values

The best direct cosmic ray limit on fast monopoles was obtained by Doke and collaborators,[7] who exposed 100 m^2 of nitrocellulose track etch detectors for a 3.3 year exposure to search for monopoles with velocities $\beta > 0.01$. They found that the flux of monopoles was less than $5.2 \times 10^{-15} cm^{-2} s^{-1} sr^{-1}$ at a 90% confidence level. The exposure was at Kitami, in Hokkaido, Japan, near sea level, with an atmospheric overburden of about 1030 g/cm^2.

This limit must be compared with the known cosmic ray flux. In the range of 10^{15} to 10^{20} eV, the flux is

$$\frac{dN}{dE} = \frac{8.0 \times 10^{20}}{E^3} cm^{-2} s^{-1} sr^{-1} eV^{-2}.$$ [8] [9]

The region below 10^{15} eV is within reach of current collider experiments, while above 10^{20} eV, the cosmic ray spectrum may die out. At 10^{14} eV, cosmic rays are about 1/3 proton, 1/3 alpha particles, and 1/3 heavier elements.[10] At higher energies, it appears that the proportion of heavy elements may increase somewhat,[11] but at a slow enough rate to neglect here. Counting feedown from the heavier nuclei (a 1 TeV alpha particle is equivalent to 4 250 GeV nucleons), the net nucleon flux is 45% of the total cosmic ray flux. Here, we will assume that the monopoles are produced via the strong interaction, and thus protons and neutrons are equivalent, so the 13% neutron component will be lumped in with the protons Countering this decrease is the fact that incoming cosmic rays do not lose all of their energy in their first collision; secondary collisions occur at a degraded energy. This partial elasticity enhances the effective flux for cross section measurements by 40%.[2]

Including these effects, the integrated flux:

$$\Phi(E > E_c) = \frac{2.5 \times 10^{20}}{E_c^2} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{eV}^{-1}$$

Although the produced monpoles are relativistic, monopole dE/dx depends on both mass and velocity,[12] and even highly relativistic lighter monpoles may thermalize in the atmosphere. Here, we will consider monopoles with masses of at least 50 GeV/c^2, assuming that lower mass monopoles would already have been discovered. A 50 GeV/c^2 Dirac monopole would have to start with at least 30 TeV of kinetic energy to pass through the atmosphere at a 75 degree zenith angle (3800 g/cm^2) and reach the detector with $\beta \sim 0.04$. This 75 degree cut reduces the solid angle used by Doke and collaborators 22%, increasing their limit to $6.7 \times 10^{-15}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ at a 90% confidence level. Depending on its charge and trajectory, the monopole will also gain or lose up to 4 TeV from its interaction with the earths' magnetic field. Heavier monopoles with the same kinetic energy will have a lower $\beta\gamma$ and hence lose less energy. At 10^{15} eV (1 TeV in the center of mass), a 50 GeV/c^2 mass monopoles will reach the surface with $\beta \sim 0.04$ if it retains 3% of the energy of the incoming proton that produces it. Although the fragmentation function for collisions involving monopoles is unknown, for heavy hadrons this would be a very loose restriction. A comparable case would be production of a 3 GeV/c momentum $b\bar{b}$ quark pair in a 1 TeV collision. If lighter monopoles become interesting, experiments at higher altitudes[13] can reach lower masses than sea level experiments.

Taking the monopole flux limit above, dividing by two because monopoles are produced in pairs and dividing by the proton flux gives:

$$\frac{\sigma(pN \rightarrow MX)}{\sigma(pN)} < 1.3 \times 10^{-35} E^2(\mathrm{eV})$$

at a 90% confidence level. $\sigma(pN)$ is the total cross section and N represents the 80% nitrogen 20% oxygen target.

Since production of a 50 GeV/c^2 monopole is a hard process, the fact that the target is air, rather than a free proton will have little effect,[14] so nuclear effects will be neglected in the following. Then, the center of mass energy is $E_{\rm cm} = \sqrt{2Em_p}$, giving

$$\frac{\sigma(pN \rightarrow MX)}{\sigma(pN)} < 3.7 \times 10^{-6} E_{\rm cm}^4 (\text{TeV}).$$

TeV units was used for ease of comparison with accelerator results. This limit is shown in Figure 1. At 1 TeV, monopoles are produced in less than 3.7 collisions per million. At 10 TeV, the limit rises to 3.7% of all collisions. A limit of 1 monopole pair per collision occurs at 22 TeV.

To find a cross section limit, it is necessary to divide by the total *pp* inelastic cross section which is about 50 mb at 1 TeV, and rises to about 100 mb at 10^6 TeV.[8] The 10^6 TeV cross section has significant uncertainty; for conservatism, we shall use the lower cross section at all energies. Then,

$$\sigma(pp \rightarrow MX) < 1.9 \times 10^{-31} E_{\rm cm}^4 (\text{TeV}) \text{ cm}^2$$

again for monopoles heavier than 50 GeV/c^2, and center of mass energies above 1 TeV. If the concentration technique presented by Fleisher *et al.*is valid, then these limits are a factor of about 1000 lower.

Monopoles could also be produced in heavy ion collisions, perhaps via an electromagnetic interaction. As was previously discussed, the flux of heavier nuclei (carbon or heavier)is comparable to the proton flux. Because the specific nuclei involved are poorly known, a 12 GeV mass (carbon) will be used in here; heavier nuclei give tighter limits. Then, taking 1/3 of the cosmic ray flux to be heavy nuclei,

$$\frac{\sigma(NN \rightarrow MX)}{\sigma(NN)} < 4.9 \times 10^{-8} E_{\rm cm}^4 (\text{TeV})$$

where N represents a generic heavy nucleus. Since the target mass is heavier, for a given energy the heavy nuclei limits are lower than the *pp* limits, as shown in

figure 1. Because $\sigma(NN)$ depends on the nuclear species, this will not be turned into an absolute limit.

The chances of improving these limits in the near future are limited. Future large scale monopole experiments are being done underground,[15] beyond the reach of cosmic ray produced monopoles. However, it is possible that a MILAGRO,[16] a proposed 5000 m^2 water Ĉerenkov cosmic ray air shower detector may be able to detect fast monopole passage by Ĉerenkov radiation or by heating the water to incandescence. If MILAGRO is indeed sensitive to fast monopoles, then, by scaling the Japanese results, in 3 years of live time, it could improve the current limits by a factor of 50.

In conclusion, we have set limits on monopole production in *pp* and heavy ion collisions at TeV center of mass energies. These limits do not depend on monopole collection schemes or astrophysical assumptions; simple earth bound detectors are used in a known cosmic ray beam.

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Figure Caption

1. The monopole production cross section as a function of the inelastic cross section, for center of mass energies between 1 and 100 TeV. The solid line is the *pp* limit; the dashed is for medium mass (12 amu) ions.

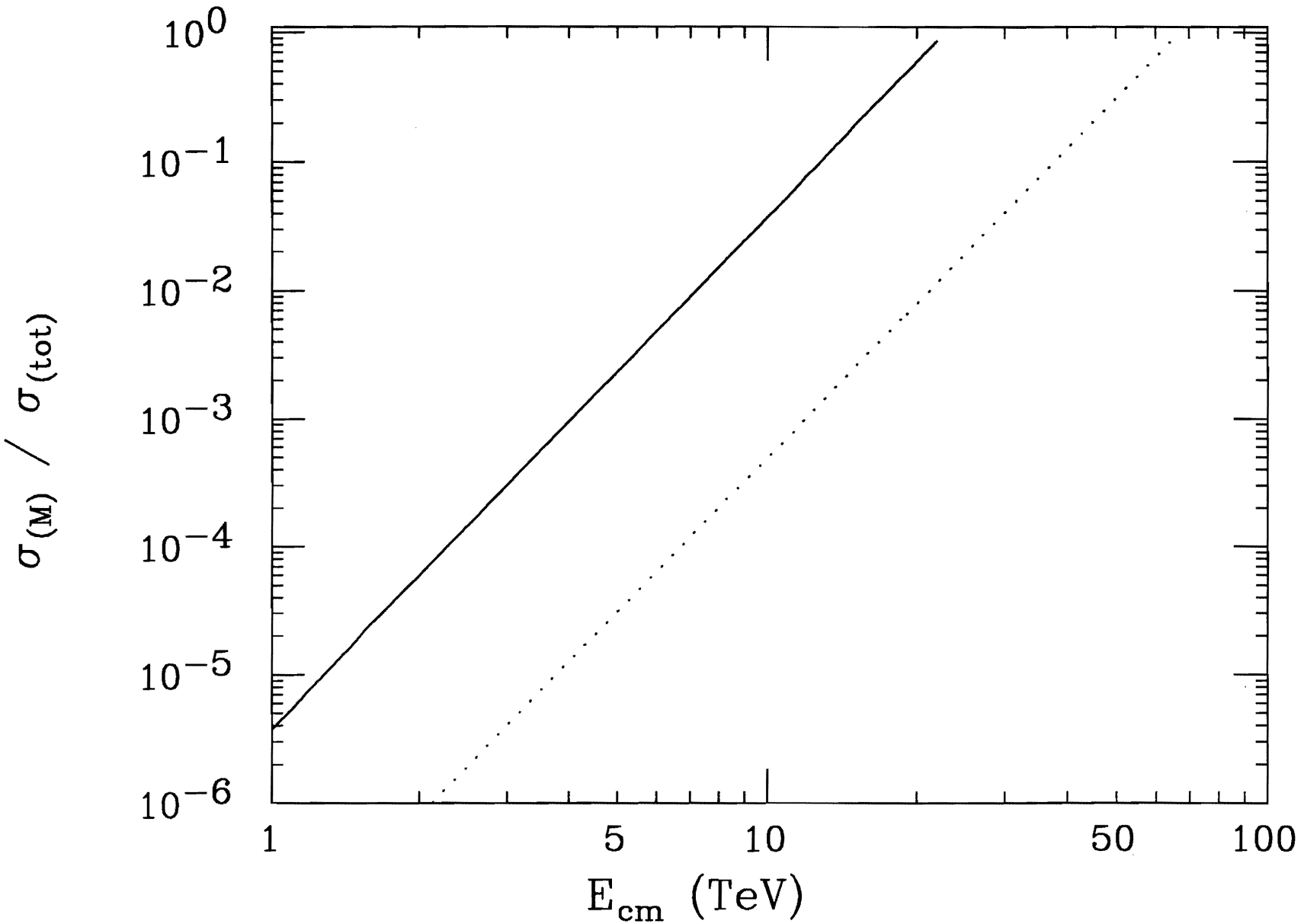
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\sigma_{(M)} / \sigma_{(tot)}$
1
5
10
50
100
E_{cm} (TeV)

Figure 1