LIMITS ON MAGNETIC MONOPOLE FLUXES IN THE PRIMARY COSMIC RADIATION FROM INVERSE COMPTON SCATTERING AND MUON-POOR EXTENSIVE AIR SHOWERS

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Flux limits for monopoles in the primary cosmic radiation have been derived on the basis of muon-poor air-shower data and the analog of inverse Compton scattering of monopoles from universal microwave background photons. Calculations on both galactic and universal scales were performed. The resulting limits are generally smaller than existing experimental limits and are applicable to strongly interacting monopoles.

The monopole hypothesis of Dirac[1] has proved to be most tenacious, even in the absence of experimental verification pursuant to considerable efforts. Added impetus has been provided by Schwinger[2] in the form of a union of the quark and monopole hypotheses wherein dually charged particles (dyons) are supposed to be the fundamental constituents of all hadrons. The existence of the monopole would furnish a rationale for charge quantization. All quantization conditions so far put forward are included in $g = ne/2\alpha$, where g is pole strength, e is electron charge, α is the fine-structure constant, and n is an integer.

There exist monopole production cross-section limits based upon accelerator experiments and upon interactions of cosmic-ray primaries with the atmosphere and with the surface of the moon. In addition, limits for monopole fluxes in the primary cosmic radiation have been deduced. Some recent published experimental results and references to earlier work are contained in two papers by Fleischer et al.[3]

An alternative means of estimating primary monopole flux limits may be realized through consideration of the 2.7°K universal microwave background, the analog of inverse Compton scattering of monopoles, and energetic primary photon/electron flux limits from muon-poor extensive air showers (EAS). Many authors have explored various astrophysical implications of inverse Compton processes. A useful early work is that of Feenberg and Primakoff,[4] and a brief review, with references, can be found in a paper by Felten and Morrison.[5] If monopoles exist in galactic or intergalactic space they should have energies such that many Compton secondary photons would have energies in the range from 10^{13} eV to more than 10^{20} eV. Experimental results on muon-poor EAS yield upper limits on primary photon/electron integral spectra at several points in this energy range. Braun and Sitte[6] have shown that it is reasonable to expect the low relative muon-number signature for showers of electromagnetic origin to persist up to primary energies as large as 10^{19} eV. For energies above 3×10^{13} eV the isotropic muon-poor EAS primary integral intensity limit given by Kamata et al.[7] has been arbitrarily divided by 10 in view of the angular distribution study of Catz et al.[8] The latter authors concluded that observed muon-poor showers are not initiated by primary photons or electrons. This yields an integral intensity limit of 2×10^{-12} (cm^2 sec sr)$^{-1}$. In a sample of ~12000 showers with primary energies above 1×10^{16} eV, Toyoda et al.[9] saw no muon-poor events —a limit of 3×10^{-16} (cm^2 sec sr)$^{-1}$ follows. At higher energies, Volcano Ranch data[10] have been used to estimate upper limits on primary photon/electron integral intensities. These estimates are (i) 1×10^{-17} (cm^2 sec sr)$^{-1}$ above 1×10^{17} eV; (ii) 1×10^{-18} (cm^2 sec sr)$^{-1}$ above 1×10^{18} eV; (iii) 3×10^{-20} (cm^2 sec sr)$^{-1}$ above 1×10^{20} eV.

In the absence of dominant energy-loss processes and given relatively small production energies, the energy spectra of monopoles in galactic space should be determined completely by the galactic magnetic field. Subject to these conditions and an average galactic magnetic field[11] of ~5 μG with a correlation length of ~10^{21} cm, Goto[12] has concluded that monopoles should be accelerated in galaxies and injected into intergalactic space with energies between ~$5n\times10^{19}$ and ~$5n\times10^{21}$ eV. According to this picture, a typical monopole history during the life of the universe would consist of production and acceleration in a galaxy, followed by injection into and propagation through intergalactic space, with approximately ten successive galactic encounters and reinjections. The concepts which led to this expected behavior for monopoles require modification in two respects. Energy loss due to inverse Compton scattering must be considered because the resultant loss rate dominates the energy gain rate in galactic fields for some pertinent pole strengths, masses, and energies. Furthermore, because of the vast distances involved, even comparatively very weak intergalactic magnetic fields can materially affect monopole spectra.

An adequate approximation to the average energy of inverse Compton secondary photons for a 2.7°K blackbody distribution of ambient photons is[5] $(8.37\times10^{-4}\text{ eV})\gamma^2$, where γ is the relativistic factor (i.e., the ratio of total energy to rest energy) for the particle involved. The resulting energy loss rate for monopoles may be written

$$\frac{dE}{dx} = -\frac{E^2}{M^2\lambda_M}(8.37\times10^{-22}), \tag{1}$$

where E is monopole energy in eV, M is monopole mass in GeV, λ_M is the mean free path in cm, and the loss rate is given in eV/cm. λ_M is related to the Compton cross section by $\lambda_M^{-1} = 400\sigma_M$, where 400 cm^{-3} is the photon density bor a blackbody distribution at $T = 2.7$°K. If radiation damping is negligible and the incident electromagnetic radiation wavelength in the monopole rest frame is large compared to the monopole Compton wavelength, then a classical derivation of σ_M, in exact analogy with the classical derivation of the Thomson cross section,[13] should be valid. Effects due to the electric charge of a dually charged particle can be neglected for all plausible combinations of charge and pole strength. The radiation-damping condition[14] (wavelength of incident radiation in monopole rest frame large compared to monopole classical radius g^2/Mc^2) can be transformed to read

$$E < (M^2/n^2)(293\times10^{20}), \tag{2}$$

and

$$E < M^2(15.9\times10^{20}) \tag{3}$$

expresses the required relation between incident photon wavelength and monopole Compton wavelength. The analog of the Thomson cross section for monopoles is $\sigma_M = (3.83\times10^{-24})n^4/M^2\text{ cm}^2$. In these relations E and M are in the same units as before and n is the integer which specifies pole strength. One can see that (2) and (3) are satisfied in practice by imposing the physical requirement that the Compton energy-loss rate cannot be greater than the monopole energy-gain rate in the galactic magnetic field. Substitution of λ_M into Eq. (1) and comparison of the result with the energy gain rate of $0.103n$ eV/cm for a 5-μG field give

$$E < (M^2/n^{1.5})(2.78\times10^{20}). \tag{4}$$

Inequality (4) is more restrictive than either (2) or (3) for $n < 10^4$. A smaller magnetic field would lead to a condition even more restrictive than (4), so intergalactic monopoles should satisfy (2) and (3).

Among conceivable monopole energy-loss processes in addition to inverse Compton scattering, e-pair production by 2.7°K photons and strong interactions with interstellar matter appear to be the most important possibilities. The threshold for pair production occurs at a monopole energy given by $\gamma_M = 1.63\times10^9$, which is well within the range pertinent here. However, in contrast to Compton scattering, the average energy loss per collision does not increase rapidly with monopole energy. In fact, the ratio of pair energy far above threshold to that at threshold is just 0.5 (in the frame in which the microwave background is isotropic). Thus, in order for pair production to compete with Compton scattering in terms of energy loss, it is necessary that the cross section rise rapidly above threshold, eventually reaching implausible values. For example, at $\gamma_M = 10^{12}$ (γ_M is the relativistic factor for the monopole), the pair production cross section must be greater than the Compton cross section by a factor of 10^6 if the corresponding energy loss rates are to be equal. Strong interactions cannot materially affect monopole energy spectra unless the cross section becomes very large. For a monopole energy of $5n\times10^{21}$ eV, an interstellar nucleon density of 0.5 cm^{-3}, an inelasticity of 0.5, and a 5-μG field, equality of loss and gain rates demands a strong-interaction cross section of $\sim10^{-22}\text{ cm}^2$. This may be compared with the π^+p cross section of $2\times10^{-25}\text{ cm}^2$ at the $N^*(1238)$ peak.

Upon concluding that it is reasonable to neglect all monopole energy loss processes but the inverse Compton effect, one is in a position to specify approximate galactic energy spectra for monopoles which are produced in the galaxy or which enter the galaxy from outside, with relatively small energies in both cases. For $M > 4.2n^{1.25}$ GeV the energy bound (4) is greater than $5n\times10^{21}$ eV. A rectangular spectrum between $5n\times10^{19}$ and $5n\times10^{21}$ eV has been adopted for this mass range. If $M < 0.42n^{1.25}$ GeV the monopole energy must be less than $5n\times10^{19}$ eV. The associated spectrum has been approximated by a delta function at the energy given by the right-hand side of (4). A rectangular spectrum between $5n\times10^{19}$ eV and the bound (4) has been used for intermediate masses.

In a static, nonrelativistic universe with no magnetic fields outside of galaxies and negligible production of monopoles in intergalactic space, monopole intergalactic energy spectra would be determined by the spectra of monopoles injected from galaxies, by the properties of the universal microwave background, and by the Hubble distance (10^{28} cm). In particular, a delta-function injection spectrum implies an intergalactic spectrum which is proportional to E^{-2} between limits defined by the injection energy and the energy lost by a monopole via the inverse Compton effect in propagating 10^{28} cm. It is not difficult to perform the integrations that lead from this simple case to the slightly more complicated intergalactic spectra which derive from rectangular injection spectra. The (probable) existence of intergalactic magnetic fields alters these intergalactic spectra substantially. Estimates[15] of the average intergalactic field vary over a wide range-0.01 μG appears to be somewhat conservative and has been adopted. It also appears reasonable to suppose that the correlation length is at least as large as the average distance between galaxies in the local supergalaxy (2×10^{24} cm). Such a field manifests itself in the form of a much larger approximate lower energy limit (E_L) and an accumulation of the area under the no-field energy distribution function below E_L into a relatively small interval about E_L. This occurs because the energy gain rate in the field becomes equal to the Compton loss rate at E_L. E_L increases as M^2, but monopole energy is ultimately limited by the influence of the correlation length and the finite size of the universe. Based upon the intergalactic field described above, $n\times10^{23}$ eV is a plausible estimate for this upper limit. This value is greater than the maximum energy achievable in galactic acceleration and is realized over a portion of the monopole mass range to be considered later. The galactic monopole spectra previously described are thus probably unrealistic for very large masses.

Two methods have been used to estimate monopole flux limits. The first of these depends only upon galactic monopole spectra and pertinent properties of the galaxy. Integral intensities I_γ of secondary photons from the monopole inverse Compton effect and monopole integral intensities I_M (assumed to be isotropic) are related by

$$I_M(E(k)) = (\gamma_M/R)I_\gamma(k), \tag{5}$$

where k is photon energy and $R = 3\times10^{22}$ cm is the radius of the galactic halo. The appropriate muon-poor EAS primary integral intensity limits listed earlier have been substituted for I_γ in (5). Comparison with monopole galactic energy spectra then yields upper limits on monopole fluxes. The results are listed in Table I for the monopole mass range over which the galactic spectra previously described are considered realistic. Photon absorption via $\gamma\gamma\to e^+e^-$ is not important within the galaxy because the maximum absorption probability per unit path length is less than 10^{-23} cm^{-1}.

Considerably smaller monopole flux limits follow from the second method of estimation. The 2.7°K microwave background is assumed to extend throughout a static, nonrelativistic universe with an intergalactic magnetic field as described before. Inverse Compton scattering of monopoles, pair production by energetic photons on background photons, inverse Compton scattering of electrons, and electron synchrotron radiation then comprise the basic interactions in an isotropic photon-electron cascade[16] which must permeate the universe if monopoles exist with the previously specified intergalactic energy spectra. This situation may be described by a pair of coupled equations which have been derived by equating loss and gain rates for photon $[G(k)]$ and electron $[F(\epsilon)]$ densities per unit energy interval. These equations contain a loss time, $T_L = 1\times10^{17}$ sec, equal to the mean time for an electron or photon to encounter a galaxy in a galactic density equal to that of the local supergalaxy. This corresponds to the simplifying assumption that an electron or photon is effectively lost to the cascade in a galactic encounter. The mean free path for electron inverse Compton scattering was evaluated with the exact Compton cross section[17] for $\epsilon > 5\times10^{12}$ eV and with the Thomson cross section for smaller primary electron energies. Values of the absorption probability per unit path length for $\gamma\gamma\to e^+e^-$ were obtained from the results (transformed from 3.5 to 2.7°K) given by Gould and Schréder.[18] The synchrotron power radiated by an electron was evaluated with a formula given by Felten and Morrison.[5] The normalized monopole energy distribution function f was approximated by adding the area under the no-field intergalactic monopole energy distribution function below $E_L/10$ to the interval $E_L/10 \to 10E_L$ in rectangular form, and by setting $f = 0$ below $E_L/10$. A computer was used to solve the coupled equations for values of $G(k)/N_M$ and $F(\epsilon)/N_M$, where N_M is monopole density. Iteration started at the highest pertinent energy for a particular case and proceeded downward to k

Table I. Primary monopole flux limits in $(cm^2\ sec\ sr)^{-1}$. Where two entries occur, the first of each pair derives from the galactic calculation and the second from the intergalactic calculation. The single entries are all from the intergalactic calculation.

n	M (GeV)								
	1	5	10	25	50	100	250	2500	10000
1	$2x10^{-20}$ $3x10^{-23}$	$2x10^{-20}$ $2x10^{-24}$	$2x10^{-19}$ $2x10^{-24}$	$7x10^{-24}$	$2x10^{-23}$	$8x10^{-23}$	$6x10^{-22}$	$2x10^{-17}$	$4x10^{-15}$
2	$1x10^{-21}$ $2x10^{-23}$	$2x10^{-21}$ $1x10^{-23}$	$6x10^{-21}$ $1x10^{-24}$	$2x10^{-19}$ $1x10^{-24}$	$2x10^{-24}$	$6x10^{-24}$	$3x10^{-23}$	$2x10^{-20}$	$7x10^{-17}$
3	$3x10^{-22}$ $6x10^{-24}$	$5x10^{-21}$ $8x10^{-24}$	$1x10^{-21}$ $1x10^{-23}$	$1x10^{-20}$ $5x10^{-25}$	$8x10^{-19}$ $7x10^{-25}$	$2x10^{-24}$	$7x10^{-24}$	$2x10^{-21}$	$7x10^{-18}$
4	$9x10^{-23}$ $4x10^{-24}$	$2x10^{-21}$ $6x10^{-24}$	$9x10^{-21}$ $7x10^{-24}$	$3x10^{-21}$ $9x10^{-24}$	$5x10^{-20}$ $4x10^{-25}$	$1x10^{-18}$ $7x10^{-25}$	$2x10^{-24}$	$4x10^{-22}$	$4x10^{-18}$
8	$5x10^{-23}$ $2x10^{-24}$	$1x10^{-22}$ $3x10^{-24}$	$5x10^{-22}$ $3x10^{-24}$	$4x10^{-21}$ $3x10^{-24}$	$9x10^{-22}$ $4x10^{-24}$	$1x10^{-20}$ $2x10^{-25}$	$4x10^{-19}$ $3x10^{-25}$	$2x10^{-23}$	$1x10^{-21}$
12	$3x10^{-22}$ $1x10^{-24}$	$3x10^{-22}$ $1x10^{-24}$	$1x10^{-22}$ $2x10^{-24}$	$7x10^{-22}$ $2x10^{-24}$	$3x10^{-21}$ $2x10^{-24}$	$7x10^{-22}$ $3x10^{-24}$	$8x10^{-20}$ $1x10^{-25}$	$3x10^{-24}$	$1x10^{-22}$

= 100 eV. $G(k)/N_M$ and $F(\epsilon)/N_M$ were integrated numerically to provide photon integral intensities and electron integral intensities as functions of monopole flux. Only the photon contributions were compared with the muon-poor EAS data to arrive at final primary monopole flux limits. These are presented in Table I, together with the results from the galactic calculation. For both methods the exhibited limits are smaller than existing experimental limits in all but a few of the cases considered.

The intergalactic viewpoint leads to smaller limits than the galactic and is applicable for all masses, but the pertinent properties of the galaxy are subject to less uncertainty than those of intergalactic space. One can see by confining his attention to the local supergalaxy that the neglect of cosmology and the assumption of equilibrium in the intergalactic case cannot introduce gross underestimates of monopole flux limits. If nothing entered this region from outside and monopole energy spectra were unchanged, the only alteration required would be a change in T_L to correspond to the transit time across the local supergalaxy. This different loss time ($T_L \simeq 2 \times 10^{15}$ sec) would serve to increase the intergalactic monopole flux limits by no more than a factor of 50.

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BACKWARD RHO PRODUCTION IN π^-p REACTIONS AT 2.3 BeV/c*†

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In a sample of 8300 events of the type $\pi^-p\to\pi^-\pi^+n$ and 6800 events of the type $\pi^-p\to\pi^-\pi^0p$ obtained with 2.3-BeV/c incident π^-, substantial backward ρ^0 production is seen. The decay angular distribution of these backward ρ^0 events was found to be anisotropic. The u distribution for the backward ρ^0's is compared with the theoretical predictions of the strong-cut Reggeized absorption model. A small amount of backward ρ^- production is also seen.

Recent experimental work has shown indications of backward ρ production in πN interactions.[1] We present data on the reactions

$$\pi^-p\to\pi^-\pi^+n \text{ (8300 events)} \tag{1}$$

and

$$\pi^-p\to\pi^-\pi^0p \text{ (6800 events)} \tag{2}$$

at 2.3 BeV/c, where we have studied in detail the very backward-produced di-pions, i.e., those events for which the center-of-mass scattering angle θ_{pN} between the incoming proton and the outgoing nucleon is near 180°. We observe substantial ρ^0 production and a small amount of ρ^- production.

The data were obtained from an exposure of 2.3-BeV/c π^- in hydrogen in the Princeton-Pennsylvania Accelerator's 15-in. bubble chamber. About 50 000 two-prong events were measured using the flying-spot digitizer (Hough-Powell device) at the University of Pennsylvania in the minimum-guidance mode (i.e., the film was prescanned and the event vertices digitized). These events were then processed through the University of Pennsylvania automatic track-following and minimum-guidance events-recognition computer programs.[2,3] The failures (about 10%) were remeasured using conventional measuring machines. The standard CERN bubble-chamber analysis programs THRESH-GRIND were used to reconstruct and kinematically fit the events.

Because of the very accurate nature of the measuring technique,[3] the fraction of misidentified events due to poor measurement was less than 1% for Reaction (1) and less than 2% for Reaction (2). Also no more than 1% of the single-