Search for Slowly Moving Magnetic Monopoles with the MACRO Detector

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A search for slowly moving magnetic monopoles in the cosmic radiation was conducted from October 1989 to November 1991 using the large liquid scintillator detector subsystem of the first supermodule of the MACRO detector at the Gran Sasso underground laboratory. The absence of candidates established an upper limit on the monopole flux of $5.6 \times 10^{-15}\,\mathrm{cm^{-2}\,sr^{-1}\,s^{-1}}$ at 90% confidence level in the velocity range of $10^{-4} \lesssim \beta < 4 \times 10^{-3}$. This result places a new constraint on the abundance of monopoles trapped in our solar system.

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Magnetic monopoles are predicted in grand unified theories (GUTs) [1]. With an expected mass approximately 2 orders of magnitude greater than the unification scale, GUT monopoles could not have been produced at accelerators. Produced in the early universe, relic monopoles in the galaxy are expected to be slowly moving with velocities comparable to typical galactic velocities of $\sim 10^{-3}c$ [2]. The survival of the galactic magnetic field requires that this monopole flux should not exceed the Parker bound of $10^{-15}\,\mathrm{cm^{-2}\,sr^{-1}\,s^{-1}}$ [2]. Recently

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an extended bound of $1.2 \times 10^{-16}\,\mathrm{cm^{-2}\,sr^{-1}\,s^{-1}}$ has been established for monopoles of mass $10^{17}\,\mathrm{GeV}/c^2$ by considering the survival of a small galactic seed field [3]. It has been argued [4,5] that monopoles may be trapped in the solar system and thus their local flux may be enhanced above the Parker bound. We concentrate in this paper on a search for these trapped monopoles that are expected to travel at velocities as low as $\sim 10^{-4}c$ (the orbital velocity about the Sun at 1 astronomical unit).

The large kinetic energy of GUT monopoles associated with their large mass implies that they are highly penetrating. Therefore, searches for GUT monopoles can be performed using underground detectors to reduce backgrounds from the cosmic radiation. The MACRO (Monopole, Astrophysics, and Cosmic Ray Observatory) detector [6], a large underground detector, is nearing completion at the Gran Sasso Laboratory in Italy, with the primary goal of searching for monopoles at flux levels below the Parker bound. The rock overburden has a minimum thickness of 3200 meters of water equivalent and attenuates the flux of cosmic ray muons by a factor of about 10^6. When completed, MACRO will have an acceptance of $\sim 10\,000\ \mathrm{m^2\,sr}$ for an isotropic flux of penetrating particles, corresponding to about three monopoles per year for a flux level at the Parker bound.

The experimental data reported in this paper uses only the first operational supermodule of the MACRO detector, which is documented in detail elsewhere [6,7]. Its dimensions are $12.6\,\mathrm{m} \times 12\,\mathrm{m} \times 4.8\,\mathrm{m}$ and its acceptance is $870\ \mathrm{m^2\,sr}$. It is surrounded on five sides by planes of liquid scintillator counters: 32 horizontal counters in two horizontal planes and 21 vertical counters in three vertical planes. Each counter is an 11 m long tank of liquid scintillator viewed by 20 cm diam hemispherical photomultiplier tubes. A horizontal counter has two phototubes at each end, while a vertical counter has only one phototube at each end. In addition, there are ten horizontal planes and six vertical planes (covering three vertical sides) of limited streamer tubes, one horizontal plane of plastic track-etch detectors and seven horizontal layers of passive rock absorber.

In the liquid scintillator subsystem, we have employed two types of specialized monopole triggers, which cover different velocity regions [7]. In this Letter, we report the monopole search results obtained from data collected using the trigger which covers the lower velocity region [7] and has also been applied to a search for nuclearites (strange quark matter) [8]. Based on the time of passage of slowly moving particles through the 19 cm thick scintillator, this trigger selects wide phototube pulses or long trains of single photoelectron pulses generated by slowly moving particles, and rejects with high efficiency any single large but narrow pulse from the residual penetrating cosmic ray muons or from radioactive decay products from walls of the hall or detector materials. In order to pick up single photoelectron pulses, whose average pulse height is 3 mV, the front-end discriminator threshold is set at only 2.5 mV, making it sensitive to electrical noise as well as to long pulse trains of low light level. To help discriminate between them, wave forms of the phototube signal are recorded by two complementary sets of wave form digitizers.

The sensitivity of this trigger to slow monopoles was measured by simulating the expected signals using light-emitting diodes (LEDs) in representative counters [7]. Figure 1 shows the measured amount of light (normalized to the light yield of minimum ionizing particles) required to achieve 90% trigger efficiency as a function of the monopole velocity. Also shown are the light yields from bare monopoles and dyons (monopoles carrying a unit electric charge or monopole-proton composites) estimated by Ficenec *et al.* based on the best fit of their measured scintillation from protons with velocities as low as $2.5 \times 10^{-4}c$ [9]. As Ficenec *et al.* have noted, the estimate for dyons is more certain than that for monopoles, due to the electric charge carried by dyons. We note that Kleber [10] has shown that monopoles will induce molecular ring currents when passing through benzenelike ring molecules in organic scintillator, which may decay optically and give more light than Ficenec *et al.*'s estimate, but a detailed calculation is difficult.

The data were collected from October 1989 to November 1991 with an accumulated live time of 542 days, during which there were 583 999 events with the slow monopole trigger present in at least one scintillator plane. After vetoing events which also fired a two-plane muon trigger requiring time of flight $< 1\,\mu\mathrm{s}$ (corresponding to $\beta > 1.5 \times 10^{-2}$), 541 918 events remained. The majority of these single plane monopole triggers were due to radioactivity pileups (i.e., many background radioactivity-induced pulses accidentally occurring within a short time

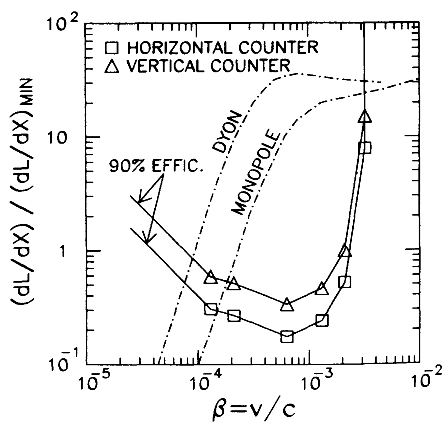

FIG. 1. The measured slow monopole trigger sensitivity compared with the expected light yields of monopoles and dyons. The probability for a particle with light yield above either measured curve to fire the corresponding counter is greater than 90%.

interval). Requiring the trigger to be present in two separate planes within 600 μs (the time of flight for a $\beta = 10^{-4}$ particle to cross the apparatus with the longest possible path length), as expected for slow monopoles, yielded 723 events, some of which were caused by power glitches which eventually ended the run. To eliminate these, candidate events were then required to occur at least 0.015 h before the end of run. This end-of-run cut reduced the total live time to 541 days and 573 candidates survived, each of which was examined and classified using a wave form analysis.

The majority of these candidates (565 events) were easily identified as due to electrical noise by the following characteristics: the presence of bipolar oscillations in their recorded wave forms (388); having no feature other than occasional isolated radioactivity-induced pulses in the wave form (169), interpreted as being caused by electrical noise on the trigger input; or having long pulse trains ($> 4\,\mu$s) simultaneously present in every channel (8), inconsistent with passage of particles.

The remaining eight candidates are of nonelectrical origins. Among them, two candidates were identified as muons because of their time-of-flight and pulse shapes; they escaped the fast muon veto because they occurred during a period when the fast muon trigger malfunctioned. Three other candidates had muon signals in one plane and radioactivity pileups in the other plane.

The remaining three candidates had wave forms consisting of 4–8 narrow pulses in sequence, where each pulse typically had a pulse height at least several times larger than the average single photoelectron pulse height, and therefore inconsistent with the expectation for monopoles. Instead, these events are consistent with being due to accidental coincidences between radioactivity pileups in different planes, for which the expected number is calculated to be 2.6, compared to the three that were observed. We note that for the passage of slow particles, the photoelectrons should be randomly but uniformly distributed to produce much smoother pulse trains than the observed "spiky" pulse trains. To quantify this analysis, the "spikiness" of a pulse train has been represented by the Campbell quantity σ^2/μ, where μ is the average pulse height of the pulse train and σ is the standard deviation of the pulse height about its mean. Campbell's theorem [11] indicates that, if the time distribution of the pulses making up the train is Poissonian, this quantity is a constant independent of the average pulse height, and thus is independent of the light yield and velocity of the traversing particle. We computed this quantity for the three candidate events as well as for monopolelike pulse trains generated by LEDs (Fig. 2). For selection of monopoles, we required at least one of the two triggered counters to have at least one end satisfying $\sigma^2/\mu < 2\,$mV. None of the remaining three candidate events satisfies this criterion. Under this criterion, the probability of rejecting a real monopole event was

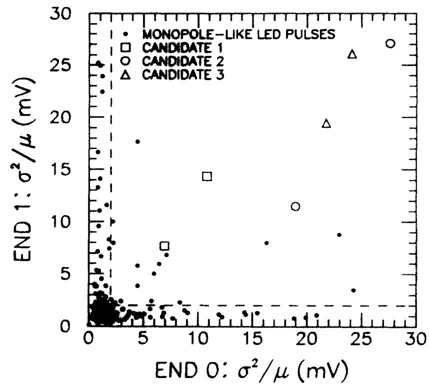

FIG. 2. The Campbell quantity σ^2/μ for wave forms at both ends of a scintillator counter. Each of the three candidate events has two entries because each triggered two counters. Most of the 881 monopolelike LED pulse trains are clustered around $\sigma^2/\mu = 1\,$mV, and the outliers are caused by the radioactivity-induced pulses superimposed on top of the LED pulse trains by accidental coincidences.

determined to be 5×10^{-4} from Fig. 2, while the probability for a radioactivity pileup event to be mistaken for a monopole was determined to be 2.2% by studying single plane pileup events. Therefore, the expected number of background events which would satisfy this cut for the entire data set was 0.06.

As a final cross-check, we have looked at the streamer tubes for slow particle triggers or tracks for the sample of the 573 candidates, and found agreement with the above classifications based on the scintillator wave forms. For future more sensitive searches, the streamer tube subsystem will give an additional strong handle. Furthermore, we note that if any candidate events survive, we can perform a rigorous inspection of the tracks in the track-etch subsystem.

Rubakov [12] and Callan [13] have speculated that for grand unified theories which do not conserve baryon number, GUT monopoles may strongly catalyze nucleon decay. With the current electronics configuration, the pulses from relativistic decay products may disrupt the proper recording of wave form signals of slow monopoles, and thus this search may be insensitive to those monopoles with a catalysis cross section $> 10^{-27}\,\text{cm}^2$. However, no evidence for any baryon number-violating process has ever been observed. Furthermore, it has been argued that the catalysis cross section may be suppressed as compared to the Rubakov-Callan prediction [14], that the Rubakov-Callan effect may vanish in the SU(5) GUT [15] or in some other GUTs [16], and that proton decay does not occur in some GUTs.

In conclusion, we have found no evidence for the passage of a slowly moving ionizing particle through MACRO and have established an upper limit on the isotropic flux of GUT monopoles at 5.6 ×

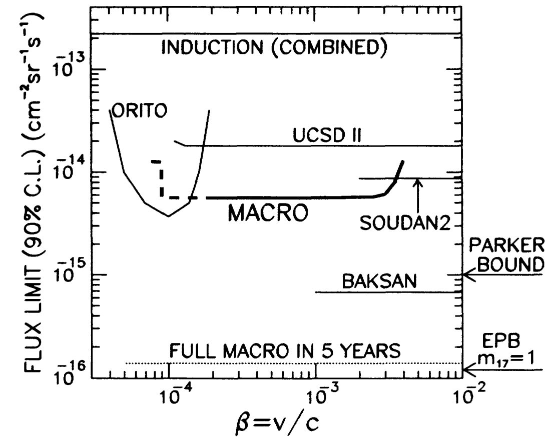

FIG. 3. The upper limit on GUT monopole flux at 90% confidence level established by MACRO. The bold solid curve indicates the sensitive velocity range for bare monopoles, and the dashed step shows the additional velocity range for dyons. Also shown are the anticipated limits reachable by the full MACRO detector after five years of operation, the Parker bound [2], the extended Parker bound (EPB) for monopoles of mass 10^{17} GeV/c^2 ($m_{17} = 1$) [3], and the results from several previous searches: induction (combined) [17], UCSD II (He-CH_4, for bare monopoles only) [18], Soudan 2 (Ar-CO_2) [20], Baksan (scintillator) [21], and Orito (CR-39) [22].

$10^{-15}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$ (90% confidence level) as shown in Fig. 3 [17–22]. This flux limit is valid in the velocity range of $\beta_0 < \beta < 3 \times 10^{-3}$, where the lower velocity limit β_0 is determined by the trigger sensitivity versus light yield shown in Fig. 1. For bare monopoles, this limit is $\beta_0 = 1.8 \times 10^{-4}$ as shown by the bold solid curve in Fig. 3. For dyons or monopole-proton composites, the velocity range extends down to $\beta_0 = 9 \times 10^{-5}$. As indicated by the dashed step in Fig. 3, an additional velocity range of $8 \times 10^{-5} < \beta < 9 \times 10^{-5}$ with the flux limit of $1.3 \times 10^{-14}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$ (90% C.L.) has been established for dyons using exclusively the more sensitive horizontal counters. Bracci *et al.* [23] have argued that bare monopoles are likely to have captured and bound protons in the early universe [24], making this dyon search especially relevant. The upper velocity limit of $3 \times 10^{-3}c$ is determined by the minimum pulse train duration (for 19 cm path length through the scintillator) required by the trigger circuit. For a trajectory with a path length longer than 19 cm, this limit extends up to $4 \times 10^{-3}c$, but with a less restrictive flux limit due to a reduced acceptance.

Finally, we note that an encounter with a star is the proposed mechanism for slowing down and trapping a monopole in the solar system [4,5] and a monopole emerging from such an encounter will have attached a proton. We emphasize that due to the experimentally established sensitivity to very slowly moving charged particles in MACRO, the flux limits presented here place new constraints on the abundance of trapped monopoles.

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