

Final Search for Lightly Ionizing Particles with the MACRO detector

The MACRO Collaboration

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We present the final results of a search for lightly ionizing particles using the entire cosmic ray data set the MACRO detector collected during its 1995-2000 run. Like the original search performed with the data of 1995-96, this search was sensitive to fractionally charged particles with an *electric* charge q as low as $\frac{e}{3}$ and with velocities between approximately 0.25c and c . The efficiency of this search was $\approx 70\%$ for $q = \frac{e}{3}$ and increased rapidly to 100 % for higher charges. No candidate events were observed. This corresponds to a 90 % C. L. upper limit on their isotropic flux of $6.1 \times 10^{-7} \text{ cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$ which represents the most stringent experimental limit ever obtained.

I. INTRODUCTION

Within the Standard Model of electroweak and strong interactions electric charge quantization remains unexplained. Since Millikan's oil drop experiment demonstrated electric charges in Nature come in discrete units, numerous experimenters have refined the original determination of the unit charge (e) and searched for free particles with fractional charge. This interest was intensified with the proposal of the quark model by Gell-Mann [1] and Zweig [2] in 1964 and its undisputed success in explaining the deep inelastic scattering experiments in the late 1960's [3]. This model—now part of the Standard Model—does require that single quarks come with a fractional charge, however, it does not allow them to exist as free particles. Quarks are confined in color-neutral baryons and mesons that carry integer electric charges.

Searches for fractionally charged particles have thus been carried out over the last decades in bulk matter, at accelerators and in cosmic rays [4, 5, 6, 7, 8, 9] without any evidence for their existence. The observation of such particles would be direct evidence of physics beyond the Standard Model. Fractionally charged particles are easily accommodated in Grand Unified Theories (GUT) of the electroweak and strong interactions. Within this framework the quantization of the electric charge is also explained as a consequence of the non trivial commutation relations between the operators in the theory. Simple extensions of the $SU(5)$ unification group allow for $\frac{e}{3}$ and $\frac{2e}{3}$ charges [10, 11] while larger groups such as $SU(8)$ [12], $SO(14)$ [13] and $SO(18)$ [14] allow for $\frac{e}{2}$ ones. Many popular superstring models [15] yield stable particles with charges down to $\frac{e}{5}$ or even smaller. Finally, some spontaneously broken QCD theories predict the possibility of primordial unconfined quarks and gluons [16] contained in superheavy quark-nucleon complexes with large noninteger charge.

Previous searches for fractionally charged particles in the penetrating cosmic radiation include the search using the first year of MACRO's running [17] as well as searches with the Kamiokande-II [18] and LSD [19] experiments. Until this search the best 90% C. L. upper flux limits were obtained by the Kamiokande experiment and are 2.1 and $2.3 \times 10^{-15} \text{ cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$ for charges $\frac{e}{3}$ and $\frac{2e}{3}$, respectively. Here we present the final results of the search for particles with fractional charge from $\frac{e}{5}$ to $\frac{2e}{3}$ in the penetrating cosmic radiation using the entire dataset of the MACRO experiment. The search method is based on the assumption of a reduced ionization and atomic excitation energy loss rate of a fractionally charged particle with respect to that of a unit charge. Since the energy loss rate of a particle of charge Q is proportional to Q^2 , a fractionally charged particle is expected to lose energy, by excitation and ionization, at a much lower rate than a minimum ionizing particle of the same velocity. The fractionally charged particles are therefore also called *Lightly Ionizing Particles* (LIPs). This search would not have been sensitive to fractionally charged particles that

may interact also strongly (e.g., standard model quarks) as these particles would not be able to penetrate large amounts of material.

II. EXPERIMENTAL SETUP

The MACRO experiment, described in detail in [20, 21], was a multipurpose underground detector located in Hall B of the Gran Sasso National Laboratory of the Italian Institute of Nuclear Physics (INFN). It was optimized for the search for magnetic monopoles [22, 23] but it also presented excellent capabilities for studying atmospheric neutrino oscillations [24, 25, 26], cosmic rays [27, 28], astrophysical point sources [29, 30], neutrinos from gravitational collapses [31, 32]. The detector had a modular structure; it was composed of six supermodules each of which was divided into a lower and an upper part ("attico"). All supermodules were equipped with three detector sub-systems: limited streamer tubes, liquid scintillator counters and nuclear track detectors. The overall dimensions of the apparatus were $76.6 \times 12 \times 9.3 \text{ m}^3$ and the acceptance for an isotropic flux of particles was $\approx 10^4 \text{ m}^2 \text{ sr}$. The detector was active in various different configurations from the fall of 1989 until December 2000.

Lightly ionizing tracks in MACRO would be signatures for fractionally charged particles. They could be identified both in the streamer tube and the scintillator system. The streamer tube system provided a three-dimensional reconstruction of the particle's trajectory. This system was more than 99% efficient in forming a track upon the passage of a fractional charge $\frac{1}{5}e$ or greater [17, 34]. The scintillator system provided redundant measurements of the particle's energy loss. Time-of-flight information with sub-nanosecond accuracy was also recorded. A Lightly Ionizing Particle (LIP) trigger was formed in hardware by combining MACRO's primary streamer tube trigger [17, 21, 34] with a coincidence of MACRO's lowest energy threshold scintillator trigger, called PHRASE [20, 21, 31], coming from at least three detector faces. The coincidence window of 400 ns among the scintillator face triggers was setting the minimum particle velocity the trigger hardware was sensitive to. This was at about $0.25c$ for most of the detector's acceptance. PHRASE provided a trigger based on a single scintillator counter with a threshold at approximately 1.2 MeV. Given that the Landau peak for cosmic ray muons was approximately 38 MeV for a typical 20 cm pathlength within a scintillator counter (see fig. 1) the 1.2 MeV energy threshold set a minimum fractional charge of $\frac{1}{5}e$ that MACRO could detect. A typical plot of the measured trigger efficiency of the low-energy PHRASE trigger as a function of energy is shown in fig. 2 as obtained with the 1995-96 data [17]. The low energy threshold of the PHRASE was periodically checked throughout the five-year run using natural radioactivity decay lines and it was maintained consistently at the 1 – 1.2 MeV level during the entire run.

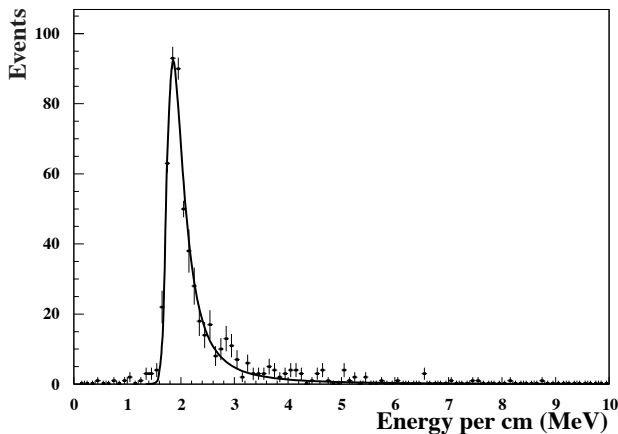


FIG. 1: Typical energy loss rate in a MACRO liquid scintillator counter. The superimposed fit is a Landau distribution folded with the photoelectron fluctuations. One may notice the low dE/dx tail of the energy loss distribution that extends within the LIP signal region.

The LIP circuitry provided the hit pattern information of the scintillator counters that exceeded the 1.2 MeV threshold. For all counters involved in a LIP trigger their photomultiplier (PMT) wave forms recorded on MACRO's 200 MHz wave form digitizer (WFD) system were read. An analysis of these wave forms could then provide the localization of the event along the scintillator counter as well as the reconstruction of the energy released. Both of these when combined with the three-dimensional track information provided by the streamer tubes could effectively reject any radioactivity or cosmic ray muon signal at a level of better than $1/10^6$ leaving a very low background search for LIPs. This was the approach in our first search for LIPS using MACRO's 1995-96 data [17].

III. DATA ANALYSIS

The MACRO scintillator subdetector was equipped with three independent systems able to record the time of flight, position and energy loss of a lightly ionizing particle as it crossed the apparatus: the primary muon trigger (called ERP), the primary gravitational collapse trigger (called PHRASE) and the Wave-Form-Digitizer system (WFD). While all three had comparable resolutions [17, 20, 21, 21, 25, 32] for minimum ionizing particles their different thresholds implied sensitivity to as low as $\sim \frac{3e}{5}$ for the ERP (given its ~ 15 MeV threshold), $\sim \frac{2e}{5}$ for the PHRASE (given its ~ 7 MeV threshold), and $\sim \frac{e}{5}$ for the LIP-triggered WFD system. The LIP trigger was designed to trigger on cosmic ray muons in addition to lightly ionizing particles. We have thus used the ERP and PHRASE systems in order to identify and reject the cosmic ray muon component that was present in our LIP trigger data set. This allowed the wave form digitizer system to be invoked only when the ERP and PHRASE had failed to record a candidate event presumably because of their energy thresholds and triggering inefficiencies relative to LIP/WFD system. The energy thresholds of the PHRASE and ERP sys-

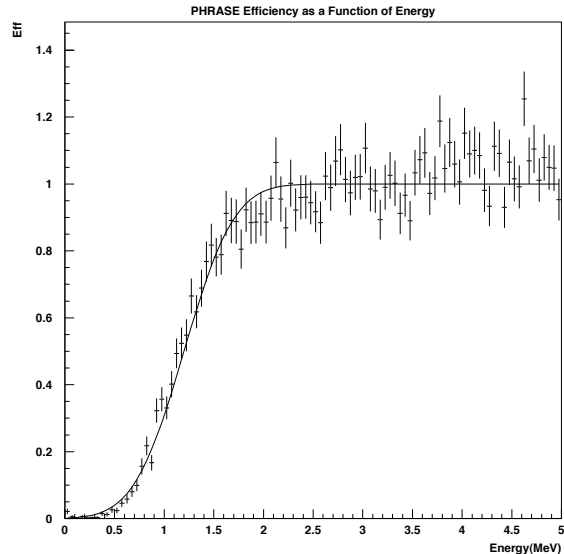


FIG. 2: Measured trigger efficiency of the low-energy PHRASE trigger (i.e., LIP trigger) as a function of the energy released in the liquid scintillator counters. Some measured efficiencies were larger than 100 % because the normalization factor used was an estimate of the true normalization as a function of energy.

tems were continuously monitored using natural radioactivity and cosmic ray muons. They were periodically adjusted in order to account for any electronic drifts or photomultiplier tube gains. This guaranteed their consistency and maintained our ability to trigger and reconstruct tracks down to $\frac{e}{5}$ charges throughout the entire data taking period.

The data set for this search comes from the 5-year run of the MACRO detector in its final configuration from July 1995 to December 2000. Run quality criteria were first applied; they required the MACRO detector to be running in its full configuration (i.e., all six supermodules, excluding counters with calibration errors) and without any serious acquisition problems (e.g., high dead time, repeated hardware errors, high voltage power supply glitches or high voltage errors what-so-ever). The integrated live-time was 1320 days and during that period 18.3×10^6 LIP triggers were collected. The analysis of these triggers proceeded as follows:

- 1) Using the streamer tube hit information, we first required a single streamer tube track reconstructed. In addition, using the LIP scintillator counter hit information, we required hits to be present in no more than four scintillator faces and within six scintillator counters in the same face. Given the geometry of the detector, no single candidate LIP track could result in such a scintillator counter hit pattern. This cut primarily rejected cosmic ray muons accompanied by electromagnetic showers.
- 2) Using the streamer tube track parameters we reconstructed the event longitudinal position along the scin-

tillator counters as well as the path length of the crossing particles in them. We required the path length to be between 13 cm and 70 cm and the hit position along the counter within the central 10.8 m part of it (i.e., rejecting tracks within the final 10 cm of a scintillator counter). Both these cuts eliminated track geometries that were more susceptible to energy reconstruction errors either due to low photoelectron statistics (short pathlengths) or to poorly calibrated PMT responses (near-PMT geometric response). When available, we required that the position along the counter provided by the scintillator timing was in agreement within 80 cm (6σ) with the position reconstructed by the streamer tube system. Following these geometrical cuts, the detector acceptance was about $3300 \text{ m}^2 \text{ sr}$ for an isotropic flux of particles.

- 3) For every LIP counter that was intercepted by a track that fulfilled all cuts so far, we assigned the energy loss as calculated for the same scintillator counter(s) by the ERP muon system in the absence of which this information was sought in the PHRASE gravitational collapse system. In lack of any energy loss information from these two systems a *zero* energy loss was assigned to that hit; this makes *a priori* the best LIP candidate event in MACRO.

This last stage of the LIP analysis enabled us to perform a measurement of the particle energy loss rate dE/dx for all cases that the LIP event was accompanied by a muon and/or the gravitational collapse trigger. The maximum dE/dx among the counters involved is plotted in figure 3. All tracks in this analysis were accompanied by a muon and/or gravitational collapse hit. This allowed us to establish the particle's dE/dx without making use of the wave form digitizer system. Since energy information from both the PHRASE and ERP systems was used in this search, we verified that in the relevant energy range ($10 \div 100 \text{ MeV}$) the two systems agreed to within 20 % or better in more than 95 % of the liquid scintillator counters (see fig. 4).

IV. RESULTS AND DISCUSSION

The *expected signal region* for this LIP search was set below 1.1 MeV/cm for the maximum energy loss rate –when measured by the ERP– in any of the scintillator counters intercepted by a streamer tube track. Since the energy loss was measured by PHRASE whenever ERP information was not available and in order to account for the potential 20% mismatch in their energy estimates, the signal region was extended up to 1.35 MeV/cm whenever a measurement was performed by PHRASE. Above this level the cosmic ray muon energy loss spectrum does not permit any identification of fractionally charged particles thus setting an upper limit of sensitivity to approximately $\frac{2e}{3}$.

As one can see in fig. 3 there is one event (run 15871, event 5649) that appears in the signal region. It corresponds to a maximum energy loss of 0.66 MeV/cm , i.e., about 20 %

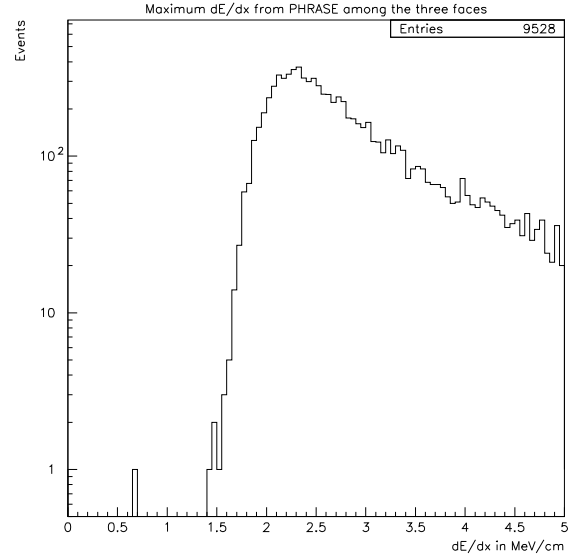


FIG. 3: Energy loss as measured by PHRASE for the LIP events that passed the track quality and geometry cuts and satisfied the requirement of a maximum energy loss rate (measured by ERP) less than 1.1 MeV/cm . This dataset was comprised primarily of events where the ERP system did not trigger at all due to inefficiencies. For these events an energy measurement was sought in the PHRASE system. The signal region is in the $[0, 1.35] \text{ MeV/cm}$ interval.

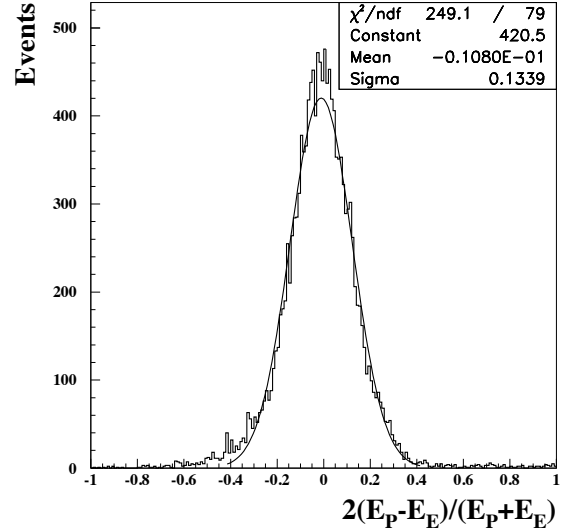


FIG. 4: Comparison between the PHRASE and ERP measured energies in the range of $10 \div 100 \text{ MeV}$. The distribution of the difference between the two energies normalized to their average shows how well these two agree. The distribution is roughly gaussian with $\sigma = 0.13$.

lower than what expected for a particle of charge $\frac{2e}{3}$ and about

a factor of 3 higher than what expected for a particle of charge $\frac{e}{3}$. Three scintillator counters were involved in this trigger; the first in one of the upper vertical layers, the second in the central horizontal layer and the third in the lower horizontal layer. There were no ERP triggers involved (suggesting the energy released in each of the counters was below 15 MeV) and only one PHRASE hit in the vertical layer was present (suggesting the energy released in the other two counters was below 7 MeV). The energy loss measured by PHRASE for this hit was 13.7 MeV and using the path length in the box provided by the tracking we computed a maximum energy loss rate of 0.66 MeV/cm. The position along the counter for this particular box measured by the PHRASE and by the streamer tube track geometry were in agreement (within 15 cm). We have examined this event by hand relying primarily on the wave forms as recorded for all the counters involved in the trigger. The apparent amplitude of the recorded wave forms was consistent with the energy thresholds for the ERP and the PHRASE. Having three scintillator counters involved in the trigger we have checked for a consistency in the relative timing of them with the crossing of a single particle of constant velocity. The relative timing between the counter in the upper part of the detector and that in the central part was consistent with the passage of a relativistic particle coming from above while the relative timing between the box in the lower part of the detector and any of the other two hits was consistent with a slowly moving upward-going particle. We thus discarded this event from the signal region.

V. CONCLUSIONS

Over the five years of running of the MACRO detector in its final configuration (1995-2000) we observed no candidates for LIPs in cosmic ray single tracks.

Given the detector's acceptance and live time we computed an integrated exposure of $3.8 \times 10^{15} \text{ cm}^2 \text{ s sr}$ which for an isotropic flux of particles yields a 90% C.L. upper flux limit of $6.1 \times 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. The search was fully efficient for charges $\frac{e}{4}$ to $\frac{2e}{3}$. The flux limit rises to higher values for lower charges as the detection efficiency drops from 100% to lower values. This limit improves the previously published MACRO result [17] by over an order of magnitude. The previously published MACRO search applies to LIPs present in both single and multi-track events while this one (as well as the ones from experiments other than MACRO) applies to LIPs present in single tracks only.

This MACRO result can be compared with those obtained by the Kamiokande [18] and the LSD [19] experiments keeping in mind that all these are limits on the local flux of LIPs at the detector site. Kamiokande and LSD quoted their results for two specific values of fractional charge, namely, $\frac{e}{3}$ and $\frac{2e}{3}$, while the MACRO result applies to a continuum of charges. It

should also be noted that all limits were obtained with the assumption of an isotropic flux of LIPs. This is reasonable if we assume that LIPs are produced in the rock around the detector (for instance, by cosmic ray muon interactions or some other unknown mechanism). However, if LIPs are produced by the

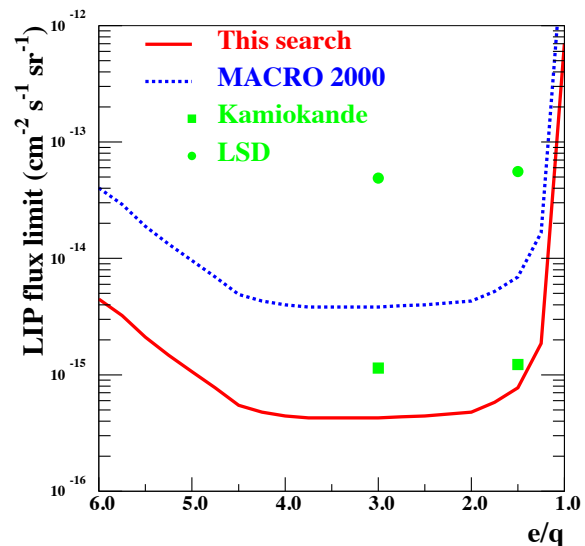


FIG. 5: The 90 % C.L. MACRO flux upper limits for LIPs (solid line) compared with previous limits from MACRO, LSD and Kamiokande.

cosmic ray interactions in the upper atmosphere or impinge on the earth from outer space, the assumption of an isotropic flux is no longer valid. In this case a detailed physical model for the production and propagation of LIPs as well as of the response of the detector would be needed in order to derive and compare results for the various experiments. In the most obvious case, LIPs without enough initial kinetic energy will not be able to reach the detector from directions below the horizon thus worsening all upper limits by a factor of two.

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