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Search for lightly ionizing particles with the MACRO detector

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Abstract. We present a search for fractionally charged particles in the penetrating cosmic radiation using the MACRO detector. The search was performed using tracking information from the streamer tubes and energy loss measurements from the scintillator subsystem. The MACRO energy threshold allowed a search sensitive to charges as low as $e/5$. The $90\,\%$ C. L. flux upper limit is $1.5 \times 10^{-15}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{sr}^{-1}$.

1 Introduction

The quantization of the electric charge is one of the most fundamental of nature's puzzles. It is not explained within the framework of the standard model, but it naturally arises within grand unification theories as a consequence of the non trivial commutation relations between the operators of the theory (Frampton and Kephart, 1982; Barr et al., 1983; Yu, 1984; Yamamoto, 1983; Dong et al., 1983; De Rùjula et al., 1978). Despite decades of searches in accelerator and cosmic ray based experiments (Smith, 1989; Klapdor-Kleingrothaus and Staudt, 1995; Lyons, 1985; Jones, 1977; Halyo et al., 2000) no one has yet reported a convincing evidence for the existence of free fractionally charged particles. Presently the best limits on the flux of fractionally charged particles come from the water Cherenkov Kamiokande-II experiment (Kamiokande, 1991); such limits, at the $90\,\%$ confidence level, are 2.1 and $2.3\times10^{-15}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{sr}^{-1}$ for charges $e/3$ and $2/3\,e$ respectively. Here we present the results of a search for particles having a fractional charge from $e/5$ to $2/3\,e$ in the penetrating cosmic radiation based on the data collected by the MACRO experiment. The results of a previous search were recently published by MACRO (MACRO, 2000).

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2 The MACRO experiment and its capabilities as a fractionally charged particle detector

The MACRO experiment (MACRO, 1993) was a modular detector composed by six different supermodules, each of them divided into a lower and an upper part ("Attico"). All supermodules were equipped with three different sub-systems: limited streamer tubes (ST) for particle tracking ($\sigma_x \approx 1$ cm), liquid scintillation counters (LSC) for energy loss and fast timing measurements and nuclear track detectors. The overall size of the apparatus was $76.6 \times 12 \times 9.3\,m^3$ and the acceptance for an isotropic flux of particles was $\approx 10^4 m^2 sr$. The detector was active, in various different configurations and with an increasing number of on-line supermodules, from autumn 1989 until the end of 2000. The STs were deployed in 14 horizontal and 12 vertical planes; each tube was 12 m long with a cell size of $3 \times 3\,\mathrm{cm}^2$. The LSCs (476 individual counters) were organized into 3 horizontal and 4 vertical layers. Each horizontal counter was $12\times0.75\times0.2\,\mathrm{m}^3$ in size and each vertical counter $12\times0.50\times0.25\,\mathrm{m}^3$; all boxes had an active length > 11 m. Both the STs and the LSCs were equipped with multiple electronic systems; here we mention only the ST muon trigger (the "Bari trigger") and two of the LSC circuits, the stellar gravitational collapse trigger PHRASE (MACRO, 1993, 1992) and the general muon trigger ERP (MACRO, 1993, 1992). The ST muon trigger used the hits recorded in a 10 μs shift register ("Fast Chain") to form an appropriate OR-combination of all signals coming from the same plane. The output signals of all planes were sent to a coincidence circuit, which searched (with a 3.3 MHz sampling frequency) for appropriate preselected combinations of them, like (for instance) one signal in four contiguous planes of the lower part. The trigger condition was generated when one of these combinations was obtained. *PHRASE* (**P**ulse **H**eight **R**ecorder **A**nd **S**ynchronous **E**ncoder) was a low energy trigger, developed for detecting neutrinos from supernova explosions. This circuit could operate with two different energy thresholds: the primary at $E_P{}^{thr} \sim 7$ MeV and the secondary at $E_P{}^{sec} \sim$

$1.2\ \mathrm{MeV}$. PHRASE was meant as an almost-zero dead time trigger with a dedicated acquisition system; therefore, the PHRASE event buffers were built separately from the rest of MACRO, but were written in the same data stream. *ERP* (**E**nergy **R**econstruction **P**rocessor) was the main scintillator muon trigger of the experiment and also had good stellar gravitational collapse capabilities. ERP had an energy threshold higher than that of PHRASE ($E_E \sim 15\ \mathrm{MeV}$). Unlike PHRASE, the ERP buffers were managed by the general MACRO acquisition system, together with the data of the ST and of the other LSC triggers. Both PHRASE and ERP were easily and reliably calibrated using cosmic ray muons (which released $\sim 40\ \mathrm{MeV}$ in the MACRO liquid scintillation counters) and natural radioactivity. We verified that in the energy range $10 \div 100\ \mathrm{MeV}$ the PHRASE and ERP measurements were in agreement within $20\,\%$ or better in more than $95\,\%$ of all liquid scintillation counters.

Fast charged particles crossing the liquid scintillators lose an amount of energy, by excitation and ionization, proportional to the square of their electric charge; therefore, relativistic particles having a charge $\alpha\,|e|$ ($|\alpha| < 1$) are expected to release an energy α^2 that of a particle with unit charge of the same velocity, like a cosmic ray muon. For instance, the energy loss rate of a cosmic ray muon in the MACRO scintillation counters was $1.8\ \mathrm{MeV/cm}$, while those expected for particles of charges $2/3\,e$ and $e/5$ were 0.8 and $0.07\ \mathrm{MeV/cm}$ respectively. Because of their reduced energy loss, the fractionally charged particles are called "lightly ionizing particles" (**LIPs**).

The LIP signature in MACRO was then a low-ionization track; the combination of a high resolution tracking system and high efficiency scintillator made MACRO a uniquely suited apparatus to look for LIPs. A custom made circuit (the *LIP*) which combined the ST and PHRASE low threshold information was developed to identify fractionally charged particles. This circuit split the whole MACRO LSC system in three parts: top, center and bottom, and generated a trigger condition when a four-fold time coincidence between these three parts and the ST occurred. The width of the time coincidence window between the three scintillator signals (set at $400\ \mathrm{ns}$) defined the velocity threshold of the LIP trigger to be $\approx 0.1\,c$. The measured LIP/PHRASE trigger efficiency as a function of the energy released in the liquid scintillator is shown in Fig. 1; since the expected energy loss for a $e/5$ particle crossing a MACRO liquid scintillator was $\approx 1.6\ \mathrm{MeV}$, the LIP trigger was sensitive to charges down to $e/5$. The detection efficiency was $\sim 75\,\%$ for charges equal to $e/5$ and grew rapidly to $100\,\%$ for higher charges. Note that the ST system was $> 99\,\%$ efficient in generating tracks for LIPs because the ST ionization threshold was ~ 0.01 that of a mininum ionizing particles (m.i.p.) (MACRO, 2000; Battistoni et al., 1985). When a LIP circuit fired, a system of $200\ \mathrm{MHz}$ custom-made wave form digitizers (WFDs) was stopped to record the waveforms of all counters involved in the event; the WFD data could then be analyzed to reconstruct the energy loss in the scintillators and identify the possible LIP candidates. This approach was followed in our previous paper

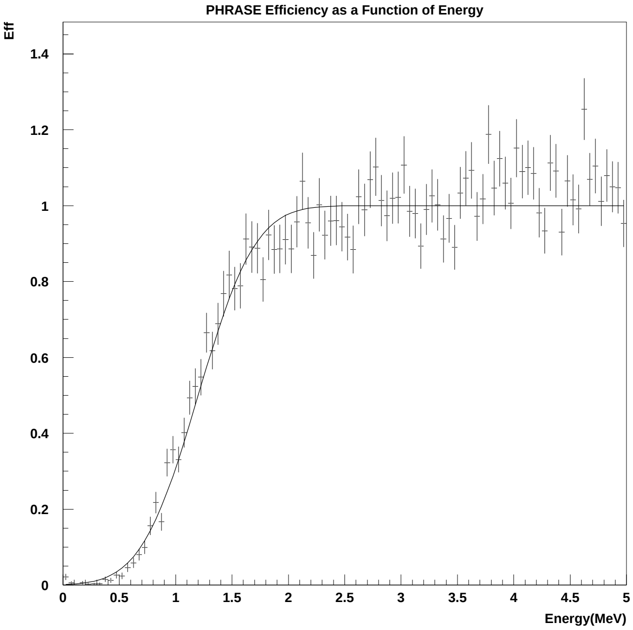

Fig. 1. The measured efficiency of triggering the low-energy PHRASE trigger and the LIP trigger as a function of the energy released in the liquid scintillation counters. Some measured efficiencies were greater than $100\,\%$ because the normalization factor used was an estimate of the true normalization as a function of energy.

(MACRO, 2000). The analysis presented here is based on a different philosophy which made use of the good position and energy resolution (compatible with that of the WFDs) of both PHRASE and ERP.

3 LIP search path

The main steps of this analysis are the following:

1) we performed a preliminary selection of the run quality, requiring that the apparatus was taking data in its full configuration and rejecting runs which suffered from hardware problems, high dead time, acquisition crashes etc.;

2) we required the ST trigger to fire and selected the events with a clean single track;

3) we required the LIP trigger to fire and used the digital information provided by this circuit to identify the scintillation counters involved in the trigger. Using a Monte Carlo simulation and the cosmic ray data we evaluated that the trigger condition required by the LIP circuit selected tracks which intercepted (in more than $96\,\%$ of the cases) no more than three detector layers and two adjacent scintillation counters in the same layer. Then we used more conservative cuts, requiring hits in no more than four scintillator layers and six scintillation counters in the same layer. These topological cuts were

expected to have no impact on LIP selection, but efficiently rejected the cosmic ray muons accompanied by electromagnetic showers;

4) we used the ST track to reconstruct the hit position along the counter and the path length of the particles in the scintillation counters. At this stage we applied also some geometrical cuts (path length between 13 and 70 cm and hit position along the counter within the central $10.8\ \mathrm{m}$ part of it) which selected the events with more reliable energy and tracking reconstructions. When the position along the counter provided by the LSC timing was available, we required that this one and the position reconstructed by the ST system were in agreement within $80\ \mathrm{cm}$, corresponding to $\sim 8\,\sigma$ of the distribution of the difference between these reconstructed positions. This cut reduced the possibility of errors in the tracking algorithm due to some random noise in the ST system. The detector acceptance, when all the analysis and geometrical cuts were folded, was about $3300\ \mathrm{m}^2\,\mathrm{sr}$ for an isotropic flux of particles;

5) we assigned the energy deposit as measured by ERP to be the energy loss for each surviving LIP trigger. If the ERP information was not present, the corresponding PHRASE information was looked for and used as a measurement of the particle energy loss. The energy loss rate dE/dx could be computed and the LIP candidates selected.

4 LIP data-set and analysis

We applied the analysis chain outlined above to two years of MACRO data, from May 1, 1998 to May 4, 2000. After the steps 1) and 2) we were left with 6.6×10^6 single ST triggers in a live time of 558.5 days; 4.0×10^6 of the LIP triggers associated with these tracks survived the topological cuts (step 3). We computed the energy loss rate using the ST and ERP information (steps 4) and 5)) and selected, as possible LIP candidates, the events with a maximum energy loss rate of $1.1\ \mathrm{MeV/cm}$, about $35\,\%$ larger than that expected from a $2/3\,|e|$ particle. Using the maximum energy loss rate among the counters as a measure of the particle ionization reduces the chance that any reconstruction error could imitate a LIP signal. There were 5126 LIP events which satisfied this requirement and in 5093 of them the ERP information was totally absent (i.e. there were no ERP triggers).

While the ERP and LIP information were parts of the same event buffer, the PHRASE data were not. Thus the PHRASE information could be used if one was able to recognize, in the PHRASE buffer, the event(s) corresponding to a LIP trigger. This was done by using the Universal Time information provided (with a $100\ \mathrm{ns}$ resolution) by the atomic clock of the experiment, which was stamped in all (PHRASE and non-PHRASE) MACRO events. A time window of $100\ \mathrm{ms}$ around any LIP trigger was selected to search for the corresponding PHRASE events; we also required PHRASE hits in

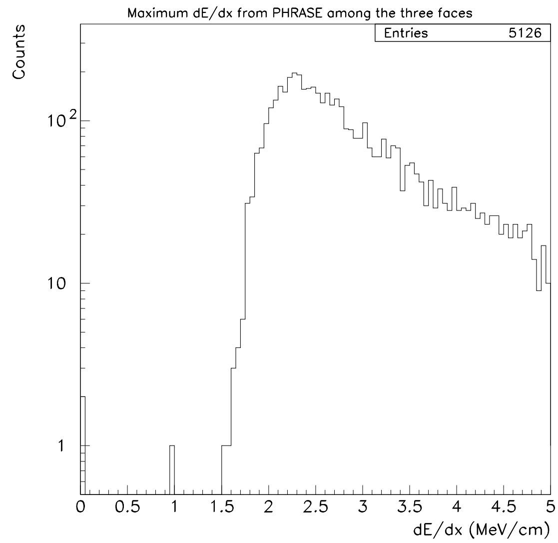

Fig. 2. Energy loss as measured by PHRASE for the 5126 LIP events that passed the track quality and geometry cuts and satisfied the requirement of a maximum energy loss rate (measured by ERP) less than $1.1\ \mathrm{MeV/cm}$. The signal region is in the $[0, 1.4]\ \mathrm{MeV/cm}$ interval. For the events in the signal region, see the text.

at least two of the boxes involved in the trigger. This matching procedure was studied in detail using much larger samples ($\sim 10^5$ LIP and ST triggers) and its inefficiency was found to be $\approx 0.07\,\%$. In order to convince ourselves that this inefficiency was not an energy threshold effect, we performed the same efficiency measurement using LIP triggers of much larger energy loss: on a sample of tracks selected requiring a minimum energy loss rate $dE/dx = 3\times$ m.i.p. we measured a matching inefficiency fully compatible with that obtained without any energy selection. Out of the 5126 LIP triggers selected in step 5), we found 5124 PHRASE events which satisfied the matching requirements. Two of the LIP events without ERP information were not matched in the PHRASE system and an energy loss rate equal to zero was assigned to them.

The energy loss rate of these 5126 events as measured by PHRASE is shown in Fig. 2. As already said, the expected signal region for this analysis was set below the $1.1\ \mathrm{MeV/cm}$ level as measured by the ERP. To be conservative and to take into account possible differences between PHRASE and ERP calibrations and energy reconstructions, we extended the signal region for PHRASE events up to $1.4\ \mathrm{MeV/cm}$. As one can see in Fig. 2, there were three events in this energy loss window: two with $dE/dx = 0$, corresponding to the LIP triggers not matched by PHRASE, and one with $dE/dx \approx 1\ \mathrm{MeV/cm}$. The energy loss rate measured by ERP for this particular event was perfectly compatible with that measured by PHRASE. In the next section we discuss the origin of these events and show that all of them were

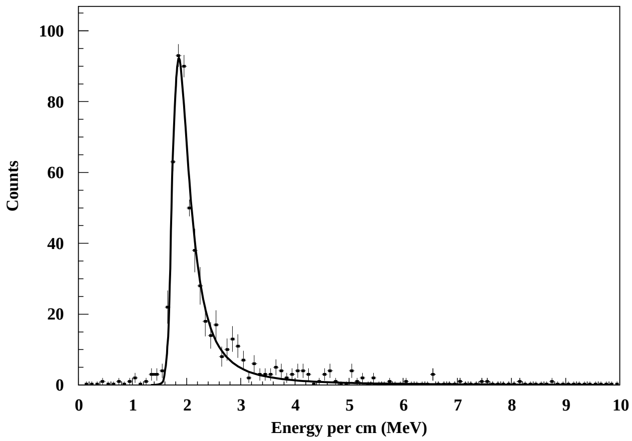

Fig. 3. Typical energy loss rate in a MACRO liquid scintillation counter. The superimposed fit is a Landau distribution folded with the photoelectron fluctuations. Note the low energy loss tail extending within the LIP region ($dE/dx < 1.4\,\mathrm{MeV/cm}$).

compatible with the expected background.

5 Background sources in the LIP search

There were two sources of background in this search for fractionally charged particles: the inefficiency of the PHRASE-LIP matching procedure and the finite resolution of the energy and path length measurements.

The first one came from the fact, already mentioned, that PHRASE and the general acquisition system operated asynchronously. Using the measured inefficiency ($0.07\,\%$) and the number of LIP/ST analyzed tracks (5126) we estimated 3.5 events without a good PHRASE matching, while 2 were observed.

The second one came from the physical and instrumental fluctuations of the energy and path length measurements. If one looks at a typical energy loss plot in a MACRO counter (Fig. 3) one can observe a low energy loss tail which extends within the LIP signal region. This tail comes from fluctuations of the photoelectron statistics, inefficiency in the light collection and occasional tracking errors. The contamination of the tail in the LIP signal region was $\approx 0.7\,\%$ for a single counter; then, a three-fold coincidence reduced this contamination to the level of $< 1/10^6$. However, when one looked at high statistics samples of tracks, the probability of observing this background in coincidence in more than one counter was not negligible; in fact, we estimated 1.2 background events due to tracking and energy reconstruction uncertainties in our 4 millions LIP triggers, while 1 was observed.

6 LIP flux limit and conclusions

Using the acceptance and live time quoted in Sections 3 and 4 respectively and including a further conservative $95\,\%$ overall efficiency, we computed a detector exposure of $1.5 \times 10^{15}\,\mathrm{cm^2\,s\,sr}$. To extract a LIP flux limit we used the Feldman and Cousins prescription (Feldman and Cousins, 1998): for an experiment with 5 expected and 3 observed background events, our exposure translated in a $90\,\%$ confidence level LIP flux limit of $1.52 \times 10^{-15}\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ in the charge interval $1/5 \div 2/3\,e$. This limit improves our previously published result by about one order of magnitude (MACRO, 2000). Presently we are extending this analysis to all MACRO data with the LIP trigger in operation, corresponding to ~ 5 years of live time. This should bring our final flux limit to the level of $\approx 6 \times 10^{-16}\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$.

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