Flux Upper Limits For Massive Rare Particles with the SLIM Experiment

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Abstract: The analysis of 380 m^2 SLIM detector after 4y exposure at the Chacaltaya Laboratory (Bolivia) is presented. Part of the work is devoted to the study carried out for defining the most efficient etching conditions and calibrations of the nuclear track detectors used in the experiment. We report flux upper limits for magnetic monopoles with masses in the range 10^5 - 10^{12} GeV. Our experiment is also sensitive to SQM nuggets and charged Q-balls; we discuss the implications of our observations on the characteristics of these Dark Matter candidates.

Introduction

The SLIM (Search for LIght magnetic Monopole) experiment was conceived as a natural extension of the MACRO experiment. This latter in fact, by exploiting the Nuclear Track Detector (NTD) technique together with other active systems (liquid scintillation and limited streamer tube detectors), was able to set the best upper limits on the flux of supermassive GUT Magnetic Monopoles (MMs) (m $> 10^{16}$ GeV) in the velocity range (β=v/c) $4\times 10^{-5} < \beta < 0.7$ [1]. However MM masses and magnetic charges depend on the underlying theory. For example Intermediate Mass Monopoles (IMMs) with 10^5 GeV $< m_{IMM} < 10^{12}$ GeV and g=2g_D, could have been produced in later phase transitions in the early Universe [2]. Underground experiments are limited to searches for IMM with $\beta > 10^{-2}$ and $m_{IMM} > 10^{10}$ GeV [3] [4]. To gain sizeable phase space (m,β) it is convenient to go to high altitude laboratories where large area detectors can be deployed. For the purpose, the relatively cheap technique of passive plastic detectors was employed. Further advantage offered by this technique was the possibility to be sensitive also to other types of exotic particles such as Nuclearites and Q-balls [5].

In this paper we present the results of the analysis of 380 m^2 of the SLIM detector after the foreseen 4 years operation.

The SLIM apparatus

The SLIM experiment, based on more than about 400 m^2 of NTDs (CR39 and Makrofol), has been deployed at the Chacaltaya High Altitude Laboratory (5230 m a.s.l.). The apparatus was completed in July 2001.

The track-etch detector is organised in modules of 24 cm x 24 cm, each made of 3 layers of CR39, 3 layers of polycarbonate and of an aluminum absorber 1 mm thick; each module is sealed in an aluminized plastic bag filled with dry air at 1 atm. From the experience acquired with MACRO, where the same CR39 material was used, we know that the detectors is not affected by "aging or fading effects", for exposure times as long as 10 years, that is, there is no appreciable dependence of the detector response on the time elapsed between the date of CR39 production and the passage of the particle (aging) or the passage of the particle and the detector processing (fading) [6].

Etching Procedures and Calibrations

Extensive studies were made in order to improve the procedures for the chemical etching of CR39 and Makrofol NTDs, the scanning with optical microscopes, the analysis and to keep a good scan efficiency at an acceptable scanning velocity. "Strong" and "soft" etching conditions were defined [7],[8].

Strong etching conditions (8N KOH + 1.25% ethyl alcohol at 77° C for 30 hours) are used for the first CR39 sheet in each module, in order to produce large tracks, easy to detect during scanning, and reduce the background.

Soft etching conditions (6N NaOH +1% ethyl alcohol at 70° C for 40 hours) are applied to the other CR39 layers in a module, if a candidate track is found in the first layer. Soft etching conditions allow more reliable measurements of the Restricted Energy Loss (REL) and of the direction of the incident particle. Makrofol layers are eventually etched in 6N KOH + Ethyl alcohol (20% by volume), at 50° C.

The detectors were calibrated with 158 A GeV In^{49+}, 30 A GeV Pb^{82+} beams and 1 A GeV Fe^{26+}. Fig. **??** shows the calibration data of our detectors as p-1 (p = v_T/v_B, where v_T and v_B are the track and bulk etching velocity, respectively) vs. REL for "soft" and "strong" etching.

For CR39, NTD "soft" etching sets the threshold at Z/β $\sim$7 (REL $\sim$50 MeV cm^2 g^{-1}). With strong etching the threshold is at Z/β $\sim$14 (REL $\sim$155 MeV cm^2 g^{-1}).

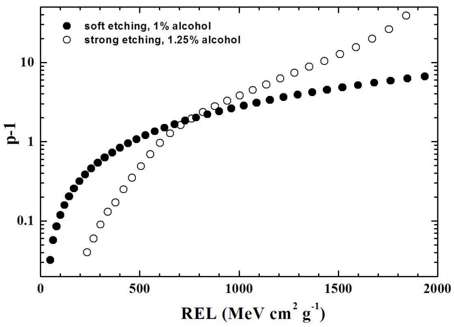

Figure 1: Reduced track etch rate (p-1) vs REL for the CR39 detectors etched in the "soft" (full circles) and "strong" (open circles) etching conditions.

The Makrofol polycarbonate has a higher threshold: Z/β $\sim$50 (REL $\sim$ 3 GeV cm^2 g^{-1}).

With the aforementioned etching conditions CR39 allows the detection of MMs for the whole β-range of $4 \times 10^{-5} < \beta < 1$ for MMs with $g > 2g_D$ and for dyons.

The Makrofol is useful for the detection of fast MMs.

Nuclearites and Q-balls with $\beta \sim 10^{-3}$ can be detected by both CR39 and Makrofol.

The analysis

The analysis of a SLIM module begins by etching the uppermost CR39 sheet using "strong" conditions in order to quickly reduce its thickness from 1.4 mm to $\sim$0.9 mm. Since MMs, nuclearites and Q-balls have a constant REL through the stack, the signal we are looking for is a hole or a biconical track with the two base-cone areas equal within the experimental uncertainties. After the strong etching, the sheets are scanned twice with a stereo microscope with a 3$\times$ magnification optical lens, looking for any possible optical inhomogeneity due to a particle track or a defect of the detector surface.

Selected inhomogeneities are further observed with an optical 20-40$\times$ microscope and classified either as defects or particle "tracks". For each par-

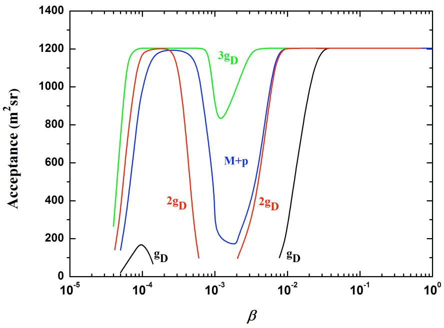

Figure 2: Geometrical acceptance of the SLIM experiment (S=382 m^2 of CR39 detectors, $\Delta \sim 4.07$ y) for a flux of downgoing (Ω=2π) magnetic monopoles with g=g$_D$, 2g$_D$, 3g$_D$ and for M+p composites.

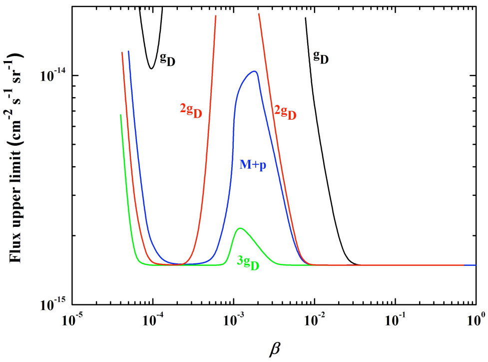

Figure 3: 90% CL upper limits for a downgoing flux of IMMs with g=g$_D$, 2g$_D$, 3g$_D$ and for dyons (M+p , g = g$_D$) plotted vs β.

ticle track the *axes* of the base-cone ellipse are measured; it is classified as “candidate” if p and θ on the front and back sides of the detector foil are equal to within 30%. For each candidate the azimuth angle φ and its position referred to fiducial marks are determined. Based on uncertainties on θ, φ and position a “coincidence” area ($\sim$ 0.5 cm^2) around the candidate expected position in the other layers is defined. The lowermost CR39 layer is etched in “soft etching” conditions; an accurate scanning at high magnification is performed around the candidate expected position. If a two-fold coincidence would be detected, also the CR39 middle layer would be analyzed as the lowermost one.

Results and Conclusions

Fig. **??** shows the geometrical acceptance of the SLIM detector (S=382 m^2) for a flux of downgoing magnetic monopoles with g=g$_D$, 2g$_D$, 3g$_D$ and for M+p composites plotted versus their β. No two-fold coincidence has been found, that is no magnetic monopole, nuclearite or Q-ball candidate was detected.

In Fig.**??** and **??** the 90% CL upper limits for a downgoing flux of MMs and nuclearites with $m_N < 8.4 \times 10^{14}$ GeV are shown. For nuclearites the present results extend to lower masses the existing limits [4] , [9]

Similar upper flux limits apply to Q-balls with galactic velocity.

In [10], different mechanisms of energy loss and propagation in relation to their possible detection with the SLIM detector were considered. In the absence of any candidate, we can rule out some of the hypothesized propagation mechanisms.

The analysis of almost the whole SLIM detector is completed. Additional 100 m^2 have been deployed in Koksil (Pakistan at 4600 m a.s.l.) since 2003. The analysis of the Koksil modules will further improve the present results.

Acknowledgments

We acknowledge the collaboration of E. Bottazzi, D. Di Ferdinando, L. Degli Esposti of INFN Bologna, G. Grandi and the technical staff of the Chacaltaya Laboratory. We thank INFN and ICTP for providing grants for non-italian citizens.

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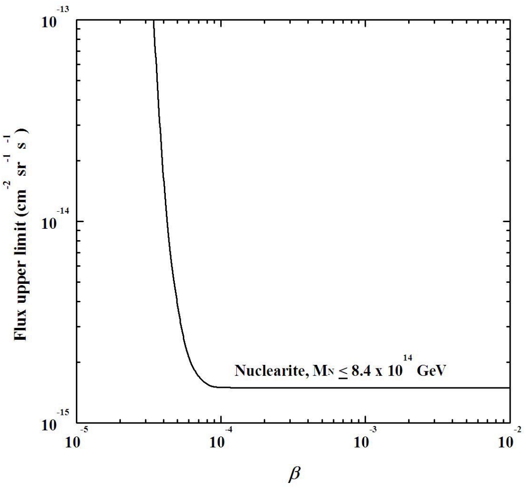

Figure 4: 90% CL upper limits for a downgoing flux of nuclearites.

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