Search for SQM in cosmic rays at high altitude laboratories

S Balestra 1, S Cecchini 1,7, F Fabbri 1, G Giacomelli 1, A Kumar 1,6, S Manzoor 1,4, J McDonald 3, E Medinaceli 1, L Patrizii 1, J Pinfold 3, V Popa 1, I Qureshi 4, O Saavedra 2,*, G Sher 4, M Shahzad 4, M Spurio 1, V Togo 1 and A Velarde 5 and A Zanini 2

1 Dip. Fisica dell’Universita di Bologna and INFN, 40127 Bologna, Italy
2 Dip. Fisica Sperimentale e Generale, Universita di Torino and INFN, 10125 Torino, Italy
3 Centre for Subatomic Research, Univ. of Alberta, Edmonton, Alberta T6G 2N4, Canada
4 PRD, PINSTECH, P.O. Nilore, Islamabad, Pakistan
5 Laboratorio de Fisica Cosmica de Chacaltaya, UMSA, La Paz, Bolivia
6 Dept. of Physics, Sant Longowal Institute of Eng. & Tech., Longowal, 148 106 India
7 INAF/IASF Sez. Bologna, 40129 Bologna, Italy
* Paper presented at the conference by O Saavedra

E-mail: saavedra@to.infn.it

Abstract. An experiment to search for intermediate mass magnetic monopoles (10^{5}-10^{12} GeV/c^{2}) and for strangelets or nuclearites in the cosmic radiation is exposed at Chacaltaya Laboratory (5230 m a.s.l.) and at Koksil, Himalaya, (4275 m a.s.l.). With the large area of nuclear track detectors (440 m^{2} at Chacaltaya and 100 m^{2} at Koksil) and the long time exposure will reach a sensitivity to the flux of SQM about 10^{-15} cm^{-2} s^{-1} sr^{-1} sr. The results of the analysis, in terms of search for SQM, of large array of detectors at Chacaltaya and exposed for more than 3.5 y are here reported.

1. Introduction
The existence of stable or metastable lumps of Strange Quark Matter (SQM) has been proposed by Witten [1] in 1984. SQM consists of roughly equal aggregates of up, down and strange quarks, it could represent the true ground state of QCD and may be the evidence for the QGP phase transition.

Several attempts have been done to search strangelets in different experimental conditions, but no evidence for their existence have been found till now. Alghought there was not dedicate experiment to search SQM directly in cosmic rays, few balloon experiments found some events, among their cosmic ray events, that can be considered as candidates for SQM [2]. On the other hand, the best limits to existence of GUT superheavy MMs and SQM has been set in underground laboratory by MACRO experiment [3], however there is still the possibility to explore their existence at lower masses. Intermediate Mass Monopoles (IMMs) of lower mass may be searched for with detectors located at high mountain altitudes or in balloons and satellites.

SQM nuggets should be stable for all baryon numbers in the range between ordinary heavy nuclei and neutron stars (A\sim 10^{57}). Nuclearite interaction with matter could depend on their mass and size [1]. In [4] different mechanisms of energy loss and propagation in relation to their
detectability with the SLIM (Search for Light magnetic Monopole) detector (described below) are considered. Much lower mass nuclearites ($A \sim 10^2$) could also reach the SLIM altitude coming from above. In the absence of any candidate, SLIM will be able to rule out some of the hypothesized propagation mechanisms, as suggested for example by Rybczynski et al. [5]

Fig. 1 shows the experimentally accessible region (minimal velocity at the top of the atmosphere versus the nuclearite mass) for arrays of Nuclear Track Detectors (NTDs) located at different altitudes. A similar plot for MMs can be found in [6].

![Figure 1](image1.png)  
**Figure 1.** Accessible regions in the plane (mass, $\beta$) for nuclearites at high altitudes and underground laboratories.

![Figure 2](image2.png)  
**Figure 2.** Upper limits (90% C.L.) to the flux of IMM obtained after analyzing 229.5 m$^2$ of SLIM CR39 detector.

2. The SLIM apparatus
The SLIM (Search for LIght magnetic Monopole) experiment, based on 440 m$^2$ of NTDs, has been deployed at the Chacaltaya High Altitude Laboratory (Bolivia, 5290 m a.s.l.) since 2001. Another 100 m$^2$ of NTDs have been installed at Koksil (Pakistan, 4600 m a.s.l.) since 2003. The complete description of the apparatus is given in [6]. Here we recall only a few features. The detector modules have been exposed under the roof of the Chacaltaya Laboratory at a height of 4 m from ground. The observed range of temperatures (0 - 25$^\circ$C) recorded every day allow us to conclude that no significant time variations have occurred in the detector response of the CR39 and Makrofol. Moreover the aluminized plastic bags in which the NTDs were sealed did not show any appreciable leakage of air (oxygen) after 3.5 years of exposure. We have reported in [6] the measurements of radon activity and the flux of cosmic ray neutrons which are in agreement with the more recent results at the same location [7].

3. Calibrations
Extensive test studies were made in order to improve the etching procedures of CR39 and Makrofol NTDs, improve the scanning and analysis procedures and speed, and keep a good scan efficiency. "Strong" and "soft" etching conditions have been defined for CR39 and Makrofol NTDs [8]. CR39 "strong" etching conditions - 8N KOH + 1.25% Ethyl alcohol at 77$^\circ$C for 30 hours. The strong etching is used for the first CR39 sheet in each module, in order to produce large tracks, easier to detect during scanning. CR39 "soft" etching conditions - 6N NaOH + 1% Ethyl alcohol at 70$^\circ$C for 40 hours. The soft etching is applied to the other CR39 layers in a module, if a candidate track is found in the first layer. It allows more reliable measurements of the restricted energy loss (REL) and of the direction of the incident particle.

The detectors have been calibrated using 1 A GeV $^{26+}$Fe from the BNL AGS, with 158 A GeV $^{49+}$In and 30 A GeV $^{82+}$Pb beams at the CERN SPS. For "soft" etching conditions the
threshold in CR39 is at REL $\sim 50$ MeV cm$^2$ g$^{-1}$; for strong etching the threshold is at REL $\sim 200$ MeV cm$^2$ g$^{-1}$. The Makrofol polycarbonate has a higher threshold (REL $\sim 2.5$ GeV cm$^2$ g$^{-1}$). More details on calibration can be found in [8]. Nuclearites with $\beta \sim 10^{-3}$ can be detected by both CR39 and Makrofol [8].

4. Analysis, results and conclusions

The analysis of a SLIM module begins by etching the top CR39 sheet using "strong" conditions in order to quickly reduce its thickness from 1.4 mm to $\sim 0.6$ mm. Since MMs, nuclearites and Q-balls have a constant REL through the stack, the signal looked 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 with a stereo microscope searching for a signal at low magnification (Field of View $\sim 1$ cm$^2$). Possible candidates are marked and further analysed under a high magnification microscope. We require the two values to be equal within 3 times the standard deviation of their difference. Finally a track is defined as a "candidate" if the REL and the incidence angles on the front and back sides are equal to within 15%. For each candidate the azimuth angle and its position referred to the fiducial marks are determined. To confirm the candidate track the bottom CR39 layer is then etched in the "soft" conditions; an accurate scan under an optical microscope with high magnification is performed in a region of about 0.5 mm around the expected candidate position. If a two-fold coincidence is found the middle layer of the CR39 (and, in case of a high Z candidate, the Makrofol layer) is analyzed with soft conditions.

Up to now no two-fold coincidence has been found, that is no magnetic monopole, nuclearite or Q-ball candidate was detected.

The area of 229.5 m$^2$ of CR39 have been etched and analysed, with an average exposure time of 3.57 years. No candidate passed the searching criteria: the 90% C.L. flux upper limits for fast ($\beta > 0.1$) IMM’s, with several magnetic charges (as shown in fig. 2) is at the level of $2.85 \times 10^{-15}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$. Similar upper limits are for nuclearites and Q-balls of any speed, all coming from above.

By the end of 2006 the 440 m$^2$ analysis will be completed and the experiment will reach a sensitivity of $10^{-15}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$ for $\beta \geq 10^{-2}$ and IMMs with $10^7 < M_{IMM} < 10^{13}$ GeV; the same sensitivity should be reached also for nuclearites and Q-balls with galactic velocities.

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References

[1] Witten A 1986 Phys. Rev. D 30 272
De Rujula A and Glashow S L 1984 Nature 312 734
[2] Price P B et al 1978 Phys. Rev. D 18 1382
Saito T et al 1990 Phys. Rev. Lett. 65 2094
Ichimura M et al 1993 Nuovo Cimento A 106 843
[3] Ambrosio M et al (MACRO Coll.) 2002 Eur. Phys. J. C 25 511 and Eur. Phys. J. C 26 163
[4] Balestra S et al 2005 preprint hep-ph/0506075
[5] Rybczynski M, Wlodarczyk Z and Wilk G 2001 Nuovo Cimento 24C 645
[6] Cecchini S et al 2003 Proc. 28th ICRC, Tsukuba 3 1657
[7] Schraube H et al 1999 Rad. Prot. Dos. 84 309
Zanini A et al 2001 Il Nuovo Cim. 24C 691
[8] Cecchini S et al 2005 Preprint hep-ex/0502034
Cecchini S et al 2005 Preprint hep-ex/0503003