Search for nuclearites with the SLIM detector

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Abstract. The strange quark matter (SQM) may be the ground state of QCD; nuggets of SQM could be present in cosmic rays (CR). SLIM is a large area experiment, using CR39 and Makrofol track etch detectors, presently deployed at the high altitude CR Laboratory of Chacaltaya, Bolivia. We discuss the expected properties of SQM, from the point of view of its search with SLIM. We present also some preliminary results from SLIM.

1 Introduction

SLIM is a large area experiment (440 m\textsuperscript{2}) installed at the Chacaltaya CR lab since 2001; an additional 100 m\textsuperscript{2} were installed at Koksil, Pakistan, since 2003 \textsuperscript{1} \textsuperscript{2} \textsuperscript{3} \textsuperscript{4} [1, 2, 3, 4]. With an average exposure time of about 4 years, SLIM would be sensitive to a flux of downgoing exotic particles at a level of $10^{-15}$ cm\textsuperscript{-2}sr\textsuperscript{-1}s\textsuperscript{-1}. The main goal of SLIM is the search for intermediate and low mass magnetic monopoles, but it can be sensible to other exotica, as nuggets of SQM (known as “nuclearites” or “strangelets”), Q-balls, etc.

We focus on the search for nuggets of SQM (both in the low mass region, in which they are expected to behave more or less like super-heavy nuclei, as well as in the intermediate mass region, that is if they are heavy enough to behave like micro-meteorites, but not so large to be able to cross the Earth) in the cosmic radiation, using the SLIM detector. After a short description of the experiment and of the analysis procedures, we briefly review the expected properties of SQM, relevant from the point of view of SLIM. We then investigate the arrival and detection conditions of cosmic ray SQM nuggets in SLIM and discuss some preliminary results yielded by the analysis of a part of the detector.

\footnote{This paper refers to the Chacaltaya location only.}
Figure 1: A sketch of a SLIM module. The stars indicate the detectors in which an etchable track is produced by the passage of different particles.

2 The experiment

SLIM (Search for Light and Intermediate mass Monopoles) is a large area detector (about 440 m$^2$) presently exposed to penetrating CR at the Laboratory of Chacaltaya (Bolivia), at an altitude of 5230 m a.s.l. The detector consists on modules of 24 × 24 cm$^2$, made of 3 sheets of CR39 and Makrofol nuclear track detectors (NTDs), and an aluminium absorber. This stack structure is similar to that used by the MACRO track-etch subdetector \[5, 6, 7\]. Fig. 1 shows the sketch of one module. Two additional Lexan sheets are placed on the top and the bottom of each stack; those detectors are not used in our analysis, their role is only to absorb some of the $\alpha$ particles produced by the Radon decays in the air around SLIM. The response of NTDs depends on the environmental conditions during their exposure; thus each module is sealed in a mylar bag, filled with dry air at the normal atmospheric pressure (note that the atmospheric pressure at Chacaltaya is 0.5 atm.).

The working principle of NTDs is qualitatively presented in Fig. 2. When a particle crosses such a detector, if the restricted energy loss (REL) is above some specific threshold, the polymeric structure is affected along its path yielding the so called “latent track”. In the particular case of a particle of electric charge $Z$ and velocity $\beta = v/c$, the produced damage is a function of $Z/\beta$. The tracks become visible after chemical etching, typically in aqueous solutions of NaOH or KOH, as the etching velocity along the latent track ($v_T$) is larger than the bulk etching velocity of the material ($v_B$). In the initial stages of the etching,
two cones are formed on both sides of the detector. The geometry of those cones depends on the REL of the incident particle; the measurement of the base area or of the length of the cones allows, through a suited calibration, to determine it. If the etching is prolonged, the two cones form a hole in the material; the REL information is lost, but the detector becomes more appropriate for fast scanning operations.

NTDs may be calibrated using beams of relativistic ions. A typical set-up consists of few sheets of detectors upstream of some target used for the beam fragmentation, and a set of downstream sheets of NTDs that would record the tracks of the non-fragmented beam ions as well as of the lighter ions produced in the target. Fig. 3 shows the distribution of the averaged areas of the etch cones in CR39 (averages are made on only two detector faces) produced by 158 AGeV In^{49} and its fragments. The exposure was made at the CERN SPS. By computing the REL values corresponding to different relativistic ions, the calibration curves for NTDs are obtained. Such curves, for the CR39 (the squares) and for the Makrofol (the circles) used in SLIM are presented in Fig. 4. The variable on the ordinate refers to the so called “reduced etching rate”, \( p = v_T/v_B \). The thresholds of the two detectors correspond to \( p = 1 \).

The strategy to search for exotic candidates in SLIM is the following: firstly, we perform a “strong” chemical etching of the upper CR39 detector in each module. In those conditions, large tracks (holes) are obtained, allowing an easy fast optical scan of the entire detector surface. If tracks are found, the other two CR39 sheets are “softly” etched (in order to obtain measurable etched cones along the possible track) and scanned in the areas predicted by the track in the first sheet. In the presence of tracks, the REL values and the orientation of tracks are measured. In order to accept a candidate, double coincidences (between the detectors above and below the Al absorber) are requested. If this is the case, the Makrofol foils are etched and scanned too. During the tests

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2 This is the first calibration of Makrofol based on the base-cone areas. 

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already performed on part of the SLIM modules, no such coincidences were found.

3 Strange Quark Matter in the cosmic rays: strangelets and nuclearites

SQM could be the ground state of quantum chromodynamics [10]. It is assumed that SQM is made of $u$, $d$ and $s$ quarks in nearly equal proportions. As the chemical potential of the $s$ quarks in SQM is slightly larger than for $u$ and $d$ quarks, SQM is always positively charged, so electrons could neutralize it. For small SQM nuggets ($M \lesssim 10^7$ GeV) the electrons would form an electronic cloud around the quark core; for larger masses some electrons or, for a quark bag radius $R \geq 1\text{A}; M \geq 8.4 \times 10^{14}\text{GeV}$, all the electrons would be in equilibrium inside the SQM [12, 13].

SQM is expected to have a density slightly larger than ordinary nuclear matter [10, 14]: the relation between the mass $M$ of SQM lumps and their baryonic number $A$ would be $M(\text{GeV}) \lesssim 0.93A$.

It was hypothesized that nuggets of SQM, with masses from those of heavy nuclei (in this mass region we are going to call them strangelets) to much higher values (nuclearites), produced in the Early Universe or in violent astrophysical processes, could be present in the cosmic radiation [11].

An upper limit for the flux of nuclearites may be obtained assuming that they represent the main contribution to the local Dark Matter (DM) density,
\[ \rho_{DM} \approx 10^{-24} \text{ g cm}^{-3} \] [11].

\[ \Phi_{\text{max}} = \frac{\rho_{DM} v^2}{2\pi M}, \] (1)

where \( v \) and \( M \) are the nuclearite average velocity and mass, respectively.

Calculations describing the production (through binary strange stars tidal disruption) and the galactic propagation of cosmic ray nuclearites were recently published [15]. The results could be valid as orders of magnitude for the entire mass range of interest.

### 3.1 Strangelets

SQM should be stable for all masses larger than about 300 GeV [11]. Strangelets with masses up to at least the multi-TeV region could be ionized and could be accelerated to relativistic velocities by the same astrophysical mechanisms of normal nuclei of the primary CR.

They would interact with detectors (in particular NTDs) in ways similar to heavy ions, but with different \( Z/A \). In ref. [12] SQM is described in analogy with the liquid-drop model of normal nuclei; the obtained charge versus mass relation is shown in Fig. 5A by the solid line, labeled “(1)”. Other authors found different relations: \( Z \approx 0.1A \) for \( A \lesssim 700 \) and \( Z \approx 8A^{1/3} \) for larger masses [16]: this charge to mass relation is shown in Fig. 5 as the dashed line, labeled “(2)”. In [14] it was assumed that quarks with different color and flavor
quantum numbers form Cooper pairs inside the SQM, the so-called color-flavor
locked (CFL) phase, increasing the stability of the strangelets. In this case, the
charge relation would be $Z \simeq 0.3A^{2/3}$, shown as the dash-dotted line in Fig. 5A
labeled “(3).”

Several CR experiments reported possible candidate events that would sug-
gest anomalously low charge to mass ($Z/A$) ratios, which could correspond to
those expected for SQM [12]. Such candidates are reviewed in [17, 18]. As
strangelets could have the same origin as CR heavy nuclei, their abundances in
the cosmic radiation could follow the same mass dependence, $\Phi \propto M^{-7.5}$, [17].
The existing candidates do not contradict such an hypothesis. The solid line
in Fig. 6 is the expected flux versus strangelet mass, assuming that the above
assumptions are correct.

Different nuclearite flux estimates were recently published [15]. They are
based on the hypothesis that large nuclearites (with masses $10^{-3} - 10^{-2}$
solar masses) are produced in binary strange stars systems, before their gravita-
tional collapse. The propagation inside the galaxy considers also the escape,
spallation (through which smaller nuclearites are produced) and re-acceleration
mechanisms. Nuclearite decays are not considered, as SQM is supposed to be ab-
olutely stable. The predicted strangelet fluxes around the Earth are presented
in Fig. 5B for “normal” and CFL strangelets as the dashed and the dot-dashed

Figure 5: A: Strangelet electric charge versus mass for different hypotheses
discussed in refs. [12, 14, 16]. See text for details. B: Expected fluxes for
strangelets in the CR near the Earth. The solid line corresponds to the as-
sumption that their abundances follow the same rule as heavy CR nuclei [17].
The dashed and dot-dashed lines are from Ref. [15], and refer to “normal” and CFL
strangelets.
lines, respectively. The differences originate from the different charge-to-mass ratios.

The CR39 used in SLIM is sensitive (in the conditions of the “strong” etching) to particles with REL $\geq 200$ MeV g$^{-1}$ cm$^2$ s$^{-1}$. This implies a minimum $A$ (at the level of the detector) between 200 and 600, depending on the chosen $A/Z$ model.

If strangelets would interact with the Earth’s atmosphere in the same way as CR nuclei, they would not reach experiments at mountain altitude. Different theoretical scenarios, both based on the SQM stability, were introduced in order to allow their deep penetration in the atmosphere; none of those mechanisms would allow them anyway to reach sea level.

Mass and size decrease of strangelets during propagation. In [17] it was assumed that strangelets could penetrate the atmosphere if their size and mass are reduced through successive interactions with the atomic air nuclei. This scenario is based on the spectator-participant picture. Two interaction models are considered: quark-quark (“standard”), and collective (“tube-like”). At each interaction the strangelet mass is reduced by about the mass of a Nitrogen nucleus (in the “standard” model), or by more (in the “tube-like model”), while the spectator quarks form a lighter strangelet that continues its flight with essentially the same velocity. Once a critical mass is reached ($A \approx 300 - 400$) neutrons would start to evaporate from strangelets; for $A \leq 230$ the SQM would become unstable and decay into normal matter. In ref. [19] an estimate was made of the sensitivity of a NTD experiment at Chacaltaya: the mass number of a nuclearite penetrating the atmosphere down to that altitude would be reduced by a factor $\approx 1/7$.

In this scenario, the minimum strangelet $A$ value at the top of the atmosphere should be between 1400 and 4200, in order to be detected in SLIM. Assuming different strangelet structure and flux hypotheses, the expected fluxes in the Earth’s vicinity would range between some $10^{-12}$ and $10^{-15}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$. More detailed calculations are given in Ref. [3]. Due to its expected sensitivity, SLIM may discern between different combinations of flux-structure hypotheses.

Accretion of neutrons and protons during propagation. A completely different propagation scenario was proposed in [18]. The authors assume that strangelets would pick-up nuclear matter during interactions with air nuclei. After each interaction, the strangelet mass would increase by about the atomic mass of Nitrogen, with a corresponding reduction of velocity. As the mass grows larger, the loss in velocity becomes smaller. They estimate that a strangelet of an initial $A \approx 64$ and an electric charge of about +2 could arrive at about 3600 m a.s.l. with $A \approx 340$ (3600 m is the altitude of a proposed NTD experiment in Sandakphu, India [18]). This mechanism would also imply an increase of the electric charge of the strangelet, thus an increase of the Coulomb barrier; this may be its main difficulty. The stability of low mass strangelets is another questionable aspect of such a model; the expected fluxes would be

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3The threshold of a NTD depends on the etching conditions. A relatively high threshold for CR39 was chosen in order to reduce the background due to recoil tracks, neutron interactions and the ambient radon radioactivity.
larger than in the fragmentation scenario, but, for this reason, they are hard to estimate. Such large fluxes seem to be in disagreement with the preliminary SLIM results, presented in the last Section of this paper.

3.2 Nuclearites

In [11] was postulated that elastic collisions with atoms and molecules of the traversed medium are the only relevant energy loss mechanism of non-relativistic nuclearites with large masses,

\[ \frac{dE}{dx} = -\sigma \rho v^2, \]

where \( \rho \) is the density of the traversed medium, \( v \) is the nuclearite velocity and \( \sigma \) is its cross section:

\[ \sigma = \begin{cases} \pi (3M/4\pi \rho_N)^{2/3} & \text{for } M \geq 8.4 \times 10^{14} \text{ GeV (corresponding to } R_N \simeq 1 \text{ Å}) \\ \pi \times 10^{-16} \text{cm}^2 & \text{for lower mass nuclearites} \end{cases} \]

with \( \rho_N = 3.6 \times 10^{16} \text{ g cm}^{-3} \). The cross section for nuclearites with \( M < 8.4 \times 10^{14} \text{ GeV} \) is determined by their electronic cloud. For nuclearites gravitationally trapped in our Galaxy, the average velocity would be \( \beta = v/c \simeq 10^{-3} \).

Very large nuclearites (\( M \gtrsim 3 \times 10^{22} \text{ GeV} \)) could cross the Earth; as the SLIM sensitivity is above the DM flux limit (Eq. 1) we consider here only down-going nuclearites.

A nuclearite of mass \( M \) entering the atmosphere with an initial velocity \( v_0 \ll c \), after crossing a depth \( L \) will be slowed down to

\[ v(L) = v_0 e^{-\int_0^L \rho(x) dx} \]

where \( \rho(x) \) is the air density. In the following we consider the parametrization of the standard atmosphere from [20],

\[ \rho(h) = a e^{-b \frac{h}{H}} = a e^{-\frac{h-b}{b}}, \]

where \( h \) is the altitude, \( a = 1.2 \times 10^{-3} \text{g cm}^{-3} \) and \( b \approx 8.57 \times 10^{5} \text{ cm} \); \( H \) is the total height of the atmosphere ( \( \simeq 50 \text{ km} \)). The integral in Eq. 4 may be solved analytically.

Fig. 6A shows the velocity with which nuclearites of different masses reach heights corresponding to typical balloon experiments (\( \simeq 40 \text{ km} \)), to SLIM, (5.29 km) and sea level. A computation valid for MACRO [7] (at a depth of 3400 mwe) is also included. The velocity thresholds for detection in CR39 and in Makrofol are shown as the dashed curves. The decrease of the velocity thresholds for nuclearite masses larger than \( 8.4 \times 10^{14} \text{ GeV} \) is due to the change in the nuclearite cross section, according to Eq. 3. An experiment at the Chacaltaya altitude lowers the minimum detectable nuclearite mass by a factor of about 2 with respect to an experiment performed at sea level. If the mass abundance of
Figure 6: A: Solid lines: arrival velocities of IMNs at different depths versus nuclearite mass, assuming an initial velocity outside the atmosphere of $\beta = 10^{-3}$. The nuclearites are supposed to come from above, close to the vertical direction. The dashed lines show the detection thresholds in CR39 (in the SLIM etching and Makrofol). B: Nuclearite detection conditions in CR39 (solid curves) and Makrofol (dashed curves), for experiments located at different altitudes.

nuclearites decreases strongly with increasing mass this could yield an important increase in sensitivity.

More general nuclearite detection conditions in CR39 and Makrofol (expressed as the minimum velocity at the top of the atmosphere versus the nuclearite mass) for different experimental locations are shown in Fig. 6B. In this case, the constraint is that nuclearites have the minimum velocity at the detector level in order to produce a track\footnote{Preliminary results and conclusions}{.}

Searches for nuclearites (mostly IMNs) were performed by different experiments\,\cite{21, 22}. The best flux upper limit was set by the MACRO experiment: for nuclearites with $\beta \simeq 10^{-3}$ and $10^{14}$ GeV $< M < 10^{22}$ GeV, the 90\% C.L. upper limit is at the level of $2 \times 10^{-16}$ cm$^{-2}$sr$^{-1}$s$^{-1}$, as a byproduct of the search for GUT magnetic monopoles\,\cite{23, 24}.

### 4 Preliminary results and conclusions

Till now, we analyzed about 214 m$^2$ of the SLIM detector, with an averaged exposure time at Chacaltaya of 3.5 years. As no candidate was found, the present 90\% CL upper limit for a flux of downgoing strangelets and nuclearites\footnote{The CR39 threshold in the MACRO case was lower than for SLIM, due to the very low background at Gran Sasso Lab.}
with $M \gtrsim 3 \times 10^{13}$ GeV, valid also for relativistic monopoles, is $3 \times 10^{-15}$ cm$^{-2}$s$^{-1}$sr$^{-1}$. This limit disfavors the hypothesis of the accretion of matter by strangelets going down in the atmosphere, and can constrain some production or propagation models.

We intend to complete the analysis by the end of 2006. Even if no magnetic monopole or SQM candidate will be found, SLIM will yield significant limits in mass regions not yet explored by other experiments, and will impose strong constraints on different scenarios describing the production and propagation of strangelets.

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