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New upper limit on Strange Quark Matter abundance in cosmic rays with the PAMELA space experiment

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In this work we present results for direct search of Strange Quark Matter in cosmic rays with the PAMELA space spectrometer. If this state of matter exists it may be present in cosmic rays as particles, called strangelets, having an anomalously high mass-to-charge (A/Z) ratio. A direct search in space is complementary to those from ground based spectrometers. Furthermore, it has the advantage of being potentially capable of directly identifying these particles, without any assumption on their interaction model with Earth's atmosphere and the long term stability in terrestrial and lunar rocks. In the energy range from 1 to $\sim 1.0 \times 10^3$ GV no such particles were found in the data collected by PAMELA between 2006 and 2009. An upper limit on the strangelet flux in cosmic rays was therefore set for particles with charge $1 \leq Z \leq 8$ and in mass $4 \leq \mathrm{A} \leq 1.2 \times 10^5$. This limit as a function of mass and as a function of magnetic rigidity allows to constrain models of SQM production and propagation in the Galaxy.

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1. Strange Quark Matter

The existence of a different state of hadronic matter other than the ordinary nuclear matter, called Strange Quark Matter (SQM), has been proposed for the first time in the '80s [1]. This kind of hadronic matter would be composed by a roughly equivalent number of u, d and s quarks. Many models suggest that the presence of strange quarks in hadrons may lower the nucleon Fermi level with respect to a system with only ordinary quark flavours [2]. If that is the case SQM should be stable and may constitute the true ground state of hadronic matter. SQM with an equal number of u, d, and s quarks is neutrally charged, however the neutrality condition may be approximate, allowing strangelets to have a small residual electrical charge. In case of a small excess of one quark species, a slightly charged particle would therefore have a very high mass and a low electric charge (apparent $A \gg Z$). The mass of a strangelet could range from the minimum stable mass [3], which strongly depends on the model employed for the calculations, up to values of $A \simeq 10^{57}$ [2]. Several papers [8, 9] have studied the conditions required to have stability for these objects: using the MIT bag model approximation [10] heavier objects appear more stable. More detailed models that take into account shell structure [11] in nuclear matter predict stability regions for strangelets with completely-filled quark shells, allowing also for lighter particles to be stable or meta-stable.
SQM could be produced in the Big Bang [3], be part of baryonic dark matter [4], present in the core of neutron stars or exist as "Strange Quark Stars" [6]. Lumps of SQM could be ejected as a consequence of collision of these stars in binary systems; subsequent collisions can inject small fragments of SQM (called strangelets) in the Galaxy, reaching the Earth where they could be identified with cosmic ray detectors or mass spectrometers.
Various experiments have tried to search for SQM in different environments, on ground, on balloons and on satellites. A review on strangelet searches and models can be found in [7].

Heavy ion experiments, such as NA52@CERN [12], tried to produce long-lived massive strangelets in the hot and dense environment provided by two colliding nuclei but no candidates were observed [13].

The Yale Wright Nuclear Structure Laboratory (WNSL) accelerator [14] was used as a mass spectrometer to search for SQM particles in lunar soil, where they could have accumulated on the Moon's surface without being deflected by the geomagnetic field. No events for Z =5,6,7,8,9 and 11 with $42 < A < 70$ were found, with a concentration of strangelets in lunar soil lower than 10^{-16} with respect to normal matter at 95% CL . Such ground based searches have the advantage of using a large amount of matter, providing high statistics. Using space-borne instruments or stratospheric balloon payloads, direct search of SQM can be performed. This has the advantage of being capable of directly identify these particles without any assumption on the interaction model with Earth's atmosphere. Furthermore, it allows to probe for lighter and potentially more abundant particles. Indeed over the years, different space-borne and balloon experiments tried to detect a strangelets, e.g. Fig 3:

- The balloon experiment HECRO-81 [19] has reported the observation of two events with Z $\sim$ 14. The mass number for this events was estimated to be A $\sim$ 350.
- The ARIEL-6 satellite [15], with Cerenkov counters and an exposure of 494 m^2 days set an upper limit at 90% CL on the flux of particles with $Z > 88$ of $\simeq 5.9 \times 10^{-12}\, cm^2\, sr^{-1}\, s^{-1}$.

- The HEAO-3 apparatus [16], with an exposure of 8 $\times 10^{11}\, cm^2\, sr\, s$ did not observe any event with $Z > 92$, providing an upper limit of 2.9 $\times 10^{-12}\, cm^2\, sr^{-1}\, s^{-1}$.

- The Skylab experiment [17], with an exposure of $1.2 \times 10^{12}\, cm^2\, sr\, s$, did not find any valid candidate, establishing an upper limit of 2.9 $\times 10^{-12}\, cm^2\, sr^{-1}\, s^{-1}$ (at 90% CL) for particles with $Z > 110$.

- The experiment TREK [18] set an upper limit for nuclei with Z $>$ 92, of 1.7 $\times 10^{-12}\, cm^2\, sr^{-1}\, s^{-1}$.

- Searches with BESS balloon spectrometer [23] have yielded no candidates for $5 \leq Z \leq 26$ for $Z/A < 0.2$.

- The AMS-01 experiment has reported the observation of two events: $Z = 8$, $A = 20$, 3.93 GV and $Z = 4$, $A = 50$, 5.13 GV [22].

2. PAMELA detector

PAMELA [24] is a space-borne detector orbiting the Earth at $\simeq$ 600 km altitude on board the Russian Resurs-DK1 satellite. Its primary goal is the study of cosmic rays (proton, helium, nuclei) in the energy range 50 MeV - 1.2 TeV [25], focusing mostly on the rare antiparticle (positron, antiproton) component. For this purpose, the apparatus consists of a number of redundant detectors capable of identifying particles providing information on charge, mass, rigidity and velocity over a very wide energy range. The instrument is built around a permanent magnet with a silicon microstrip tracker, providing charge and track deflection information. A scintillator system provides trigger, time of flight and additional charge information. A silicon-tungsten calorimeter is used to perform hadron/lepton separation in the measurement of antimatter component. An anticoincidence system of plastic scintillators is used to reject spurious events in the offline phase. A more detailed description of the device and the data handling can be found in [21].

3. The analysis

PAMELA is thus particularly well-suited for SQM search. Indeed, the magnetic spectrometer, together with the TOF system allows to probe very efficiently the range of light mass ($4 \leq A \leq 10^5$). In case of SQM produced by the collision of Strange Quark Stars and subsequent fragmentation in the Galaxy, this mass range should be the one most favoured and potentially the one with the highest flux, even though models disagree on the expected flux [5, 6, 43, 44, 45]. Rigidity dependent upper limits on the SQM flux can thus constrain several models of strangelets production and propagation in the Galaxy. In this work we present the most stringent limits for nuclei from Hydrogen to Oxygen obtained in space using the data collected by the PAMELA experiment from July 2006 to December 2009. For an incoming particle, PAMELA is capable of measuring the charge Z, the velocity v and the magnetic rigidity R; it is therefore possible to calculate the mass $M = m_p A$ (where m_p is the proton mass and A is the atomic number) of the particle itself through the relation

$$M = m_p \cdot A = \frac{Z \cdot R}{\beta \cdot \gamma} \tag{3.1}$$

where $\beta=\frac{v}{c}$ is the particle velocity and γ is the Lorentz factor. The quantity $\frac{A}{Z}=\frac{R}{m_p\beta\gamma}$ can be used to characterize elements both of ordinary and exotic origin. For example, stable nuclei of ordinary matter have values of $1 \leq A/Z \leq 3$, with average value of $A/Z \simeq 2$, corresponding to an almost equal number of protons and neutrons. Unstable nuclei, which can be also produced in hadronic interactions in the detector, could have a higher A/Z ratio; SQM is expected to be more stable for higher mass/charge ratios.

In order to search for SQM with PAMELA, the following observables have been used to determine the A/Z value:

- *Velocity*. Up to 12 β measurements are provided by the Time-of-Flight system, each one obtained combining the information from the 6 planes of scintillators. Given all the possible combinations between the planes, a total averaged estimation for β can be achieved and spurious velocity measurements are rejected.
- *Deflection*. The curvature η of the particle inside the magnetic field is measured in the tracking system with up to 6 planes in the bending view, allowing different checks of the measured rigidity $R=\eta^{-1}$, reconstructed by a fitting algorithm.
- dE/dx. The multiple measurements in the tracker (up to 12) and in the scintillators (up to 6) provide information on particle charge Z and also an independent check of the particle velocity according to the Bethe-Bloch formula.

A compromise between selection efficiency and noise rejection has been reached requiring particles with at least 4 tracker planes hit and agreement between the majority of the β measurements in the TOF. A better isotopic resolution [28] can be achieved by placing stronger selection criteria on the TOF and the magnetic spectrometer, but at the expense of lower selection efficiency.

The analysis has been divided in two regions of interest:

(a) low velocity events, with $\beta < 1$ and with R $<$ 5 GV;

(b) relativistic events, where $\beta \simeq 1$ and with R $>$ 5 GV.

In Fig 1 (left) the A/Z distribution for particles with $Z=1,2$ and with $R<5$ GV **(a)** is shown. The region $A/Z>8$ has been considered in this work; because of the possible presence of metastable Helium isotopes that can be produced in interaction with the top of the detector (e.g. ^6He and ^8He) and the presence of tritium, this region appears safe enough to search for anomalous A/Z candidates.

For $R \geq 5$ GV **(b)**, a SQM candidate would exhibit a value of $\beta < 1$. In Fig 1 (right) the $1/\beta$ distribution for $Z=1,2$ particles is shown.

The search of heavy particles has been limited in the region of $2 < 1/\beta < 50$. The value of $1/\beta$ = 50 is determined by the TOF system, which can record events hitting the planes with a maximum time difference of 0.1 ms [29].

The data set under study shows no candidate in the above mentioned regions for 1.9×10^7 H, 5.8×10^6 He and 3.2×10^4 nuclei with $3 \leq Z \leq 8$. The overall upper limit for a particle with $1 \leq Z \leq 8$ is therefore 1.2×10^{-7}. The high precision measurements and high statistics allow to

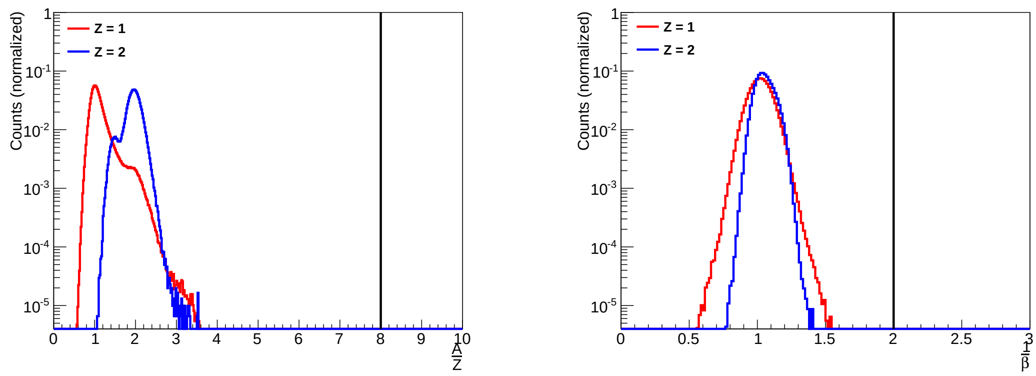

Figure 1: Left panel: A/Z distribution for H, He, considering events with $R < 5$ GV. The bump in the distribution of H and He indicates the presence of isotopes such as Deuterium, Tritium and ^{3}He. Right panel: $1/\beta$ distribution for $R \geq 5$ GV H, He. Note the better resolution for Helium due to the higher charge released in the scintillators.

set both differential and integral upper limits as function of rigidity for several species. Assuming poissonian statistics, the upper limit (95% CL) on the differential flux over the rigidity interval between R and R+ΔR is given by

$$l_Z(R+\Delta R) = \frac{3}{\alpha_Z(R+\Delta R)} \tag{3.2}$$

where $\alpha_Z = \alpha_Z(R)$ is the acceptance of PAMELA, which is determined by the Geometrical Factor GF, the live time T_{live} and the selection efficiency ε of the instrument. The selection criteria (and thus the efficiency) vary with nuclear species and the particle rigidity: $\varepsilon = \varepsilon(Z,R)$. Given the differential cosmic ray flux for each species Z, $\phi_Z(R)$, can be written as

$$\phi_Z(R+\Delta R) = \frac{n_Z(R+\Delta R)}{T_{live} \cdot GF \cdot \Delta R \cdot \varepsilon}. \tag{3.3}$$

Consequently, the upper limit $l_Z(R)$, can be expressed as

$$l_Z(R+\Delta R) = \frac{3 \cdot \phi_Z(R+\Delta R)}{n_Z(R+\Delta R)} \tag{3.4}$$

where $n_Z(R)$ is the number of nuclei with charge Z measured in the interval between R and $R+\Delta R$.

It is therefore possible to evaluate $l_Z(R+\Delta R)$ from the number of nuclei n_Z and the theoretical flux ϕ_Z for a particular species Z, without explicitly evaluating $\varepsilon(Z,R)$.

Analogously, an integral upper limit can be defined, $L_Z(R)$, taking the ratio between the integral flux $\Phi_Z(R) = \int_{R'>R} \phi_Z(R')dR'$ and the integral counts $N_Z(R) = \int_{R'>R} n_Z(R')dR'$:

$$L_Z(R) = \frac{3 \cdot \Phi_Z(R)}{N_Z(R)}. \tag{3.5}$$

In Fig 2 the value of $L_Z(R)$ is shown: an upper limit as a function of rigidity allows to directly compare the SQM flux with the cosmic ray one and therefore improve SQM production and propagation models.

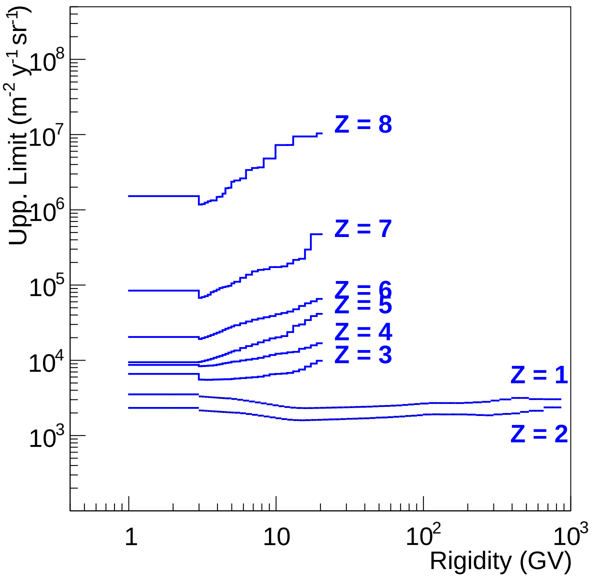

Figure 2: Integral upper limit in terms of rigidity, as measured by PAMELA, for nuclei up to Z=8.

Furthermore, to compare with previous measurements the resulting integral upper limit was expressed as a function of mass M. This can be achieved transforming the original rigidity binning in a mass binning, using Eq. 3.1. In a plane R-β, the events are collected with a binning that can be thought as rectangles with vertices in R, $R+\Delta R$, β_{min} and β_{max}. The minimum and maximum β are evaluated according to Eq. 3.1, considering that a particle with given A/Z would have different velocity at different rigidity. For a fixed rigidity, a mass interval is defined, expressed in baryon number A, and it ranges from $A_{min} = ZR \cdot (m_p \beta_{max} \gamma_{max})^{-1}$ to $A_{max} = ZR \cdot (m_p \beta_{min} \gamma_{min})^{-1}$. In this way we map each rectangle in R-β plane into a trapezoid in R-A plane. For the explored mass range, we then obtain the upper limit as a function of Baryon Number A, which is shown in Fig 3.

4. Results and conclusions

In conclusion, we have analysed PAMELA data from July 2006 to December 2009, looking for Strange Quark Matter in space. No anomalous A/Z particle has been found (for $Z \leq 8$) in the rigidity range $1 \leq \mathrm{R} \leq 1.0 \times 10^3$ GV and mass range $4 \leq \mathrm{A} \leq 1.2 \times 10^5$ improving upper limits as a function of rigidity and baryon number (Fig 2, 3). This can help in constraining or ruling out models of SQM production and propagation in Big Bang and in the Galaxy. Our data exclude some models in the light mass range. Since data taking is continuing, the search will continue with a more extended data set.

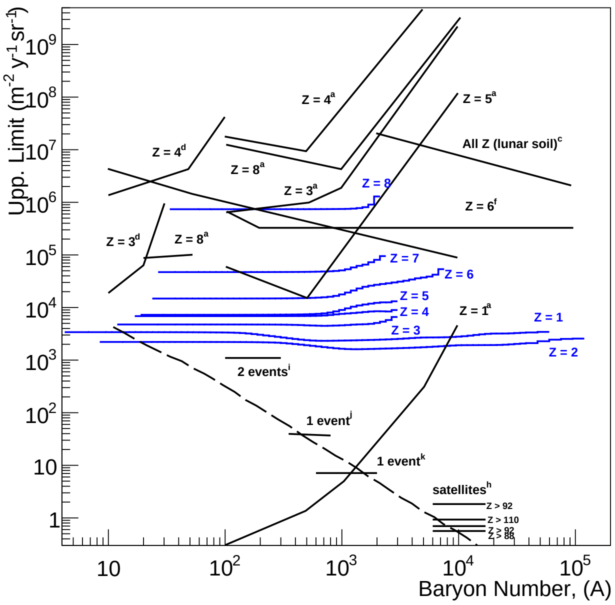

Figure 3: Integral upper limits in terms of Baryon number (A) as measured by PAMELA, for nuclei up to Z=8 compared with previous results. The dashed line is the predicted flux [2]. The solid black lines represent previous experimental limits for strangelets which are translated into flux limits. The curves labelled a[30], b[31], d[32], e[33] and f[34], come from relic searches in terrestrial material. The curve labelled c[36] comes from searches which bombard materials with slow moving heavy ions. The curves labelled with h[15, 16, 17, 18] represent satellite based searches. The curves labelled with i[19], j[23] and k[42] represent previous detections of events consistent with strangelet signals by balloon-borne cosmic ray detectors.

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