New Upper Limit on Strange Quark Matter Abundance in Cosmic Rays with the PAMELA Space Experiment

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(Received 10 July 2015; revised manuscript received 7 August 2015; published 8 September 2015)

In this work we present results of a direct search for strange quark matter (SQM) 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 a high density and 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 rigidity range from 1.0 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 mass $4 \leq A \leq 1.2 \times 10^5$. This limit as a function of mass and as a function of magnetic rigidity allows us to constrain models of SQM production and propagation in the Galaxy.

DOI: 10.1103/PhysRevLett.115.111101 PACS numbers: 98.70.Sa, 21.65.Qr, 95.55.Vj

The existence of a different state of hadronic matter other than the ordinary nuclear matter, called strange quark matter (SQM), was proposed for the first time in the 1980s [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 flavors [2]. If that is the case, SQM should be stable and may constitute the true ground state of hadronic matter. Instead of being separated in nucleons, quarks would therefore be lumped together, so that quark matter would be much denser than ordinary matter. SQM with an equal number of u, d, and s quarks is electrically neutral; however, the neutrality condition may be approximate, allowing strangelets to have a small residual electrical charge. In the 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 [4,5] have studied the conditions required to have stability for these objects: using the MIT bag model approximation [6], heavier objects appear more stable. More detailed models that take into account shell structure [7] in nuclear matter predict stability regions for strangelets with completely filled quark shells, allowing also for lighter particles to be stable or metastable.

SQM could be produced in the big bang [3], be part of baryonic dark matter [8], be present in the core of neutron stars, or exist as "strange quark stars" [9]. 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, reach 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 the ground, on balloons, and on satellites. A review of strangelet searches and models can be found in Ref. [10].

Heavy ion experiments, such as NA52@CERN [11], tried to produce long-lived massive strangelets in the hot and dense environment provided by two colliding nuclei, but no candidates were observed [12].

The Yale Wright Nuclear Structure Laboratory accelerator [13] 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% C.L. 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, a direct search of SQM can also be performed. This has the advantage of being capable of directly identifying these particles without any assumption on the interaction model with Earth's atmosphere. Furthermore, it allows us to probe for lighter and potentially more abundant particles.

Indeed, over the years, different space-borne and balloon experiments tried to detect strangelets.

(i) The balloon experiment HECRO-81 [14] has reported the observation of two events with $Z \sim 14$. The mass number for these events was estimated to be $A \sim 350$.

(ii) The ARIEL-6 satellite [15], with Cherenkov counters, presented an analysis of $Z \geq 34$ during 427 days of data taking, finding no SQM candidates.

(iii) The HEAO-3 apparatus [16], with an exposure of 8×10^{11} cm^2 sr s, reported both abundances of odd-even element pairs ($33 \leq Z \leq 60$) and abundances of element groups ($Z > 60$) and did not find any candidate.

(iv) The SkyLab experiment [17], with 1.2 m^2 Lexan track detectors, did not find any valid candidate in the superheavy ($Z > 110$) nuclei range.

(v) The experiment TREK [18] explored the $Z > 50$ region, finding no strangelet candidate.

(vi) Searches with the BESS balloon spectrometer [19] have yielded no candidates for $5 \leq Z \leq 26$ for $Z/A < 0.2$.

(vii) 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 [20].

PAMELA [21] is a space-borne detector orbiting 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 [22], focusing mostly on the rare antiparticle (positron [23,24], antiproton [25,26]) 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. The spatial resolution of the silicon sensors in the bending view is (3.0 ± 0.1) μm, resulting in a maximum detectable rigidity of 1.2 TV [21]. A scintillator system provides trigger, time-of-flight (with a measured time resolution better than 300 ps), and additional charge information. A silicon-tungsten calorimeter is used to perform hadron-lepton separation in the measurement of the antimatter component. An anticoincidence system of plastic scintillators is used to reject spurious events in the off-line phase. A more detailed description of the device and the data handling can be found in Ref. [27]. PAMELA is thus particularly well suited for a SQM search. Indeed, the magnetic spectrometer, together with the TOF system allow us to very efficiently probe the range of light mass ($4 \leq A \leq 10^5$). In the 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 favored and potentially the one with the highest flux, even though models disagree on the expected flux [9,28–31]. Rigidity-dependent upper limits on the SQM flux can thus constrain several models of strangelet production and propagation in the Galaxy. In this work we present the most stringent limits for SQM particles with the same charge as 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

$$M = m_p A = \frac{ZR}{\beta\gamma}, \qquad (1)$$

where $\beta = v/c$ is the particle velocity and γ is the Lorentz factor. The quantity $A/Z = R/m_p\beta\gamma$ can be used to characterize elements of both 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 also be 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 [32] 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: region a, low velocity events, with $\beta < 1$ and with $R < 5$ GV, and region b, relativistic events, where $\beta \simeq 1$ and with $R \geq 5$ GV.

In Fig. 1 (top) the A/Z distribution for particles with $Z = 1, 2$ and with $R < 5$ GV (region a) is shown. The sector $A/Z > 8$ 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., ^{6}He and ^{8}He) and the presence of tritium, this region appears safe enough to search for anomalous A/Z candidates.

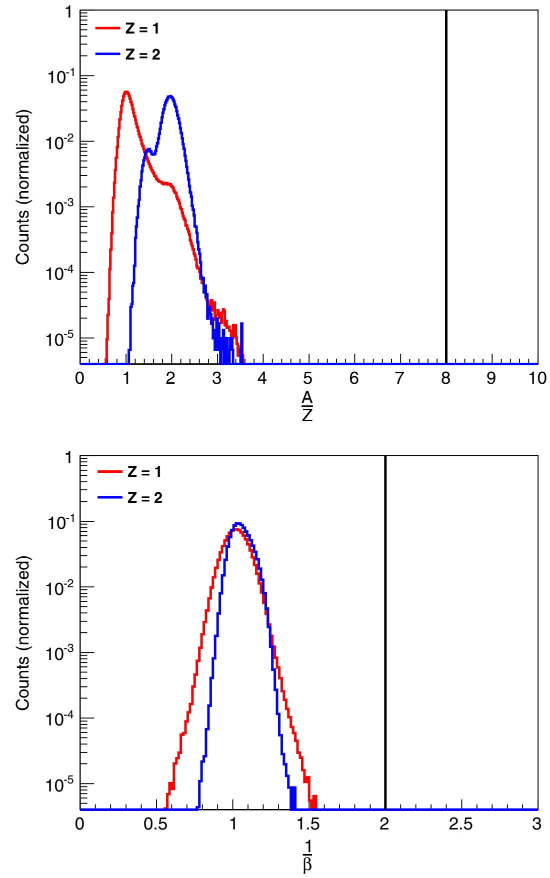

FIG. 1 (color online). Top panel: A/Z distribution for H (left peak), He (right peak), considering events with $R < 5$ GV. The bumps in the distribution of H and He indicate the presence of isotopes such as deuterium, tritium, and ^{3}He (region a in text). Bottom panel: $1/\beta$ distribution for $R \geq 5$ GV H (wider distribution), He (narrower distribution). Note the better resolution for helium due to the higher charge released in the scintillators (region b in text).

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

The search for 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 [33].

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 SQM/matter flux ratio 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 us to set both differential and integral upper limits as a function of rigidity for several species. Assuming Poissonian statistics, the upper limit (95% C.L.)

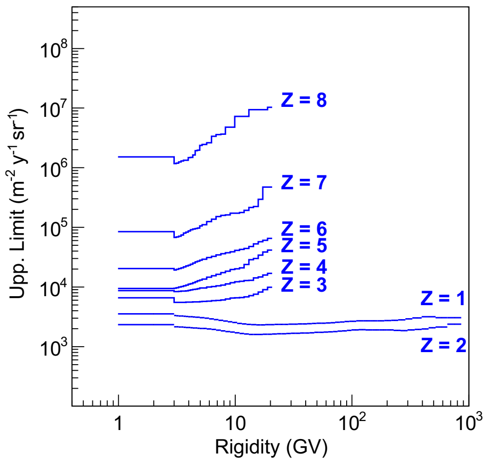

FIG. 2 (color online). Integral upper limit in terms of rigidity, as measured by PAMELA, for nuclei up to $Z = 8$.

on the differential flux over the rigidity interval between R and $R + \Delta R$ is given by

$$l_Z(R + \Delta R) = \frac{3}{\alpha_Z(R + \Delta R)\Delta R}, \tag{2}$$

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: $\epsilon = \epsilon(Z, R)$. The differential cosmic-ray flux for each species Z, $\phi_Z(R)$, can be written as

$$\phi_Z(R + \Delta R) = \frac{n_Z(R + \Delta R)}{T_{\mathrm{live}} \cdot \mathrm{GF} \cdot \Delta R \cdot \varepsilon} \tag{3}$$

where $n_Z(R)$ is the number of nuclei with charge Z measured in the interval between R and $R + \Delta R$. Consequently, the upper limit $l_Z(R)$ can be expressed as

$$l_Z(R + \Delta R) = \frac{3\phi_Z(R + \Delta R)}{n_Z(R + \Delta R)}. \tag{4}$$

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 $\epsilon(Z, R)$.

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 $N_Z(R) = \int_{R'>R} n_Z(R')dR'$:

$$L_Z(R) = \frac{3\Phi_Z(R)}{N_Z(R)}. \tag{5}$$

In Fig. 2 the value of $L_Z(R)$ is shown: an upper limit as a function of rigidity allows us to directly compare the SQM

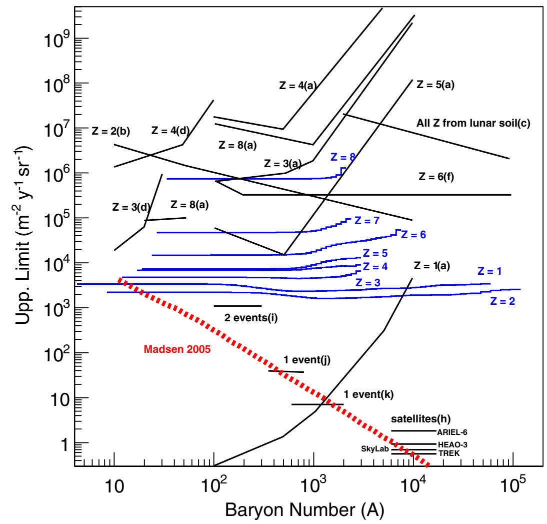

FIG. 3 (color online). Integral upper limits in terms of baryon number (A) as measured by PAMELA, for nuclei up to $Z = 8$ compared with previous results. The dotted line is the predicted flux of strangelets [3]. The solid black lines represent previous experimental limits for strangelets which are translated into flux limits. The curves labeled (a) [34], (b) [35], (d) [36], (e) [37], and (f) [38] come from relic searches in terrestrial material. The curve labeled (c) [39] comes from searches which bombard materials with slow-moving heavy ions. The curves labeled with (h) [15–18] represent satellite-based searches, obtained from the exposure of the single experiments assuming Poissonian statistics. The curves labeled with (i) [14], (j) [19], and (k) [40] represent previous detections of events consistent with strangelet signals by balloon-borne cosmic-ray detectors.

flux with the cosmic-ray one and therefore improve SQM production and propagation models. 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. (1). In a plane $R - \beta$, the events are collected with a binning that can be thought of as rectangles with vertices in R, $R + \Delta R$, β_{min}, and β_{max}. The minimum and maximum β are evaluated according to Eq. (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 $A_{\mathrm{min}} = ZR(m_p\beta_{\mathrm{max}}\gamma_{\mathrm{max}})^{-1}$ to $A_{\mathrm{max}} = ZR(m_p\beta_{\mathrm{min}}\gamma_{\mathrm{min}})^{-1}$. In this way we map each rectangle in thr $R - \beta$ plane into a trapezoid in the $R - A$ 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.

In conclusion, we have analyzed 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 $1 \leq R \leq 1.0 \times 10^3$ GV and mass range $4 \leq A \leq 1.2 \times 10^5$ improving upper limits as a function of rigidity and baryon number (Figs. 2 and 3). This can help in constraining or ruling out models of SQM production and propagation in the big bang and in the Galaxy. Our data exclude the model of Ref. [3] in the light mass range (red dotted line in Fig. 3). Since data taking is continuing, the search will continue with a more extended data set.

We acknowledge support from the Italian Space Agency (ASI), Deutsches ZentrumfürLuft- und Raumfahrt (DLR), the Swedish National Space Board, the Swedish Research Council, the Russian Space Agency (Roscosmos) and the Russian Foundation for Basic Research.

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