1 Introduction

PAMELA consists of a Time of Flight, a magnetic spectrometer and a silicon/tungsten calorimeter used to precisely measure the particle and antiparticle component in cosmic rays [1]. Detector redundancy and independent measurement makes it well suited to search for up-to-now unobserved particles with high mass/charge ratio, such as strange quark matter. In this work we present the upper limits to the flux of $Z = 1$ and $Z = 2$ in terms of rigidity and atomic mass. These limits are currently the most stringent ones in the range 1-1000 GV and overlap with lunar soil searches.

2 Strange quark matter

It has been speculated [15] that quark matter could exist in stable or meta-stable form in cosmic rays. These objects - often named strangelets for their hypothesized strange quark content - could be produced in the Big Bang or be ejected in the stellar collapse, producing quark stars. Several papers [18, 19] have studied the conditions required to have stability for these objects: most of them use the MIT bag model approximation, resulting in heavier objects being more stable. Other calculations take into account shell models [2]. In the current models these particles would not be bounded in $A$ number, ranging from the mass of an hypothetical quark star ($A \sim 10^{57}$) to chunks of quark matter of $A \sim 10^{13}$.

The negative charges of the strange and down quark can cancel out the positive charge of the up quark producing neutral (if $N_u = N_d = N_s$) or slightly...
charged nuclei in case of a small excess of $u$ or $d$ quarks. If this model is correct, these particles would have a very high value of $A$ and a low value of $Z$. Under the additional hypothesis [4] of Colour-Flavor Locking, where couples of quarks are joined in Cooper pairs with $\sim 100$ MeV binding energy, the following relation would apply:

$$Z \approx 0.3 m_{150}^2 A^{2/3}$$  \hspace{1cm} (1)

If CFL is not present the relation would be instead

$$Z \approx 0.1 m_{150}^2 A \hspace{0.5cm} \text{for} \hspace{0.5cm} A \ll 10^3$$  \hspace{1cm} (2)

$$Z \approx 8 m_{150}^2 A^{1/3} \hspace{0.5cm} \text{for} \hspace{0.5cm} A \gg 10^3$$  \hspace{1cm} (3)

Although strangelets are assumed to be more stable for heavier masses, there is also the possibility that lighter particles may be present in the cosmic radiation. If this is the case, a lighter component might also be more abundant due to the fragmentation in the interstellar medium. A complete review on strangelet search and models can be found in the work by E. Finch [3].

3 Experimental evidence

Various experiments have looked for strange quark matter using mass spectrometers, balloon-borne apparatus and space detectors both of active and passive nature. A particle with an exactly equal number of $u$ and $d$ quarks would be electrically neutral and thus detectable only with extreme difficulty. However they may have a low electric charge due to a slight excess of $u$ and $d$ quarks, which would tend to fill the Fermi levels before the $s$ quarks because of their lighter mass. Cosmic ray experiments have thus looked for heavy particles with small electric charge.

Heavy ion experiments, which used beams of gold, sulfur, lead and other massive nucleons, allowed to test strangelets production in the hot and dense environment provided by two colliding nuclei The NA52@CERN-SPS is the only dedicated experiment at CERN built to search for strange quark matter in sulfur-tungsten and lead-lead interactions (respectively with 200 A GeV S + W beam [17] and with the 158 A GeV Pb + Pb beam [16]). These experiments, together with others, didn't observe strangelets events, binding the production rate of this kind of exotic matter with upper limits.

The ARIEL-6 satellite, with his Cherenkov counters and the exposure of 494 m$^2$ days set an upper limit at 90% CL on the flux of particles with $Z > 88$ around $5.9 \times 10^{-12}$ cm$^2$ sr$^{-1}$ s$^{-1}$.

The HEAO-3 apparatus, with an exposure of $8 \times 10^{11}$ cm$^2$ sr s didn't observe any event with $Z > 92$, giving an upper limit of $2.9 \times 10^{-12}$ cm$^2$ sr$^{-1}$ s$^{-1}$.

The Skylab experiment, with an exposition of $1.2 \times 10^{12}$ cm$^2$ sr s, didn't 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 $Z > 110$.

Even the experiment TREK didn't isolate strange nuclei with $Z > 92$, setting the upper limit to $1.7 \times 10^{-12}$ cm$^2$ sr$^{-1}$ s$^{-1}$.

The balloon experiment HECRO-81 (with Time-of-Flight) has reported the observation of two events with $Z \sim 14$ below the local magnetic cutoff under the hypothesis of a normal nucleus with rigidity corresponding to the measured speed. The corresponding mass number for this events was estimated [6] to be $A \sim 350$.

More recently, searches with BESS balloon spectrometer have yielded no candidates for $5 \leq Z \leq 26$ for $Z/A < 0.2$. AMS-01 has reported the observation of one $Z = 2, A = 18$ event [7]. A different analysis of AMS data [5], finds two events: $Z = 2, A = 33.00, 13.35$ GV and $Z = 2, A = 64.83, 31.68$ GV. The same reference reports of an unpublished analysis giving two events: $Z = 8, A = 20, 3.93$ GV and $Z = 4, A = 50, 5.13$ GV. There are no common candidates to the various AMS analyses, even though the selection criteria were slightly different.

In 2009 R. Han et al. [7]. published their results on a search aimed to observe stable strangelets relics in lunar soil ($A \sim 54$) using the tandem Van der Graaf accelerator as a mass spectrometer. The advantage of using this kind of extraterrestrial environment is that Moon has neither magnetic field nor geological activity, so that an hypothetical strangelets will remain confined in our satellite’s surface for hundreds of millions of years.

4 PAMELA detector

PAMELA is constituted by a number of highly redundant detectors capable of identifying particles providing charge, mass, rigidity and $\beta$ over a very wide energy range. A more detailed description of the device and the data handling can be found in [1]. The instrument is built around a permanent magnet with a silicon microstrip a 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. A shower tail catcher and a neutron detector at the bottom of the apparatus increase this separation. In this analysis, given the dominant proton flux in cosmic rays, it was not necessary to use information from these subsystems. An anticounter system is used to reject spurious events in the offline phase. Around the detectors are housed the readout electronics, the interfaces with the CPU and all primary and secondary power supplies. All systems (power supply, readout boards etc.) are redundant with the exception of the CPU which is more tolerant to failures. The system is enclosed in a pressurized container located on one side of the Resurs-DK1 satellite. Total weight of PAMELA is 470 kg; power consumption is 355 W; geometrical factor is 21.6 cm$^2$sr.

5 Selection criteria

The advantage of PAMELA is the redundancy and complementarity of its measurements.

- There are 12 $\beta$ measurements obtained combining the information from the 6 planes of scintillators (two independent measurements for $\beta$ are possible). Data from the TOF system is combined in a weighted average which rejects spurious velocity measurements, in order to provide an optimal measurement of $\beta$ itself.
- Multiple $dE/dx$ measurements in the tracker and in the scintillators provide an independent check of the particle velocity according to the Bethe – Bloch formula.
- Deflection is measured in the tracker with up to 6 planes in the bending view, allowing different checks.
of the measured rigidity, reconstructed by a fitting procedure.

- Additional information for non-interacting particles comes from the energy loss and range measurement in the tracking calorimeter, following the particle up to its Bragg peak, and thus determining initial kinetic energy.

In this analysis we have required only particles with at least 4 tracker planes hit, good $\beta$ measurement to augment statistics and precision at the same time.

6 PAMELA search for anomalous $A/Z$ particles

Search of heavy particles with PAMELA can be divided in two regions:

- low velocity events, with $\beta < 1$;
- relativistic events, where $\beta \approx 1$.

In the former case, for an incoming particle of mass $m_pA$ ($m_p$ proton mass, $A$ atomic number) PAMELA is capable to measure charge $Z$, velocity $\beta$ and rigidity $R$ of the incoming particles. We have:

$$ R = \frac{p \cdot c}{Z \cdot e} = \frac{M \cdot \gamma \cdot v}{Z \cdot e} $$

that, by transforming $v$ in $\beta$ and expliciting $\gamma$, can be rewritten as

$$ \frac{m_p \cdot A \cdot \beta}{\sqrt{1 - \beta^2}} = Z \cdot R $$

Finally we obtain:

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

(6)

Stable nuclei have values of $1 \leq A/Z \leq 3$, with average value of $A/Z \approx 2$, corresponding to an equal number of protons and neutrons. Unstable nuclei - which can be produced in hadronic interactions in the detector - could have a higher ratio; for instance $^6He$, with a decay time of $119\; ms$ has $A/Z = 4$. Strange quark matter is believed to be more stable for higher mass/charge ratio; it can be characterized in terms of $Z$ and $A$ even though the two numbers do not refer to the number of protons and neutrons contained.

In Figure 1 we show the $A/Z$ resolution for particles with $R < 3\; GV$. A fit of the peak gives a mass resolution of 0.05 amu. In this analysis we have considered $Z = 1, A > 8$ region and $Z = 2, A > 10$ region. A better isotopic resolution can be achieved by placing stronger cuts in the TOF and the magnet, but at the expense of lower selection efficiency. Due to the possible presence of metastable Helium isotopes such as $^6He$ and $^3He$ and the presence of tritium we have placed out search region for particles with $A/Z \geq 6$.

For $R > 3\; GV\; $ $\beta \approx 1$ for normal matter: a heavier particle candidate would have a lower $\beta$ at these rigidities. In Figure 2, is shown the $1/\beta$ distribution for $Z = 1$ and $Z = 2$ particles. The better resolution for Helium is due to the higher charge released in the scintillator system, resulting in a lower jitter in the TDC (Time to Digital Converters). The non-Gaussian tail is mostly due to contribution of non-relativistic particles and - in case of $Z = 1$ - to deuterium and tritium (mostly between $2.5 < R < 5\; GV$). Based on this distribution we have defined the search of heavy particles in the region of $2 < 1/\beta < 50$.

The selected events show no candidate in the above mentioned regions for $1.9 \cdot 10^7\; H$ and $5.8 \cdot 10^6\; He$.

This upper limit (at 95% confidence level) in a given rigidity is given by

$$ l(R) = \frac{3}{T_{live} \cdot GF \cdot \Delta R \cdot \epsilon} $$

(7)

where $T_{live}$ is the live time of the detector $GF$ is the Geometrical Factor and $\epsilon$ is the overall selection efficiency of the cuts described before. The number of particles $n(R)$ measured by PAMELA at a given rigidity is given by:

$$ \phi(R) = \frac{n(R)}{T_{live} \cdot GF \cdot \Delta R \cdot \epsilon} $$

(8)

where $\phi(R)$ is the cosmic ray flux. Therefore:

1. We used a multi-Gaussian fitting function, although the distribution is not Gaussian, being the result of the product of $1/\beta$ (which has a Gaussian distribution) and $R$, which is the inverse of the deflection and thus is distributed as the inverse of a Gaussian.
\[ l(R) = \frac{3 \cdot \phi(R)}{n(R)} \]  

(9)

In Figure 3 we plot the value of \( l(R) \) for protons and Helium.

![Figure 3: Upper limit in terms of rigidity, as measured by PAMELA, for protons and Helium.](image)

To evaluate the corresponding upper limit in terms of mass we recall that for \( R > 3 \) GV our range of search for heavy matter goes from \( \beta_{\min} = 0.02 \) to \( \beta_{\max} = 0.5 \). At a given rigidity \( R \) the mass search interval, therefore, ranges from \( M_{\min} = \frac{R}{\beta_{\max}} \) to \( M_{\max} = \frac{R}{\beta_{\min}} \). So, for the whole mass range, we obtain the two curves (for Hydrogen and Helium) showed in Figure 4.

![Figure 4: Upper limits in terms of Baryon number (A) as measured by PAMELA, for protons and Helium.](image)

7 Conclusions

Since no anomalous \( A/Z \) particle has been found (for \( Z = 1 \) and \( Z = 2 \)), in this work we present the two upper limits for Hydrogen and Helium as a function of rigidity \( R \) (Figure 3) and Baryon Number \( A \) (Figure 4). Search of valid candidates will be soon extended to \( Z > 2 \) nuclei, with the same procedure used here.

References