IL NUOVO CIMENTO Vol. 27 C, N. 5 Settembre-Ottobre 2004
DOI 10.1393/ncc/i2005-10005-9

Blind search for strangelets with the AMS space experiment

D. Baldassari
Università di Bologna, INFN - Bologna, Italy

(ricevuto il 20 Gennaio 2005)

Summary. — The existence of systems composed of a confined Fermi-gas of up, down and strange quarks that could have a higher density and even be in a lower energy state seems to be very likely. Strangelets are chunks of Strange Quark Matter, that could have formed in the collisions of binary systems composed of a strange star and this is the reason why they could be more easily detected in cosmic rays. The AMS space experiment is able to distinguish strangelets from heavy nuclei from the characteristic value of the Z/A ratio, as previous analyses show. This is an overview of the blind-analysis work that will be done on the data collected during the AMS test flight.

PACS 12.39.Mk – Glueball and nonstandard multi-quark/gluon states.
PACS 12.38.Mh – Quark-gluon plasma.
PACS 14.65.Bt – Light quarks.

1. – Physics of strangelets

In 1971 Bodmer [1] suggested the existence of systems composed of a confined Fermi-gas of up, down and strange quarks that could have a higher density and still have a lower Fermi energy.

Figure 1 shows the energy level for quark matter and strange quark matter. As shown, the introduction of the strange quark lowers the energy per baryon resulting in a more stable system. This state, called Strange Quark Matter (SQM), could be the real ground state of hadronic matter [2].

Chunks of SQM, for which the surface effects become important and which are too small to maintain an electron gas inside, are called "strangelets" and they are more relevant for AMS searches since they are believed to be long-lived particles and have survived interactions with the interstellar medium and reached the detector. The size of strangelets is unlimited and greater than a minimum value which lies between $A = 6$ (2u, 2d, 2s) and $A = 100$.

A very important characteristic of strangelets, considered the best experimental signature for these particles, is that the charge-to-mass ratio is very small compared to

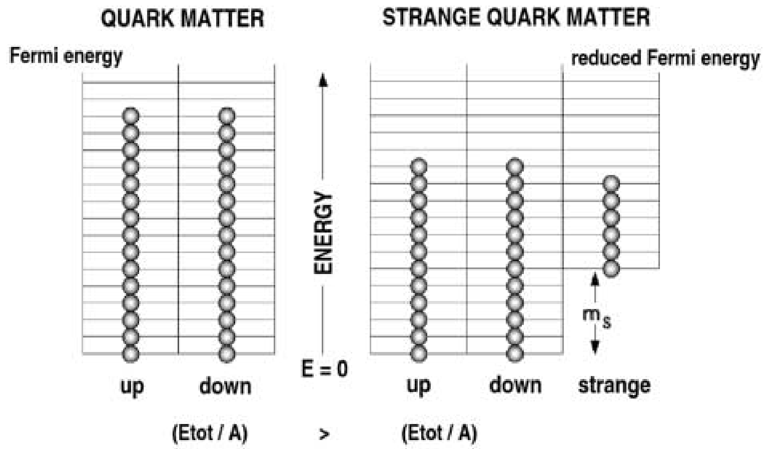

Fig. 1. – Energy level diagram for quark matter and strange quark matter. The introduction of the s-quark lowers the total energy per baryon of the system [2].

ordinary nuclei. This characteristic is true for all parameter values even when strange-quark mass is large.

In fig. 2, on the left the structure of a nucleus of ordinary matter (^{12}C) is pictured, on the right the corresponding strangelet with the same baryon number $A = 12$ [3]. It is worth notincing how the addition of the strange quark to the system lowers the charge and consequently the Z/A ratio, which results much lower than the corresponding value for the ordinary nucleus.

SQM at high density may be in a so-called colour-flavour locked (CFL) phase where quarks form Cooper pairs [4]. A Cooper pair is formed of two quarks with different colour and flavour and opposite momenta, which allows for charge neutrality. Such a state would be significantly more bound than ordinary quark matter, and this increases

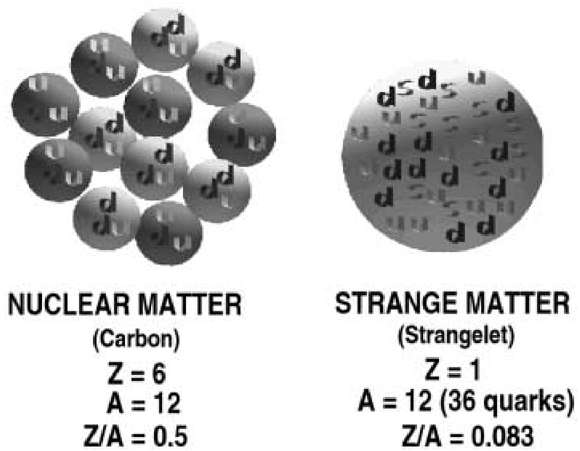

Fig. 2. – On the left the structure of a nucleus of ordinary matter (^{12}C) is pictured, the figure on the right represents a strangelet with the same baryon number $A = 12$ [3].

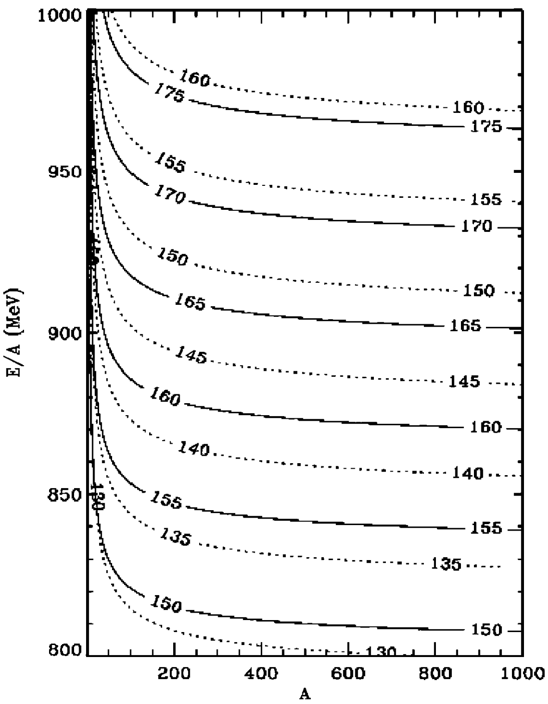

Fig. 3. – Energy per baryon in MeV as a function of A for ordinary strangelets (solid curves) and CFL strangelets (dotted curves) for $B^{1/4}$ in MeV as indicated. All calculations are performed within the MIT bag model [5].

the possibility that quark matter composed of u-, d- and s-quarks may be metastable or absolutely stable. In this case, colour-flavour–locked quark matter would be the actual ground state of hadronic matter.

The charge properties of ordinary strangelets and CFL strangelets are quite different. In particular, ordinary strangelets appear to have

$$Z \approx 0.1\, m_{150}^2\, A, \qquad A \ll 10^3 \tag{1}$$

$$Z \approx 8\, m_{150}^2\, A^{1/3}, \qquad A \gg 10^3 \tag{2}$$

whereas CFL strangelets have [4]

$$Z \approx 0.3\, m_{150}^2\, A^{2/3}. \tag{3}$$

As fig. 3 illustrates, colour-flavour–locked strangelets have an E/A as a function of A that behaves much like that of ordinary strangelets. For high baryon number a bulk value is approached, but for low A the finite-size contributions from surface tension and curvature notably increase E/A, destabilizing the system.

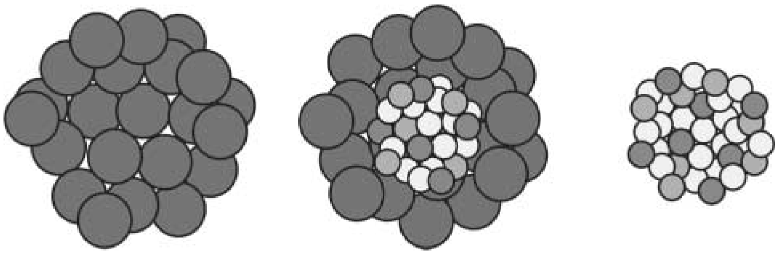

Fig. 4. – Schematic structure of star of mass $M = 1.4\,M_{\odot}$. Stars with a structure represented on the left are basically common neutron stars, the ones showed in the middle are "hybrid" stars and the farthest on the right are strange stars.

2. – Astrophysical sources

The most probable location where SQM could have formed is deep inside neutron stars, where the extremely large pressures generated by the overlayers of neutrons may be sufficient to start the reactions that will make neutrons transit to a quark matter state. The quark matter at first will look like a sea of only u- and d-quarks concentrated at the core of a neutron star. Once formed, however, the quark matter core would make transition into strange matter on a very short time scale, if such matter really has lower energy at high external pressure.

At the beginning, the non-strange quark matter core was in equilibrium with the overlaying layer of neutrons, but since the strange matter core has lower free energy than the neutrons, its formation disrupts the equilibrium. The strange quark matter core grows absorbing neutrons at the interface and crumbles its way outward toward the surface. The star can undergo two different destinies. If the internal energy is lower than the energy of nuclear matter even at zero external pressure, the strange matter will eat its way out to the surface of the star creating a so-called "strange star". On the other hand, if below some non-zero pressure, strange matter energy is no longer lower than nuclear matter's, the conversion will stop. Even in this second case a large fraction of the star could be converted to strange matter giving birth to a "hybrid star", a neutron star with quark core (see fig. 4). The "burning" of a neutron star as it converts to strange matter is not thought to make the star explode, because the free-energy difference between strange matter and nuclear matter is small compared to the gravitational binding energy [6].

Cosmic-ray strangelets are believed to form from collisions of binary compact star systems containing exactly strange stars. In the environment of the binary system they will travel on complex "figure-8" orbits at a typical speed of 0.1 c, and eventually undergo collisions. It is thought that most of the kinetic energy in these collisions goes to fragmentation of the lumps into smaller strangelets, and that they will more likely be accelerated via the same mechanisms as ordinary cosmic rays.

Strangelets are mostly charged and are therefore bound to the galactic magnetic field. They interact with the interstellar medium loosing kinetic energy in electrostatic interactions, and they gain energy by Fermi acceleration in shock waves, for example from supernovae explosions.

In particular, it is believed that strangelets share two of the features found experimentally for nuclei, namely a power law distribution: $N(E)\mathrm{d}E \propto E^{-2.5}$ (where E is the kinetic energy per baryon of the cosmic-ray particle), and an average confinement time in the galaxy of 10^7 years.

TABLE I. – *Terrestrial searches for strangelets.*

Experiment	Beam particle	Beam energy per nucleon	Charge range	Mass range	Year
AGS E814	Si	14.6 GeV	$Z = +1$ $Z = +2$	$3 < A < 10$ $6 < A < 20$	1990
AGS E878	Si/Au	10.8 GeV	$Z = +1$ $Z = +2$	$3 < A < 15$ $6 < A < 30$	1995
SPS NA52	Pb	158 GeV	$Z = +1$ $Z = +2$	$10 < A < 50$ $10 < A < 50$	1996

3. – Experimental searches for strangelets

A lot of searches have been carried on since the existence of a new state of matter was postulated.

Terrestrial searches for SQM droplets have been carried out in the collision of ultrarelativistic particles like protons, kaons and heavy ions in accelerators. Table I summarizes the current published results and some of the main characteristics of the works.

All of these heavy-ion experiments (indipendent of the energy range and of the colliding system) reported null results for the observation of strangelets of any charge.

On the other hand, experiments on board of satellites and ballons registered three events which have been associated with the passage of strangelets through the detector, as reported in table II.

4. – The AMS detector

The *Alpha Magnetic Spectrometer* AMS-02 will be the first spectrometer for charged particles to stay on board of the International Space Station ALPHA (ISSA) for three years to detect cosmic rays. A prototype AMS-01 (see section of the detector in fig. 5) first flew on the space shuttle *Discovery* on mission STS-91 in June 1998, to test the technique and report some data.

The mission lasted 10 days between June 2nd and June 12th 1998, during this the shuttle orbit inclination was the same as the ISS orbit, 51.7° on the geographic equator and the geodetic altitude ranged from 320 km to 390 km. More than 100 million triggers were registered which have been exploited from the most recent strangelets searches.

TABLE II. – *Ballon and satellite experiments.*

Experiment	Charge	Mass	Flux estimate $(\mathrm{cm}^2 \cdot \mathrm{sr} \cdot \mathrm{s})^{-1}$
HECRO-81	$Z = 14$	110–370	3.3×10^{-9}
ET	$Z = 32$	—	1.1×10^{-10}
ARIEL-6	$Z = 88$	—	5.4×10^{-12}

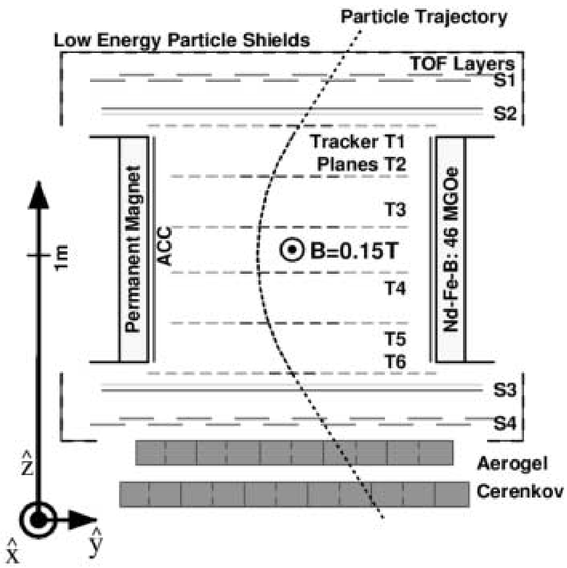

Fig. 5. – AMS-01 section.

Assuming strangelets properties to be similar to those of ordinary nuclei, assuming they travel to the speed of light and they have a charge-to-mass relation as the one for CFL strangelets, $Z = 0.3A^{2/3}$, and assigning one baryon number to them all, A, the strangelet flux at AMS would be

$$F = 5 \times 10^5 (\mathrm{m}^2 \mathrm{y\ sr})^{-1} \times R_4 \times M_2 \times V_{100}^{-1} \times t_7\,, \qquad (4)$$

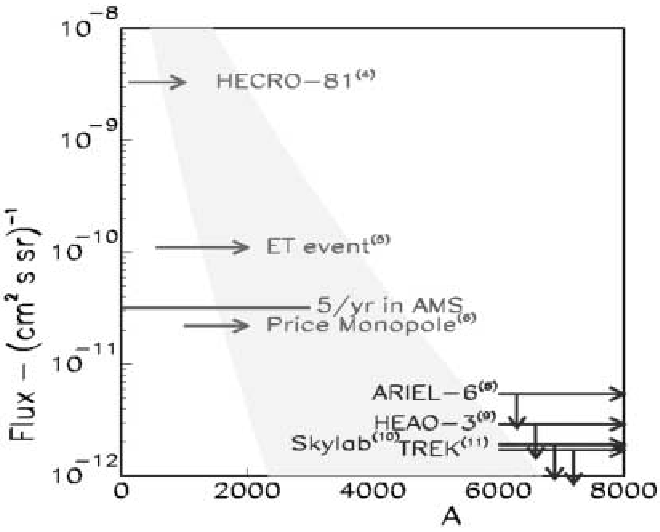

Fig. 6. – Range of strangelet flux as a function of their mass. The shaded region represents the flux expected at AMS. Also shown are limits on the flux estimated by previous experiments [3].

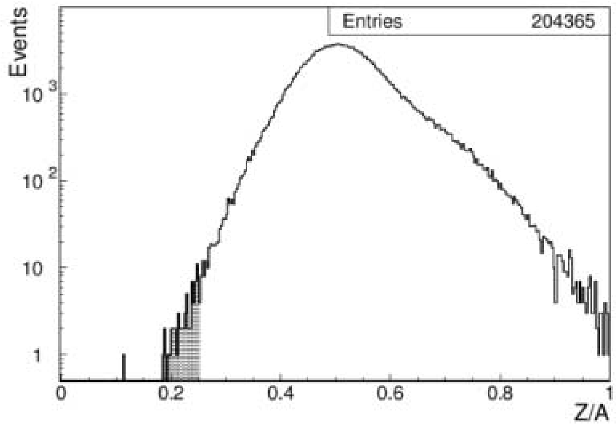

Fig. 7. – Measured Z/A distribution. There is one event with very low $Z/A = 0.114$ situated outside the distribution [8].

where

- R_4 is the number of collisions of a strange star in our galaxy per 10^4 years,
- M_2 is the mass of strangelets ejected per collision in units of $10^{-2} M_{\odot}$,
- V_{100} is the effective galactic volume in units of 100 kpc^3 over which strangelets are distributed,
- t_7 is the average confinement time in units of 10^7 years,

where all these factors are approximately equal to one [7].

The shaded band in fig. 6 shows the expected flux at AMS as a function of strangelets mass, assuming again that all strangelets have the same atomic number. There are many uncertainties involved in the strangelets flux calculation although the number chosen are the current best estimates. However, the predicted flux is high enough so that if SQM is stable at zero pressure, a significant signal should be detected at AMS.

5. – Previous searches for strangelets

The search for strangelets in the AMS-01 data has already been carried out in different ways by V. Choutko and E. Finch, who found 3 possible candidates for strangelets.

In Choutko's "Search for Doubly Charged ACR(1) with AMS at STS-91", the possibility is considered that multiply ionized cosmic rays may represent a background for low-mass strangelet search, together with those ion events where either the rigidity or the velocity was wrongly measured. As the main signature for strangelets is the low Z/A ratio (< 0.2 for ACR, < 0.12 for strangelets), the signal could be easily distinguished.

In fig. 7 one shows the distribution of Z/A for the events which survived the cuts, it is worth noticing that one single event appears to be outside the distribution and that it

(1) Cosmic Rays with Anomalous Z/A ratio.

TABLE III. – *Candidate characteristics.*

Run no.	Event no.	Charge	Rigidity (GV)	A	β	Z/A
897036742	466507	2	4.31 ± 0.38	18	2.1	0.114 ± 0.01

has a value of Z/A that does not match with normal nuclei. In table III the properties of this event are shown [8].

Finch of Yale University also performed a search for strangelets from AMS-01 data, following the analysis by Choutko with the only difference in the choice of the parameter, rigidity/$\beta\gamma$ which corresponds to A/Z.

This time two possible candidates were identified which both have reasonable track quality, large measured A/Z ratio and *beta* measurement which implies that they have a rigidity significantly smaller than the geomagnetic cut-off if they are normal nuclei [9].

In fig. 8 the distribution of $R/\beta\gamma$ is plotted for the simulated events in a velocity range β close to where the $Z = 8$ event track was found. Table IV summarizes the events' properties.

6. – Blind search for strangelets

Although this analysis follows closely the works done by Choutko and Finch, it distinguishes for the use of the blind-analysis technique. A "blind analysis" is a measurement which is performed without looking at the answer and it is an optimal way to reduce experimenter's bias. In fact, the cuts applied on the simulated events are based on plots and ideas and only at the end there is a comparison of the results with the original data, this way the unintended influence on a measurement towards prior results or theoretical expectations could be avoid.

First step of this analysis is the simulation Monte Carlo of a sample of background particles, mainly composed of helium, and a sample of strangelets of charge 2 and different masses. When the sample will be completed we will apply preliminary cuts that will able us to reject mismeasured events and particles that did not traverse the whole detector.

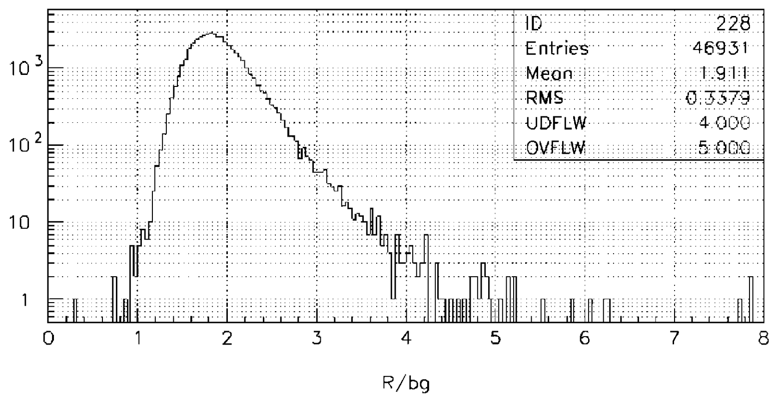

Fig. 8. – The plot shows the distribution of $R/\beta\gamma$ for simulated events close to where the $Z = 8$ event track was found [9].

TABLE IV. – *Characteristics of Finch's candidates.*

Run no.	Event no.	Charge	Rigidity (GV)	A	β	$R/\beta\gamma$	Z/A
896932002	178882	8	3.93	20	0.5310	6.275	0.159
896954936	203075	4	5.13	50	0.7163	5.000	0.2

Later we will apply cuts based on what is the distribution of the sample in order to reject all the background and keep only the survived signal. Only at the end, the same cuts will be applied on the experimental data and we will look for the survived data.

Up to now, the simulation of the background sample and the mass 6 and 20 is terminated. We are still waiting for the mass 50 and 100 strangelets sample. Subsequentely we will apply preliminary cuts to reject mismeasured events and finally calibrate cuts on the basis of the $R/\beta\gamma$ *vs.* $R_{\text{cut-off}}/\beta\gamma$ plot to reject all the background.

Only at the end we will look at the experimental data and make the plot and apply the same cuts to see if any event survives the cuts.

This analysis is a preliminary work which exploits data collected during the test flight of AMS. To have a more complete and precise result, we should wait for the NASA mission which will take AMS-02 on board of the International Space Station where it will stay for 3 years at the end of which we will have a wider sample of data with more precise measurements.

REFERENCES

[1] BODMER A., *Phys. Rev. D*, **4** (1971) 1601.
[2] COE S. D., PhThesis D., *The Search for Strangelets in Relativistic Heavy-Ion Collisions*, Yale University, New Haven, CT, USA (1997).
[3] CHIKANIAN A., FINCH E., MADSEN J., MAJKA R. and SANDWEISS J., *Detecting Strangelets with AMS-02*, AMS note 2002-02-01.
[4] MADSEN J., *Phys. Rev. Lett.*, **87** (2001) 172003.
[5] MADSEN J., *J. Phys. G*, **28** (2002) 1737.
[6] BUSZA W., JAFFE R. L., SANDWEISS J. and WILCZEK F., *Rev. Mod. Phys.*, **72** (2000) 1125.
[7] AMS COLLABORATION, *The Alpha Magnetic Spectrometer (AMS) on the International Space Station, Part I, Results from the test flight on the Space Shuttle*, *Phys. Rep.*, **366/6** (2002) 331.
[8] CHOUTKO V., in *Search for Double Charged Anomaluos Heavy Nuclei with AMS detector in Space* (University Academy Press Inc.) 2003, pp. 1765-1769.
[9] FINCH E., in *Work on Evaluation of AMS-01 Strangelets Candidates*, AMS Technical Report (2003).