Search for Strange Matter by Heavy Ion Activation

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We present the results of an experimental search for stable strange matter using the heavy ion technique, based on properties of strangelets. We studied samples of a meteorite, terrestrial nickel ore, and lunar soil. Our search improved by 2 to 3 orders of magnitude the existing experimental limit on the strange matter content in normal matter and enabled probing the flux of low mass strangelets on the lunar surface for the first time.p [S0031-9007(98)07179-8]

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Suggestions of various forms of tightly bound strongly-interacting matter have been made in the past [1]. Strange matter, aggregates of up, down, and strange quarks are a possible form of these systems. If strange matter exists and is absolutely stable, it would be the true ground state of the strong interaction. Witten [2] suggested that particles of stable strange matter, also called strangelets, would contribute significantly to dark matter. De Rújula and Glashow [3] discussed different methods to detect strangelets in the Earth and in space-based experiments. Later, Alcock and Farhi [4] placed severe restrictions on scenarios for strange matter survival in the hot temperatures of the early Universe. Nevertheless, there is no evidence against the stability of strange matter and, although not produced cosmologically, it could be present in today's Universe.

A favorable astrophysical environment for the formation of strange matter would be inside neutron stars [5,6]. In fact, if strange matter is stable, all neutron stars would be "strange stars" [7]. The decay of the orbits of binary pairs of such compact stars lead to their collision, allowing for a fraction of their material to be ejected into the galaxy [8,9]. Experimental searches for strange matter have been performed using a variety of techniques, each sensitive to a different mass range. Searches were performed in cosmic ray experiments, where strangelets would show anomalous energy losses in matter [10–12]. Experimental limits on the concentration of strange matter in normal matter, in the $400 < A < 10^7$ amu mass range, are due to Brügger and collaborators [13]. Accelerator mass spectrometry is the most sensitive technique to search for low mass strangelets ($A < 300$). The production of low mass strangelets would be evidence of the quark and gluon plasma [15]. More speculatively, strangelets could be "grown" by neutron absorption and be used as an energy source, since strange matter absorbs normal matter exothermically [16].

The properties of stable strange matter were evaluated by Farhi and Jaffe [17]. Berger and Jaffe [18] developed a mass formula for strangelets and studied their possible decay modes and stable configurations. Takahashi and Boyd [19] extended this model. Stable strange matter has positive charge, but lower than ordinary matter of the same mass. Consequently, it presents a lower Coulomb barrier than ordinary nuclear matter. This property led Farhi and Jaffe [20] to propose a method to search for strange matter by heavy ion activation. In such an experiment, when normal matter penetrates the Coulomb barrier of a strangelet, the quarks will "dissolve" and release energy inside the strangelet. The energy added to the system is given by $\Delta E = IA_B + K$, where I is the extra binding energy per nucleon of stange matter relative to that of normal matter, A_B is the mass of the beam nucleus, and K is the kinetic energy of the beam. I could be as large as 5 to 20 MeV [21], meaning that energies of the order of GeV's can be released in the interaction. Depending on the masses of the strangelet and projectile, some of this energy (E_M) will be used by the system to regain flavor equilibrium via weak decays [18]. The remaining available energy will be released in the form of photons. The time scale for these two types of deexcitation could be very different, although we expect the photon deexcitation to be prompt and the weak decays to occur within the time scale of weak interactions. We assumed that none of the energy released in weak decays contributed to our signal.

The argument against the emission of nucleons from excited strangelets can be understood as follows: Particle emission would require the deconfined quarks inside the strangelet to gain the configuration of a particle, say, a neutron. This would imply an unlikely high local concentration of energy and, as shown in [18], is a negligible decay mode for strangelets with $A > 2000$. Pion emission would require a very energetic quark near the boundary of the strangelet [22]. Subthreshold

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pion production and preequilibrium nucleon emission, as observed in heavy ion collisions, have very low cross sections and are negligible for low energy projectiles [23,24].

The excited strangelet is modeled by a Fermi gas with a uniform temperature $T = [(2\mu\delta E)/(\pi^2 A)]^{1/2}$. T characterizes the spectrum of emitted photons. In this equation, A is the baryon number of the strangelet, μ is the quark chemical potential ($\mu \sim 300$ MeV), and $\delta E = \Delta E - E_M$, where ΔE and E_M have been previously defined. According to [20], strangelets are not opaque to photons of these characteristic energies, implying that the spectrum of emitted photons will be similar, but not equal, to that of a cooling blackbody. Depending on its mass, the excited strangelet will radiate many low energy photons, indicating that such an experiment requires a detector with a large solid angle, high granularity, and sensitivity to a broad energy range.

We used the GAMMASPHERE [25] detector array to perform this search. It is composed of 110 elements of high-purity germanium (Ge) detector surrounded by bismuth germanite (BGO) crystals. The 4π solid angle coverage is shared by the Ge detector (45%) and the BGO crystals (55%). The Ge detectors are sensitive to a wide range of energies, from 20 keV to 20 MeV. The total Ge detector's efficiency at 20 keV is approximately 3%. The BGO crystals cover the energy range from 20 keV to 10 MeV. Our sensitivity to photons of about 20 keV would be enhanced in a strange matter interaction by pileup, induced by the high multiplicity of low energy photons within the 1 μs electronic time window.

We performed our experiment at the 88-inch Cyclotron, using ^{136}Xe projectiles at 450 MeV, below the Coulomb barrier for all normal matter. The beam of 250 nA was delivered in the charge state 26^+. Three samples were examined: nickel ore, obtained 2070 m underground [26], the Allende meteorite [27], and lunar soil collected by the Apollo-17 mission [28]. The lunar soil sample is composed of very fine grains. 200 mg of this soil was compressed into an aluminum cup to produce a suitable target. The beam current could not be monitored continuously, because the beam was stopped in the thick insulating targets. However, periodic measurements of its current, performed upstream during the irradiation time, confirmed its stability. The range of the beam in the samples was calculated using the code TRIM [29]. Since the composition of all of the samples was very similar, SiO_2 being the main component, the calculated ranges of the beam in these targets are all of about 36 μm. Table I summarizes the data used to obtain our results.

Our sensitivity was evaluated by a Monte Carlo method using GEANT 3.21 [30]. The response of GAMMASPHERE to a strange matter signal was evaluated for $I = 5$ MeV. In this case, if the interacting beam is ^{136}Xe, then $\Delta E = 1.13$ GeV. E_M was evaluated as a function of the strangelet mass through the mass formula derived in [18]. E_M depends on the charge (Z) and hypercharge (Y) of the stable strangelet configuration. If the strangelet is large, the addition of a ^{136}Xe nucleus should not change its equilibrium flavor. Thus, we assumed $|Z'_m - Z_m| \ll 54$ and $|Y'_m - Y_m| \ll 136$, where Z_m is the charge and Y_m is the hypercharge of the stable strangelet before the addition of a ^{136}Xe nucleus, and Z'_m is the charge and Y'_m is the hypercharge of the stable strangelet with $A' = A + 136$. This approximation is valid for strangelets with masses $A \geq 2000$ amu. (According to Ref. [18], $Z_m = 105$ for a strangelet of mass 2000, and $Z'_m = 110$ for a strangelet of mass 2136. These values were obtained assuming 150 MeV for the mass of the strange quark m_s and 300 MeV for the up-quark chemical potential μ_0.) For the simulation we approximated the spectrum of emitted photons to that of a blackbody characterized by the temperature T. Table II shows the total net energy available δE, the characteristic strangelet temperature, and the expected number of photons released.

A strange matter signal would present high multiplicity and high energy deposition in the detectors. We used four parameters to select candidate events: the Ge detector multiplicity (NGE), the BGO detector multiplicity (NBGO), the total energy deposited in all Ge detectors (ΣEGE), and the total energy deposited in all BGO detectors (ΣEBGO). All of these quantities depend on the total energy released in the interaction and on the individual energy of the photons released. Thus, for the same beam impinging onto a strangelet, they are functions of the baryon number of the strangelet and the total energy available (δE). Figure 1 shows the comparison between

TABLE I. Summary of data used in the analysis. The ^{136}Xe charge state in all irradiations was 26^+. $\langle A \rangle$ represents the average beam current during irradiation

Time (h)	$\langle A \rangle$ (nA)	Target
4.0	250	Allende met.
5.1	250	Ni ore
15.1	0	BKG
13.2	220	Lunar soil
16.3	0	BKG

TABLE II. Characteristic signal expected from interactions of ^{136}Xe and strangelets of different masses. δE is the energy released in the form of photons, T is the characteristic temperature of the photon spectrum, and N_γ is the expected number of emitted photons per strange matter event.

A (amu)	δE (GeV)	T (keV)	N_γ
2×10^3	0.11	1855.3	61
5×10^3	0.72	2961.3	144
1×10^4	0.92	2370.0	391
1×10^5	1.11	820.0	1353
1×10^6	1.13	261.5	4314
1×10^7	1.13	82.7	13 653
1×10^8	1.13	26.2	43 178

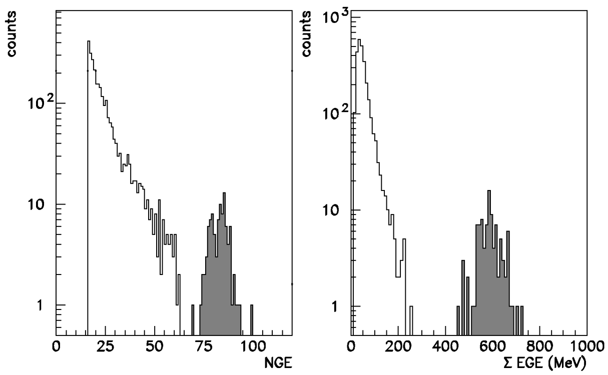

FIG. 1. Comparison between the measured distribution of NGE and ΣEGE and the expected distributions for strange matter events. The simulated values (hatched) shown here were obtained for 100 interactions of ^{136}Xe and 10^4 amu mass strangelets. The experimental distributions are from the bombardment of the lunar soil sample. The section criterion used is NGE $>$ 15 and NBGO $>$ 15.

the experimental distribution of NGE and ΣEGE, and their distributions predicted by Monte Carlo calculations. The experimental distributions are from the bombardment of the lunar soil sample.

The distributions of NGE, NBGO, ΣEGE, and ΣEBGO used in the analysis were obtained by the generation of 100 events for strangelet masses ranging from 2000 to 10^8 amu. These distributions are Gaussian, and the event selection criterion was to accept events if the experimental values of NGE, NBGO, ΣEGE, and ΣEBGO were within two standard deviations from the fitted Monte Carlo predictions. No events in the data satisfy this criterion, thus enabling us to set upper limits on the concentration of strangelets in our samples.

Experimental events with relatively high multiplicity and energy deposition were due to cosmic-ray background. They are also present, with the same rate, in background data. For example, the event rate in the background for ΣEGE $>$ 150 MeV is 4.2 per hour.

We tested the efficiency for the retrieval of high multiplicity events from the data using simulated events randomly inserted in the data set. The retrieval efficiency of these events, using the event selection described above, is 100%. Pulsar data was also taken and analyzed at different frequencies and amplitudes in order to verify the readout of high multiplicity events.

The concentration (n) of the strangelet in our samples is given by

$$n = \frac{N}{\sigma r_{\text{beam}} p}, \tag{1}$$

where N is the number of events observed, $\sigma = \sigma_0 A^{2/3}$ is the cross section for the interaction, r_{beam} is the range of the beam particles in the samples, and p is the number of particles impinging the sample. σ is a purely geometric quantity, and $\sigma_0 = 3.04 \times 10^{-26}$ cm^2 was obtained assuming a baryon number density of 0.25 fm^{-3} [4,20].

We plot in Fig. 2 our results for the three studied samples, assuming an upper limit of 1 for N. For comparison, the results by Brügger and collaborators [13] have been included in the plot. If strangelets indeed behave as described by Farhi and Jaffe [17], then our experiment has certainly improved, by 3 orders of magnitude, Brügger's limit for strangelets with masses between 2000 and $A = 10^7$. We also set a limit for strangelets with masses up to $A = 10^8$, a range inaccessible to Brügger's experiment. The sensitivity of our experiment to high mass strangelets was determined by the sensitivity of GAMMASPHERE to low energy photons. For $A = 10^8$, the average energy of emitted photons in a strange matter event is 26 keV. Below this energy, the efficiency of the array, and hence its sensitivity, is very small.

Our experiment was mostly sensitive to light strangelets $(A < 10^9)$ which, if present as cosmic rays, would have been absorbed into the Earth's atmosphere. Since the Moon has no atmosphere, and its surface has been exposed for millions of years, the upper limit of the concentration of strange matter in the lunar soil can be used to deduce a limit for the flux of impinging strangelets. The lunar sample was collected from the top 0.5 to 1 cm surface, at the base of the Sculptured Hills, Station 8 [28]. Details of this sample can be found in [31,32]. The presence of high cosmic ray track densities in the sample suggests that the integrated lunar surface exposure age is about 100 My [33]. Using the range of strange matter in normal matter suggested by De Rújula and Glashow [3], our concentration limits, and the integrated lunar surface exposure age, we have deduced a limit on the flux of strangelets on the surface of the Moon. Figure 3 shows our results as a function of the strangelet mass. For comparison, we plotted the limits obtained by Shirk and Price [34].

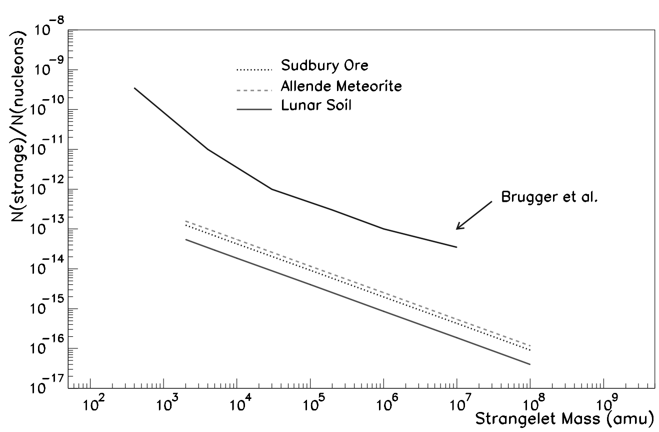

FIG. 2. Experimental limit on the concentration of strangelets in our samples. The limits are based on the number of events that survived the cuts described in the text (i.e., have NGE, NBGO, ΣEGE, and ΣEBGO within 2 standard deviations from the expected values). The results from Brügger [13] and collaborators obtained with an iron meteorite have been plotted for comparison. $N_{\text{strange}}/N_{\text{nucleons}}$ is the concentration of strangelets per nucleons contained in the sample.

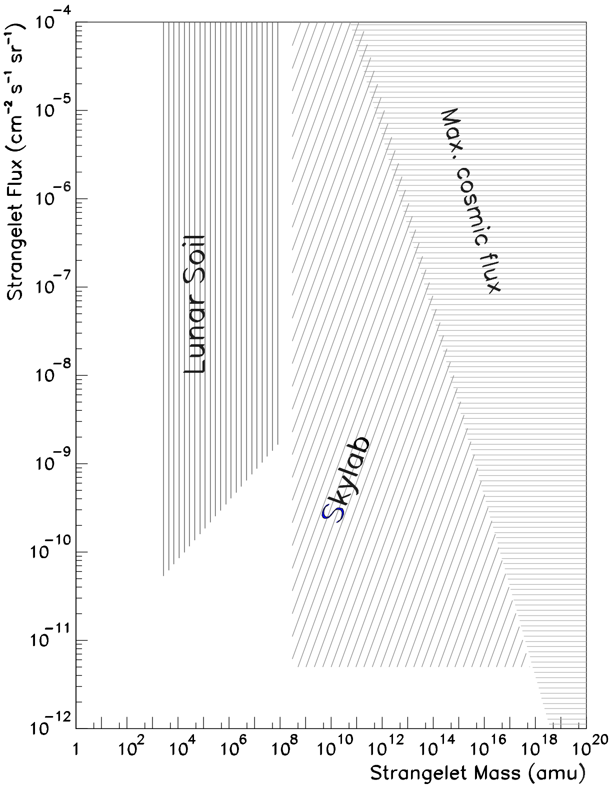

FIG. 3. Limits on the flux of strangelets impinging on the lunar surface obtained in this experiment. The results from Shirk and Price [34] were also plotted for comparison. Maximum cosmic flux refers to the cosmic flux of strangelets, assuming that all of the dark matter in the Universe is composed of strangelets.

Based on the limit on the flux of strangelets in cosmic rays, we deduced an upper limit for the mass density of strangelets in the Galaxy. Assuming that strangelets have a typical galactic velocity of 3×10^7 cm/s, the upper limit for their mass density will range from 3×10^{-37} g/cm^3 for $A = 5000$ strangelets, to 2×10^{-31} g/cm^3 for $A = 10^8$ strangelets. These values should be compared with the upper bound estimate of 10^{-29} g/cm^3 deduced by Glendenning [8] and based on the collapse of binary compact stars. Even though our upper limits are 2 to 8 orders of magnitude lower than the previous estimated values, many quantities have large uncertainties. The fraction of pulsars that occur in binary compact systems and the fraction of mass ejected in binary star collisions, for example, are subjects of current study. Consequently our results do not rule out the existence of strange matter in the Universe.

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