Search for Strange Matter by Heavy Ion Activation

M.C. Perillo Isaac, Y.D. Chan, R. Clark, M.A. Deleplanque, M.R. Dragowsky*, P. Fallon, I.D. Goldman†, R.M. Larimer, I.Y. Lee, A.O. Macchiavelli, R.W. MaclLeod, K. Nishiizumi‡, E.B. Norman, L.S. Schroeder, F.S. Stephens

Lawrence Berkeley National Laboratory - Berkeley CA 94720
*Oregon State University, Corvallis OR 97331
†University of Sao Paulo, Sao Paulo, Brazil
‡Space Sciences Laboratory, University of California, Berkeley CA 94720

We present the results of an experimental search for stable strange matter using the heavy ion activation technique. We studied samples of a meteorite, terrestrial nickel ore, and lunar soil. Our search improved the existing experimental limit on the strange matter content in normal matter by 2 to 3 orders of magnitude, and allowed us to probe for the first time the flux of low mass strangelets on the lunar surface.

95.35.+d,12.38.Mh, 21.65.+f, 24.85.+p

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 theoretically possible form of these systems. If strange matter exists and is absolutely stable, it would be the true ground state of the strong interaction. E. Witten [2] raised the possibility that particles of stable strange matter, also called strangelets, would be a significant dark matter candidate. De Rújula and Glashow [3] suggested 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 possibility that strange matter is stable and, although not produced cosmologically, is present in today’s Universe. It should, therefore, be possible to probe its concentrations in Earth-based experiments.

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 are ”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 injected into the galaxy [8,9].

Experimental searches for strange matter have been performed using a variety of techniques, sensitive to different strangelet mass ranges. Searches were performed in cosmic ray experiments, where the strangelets would show anomalous energy loss in matter [10,11,12]. Experimental limits on the concentration of strange matter in normal matter are due to Brügger and collaborators [13], for strangelets in the 400 < A < 10^7 amu mass range. Accelerator mass spectroscopy is the most sensitive technique for detecting low mass strangelets (A<300), relying on the assumption that strangelets would possess the same chemical properties as normal nuclei with the same charge, behaving as ultra-heavy isotopes [14]. It was also pointed out that low mass strangelets, produced in heavy ion collisions, would be evidence of the production of quark and gluon plasma [15]. More speculatively, they could be "grown" by neutron absorption and could be used as an energy source [16], since strange matter absorbs normal matter exothermically.

The properties of stable strange matter were calculated by Farhi and Jaffe [17]. Berger and Jaffe [18] developed a mass formula for strangelets and studied stable configurations and possible decay modes of highly excited strangelets. Extensions to this model were performed by Takahasi and Boyd [19]. Stable strange matter has positive, but lower charge than ordinary matter for the same mass. Consequently it presents a lower Coulomb barrier than ordinary nuclear matter, leading Farhi and Jaffe [20] to propose a method to search for strange matter via heavy ion activation. In such an experiment, when normal matter penetrates the Coulomb barrier of a strangelet, the quarks in normal matter will "dissolve" inside the strangelet, releasing energy. The energy added to the system is given by ΔE = IA_B + K, where I is the extra binding energy per nucleon of strange 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 [24], meaning that energies of the order of GeV’s can be released in the interaction. Nevertheless, some of this energy, E_M, will be used by the system to regain flavor equilibrium [15]. The remaining energy available will be released in the form of photons.

The argument against the emission of nucleons from excited strangelets can be understood as follows: particle emission requires that the deconfined quarks inside the strangelet gain the configuration of a particle, say a neutron. This would imply an improbably high local concentration of energy, and as shown in [18] is an unimportant decay mode for strangelets with A > 2000. Similarly, the mechanism for pion production, through the creation of a quark-antiquark pair, requires a very energetic quark near the boundary of the strangelet [21]. Particle emission, such as observed in heavy-ion, collision are also unlikely, since subthreshold pion production and pre-equilibrium nucleon emission have very low cross sec-
The excited strangelet is modeled by a fermi gas with uniform temperature \( T = ( (2 \mu \delta E) / (\pi^2 A) )^{1/2} \), characteristic of the photon spectrum emitted in the de-excitation. In this equation, \( A \) is the baryon number of the strangelet, \( \mu \) is the quark chemical potential (roughly 300 MeV), and \( \delta E = \Delta E - E_M \), with \( \Delta E \) and \( E_M \) previously defined. According to [20], the strangelets are not opaque to photons with energies characteristics of these temperatures, implying that the spectrum of photons emitted will be similar but not equal to the spectrum of a cooling black body. 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.

The GAMMASPHERE [25] detector array is an ideal instrument to perform this search. GAMMASPHERE is a gamma-ray detector array composed of 110 elements. Each element has a high-purity germanium (Ge) detector surrounded by bismuth germanate (BGO) crystals. The 4\( \pi \) 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, while the BGO crystals cover the energy range from 20 keV to 10 MeV. Furthermore, our sensitivity to low energy photons, of the order of 20 keV, is enhanced in a strange matter interaction by the high multiplicity of low energy photons, generating high energy deposition in the detectors due to pile-up.

We performed our experiment at the 88-Inch Cyclotron, using \(^{136}\text{Xe}\) at 450 MeV, delivered at 250 enA. Three samples from distinct origins were examined: nickel ore found at 2070 m underground [24], the Allende meteorite [27], and lunar soil collected in the Apollo-17 mission [28]. The lunar soil sample is composed of very fine grains, and 200 mg of this soil was compressed into an aluminum cup to produce a suitable target.

Table 1 summarizes the data used to obtain our results. The beam current could not be monitored continuously, since the beam stopped in the thick insulating targets, but periodic measurements of the beam current performed upstream during the irradiation time confirmed the beam stability. The range of the beam in the samples was calculated using TRIM [29]. The composition of all the samples is very similar, \( \text{SiO}_2 \) being the main component. The calculated ranges of the beam in these targets are all of the order of 36\( \mu \)m.

The sensitivity of this experiment was evaluated by Monte Carlo 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 \(^{136}\text{Xe}\), the energy available, \( \Delta E \), is 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 \(^{136}\text{Xe}\) nucleus should not change its equilibrium flavor. We assumed that \( |Z_m - Z_0| \ll 54 \) and that \( |Y_m - Y_0| \ll 136 \), where \( Z_m \) and \( Y_m \) are the charge and the hypercharge of the stable strangelet before the addition of a \(^{136}\text{Xe}\) nucleus, and \( Z'_m \) and \( Y'_m \) are the charge and 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, \( \mu_0 \).

For the simulation, we also assumed that the spectrum of photons emitted is that of a black body characterized by the temperature \( T \). Table 2 shows the net total energy available, \( \delta E \), the characteristic strangelet temperature, and the expected number of photons released.

The characteristics of a strange matter signal are high multiplicity and high energy deposition in the detector. We used four parameters to select strange matter event candidates: the Ge detector multiplicity, NGE; the BGO detector multiplicity, NBGO; the total energy deposited in all Ge detectors, \( \Sigma_{\text{EGE}} \); and the total energy deposited in all BGO detectors, \( \Sigma_{\text{EBGO}} \). These quantities are all functions of the total energy released in the interaction and 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 \( \delta E \).

Figure 1 shows the comparison between the experimental distribution of NGE and \( \Sigma_{\text{EGE}} \) and the distributions predicted by Monte Carlo calculations. The experimental distributions correspond to the bombardment of the lunar soil sample. The distributions of NGE, NBGO, \( \Sigma_{\text{EGE}} \), and \( \Sigma_{\text{EBGO}} \) were obtained by the generation of 100 events for strangelet masses ranging from 2000 to \( 10^8 \) amu. These distributions were fitted to gaussian curves and events from our data set were selected if NGE, NBGO, \( \Sigma_{\text{EGE}} \), and \( \Sigma_{\text{EBGO}} \) were within two standard deviations from the fitted Monte Carlo predictions. No events in our data satisfy these cuts, allowing us to set upper upper limits on the concentration of strangelets in our samples.

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

The concentration of strangelet in our samples, \( n \), is given by the relation:
\[ n = \frac{N}{\sigma \times \tau_{\text{beam}} \times p} \tag{0.1} \]

where \( N \) is the number of events observed, \( \sigma = \sigma_0 A^{2/3} \) is the cross section for the interaction, \( \tau_{\text{beam}} \) is the range of the beam particles in the samples, and \( p \) is the number of particles impinging the sample. \( \sigma \) is purely geometric, and \( \sigma_0 = 3.04 \times 10^{-26} \text{ cm}^2 \) is obtained assuming a baryon number density of 0.25 fm\(^3\). \( \tau_{\text{beam}} \) is the range of particles impinging the sample.

In figure 2 we plot the limits obtained, assuming 1 as an upper limit for \( N \), for the three samples analyzed. For comparison, the limits obtained by Brügger and collaborators in ref. [13] are also in the plot. Our experiment was able to improve Brügger’s limit for strangelet masses between 2000 and \( A = 10^7 \) by 3 orders of magnitude, and to set limits for strangelets masses of the order of \( A = 10^8 \), a range inaccessible to Brügger’s experiment. Our experiment was mostly sensitive to light strangelets, with masses below \( A = 10^3 \), which, if present as cosmic rays, would be absorbed in the Earth’s atmosphere. Since the Moon has no atmosphere and its surface has been exposed for millions of years, the upper limit in concentration of strange matter in the lunar soil allows us to derive a limit for the flux of strangelets impinging the surface of the Moon.

The sample used was collected at a depth of upper 0.5 to 1 cm at the base of the Sculptured Hills, Station 8 [28]. Details on the analysis of this sample can be found in [31]. The presence of high cosmic ray track densities in the sample indicates that the integrated lunar surface exposure age is of the order of 100 My [3]. Taking into account the range of strange matter in normal matter suggested by De Rújula and Glashow [8], the range of strange matter masses to which our experiment is sensitive, and the integrated lunar surface exposure age, we are able to estimate a limit on the flux of strangelets on the surface of the Moon.

Figure 3 shows the upper limits on the flux of strangelets as a function of their mass obtained by this experiment. For comparison, the limits in the flux of strangelets obtained by Shirak and Price [33]. Limits on the incoming flux of strangelets in the Earth’s atmosphere obtained by Porter and collaborators [32] are also consistent with those obtained by [33]. Porter’s limits were derived from four experiments originally carried out to detect high energy cosmic gamma-rays, and are limited only to high-mass strangelets.

The limit on the flux of strangelets in the surface of the Moon allows us to set upper limits for the mass density of strangelets in the Galaxy. If strangelets have a typical galactic velocity of \( 3 \times 10^7 \text{ cm/s} \), the upper limits for the mass density of strangelets of different masses will vary from \( 3 \times 10^{-25} \text{ g/cm}^3 \) for \( A=5000 \) strangelets, to \( 2 \times 10^{-31} \text{ g/cm}^3 \) for \( A=10^8 \) strangelets. These limits should be compared with the upper bound estimated by Glendenning based on the collapse of binary compact stars [3], \( 10^{-29} \text{ g/cm}^3 \). We note that that our results do not rule out the possibility of the existence of strange matter in the Universe. Even though our upper limits are 2 to 8 orders of magnitude lower than the previous estimates, many quantities carry large uncertainties, such as the fraction of pulsars that occur in binary compact systems and the fraction of mass ejected in binary stars collisions.

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

| Time (hours) | $< A >$ (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 $^{136}\text{Xe}$ and strangelets of different masses. $\delta E$ is the energy released in the form of photons, $T$ is the characteristic temperature of the photon spectrum and $N_\gamma$ is the expected number of photons emitted per strange matter event.

| $A$ (amu) | $\delta E$ (GeV) | $T$ (keV) | $N_\gamma$ |
|-----------|------------------|-----------|------------|
| $2 \times 10^3$ | 0.11 | 1855.3 | 61         |
| $5 \times 10^3$ | 0.72 | 2961.3 | 144        |
| $1 \times 10^4$ | 0.92 | 2370.0 | 391        |
| $1 \times 10^5$ | 1.11 | 820.0  | 1353       |
| $1 \times 10^6$ | 1.13 | 261.5  | 4314       |
| $1 \times 10^7$ | 1.13 | 82.7   | 13653      |
| $1 \times 10^8$ | 1.13 | 26.2   | 43178      |

FIG. 1. Comparison between the measured distribution of NGE and $\Sigma\text{EGE}$ and the expected distributions for strange matter events. The simulated values (hatched) shown here were obtained for 100 interactions of $^{136}\text{Xe}$ and strangelets of mass $10^4$ amu. The experimental distributions correspond to the bombardment of the lunar soil sample and require NGE $> 15$ and NBGO $> 15$.

FIG. 2. Experimental limit on the concentration of strangelet in our samples. The limits are based on the number of events which survive the cuts described in the text, i.e., have a NGE, NBGO, $\Sigma\text{EGE}$ and $\Sigma\text{EBGO}$ within 2 standard deviations from the expected values. The results from Brügger and collaborators obtained in an iron meteorite are also plotted for comparison. $N_{\text{strange}}/N_{\text{nucleons}}$ is the concentration of strangelets per nucleons in the sample.
FIG. 3. Limits on the flux of strangelet impinging on the lunar surface obtained by this experiment, and by Shirk and Price from a Lexan array on the Skylab space station. Excluded regions are the hatched areas. Maximum cosmic flux refers to the cosmic flux of strangelets assuming that all the dark matter in the universe is composed of strangelets. We used the estimation of the range of strangelet given by De Rújula and Glashow as a function of the strangelet mass to evaluate their range, and considered the integrated exposure of the lunar soil sample, $10^8$ years.