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(Received 27 March 2009; published 27 August 2009)

We report results from a search for strangelets (small chunks of strange quark matter) in lunar soil using the Yale WNSL accelerator as a mass spectrometer. We have searched over a range in mass from $A = 42$ to $A = 70$ amu for nuclear charges 5, 6, 8, 9, and 11. No strangelets were found in the experiment. For strangelets with nuclear charge 8, a concentration in lunar soil higher than 10^{-16} is excluded at the 95% confidence level. The implied limit on the strangelet flux in cosmic rays is the most sensitive to date for the covered range and is relevant to both recent theoretical flux predictions and a strangelet candidate event found by the AMS-01 experiment.

DOI: 10.1103/PhysRevLett.103.092302 PACS numbers: 21.65.Qr, 14.80.−j, 36.10.−k

Strange quark matter (SQM) is a proposed state of hadronic matter made up of roughly one-third each of up, down, and strange quarks in a single hadronic bag that can be as small as an atomic nucleus or as large as a star. It has been over 30 years since the first suggestion that the true ground state of cold hadronic matter might be SQM rather than nuclear matter [1,2]. If true, the implications would be tremendous for both basic research and applied science [3]. With this motivation, many searches for stable SQM have been undertaken using a variety of methods. These searches have collectively observed a handful of interesting events but have neither been able to find compelling evidence for stable SQM nor to rule out its existence.

The idea that quark matter made of only up and down quarks is stable can be dismissed immediately by the observation that normal nuclear matter does not decay into it. However, in the case of SQM such a decay would require many simultaneous weak interactions, making it prohibitively unlikely. The stability of SQM cannot yet be determined from first principles within QCD, but has been addressed in various phenomenological models. The most commonly used of these is the MIT Bag Model [4,5], which also has been extended to include the effects of color flavor locking (CFL) [6,7]. The results of such calculations are inconclusive, but for a significant part of the reasonable parameter space in these models, SQM is in fact absolutely stable for baryon number greater than some minimum value A_{min} [5,8]. A_{min} is typically found to be larger than 50 and smaller than 1000 although shell effects which are important for $A \lesssim 100$ may cause islands of stability at A values smaller than A_{min}. The key point is that SQM stability is a question that must be settled experimentally or observationally.

If SQM is stable at zero pressure, all compact stars which are commonly thought of as neutron stars may in fact be ''strange stars,'' i.e., composed of SQM [9]. A strange star which is a member of a binary system will eventually suffer a collision with its partner, possibly resulting in the ejection of some fraction of its mass in the form of strangelets. This should ultimately lead to a flux of strangelets in cosmic rays [10,11]. The resulting flux of strangelets at the moon is estimated to be about 2000 per (m^2 yr sr) [10] assuming all the ejected SQM mass to be in the form of strangelets of one particular baryon number (and is a lower limit to the integrated flux if the SQM mass is distributed below a given A), which oversimplifies the real scenario. It is not, however, unreasonable to expect that the distribution may be clustered broadly around A_{min} [12] so that near A_{min} this flux estimation may not be a gross overestimation. Recent strange star collision simulations [13] show that the calculation in Ref. [10] may underestimate the total galactic ejection rate by 1 or 2 orders of magnitude for strongly bound SQM, whereas the ejection rate may be negligible for loosely bound SQM. Given the large uncertainties, the theoretical calculation [10] should be considered a very rough guide.

Previous experiments (reviewed in [14,15]; see [16] for a lunar soil experiment using a heavy ion activation technique) have searched for cosmic strangelet relics in terrestrial materials, meteorites, and lunar soil. There have also been satellite and balloon-borne detectors which would be sensitive to a possible strangelet component in cosmic radiation. Some searches for strangelets with particular nuclear charges have reported negative results at sensitivity levels lower than theoretical predictions [15]. While these results rule out certain strangelet charge states at this level, they do not generally disprove the hypothesis of stable SQM or strange stars.

Meanwhile, candidate events consistent with strangelet characteristics have been published by several experiments

[17–19]. The search reported here was specifically motivated by two SQM candidate events found by the Alpha Magnetic Spectrometer (AMS) Collaboration during the AMS-01 prototype flight in 1998 [20]. One of the events was reconstructed as having a nuclear charge of $Z = +8$ and a mass $A = 54^{+8}_{-6}$, which we will denote as ^{54}O [21]. The ^{54}O event was presented at a collaboration meeting but not published in anticipation of the mounting of the full AMS experiment (AMS-02) on the International Space Station which was originally scheduled for 2003 and would easily prove or disprove these events. With the delay of the AMS experiment, it has become interesting to follow up on these events by other means.

In this Letter we report a search for low mass ($A \approx 54$) strangelet relics in lunar soil using the A. W. Wright Nuclear Structure Laboratory (WNSL) tandem accelerator [22] as a mass spectrometer. The advantage of using lunar soil over terrestrial material is that the moon has neither magnetic field (so low energy strangelets are not turned away) nor geological activity (so that strangelets that stop near the surface tend to remain there for hundreds of millions of years). The search reaches single event sensitivity levels around 3 parts in 10^{17} and the implied sensitivity to SQM as a component of cosmic rays falls near the theoretical flux prediction and below the flux implied by the AMS-01 candidate event.

For this experiment, we obtained 15 g of lunar soil sample No. 10084 from NASA. This fine particulate sample was collected from the top 7.5 cm of the lunar surface [23] and has a cosmic ray exposure age of 520 ± 120 Myr [24]. This sample is used (in 0.1 g increments) as source material for the tandem accelerator.

The accelerator is shown schematically in Fig. 1. Negative ions of the source material are formed in a cesium sputter source [25] and accelerated to 20 keV before undergoing a 90° bend in the inflector magnet. The inflector magnet is set to transmit ions with a given mass A_0 and charge $Q = -1$. Following this, the ions enter the main acceleration tank and are accelerated towards the positive terminal at 17 MV, where a 10 μg/cm^2 carbon foil strips electrons from the ions. For 17 MeV ^{54}O strangelets, the most probable stripped charge state is $Q = +5$ [26]. The stripped (and therefore positive) ions are accelerated away from the terminal to ground, and then go through another 90° bend in the analyzing magnet, which is set to transmit charge $Q = +5$ (total energy 102 MeV) ions only. The mass acceptance δ_m/m of the inflector and analyzing magnets (with all slits wide open) are both approximately 0.6%, and so we cover the mass range with a step size of 1/4 amu. Finally, the ions enter our detector system as described below.

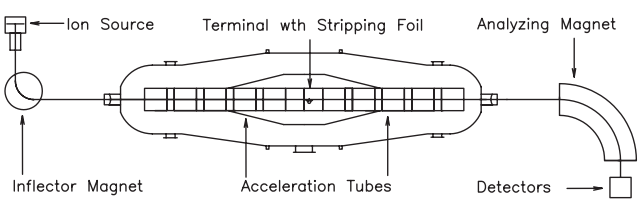

FIG. 1. Schematic figure of the Yale WNSL Tandem accelerator (not to scale). Beam direction is from left to right.

The long- and short-term performance of the accelerator was observed closely. Electrostatic accelerators usually rely on beam trajectory feedback to regulate their terminal voltages V_T. However, in our experiment, when set for a noninteger mass A_0, there is no normal nuclear ion beam transmitted through the machine. Therefore, V_T is held constant by generating voltmeters inside the accelerator tank wall. The short-term (~1 h) stability of the accelerator was verified with known beams and then monitored by observing the beam current in a Faraday cup near our detector system and the beam position on a ZnS fluorescent screen. The long-term stability was monitored by periodic short checks, performed roughly every 4 h, of the transmission of beams of known elements within (or doped into) the lunar soil and readjustment of V_T when appropriate.

When set for a mass A_0 different from any normal nuclear mass, the accelerator and beam transport itself gives a background rejection for a strangelet search on the order of 1 part in 10^{12}. For integer values of A_0, the rejection can be as poor as 10^{-3}. To reach a level of 10^{-17} over the entire mass range, we use a detector system after the analyzing magnet.

With nearly as many strange quarks as up and down quarks in the hadronic bag, a strangelet has a much smaller nuclear charge-to-mass ratio than normal nuclei. In this experiment, we exploit the fact that strangelets' charge-to-mass ratio gives them a smaller dE/dx and a larger stopping range than normal nuclei of similar mass and incident energy. In this Letter, we assume dE/dx of ^{54}O is only affected by the smaller velocity compared to normal oxygen with the same incident energy. We use the simulation program SRIM [27] to calculate dE/dx and stopping range of strangelets.

Our detector system is shown schematically in Fig. 2. All the components except the argon scintillator can be withdrawn from or inserted into the beam line remotely. The scintillation counter and the ZnS screen (viewed by a camera imaging the screen) were used as monitors of beam quality and stability throughout the running period and to make various transmission measurements.

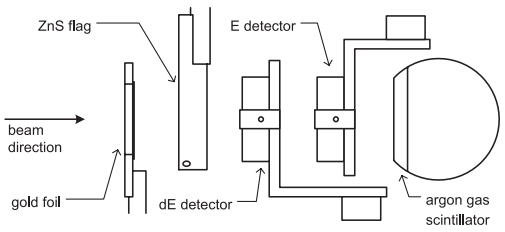

FIG. 2. Schematic setup of the detector system. All the components, except the scintillator, can be withdrawn from and inserted into the beam line remotely.

For normal running during the strangelet search, the gold foil and both silicon counters are put into the beam line. The Au foil thickness of 10 μm is chosen so that a 102 MeV strangelet ^{54}O entering the foil will exit with about 40 MeV [27]. A normal nucleus of comparable mass and incident energy will stop in a length of 7 μm. To penetrate the foil, an ion must have higher energy and/or less mass (and so should generally be inconsistent with rigidity selection through the accelerator).

The final level of background discrimination comes from our silicon (dE, E) telescope. The first silicon (dE) detector, which measures the energy loss of a penetrating strangelet, has a circular cross-sectional active area of 40 mm^2 and is 11.7 $\pm$ 1.3 μm thick. The second silicon (E) detector, which measures the remaining energy, has a cross section of 100 mm^2 and is 100 μm thick. The energy resolutions of the dE and E detectors averaged 0.3%. A strangelet incident on our detector system would penetrate the foil and leave well-defined signals in the two silicon detectors. For example, ^{54}O would deposit about 16 MeV in the dE detector and leave the remaining 24 MeV for collection by the E detector.

Some background particles, most abundantly knocked-out carbon ions, survive the analyzing magnet's rigidity selection and enter our detector system. These ions left nonzero signals in both the dE and E silicon counters, but in no case were these signals within 10 MeV of the expected strangelet signal on the dE vs E plot. The experiment was therefore free of background. The counting rates of these carbon ions (when they appeared, which were rare cases) were less than 10 Hz, so the dead time of the detectors was negligible.

We have searched over a range in mass from 42 to 70 amu and found no strangelet candidate events. The single event sensitivity limit for strange oxygen with a given mass A_0 can be calculated as

$$s = \frac{1}{1.5 \times I \times T \times P_{+5} \times \epsilon_T(5)}, \quad (1)$$

where I is the current of ^{16}O out of the ion source. $1.5 \times I$ gives the total ion current out of lunar soil source, considering the relative abundance of oxygen atoms in lunar soil and negative ion forming efficiency by sputtering. T is the running time per mass setting. P_{+5} is the probability of a strangelet oxygen with given mass A_0, and kinetic energy 17 MeV being stripped to a charge state of $Q = +5$. $\epsilon_T(5)$ is the transmission efficiency of charge $+5$ beam through the tandem from the source to our detectors (not including stripping probability).

The running time T was nominally 2 h for each mass setting. The current of ^{16}O, which averaged approximately 7×10^{13} particles per second, was measured with a Faraday cup after the inflector magnet before and after each run. P_{+5} is calculated for each mass from the formula given in [26]. These stripping probabilities depend only on the velocity and bare charge of the nucleus and the formula used is a parametrization of experimental data. Because $+5$ is the most likely stripped charge state to emerge from the carbon foil, experimental measurements have been made at similar energies and the interpolation via this formula introduces little uncertainty. We find the value to be, on average, 0.4 $\pm$ 0.1.

The dominant systematic uncertainty in our sensitivity comes from the determination of $\epsilon_T(5)$. Direct measurement of $\epsilon_T(5)$ is unfeasible because of the large uncertainty of stripping probability p_{+5} for a normal nucleus with $A_0 \sim 54$ and incident energy of 17 MeV. We determined $\epsilon_T(5)$ by measuring $\epsilon_T(Q)$ versus stripped charge Q for a variety of mass states to determine the dependence of $\epsilon_T(Q)$ on mass and charge. This involved improving the existing measurements for charge state stripping for various charge states which was done in a separate apparatus not described here. From the reproducibility of and variation in these measurements, we estimate a systematic uncertainty of $\pm$50% on $\epsilon_T(5)$.

The 95% confidence level (C.L.) upper limit for strange oxygen concentration in lunar soil is about 10^{-16}, as shown in Fig. 3 by the black solid line. The gray area corresponds to the systematic uncertainties of the 95% upper limits.

The search was optimized in this mass range for strangelets of nuclear charge $Z = 8$ (i.e., strange oxygen), but was sensitive to strangelets of different Z values. These limits are different than the $Z = 8$ limits because nuclei of other Z values will generally have different efficiencies for producing negative ions in the sputtering ion source and different probabilities for stripping to $Q = +5$ in the carbon foil. When these differences are accounted for (in the former case, by consulting [28] and making measurements of source currents for various nuclei; in the latter case, by

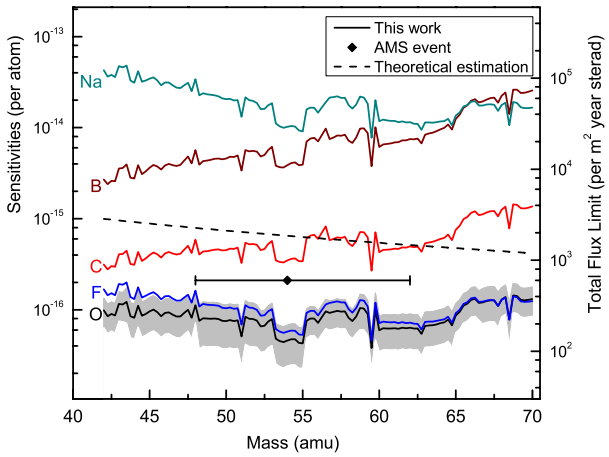

FIG. 3 (color online). The 95% C.L. upper limits of our search for different strangelet elements are shown in solid lines, with the element names on the left-hand side. The y axis on the right-hand side shows the implied flux limits for cosmic ray strangelets. The dashed line corresponds to theoretical estimation of strangelet flux in cosmic rays at the moon [10]. The gray area represents the systematic uncertainties for strange oxygen search limits.

simply using [26]), we obtain the limits for strange boron, carbon, fluorine, and sodium shown in Fig. 3. This experiment is not sensitive to strange nitrogen, neon, or magnesium at all because these elements do not form negative ions by sputtering.

These sensitivity results can be transformed into limits on the cosmic strangelet flux. The transformation between search sensitivity and flux limit is determined by this lunar sample's exposure age to cosmic rays and strangelets' stopping range in lunar soil. For a commonly used energy spectrum [10], approximately 40% of the incident strangelets would stop in the top 7.5 cm of lunar material [27], from which the lunar soil sample No. 10084 was collected. Using these numbers, the upper flux limits determined from this search are shown by the right y axis in Fig. 3. Additional uncertainties introduced in the transformation process are not considered.

Cosmic strangelet flux limits can also be derived from results of terrestrial searches for strangelets [29]. A rough comparison [15] shows that the search reported here is more sensitive for $Z = 8$ strangelets in cosmic rays by some 4 orders of magnitude than terrestrial searches and also gives the best existing limit for nearby charge states.

One important result of this search is that from 42 to 70 amu our limits are inconsistent at the 95% C.L. with a strangelet flux corresponding to the nominal value indicated by the AMS-01 $Z = 8$ candidate event, assuming strangelets to be absolutely stable. Taking into account the statistical uncertainty for that event we find the results of the two experiments inconsistent at the 86% C.L. for the central mass value $A = 54$ and at the 78% C.L. for the total mass range covered. We may in addition calculate the probability that our lunar soil experiment should find zero events under the assumption that the AMS-01 $Z = 8$ event is real. We find that the conditional probability (with the Bayesian assumption of a flat prior probability density function for the strangelet flux) is less than 1% for $A = 54$ and $\sim$2% for the whole mass range (with search limits uncertainties considered), which indicates that the ^{54}O event is highly unlikely to be real given the result of this search.

We can extend our search to a higher mass range by simply running more and/or altering the beam line so that the mass acceptance is larger (though this would of course greatly increase the expense of the experiment). Because the search was influenced by the AMS-01 event, the covered mass region is not centered around the region considered theoretically to be the most likely for $Z = 8$ strangelets, i.e., 80–140 amu [for $A \ll 1000$, $A = 10(Z)$ for standard bag model calculations and $A = 6(Z)^{3/2}$ for the case when CFL is included [7]; Ref. [30] finds that CFL strangelets may have $Z = 0$ if the pairing energy is high]. Also, we could improve our limits drastically by enriching the heavy isotope concentration in the lunar samples, though this would restrict our sensitivity to strange oxygen only.

The existence of stable SQM remains an open question.

The authors thank P. Parker, J. Clark, A. Parikh, C. Deibel, and C. Wrede for their help, especially in the stripping probability measurements. We also gratefully acknowledge the valuable contributions of G. Lin, T. Hurteau, H. Lippincott, R. Terry, J. Baris, T. Barker, W. Garnett, and other WNSL operators. The work is supported by U.S. Department of Energy under Contracts No. DE-FG02-92ER-40704 and No. DE-FG02-91ER-40609, and by the Danish Natural Science Research Council.

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