A search for stable strange quark matter nuggets in helium

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Abstract

A search for stable strange quark nuggets has been conducted in helium and argon using a high sensitivity mass spectrometer. The search was guided by a mass formula for strange quark nuggets which suggested that stable strange helium might exist at a mass around 65 u. The chemical similarity of such "strangelets" to noble gas atoms and the gravitational unboundedness of normal helium result in a large enhancement in the sensitivity of such a search. An abundance limit of no more than $2 \cdot 10^{-11}$ strangelets per normal nucleus is imposed by our search over a mass region from 42 to 82 u, with much more stringent limits at most (non-integer) masses.
I. INTRODUCTION

Witten [1] suggested in 1984 that strange matter consisting of up, down, and strange quarks might be stable. A previous study of such “strangelets” by Chin and Kerman [2] had suggested the possibility that such quark matter might actually be at least a metastable phase of nuclear matter. A mass formula was developed in the context of quarks confined to a (nuclear) bag by Farhi and Jaffe [3] and by Berger and Jaffe [4]; their formula depended only on the bag constant and the strange quark mass in the nuclear medium. It was used to study the possible stability of strangelets as a function of baryon number, as well as possible decay modes. Those studies confirmed the possibility that strangelets might be stable, although the most likely masses for stable strangelets were suggested by the mass formula as being very large, possibly having baryon numbers larger than the heaviest stable nuclei.

However, Takahashi and Boyd [5] extended the Farhi-Jaffe-Berger mass formula to include shell effects. The magic numbers for quarks in a strangelet were calculated in the spherical cavity model of DeTar and Donoghue [6]. Configuration mixing and deformation effects were included using prescriptions of Myers and Swiatecki [7]. The resulting corrections were then added to the Farhi-Berger-Jaffe mass formula. The mass formula indicated that a charge 2 strangelet has a reasonable chance of being stable, and, if so, would be expected to have a mass around 65 u. Furthermore, this mass prediction does not depend critically on the shell correction parameter, although the boundedness of the resulting strangelets certainly does.

While the possible existence of strangelets is of obvious interest in its own right, it has also been shown [8] that they could have interesting astrophysical consequences. At an abundance of 1 in $10^{15}$ normal nuclei, strangelets could, if they existed with charge 2, affect stellar evolution. This is due to the greatly reduced Coulomb barrier they would have for hydrogen burning compared, e.g., to the nuclei involved in CNO cycle burning. Furthermore, heavy nuclides, such as strangelets, could have settled to the cores of stars so
that a strangelet abundance level sufficient to affect stellar burning might correspond to a significantly lower mean cosmic abundance.

Because of the tendency for stable strangelets to be very massive, the existence of light strangelets in the cosmos may well depend on some sort of processing mechanism. This was studied by Boyd and Saito [8]. They concluded that if massive strangelets are produced as high energy particles in, e.g., collisions of neutron stars, as was suggested by Witten [1], the collisions of the high energy strangelets with the particles of the nebula which resulted from the supernovae that produced the neutron stars could well do the processing necessary to spall off many light strangelets. Furthermore, this possibility appears to be consistent, both in strangelet mass and energy, with the possible high energy strangelets seen in the cosmic ray experiments of Saito et al. [9].

It should be noted that even the possibility for production of strange objects is controversial. Alcock and Farhi [10] studied possible strangelet production in the big bang, but concluded that any remnant strangelets, unless they were extraordinarily massive, would have evaporated shortly after the big bang. This, however, has been disputed by Madsen et al. [11]. Witten [1] suggested that strangelets could result from collisions of collapsed strange stars. However, Madsen [12] and others concluded this to be an impossibility, due to the need for a fairly thick crust on the surfaces of neutron stars so as to explain pulsar glitches [13]. However, the structure of strange stars has been shown by others [14] to be quite capable of producing the sort of crust necessary to explain the glitches.

In the present study we have adopted a purely experimentalist approach, ignoring the theoretical controversies that exist and designing a search for strangelets that takes advantage of terrestrial selection processes to enhance their abundance. Searches have been conducted previously (see [15] and references therein), most notably on a range of nuclides including H, Li, Be, B, C, O, F, and Na to extremely low abundance limits: $10^{-15}$ to $10^{-25}$ strangelets per normal nucleus. That search, however, did not include He, for which special properties exist. The present search, guided by the Takahashi-Boyd mass formula, was based on the hypothesis that stable strange helium nuclei, i.e., charge 2 strangelets, exist.
The sensitivity of this search relies on the noble gas chemistry such an entity would have, coupled with the abundance enhancement it would have as a terrestrial helium “atom”.

If charge 2 strangelets exist, then the Earth would effectively enrich the strangelet to He ratio. Neither isotope of helium is gravitationally bound to the Earth, nor does He interact chemically to form molecules that would be bound (as does H). However, strangelets possessing the 65 u mass suggested by the Takahashi-Boyd mass formula would be gravitationally bound over the time of formation of the Earth’s present atmosphere. This effect greatly enhances the limit obtained by our experimental search. The special features involving this type of helium search were described by Boyd and Caffee [16].

Section II describes the noble gas mass spectrometric facility at Lawrence Livermore National Laboratory where the experiment was performed and also estimates the enhancement in terrestrial helium that results from the gravitational unboundedness of ordinary helium. Section III describes the data analysis and results, and section IV summarizes the results of our study.

II. EXPERIMENTAL DETAILS

A. Mass spectrometric facility and data acquisition

The spectrometer used in this experiment consists of two major components: the gas aliquotting and purification system and the mass spectrometer itself. The spectrometer in turn is comprised of an electron bombardment ionization source, a magnetic sector, and detectors – an axial pulse-counting electron multiplier and an off-axis faraday cup.

Known amounts of noble gases were aliquotted using a combination of calibrated volumes and capacitive manometers. After a known amount of air was aliquotted, the noble gases (which are trace constituents) were purified from air using a titanium sublimation pump and a series of SAES non-evaporative alloy getters. After purification, the noble gases were separated from each other using cryogenic techniques.
After purification and separation, the noble gas species of interest was admitted into the spectrometer, which was run in a static mode. Singly ionized species were accelerated to $\sim 4.5$ keV and were then mass analyzed by a standard double focusing magnetic sector. The beam finally passed through object slits placed directly in front of the axial detector. The mass resolving power ($M/\Delta M$) of this instrument using the axial detector is about 600. There is also an off-axis faraday cup for the measurement of higher ($\gtrsim 10^5$ counts sec$^{-1}$) beam currents, which measures current via an ultra-stable sensitive electrometer. The magnetic field was controlled by a Hall probe field regulator and had a stability of the order of ppm. Operationally there were $> 20$ discrete DAC settings at the peak of each mass. The entire system was controlled by a Macintosh computer running LabView. A scan of a particular mass range was accomplished by changing the magnetic field setting of the magnet in discrete steps and, after each step, acquiring data for a predetermined period of time. The data were then stored on disk for later retrieval.

### B. Enhancement of measured abundance limits

The measured strangelet abundance limit in air will be enhanced over the cosmic value due to the gravitational unboundedness of the primordial terrestrial helium. Assume that the abundance of noble gas $x$ in air, $x_a$, is characteristic of its cosmic abundance $x_c$. If $x$-atoms are gravitationally bound, the ratio $x_a/x_c$ would be expected to be roughly the same for different gases $x$. For the two heaviest stable noble gases, Xe and Kr, (with $x_a$ expressed as a volume content fraction [17] and $x_c$ in units of atoms per $10^6$ silicon atoms [18])

$$\text{Xe}_a/\text{Xe}_c = 1.9 \cdot 10^{-8}$$

and

$$\text{Kr}_a/\text{Kr}_c = 2.5 \cdot 10^{-8}$$

confirming our assertion. For Ar, the ratio is $9.2 \cdot 10^{-8}$, for Ne it falls to $5.3 \cdot 10^{-12}$, and for He to $1.9 \cdot 10^{-15}$. The amount by which this last ratio differs from that for the heaviest
noble gases, $1 \cdot 10^7$, gives the enhancement for our experiment. It should be noted that most of terrestrial helium is not that which existed at the time the Earth was formed, but has been produced since that time by decay of transuranic nuclides.

Our experiment determined the ratio in air of charge 2 strangelets to $^4\text{He}$. What is desired, however, is the cosmic value of that ratio, $\text{Str}_c/\text{He}_c$, given by

$$\frac{\text{Str}_c}{\text{He}_c} = \frac{\text{Str}_a}{\text{He}_a} \frac{[\text{He}_a \text{ Xe}_c]}{[\text{He}_c \text{ Xe}_a]}$$

all values of which are known or determined in our experiment. The inverse product of the term in brackets gives the $10^7$ enhancement factor (in addition to a correction for units) due to the gravitational unboundedness of $^4\text{He}$.

This argument depends on the assumption that there are no components in the mass spectrometer that would select strangelets over $^4\text{He}$. Since there are numerous cryopumps in the spectrometer, one must consider the effects on the boiling point of changing the nuclear mass in helium from 4 to 65 u. This is described in detail by Wilks [19], who gives the procedure for determining the boiling point for $^{65}\text{He}$; we calculated it to be 7 K. Thus the cryopumps in the system, which operate at a variety of temperatures, but always above 10 K, should not affect the strangelet to $^4\text{He}$ abundance ratio.

The helium “supply” we used was just the helium from air, isolated in the spectrometer by freezing out all other gases. Thus no additional caveats over those discussed above are necessary. We also ran a series of experiments using Argon obtained from air. The Argon was isolated by taking advantage of its unique adsorption on activated charcoal at liquid nitrogen temperatures. With only argon adhering to the charcoal, all other gases could be pumped out. Then with the pump closed off, the charcoal is heated to expel the argon. Only argon (and no helium or strange matter) would be expected to survive this adsorption isolation, because, although strangelets are closer in mass to argon than helium, the adsorption depends on electronic properties, such as boiling point, polarizability, etc.

The ratio of heavy to regular helium on Earth should be well represented by its concentration in air at sea level. The height above the Earth at which the gas is sampled has no
bearing on this ratio, because all atmospheric gases, even heavy ones such as CO₂, are well mixed up to about 80 km [20]. Also, heavy helium would not be expected to settle to the bottom of the ocean. The oceans recirculate their deep water within atmospheric contact in less than 1000 years [21], a short time compared to the age of the Earth, which allows equilibrium to be established between the helium in the oceans and the atmosphere. Finally, the oceans do not represent a significant reservoir of helium, since the solubility of helium is very low [22]. Thus we conclude that a measurement of the ratio of heavy to regular helium in air should not be affected by any sinks in the heavy helium.

III. DATA ANALYSIS

Mass spectra were accumulated in successive runs with helium, argon, and then a background run with no gas. Data were collected by stepping through the allowed range of the magnetic field, pausing for a preset time (4 sec) at each setting to count the number of particles hitting the multiplier. Using a mass calibration based on known peaks in the spectrum (CO₂ at mass 44 and C₆H₆ at mass 78), we obtained a counts vs. mass spectrum for each case. While we had hoped to do a direct subtraction of the background spectra from the helium spectra, this was not possible due to the somewhat random nature of the background, which caused the peaks to have slightly different heights and widths in the different spectra. However, strangelet candidates can be ruled out at some level by visual inspection; an anomalous peak in the helium spectrum which also appears at comparable strength in the argon spectrum, several of which were observed, is not likely to be a strangelet.

Figure 1 shows the data and results for the mass scan from 42 to 82 u. The dominant peaks are hydrocarbon contaminants, which appear mostly at integer masses, but also at half integer masses for doubly stripped hydrocarbons. Since the counting interval is four seconds and the efficiency of the multiplier is 75%, the lowest possible counting rate is \((1/4)/0.75 = 0.3333\) counts per second, as seen on the graph.

The upper limit for the strangelet abundance detected by our experiment is derived by
assuming that all the events are due to strangelets. To compute the abundance limit, the count rate at a particular mass value is divided by the known amount of regular helium in the beam of the spectrometer ($\sim 5 \cdot 10^6$ per second) and the enhancement factor of $1 \cdot 10^7$. Another factor of 11.3 in the denominator converts the abundance of strangelets relative to the abundance of cosmic helium (8.9% number fraction) to the abundance of strangelets compared to all nuclei [8].

For the first and second halves of the mass region, the maximum count rates are $\sim 10^4$ and $\sim 10^3$, with corresponding abundance limits for these overall regions of $2 \cdot 10^{-11}$ and $2 \cdot 10^{-12}$ strangelets per nucleus. Away from the mass peaks at integer and half integer values, the maximum count rate drops to no more than 10, yielding a lower limit of $2 \cdot 10^{-14}$ strangelets per nucleus in these mass regions. This value cannot be quoted for the entire region, however, since the amount of strangelets present in the contaminant peaks is unknown.

**IV. SUMMARY**

If quark matter is present in the universe, then charge 2, helium-like strangelets might exist at some level in the terrestrial atmosphere. We have performed a sensitive mass spectrometric search for strangelets from 42 to 82 u. No definitive strangelet candidates were observed in our data, but upper limits on the cosmic strangelet to normal nucleus abundance are deduced to be $2 \cdot 10^{-11}$ for masses in the 42 to 60 u range, and $2 \cdot 10^{-12}$ for masses between 60 and 82 u.

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FIGURES

FIG. 1. Normalized data, and also final abundance limits as determined by our experiment. Peaks at all integer values and some half-integer values indicate the presence of hydrocarbon contaminants. For a), a reasonable upper limit for the abundance is $2 \cdot 10^{-11}$, and for b), the limit is $2 \cdot 10^{-12}$. 
counts per second

Mass (u)

Abundance Limit

benzene

10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7}

2 \times 10^{-16} 2 \times 10^{-15} 2 \times 10^{-14} 2 \times 10^{-13} 2 \times 10^{-12} 2 \times 10^{-11} 2 \times 10^{-10} 2 \times 10^{-9} 2 \times 10^{-8}