A possible explanation for AMS doubly charged anomalous event

Yun Zhang, and Ru-Keng Su

1Department of physics, Fudan University, Shanghai 200433, P. R. China

2China Center of advanced Science and Technology (World Laboratory) P. O. Box 8730, Beijing 100080, P. R. China

Abstract

By means of the quark mass density-dependent model, a possible explanation for the doubly charged anomalous event with $Z/A = 0.114$ reported by Alpha Magnetic Spectrometer Collaboration is given. It seems a strangelet. The composition, radius and mean lifetime of this strangelet are given.

PACS numbers: PACS number: 12.39.Ki, 21.65.+f, 11.10.Wx, 25.75.-q
According to the argument of Greiner et. al [1], the strangelet could serve as an unambiguous signature for the existence of the quark gluon plasma (QGP). The detection of strangelets has long been a main subject in the relativistic heavy ion collision (RHIC) experiments and the cosmic-ray space experiments concerning with the search for anomalously heavy nuclei [2, 3, 4], and unfortunately, by now, it has not been found yet.

Recently, a very interesting anomalous event has been announced by the Alpha Magnetic Spectrometer (AMS-01) Collaboration [5]. Within more than four million He events collected by AMS-01 detector, one that has \( Z/A \) of 0.114 ± 0.01, kinetic energy of 2.1 GeV and corresponds to the flux of \( 5 \times 10^{-5} (m^2 \cdot sr \cdot sec)^{-1} \) was found. This was a doubly charged anomalous event and it strongly needed further explanation from theoretical view of point whether the event denoted a small lump of strange quark matter, i.e. strangelet, or only a nuclei [5].

This paper evolves from an attempt to give a possible explanation for this doubly charged and heavy mass event. We will employ the quark mass density-dependent (QMDD) model which was firstly suggested by Fowler, Raha and Weiner [6] and then used by many authors to study the stability and other properties of strange quark matter [7, 8, 9, 10]. In a series of our previous papers [12, 13, 14, 15, 16], based on the Friedberg-Lee model [17], we extended the QMDD model to a quark mass density- and temperature-dependent (QMDTD) model at finite temperature. The thermodynamical properties and the stability of strangelets [12, 13, 14], the dibaryon system [15] and the photo strange star [18] have been discussed by using QMDTD model. At zero temperature, the QMDTD model reduces to the QMDD model. Since the AMS-01 experiment was flown on the space shuttle Discovery during flight STS-91 (1998) in a 51.70 orbit at altitudes between 320 and 390 Km, the temperature of cosmic space is very low and we will neglect the temperature effect in our calculation.

According to QMDD model [6, 7, 8, 9, 10], the masses of \( u, d \) quarks and strange quarks (and the corresponding anti-quarks) are given by

\[
m_q = \frac{B}{3n_B}, \quad (q = u, d, \bar{u}, \bar{d}),
\]

\[
m_{s,\bar{s}} = m_{s0} + \frac{B}{3n_B},
\]

where \( n_B \) is the baryon number density, \( m_{s0} \) is the current mass of the strange quark and \( B \) is the vacuum energy density. One can proved that the properties of strange matter in the
QMDD model are nearly the same as those obtained in the MIT bag model [8].

At zero temperature, the particle number \( N_i \) \((i = u, d, s)\) reads

\[
N_i = \int_0^\infty \sqrt{\mu_i^2 - m_i^2} \rho(k) dk;
\]

and the total energy of the strangelet is

\[
A = \sum_i \int_0^\infty \sqrt{\mu_i^2 - m_i^2} \sqrt{m_i^2 + k^2} \rho(k) dk;
\]

where \( \mu_i \) is the chemical potential of the quark and \( \rho(k) \) is the density of states. For a spherical cavity, \( \rho(k) \) can be obtained by multi-reflection theory \([19]\) or by numerical calculation \([20]\). The result is

\[
\rho(k) = \frac{d}{dk} \left\{ \xi \cdot (kR)^3 + \zeta \cdot (kR)^2 + \eta \cdot (kR) \right\},
\]

where \( R \) is the radius of the bag,

\[
\xi = \frac{2g}{9\pi},
\]

\[
\zeta \left( \frac{m}{k} \right) = \frac{g}{2\pi} \left\{ \left[ 1 + \left( \frac{m}{k} \right)^2 \right] \tan^{-1} \left( \frac{k}{m} \right) - \left( \frac{m}{k} \right) - \frac{\pi}{2} \right\},
\]

and

\[
\eta \left( \frac{m}{k} \right) = \frac{g}{2\pi} \left\{ \frac{1}{3} + \left( \frac{k}{m} + \frac{m}{k} \right) \tan^{-1} \frac{k}{m} - \frac{\pi k}{2m} \right\} + \left( \frac{m}{k} \right)^{1.45} \frac{g}{3.42 \left( \frac{m}{k} - 6.5 \right)^2 + 100}.
\]

The strangeness number \( |S| \) of the strangelet reads

\[
|S| = N_s;
\]

the baryon number \( N \) of the strangelet is

\[
N = \frac{1}{3} (N_u + N_d + N_s),
\]

and the electric charge \( Z \) of the strangelet is

\[
Z = \frac{2}{3} N_u - \frac{1}{3} N_d - \frac{1}{3} N_s.
\]

The stability condition of strangelets for the radius reads

\[
\frac{\delta A}{\delta R} = 0.
\]
The chemical potentials of quarks $\mu_u, \mu_d, \mu_s$ of a strangelet with fixed strangeness number, baryon number and electric charge could be obtained by solving Eqs. (9), (10), (11) and (12) self-consistently. In the following, we limit our calculation in the area

$$Z \geq -N,$$

$$|S| + Z \leq 2N$$

to keep the particle numbers of $u, d,$ and $s$ quarks positive.

At zero temperature, the stability of a strangelet is determined by its energy. Since the strangeness number $|S|$ and the electric charge $Z$ are conserved in the strong process, a general expression of a two-body strong decay for strangelet $Q(N, |S|, Z)$ can be written as

$$Q(N, |S|, Z) \rightarrow Q(N - 1, |S| - |S_x|, Z - Z_x) + x(1, |S_x|, Z_x),$$

with the energy balance of the corresponding reaction satisfies

$$E(N, |S|, Z) > E(N - 1, |S| - |S_x|, Z - Z_x) + m_x,$$

where $x$ stands for a baryon with strangeness number $S_x$ and electric charge $Z_x$. For the weak process, the electric charge $Z$ is still conserved but $\Delta S = \pm 1$, therefore,

$$Q(N, |S|, Z) \rightarrow Q(N - 1, |S| - |S_x| - 1, Z - Z_x) + x(1, |S_x|, Z_x),$$

if the energy balance of the corresponding reaction satisfies

$$E(N, |S|, Z) > E(N - 1, |S| - |S_x| - 1, Z - Z_x) + m_x.$$

A strangelet that decays via strong processes is called unstable strangelet and the one could withstand strong decay and only decays via weak processes is called metastable strangelet.

Our results are shown in Figure 1, 2 and Table 1. There are two parameters, namely, bag constant $B$ and current mass of strange quark $m_{s0}$ in the QMDD model. We fix $B_0 = 170$ MeV fm$^{-3}$, $m_{s0} = 150$ MeV first. The stability of strangelets with fixed electric charge $Z = 2$ and different baryon number $N$ and strangeness number $|S|$ is shown in Figure 1, where open circles stand for the unstable strangelets and filled circles stands for the metastable strangelets. The strangelet with the energy most close to that of the anomalous
event in AMS-01 detection \((\frac{Z}{A} = 0.114, A = 17.5 \text{ u})\) is \(Q(14, 23, 2)\), which is a metastable strangelet and is represented by a filled square in Figure 1. The strangelet \(Q(14, 23, 2)\) is composed by 23 strange quarks, 16 up quarks and 3 down quarks. In Figure 2, we draw the curve of its energy as the function of the radius. While the energy of the strangelet has its minimal value, the corresponding radius is called the stable radius of the strangelet, and the stable radius reads 1.992 fm for \(Q(14, 23, 2)\).

One of the interested properties of the strangelet in the experimental detection is its mean lifetime \(\tau\). Employing the decay formula given by Chin and Kerman\[15, 21\]

\[
\frac{1}{\tau} = \left[ C^2 \mu_s^5 / 192 \pi^3 \right] \sin^2 \theta_c F(z),
\]

with

\[
F(z) = 1 - 8z + 8z^3 - z^4 - 12z^2 \ln z,
\]

\[
z = \mu_u^2 / \mu_s^2,
\]

where the Cabibbo angle is given by \(\sin \theta_c \simeq 0.22\), and considering relativistic factor \(\beta = 0.462\), we obtain that the dynamical mean lifetime \(\tilde{\tau}\) for \(Q(14, 23, 2)\) is \(2.25 \times 10^{-8} \text{ s}\), which is long enough for experimental detection.

Obviously, above result depends on the choice of parameters \(B\) and \(m_{s0}\). In fact, the available choices of \(B\) and \(m_{s0}\) are limited in an area called "stability window" which is shown in Ref. \[12\] for QMDD model. To confirm our result, we choose 4 different parameter pairs \((B, m_{s0})\) in this window and other two pairs \((57.54 \text{ MeV fm}^{-3}, 280 \text{ MeV}), (396.93 \text{ MeV fm}^{-3}, 150 \text{ MeV})\) given by references \[11, 22\] to calculate, and results are shown in Table 1

| \(B\) (MeV fm\(^{-3}\)) | \(m_{s0}\) (MeV) | Metastable Strangelet | Composition | \(E\) (u) | \(R\) (fm) | \(\tilde{\tau}\) (s) |
|----------------|--------------|----------------------|-------------|-------|--------|--------|
| 170            | 150          | \(Q(14, 23, 2)\)    | 16u3d23s   | 17.53 | 1.992  | 2.25 \times 10^{-8} |
| 180            | 150          | \(Q(14, 22, 2)\)    | 16u4d22s   | 17.50 | 1.962  | 2.52 \times 10^{-8} |
| 190            | 150          | \(Q(13, 24, 2)\)    | 15u0d24s   | 17.58 | 1.911  | 1.41 \times 10^{-8} |
| 220            | 75           | \(Q(14, 24, 2)\)    | 16u2d24s   | 17.55 | 1.911  | 1.59 \times 10^{-7} |
| 57.54          | 280          | \(Q(15, 25, 2)\)    | 17u3d25s   | 17.68 | 2.550  | 2.13 \times 10^{-9} |
| 396.93         | 150          | \(Q(11, 20, 2)\)    | 13u0d20s   | 17.51 | 1.517  | 1.47 \times 10^{-8} |

We see from Table 1 that we can always find a metastable strangelet that satisfies the condition \(\frac{Z}{A} = 0.114\), although their compositions, radiuses and dynamic mean lifetime are
different. Therefore, we come to the conclusion that the doubly charged anomalous heavy event detected by AMS-01 could attribute to a metastable strangelet, and this conclusion given by QMDD model is not parameters dependent.

In summary, by means of the QMDD model, we give a possible explanation for the doubly charged anomalous heavy event found by AMS-01 detector. It seems a strangelet. This conclusion dose not depend on the choices of the model parameters. Of course, we need more events to confirm the existence of the strangelet and we hope AMS-02 could provide us more information of this topic.

I. ACKNOWLEDGMENT

We thank professors Zuo-Xiu He and Cheng-Rue Qing for helpful discussions. This work was supported in part by the NNSF of China under contract Nos. 10375013, 10247001 and 10235030, by the National Basic Research Program 2003CB716300 of China and the Foundation of Education Ministry of China under contract 2003246005.

II. FIGURE CAPTIONS

Figure 1. The baryon number $N$ as a function of the strangeness number $S$ for unstable strangelets (open circles) and metastable strangelets (filled circles) with electric charge number $Z = 2$.

Figure 2. The energy of the strangelet $Q(14, 23, 2)$ as a function of radius $R$.

III. TABLE CAPTIONS

Table 1. The energy, stable radius, and dynamic mean lifetime of the strangelets which has the energy around 17.5 u with different parameters setting.

[1] C. Greiner, P. Koch and H. Stöcker, Phys. Rev. Lett. 58, 1825 (1987), Phys. Rev. D 44, 3517 (1991).
[2] T. Saito et. al, Phys. Rev. Lett. 65, 2094 (1990); M. Ichimura et. al, Nuovo Cimento A 106, 843 (1993).

[3] M. Aguilar et. al, Phys. Rep. 366, 331 (2002).

[4] J. Alcaraz et. al, Phys. Lett. B 494, 193 (2000).

[5] V. Choutko, the 28th Inter. Cosmic Ray Conference, 1765 (2003).

[6] G. N. Fowler, S. Raha and R. M. Weiner, Z. Phys. C 9, 271 (1981).

[7] S. Chakrabarty, Nuovo Cimento Soc. Ital. Fis., B 106, 1023 (1991), Phys. Rev. D 43, 627 (1991), Phys. Rev. D 48, 1409 (1993).

[8] O. G. Benrenuto and G. Lugones, Phys. Rev. D 51, 1989 (1995); G. Lugones and O. G. Benrenuto, Phys. Rev. D 52, 1276 (1995).

[9] G. X. Peng, H. C. Chiang, B. S. Zou, P. Z. Ning and S. J. Luo, Phys. Rev. C 62, 025801
(2000); G. X. Peng, H. C. Chiang, P. Z. Ning and B. S. Zou, Phys. Rev. C 59, 3452 (1999).

[10] P. Wang, Phys. Rev. C 62, 015204 (2000).

[11] J. Schaffner-Bielich, C. Greiner, A. Diener and H. Stöcker, Phys. Rev. C 55, 3038 (1997).

[12] Y. Zhang, and R. K. Su, Phys. Rev. C 65, 035202 (2002).

[13] Y. Zhang, R. K. Su, S. Q. Ying and P. Wang, Europhys. Lett. 56, 361 (2001).

[14] Y. Zhang, and R. K. Su, Phys. Rev. C 67, 015202 (2003).

[15] Y. Zhang, and R. K. Su, J. Phys. G 80, 811 (2004).

[16] Y. Zhang, and R. K. Su, Mod. Phys. Lett. A 18, 143 (2003).

[17] T. D. Lee, Particle Physics and Introduction to Field Theory (Chur: Harwood Academic) 1981.

[18] V. K. Gupta et. al, Inter. J. Mod. Phys. D 21, 583 (2003).
[19] R. Balian, and C. Block, Ann. Phys. 60, 401 (1970); T. H. Hansson, and R. L. Jaffe, Phys. Rev. D 35, 213 (1989); J. Madsen, Phys. Rev. D 50, 3328 (1994).

[20] Y. Zhang, W. L. Qian, S. Q. Ying and R. K. Su, J. Phys. G: Nucl. Part. Phys. 27, 2241 (2001).

[21] S. A. Chin and A. K. Kerman, Phys. Rev. Lett. 43, 1292 (1979).

[22] S. Chakrabarty, S. Raha, and B. Sinha, Phys. Lett B 229, 112 (1989).