Dibaryon systems in the quark mass density- and temperature-dependent model

Yun Zhang$^{1,3}$ and Ru-Keng Su$^2$

$^1$Department of physics, Fudan University, Shanghai 200433, P. R. China
$^2$China Center of advanced Science and Technology (World Laboratory)
P. O. Box 8730, Beijing 100080, P. R. China
$^3$Surface Physics Laboratory (National Key Laboratory), Fudan University,
Shanghai 200433, P. R. China

Abstract

Using the quark mass density- and temperature-dependent model, we have studied the properties of the dibaryon systems. The binding energy, radius and mean lifetime of $(\Omega\Omega)_0^+$ and $(\Omega\Xi^-)$ are given. We find the dibaryons $(\Omega\Omega)_0^+$, $(\Omega\Xi^-)$, $(\Omega\Xi^0)$ are metastable at zero temperature, but the strong decay channel for $(\Omega\Omega)_0^+$ opens when temperature arrives at 129.3 MeV. It is shown that our results are in good agreement with those given by the chiral $S(3)$ quark model.

PACS number: 12.39.Ki, 14.20.Jn, 11.10.Wx, 24.85.+p
I. INTRODUCTION

Since Jaffe predicted the existence of $H$ particle [1], the study of dibaryon systems has attracted more and more attentions [2–14]. A lot of theoretical models, for example, the constituent quark model in which the effective degrees of freedom are constituent quarks and gluons [12]; the quark-mesons exchange model in which the effective degrees of freedom are constituent quarks and Goldstone bosons [9,13]; the chiral SU(3) quark model [6–8,14], ... had been employed to predict the bound states of dibaryon systems. Many particles, namely, $H$ dihyeron [1–3], $d'$ particle [5], $(\Omega\Omega)_{0+}$ and $\Omega^{-}\Xi^{0}$ [6–8,14], $\Delta\Delta$ [9,11] have been suggested to be candidates for being observed in the experiment. Unfortunately, the convincing experimental evidence for the existence of these particles has not yet been found. Then it is essential to confirm which dibaryon would be the best one to be detected in the experiment. Therefore, it is necessary to address the above dibaryons from different point of views, different models and different treatments, because it can open the field of vision and choose the best detectable candidate after comparing the results given by different models. This is the first motivation to employ our quark mass density- and temperature-dependent (QMDTD) model [15–18] to study the dibaryon system.

The second motivation is to extend the study of dihyeron to finite temperature. The strangeness enhancement was observed in relativistic heavy ion collision (RHIC) recently [19,20]. The dihyeron can be found from the extreme condition of RHIC easily than that from the usual one. According to the thermal model of RHIC, a fireball with high temperature and high density is formed. Employing a suitable model to study the stability and the thermodynamic properties of dibaryon at finite temperature can help us to learn the detectable possibility of dihyeron.

In previous papers, by means of the QMDTD model, we studied the thermodynamic behavior and stability of $A = 5$ and $A = 10$ strangelets at finite temperature where $A$ is the baryon number [15,18]. We found that the stable strangelets only exist in the high strangeness module and high negative charge region. For $A = 2$ dibaryon system, $(\Omega\Omega)_{0+}$ has the maximum strangeness module and maximum negative charge. It is of interest to study $A = 2$ dibaryon system by using QMDTD model.

The organization of this paper is as follows. In next section, we give the main formulas of the QMDTD model. The results including stability, binding energy, radius, lifetime for dibaryon systems at zero temperature are presented in Sec. III. In Sec. IV, we will discuss the stability of dibaryon via possible strong and weak decays at finite temperature. The last section contains a summary.

II. QMDTD MODEL

QMDTD model is a non-permanent quark confinement model [16] because it is based on the Friedberg-Lee model [21]. It has been used to study the thermodynamic properties of strangelets [15,17,18] and the photo strange star [22]. The detail of this model can be found in [15–18]. Here we only write down the main steps which is necessary for calculating the thermodynamic quantities.

According to the QMDTD model, the masses of $u, d$ quarks and strange quarks (and the corresponding anti-quarks) are given by [15–18]
\[ m_q = \frac{B(T)}{3n_B}, \quad (q = u, d, \bar{u}, \bar{d}), \]  
\[ m_{s, \bar{s}} = m_{s0} + \frac{B(T)}{3n_B}, \]  
\[ m_{s, \bar{s}} = m_{s0} + \frac{B(T)}{3n_B}, \]  
where \( n_B \) is the baryon number density, \( m_{s0} \) is the current mass of the strange quark and \( B(T) \) is the vacuum energy density which satisfies

\[ B(T) = B_0 \left[ 1 - a \left( \frac{T}{T_c} \right) + b \left( \frac{T}{T_c} \right)^2 \right], \quad 0 \leq T \leq T_c, \]  
\[ B(T) = 0, \quad T > T_c, \]

where \( B_0 \) is the vacuum energy density inside the bag (bag constant) at zero temperature , \( T_c = 170 \text{ MeV} \) is the critical temperature of quark deconfinement phase transition, and \( a, b \) are two adjust parameters. The values of \( a, b \) are fixed as

\[ a = 0.65, \quad b = -0.35. \]

Using the same argument as that of Ref. [6], in RHIC experiments, the fireball expands until freeze-out. The production of a large amount of particles and violent collisions between them in the fireball finally lead to the thermal and chemical equilibrium, soon after it reaches high temperature and high density. The thermodynamic potential in the fireball reads [6]

\[ \Omega = -\sum_i T \int_0^\infty dk \frac{dN_i(k)}{dk} \ln \left( 1 + e^{-\beta (\varepsilon_i(k) - \mu_i)} \right), \]

where \( \varepsilon_i(k) = \sqrt{m_i^2 + k^2} \) is the single particle energy and \( m_i \) is mass for quarks and antiquarks. \( \frac{dN_i(k)}{dk} \) is the density of states for various flavor quarks. For a dibaryon, its geometry can be taken as a sphere. The density of states of a spherical cavity has been calculated in our previous paper, it reads [23]:

\[ N_i(k) = A_i(kR)^3 + B_i(kR)^2 + C_i(kR), \]

\[ A_i = \frac{2g_i}{9\pi}, \]

\[ B_i = \frac{g_i}{2\pi} \left\{ \left[ 1 + \left( \frac{m_i}{k} \right)^2 \right] \tan^{-1} \left( \frac{k}{m_i} \right) - \left( \frac{m_i}{k} \right) - \frac{\pi}{2} \right\}, \]

\[ C_i = \frac{g_i}{2\pi} \left\{ \frac{1}{3} + \left( \frac{m_i}{k} + \frac{m_i}{k} \right) \tan^{-1} \frac{k}{m_i} - \frac{\pi k}{2m_i} \right\} + \left( \frac{m_i}{k} \right)^{1.45} \frac{g_i}{3.42 \left( \frac{m_i}{k} - 6.5 \right)^2 + 100}, \]

where \( g_i \) is the total degeneracy.
Since the quark mass $m_i$ depends on the density, the thermodynamic potential $\Omega$ is not only a function of temperature, volume and chemical potential, but also of density. The expression of total energy density reads \([15–18]\)

$$\varepsilon = \frac{\Omega}{V} + \sum_i \mu_i n_i - \frac{T}{V} \frac{\partial \Omega}{\partial T}_{\mu_i, n_B},$$

(11)

where $n_B = A/V$ is the baryon number density and $A$ is the baryon number of the strangelet, $V = \frac{4}{3}\pi R^3$ is the volume of the strangelet. The number density of each particle can be obtained by means of

$$n_i = -\frac{1}{V} \frac{\partial \Omega}{\partial \mu_i} \bigg|_{T, n_B}.$$  

(12)

At finite temperature, we must include the contributions of the anti-particles, therefore, the baryon number for $i$ quark is given by

$$\Delta N_i = (n_i - n_i) \times V = \int_0^\infty dk \frac{dN_i(k)}{dk} \left( \frac{1}{\exp[\beta(\varepsilon_i - \mu_i)] + 1} - \frac{1}{\exp[\beta(\varepsilon_i + \mu_i)] + 1} \right).$$  

(13)

The strangeness number $|S|$ of the strangelet reads

$$|S| = \Delta N_s,$$

(14)

the baryon number $A$ of the strangelet satisfies

$$A = \frac{1}{3}(\Delta N_u + \Delta N_d + \Delta N_s).$$  

(15)

The electric charge $Z$ of the strangelet is

$$Z = \frac{2}{3}\Delta N_u - \frac{1}{3}\Delta N_d - \frac{1}{3}\Delta N_s.$$  

(16)

At finite temperature, the stability condition of strangelets for the bag radius $R$ reads

$$\frac{\delta F}{\delta R} = 0.$$  

(17)

where the free energy $F$ of strangelet is

$$F = E - T\tilde{S},$$

(18)

$E = \varepsilon V$ is the total energy, and

$$\tilde{S} = \sum_i \tilde{S}_i = -\sum_i \frac{\partial \Omega}{\partial T}_{\mu_i, n_B}$$

(19)

is the entropy. For the dibaryon system, baryon number $A$, the strangeness number $|S|$, and electric charge $Z$ are given. Solving above equations self-consistently, we obtain the thermodynamic quantities of dibaryon systems. 

4
III. RESULT AT ZERO TEMPERATURE

A. Stability

Firstly, we use the same arguments as that of Ref. [24,15] to study the stability of dibaryons at zero temperature. For a dibaryon \(Q(A,|S|,Z)\), its baryon number \(A\), strangeness number \(|S|\) and electric charge \(Z\) are conserved in the strong process. A general expression of a two-body strong baryon decay for a dibaryon bound state can be written as

\[
Q(2,|S|,Z) \rightarrow x(1,|S_x|,Z_x) + y(1,|S| - |S_x|,Z - Z_x),
\]

where \(x\) and \(y\) stand for baryons. For example, in the case of \((\Omega\Omega)^0_+\), \(x\) and \(y\) are free \(\Omega\), respectively. At zero temperature, the process (20) is allowed if the energy balance of the corresponding reaction satisfies

\[
E(2,|S|,Z) > m_x + m_y,
\]

where \(E\) stands for the energy of the dibaryon bound state.

In the weak process, the baryon number \(A\) and the electric charge \(Z\) are conserved, but the strangeness number \(|S|\) is not conserved. For the weak decay, \(\Delta|S| = \pm 1\). Therefore, a general expression of a two-body weak decay for dibaryon can be written as

\[
Q(2,|S|,Z) \rightarrow x(1,|S_x|,Z_x) + y(1,|S| - |S_x| \pm 1, Z - Z_x),
\]

This process is allowed at zero temperature if the energy balance of the corresponding reaction satisfies

\[
E(2,|S|,Z) > m_x + m_y,
\]

For example, the two-body weak decay to pure hadrons channel for \((\Omega\Omega)^0_+\) is

\[
(\Omega\Omega)^0_+ \rightarrow \Omega + \Xi^-.
\]

In addition, \((\Omega\Omega)^0_+\) can also decay to another dibaryon and a hadron via weak processes

\[
(\Omega\Omega)^0_+ \rightarrow (\Omega\Xi^0) + \pi^-,
\]

\[
(\Omega\Omega)^0_+ \rightarrow (\Omega\Xi^-) + \pi^0,
\]

provided

\[
E(2,6,-2) > E(2,5,-1) + m_{\pi^-},
\]

\[
E(2,6,-2) > E(2,5,-2) + m_{\pi^0},
\]

respectively. On the other hand, the three-body weak decay channels for \((\Omega\Omega)^0_+\) particle read

\[
(\Omega\Omega)^0_+ \rightarrow \Omega + \Lambda + K^-,
\]

\[
(\Omega\Omega)^0_+ \rightarrow \Omega + \Xi^0 + \pi^-,
\]

\[
(\Omega\Omega)^0_+ \rightarrow \Omega + \Xi^- + \pi^0.
\]
These channels can open provided the energy $E(2, |S|, Z)$ is large than the sum of masses of the corresponding three particles.

We choose the following area

$$N_s - N_T \geq 0, \quad Z \geq -A, \quad |S| + Z \leq 2A.$$  

(32) \hspace{1cm} (33) \hspace{1cm} (34)

to investigate the stability of dibaryon systems. By using the definition of Schaffner-Bielich et. al [24], a dibaryon is called unstable if the inequality (21) is satisfied because in this case the strong decay occurs. A dibaryon is called metastable if the inequality (21) is not satisfied but at least one of the weak decay inequalities is satisfied, in this case the weak decay occurs. Other cases in which all inequalities be broken are called absolutely stable.

Noting that the free energy $F$ reduces to the energy $E$ at zero temperature, we can study the stability of dibaryon system by using the formulas of Sec. II for QMDTD model. Our result is shown in Fig. 1 where open circles stand for the unstable dibaryons and filled circles for the metastable dibaryons. We find no dibaryon can be absolutely stable at zero temperature. But three dibaryons, $(\Omega\Omega)_{0^+}$, $(\Omega\Xi^-)$ and $(\Omega\Xi^0)$ corresponding to $Q(2,6,-2)$, $Q(2,5,-2)$ and $Q(2,5,-1)$, respectively, are metastable. For $(\Omega\Omega)_{0^+}$ particle, its strong decay channel and a weak channel (29) are forbidden, and the other weak channels, (24)-(25), (30) and (31), are permitted. The above conclusions are the same as that of Ref. [6–8], though results of [6–8] are established on the chiral SU(3) quark model and ours on the QMDTD model.

### B. Binding energy and stable radius

Secondly, we study the binding energy and the stable radius for above metastable dibaryons. The binding energy of $(\Omega\Omega)_{0^+}$ is

$$B(\Omega\Omega)_{0^+} = 2 \times m_\Omega - E(\Omega\Omega)_{0^+}. \quad (35)$$

The stable radius $R$ of $(\Omega\Omega)_{0^+}$ is determined by the condition

$$\frac{\delta E(\Omega\Omega)_{0^+}}{\delta R} = 0 \quad (36)$$

at zero temperature. Obviously, the binding energy $E(\Omega\Omega)_{0^+}$ depend on the values of the two parameters $B_0$ and $m_{s0}$. The permitted ranges of $B_0$ and $m_{s0}$ are called ”stability window” of the strange quark matter. We have calculated this stability window in Ref. [16] for QMDTD model. The binding energy and stable radius of $(\Omega\Omega)_{0^+}$ state for fixed $m_{s0} = 150$ MeV and different $B_0$ are shown in Table 1:

| $B_0$ (MeV fm$^{-3}$) | $m_{s0}$ (MeV) | $B(\Omega\Omega)_{0^+}$ (MeV) | $R$ (fm) |
|----------------------|---------------|-----------------------------|----------|
| 170                  | 150           | 162.7                       | 1.13     |
| 175                  | 150           | 143.7                       | 1.12     |
| 180                  | 150           | 125.2                       | 1.11     |
| 182.5                | 150           | 116.1                       | 1.11     |
| 190                  | 150           | 89.2                        | 1.10     |

(Table 1)
We find that the value of binding energy of \((\Omega\Omega)_0^+\) calculated by our model is in good agreement with that by chiral SU(3) quark model. Hereafter we choose parameters \(B_0 = 182.5\) MeV fm\(^{-3}\) and \(m_{s0} = 150\) MeV, because the binding energy 116.1 MeV is just equals to that predicted in Ref. [6]. With these parameters, we draw the energy of \((\Omega\Omega)_0^+\) state as a function of radius in Fig. 2. It is found the stable radius \(R = 1.11\) fm is a little bigger than 0.84 fm given by chiral SU(3) quark model.

To compare our result with chiral SU(3) quark model furthermore, we also calculate the binding energy of \((\Omega\Xi^-)\) dibaryon

\[ B(\Omega\Xi^-) = m_\Omega + m_{\Xi^-} - E(\Omega\Xi^-). \tag{37} \]

and its stable radius. The results are shown in Table 2:

| \(B_0\) MeV fm\(^{-3}\) | \(m_{s0}\) MeV | \(B(\Omega\Xi^-)\) MeV | \(R\) fm |
|--------------------------|----------------|-------------------|--------|
| 170                      | 150            | 114.0             | 1.13   |
| 175                      | 150            | 96.5              | 1.12   |
| 180                      | 150            | 79.4              | 1.12   |
| 182.5                    | 150            | 71.0              | 1.11   |
| 190                      | 150            | 46.2              | 1.10   |

We find that the values of binding energies of the \((\Omega\Xi^-)\) is also consistent with the chiral SU(3) quark model [7]. The difference between \((\Omega\Omega)_0^+\) and \((\Omega\Xi^-)\) is about several tens MeV. In particular, we hope to emphasize that the QMDTD model gives the same conclusion as that of chiral SU(3) quark model: the dibaryon \((\Omega\Omega)_0^+\) is a deeply bound state, and its binding energy is maximum in dibaryon systems.

### C. Mean lifetime

The key for the detectability of the dibaryon is to study its mean life time. Instead of the calculation of two-body decay Feynman diagram [6], we employ a decay formula which is first given by Chin and Kerman [25] to estimate the mean life time of \((\Omega\Omega)_0^+\) and \((\Omega\Xi^-)\) via weak decay. The decay formula is

\[ 1/\tau = [G^2\mu_\Omega^5/192\pi^3]\sin^2\theta_c F(z), \tag{38} \]

with

\[ F(z) = 1 - 8z + 8z^3 - z^4 - 12z^2\ln z, \tag{39} \]

\[ z = \mu_\Omega^2/\mu_s^2, \tag{40} \]

where the Cabibbo angle is given by \(\sin\theta_c \simeq 0.22\). With Eqs. (38)-(40), we can roughly estimate order-of-magnitude of the dibaryon’s mean life time. The coupling constant \(G\) is determined as follows: using Eq. (38) to calculate the decay mean lifetime of \(\Omega\) for following channels:

\[ \Omega \to \Lambda + K^-, \tag{41} \]
\[ \Omega \to \Xi^0 + \pi^-, \tag{42} \]
\[ \Omega \to \Xi^0 + \pi^0 \tag{43} \]
and fit the value with the $\Omega$ mean lifetime $8.21 \times 10^{-11}$ s to determine coupling constant $G$. Then use this coupling constant $G$ to calculate the lifetime of the $(\Omega\Omega)_{0^+}$ and $(\Omega\Xi^-)$. With the parameters $B_0 = 182.5$ MeV fm$^{-3}$, $m_{s0} = 150$ MeV, we obtain the mean lifetime is $4.7 \times 10^{-11}$ s for $(\Omega\Omega)_{0^+}$ and $6.2 \times 10^{-11}$ s for $(\Omega\Xi^-)$, respectively.

IV. RESULT AT FINITE TEMPERATURE

Now we turn to discuss the thermodynamic properties, especially, the stability of dibaryons at finite temperature. Since according to the chiral $SU(3)$ quark model and QM DTD model, the best stable candidate of dibaryons is $(\Omega\Omega)_{0^+}$ at zero temperature, we focus our attention only on $(\Omega\Omega)_{0^+}$ in this section. Instead of the energy at zero temperature, we calculate the free energy density first. Given the strangeness number, baryon number and electric charge, the free energy and stable radius for dibaryons and baryons can be obtained self-consistently by using the formulas in Sec. II.

As was pointed out by [6–8] and sec. III, the strong decay channel

$$(\Omega\Omega)_{0^+} \rightarrow \Omega + \Omega,$$

is forbidden because the binding energy of $(\Omega\Omega)_{0^+}$ is large. But at high temperature, a metastable dibaryon can absorb enough energy from the hot environment to overcome its binding energy and open the strong decay channel. To study the possibility of strong decay, we treat the $(\Omega\Omega)_{0^+}$ and $\Omega$ as a six quarks cluster with $Q(2, 6, -2)$ and a three quarks cluster with $Q(1, 3, -1)$ respectively, and calculate their free energy density. Define

$$\Delta f = f(\Omega\Omega)_{0^+} - 2f(\Omega)$$

as the difference between the free energy density of $(\Omega\Omega)_{0^+}$ and two separate $\Omega$ system, the curve of $\Delta f$ vs. temperature $T$ is shown in Fig. 3. We find $\Delta f$ increases with temperature. It becomes zero when temperature arrives at $T_0 = 129.3$ MeV. When $T > T_0$, $\Delta f > 0$, the strong decay channel opens. This result is reasonable if we notice that the temperature $T_0$ is a little bigger than the binding energy of $(\Omega\Omega)_{0^+}$, 116.1 MeV.

Since the strong decay of $(\Omega\Omega)_{0^+}$ will open and $(\Omega\Omega)_{0^+}$ becomes unstable when $T > T_0$, the favourable detectability of $(\Omega\Omega)_{0^+}$ must be taken in the regions $0 \leq T \leq 129.3$ MeV. This temperature regions seem wide enough for detectability in RHIC experiments. Of course, in order to help the design of a detectable experiment, it is necessary to get more information about $(\Omega\Omega)_{0^+}$ in this metastable regions. For this purpose, we study the temperature dependence of the radius and the mean lifetime of $(\Omega\Omega)_{0^+}$ in $0 \leq T \leq T_0$ regions.

The curves of stable radius $R$ vs. $T$ for $(\Omega\Omega)_{0^+}$ is shown in Fig. 4. We see that the radius increases from 1.11 fm to 1.89 fm when temperature increases from 0 to 129.3 MeV, the volume of the bag expands when temperature increases.

Finally, we still use Eqs. (38)-(40) to study the temperature effect on the mean lifetime. Instead of Fermi energies of quarks at zero temperature in these equations, we use the temperature dependent chemical potentials $\mu_u(T)$ and $\mu_s(T)$ to estimate the order of magnitude for the mean lifetime of $(\Omega\Omega)_{0^+}$. We find that the order of magnitude is not less than $10^{-11}$ s in the whole metastable temperature regions.
V. SUMMARY

In summary, we have studied thermodynamic properties of dibaryons by using QMDTD model. At zero temperature, we find that only three dibaryons, namely, $(\Omega \Omega)_{0+}$, $(\Omega \Xi^-)$ and $(\Omega \Xi^0)$, are metastable. At least one weak decay channel opens for these states and all the strong decay channels close. We calculate the binding energy, stable radius as well as the mean lifetime of $(\Omega \Omega)_{0+}$ and $(\Omega \Xi^-)$, it is found that our results are in good agreement with those given by chiral $SU(3)$ quark model. Using two essentially different models and get the same conclusion, this result strongly compels us to support $(\Omega \Omega)_{0+}$ is the most favorable candidate of dibaryon for detectability, because its binding energy is maximum.

Extending our investigation to finite temperature, we find the strong decay channel will open and $(\Omega \Omega)_{0+}$ will become unstable when temperature arrives at $T_0 = 129.3$ MeV. We also calculate the radius and the lifetime of $(\Omega \Omega)_{0+}$ at finite temperature.

VI. ACKNOWLEDGMENT

We thank professors Y. W. Yu, Z. Y. Zhang, T. H. Ho, C. R. Ching and P. N. Shen for helpful discussions, we also thank professor F. Wang for sending us his reprints. This work was supported in part by the NNSF of China under contract Nos. 10047005, 19947001 and 10235030.

VII. FIGURE CAPTIONS

Figure 1. The electric charge $Z$ as a function of the strangeness number $|S|$ for unstable strangelets (open circles), metastable strangelets (filled circles) with baryon number $A = 2$ at zero temperature.

Figure 2. The energy per baryon number $E/A$ as a function of the radius $R$ for $(\Omega \Omega)_{0+}$ particle.

Figure 3. The difference of free energy density between $(\Omega \Omega)_{0+}$ particle and two free $\Omega$ particles $\Delta f$ as a function of temperature $T$.

Figure 4. The stable radius $R$ as a function of the temperature $T$ for $(\Omega \Omega)_{0+}$ particle.

VIII. TABLE CAPTIONS

Table 1. The binding energy and stable radius of $(\Omega \Omega)_{0+}$ particle.
Table 2. The binding energy and stable radius of $(\Omega \Xi^-)$ particle.
REFERENCES

[1] R. J. Jaffe, Phys. Rev. Lett. 38, 195 (1977).
[2] M. Oka, K. Shimizu, and Yazaki, Nucl. Phys. A 464, 700 (1987).
[3] U. Straub, Z. Y. Zhang, K. Brauer, A. Faessler, and S. K. Khadkikar, Phys. Lett. B 200, 241 (1988).
[4] K. Imai, Nucl. Phys. A 553, 667 (1993).
[5] A. J. Buchmann et al., Phys. Rev. C 57, 3340 (1998).
[6] Z. Y. Zhang, Y. W. Yu, C. R. Ching, T. H. Ho, and Z. D. Lu, Phys. Rev. C 61, 065204 (2000).
[7] Q. B. Li, P. N. Shen, Z. Y. Zhang, and Y. W. Yu, Nucl. Phys. A 683, 487 (2001).
[8] Y. W. Yu, Z. Y. Zhang, and X. Q. Yuan, Commun. Theor. Phys. 31, 1 (1999).
[9] F. Wang, G. H. Wu, L. J. Teng, T. Goldman, Phys. Rev. lett. 69, 2901 (1992).
[10] K. Yazaki, Prog. Theor. Phys. Suppl. 91, 146 (1987).
[11] J. L. Ping, F. Wang, and T. Goldman, Nucl. Phys. A 688, 871 (2001).
[12] N. Isgur, Phys. Rev. D 21, 1868 (1980).
[13] L. Y. Glozman, and D. O. Riska, Phys. Rep. 268, 263 (1996).
[14] Z. Y. Zhang, Y. W. Yu, P. N. Shen, and L. R. Dai, Nucl. Phys. A 625, 59 (1997).
[15] Y. Zhang, and R. K. Su, Phys. Rev. C 67, 015202 (2003).
[16] Y. Zhang, and R. K. Su, Phys. Rev. C 65, 035202 (2002).
[17] Y. Zhang, R. K. Su, S. Q. Ying, and P. Wang, Europhys. Lett. 56, 361 (2001).
[18] Y. Zhang, and R. K. Su, Phys. Rev. C 65, 035202 (2002).
[19] WA97 Collaboration, Mode. Phys. Lett. A 449, 143 (2003).
[20] P. Koch, B. Müller and J. Rafelaki, Phys. Rep. 142, 167 (1986).
[21] T. D. Lee, Particle Physics and Introduction to Field Theory, (harwood Academic, Chur, 1981).
[22] V. K. Gupta, A. Gupta, S. Singh, and J. D. Anand, astro-ph/0206111 (2002).
[23] Y. Zhang, W. L. Qian, S. Q. Ying, and R. K. Su, J. Phys. G 27, 2241 (2001).
[24] J. Schaffner-Bielich, C. Greiner, A. Diener, and H. Stöcker, Phys. Rev. C 55, 3038 (1997).
[25] S. A. Chin and A. K. Kerman, Phys. Rev. Lett. 43, 1292 (1979).
Figure 1
Figure 2
Figure 3
Figure 4