High-density kaonic-proton matter (KPM) composed of $\Lambda^* \equiv K^- p$ multiplets and its astrophysical connections

Yoshinori Akaishi$^{1,2}$ and Toshimitsu Yamazaki$^{1,3}$

1 RIKEN, Nishina Center, Wako, Saitama 351-0198, Japan
2 High-Energy Accelerator Research Organization (IPNS/KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0002, Japan
3 Department of Physics, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan

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We propose and examine a new high-density composite of $\Lambda^* \equiv K^- p = (s\bar{u}) \otimes (uud)$, which may be called Kaonic Proton Matter (KPM), or simply, $\Lambda^*$-Matter, where substantial shrinkage of baryonic bound systems originating from the strong attraction of the $(KN)$'s interaction takes place, providing a ground-state neutral baryonic system with a huge energy gap. The mass of an ensemble of $(K^-p)_m$, where $m$, the number of the $K^-p$ pair, is larger than $m \approx 10$, is predicted to drop down below its corresponding neutron ensemble, $(n)_m$, since the attractive interaction is further increased by the Heitler-London type molecular covalency, as well as by chiral symmetry restoration of the QCD vacuum. Since the seed clusters $(K^-p, K^-pp)$ are short-lived, the formation of such a stabilized relic ensemble, $(K^-p)_m$, may be conceived during the Big-Bang Quark Gluon Plasma (QGP) period in the early universe before the hadronization and quark-antiquark annihilation proceed. At the final stage of baryogenesis a substantial amount of primordial $(\bar{u}, d)$'s are transferred and captured into KPM, where the anti-quarks find places to survive forever. The expected KPM state may be cold, dense and neutral $qq$-hybrid (Quark Gluon Bound (QGB)) states, $(s\bar{u} \otimes uud)_m$, to which the relic of the disappearing anti-quarks plays an essential role as hidden components. Explosive production of KPM from supernova precursors is considered as a possible observational astronomical process.

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Introduction

In the present paper we propose and examine a new high-density neutral matter, anti-Kaonic Proton Matter (KPM), composed of hitherto known units of

$$\Lambda^* \equiv K^- p = (s\bar{u}) \otimes (uud), \quad (1)$$

which may be called KPM, or simply, $\Lambda^*$-Matter ($\Lambda^*$-M). Its free unit, $\Lambda^*$, first predicted by Dalitz and Tuan [3], has been identified to be a known resonance state of $\Lambda(1405)$ with a mass of $M = 1405$ MeV/$c^2$ [2]. Its spectacular nature was not fully realized before.

The present investigation arises from our recent theoretical finding of high-density anti-Kaonic ($K$) few-body Nuclear Clusters (KNC) [2,10], where nuclear systems with a density of $\rho \approx 3\rho_0$ ($\rho_0$ being the normal nuclear density, 0.17 fm$^{-3}$) are spontaneously formed, driven by the strong $(KN)l=0$ attraction without the aid of gravity. We start our discussion from empirical information concerning the most important building blocks: $K^-p$ (= $\Lambda^*$), $K^-pp$ and $K^-K^-pp$.

i) Recent observations [11,12] of the predicted dense state of $\Lambda^*-p \approx K^-pp$ [8], which is the simplest form of $KNC$, support the theoretical framework for dense kaonic nuclear bound states [2,10].

ii) Furthermore, a recent analysis [13] of high-precision measurements of photo-induced reaction $\rho(\gamma, K^+)\Sigma^0 p^0$ at CLAS [14] has yielded a precise value for $M(\Sigma^0 p^0)$, which reconfirms the traditional value of the $\Lambda(1405)$ resonance mass [2] (1405.1$^{+1.3}_{-1.0}$ MeV/$c^2$) that favors the strong $(KN)l=0$ attraction in contrast to the prevailing double-pole hypothesis, which claims a much weaker attraction with a mass of $M \approx 1420$ MeV/$c^2$ [13,16].

iii) In $K^-pp \sim \Lambda^* p$ and $K^-K^-pp \sim \Lambda^*\Lambda^*$ a molecular analogy stands even for the systems of nuclear interactions [7], and the Heitler-London type covalent bonding effect [17] plays an important role as wide-ranging multiple bonding forces [9].

iv) The spontaneous nuclear shrinkage causes an enhancement of the $KN$ interaction by Chiral Symmetry Restoration (CSR) that iterates further production of higher nuclear densities, and thus of larger kaonic binding energies and decreased masses of the KPM ensemble.

v) Thus, the joint effect of the multiple bonding of $\Lambda^*$ and the CSR may cause a large energy gap, where the ground state of the $\Lambda^*$ multiplet may become well below that of the corresponding neutron ensemble:

$$M[(K^-p)_m] \text{ per baryon} < M[(n)_m] \text{ per baryon} \quad (2)$$

Multiple bonding of $\Lambda^* = K^- p$

The double kaonic cluster, $K^- K^- pp$, initially predicted by [2], shows a well developed deeply bound structure of two $\Lambda^*$'s, whereas they persist to keep the identification as $\Lambda^* (= K^- p)$. Here, we comment on the interaction of the two $\Lambda^* (= K^- p)$'s. The original migrating exchange force of Heitler and London [17] was considered between two fermionic electrons in $H^+H^0$ and $H^0H^0$ molecules. In the present case, on the contrary, the migrating particles are bosonic $K^-$ mesons, the wave function of which is

$$\Phi(\vec{r}_1, \vec{r}_2) = N(D)[\phi_a(\vec{r}_1)\phi_b(\vec{r}_2) + \phi_b(\vec{r}_1)\phi_a(\vec{r}_2)], \quad (3)$$
where the two protons sit on sites $a$ and $b$ which are separated by a distance of $D$. Then, the exchange interaction is obtained as

$$\Delta U(D) \equiv U(D) - U(\infty) \approx 4 |N(D)|^2 \times (4)$$

$$\langle \phi_a | V_{K-p} | \phi_b \rangle \langle \phi_b | \phi_a \rangle + \langle \phi_b | V_{K-p} | \phi_a \rangle \langle \phi_a | \phi_b \rangle, (5)$$

where $U(D) = \langle \Phi | \sum_{j=a,b} V_{K-p_j} | \Phi \rangle$ with an effective $K N$ interaction, $V_{K-p}$, as given by a $g$-matrix in [3].

This $\Delta U(D)$, shown in Fig. 1, is a bonding potential due to doubly migrating $K^-$’s, and is about twice as strong as the one from single $K^-$ migration in $K^-pp$, discussed in [6]. On the other hand, if we artificially assume the migrating particles to be spinless fermions, the two terms of Eq. (4) should be subtracted, and would yield a much weaker bonding. It is noted that the bonding from multi-$K^-$ migrations is always additively constructed due to the bosonic nature of $K^-$. In this way, the $K^-$’s bring about a much stronger binding effect. We have obtained the effective potential between the two $\Lambda^*(=K^-p)$’s by folding the bonding potential, $\Delta U$, the $K^-$-repulsive potential, $V_{KK}$, and a realistic $NN$ potential having a repulsive core, with the internal $K^-p$ distribution of $\Lambda^*$.

We applied the effective $\Lambda^*$-$\Lambda^*$ interaction thus obtained to calculate the binding energies of multiple $\Lambda^*$-$\Lambda^*$ systems that approximate multiple ($K^-p)_m$ states. Here, we take into account the possible combinations of $\Lambda^*$-$\Lambda^*$ bonding, as the number of bonding increases with the multiplicity being $2, 6, 12, 20, 30, \ldots$, for $m = 2, 3, 4, 5, 6, \ldots$, respectively. The results obtained by using a variational method (ATMS [21] employed in [7]) are shown in Fig. 2 which indicate that the energy level per each $\Lambda^*$ of a multiple $\Lambda^*_m$ state drops down, and finally exceeds the threshold level of free $\Lambda$ emission, when the $\Lambda^*$ multiplicity becomes larger than some critical number. The number is estimated to be 10, if the effect of CSR (discussed in the next section) that will enhance the assumed basic $KN$ interaction is taken into account. Such a multiplet as $(\Lambda^*)_m > 10$ could be stable against any strong-interaction decay.

Figure 3 shows a stable ensemble of $\Lambda^*$’s together with Heitler-London type covalent bonding of bosonic $K^-$, that produces super-strong nuclear interaction [7]. A mean-field model for multi $K$’s in nuclei is employed in [18], but lacks just this multi-bonding mechanism of the super-strong nuclear attraction, which gives a drastic non-linear decrease of $M[(K^-p)_m]$ as $m$ increases. It should be mentioned that the $K^-$ in a nucleus cannot keep to hold its independent-particle motion in mean field by yielding a marked $(\Lambda^* = K^-p)$ cluster correlation. In fact, the $K^-$ in a nucleus does not satisfy the gheilingh condition for independent-particle motion discussed by Gomes et al. [19].

In order to see the effect of CSR on the size of the basic $\Lambda^*$-$\Lambda^*$ system, distributions of the $\Lambda^*$ distance obtained from Faddeev-Yakubovsky calculation for $K^-K^-pp$ [10] is also shown in Fig. 3.

**Stability and stiffness of KPM**

Here, we consider the basic stability of KPM. The longevity of KPM depends on its stiffness against the addition of external foreign substances and the subtraction of internal components. The total mass of the $\Lambda^*$ multiplet in the preceding section, $M[(\Lambda^*)_m]$ per baryon, is well approximated as

$$M[(\Lambda^*)_m]c^2 \approx m 1405 [\text{MeV}] + \frac{m(m-1)}{2} \langle \Delta U \rangle_{av}. \ (6)$$

with $\langle \Delta U \rangle_{av} = -135$ MeV for $m = 4 \sim 8$. Then, the $\Lambda^*$ separation energy, $S_m(\Lambda^*)$, for the $(\Lambda^*)_m \to \Lambda^* + (\Lambda^*)_{m-1}$ process is given by

$$S_m(\Lambda^*) = -(m-1) \langle \Delta U \rangle_{av}. \ (7)$$

It is noted that $S_m$ is 2-times larger than $BE_m$ (binding energy per $\Lambda^*$), that is the mass difference between a free $\Lambda^*$ and a bound $\Lambda^*$ in $(\Lambda^*)_m$, due to a rearrangement of the $(\Lambda^*)_m$ cluster. The $S_6(\Lambda^*)$ is estimated to be 675 MeV, which is almost 2-orders of magnitude larger than the nucleon separation energy of about 8 MeV from usual nuclear systems. $S_m(\Lambda^*)$ becomes larger with $m \geq 6$.

As for the weak decay of $(\Lambda^*)_m$, the $Q$-value of the $(\Lambda^*)_m \to n + (\Lambda^*)_{m-1}$ non-leptonic process is given by

$$Q_m(\Lambda^* \to n) = (1405 - 940)[\text{MeV}] + (m-1) \langle \Delta U \rangle_{av}. \ (8)$$

In the case of $m = 6$, the weak decays of single $\{\Lambda^* \to n\}$ and also $(2 \sim 4) \times \{\Lambda^* \to n\}$ are prohibited kinematically.
and the medium, the quark condensate decreases toward zero, suggesting the origin of this enhanced interaction in terms of that assumed in the original prediction. Here, we consider the enhancement factor non-trivially below the nucleon mass, as shown in Fig. 2. Only \((5 \sim 6) \times \{\Lambda^* \rightarrow n\}\) take place through simultaneous weak decays, which are profoundly suppressed by the decay multiplicity.

Similarly, the kaon weak-decay \(\{K^- \rightarrow e^- + \bar{\nu}\}\) process of \((\Lambda^*)_{m} \rightarrow e^- + \bar{\nu} + p + (\Lambda^*)_{m-1}\) is strongly suppressed at \(m = 6\) and is prohibited at \(m \geq 8\).

**Chiral symmetry restoration for \(\bar{K}N\)**

The recent experimental data on \(K^-pp\) from DISTO \[11\] and J-PARC E27 \[12\] gave a binding energy of about 100 MeV, which is a factor of 2 larger than the original prediction \[4\] based on the empirical \(\Lambda(1405)\) mass. A recent Faddeev-Yakubovsky calculation \[10\] shows that the observed binding energy corresponds to an effective \(KN\) interaction which is about 17% more attractive than that assumed in the original prediction. Here, we consider the origin of this enhanced interaction in terms of the chiral-symmetry restoration (CSR) effect \[21\] \[27\].

In general, when CSR takes place in dense nuclear medium, the quark condensate decreases toward zero, and the \((KN)^{m=0}\) interaction is expected to increase in magnitude. A naive qualitative estimate was made in \[10\] by employing a model of Brown, Kubodera and Rho (BKR) \[27\]. Figure 3 shows the estimated quark condensate (straight line) and the enhancement factors \(F_{KN}^{m=0}\) as functions of the nuclear density \(\rho(r)\), where \(\omega\) is a "QCD-vacuum clearing factor". In the case of \(KN^{m=0}\), a drastic situation takes place \[10\]: \(F_{KN}\) increases and amplifies the binding energy and shrinks the nucleus further, leaving less and less room for the QCD vacuum with further increasing the \(\omega\) and \(F_{KN}\) factor nonlinearly. An enhancement factor of 1.5 corresponding to the density \(\rho/\rho_0 \approx 2\) produces an enormous multiplication of the binding energy of \(K^-K^-pp\) \[10\]. Although the above estimate is very rough, the CSR effect in combination with the Heitler-London type enhancement is expected to bring the KPM mass of moderate multiplicity \((m \sim 10)\) well below the nucleon mass.

**How can KPM be formed?**

As the KPM seed clusters, \(K^-p, K^-pp\) and \(K^-K^-pp\), are short-lived with \(\Gamma \sim 100\) MeV, they cannot survive during the cascading collisions toward heavier clusters. Exceptional cases might take place during the initial phase of the early universe, where quarks \((u, d, s, \bar{u}, \bar{d}, \bar{s})\) and gluons are produced in quark gluon plasma (QGP) at extreme high temperatures and densities, but probably before the hadronization stage, as illustrated in Fig. 5.
FIG. 4: Chiral symmetry restoration effect of $\pi$ and $\bar{K}$ (see details [11]). (Lower half) The QCD condensate $|\langle \bar{q} q \rangle|$ decreases with the medium nuclear density $\rho$ in units of $\rho_0$. (Upper half) The enhancement factors by CSR, $F_{KN}$, for various $\omega$ values of the vacuum clearing factor $[27]$.

Since the KPM seeds, particularly, $K^- p \equiv \Lambda^*$ and $K^- p p \equiv \Lambda^* p$, are distinctly deep bound with binding energies of around $50 \sim 100$ MeV, whereas other quarks and hadrons are relatively shallowly bound, we expect that during the course of decreasing temperatures ($kT \approx 100$ MeV, and in expansion), the seeds are likely to become deep quasi-stable self-trapping centers, and recombined with other seeds that have just been born nearby. The star-like red objects illustrated in Fig. 5(b) represent such just-born fresh composites of $\Lambda^*$ multiplets with $m \sim 10$. They undergo further combinations to become a large-scale more stable KPM. This process is in competition with the branching ratio of $\Lambda^*$ formation $\{\bar{u} \bar{u} + u u \rightarrow s(\bar{u}u) ud\}$ to the normal $\bar{q} q$ annihilation background, $\bar{q} + q \leftrightarrow g'$ in the early universe. Certainly, such competition occurs in the QCD level, and we need more knowledge on its answer.

It is to be noted that the basic unit of KPM, $\{(\bar{u} u)(u d)\}$, involves a $\bar{u}-u$ pair, which is essential in producing this deeply bound system. This system possesses one $\bar{u}$ quark per unit that has been transferred from the primordial QGP phase. Figure 5(d), (e), and (f) shows symbolically (d) a disappearing ANTI-MATTER sector that involves originally unbound $\bar{q}$ before $\bar{q} q$ annihilation, and (f) a dominating MATTER sector of relative baryon density around $2 \times 10^{-8}$, resulting after $\bar{q} q$ annihilation and baryogenesis. During the anti-quark disappearing stage relic and stable composites of $\{(\bar{u}u)(u d)\}$ are formed, and constitute a (e) HYBRID sector. In other words, a substantial fraction of anti-particles may remain being hidden relics in the KPM phase as an unknown astronomical object.

FIG. 5: (Upper) Formation of KPM from the primordial Bang (a) and (b), where $u, \bar{u}, d, \bar{d}, s, \bar{s}$ quarks are produced in QGP at high temperatures and densities. With decreasing temperature it proceeds to the pre-hadronization stage, where $K^- p, K^- pp$ and $K^- K^- pp$ with large binding energies are formed, as indicated by the star-like red symbols. Then, stable $\Lambda^*$ composites are formed, which eventually grow larger and larger, but will become cold matter with eventual formation of Quark-Gluon-Bound (QGB) states. (Lower) Three quark sectors in the early universe during the disappearance of anti-quark matter: (d) the disappearing ANTI-QUARK sector, (e) quark-anti-quark HYBRID sector, where relic and stable precursors of $K^- p = s(\bar{u}u) ud$ are born, and (f) remaining ordinary QUARK sector.

Formation of Quark-Gluon Bound (QGB) states

Annihilating, but still surviving, anti-quarks contribute to forming seeds for KPM: $\Lambda^* \equiv [s(\bar{u}u) ud]$. This particle-anti-particle hybrid state has very strong attractive interactions with surrounding similar species; thus, multiple $\Lambda^*$ states are composited and their mutual fusions take place in a short time and on a large scale, as if it occurred in a sudden phase transition.

The above $\Lambda^*$’s that are defined as $K^- p$ in the language of hadrons may be born directly from constituents of QGP from the beginning, but eventually become cooled so as to be changed into the new phase: Quark Gluon Bound (QGB) states. While being cooled furthermore, its QGB phase may remain unchanged. Whether KPM could form a macroscopic object or not, the possibility of KPM fragments as low-temperature QGB states should be an extremely interesting problem, as no such quark-gluon bound states at low temperatures have been experienced so far either empirically or theoretically.
Production of KPM from supernova explosions

Finally, we consider possible population of KPM in connection with neutron stars $[\eta]_{\text{NS}}$, which is somewhat similar to kaon condensation as discussed by Kaplan and Nelson \[30\] and Brown et al. \[31\]. The neutron stars (NS) once produced may proceed to KPM in gentle multiple decay processes that occur slowly:

$$[\eta]_{\text{NS}} \rightarrow [K^-p]_{\text{KPM}} + (\nu + \bar{\nu})' s. \quad (9)$$

On the other hand, precursors of supernova explosion may undergo explosive processes toward not only to neutron-star (NS) formation but also to KPM formation:

$$[e^-, p, n]_{\text{supernova}} \rightarrow \nu'/s + [\eta]_{\text{NS}} + n's, \quad (10)$$

$$[e^-, p, n]_{\text{supernova}} \rightarrow \nu'/s + [K^-p]_{\text{KPM}} + n's. \quad (11)$$

This latter process has never been considered nor observed. It may be an interesting process, as we may anticipate some astronomical observational signals.

Concluding remarks

Very recently, new experiments have been carried out to search for hadron production in extremely high-energy Pb + Pb collisions at LHC-ALICE \[32, 33\], where the most important precursor $K^−K^-pp$ toward KPM (see Fig. 2) can be investigated. Such a precursor can also be produced in the reactions $(p+p \rightarrow \Lambda^*+\Lambda^*+K^++K^+)$ at lab energies of around 7 GeV \[28, 29\]. One can also study the $(\Lambda^*)_m$ multiplets with moderate multiplicity, $m$, in heavy-ion reactions, which are expected to exist as metastable fragments with various lifetimes. They might include important QGB fragments.

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