Invariant-Mass Spectroscopy for Condensed Single- and Double-\(\bar{K}\) Nuclear Clusters to be Formed as Residues in Relativistic Heavy-Ion Collisions

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Using a phenomenological KN interaction combined with the method of Antisymmetrized Molecule Dynamics., we predict that few-body double-\(\bar{K}\) nuclei, such as ppK\(^-\) and ppnK\(^-\)K\(^-\), as well as single-\(\bar{K}\) nuclei, are tightly bound compact systems with large binding energies and ultra-high nucleon densities. We point out that these \(\bar{K}\) nuclear clusters can be produced as residual fragments in relativistic heavy-ion collisions and that their invariant masses can be reconstructed from their decay particles.

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1. Introduction

Recently, exotic nuclear systems involving a \(\bar{K}\) (K\(^-\) or K\(^0\)) as a constituent have been investigated theoretically \[1, 2, 3, 4\] based on phenomenologically constructed KN interactions (hereafter referred to as \(\Lambda\bar{Y}\)), which reproduce low-energy KN scattering data \[2\], kaonic hydrogen atom data \[2\] and the binding energy and decay width of \(\Lambda(1405)\). These interactions are consistent with a prediction based on a chiral SU(3) effective Lagrangian \(2\) and with a recent experimental indication on decreased \(n\)-invariant-mass spectra of decay particles of \(\bar{K}\) clusters, method, \(\bar{K}\) (K\(^-\)K\(^+\)) strongly attractive in-medium K\(^-\)K\(^+\) limit, \(\rho\) nucleon volume, these \(\bar{K}\) clusters may be in deconfined \(\rho\) quark-gluon states, which can better be named “\(s\)-quark nuclear clusters”. Interesting questions naturally arise: how about the structure of double-\(K\) nuclei and how can they be produced and identified? In the present paper we report on the results of our calculations on the structure of the simplest systems, ppK\(^-\)K\(^-\) and ppnK\(^-\)K\(^-\), and then propose to identify \(K\) clusters as residues (“\(K\) fragments”) after relativistic heavy-ion reactions. This method, \textit{decay-channel spectroscopy}, is to reconstruct invariant-mass spectra of decay particles of \(K\) clusters, in contrast to \textit{formation-channel spectroscopy} to use direct reactions, such as (K\(^-\), n) \[1, 10\] and (K\(^-\), \(\pi^-\)) \[2\].

2. Double \(\bar{K}\) clusters

2.1 ppK\(^-\)K\(^-\)

We applied the same theoretical treatments as given in \[1, 2\] to double-K systems. We used the Tamagaki potential (OPEG) \[11\] as a bare NN interaction and the \(\Lambda\bar{Y}\) KN interaction as a bare KN interaction, whereas we neglected the K\(^-\)K interaction simply because of a lack of information. We show the result of a variational calculation in Fig. \[1\]. The hitherto untouched ppK\(^-\)-system was predicted in a previous paper to be bound with a binding energy \(E_K = 48\) MeV and a width \((\Gamma_K = 61\) MeV) \[2\]. The p-p rms distance is 1.90 fm, close to the normal inter-nucleon distance. In the ppK\(^-\)K\(^-\) system, on the other hand, the binding energy and width were calculated to be \(E_K = 117\) MeV and \(\Gamma_K = 35\) MeV, and the p-p rms distance is very much reduced to 1.3 fm. Thus, the addition of a \(K\) increases the binding energy and the nucleon density. Since these bound states lie above the \(\Sigma\pi\) emission threshold, their widths are dominated by the main decay channel (K\(^-\)p \(\to\) \(\pi\Sigma\)).

2.2 ppnK\(^-\)K\(^-\) and ppnK\(^-\)K\(^-\)

It was already predicted that the ppnK\(^-\) system has a much stronger binding and a much higher density than ppK\(^-\), indicating that the addition of a neutron further strengthens the binding of the system. Thus, it is interesting to investigate the ppnK\(^-\)K\(^-\) system. We constructed the effective NN-central force and the KN force with the G-matrix method, and carried out an AMD calculation of ppnK\(^-\)K\(^-\). We found that the double-K cluster (ppnK\(^-\)K\(^-\)) is indeed more tightly bound than the single-\(K\) cluster (ppnK\(^-\)), as shown in Fig. \[2\] where we present the density contours of \(^3\)He, ppnK\(^-\) and ppnK\(^-\)K\(^-\). The central nucleon reaches \(\rho(0) \sim 3\) fm\(^{-3}\). The ppnK\(^-\)K\(^-\) system is shown to be bound even deeper. We summarize these results in
2. Structure of ppK

![Structure of ppK image]

1.90 fm

1.36 fm

K− pp

p K−

K−

p

E = -48 MeV

Γ = 61 MeV

2. Structure of ppK−K−

![Structure of ppK−K− image]

1.3 fm

1.5 fm

Γ = 61 MeV

Γ = 35 MeV

E = -117 MeV

E = -117 MeV

FIG. 1: Schematic structure diagrams for the calculated ppK− and ppK−K− nuclei. The rms radius of K− and rms inter-nucleon and inter-K distances are shown.

Table I together with the results on single-¯K clusters [3, 4]. ΓK, the width for decaying to Λπ and Σπ, was evaluated by calculating the expectation value of the imaginary potential contained in the effective AYN interaction with the wave function obtained by the AMD calculation. No additional widths of other origins are taken into account at this stage.

2.3 Possible suppression of the direct formation and decay of ¯K clusters

The compact ¯K clusters predicted here are very different from ordinary nuclei in many respects. Their densities at the center are extremely high in view of the expected boundary between the hadron phase and the quark-gluon phase [12, 13, 14, 15]. Thus, their structure can most likely be described in terms of deconfined quarks, rather than of “nucleons + K−”. Although the nuclear structure of such cold and dense strange nuclei, possibly in a quark-gluon phase, has not been touched theoretically, we expect that their decays to hadrons may be suppressed because of the need to rearrange of quarks and gluons into hadrons. On one hand, this would be a welcome feature, because the possible suppression of decays of ¯K clusters favours the discreteness of these bound states for better spectroscopic observation. On the other hand, we anticipate that the same mechanism would also reduce the formation probability of these clusters via direct reactions on normal nuclear targets, such as (K−, π−) and (π+, K+) reactions for single-¯K nuclei [2]. Few-body double-¯K clusters can in principle be produced by ΔS = −2 direct reactions: d(K−, K0)ppK−K− and 3He(K−, K+)ppnK−K−. When the formation of such a bound state is suppressed, no visible peak may be shown above a quasi-free background of p(K−, K+)Ξ− in an inclusive spectrum. This would be a serious problem.

3. ¯K clusters as residues in heavy-ion collisions

![Calculated density contours of ppn, ppnK− and ppnK−K− image]

FIG. 2: Calculated density contours of ppn, ppnK− and ppnK−K−.
TABLE I: Summary of predicted \( \bar{K} \) clusters. \( M \): total mass [MeV]. \( E_K \): total binding energy [MeV]. \( \Gamma_K \): decay width [MeV]. \( \rho(0) \): nucleon density at the center of the system [fm\(^{-3}\)]. \( R_{\text{rms}} \): root-mean-square radius of the nucleon system [fm]. \( k_p \) and \( k_K \): rms internal momenta [fm\(^{-1}\)] of p and \( \bar{K} \), respectively.

| K cluster   | \( M \) [MeV] | \( E_K \) [MeV] | \( \Gamma_K \) [MeV] | \( \rho(0) \) [fm\(^{-3}\)] | \( k_p \) [fm\(^{-1}\)] | \( k_K \) [fm\(^{-1}\)] |
|-------------|---------------|-----------------|---------------------|-----------------|-----------------|-----------------|
| \( pK^- \)   | 1407          | 27              | 40                  | 0.59            | 0.45            | 1.37            |
| \( ppK^- \)  | 2322          | 48              | 61                  | 0.52            | 0.99            | 1.49            |
| \( pppK^- \) | 3211          | 97              | 13                  | 1.56            | 0.81            | 1.18            |
| \( ppnK^- \) | 3192          | 118             | 21                  | 1.50            | 0.72            | 1.50            |
| \( ppppK^- \)| 4171          | 75              | 162                 | 1.68            | 0.95            | 1.12            |
| \( ppnK^- \) | 4135          | 113             | 26                  | 1.29            | 0.97            | 1.12            |
| \( ppnnK^- \)| 4135          | 114             | 34                  | 1.12            |                 |                 |
| \( ppK^- \)  | 2747          | 117             | 35                  |                 |                 |                 |
| \( ppnK^- \) | 3582          | 221             | 37                  | 2.97            | 0.69            |                 |
| \( ppnnK^- \)| 4111          | 230             | 61                  | 2.33            | 0.73            |                 |

Now, we point out that \( \bar{K} \) clusters may be found as residues of relativistic heavy-ion reactions, where \( K^- \) mesons and \( \Lambda \) hyperons are produced abundantly [8, 14]. Usually, these strange particles are used as probes to study the size and temperature of fireballs produced in heavy-ion collisions. Here, we present a totally different view, namely, we propose to search for single-\( \bar{K} \) and double-\( \bar{K} \) clusters as residues of relativistic heavy-ion reactions, where the probability of forming strongly bound \( \bar{K} \) clusters is expected to be rather high. The dense medium provided in heavy-ion collisions should enhance such \( \bar{K} \) cluster productions. Furthermore, once a \( \bar{K} \) cluster having a binding energy of \( \sim 100 \text{ MeV} \) is produced in a chaotic nuclear medium, its tight binding will make its dissociation difficult even at a high temperature of \( 50 \sim 100 \text{ MeV} \). Thus, \( \bar{K} \) clusters, once created, tend to survive through collisions, and escape in the freeze-out phase. They ultimately decay via their own decay modes, from which the invariant masses of the parent \( \bar{K} \) clusters may be reconstructed. In central collisions of relativistic heavy ions, a dense and hot fireball is produced, and as the fireball expands, they reach a “freeze-out” phase, in which the produced hadrons are expected to be in thermal equilibrium. Recently, it is shown that particle emission data are well accounted for by a thermal equilibrium model in terms of a temperature \( (T_f) \) and a baryon chemical potential \( (\mu_B) \) as parameters [16, 17, 18]. In the following we consider various steps toward the formation and decay of \( \bar{K} \) clusters.

i) Abundant production of \( K^- \)-’s in heavy-ion reactions

\( K^- \) mesons are abundantly produced even in sub-threshold nuclear reactions [8, 14]. This phenomenon is interpreted as being due to the decreased \( \bar{K}^- \) mass in the nuclear medium, which is caused by a strong attraction between \( K^- \) and p. They are embedded in an attractive nuclear potential (the mass of \( K^- \) is effectively reduced), as shown in Fig. 3 (upper) and continue to undergo collisions with nucleons.

Some of the \( K^- \)-’s may escape from the nuclear region as free \( K^- \) mesons, whereas the others may form tightly bound \( \bar{K} \) clusters. (Lower) Deep self-trapping potentials for \( \bar{K} \) clusters are produced intermittently, where \( K^- \) and a few nucleons encounter.

\[
(K^-)_{\text{medium}} \rightarrow (K^-)_{\text{heated}} \rightarrow (K^-)_{\text{free}}. \tag{1}
\]

It is to be noted that the same attractive interaction is the origin of \( \bar{K} \) clusters. In this sense, the “subthreshold” \( K^- \) mesons are brothers of \( \bar{K} \) clusters; both are born from the same parents, in-medium \( K^- \)-’s.

ii) Evolution of \( \bar{K} \) clusters as deep trapping centers

\( K^- \)-’s may produce extra-deep and localized self-trapping potentials, as schematically shown in Fig. 3 (lower), which are intermittently accommodated by a few correlated nucleons (notably, \( p^2 \), \( p^2n \) (\(^4\text{He}) \) and \( p^2n^2 \) (\(^4\text{He}) \)). Under such circumstances, the \( K^- \)-’s become self-trapped together with an ensemble of [ppn], for example. Since \( \bar{K} \) clusters once produced are hardly destroyed by further collisions because of their extremely large binding energies compared to the temperature, we expect a cascade evolution of \( \bar{K} \) clusters, as shown below.
These processes occur as collisional capture processes, when aided by surrounding nucleons, which transfer energies and momenta to form $\bar{K}$ clusters efficiently. The energy diagram for this cascade evolution was calculated, as shown in Fig. 4. The deepest trapping center among the single-$\bar{K}$ clusters is $ppnK^-$. The double-$\bar{K}$ clusters, $ppnK^-K^-$ and $pppnK^-K^-$, are the deepest among the double-$\bar{K}$ clusters. The probability of forming such deep traps can be estimated by a coalescence model [20, 21]. Realistic simulations for heavy-ion reaction residues, such as RQMD [22] and HSD [23], can be extended so as to include the $\bar{K}$ cluster productions, which will be important.

iii) $\Lambda(1405)$ and $\Lambda(1520)$ as doorway particles

Productions of $\Lambda(1405)$ and $\Lambda(1520)$ in heavy-ion reactions can also be sources of $\bar{K}$ clusters, since $\Lambda(1405)$ is a bound state of $K^- + p$ and $\Lambda(1520)$ is a resonance state of $KN$. When they are produced in a nuclear medium, they proceed to kaonic bound states, forming $\bar{K}$ clusters. The role of these excited hyperons as doorways to kaonic systems was studied in the case of $(K^-, \pi^-)$ reactions [2]. Likewise, excited hyperons with $S = -2$ can be a doorway to double-$K$ clusters.

iv) Direct formation of $\bar{K}$ clusters from QGP

When the temperature of a primordial fireball exceeds a freeze-out temperature ($T > T_f \sim 150$ MeV) it is expected to be in a hot quark-gluon plasma (QGP). Since the $K$ clusters are by themselves dense, and are likely to be in a deconfined quark-gluon phase, as in QGP, they will be spontaneously formed, like clusterized islands, remaining in an expanding hadron gas medium throughout the freeze-out phase (see Fig. 4):

$QGP \rightarrow$ evaporating hadrons + $\bar{K}$ clusters. (16)

Here, the $s$ quarks in a primordial QGP will act as seeds for $K$ clusters, which are eventually formed in a self-organized way and are decoupled from evaporating hadrons. In this way, $\bar{K}$ clusters are produced directly as “island-like” residues from QGP. This process is different from the cascade evolution process considered above, and the probability of each $s$-quark to proceed to a $\bar{K}$ cluster (even to a double-$\bar{K}$ cluster) is expected to be high. The time for their formation as well as the time for their decay are close to the freeze-out time.

4. $\bar{K}$-cluster invariant-mass spectroscopy

Eventually, $\bar{K}$ clusters decay via strong interactions by their own intrinsic decay modes. Whether these decays occur inside or outside the nuclear collision volume, is a key problem. The condition to observe the free decay of a $\bar{K}$ cluster with a decay width $\Gamma_K$ is

$$\tau_K = \frac{\hbar}{\Gamma_K} > \tau_f,$$  (17)

where $\tau_f$ is the freeze-out time. For $\Gamma_K = 20$ MeV, $\tau_K \sim 10 \text{ fm}/c$, which is marginally longer than the calculated freeze-out time, $\tau_f \sim 5 \text{ fm}/c$. Thus, most $K$ clusters formed in the freeze-out phase are likely to survive and undergo free decays.

The above discussions indicate that the $\bar{K}$ clusters must be as abundantly produced as the free $K^-$ mesons, and that their decays can be tracked. The unique signature for $\bar{K}$ cluster formation is a clear peak to be revealed

![Fig. 4: Cascade evolution of $\bar{K}$ clusters as deep traps in heavy-ion collisions. The calculated binding energies are shown.](image-url)
in the invariant-mass spectra of its decay particles, if all of the decay particles with their energies and momenta are correctly identified. This method applies to limited cases, where \( \bar{K} \) clusters can decay to trackable particles, such as

\[
\begin{align*}
i) \quad ppK^- & \rightarrow \Lambda + p, \\
ii) \quad ppnK^- & \rightarrow \Lambda + d, \\
iii) \quad pppK^- & \rightarrow \Lambda + p + p, \\
iv) \quad ppnnK^- & \rightarrow \Lambda + t, \\
v) \quad pppnK^- & \rightarrow \Lambda + \text{He}^3, \\
vi) \quad ppK^-K^- & \rightarrow \Lambda + \Lambda, \\
vii) \quad pppK^-K^- & \rightarrow \Lambda \Lambda + p, \\
viii) \quad pppnK^-K^- & \rightarrow \Lambda \Lambda + d.
\end{align*}
\]

These decay processes are energetically the most favoured, though their branching ratios are not known. In the following, we show that this is indeed feasible.

Recently, \( \Lambda \) hyperons have been identified in high-energy heavy-ion reactions at GSI-SIS from the energies and momenta of their decay vertices, \( p + \pi^- \), by a large 4\( \pi \) detector (FOPI) \[19\]. The average multiplicity of \( \Lambda \) at a H.I. energy of 2\( A \) GeV is about 0.15 after a correction for the reconstruction efficiency, whereas the average multiplicity of \( p \) is about 40 \[19\]. Since the observed yields of \( d \), \( t \) and \( \text{He}^3 \) are also sizable, we expect that the formation of \( \bar{K} \) clusters is highly probable. Invariant-mass spectra for the above processes can be composed from charged-particle tracks (\( p \), \( d \), \( t \) and \( \text{He}^3 \)) in connection with a \( \Lambda \)-associated \( p - \pi^- \) trajectories, though there will be a substantial background of combinatorial origin. The first goal should be to identify two important single-\( \bar{K} \) clusters, \( ppK^- \) and \( ppnK^- \). The \( ppK^- \) nucleus is being searched for by using the \( ^4\text{He} \)(stopped \( K^- \), n) reaction at KEK \[26\].

Once single-\( \bar{K} \) clusters are found, the next step will be to pursue double-\( \bar{K} \) clusters. Abundant productions of \( \Lambda \) are also observed at the RHIC energy by PHENIX \[27\] and STAR \[28\]. Here, the multiplicities of \( K^- \) are large, so that a large production of double-\( K \) clusters is expected. It is to be noted that the future GSI accelerator will provide 40 GeV/u heavy-ions, which will be suitable for \( K \) cluster invariant-mass spectroscopy in view of the large baryon density to be achieved in collisions, and also of abundant strangeness production \[29\].

\[\text{FIG. 5: Quark gluon plasma and its transition to evaporating hadron gases with heavy and dense residues of} \ \bar{K} \ \text{clusters.}\]

\[\text{FIG. 6: Schematic diagram for the density dependences of the bound-state energies of various baryon composite systems (}\ pK^-n^a\ \text{)}\]
an amount, \( \Delta M \approx q^2/(2M_N) \), as calculated in [31]. For \( \rho \approx 3\rho_0 \) this “red shift” amounts to \( \sim 50 \) MeV.

We can conceive a further extension of the double-K systems to multi-K nuclear matter. Whereas the nucleons and hyperons are hard to compress, presumably because of the Pauli repulsion in the quark sector, multi-quark clusters and hyperons are hard to compress, presumably the corresponding non-strange matter. The equation of state of strangeness-rich systems may be intuitively understood as a result of the non-existence of Pauli blocking in the \((u,d)\) quark sector by implanting \( K^- \), since \( K^- \) is composed of \( s\bar{u} \). Here, kaon condensation may also play an essential role [33]. Fig. 1 shows schematically the expected dependences of multi-K bound states as compared with non-K nuclei. The \( K \) matter with a large \( K \) fraction \(( K^-/N \sim 1) \) may be more stable than the corresponding non-strange matter. The equation of state for describing gravity-assisted dense stars will be obtained from empirical bases, when the double-K nuclei, as predicted here, are investigated experimentally.

So far, the present treatment does not contain the effect of chiral symmetry restoration at high density. If the KN interaction is increased along with a restoration of the chiral symmetry, as observed in deeply bound pionic nuclei [32], the \( K^- \) energy line is bent downward with the increase of \( \rho \); \( K \) clusters may be more bound and denser, and the \( K \) matter may become more stable. The \( K \) (or \( s \)-quark) clusters, which we propose to study experimentally, will provide not only a unique playground to study possible quark-gluon phases of dense and bound nuclear systems, but also a key to understanding the neutron and strange matter.

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