Experimental investigation of dense kaonic nuclear states

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Various experimental methods to investigate dense kaonic nuclear bound states are proposed and discussed. The first type is "missing-mass spectroscopy" of strangeness-transfer reactions, such as (K^-, N), (K^-, π^-) and $(\pi^{+/-}, K^{0/+})$. The second type is "invariant-mass spectroscopy" for simple $\bar{\mathrm{K}}$ bound states ($\bar{\mathrm{K}}$ clusters) such as ppK^- and $pppK^-$, which are expected to be formed as residues of heavy-ion reactions and strangeness compound states. In particular, the double-$\bar{\mathrm{K}}$ clusters, ppK^-K^- and $pppK^-K^-$, can be investigated in heavy-ion reactions of high energy and density.

1. Introduction

Recently, exotic nuclear systems involving a $\bar{\mathrm{K}}$ (K^- or $\bar{\mathrm{K}}^0$) as a constituent have been investigated theoretically [1–5] based on phenomenologically constructed $\bar{\mathrm{K}}$N interactions (hereafter referred to as AY). The strongly attractive K^--p interaction is expected to cause not only enormous binding of K^- in proton-rich nuclei, but also shrinkage of $\bar{\mathrm{K}}$-bound nuclei. The calculated bound states in ppnK^-, ppnnK^- and ^{8}BeK^- lie below the $\Sigma\pi$ emission threshold, which is the main decay channel of $\bar{\mathrm{K}}$N and, thus, are predicted to have narrow decay widths. These few-body treatments have been further extended to more complex systems by the method of Antisymmetrized Molecular Dynamics (AMD) [3–5].

The predicted $\bar{\mathrm{K}}$ bound states have central nucleon densities ($\rho(0)$), 4-9 times as much as the normal nuclear density ($\rho_0 = 0.17$ fm^{-3}), with large binding energies ($E_K \approx 100$ MeV). Such strongly bound compact systems can be called "$\bar{\mathrm{K}}$ nuclear clusters". Since the predicted nucleon densities very much exceed the nucleon compaction limit, $\rho_c \approx 1/v_N \approx 2.3\rho_0$, with $v_N \approx 2.5$ fm^3 being the nucleon volume, it may be questionable to apply the existing hadronic $\bar{\mathrm{K}}$N and NN interactions to such dense systems. Whereas the $\bar{\mathrm{K}}$ clusters are expected to be in deconfined quark-gluon states [7–9], there is no theoretical treatment available on "dense and cold" microscopic systems. Thus, our strategy is:

i) to provide experimentalists with theoretical binding energies and widths for expected $\bar{\mathrm{K}}$ clusters as a 0th-order guiding reference,

ii) independently to search for $\bar{\mathrm{K}}$ clusters, and

iii) if observed, to examine their properties in comparison with the guiding reference.

Any discrepancy between theory and experiment will imply various unexplored physics questions beyond the conventional nuclear physics, such 1) relativistic effects of bound $\bar{\mathrm{K}}$, 2) nuclear incompressibility, 3) spin-orbit interactions, 4) modification of the $\bar{\mathrm{K}}$N interaction due to possible chiral symmetry restoration, etc.

In this presentation we discuss two major experimental methods: *formation-channel spectroscopy: missing-mass spectroscopy* using direct reactions, such as (K^-, n) [1, 11] and (K^-, π^-) [2] and *decay-channel spectroscopy: invariant-mass sepctroscopy* of decay particles of $\bar{\mathrm{K}}$ clusters [6]. Very recently, an experimental indication of a deep kaonic bound state, $ppnK^-$, has been obtained from a ^{4}He$(stopped - K^-, n)$ experiment at KEK [10]. This first experimental signal shows that the binding energy is substantially larger than predicted based on non-relativistic regime, and stimulates further theoretical and experimental studies.

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

$\bar{\mathrm{K}}$ cluster	Mc^2 [MeV]	E_K [MeV]	Γ_K [MeV]	$\rho(0)$ [fm^{-3}]	R_{rms} [fm]	k_p [fm^{-1}]	k_K [fm^{-1}]
pK^-	1407	27	40	0.59	0.45	1.37	1.37
ppK^-	2322	48	61	0.52	0.99	1.49	1.18
$pppK^-$	3211	97	13	1.56	0.81		
$ppnK^-$	3192	118	21	1.50	0.72		
$ppppK^-$	4171	75	162	1.68	0.95		
$pppnK^-$	4135	113	26	1.29	0.97		
$ppnnK^-$	4135	114	34		1.12		
ppK^-K^-	2747	117	35				
$ppnK^-K^-$	3582	221	37	2.97	0.69		
$pppnK^-K^-$	4511	230	61	2.33	0.73		

2. Direct reactions to populate $\bar{\mathrm{K}}$ nuclei

2A. (stopped-K^-,n)

The ppnK^- system can be populated by ^{4}He(stopped K^-, n) reaction, in which the "Auger neutron" serves as an indicator of the bound state [1]. An experiment has been carried out at KEK, indicating a candidate for the predicted bound state with a mass of $M \sim 3140$ MeV and a total binding energy of ~ 170 MeV [10], as shown in Fig. 1. This value is significantly larger than the predicted value of 118 MeV, suggesting that the $\bar{\mathrm{K}}$N interaction in this nuclear system may be enhanced over the bare one by ~ 20 %.

2B. (K^-, N) reaction

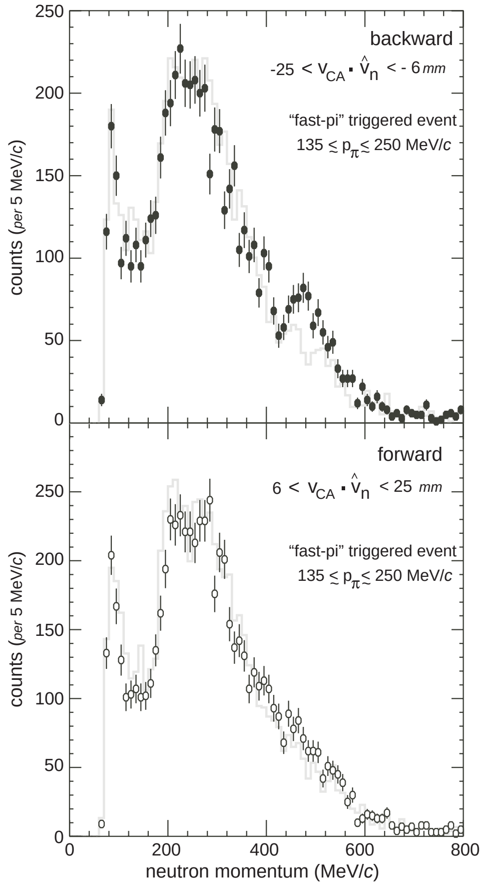

FIG. 1: The first indication of a deeply bound kaonic state of ppnK$^-$ populated in the ^{4}He(stopped K$^-$,n) reaction. The momentum spectra of neutrons tagged by backward (upper) and forward (lower) fast pions, showing a peak at $p_n \sim 480$ MeV. From Iwasaki *et al.* [10].

The reaction of (K$^-$, N) can be used to populate $\bar{\rm K}$ bound states, in which the incoming $\bar{\rm K}$ knocks out one of the target nucleons and stops in the nucleus. This process was studied in Ref.[11].

2C. (K$^-$, π^-) and ($\pi^{+/-}$, K$^{+/0}$) reactions

Various exotic $\bar{\rm K}$ nuclei can be populated in *strangeness exchange reactions* such as (K^-, π^-) and $(\pi^{+/-}, K^{0/+})$. Table II lists kaonic nuclei to be produced.

The spectral shape of the bound-K$^-$ region populated in direct reactions, (K^-, π^-) and (π^+, K^+), was calculated based on the Λ^* doorway model [2, 12]. In this treatment the formation of kaonic systems proceeds via the elementary production of $\Lambda(1405)$ by $n(K^-, \pi^-)\Lambda^*$ and $n(\pi^+, K^+)\Lambda^*$, which is then melted to form koanic states. The results for (π^+, K^+) and (π^-, K^0) on targets of d, ^{3}He and ^{4}He are shown in Fig. 2. The dense kaonic states produced from ^{3}He and ^{4}He are shown to be well separated from the huge "quasi-free" continuum. On the other hands, the ppK$^-$ state is broader in the natural width and closer in energy to the $\Lambda(1405)$ threshold, and thus its broad peak is partially separated from the quasi-free continuum. We need an efficient tagging to enhance the bound-state peak.

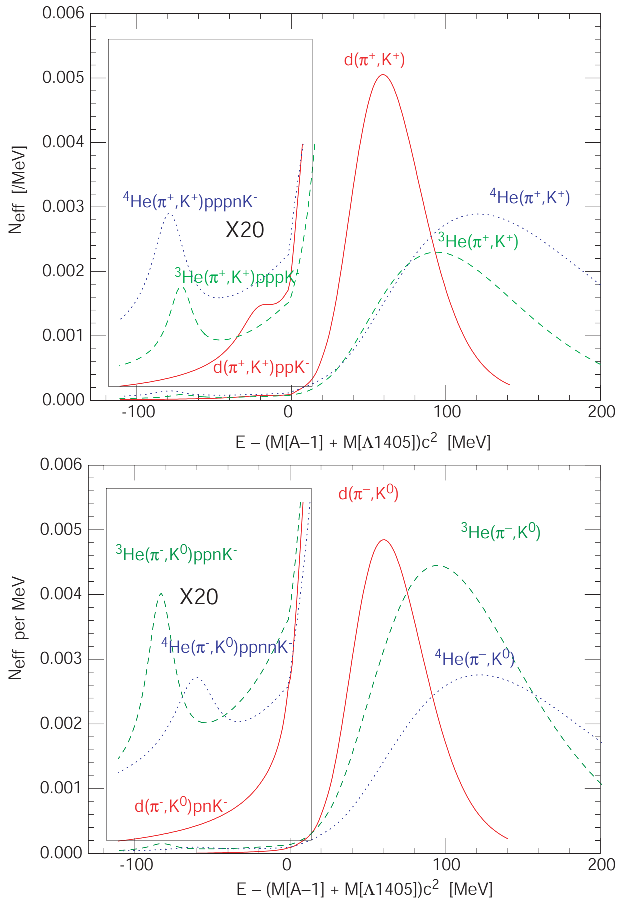

FIG. 2: Spectra ($N_{\rm eff}$) of (π^+,K$^+$) and (π^-,K^0) at $p_\pi = 1.5$ GeV/c on d, ^{3}He and ^{4}He as functions of $E_K - [M(A-1) + M(\Lambda_{1405})]c^2$. Calculated based on the Λ^* doorway model [12]. Note that at the present stage the final state $S = 0$ pnK$^-$ state (iso-doublet of ppK$^-$) is not taken into account; with this consideration the lower spectrum of d(π^-, K^0) would be similar to the upper one of d(π^+, K^+).

2D. $\bar{\rm K}$ clusters from compound $\bar{\rm K}$ states

The "quasi-free" component involves excited continuum compound states of K$^-$ nuclear systems, which immediately emit nucleons and end up in kaonic bound states. This is similar to the known situation in hyperfragment formation [13, 14]. Such a "decay-channel" spectroscopy is even more feasible for kaonic bound states, because of their strong binding and characteristic decay channels from which invariant-mass spectra can be easily reconstructed, as discussed in Section 3. The production cross sections of hyperfragments from continuum compound process were calculated by Sano *et al.* [15]. The same method can be extended to the case of $\bar{\rm K}$ fragments.

TABLE II: Various reactions to produce exotic $\bar{\mathrm{K}}$ bound systems

	(K^-,p)	(K^-,n)	(K^-,π^-) (π^-,K^0)	(π^+,K^+)	(π^+,K^0)	(p,K^+)	(p,K^0)
ΔQ	-2	-1	-1	0	+1	0	+1
Target							
p	-	-	Λ, Λ^*	Σ^+, Σ^{+*}	-	ppK^-	-
$[n]$	-	-	Σ^-, Σ^{-*}	pnK^-	ppK^-		
d	-	Λ, Λ^*	pnK^-	ppK^-	-	$ppnK^-$	$pppK^-$
^{3}He	pnK^-	ppK^-	$ppnK^-$	$pppK^-$	-	$pppnK^-$	$ppppK^-$
^{4}He	$pnnK^-$	$ppnK^-$	$ppnnK^-$	$pppnK^-$	$ppppK^-$	$pppnnK^-$	$ppppnK^-$

3. Decay-channel spectroscopy of $\bar{\mathrm{K}}$ clusters as residues of heavy-ion reactions

3.1 Evolution of $\bar{\mathrm{K}}$ clusters as deep trapping centers

The K$^-$ mesons born in a fireball of heavy-ion collisions produce extra-deep and localized self-trapping potentials, which are intermittently accommodated by a few correlated nucleons (notably, p^2, p^{2}n (^{3}He) and p^{2}n^2 (^{4}He)). Since $\bar{\mathrm{K}}$ 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 $\bar{\mathrm{K}}$ clusters [6], as shown in Fig. 3. These processes occur as *collisional capture processes*, when aided by surrounding nucleons, which transfer energies and momenta to form $\bar{\mathrm{K}}$ clusters efficiently.

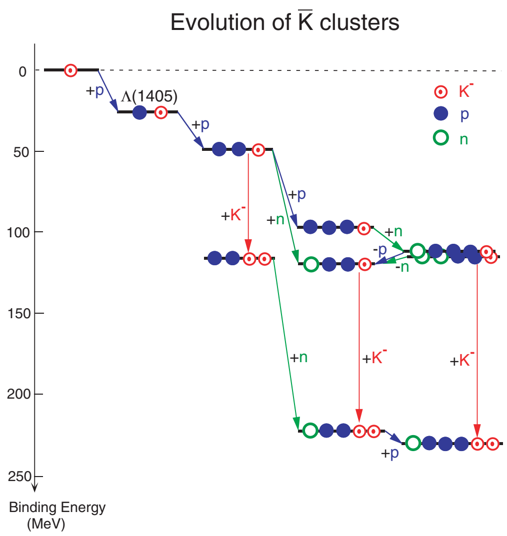

FIG. 3: Cascade evolution of $\bar{\mathrm{K}}$ clusters as deep traps in heavy-ion collisions. The calculated binding energies are shown.

3.2 Direct formation of $\bar{\mathrm{K}}$ clusters from QGP

In central collisions of relativistic heavy ions, a dense and hot fireball is produced. When the temperature of a primordial fireball exceeds a QCD transition temperature ($T > 150$ MeV) it is expected to be in quark-gluon plasma (QGP). Since the $\bar{\mathrm{K}}$ clusters are by themselves dense, and are likely to be in a deconfined quark-gluon phase, as in QGP, they will be spontaneously formed in a self-organized way, like clusterized islands, remaining in a cooling and expanding hadron-gas medium throughout the freeze-out phase, as schematically shown in Fig. 4. Here, the s quarks in a primordial QGP act as seeds for $\bar{\mathrm{K}}$ clusters.

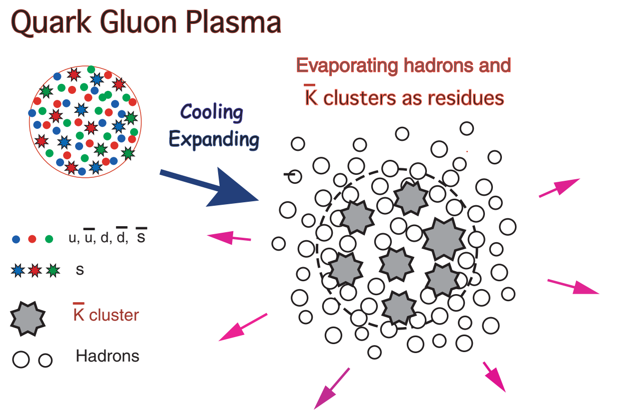

FIG. 4: Quark gluon plasma and its transition to evaporating hadron gases with heavy and dense residues of $\bar{\mathrm{K}}$ clusters.

Recently, it was shown that particle emission data including strange particles are well accounted for by a hadro-chemical equilibrium model in terms of the freeze-out temperature, the baryon chemical potential and the fireball volume as parameters [16]. In this model all particles (or states) are treated on equal footing, and the yields of various $\bar{\mathrm{K}}$ clusters have been calculated by Andronic *et al.* [17], as discussed in the next section.

3.3 $\bar{\mathrm{K}}$-cluster invariant-mass spectroscopy

Eventually, the $\bar{\mathrm{K}}$ clusters formed in heavy-ion collisions decay via strong interactions by their own intrinsic decay modes. The condition to observe the free decay of a $\bar{\mathrm{K}}$ cluster with a decay width Γ_K is

$$\tau_K = \hbar/\Gamma_K > \tau_f, \qquad (1)$$

where τ_f is the freeze-out time. For the predicted decay width of $\Gamma_K \approx 20$ MeV, $\tau_K \approx 10$ fm/c, which is marginally longer than the calculated freeze-out time, $\tau_f \sim 5$ fm/c [18–21]. Thus, most $\bar{\mathrm{K}}$ clusters formed in (and before) the freeze-out phase are likely to survive and undergo free decays.

The unique signature for $\bar{\mathrm{K}}$ cluster formation is a clear peak to be revealed in invariant-mass spectra of its decay particles, provided that all of the decay particles with their energies and momenta are correctly identified. This method applies to limited cases, where $\bar{\mathrm{K}}$ clusters can decay to trackable particles, such as

$$i)\ ppK^- \rightarrow \Lambda + p, \quad (2)$$
$$ii)\ ppnK^- \rightarrow \Lambda + d, \quad (3)$$
$$iii)\ pppK^- \rightarrow \Lambda + p + p, \quad (4)$$
$$vi)\ ppK^-K^- \rightarrow \Lambda + \Lambda, \quad (5)$$
$$vii)\ pppK^-K^- \rightarrow \Lambda + \Lambda + p. \quad (6)$$

These decay processes are energetically the most favoured, though their branching ratios are not known.

The "decay-channel spectroscopy" on ppnK^- is being examined by Herrmann [22] by using the experimental data of Λ and d, obtained from the FOPI detector of GSI [23]. This can be compared with a recent result of the "entrance-channel spectroscopy" performed at KEK [10].

Recent calculations of Andronic *et al.* [17] based on a hadron-gas model [16] give $Y(ppnK^-) \sim 3 \times 10^{-3}$ per total charged pion, or ~ 0.06 per collision, when the incident energy is 2 GeV/u. It is interesting to note that this yield is larger than $Y(K^-)$. This means that, even if the decay branching to $\Lambda + d$ is 0.1, the $ppnK^- \rightarrow \Lambda + d$ signal can be identified with a ratio of $R \sim 0.02$ over a large combinatorial background.

The calculated yield of the double-$\bar{\mathrm{K}}$ cluster, pp$\mathrm{K}^-\mathrm{K}^-$, has a maximum at the c.m. collision energy of $\sqrt{s} = 5 - 10$ GeV/u (the incident energy around 30 GeV/u), and amounts to $Y(ppK^-K^-) \sim 2 \times 10^{-4}$ per total charged pion, or ~ 0.01 per collision [17]. In view of such a large yield the invariant-mass spectroscopy for $\Lambda + \Lambda$ may also be feasible. The future accelerator at GSI will provide 30-40 GeV/u heavy-ions [24], which is suitable for double-$\bar{\mathrm{K}}$-cluster invariant-mass spectroscopy in view of the large baryon density to be achieved in collisions, and also of abundant strangeness production.

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