New way to produce dense double-antikaonic dibaryon system, $\bar{K}\bar{K}NN$, through $\Lambda(1405)$-doorway sticking in $p+p$ collisions

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Abstract: A recent successful observation of a dense and deeply bound $\bar{K}$ nuclear system, K^-pp, in the $p + p \to K^+ + K^-pp$ reaction in a DISTO experiment indicates that the double-$\bar{K}$ dibaryon, K^-K^-pp, which was predicted to be a dense nuclear system, can also be formed in $p + p$ collisions. We find theoretically that the K^--K^- repulsion plays no significant role in reducing the density and binding energy of K^-K^-pp and that, when two $\Lambda(1405)$ resonances are produced simultaneously in a short-range $p + p$ collision, they act as doorways to copious formation of K^-K^-pp, if and only if K^-K^-pp is a dense object, as predicted.

Keywords: double kaonic nuclei, double Lambda (1405) production, K^-K^-pp, pp reaction

I. Introduction

For the past decade we have predicted and studied deeply bound and dense kaonic nuclear states using an empirically based coupled-channel $\bar{K}N$ complex potential.[1)–7)] The structure of the most basic system, K^-pp, first predicted in 2002,[2)] was studied in detail by a realistic three-body calculation,[6),7)] and hence a molecular nature of the strong binding was revealed. The K^-pp system was shown to be close to a Λ^*-p, where $\Lambda^* \equiv \Lambda(1405)$ is a quasi-bound $I = 0$ $\bar{K}N$ pair, like an "atom". This study led us to a new concept of nuclear force, "super-strong nuclear force", which is caused by a migrating real $\bar{K}$ between two nucleons as in molecular covalency.[8)] It has a binding strength nearly 4-times as large as that of the ordinary nuclear force. This "kaonic origin of nuclear force" is contrasted to the ordinary "pionic origin of nuclear force" by Nishijima.[9)]

Since the $p + p$ collision at high energy is known to produce Λ^* among other hyperons, as revealed in $\Delta M(pK^+)$ missing-mass spectra,[10),11)] we proposed a nuclear reaction to populate and identify K^-pp,[7)]

$$p + p \to K^+ + \underline{p + \Lambda^*},$$
$$\hookrightarrow p\Lambda^* \to K^-pp, \qquad [\text{I.1}]$$

with a subsequent decay:

$$K^-pp \to p + \Lambda. \qquad [\text{I.2}]$$

The observed production cross section of Λ^* at an incident proton energy, $T_p \sim 3\,\text{GeV}$, is about 10% of the cross section, $\sigma_\Lambda \sim 50\,\mu\text{b}$, for the ordinary $\Lambda(1115)$. It was theoretically clarified that the produced Λ^* serves as a doorway to form a complex Λ^*-$p \approx K^-pp$. This sticking process occurs strongly when the formed K^-pp has a small p-p distance that matches the small proximity of the $p + p$ collision (with a short collision length of $\sim \hbar/m_\rho c \sim 0.3\,\text{fm}$ helped by a large momentum transfer of $\sim 1.6\,\text{GeV}/c$ at $T_p \sim 3\,\text{GeV}$). In other words, the doorway particle, $\Lambda(1405)$, sticks to the participating p at a high probability to form a K^-pp state, if and only if it is dense, and thus the occurrence of this reaction would provide definite evidence for the dense $\bar{K}$ nuclear state, as predicted.

Very recently, this reaction process was searched for in old DISTO experimental data of exclusive events of $pp \to p + \Lambda + K^+$ at $T_p = 2.85\,\text{GeV}/c$, and was indeed found to take place.[12)] A broad peak showing $M = 2267 \pm 2(stat) \pm 5(syst)\,\text{MeV}/c^2$ was revealed with as much intensity as free Λ^* emission, as shown in Fig. 1 (Upper). Thus, this experiment has proven that the state observed is a dense K^-pp. Additional evidence that the state is strongly related to Λ^* production in the entrance channel has been

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obtained from the incident energy dependence of the cross section.[13] The observed mass of K^-pp in DISTO is much smaller than the original prediction of refs. 5), 7). Two more versions of predictions in which the $\bar{K}N$ interaction is enhanced by 17% (B) and 25% (C) are given in ref. 7), as reproduced in the same figure. The version (C), 25% enhanced one, seems to be compatible with the observation. An independent indication for a similar state in K^- absorption by light nuclei was reported from a FINUDA experiment.[14] There are also theoretical calculations of K^-pp by the Faddeev method.[15]–[17]

It is extremely interesting and important to extend the search to double-$\bar{K}$ nuclear clusters, since they may serve as precursors to kaon condensation.[18]–[20] Previously in 2004, we predicted the simplest double-$\bar{K}$ nuclear clusters, K^-K^-pp and K^-K^-ppn, using the original AY interaction combined with the G-matrix method,[5] which were shown to have deeper binding and higher density than K^-pp. Invariant-mass spectroscopy for their decay particles, $\Lambda + \Lambda$ and $\Lambda + \Lambda + p$, was proposed therein. In view of the DISTO data, the $\bar{K}N$ interaction and thus the actual binding of K^-K^-pp may be much stronger than in the original prediction. How can one produce such double $\bar{K}$ nuclei? This is a crucial and important question. There is an exotic proposal to make use of antiproton absorption in ^{4}He.[21],[22]

In the present short communication we propose a new method to form $\bar{K}\bar{K}NN$ nuclear clusters in $p + p$ collisions and point out some important aspects. This was triggered by the successful observation of K^-pp in the $p + p$ collision. We extended our thinking about the case of $pp \rightarrow K^+ + K^-pp$ to a new process, $pp \rightarrow K^+ + K^+ + K^-K^-pp$, and carried out its formulation and numerical calculations. A detailed report on the results and implications will be given elsewhere.[23] Let us first discuss the structure of K^-K^-pp.

II. Structure of K^-K^-pp

Schematic structures of calculated K^-pp and K^-K^-pp states are shown in Fig. 2. The former was comprehensively studied in ref. 7), where a variational method (ATMS)[24] was employed. The structure is well approximated by a molecule type, with $\Lambda^* = K^-p$ as a "hydrogen atom", which is coupled with another proton, and the K^- meson migrates between the two protons, causing a super-strong nuclear force. This mechanism is understood to be a general mechanism for producing dense nuclear states around $\bar{K}$.

The structure of K^-K^-pp was calculated by using the same AY interaction, as reported in ref. 5). The binding energy is $B_{KK} = 117$ MeV, much larger than that in K^-pp, $B_K = 48$ MeV. The mean distance of $p - p$ was found to be 1.3 fm for K^-K^-pp, whereas it is 1.9 fm for K^-pp. Namely, K^-K^-pp is deeper bound and denser than K^-pp. As in the case of K^-pp (see Fig. 4 of ref. 7)), K^-K^-pp is approximately composed of Λ^*-Λ^*, where the two K^- mesons migrate between the two protons. Thus, we take the following interaction form between Λ^*-Λ^* to represent arbitrarily chosen level energy and width of K^-K^-pp:

$$H_{\Lambda^*\Lambda^*} = -\frac{\hbar^2}{2\mu_{\Lambda^*\Lambda^*}}\vec{\nabla}^2 + U_{\Lambda^*\Lambda^*}(r), \qquad \text{[II.3]}$$

where

$$U_{\Lambda^*\Lambda^*}(r) = (V_0 + iW_0)\left(\frac{r}{b}\right)^2 \exp\left(-\frac{r}{b}\right) \qquad \text{[II.4]}$$

with potential strength parameters, V_0 and W_0, and a range b, which is related to the rms distance of Λ^*-Λ^*.

Since the experimentally identified K^-pp has a substantially deeper binding ($B_K \sim 105$ MeV as compared with the originally predicted value of 48 MeV),[12] corresponding to a 25% enhanced $\bar{K}N$ interaction, K^-K^-pp is likely to have a much larger binding energy than the originally predicted one. We thus presume that the binding energy can be 150 MeV or more. For such cases we use the $\Lambda^* - \Lambda^*$ model Hamiltonian to describe any arbitrarily chosen energy E in the following formalism and calculation. The E we use is defined with respect to the emission threshold of $\Lambda^* + \Lambda^*$ and is thus connected to B_{KK} and M as $B_{KK} = -(E - 2 \times 27\,\text{MeV})$ and $M = (2M_p + 2m_K) + (E - 2 \times 27\,\text{MeV})/c^2$. For the time being we take the bound K^-K^-pp energy to be

$$E = -150 - i75 \,\text{MeV} \qquad \text{[II.5]}$$

as a standard one. This energy is produced by the $\Lambda^* - \Lambda^*$ potential with $V_0 = -543$ MeV and $W_0 = -181$ MeV for $b = 0.3$ fm. As shown in Fig. 3 (black solid curve), this potential form expresses molecule-type bonding like the Morse potential, characterized by a short-range repulsion together with a long-range attraction.

So far, no extra interaction between the two K^- mesons has yet been taken into account. We now consider the K^--K^- interaction, which is constructed by Kanada-En'yo and Jido[25] to be:
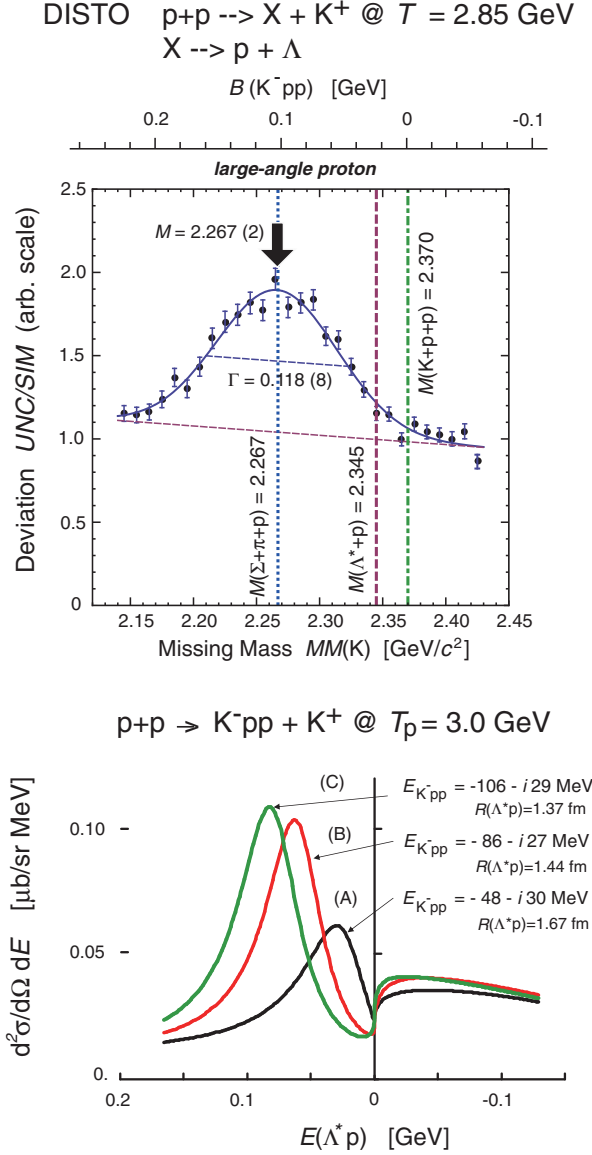
Fig. 1. (Upper) Observed *DEVIATION* spectrum of the missing-mass of K^+, showing a dominant peak of K^-pp, in $pp \to K^+ + K^-pp$.[12] (Lower) Theoretical mass (energy) spectra of K^-pp in the same reaction for three versions of the $\bar{K}N$ interaction.[7] The experimental data seem to be compatible with the version C, namely, the 25% enhanced one.

$$v_{\bar{K}\bar{K}}(r_{KK}) = v_0 \exp\left[-\left(\frac{r_{KK}}{b_{KK}}\right)^2\right], \qquad [\text{II.6}]$$

with $v_0 = 313\,\text{MeV}$ and $b_{KK} = 0.47\,\text{fm}$, based on the result of a lattice QCD calculation.[26] This looks a very repulsive interaction, as shown in Fig. 3 (blue solid curve), which would reduce the binding of the two Λ^*'s significantly. If we could add the above
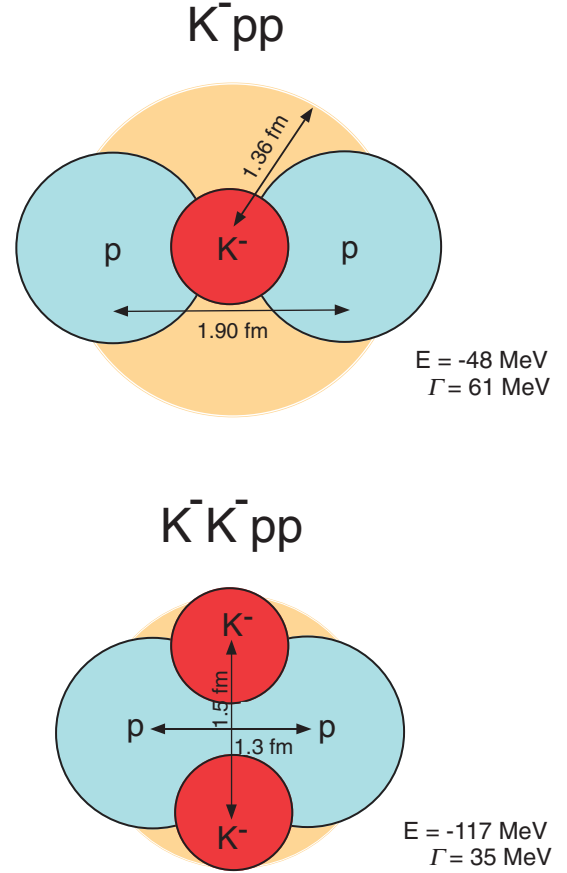

Fig. 2. Schematic structure diagrams for the calculated K^-pp and K^-K^-pp nuclei. The rms radius of K^- and the rms inter-nucleon and inter-$\bar{K}$ distances are shown.
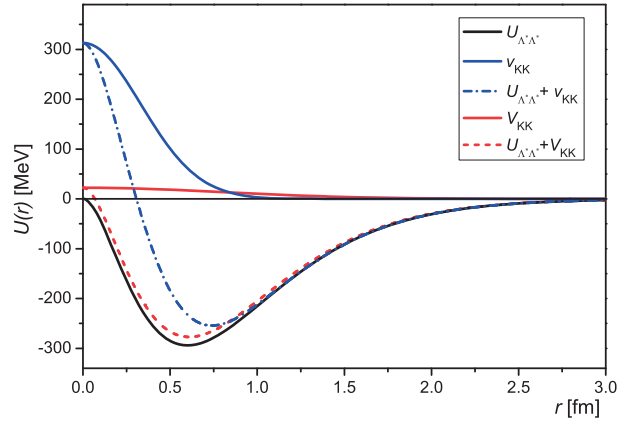

Fig. 3. (Black solid curve) The Λ^*-Λ^* potential for the case of $E = -150 - i75\,\text{MeV}$. (Blue solid and dash-dotted curves) The bare K^--K^- potential without finite-size correction, v_{KK}, and the incorporated Λ^*-Λ^* potential, respectively. (Red solid and dashed curves) The effective K^--K^- potential with finite-size correction, V_{KK}, and the incorporated Λ^*-Λ^* potential, respectively.

interaction to $H_{\Lambda^*\Lambda^*}$ (blue dashed curve), it would bring a reduction of the K^-K^-pp binding energy by 34 MeV. However, this procedure is not valid; when we incorporate the above interaction into $H_{\Lambda^*\Lambda^*}$, we have to correct for the finite size of Λ^*'s, in which the K^- mesons are orbiting. We now take the K^- meson distribution in Λ^* to be expressed by

$$\rho_K(r_K) = \left(\frac{a^3}{\pi^{3/2}}\right) \exp\left[-\left(\frac{r_K}{a}\right)^2\right] \qquad \text{[II.7]}$$

with $a = 1.11$ fm, corresponding to an rms distance of $R_{\text{rms}} = 1.36$ fm.[7] Then, after the correction for the center of mass, we obtain a double folding potential for the finite size:

$$V_{KK}(r) = v_0 \frac{1}{f^3} \exp\left[-\left(\frac{r}{f b_{KK}}\right)^2\right], \qquad \text{[II.8]}$$

with

$$f = \sqrt{1 + 2\left(\frac{a}{b_{KK}} \frac{M_p}{M_p + m_K}\right)^2} \sim 2.41. \quad \text{[II.9]}$$

Effectively, the inclusion of the finite size of Λ^* enlarges the range parameter, b_{KK}, by a factor of $f = 2.4$, and weakens the repulsive potential strength by a factor of $f^{-3} \sim 0.072$. For a point-like K^- distribution, $a \to 0$ and $f \to 1$. Thus, the folded K^--K^- interaction is lowered and longer-ranged, as shown in Fig. 3 (red solid curve), and the total Λ^*-Λ^* potential is slightly increased, as shown in Fig. 3 (red dashed curve). The K^--K^- interaction plays no significant role in the structure and formation of K^-K^-pp; it yields a reduction of the binding energy of K^-K^-pp by only ~ 13 MeV.

It is often said that kaon condensation is unlikely because of the repulsion among $\bar{K}$'s. When the kaon condensed matter is composed of Λ^* particles through the super-strong nuclear force, as envisaged in ref. 7), then, the bare K^--K^- repulsion is suppressed greatly from the above consideration of the finite size of Λ^*.

III. K^-K^-pp formation in the $p + p$ collision

The ingredients of the nuclear reactions that we consider are shown in Fig. 4. Case a) is for the formation of K^-pp,[7] in which a Λ^* is produced with a large momentum transfer at nearly the same position as the participating proton within a very short collision length of $\hbar/m_\rho c \sim 0.3$ fm. This Λ^* sticks to the participating scattered proton to form $X = K^-pp$, as indicated by a sepia bold broken line. The vector sum of the Λ^* and K^+ momenta is balanced by the momentum of the scattered

proton. Likewise, as shown in b), the $p + p$ collision at a high enough energy produces two Λ^*'s together with two K^+'s. Here, the proton in Case a) is replaced by another pair of Λ^* and K^+, and the two Λ^*'s stick to each other, forming $X = K^-K^-pp$, as shown.

The free Λ production cross section in $p + p$ collision is known to be

$$\sigma_\Lambda \sim 10^{-3} \times \sigma_{\text{total}} \sim 50 \, \mu\text{b}, \qquad \text{[III.10]}$$

and the free Λ^* production cross section at 2.83 GeV is known from ref. 11) to be

$$\sigma_{\Lambda^*} \sim 4.5 \, \mu\text{b} \sim 0.10 \times \sigma_\Lambda, \qquad \text{[III.11]}$$

No free double-Λ^* production is known at all, and thus, only a rough estimate can be made here. The production of two normal Λ's is expected to take place at a rate of

$$\sigma_{\Lambda+\Lambda} \sim 0.001 \times \sigma_\Lambda \sim 50 \, \text{nb}. \qquad \text{[III.12]}$$

Thus, the free double-Λ^* production can be

$$\sigma_{\Lambda^*+\Lambda^*} \sim 0.01 \times \sigma_{\Lambda+\Lambda} \sim 0.5 \, \text{nb}. \qquad \text{[III.13]}$$

Since the production of a single Λ^*, eq. [I.1], is associated with a short-range collision ($m_B \sim m_\rho$), its cross section is small, but the same hard collision can produce another Λ^*. So, the cross section for double Λ^*'s may not be so small as given in eq. [III.13]. These very rough estimates, of course, depend on the incident energy. We lack good experimental and theoretical information. The problem here, however, is to investigate how much fraction of $\sigma_{\Lambda^*+\Lambda^*}$ can contribute to the formation of the bound K^-K^-pp.

Let us make an extension of the reaction [I.1] to double-$\bar{K}$ production:

$$p + p \to K^+ + K^+ + \underline{\Lambda^* + \Lambda^*},$$
$$\hookrightarrow \Lambda^*\Lambda^* \to K^-K^-pp,$$
$$\text{[III.14]}$$

with a subsequent decay:

$$K^-K^-pp \to \Lambda + \Lambda, \qquad \text{[III.15]}$$

and others.

Then, the same mechanism as proven experimentally in the case of K^-pp can be applied to K^-K^-pp formation, where the simultaneous production of two doorway Λ^*'s within a short distance, given by the intermediate boson with a mass m_B, helps their sticking into a dense $\Lambda^*\Lambda^* \approx K^-K^-pp$. Thus, we have formulated and calculated the cross sections according to Fig. 5, where two K^+'s with $(E^{(1)}, \vec{k}^{(1)})$ and $(E^{(2)}, \vec{k}^{(2)})$, and a $\Lambda^*\Lambda^*$ complex with
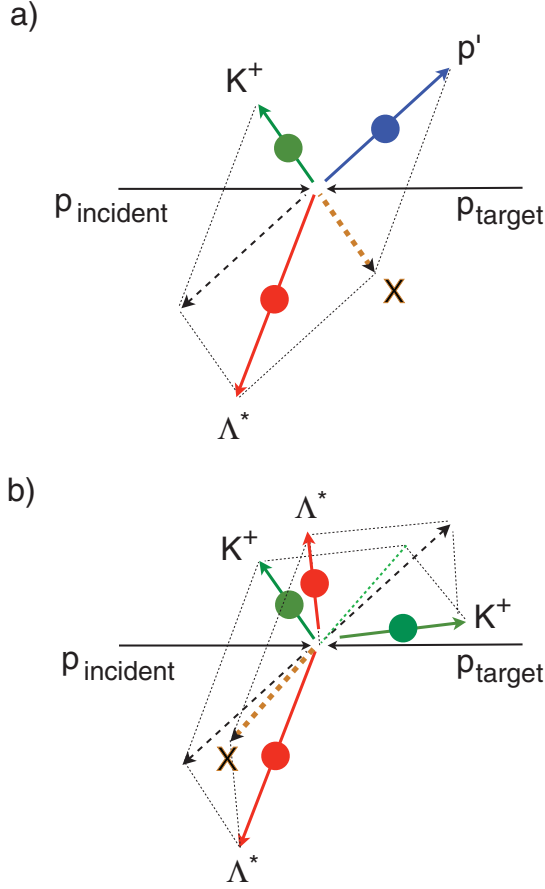
a)

b)

Fig. 4.   Reaction diagrams involving $\Lambda^* = \Lambda(1405)$ as a doorway in the center-of-mass system of $p + p$ collisions. a) For $pp \to p + K^+ + \Lambda^* \to K^+ + K^- pp$ and b) for $pp \to K^+ + \Lambda^* + K^+ + \Lambda^* \to K^+ + K^+ + K^- K^- pp$. In a) the vector sum of the Λ^* and K^+ momenta is balanced by the scattered-proton momentum, and in b) this is replaced by another pair of Λ^* and K^+. The momentum of X, expressed by a sepia bold broken line, is composed of those of p and Λ^* in a) and those of $\Lambda^* + \Lambda^*$ in b).

(a)

(b)

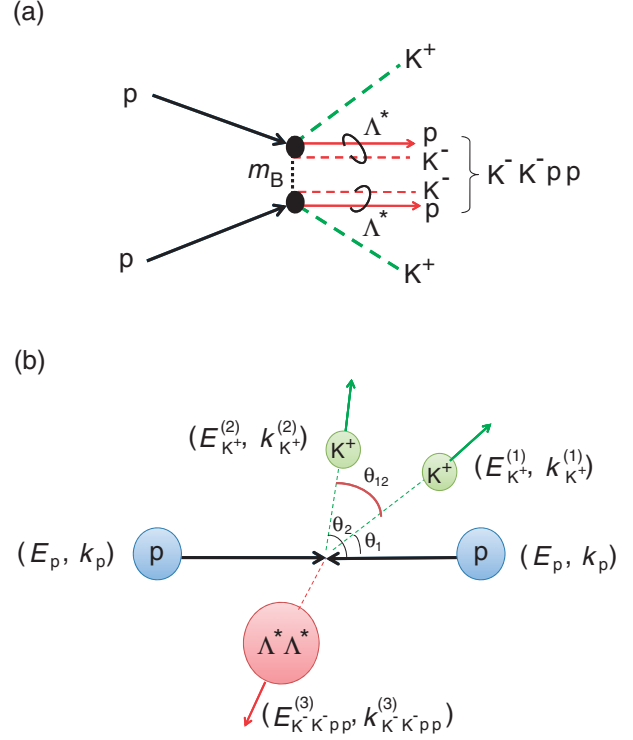Fig. 5.   (a) Elementary process for $p + p \to K^+ + K^+ + K^- K^- pp$ via the production of two Λ^*'s as doorways. The intermediate boson with a mass m_B is shown. (b) Kinematical event pattern for the production of two K^+'s and a $\Lambda^*\Lambda^*$.

$(E^{(3)}, \vec{k}^{(3)})$ are shown. A detailed report will be given elsewhere.[23] The essential ingredients are as follows.

1)   A large momentum transfer $Q = |\vec{k_p} - \vec{k^{(3)}}| \sim 1.8\,\mathrm{GeV}/c$ in the $p - p$ reaction at $T_p \sim 7\,\mathrm{GeV}$.
2)   A short collision range of $\beta \sim \hbar/m_\rho c \sim 0.26\,\mathrm{fm}$.
3)   Compactness of $K^- K^- pp$ (a short distance of Λ^*-Λ^*).

These three variables are physically independent, but collaborate jointly in the formation of a compact $K^- K^- pp$ in high-energy $p + p$ collisions. The elementary process, $7\,\mathrm{GeV}\ p \to K^+ + \Lambda^*$, alone cannot occur in the free space, since the momentum conservation is not fulfilled. This process is realized

only when some part of the momentum is transferred to another Λ^* by virtual meson exchange with a mass m_B, which we express in terms of the interaction,

$$\frac{\exp(-r/\beta)}{\beta^2 r} \qquad [\mathrm{III.16}]$$

with

$$\beta = \frac{\hbar}{m_B c}. \qquad [\mathrm{III.17}]$$

Therefore, this interaction is inevitable in the present $\Lambda^*\Lambda^*$ formation reaction. If two Λ^*'s move together as a result of the momentum transfer, the Λ^*-Λ^* relative momentum becomes much smaller than $Q = 1.8\,\mathrm{GeV}/c$ and may match the Fourier transform:

$$\frac{\Psi_{\Lambda^*\Lambda^*}(k)}{k} Y_{00}(\hat{k}) = \frac{1}{(2\pi)^3} \int d\vec{r} \exp(-i\vec{k}\vec{r}) \phi_{\Lambda^*\Lambda^*}(\vec{r}), \qquad [\mathrm{III.18}]$$

for the bound-state wavefunction $\phi_{\Lambda^*\Lambda^*}(\vec{r})$. The bound-state wavefunction distributes centered

around $400\,\mathrm{MeV}/c$, which justifies our use of the non-relativistic Schrödinger equation. So, we investigate the relative-momentum distribution which contributes to the formation amplitude (A) of the reaction:

$$A = \int d\vec{r}\, \exp(-i\vec{Q}\vec{r})\, \frac{\exp(-r/\beta)}{\beta^2 r}\, \phi_{\Lambda^*\Lambda^*}(\vec{r}) \quad [\text{III.19}]$$

$$= (4\pi)^{5/2} \int_0^\infty dk F_\beta(k;Q) k \Psi_{\Lambda^*\Lambda^*}(k), \qquad [\text{III.20}]$$

where

$$F_\beta(k;Q) = \frac{1}{(4\pi)^2} \int d\hat{k}$$
$$\times \int d\vec{r}\, \exp(-i(\vec{Q}+\vec{k})\vec{r}) \frac{\exp(-r/\beta)}{\beta^2 r}$$
$$= \frac{1}{4Qk\beta^2} \ln \frac{1 + \beta^2(Q+k)^2}{1 + \beta^2(Q-k)^2}. \qquad [\text{III.21}]$$

The function $F_\beta(k;Q)$ expresses a momentum window function, as shown in Fig. 6 (upper). It approaches $\to 1$ in the limit of $\beta \to 0$, and its scale decreases as β increases. The window function with $m_B = m_\pi$ $(\beta = 1.41\,\mathrm{fm})$ is much smaller than that with $m_B = m_\rho$ $(\beta = 0.26\,\mathrm{fm})$. Figure 6 (lower) shows the integrand of the formation amplitude as a function of the relative momentum (k) between the two Λ^*'s. Due to the effect of the interaction, $\exp(-r/\beta)/(\beta^2 r)$ with $m_B = 770\,\mathrm{MeV}/c^2$, the function distributes in a rather flat form below the momentum transfer $Q = 1.8\,\mathrm{GeV}/c$. Then, the integrand functions of A resemble the relative-momentum distributions of the bound-state wavefunction $\Psi(k)$, which range from 200 to $1000\,\mathrm{MeV}/c$, depending on the range (b) of Λ^*-Λ^*.

In many cases of ordinary reactions the momentum window, F, is given as

$$F(k;Q) = \frac{1}{(4\pi)^2} \int d\hat{k} \int d\vec{r}\, \exp[-i(\vec{Q}+\vec{k})\vec{r})] \frac{1}{L^3}$$
$$= \frac{\pi}{2L^3 Q^2} \delta(k-Q) \qquad [\text{III.22}]$$

with a normalization length (L). In this case the integrand of A concentrates at $k = Q$ and an accurate description of high-momentum component of the wavefunction is required, but this is not the case of our present reaction.

The production cross section of $K^- K^- pp$ $(\approx \Lambda^*\Lambda^*)$ at energy E is given, besides the factor composed of the relevant kinematical variables, by a dynamical spectral function:

$$S(E) = -\frac{1}{\pi}$$
$$\times \mathrm{Im}\left[\iint d\vec{r'} d\vec{r} f^*(\vec{r'})\langle\vec{r'}| \frac{1}{E - H_{\Lambda^*\Lambda^*} + i\epsilon} |\vec{r}\rangle f(\vec{r})\right]$$
$$= -\frac{8\mu_{\Lambda^*\Lambda^*}}{\hbar^2} \sum_{\ell=0}^\infty (2\ell+1)\mathrm{Im}\left[\frac{1}{W(u_\ell^{(0)} u_\ell^{(+)})} \right.$$
$$\times \int_0^\infty d\vec{r'} \int_0^\infty d\vec{r}\, \exp\left(-\frac{r'}{\beta}\right) j_\ell(Qr') u_\ell^{(0)}(r_<)$$
$$\left. \times u_\ell^{(+)}(r_>) j_\ell(Qr) \exp\left(-\frac{r'}{\beta}\right) \right], \qquad [\text{III.23}]$$

with

$$f(\vec{r}) = \frac{\beta}{r} \exp\left(-\frac{r}{\beta} + i\vec{Q}\vec{r}\right), \qquad [\text{III.24}]$$

where $u_\ell^{(0)}(r)$ and $u_\ell^{(+)}(r)$ are the stationary and outgoing solutions of the Schrödinger equation, respectively, and W is their Wronskian. The $\Lambda^*\Lambda^*$ Hamiltonian is given by [II.3] and [II.4].

We calculated the differential cross sections under various conditions. Figure 7 shows the calculated cross sections at an incident proton energy of $7\,\mathrm{GeV}$. The level energy of $K^- K^- pp$ with respect to the $\Lambda^* + \Lambda^*$ emission threshold is assumed to be $E = -200, -150, -100$ and $-50\,\mathrm{MeV}$ with a width of $150\,\mathrm{MeV}$; also, the range of the Λ^*-Λ^* interaction in the form [II.4] is assumed to be $b = 0.3\,\mathrm{fm}$, which corresponds to $R_{\mathrm{rms}} = 0.94\,\mathrm{fm}$ for the $E = -150\,\mathrm{MeV}$ case.

Each spectrum shows a characteristic shape composed of three parts:

- **QF** (quasi-free): $M > M(2\Lambda^*)$,
- **CUSP** (cusp): $M \approx M(2\Lambda^*)$,
- **BS** (bound-state): $M \approx M(K^- K^- pp)$.

The continuum QF component extends from $M(2\Lambda^*)$ to the kinematical limit. This might be supposed to be the main part, dominating the whole spectrum. Surprisingly, however, in the bound region $M < M(2\Lambda^*)$, a large peak corresponding to $M(K^- K^- pp)$ dominates the spectrum. This situation is quite similar to the case of $p + p \to K^+ + K^- pp$ formation, and reflects the compact nature of $K^- K^- pp$. Near the threshold mass, $M(2\Lambda^*)$, we predict a narrow structure, which can be explained as being a threshold cusp or an excited bound state. Such a narrow structure is smeared out by the large width of Λ^*. From this figure we recognize that the BS structure is enhanced as the binding energy (and thus the density) increases, in accordance with intuition. We find the BS/QF ratio to be $BS/QF = 0.43, 1.09$, and 1.21 for $E = -100, -150$, and
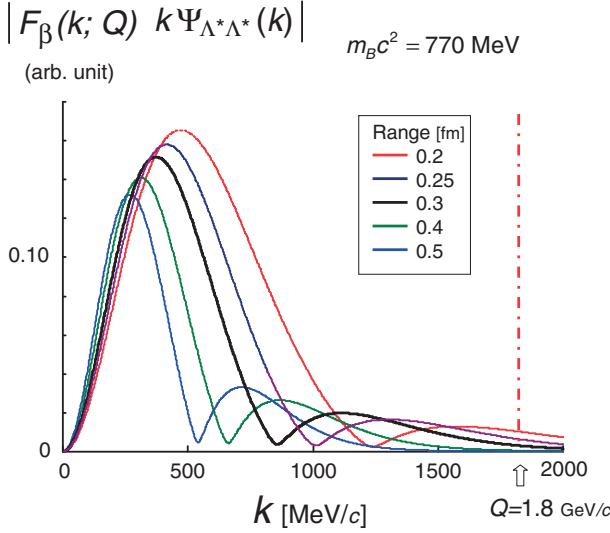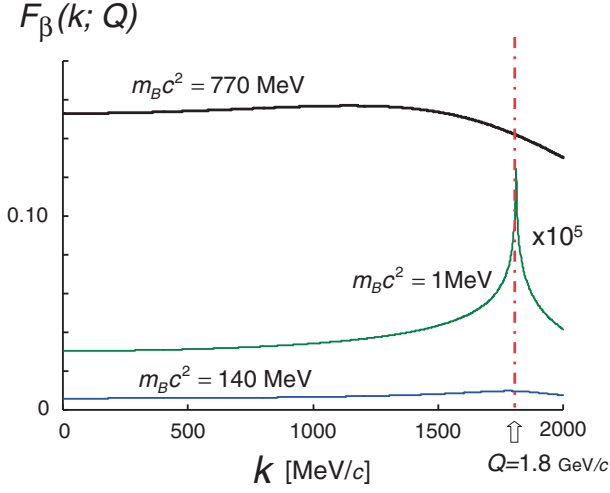
Fig. 6. (Upper) The momentum window function $F_\beta(k; Q)$. (Lower) The integrands of the formation amplitude as a function of the relative momentum of Λ^*-Λ^*, which are nearly the same as the wavefunctions $|\Psi(k)|$, for various values of b.

Fig. 7. Differential cross sections for various bound-state energies of the K^-K^-pp system, E. For $T_p = 7.0\,\text{GeV}$, $b = 0.3\,\text{fm}$ and $\theta_{12} = 180°$.

Fig. 8. Differential cross sections of $p + p \to K^+ + K^+ + K^-K^-pp$ with $E = -150 - i75\,\text{MeV}$ for various range parameters, b, which correspond to different Λ^*-Λ^* rms distances, $R_\text{rms}(\Lambda^*\Lambda^*)$, as shown in the inset. For $T_p = 7.0\,\text{GeV}$ and $\theta_{12} = 180°$.

$-200\,\text{MeV}$, respectively. The peak intensity dominates over the QF continuum region, indicating that the K^-K^-pp production occurs with the same probability as the free emission of two Λ^*'s.

To see the situation more clearly, we set E to the standard case, $-150\,\text{MeV}$, and varied the range, b, for which we obtained different potential parameters. Figure 8 shows the differential cross sections for various ranges of the interaction. The range parameters we varied, $b = 0.2, 0.25, 0.3, 0.4$ and $0.5\,\text{fm}$, correspond to different *rms* distances of Λ^*-Λ^* as $R_\text{rms} = 0.74, 0.84, 0.94, 1.13$ and $1.32\,\text{fm}$, respectively. This figure demonstrates clearly that a more compact
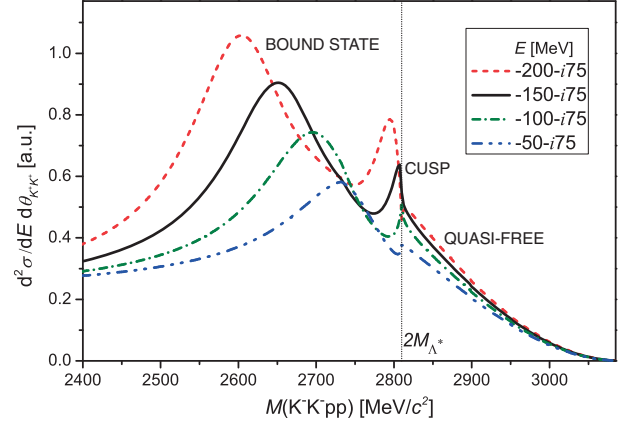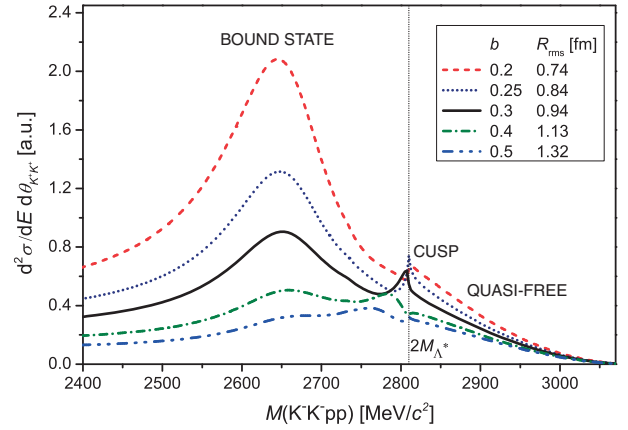

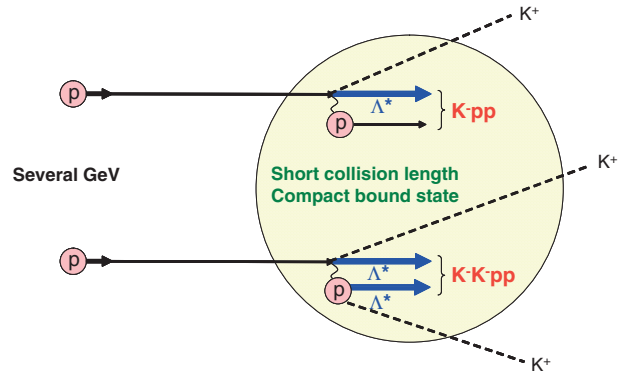
Fig. 9. Schematic picture of the formation of basic kaonic nuclear clusters, K^-pp and K^-K^-pp, which are doorways to *Swan Nuclear Physics*.

system is more favorably populated with a larger cross section. The reason for this is well explained in terms of the relative momentum k of Λ^*-Λ^* in Fig. 6. The BS/QF ratio is seen to be 2.51, 1.60, 1.09 and 0.36 for $b = 0.2$, 0.25, 0.3 and 0.4 fm, respectively. This behavior can be used to determine R_{rms} from an observed spectrum of $M(K^-K^-pp)$. In other words, an observation of BS will indicate that $R_{rms} < 1.0$ fm.

IV. Concluding remarks: toward "Swan Nuclear Physics"

Stimulated by a recent successful observation of the most basic single-$\bar{K}$ nuclear cluster, K^-pp, in the reaction $p + p \rightarrow K^+ + K^-pp$[12] in agreement with the proposed reaction mechanism of "enhanced sticking of Λ^*-p doorway",[7] we have presented a further idea that the simplest double-$\bar{K}$ nuclear cluster, K^-K^-pp, can be produced efficiently in the reaction $p + p \rightarrow K^+ + K^+ + K^-K^-pp$, and found that a similar kind of "Λ^*-Λ^* enhanced-sticking" mechanism exists; the K^-K^-pp cluster can be produced as much as the free production of $\Lambda^* + \Lambda^*$ with the proton energy around 7 GeV, if it is a deeply bound and dense object. Detailed accounts will be published elsewhere.[23] Such a proton beam will be available in J-PARC in Japan and also in the FAIR project in Darmstadt. Since K^-K^-pp is the most important gateway toward kaon condensation physics, we hope experimentalists will pursue how to realize such an experiment.

We have also found that the K^--K^- repulsion inside K^-K^-pp gives only a small effect on its structure, which does not alter the dense nature of double-$\bar{K}$ clusters. In $\bar{K}$ nuclei the s quark combined with $\bar{u}$ or $\bar{d}$ quark in $\bar{K}$ plays a unique and dominant role in forming dense nuclear systems. The essence of physics here is i) the strong attraction of intruder ($\bar{u}, \bar{d}$) quarks with surrounding (u, d) quarks without short-range repulsive barrier, and in addition, ii) the super-strong nuclear force caused by migrating $\bar{K}$ mesons, as clarified in ref. 6). We call this new paradigm *Swan Nuclear Physics*, since an alternative naming of *SWAN* given for the strangeness (and the second generation of elementary particles) by the late Professor K. Nishijima[27] is quite suitable for expressing the essentially important role of s quarks. High-energy $p + p$ collisions populate effectively the kaonic nuclear clusters, K^-pp and K^-K^-pp, by satisfying two conditions of a) short collision length and b) compactness of produced clusters. Thus, several-GeV $p + p$ collisions in a target nucleus provide just efficient doorways to *Swan Nuclear Physics*, as depicted in Fig. 9. Needless to say, this paradigm is deeply connected to the physics of kaon condensation and $\bar{K}$-condensed matter and stars,[18]–[20] and eventually to the physics of cold and dense quark matter.

Finally, we note that the present reaction mechanism (high-momentum transfer high-sticking process for the formation of a dense kaonic cluster) provides an efficient way to *directly* forming K^-pp and K^-K^-pp clusters, not only in the $p + p$ reaction but also in p-nucleus and heavy-ion reactions, in contrast to the thermal equilibrium processes.[28] For the direct production processes, large incident energies, such as 3 GeV for K^-pp and 7 GeV for K^-K^-pp, are necessary. Thus, high-energy reactions with kinetic energies of more than 7 GeV/N will be an interesting field to produce multi-$\bar{K}$ nuclear systems.[5]

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