Kaon and Nucleon States with Hidden Charm

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K

The interaction between K and D/D^* is attractive and form the states $D_{s0}(2317)$ and $D_{s1}(2460)$;

The DD^* interaction is also attractive and forms the states $X(3872)$ and $Z_c(3900)$;

The quantum numbers of the state formed by KDD^* correspond to the quantum numbers of a K^* state (with hidden charm).

So far, there is no experimental search for Kaons in the energy region of $m_K + M_D + M_{D^*}$ 4370 MeV, the last one listed by the PDG is $K(3100)$.

N

Recently, the LHCb collaboration has claimed the existence of pentaquarks with hidden charm and non-zero strangeness with masses around 4500 MeV
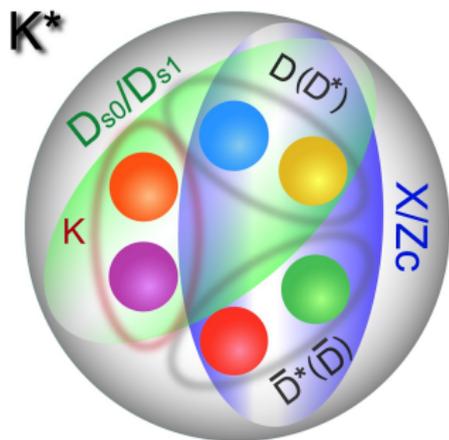
The interaction between N and D/D^* is also attractive and form, for example, the state $_c(2595)$;

The NDD^* threshold lies around 4814 MeV and considering the strong ND interaction (binding energy 200 MeV) we can get states 4600 MeV, close to the P_c masses found[1,2];
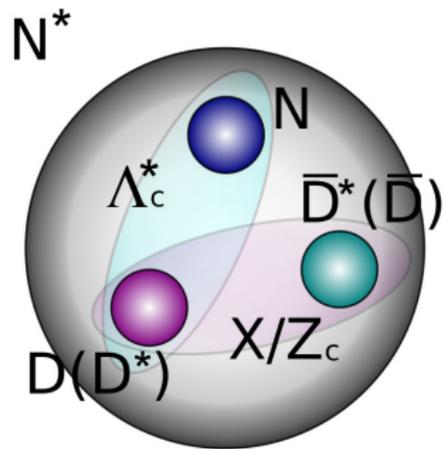
1 Phys. Rev. Lett., 122(22):222001,2019, [2] Phys. Rev. Lett., 115:072001,2015 - R. Aaij et al.;
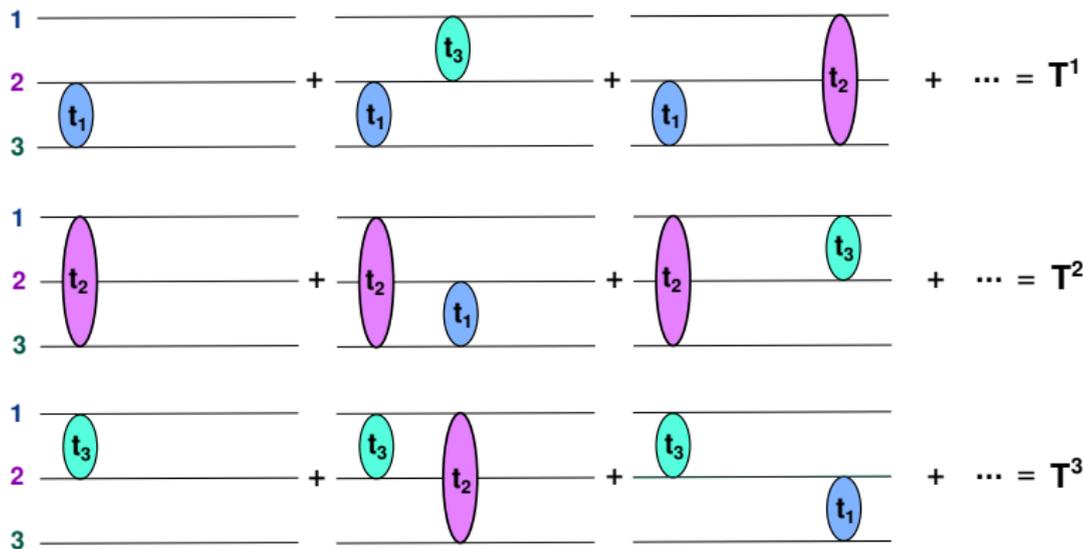
(a) K^* molecular state

(b) N^* molecular state

It may be illustrated as

with $T = T^1 + T^2 + T^3$.

These diagrams can be mathematically written as the series

$$T^1 = t_1 + t_1 G t_2 + t_1 G t_3 + t_1 G t_2 G t_1 + t_1 G t_2 G t_3 + ...$$
$$T^2 = t_2 + t_2 G t_1 + t_2 G t_3 + t_2 G t_1 G t_2 + t_2 G t_1 G t_3 + ...$$
$$T^3 = t_3 + t_3 G t_1 + t_3 G t_2 + t_3 G t_1 G t_3 + t_3 G t_1 G t_2 + ...$$

that can be written as the Faddeev equations for the problem

$$T^1 = t_1 + t_1 G T^2 + t_1 G T^3,$$
$$T^2 = t_2 + t_2 G T^1 + t_2 G T^3,$$
$$T^3 = t_3 + t_3 G T^1 + t_3 G T^2,$$

with $T = T^1 + T^2 + T^3$.

We use the Fixed Center Approximation (FCA) to solve the Faddeev equations

DD^* form a cluster and the 3rd particle rescatters with the members of the cluster;

With $T = T^1 + T^2$.

Such that, all we need to solve is

$$T^1 = t_1 + t_1 G T^2, \qquad T^2 = t_2 + t_2 G T^1,$$

where t_1 is the two-body t-matrix for $KD(ND)$, t_2 the one between $KD^*(ND^*)$ and G is the propagator in the cluster[3]

$$G_K = \frac{1}{2M_a} \int \frac{d^3\mathbf{q}}{(2\pi)^3} \frac{1}{q_0{}^2} \frac{F_a(\mathbf{q})}{\mathbf{q}^2 - m_K^2 + i\epsilon}, \tag{1}$$

$$G_N = \frac{1}{2M_a} \int \frac{d^3\mathbf{q}}{(2\pi)^3} \frac{m_N}{\omega_N(\mathbf{q})} \frac{F_a(\mathbf{q})}{q_0 - \omega(\mathbf{q}) + i\epsilon}, \tag{2}$$

and F_a is a form factor related to the molecular nature of the cluster.

[3] Phys. Rev., C83:065207, 2011 - Ju-Jun Xie, A. Martínez Torres, E. Oset

$F_a(\mathbf{q})$ is given by[4,5,6]

$$F_a(\mathbf{q}) = \frac{1}{N} \int\limits_{|\mathbf{p}|,|\mathbf{p}-\mathbf{q}|<} d^3\mathbf{p} f_a(\mathbf{p}) f_a(\mathbf{p}-\mathbf{q}), \qquad (3)$$

$$f_a(\mathbf{p}) = \frac{1}{\omega_{a1}(\mathbf{p})\omega_{a2}(\mathbf{p})} \cdot \frac{1}{M_a - \omega_{a1}(\mathbf{p}) - \omega_{a2}(\mathbf{p})}, \qquad (4)$$

with $N = F_a(\mathbf{q} = 0)$, and $\omega_A(\mathbf{p}) = \sqrt{m_A^2 + \mathbf{p}^2}$.

[4] PRD81,014029(2010) - D. Gamermann, J. Nieves, E. Oset, and E. Ruiz Arriola, [5] Few Body Syst.,61(4):35,2020 - A. Martínez Torres, K. P. Khemchandani, L. Roca and E. Oset , [6] Phys. Rev., D83:116002, 2011 - A. Martínez Torres, E. J. Garzón, E. Oset, and L. R. Dai.

We have 3 possible configurations of the system: $|KX, I = 1/2, I_3 = 1/2\rangle$, $|KZ_c, I = 1/2, I_3 = 1/2\rangle$ and $|KZ_c, I = 3/2, I_3 = 3/2\rangle$

Let's consider for example the case $|KX, I = 1/2, I_3 = 1/2\rangle$.

$$|KX\rangle = |K, 1/2, 1/2\rangle \quad |DD^*, 0, 0\rangle,$$

So t_1 for the process $KX \to KX$ is given by

$$\langle KX| t_1 |KX\rangle_1 = t_1 g_{11} = \frac{1}{4}(3t_{KD}^{I=1} + t_{KD}^{I=0}),$$

where the subscript $\{11\}$ stands for $KX \to KX$ scattering.

Repeating the process for the channels $KX \to KZ$ and $KZ \to KZ$ we get for t_1

	KX	KZ
KX	$\frac{1}{4}\left(3t_{KD}^{l=1} + t_{KD}^{l=0}\right)$	$\frac{3}{4}\left(t_{KD}^{l=1} \quad t_{KD}^{l=0}\right)$
KZ	$\frac{3}{4}\left(t_{KD}^{l=1} \quad t_{KD}^{l=0}\right)$	$\frac{1}{4}\left(t_{KD}^{l=1} + 3t_{KD}^{l=0}\right)$

Calculations of t_2: change $D \to D^*$ and add a global minus sign on the non-diagonal terms.

$$t_{AB} = V_{AB} + V_{AB}G_{AB}t_{AB}, \qquad \text{Bethe-Salpeter} \qquad (5)$$

G_{AB} is the two-body loop function for the channel made of hadrons A and B: It is regularized with a cut-off or with dimensional regularization

KX and KZ_c

In case of the KD/KD^* system, we have followed Ref. *Phys. Rev., D76:0740 16, 2007* where the amplitude V_{AB} is obtained from the following Lagrangian

$$L = \frac{1}{4f^2} \left\{ \partial^\mu P[\phi, \partial_\mu P]P^\dagger \quad P[\phi, \partial_\mu]\partial^\mu P^\dagger \right\}, \qquad (6)$$

$$P = \begin{pmatrix} D^0 & D^+ & D_s^+ \end{pmatrix} \qquad P^\dagger = \begin{pmatrix} D^0 \\ D^- \\ D_s^- \end{pmatrix}$$

$$\phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & K^0 & \frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

We have used two models to describe the *ND* $\quad$ *ND** coupled channel system:

> The first one of Ref. *Phys. Rev., D79:054004, 2009*, which uses arguments based on SU(4) and heavy quark spin symmetries;
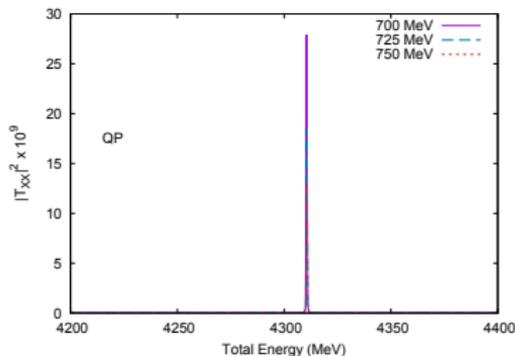
> The second one of Ref. *Eur. Phys. J., A51(2):16, 2015*, which uses arguments of *SU*(8) spin flavor symmetry

In both cases there is a dynamical generation of $\quad_c$(2595) in the *ND*, *ND** and coupled channels;
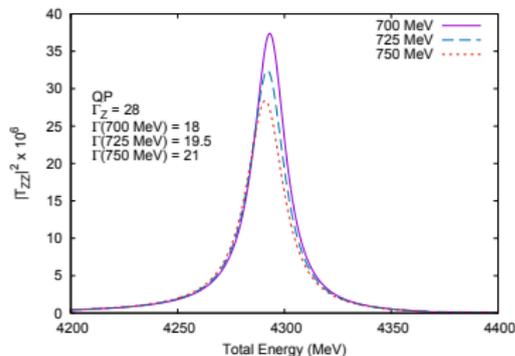
At higher energies, there are differences between the states predicted by the two models.

Figures (c) and (d) show the results for the $KX \to KX / KZ \to KZ$ with $I = 1/2$ and $J^P = 1^-$

(c) $KX \to KX$ without the transition $KX \to KZ$
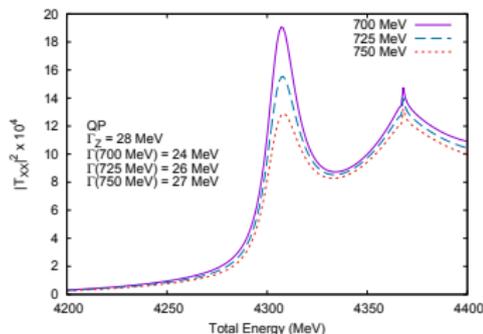

(d) $KZ \to KZ$ without the transition

These results correspond to a situation where the transition $KX \to KZ_c$ is switch off
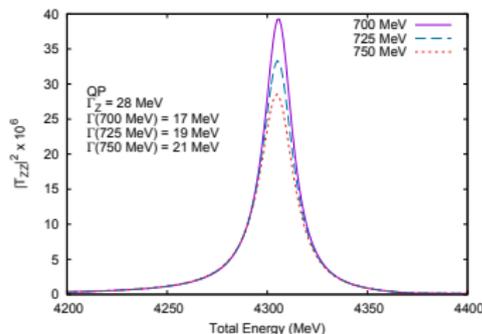
[7] Phys. Lett. B 2018.08.034 - Xiu-Lei Ren, Brenda B. Malabarba, Li-Sheng Geng, K.P.Khemchandani and A. Martínez Torres

Switching on $KX \to KZ_c$

(e) $KX \to KX$ with transiton $KX \to KZ$

(f) $KZ \to KZ$ with transition

Thus, our study shows the generation of $K^*(4307)$.

A similar result has been also found in Ref. *Chin. Phys. C43 (2019) 014012* with a different model.

A K^* state with such a molecular nature can be observed in the $KJ/\psi\pi$ invariant mass since $Z_c(3900) \to J/\psi\pi$

$$\boxed{B \to J/\psi\pi K\pi}$$

Which was used by the Belle collaboration to observe the *X*(3872) in the $J/\psi\pi\pi$ invariant mass distribution[8].

Our group has studied this decay in Ref. *Phys. Rev. D 102, 016005 (2020)*

[8] Phys. Rev., D91(5):051 101, 2015 - A. Bala et al. (Belle Collaboration)

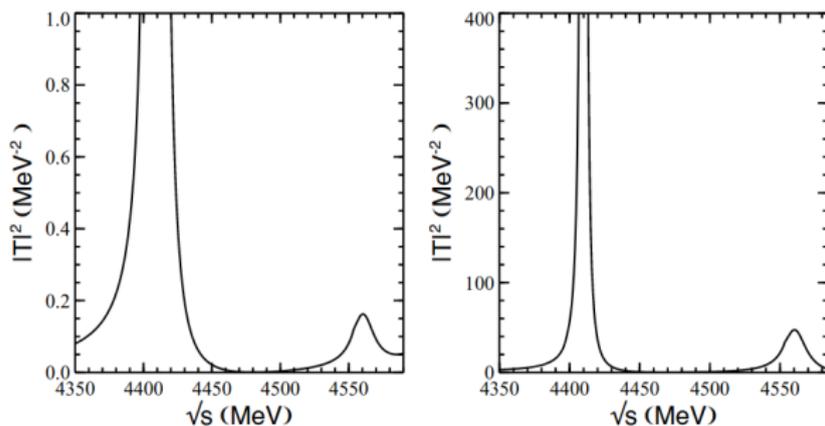SU(4) and Heavy-quark Spin Symmetries

Figure: Modulus squared of the T-matrix for the *NX* → *NX* (left) and *NZ_c* → *NZ_c*(right) transitions for $I(J^P) = 1/2(1/2^+)$ as functions of $\sqrt{s}$

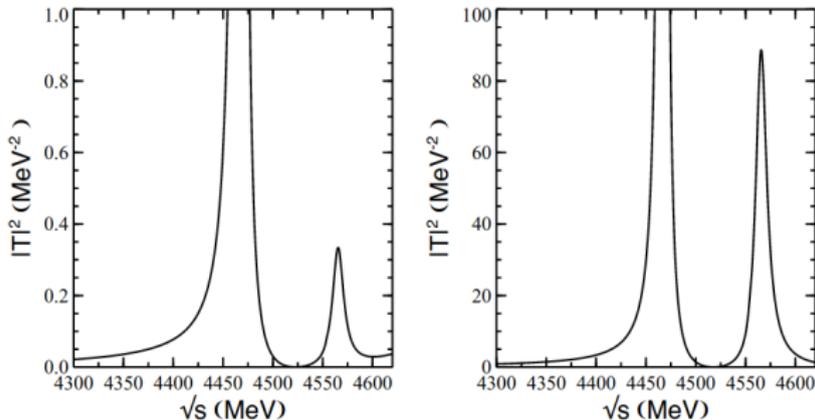Figure: Modulus squared of the T-matrix for the *NX → NX* (left) and *NZ_c → NZ_c* (right) transitions for $I(J^P) = 1/2(3/2^+)$ as functions of $\sqrt{s}$

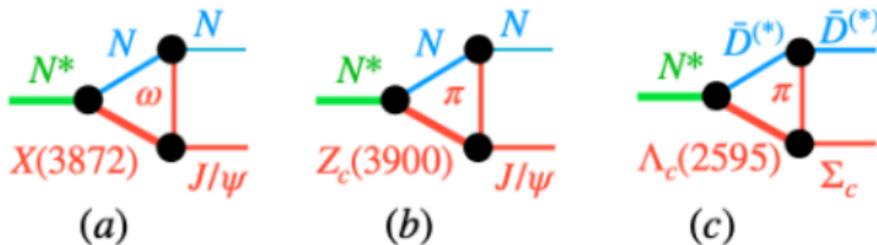| Spin-parity	Mass(MeV)	Width(MeV)
$1/2^+$	4404 - 4410	2
$1/2^+$	45556 - 4560	4 - 20
$3/2^+$	4467 - 4513	3 - 6
$3/2^+$	4558 - 4565	5 - 14

So we find degenerated N^* states with spin-parities $1/2^+$ and $3/2^+$

The *N** state can decay to channels like *NJ/ψγ*, *NJ/ψπ* and also to channels like $\pi_c D$.

The $J/\psi p$ invariant mass reconstructed in Ref. *Phys. Rev. Lett., 122(22):222001, 2019* shows fluctuations around 4400 MeV and 4550 MeV.

Our findings imply that a K^* meson around 4307 MeV should be observed in experimental investigations;

Treating DD^* as a cluster leads us to the generation of a state with molecular nature;

The result found here is a prediction for a K^* with hidden charm.

The generation of $_c$(2595) in the DN D^*N system together with the clustering of $D(D^*)$ and $D^*(D)$ as X(3872) or Z_c(3900) produces enough attraction to form isospin 1/2 states with masses around 4400-4600 MeV and positive parity;

Thank You!