DFNC - IFUSP

Kaon and Nucleon States with Hidden Charm

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Motivation

K^*

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

The $D\bar{D}^*$ interaction is also attractive and forms the states $X(3872)$ and $Z_c(3900)$;

The quantum numbers of the state formed by $KD\bar{D}^*$ 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 $m_K + M_D + M_{D^*} \approx 4370$ MeV, the last one listed by the PDG is $K(3100)$.

Motivation

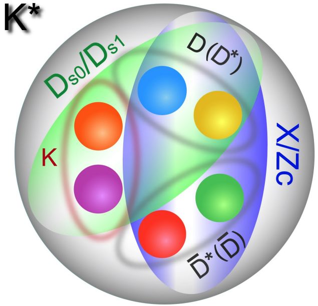
N^*

Recently, the LHCb collaboration has claimed the existence of pentaquarks with hidden charm and non-zero strangeness with masses around ~ 4500 MeV

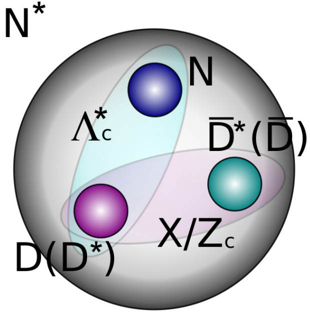
The interaction between N and D/D^* is also attractive and form, for example, the state $\Lambda_c(2595)$;

The $ND\bar{D}^*$ threshold lies around 4814 MeV and considering the strong ND interaction (binding energy $\sim$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.;



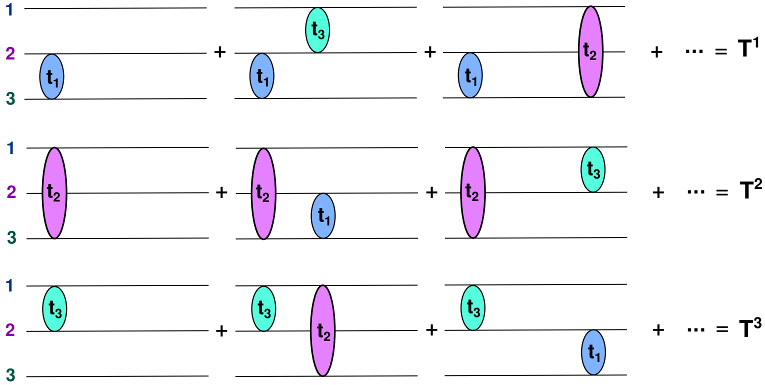
(a) K^* molecular state



(b) N^* molecular state

Three Body Interaction

It may be illustrated as



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

These diagrams can be mathematically written as the series

$$
\begin{aligned}
T^1 &= t_1 + t_1 G t_2 + t_1 G t_3 + t_1 G t_2 G t_1 + t_1 G t_2 G t_3 + \ldots \\
T^2 &= t_2 + t_2 G t_1 + t_2 G t_3 + t_2 G t_1 G t_2 + t_2 G t_1 G t_3 + \ldots \\
T^3 &= t_3 + t_3 G t_1 + t_3 G t_2 + t_3 G t_1 G t_3 + t_3 G t_1 G t_2 + \ldots
\end{aligned}
$$

that can be written as the Faddeev equations for the problem

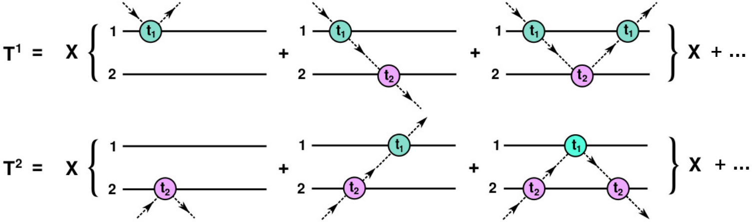
$$
\begin{aligned}
T^1 &= t_1 + t_1 G T^2 + t_1 G T^3, \\
T^2 &= t_2 + t_2 G T^1 + t_2 G T^3, \\
T^3 &= t_3 + t_3 G T^1 + t_3 G T^2,
\end{aligned}
$$

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

Fixed Center

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

- $D\bar{D}^*$ form a cluster and the 3^{rd} 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 $K\bar{D}^*(N\bar{D}^*)$ and G is the propagator in the cluster[3]

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

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

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]

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

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

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 $|KX, I=1/2, I_3=1/2\rangle$.

$$|KX\rangle = |K, 1/2, 1/2\rangle \otimes \left|D\bar{D}^*, 0, 0\right\rangle,$$

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

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

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	$\frac{1}{4}\left(3t_{KD}^{I=1} + t_{KD}^{I=0}\right)$	$\frac{\sqrt{3}}{4}\left(t_{KD}^{I=1} - t_{KD}^{I=0}\right)$
KZ	$\frac{\sqrt{3}}{4}\left(t_{KD}^{I=1} - t_{KD}^{I=0}\right)$	$\frac{1}{4}\left(t_{KD}^{I=1} + 3t_{KD}^{I=0}\right)$

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

$$t_{AB} = V_{AB} + V_{AB}G_{AB}t_{AB}, \qquad \textbf{Bethe-Salpeter} \tag{5}$$

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 $KD/K\bar{D}^*$ system, we have followed Ref. *Phys. Rev., D76:0740 16, 2007* where the amplitude V_{AB} is obtained from the following Lagrangian

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

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

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

Two Body Interactions - N^*

We have used two models to describe the $ND - ND^*$ coupled channel system:

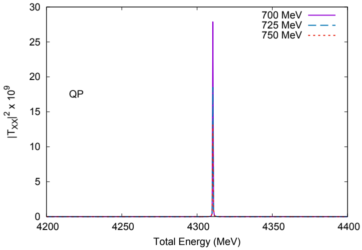
- The first one of Ref. *Phys. Rev., D79:054004, 2009*, which uses arguments based on SU(4) and heavy quark spin symmetries;
- The second one of Ref. *Eur. Phys. J., A51(2):16, 2015*, which uses arguments of $SU(8)$ spin flavor symmetry

In both cases there is a dynamical generation of $\Lambda_c(2595)$ in the ND, ND^* and coupled channels;

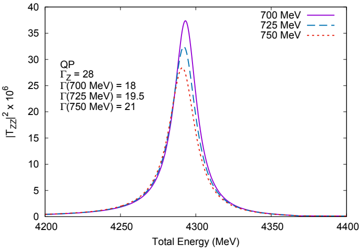
At higher energies, there are differences between the states predicted by the two models.

Results - K^* [7]

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 $KX \to KZ$

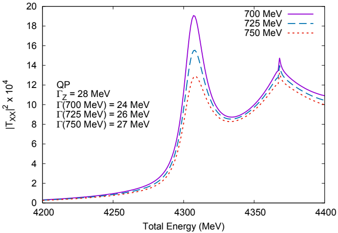


(d) $KZ \to KZ$ without the transition

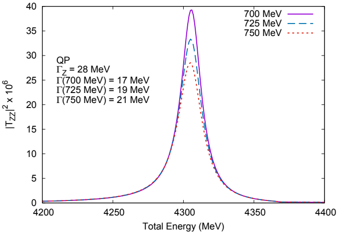
These results correspond to a situation where the transition $KX \to KZ_c$ is switch off

[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.

Observations of K^*

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

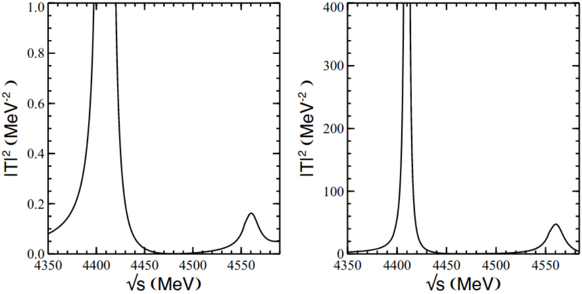


Figure: Modulus squared of the T-matrix for the $NX \to NX$ (left) and $NZ_c \to NZ_c$(right) transitions for $I(J^P) = 1/2(1/2^+)$ as functions of $\sqrt{s}$

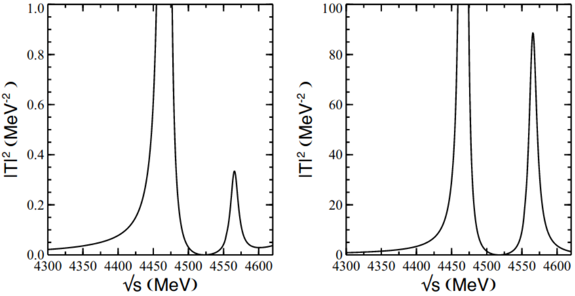


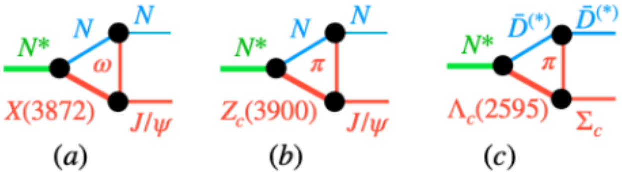
Figure: Modulus squared of the T-matrix for the $NX \to NX$ (left) and $NZ_c \to NZ_c$(right) transitions for $I(J^P) = 1/2(3/2^+)$ as functions of $\sqrt{s}$

Results - N^*

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

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

The N^* state can decay to channels like $NJ/\psi\gamma$, $NJ/\psi\pi$ and also to channels like $\pi\Sigma_c\bar{D}$.



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

Conclusions

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

Treating $D\bar{D}^*$ 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.

Conclusions

The generation of $\Lambda_c(2595)$ in the $DN - D^*N$ system together with the clustering of $D(D^*)$ and $\bar{D}^*(\bar{D})$ 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!

FAPESP

CNPq