Scalar meson in Ds decays

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Outline:
1. Introduction
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Motivation

- Observation

BESIII, PRL123, 112001 (2019),

\[ \mathcal{B}(D_{s}^{+} \to \pi^{+}\pi^{0}\eta) = (9.50 \pm 0.28 \pm 0.41) \times 10^{-2}, \]

\[ \mathcal{B}(D_{s}^{+} \to \eta(\rho^{0} \to)\pi^{+}\pi^{0}) = (7.44 \pm 0.52 \pm 0.38) \times 10^{-2}, \]

\[ \mathcal{B}(D_{s}^{+} \to \pi^{+(0)}(a_{0}^{0(+) \to})\pi^{0(+)\eta}) = (1.46 \pm 0.15 \pm 0.23) \times 10^{-2}, \]

\[ a_{0} \equiv a_{0}(980) \]

\[ M_{\pi^{+}\pi^{0}} > 1.0 \text{ GeV}/c^{2}. \]
\[ D_s^+ \rightarrow \pi^{+(0)} (a_0^{0(+) \rightarrow}) \pi^{0(+)\eta} \]

claimed as the \( W \)-annihilation process.

with the assumption that \( a_0 \) is a p-wave scalar meson.

Elimination of \( \bar{s} \) in \( D_s^+ \).

Productions of \( a_0^{+,0} \), equal sizes.
Theoretical difficulties

\[ \mathcal{B}(D_s^+ \rightarrow \pi^+ \rho^0) = (2.0 \pm 1.2) \times 10^{-4} \]

\[ \mathcal{B}(D_s^+ \rightarrow \pi^{+(0)}(a_0^{0(+) \rightarrow})\pi^{0(+)\eta}) = 1.46 \times 10^{-2} \]

\[ \mathcal{B}(D_s^+ \rightarrow \pi^+\eta) = (1.70 \pm 0.09) \times 10^{-2} \]

\[ \mathcal{B}(D_s^+ \rightarrow \pi^+f_0(980)) \sim O(10^{-2}) \]
- G-parity violation:

$\text{WA } c\bar{s} \to W^+ \to u\bar{d}$ decay

the $G$-parities of $u\bar{d}$ and $a_0\pi$, odd and even, respectively.

Cheng, Chiang, PRD81, 074021 (2010),

WA process for $D^{+}_s \to a_0\pi$ should be suppressed.
Estimation

\[ \mathcal{B}_{WA}(\eta) \equiv \mathcal{B}(D^+ \to \pi^+(0)(a_0^{0(+)} \to)\pi^0(+)+\eta) \]
\[ = \left( \frac{f_D}{f_{D_s}} \right)^2 \left( \left| \frac{V_{cd}}{|V_{cs}|} \right| \right)^2 \frac{\tau_D}{\tau_{D_s}} \left( \frac{m_{D_s}}{m_D} \right)^3 \times \mathcal{B}(D^+_s \to \pi^+(0)(a_0^{0(+)} \to)\pi^0(+)+\eta) \]
\[ = (1.2 \pm 0.2) \times 10^{-3} \]

\[ \mathcal{B}(a_0 \to \pi\eta + K\bar{K}) \simeq 100\% \text{ [pdg]}: \]
\[ \mathcal{B}_{WA}(\eta') = \mathcal{B}(D^+ \to \pi^+(0)a_0^{0(+)}+) \times \mathcal{B}(a_0^{0(+)} \to \pi^0(+)+\eta') \simeq 0 \]
\[ \mathcal{B}_{WA}(\eta) \gg \mathcal{B}_{WA}(\eta') \simeq 0 \]

(a)

(b)
• $\mathcal{B}_\rho(\eta^{(i)}) \equiv \mathcal{B}(D^+ \to \eta^{(i)} (\rho^+ \to) \pi^+ \pi^0)$

$\mathcal{B}_\rho(\eta, \eta') = (1.5 \pm 0.5, 1.2 \pm 0.1) \times 10^{-3}$

Li, Lu, Qin, Yu, PRD89, 054006 (2014);
Cheng, Chiang, PRD100, 093002 (2019).

• $\mathcal{B}(\eta^{(i)}) = \mathcal{B}_\rho(\eta^{(i)}) + \mathcal{B}_{WA}(\eta^{(i)})$

$\mathcal{B}(\eta, \eta') \equiv \mathcal{B}(D^+ \to \pi^+ \pi^0 \eta, \pi^+ \pi^0 \eta')$

$= (1.4 \pm 0.4, 1.6 \pm 0.5) \times 10^{-3}$ [pdg].

$\mathcal{B}_{WA}(\eta, \eta') = (1.2 \pm 0.2, 0) \times 10^{-3}$. 
Since you have eliminated the impossible, whatever remains, however improbable, must be the truth.

Why $a_0$ needs to be a p-wave meson? 
$a_0$, tetraquark?

- meson, baryon, tetraquark, pentaquark, hexaquark.
  unicycle (1-wheel), bicycle (2-wheel), ...

- multi-quark bound state besides $M, B$
  proposed by Murray Gell-Mann and George Zweig.
Multiquark states have been discussed since the quark model was proposed.

A $\text{SU}_3$ Model for Strong Interaction Symmetry and Its Breaking

8182/TH.401
17 January 1964

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number $\frac{1}{3}$ and is consequently fractionally charged. $\text{SU}_3$ (but not the Righthand Way) is adopted as a higher symmetry for the strong interactions. The breaking of this symmetry is assumed to be universal, being due to mass differences among the aces. Extensive space-time and group theoretic structure is then predicted for both mesons and baryons, in agreement with existing experimental information. An experimental search for the aces is suggested.

5) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\overline{AAAA}$, $\overline{AAAAA}$, etc., where $\overline{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\overline{AA}$, $\overline{AAA}$, etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\overline{A}A$ and AAA, that is, "deuces and treys".
Multiquark states have been discussed since the 1st page of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" 1-3, we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone 4). Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

\[ n_t - n_F = 0 \]

would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin \( \frac{1}{2} \) and \( z = -1 \), so that the four particles \( d^-, s^-, u^0 \) and \( b^0 \) exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon \( b \) if we assign to the triplet \( t \) the following properties: spin \( \frac{1}{2} \), \( z = -\frac{1}{3} \), and baryon number \( \frac{1}{3} \). We then refer to the members \( u^\frac{2}{3} \), \( d^{-\frac{1}{3}} \), and \( s^{-\frac{1}{3}} \) of the triplet as "quarks" 6) and the members of the anti-triplet as anti-quarks \( \bar{q} \). Baryons can now be constructed from quarks by using the combinations \( (qq) \), \( (qqqq) \), etc., while mesons are made out of \( (q\bar{q}) \), \( (qqqq) \), etc. It is assuming that the lowest baryon configuration \( (qq) \) gives just the representations 1, 8, and 10 that have been observed, while the lowest meson configuration \( (q\bar{q}) \) similarly gives just 1 and 8.
- **XYZ states: tetraquark with $c\bar{c}$**

  $X(3872)$, $c\bar{c}u\bar{u}(dd)$; $Y(4140)$, $c\bar{c}s\bar{s}$; $Z_c(4430)^+$, $c\bar{c}ud\bar{d}$.


  $\mathcal{B}(\Lambda_b \rightarrow \Lambda(X(3872)^0 \rightarrow) J/\psi \pi^+\pi^-) = (5.2 \pm 1.8) \times 10^{-6}$

  $\mathcal{B}(\Lambda_b \rightarrow \Lambda(Y(4140) \rightarrow) J/\psi \phi) = (4.7 \pm 2.6) \times 10^{-6}$

- **$X(5568)$: tetraquark with 4 flavors**

  $X(5568) \rightarrow B_s^0 \pi^\pm$

  D0 Collaboration [1602.07588, PRL117, 022003 (2016)]

  LHCb disapproved [1608.00435, PRL117, 152003 (2016)]
• tetraquark, promising

$f_0(600)$, $ud\bar{u}\bar{d}$; $f_0(980)$, $us\bar{u}\bar{s}$;

lighter than 1 GeV

PRL110, 261601 (2013), Steven Weinberg

Scalar mesons below 1 GeV

• Controversial identifications

$a_0^+, a_0^0, f_0(980)$

p-wave $(ud)$, $(u\bar{u} - d\bar{d})/\sqrt{2}$, $s\bar{s}$

compact $s\bar{s}(ud)$, $s\bar{s}(u\bar{u} - d\bar{d})/\sqrt{2}$,

$s\bar{s}(u\bar{u} + d\bar{d})/\sqrt{2}$ tetraquarks
Scalar mesons above 1 GeV

- $f_0(1710)$, $f_0(1500)$, $f_0(1370)$

mix with $n\bar{n} = (u\bar{u} + d\bar{d})/\sqrt{2}$, $s\bar{s}$, and $g\bar{g}$

leading to $3 \times 3$ mixing matrix

X.G. He et al., PRD73, 051502 (2006)

$M_{n\bar{n}} < M_{s\bar{s}} < M_{g\bar{g}}$

$M_{n\bar{n}} < M_{g\bar{g}} < M_{s\bar{s}}$

Vincent Mathieu
Short-distance effects?

- $f_0 - a_0$ mixing  
  Wei Wang, PLB759, 501 (2016)
- not for $a_0^+$
- constraint from $D_s^+ \rightarrow a_0^0 e^+ \nu_e$
Long-distance effects?

\[ \bullet \phi \rightarrow a_0 \gamma \]

PHYSICAL REVIEW D 73, 054017 (2006)

Chiral approach to phi radiative decays

Deirdre Black, 1,* Masayasu Harada, 2,† and Joseph Schechter 3,‡
\[ \mathcal{B}(D^+_s \to \eta \rho^+) = (8.9 \pm 0.8)\% \]
\[
\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cs} V_{ud} \left[ c_1 (\bar{u}d)(\bar{s}c) + c_2 (\bar{s}d)(\bar{u}c) \right]
\]
\[
\mathcal{A}(D_s^+ \to \eta \rho^+) = \frac{G_F}{\sqrt{2}} V_{cs} V_{ud} a_1 \langle \rho^+ | (\bar{u}d) | 0 \rangle \langle \eta | (\bar{s}c) | D_s^+ \rangle
\]
\[
\langle \eta | (\bar{s}c) | D_s^+ \rangle = (p_{D_s} + p_{\eta})_\mu F_+(t) + q_\mu F_-(t)
\]
\[
\langle \rho^+ | (\bar{u}d) | 0 \rangle = m_\rho f_\rho \epsilon^*_\mu
\]
\[
F(t) = \frac{F(0)}{1 - a(t/m_{D_s}^2) + b(t^2/m_{D_s}^4)}
\]
\[
a_1 = 1.02 \pm 0.05 \quad \bullet \mathcal{B}(D_s^+ \to \eta \rho^+) = (8.9 \pm 0.8)\%
\]
\[
\mathcal{A}(a_0 \to \eta \pi) = g_{a_0 \eta \pi}
\]
\[
\mathcal{A} (\rho^+ \to \pi^+ \pi^0) = g_{\rho \pi \pi} \epsilon \cdot (p_{\pi^+} - p_{\pi^0})
\]
\[
\mathcal{A}_{a+b} \equiv \mathcal{A}(D_s^+ \rightarrow \pi^+(a_0^0 \rightarrow \pi^0)\eta + \pi^0(a_0^+ \rightarrow \pi^+\eta) = \mathcal{A}_a + \mathcal{A}_b,
\]

\[
\mathcal{A}_a \equiv \mathcal{A}(D_s^+ \rightarrow \pi^+(a_0^0 \rightarrow \pi^0\eta) = \frac{1}{m_{12}^2 - m_{a_0^0}^2 + im_{a_0^0}\Gamma_{a_0^0}}
\]

\[
\times i \int \frac{d^4q_3}{(2\pi)^4} \frac{\hat{\mathcal{A}}_a}{(q_1^2 - m_{\rho^+}^2 + i\epsilon)(q_2^2 - m_\eta^2 + i\epsilon)(q_3^2 - m_{\pi^0}^2)}F_a^2(q_3^2),
\]

\[
\mathcal{A}_b \equiv \mathcal{A}(D_s^+ \rightarrow \pi^0(a_0^+ \rightarrow \pi^+\eta) = \frac{1}{m_{23}^2 - m_{a_0^+}^2 + im_{a_0^+}\Gamma_{a_0^+}}
\]

\[
\times i \int \frac{d^4q_3}{(2\pi)^4} \frac{\hat{\mathcal{A}}_b}{(q_1^2 - m_{\rho^+}^2 + i\epsilon)(q_2^2 - m_\eta^2 + i\epsilon)(q_3^2 - m_{\pi^0}^2)}F_b^2(q_3^2),
\]

\[
\hat{\mathcal{A}}_{a(b)} = \mathcal{A}(D_s^+ \rightarrow \eta\rho^+)\mathcal{A}(\eta\pi^0(+) \rightarrow a_0^{0(+)}\pi^0(+)\mathcal{A}(\rho^+ \rightarrow \pi^+0)\pi^0(+)\mathcal{A}(a_0^{0(+)} \rightarrow \eta\pi^0(+))
\]

\[
F_{a(b)}(q_3^2) = \frac{m_{\pi^0(+)}^2 - \Lambda^2}{q_3^2 - \Lambda^2}, \quad \Lambda = (1.6 \pm 0.2) \text{ GeV}
\]

\[ \mathcal{B}(D_s^+ \to a_0^{0(+)\pi^{+}(0)}) = (1.7 \pm 0.4) \times 10^{-2}, \]
\[ \mathcal{B}(D_s^+ \to \pi^{+}(0)(a_0^{0(+)\rightarrow})\pi^{0(+)}\eta) = (1.5 \pm 0.3) \times 10^{-2}, \]
\[ \mathcal{B}(D_s^+ \to \pi^{+}(0)(a_0^{0(+)\rightarrow})\pi^{0(+)\eta}) = (1.46 \pm 0.15 \pm 0.23) \times 10^{-2} \]

- \( D_s^+ \to \pi^+(a_0^0 \to)\pi^0\eta \) and \( D_s^+ \to \pi^0(a_0^+ \to)\pi^+\eta \)

large interference with a relative phase of \( 180^\circ \)

\[ \rho^+(q_4) \to \pi^0(q_3)\pi^+(q_4 - q_3), \rho^+(q_4) \to \pi^+(q_3)\pi^0(q_4 - q_3) \]

\[ \mathcal{A}_a(\rho^+ \to \pi^+\pi^0) = -\mathcal{A}_b(\rho^+ \to \pi^0\pi^+) \]

30% cancellation to the total branching ratio.
● Revision
check the cusp mechanism from $f_0 - a_0$ mixing
add the decay width of $\rho$ in the triangle loop
remove the sensitivity of the cut-off

● Distinguishing scalar meson in the $D_s^+$ decays
Without quark annihilation,
$a_0$ is formed with four quarks.
tetraquark state?

PHYSICAL REVIEW D 82, 034016 (2010)
Distinguishing two kinds of scalar mesons from heavy meson decays
Wein Wang$^{1,2,*}$ and Cai-Dian Lü$^{1,†}$

Use of $B \to J/\psi f_0$ Decays to Discern the $q\bar{q}$ or Tetraquark Nature of Scalar Mesons
Sheldon Stone and Liming Zhang
Summary

- With the triangle rescattering, we have been able to explain

\[ \mathcal{B}(D_s^+ \rightarrow \pi^+(a_0^0 \rightarrow)\pi^0\eta, \pi^0(a_0^+ \rightarrow)\pi^+\eta). \]

- There exists one scenario for \( a_0 \) in association with \( s\bar{s} \) and \( q\bar{q} \) both, which provides a possibility that \( a_0 \) can be a tetraquark.

This makes the observation by BESIII important.
Thank You