Tetraquarks

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Mesons build from two quarks and two antiquarks

$$T = [q_1 q_2][\bar{q}_3 \bar{q}_4]$$

Experimentally known candidates:

- $a_0(980)$ — $[qs][\bar{q}\bar{s}]$?
- $X(3872)$ *etc.* — $[qc][\bar{q}\bar{c}]$?
- $Z_b(10610)$, $Z_b(10650)$ — $[qb][\bar{q}\bar{b}]$?

Could there be tetraquarks build from four heavy quarks?

$$[QQ][\bar{Q}\bar{Q}]$$

General properties

- Do not fit into usual quarkonia scheme

$$X(3872) \to J/\psi\rho, \quad X(3872) \to J/\psi\omega$$

- Lie near threshold of double production of usual mesons

$$M[Z_b(10650)] - M[\Upsilon(4S)] = 71 \text{ MeV}$$

- Decay mainly into these mesons

$$X(3872) \to J/\psi\omega, \qquad Z_b(10650) \to \Upsilon(2S)\pi$$

- Small widths

$$\Gamma[X(3872)] \approx 2.3 \text{ MeV}$$

Spectroscopy

Diquark model

Bound state of two almost pointlike diquarks

Color structure

$$(Q_1 Q_2 \bar{Q}_3 \bar{Q}_4) = [Q_1 Q_2]_{\bar{3}_c} [\bar{Q}_3 \bar{Q}_4]_{3_c} + [Q_1 Q_2]_{6_c} [\bar{Q}_3 \bar{Q}_4]_{6_c}$$

- $6_c \otimes 6_c$ — *repulsive*,
- $3_c \otimes \bar{3}_c$ — attractive

Schroedinger equations

$$\left[-\frac{1}{2m_Q}\nabla^2 + \frac{1}{2}V(r) \right] \Psi_{\mathrm{diq}}(r) = \delta E_{\mathrm{diq}} \Psi_{\mathrm{diq}}(r)$$

$$\left[-\frac{1}{2m_{\mathrm{diq}}}\nabla^2 + V(r) \right] \Psi_T(r) = \delta E_T \Psi_T(r)$$

Tetraquark states can be characterized by total and diquark spins

$$|J; S_{12}, S_{34}\rangle$$

or total spin and P-, C-parities

$$|J^{PC}\rangle$$

$$\left|0^{++}\right\rangle = |0;0,0\rangle\,, \qquad \left|0^{++'}\right\rangle = |0;1,1\rangle\,,$$

$$\left|1^{+\pm}\right\rangle = \frac{1}{\sqrt{2}}\left(|1;0,1\rangle \pm |1;1,0\rangle\right), \qquad \left|1^{+-'}\right\rangle = |1;1,1\rangle\,,$$

$$\left|2^{++}\right\rangle = |2;1,1\rangle$$

After spin-spin interation theses states mix with each other

Splitting

Spin-spin interaction hamiltoinan

$$H = M_0 + 2\sum_{i<j} \kappa_{ij}(\mathbf{S}_i \mathbf{S}_j)$$

κ_{ij} can be determined from wave function $R(0)$

- $[QQ]$

$$\kappa_{ij} = \frac{2\alpha_s}{9m_Q m_Q}|R_{[QQ]}(0)|^2$$

  $R_{[QQ]}(0)$ from Schroedinger equation

- $(Q = barQ)$

$$\kappa_{ij} = \frac{4\alpha_s}{9m_Q m_Q}|R_{[QQ]}(0)|^2$$

  $R_{[QQ]}(0)$ from $\Gamma(V \to ee)$ or $M_V - M_P$

T_{4Q}

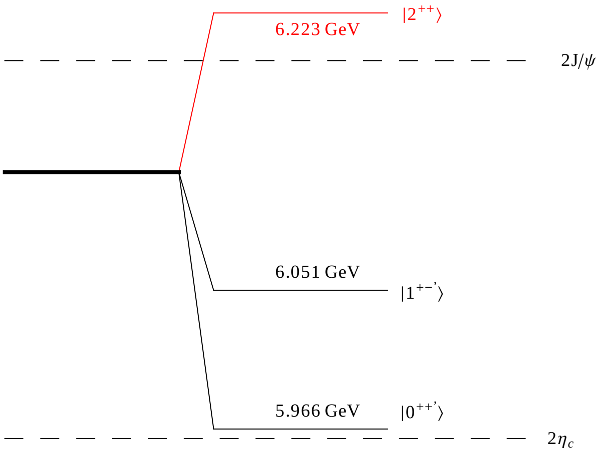
In the case of identical quarks only $S_{\mathrm{diq}} = 1$ is possible

$$
\begin{aligned}
M\left(0^{++'}\right) &= M_0 + \kappa_{12} - 2\kappa_+, \\
M\left(1^{+-'}\right) &= M_0 + \kappa_{12} - \kappa_+, \\
M\left(2^{++}\right) &= M_0 + \kappa_{12} + \kappa_+.
\end{aligned}
$$

where

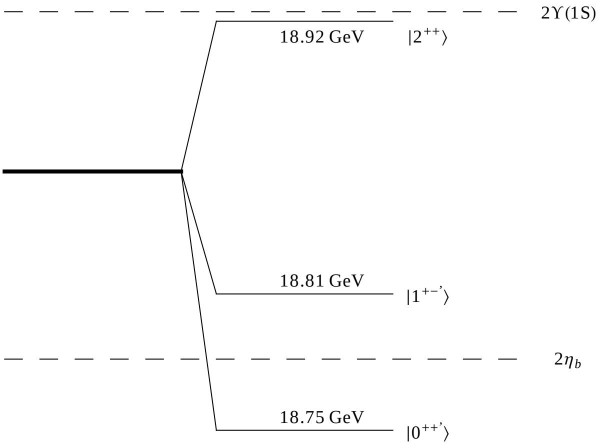
$$\kappa_+ = 2\kappa_{(Q\bar{Q})}$$

T_{4c}



Only tensor state lies above $2J/\psi$ production threshold

T_{4b}



All states are below 2Υ threshold

1^{++}, 2^{++}

$$M\left(1^{++}\right) = M_0 - \kappa_{12} - \kappa_-, \quad M\left(2^{++}\right) = M_0 + \kappa_{12} + \kappa_+$$

0^{++}

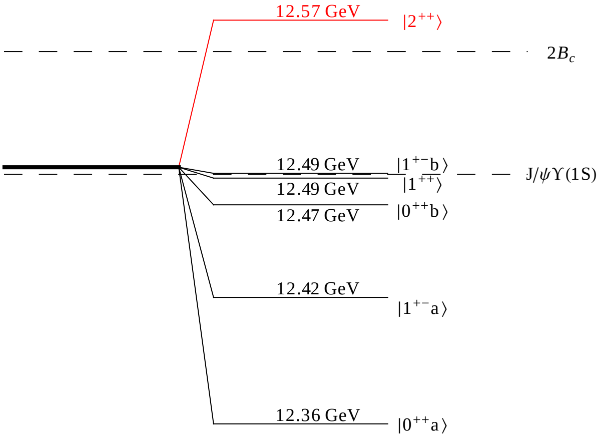
$$H \left[\begin{array}{c} |0^{++}\rangle \\ |0^{++\prime}\rangle \end{array} \right] = \left[\begin{array}{cc} M_0 - 3\kappa_{12} & -\sqrt{3}\kappa_- \\ -\sqrt{3}\kappa_- & M_0 + \kappa_{12} - 2\kappa_+ \end{array} \right] \left[\begin{array}{c} |0^{++}\rangle \\ |0^{++\prime}\rangle \end{array} \right],$$

1^{+-}

$$H \left[\begin{array}{c} |1^{+-}\rangle \\ |1^{+-\prime}\rangle \end{array} \right] = \left[\begin{array}{cc} M_0 - \kappa_{12} + \kappa_- & \kappa_{13} - \kappa_{24} \\ \kappa_{13} - \kappa_{24} & M_0 + \kappa_{12} - \kappa_+ \end{array} \right] \left[\begin{array}{c} |1^{+-}\rangle \\ |1^{+-\prime}\rangle \end{array} \right].$$

$$\kappa_\pm = \kappa_{(b\bar{c})} \pm \left(\kappa_{(b\bar{b})} + \kappa_{(c\bar{c})}\right)/2$$

$T_{2[bc]}$



Only tensor state lies above $J/\psi\Upsilon$ and $2B_c$ thresholds

Production

General remarks

$$gg \to 2\mathrm{diq}$$

Below $2\Xi_{QQ}$ production threshold diquarks can hadronize into

- light mesons, 4 heavy mesons
- 2 quarkonia
- Tetraquark (with subsequent decay into 2 quarkonia)

Duality relation

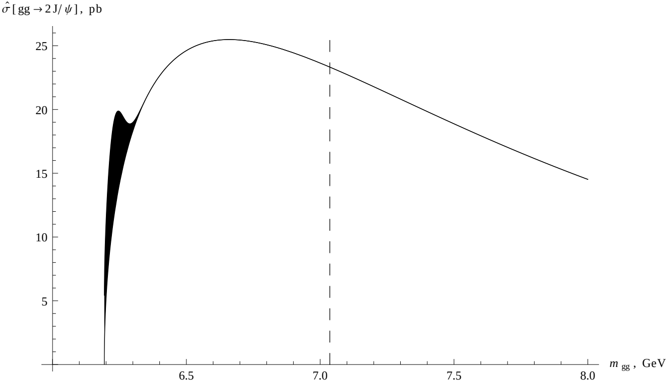
$$S_T = \int_{2M_{\mathcal{Q}}}^{2M_{\Xi_{QQ}}} dm_{gg}\hat{\sigma}[gg \to T \to 2\mathcal{Q}] = \epsilon \int_{2m_{[QQ]}}^{2M_{\Xi_{QQ}}} dm_{gg}\hat{\sigma}(gg \to 2\mathrm{diq})$$

$$\epsilon < 1$$

$$\hat{\sigma}(gg \to T_{4c} \to 2\mathcal{Q}) = \frac{S_T}{\sqrt{\pi}\Delta} \exp\left\{-\frac{(m_{gg} - M_{T_{4c}})^2}{\Delta^2}\right\},$$

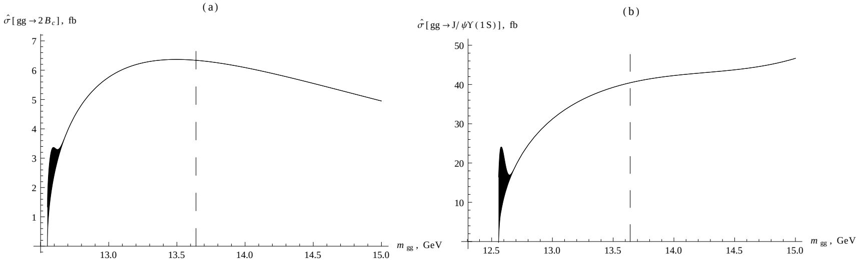
$gg \to T_{4Q} \to 2V$

For T_{4c} only $|2^{++}\rangle$ is above $2J/\psi$ production theshold



For T_{4b} all tetraquarks are below $2\Upsilon(1S)$ threshold

$gg \to T_{2[bc]} \to 2\mathcal{Q}$



Conclusion

- Spectroscopy of $T_{4c} = [cc][\bar{c}\bar{c}]$, $T_{4b} = [bb][\bar{b}\bar{b}]$ and $T_{2[bc]} = [bc][\bar{b}\bar{c}]$ is considered
- Tensor T_{4c} can be observed in $2J/\psi$ mass distribution
- Tensor T_{4b} lies below 2Υ threshold
- Tensor $T_{2[bc]}$ can be observed in $2B_c$ or $J/\psi\Upsilon$ distributions

Thank You for Your attention