X(3872)

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Introduction

Several models for the X(3872)

- friendly but critical survey of models,
- a simple chromomagnetic model seemingly explains small width and bluedecay patterns,
- tentative extrapolation to other configurations
- Work in collaboration with H. Høgaasen (Oslo), P. Sorba (Annecy) and F. Buccella (Napoli)
X(3872), Exp. results, B decay

Belle (KEK) $X(3.872)$ CDF (Fermilab)

Accidental agreement? $X = c\bar{c}$ (2$^{-+}$ or 2$^{--}$ or ...), or a molecular (multiquark) state?

$M = 3872.0 \pm 0.6 \pm 0.5$ MeV

$M( D^0 + D^{*0}) = 3871.5 \pm 0.5$ MeV

n.b. $M( D^+ + D^{*-}) = 3879.5 \pm 0.7$ MeV
X(3872), Exp. results, cont., BaBar
$X(3872)$, exp., cont., $D0$
X(3872) not seen in $\gamma\gamma$ and in ISR

(from K. Seth's recent review)

At CLEO [15] we have analyzed $\sim 15$ fb$^{-1}$ of $e^+e^-$ collision data taken in the bottomonium region for possible production of X(3872) in two–photon fusion and ISR, and have established the following 90% confidence limits:

- Two–photon fusion ($J^{PC}(X) = J^{P+}$): $(2J + 1)\Gamma(X \rightarrow e^+e^-) < 0.65$ eV,
- ISR ($J^{PC}(X) = 1^{--}$): $\mathcal{B}(X \rightarrow \pi^+\pi^- J/\psi) \times \Gamma(X \rightarrow e^+e^-) < 8.3$ eV.

- See, also, Babar.
- Hence $J^{PC} = 1^{--}$ excluded, as well as many $C = +$. But $1^+$ permitted, as not coupled to $\gamma\gamma$ (Landau, Lee & Yang).
X(3872) summary

- $M = 3871.7 \pm 0.6$ MeV
- $m(D^0) + m(D^0_0\bar{)} = 3871.3 \pm 1.0$ MeV
- $\Gamma < 2.3$ MeV
- $J^{PC} = 1^{++}$ favoured, $I = 0$ also favoured

1) SEARCH FOR A CHARGED PARTNER OF THE X(3872) IN THE B MESON DECAY $B \rightarrow X^0 - K$, $X^0 \rightarrow J/\psi + K^*$, $X^0 \rightarrow J/\psi + \pi^0$, $X^0 \rightarrow J/\psi + \pi^+\pi^-$

Published in Phys.Rev.D71:031501,2005
e-Print Archive: hep-ex/0412051

- Decays seen
  - $X \rightarrow J/\psi + \gamma$
  - $X \rightarrow J/\psi + \omega$
  - $X \rightarrow J/\psi + \pi^+\pi^-$

Evidence for $X(3872) \rightarrow\gamma$ $J/\psi$ and the sub-threshold decay $X(3872) \rightarrow\omega$ $J/\psi$

Authors: K. Abe et al. (Belle Collaboration)
Report–no: BELLE–CONF–0540
Early speculation by Gilles and Tye (1978), Mandula and Horn (1978), and Hasenfratz, Horgan, Kuti and R. (1980)

The gluon, being coloured, is not only the vector of the interaction, it can also play a constituent role.
Models for X and Y
Hybrids of heavy quarkonia

- The gluon, being coloured, is not only the vector of the interaction, it can also play a constituent role.
- **Ordinary quarkonium**: governed by $V_{Q\bar{Q}}$, a kind of Born–Oppenheimer potential with the gluon field in its ground-state
- **Hybrid quarkonium**: Next Born–Opppenheimer potential, with gluon field excited.
- **Further predictions** Flux-tube models, lattice QCD, etc., usually give masses a little higher, and indicate some signatures in the decay pattern (Pene et al.)
Models for X and Y
Hybrids of heavy quarkonia

\[
\begin{align*}
V(r) & \quad (\text{GeV}) \\
\alpha = 0.385 \\
\Lambda_B = 235 \text{MeV} \\
m_c = 1.35 \text{GeV} \\
m_b = 4.75 \text{GeV}
\end{align*}
\]
Models for X and Y

Hybrids 1980 predictions

\[ c\bar{c}g \sim 4 \text{ GeV} \quad \text{and} \quad b\bar{b}g \sim 10.4 \text{ GeV} \]

Mass and some properties of X(3940) makes it a possible candidate for hybrid.
Mesons molecules

- Yukawa interaction acts between all hadrons, provided they contain light quarks.
- In particular, it was predicted that a strong attraction is induced by pion exchange in

\[ D \bar{D}^* + \text{c.c.} \]
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- In particular, it was predicted that a strong attraction is induced by pion exchange in
  \[ \bar{D}D^* + \text{c.c.} \]
- See Voloshin et al., Törnqvist, Manohar, Swanson, Braaten, Barnes et al., Close et al., Riska & Julia-Diaz, etc.
- NN potential read as a convolution of \( qq \) potentials, thus the long-range hadron–hadron potential can be estimated.
- \( D\bar{D}^* + \text{c.c.} \) potential weaker than the NN one, but experienced by heavier particles, hence binding can be envisaged.
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- \( \bar{D}D^* + \text{c.c.} \) potential weaker than the NN one, but experienced by heavier particles, hence binding can be envisaged.
- Hence when the \( X(3872) \) was discovered just at the \( D^0\bar{D}^{0,*} \) threshold, it was considered as a good candidate.
Mesons molecules

But

- a previous attempt to identify molecules in the hidden-charm spectrum

Hydronic molecules and the charmion atom

M. B. Voloshin and L. B. Okun'
Institute of Theoretical and Experimental Physics

We consider the possible existence of levels in a system consisting of a charmed particle and a charmed antiparticle; these levels result from exchange of ordinary mesons ($\omega, \rho, \phi$, etc.). An interpretation of the resonances in $e^+e^-$ annihilation in the region 3.9–4.8 GeV is proposed.

Molecular Charmonium: A New Spectroscopy?

A. De Rújula, Howard Georgi*, and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

Received 23 November 1976

Recent data compel us to interpret several peaks in the cross section of $e^+e^-$ annihilation into hadrons as being due to the production of four-quark molecules, i.e., resonances between two charmed mesons. A rich spectroscopy of such states is predicted and may be studied in $e^+e^-$ annihilation.
Mesons molecules

\[ g^2(DD) = \sigma(D\bar{D})(1 - 4m_D^2/s)^{-3/2}, \]
\[ 4g^2(DD^*) = \sigma(D\bar{D}^* + D^*\bar{D})(1 - (m_D + m_{D^*})^2/s)^{-3/2}, \]
\[ 7g^2(D^*D^*) = \sigma(\bar{D}^*D^*)(1 - 4m_{D^*}^2/s)^{-3/2}, \]

where \( p \)-wave phase-space factors as well as the spin-counting factors 1:4:7 have been included.\(^5\)

Data at \( \sqrt{s} = 4.028 \) GeV yield \( g^2(DD) : g^2(DD^*) : g^2(D^*D^*) \sim 1:5:100. \) The anomalously strong coupling to \( D^*\bar{D}^* \) may seem inexplicable until we recall that the energy 4.028 GeV was chosen because the cross section peaks there. What is seen at this special energy is evidently the decay of a resonance. The large coupling strength to \( D^*\bar{D}^* \) indicates that this resonance is essentially made up of a \( D^* \) and \( \bar{D}^* \). We envisage that the 4.028 GeV state can be regarded as a short-lived
Mesons molecules

- failed. The preferential decay of $\psi(4.04)$ into $D\overline{D}^* + \text{c.c.}$, as compared to $D\overline{D}$ and $D^*\overline{D}^*$, the suppressed decay of $\psi(4.4)$, come from their nodal structure.

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2) STRONG DECAYS OF PSI-PRIME-PRIME (4.028) AS A RADIAL EXCITATION OF CHARMONIUM.
By A. Le Yaouanc, L. Oliver, O. Pene, J.-C. Raynal (Orsay, LPT)., LPTHE 77/25, Jun 1977. 9pp.
Published in *Phys.Lett.B71:397,1977*

1) WHY IS PSI-PRIME-PRIME-PRIME (4.414) SO NARROW?
Published in *Phys.Lett.B72:57,1977*

3) CHARMONIUM: COMPARISON WITH EXPERIMENT.
Published in *Phys.Rev.D21:203,1980*
Mesons molecules
Mesons molecules

- in $D\bar{D}^* \rightarrow D^*\bar{D}$, there is a transfer of energy. Non local potential, with reduced range, less effective for binding (Suzuki).
- no evidence for hard core to prevent from dominance of short-range forces
- some extension of meson–meson molecules even more speculative, e.g., $J/\psi - \omega$! apart from coming back to the bootstrap theory of strong interaction
Mesons molecules

A detailed study by Swanson indicates
- Pion exchange good enough to bind $B\bar{B}^* + c.c.$
- Too weak for $D\bar{D}^* + c.c.$
- Supplemented by $D\bar{D}^* \leftrightarrow J/\psi + \omega$, surprisingly large.

![Graph showing wavefunction components and component strength vs. binding energy.](image)
Diquark–antidiquark
Cara semplicità, quanto mi piaci!

- Picture promoted by several authors, in particular Maiani et al.
- Describe X and Y as \((cq) - (\bar{c}\bar{q})\) and \((cs) - (\bar{c}\bar{s})\).

**Four quark interpretation of \(Y(4260)\)**

We propose that the \(Y(4260)\) particle recently announced by *BABAR* is the first orbital excitation of a diquark-antidiquark state \([cs][\bar{c}\bar{s}]\). Using parameters recently determined to describe the \(X(3872)\) and \(X(3940)\) we show that the \(Y\) mass is compatible with the orbital excitation picture. A crucial prediction is that \(Y(4260)\) should decay predominantly in \(D_s\bar{D}_s\). The \(Y(4260)\) should also be seen in \(B\) nonleptonic decays in association with one kaon. We consider the full nonet of related four-quark states and their predicted properties. Finally, we comment on a possible narrow resonance in the same channel.
Diquark–antidiquark
Cont.

But

- clustering not demonstrated, unlike that of orbitally excited baryons.
- diquark mass arbitrary and chosen somewhat low
- $(cs)(cs)(cs)$ looks bound with respect to $(ccc) + (sss)$, but the authors do not worry much.
- same type of diquarks, or triquarks, led to unconfirmed dibaryons, baryonia and pentaquarks.
- the very small width of $X(3872)$ does not come naturally
QCD Sum Rules

- Work in progress, by S. Narison (Montpellier), Marina Nielsen and R. Matheus (Sao Paulo) and J.M.R.
- $X(3872)$ comes rather well with an operator inspired by the diquark–antiquark picture,
- Operators inspired by the chromomagnetic models have higher dimension and thus hardly change much the results
- narrow width remains puzzling
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narrow width remains puzzling
In QED, the $-\alpha/r$ comes from one photon exchange, in the NR limit.

Spin corrections are expressed by the Breit–Fermi terms, to be treated at first order:

$$V_{ss} = \frac{\alpha}{12m_1m_2} \delta^{(3)}(\vec{r}) \vec{\sigma}_1 \cdot \vec{\sigma}_2 + \text{terms for } \ell \geq 1$$

pushing, e.g., orthohydrogen above parahydrogen,

in 1975, DGG + Bag model + Zhakarov, Lipkin, Isgur, Karl, etc.
Chromomagnetic interaction: applications

- In short, for S-waves,

\[ H_{SS} = - \sum_{i<j} C_{ij} \vec{\sigma}_i \cdot \vec{\sigma}_j \tilde{\lambda}_i \cdot \tilde{\lambda}_j, \]

called spin-colour or chromomagnetic Hamiltonian, where the strength factors contain the gluon coupling, the inverse (effective) quark masses and the short range correlations.

- a convincing phenomenology has been developed for ordinary hadrons on this Hamiltonian and the \( \ell \geq 1 \) terms not written here: Le Yaouanc et al., Isgur and Karl,
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- an important progress by Jaffe in 1977, demonstrating that in the limit where \( C_{ij} = C \) factors out, a striking coherence is observed

\[ \langle H_{SS}(uuddss) \rangle \leq 2 \langle H_{SS}(uds) \rangle , \]

suggesting a stable \( H = (uuddss) \) about 150 MeV below its dissociation threshold into two \( \Lambda(uds) \).
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suggesting a \textbf{stable} \( H = (uuddss) \) about 150 MeV below its dissociation threshold into two \( \Lambda(uds) \).

Leading to an intense experimental activity (search for the H and its analogues)
Chromomagnetic interaction: applications

As well as an intense theoretical activity to analyse in specific models, the strong competition between $H$ and $(\Lambda - \Lambda)$, when all terms and all possible refinements of the Hamiltonian are included. See, e.g., Yazaki et al., Fleck, Gignoux, R., Silvestre-Brac, Phys.Lett.B220 (1989) 616, and many others.
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23) QUARK CLUSTER MODEL AND CONFINEMENT.

3) H PARTICLE STABILITY IN THE NONRELATIVISTIC QUARK MODEL.
Chromomagnetic interaction: applications

and to predict other favourable configurations

- baryonium, Chan H.M., Høgaasen,
- meso-baryon, De Swart, Sorba,
- dibaryons Aerts et al.
- **Heavy pentaquark** (1987-vintage) Gignoux et al., Lipkin

\[
(\bar{Q}qqqq) < (\bar{Q}q) + (qqq) ?
\]

- Thorough survey by Silvestre-Brac and Leandri, Lichtenberg et al., etc.
Application to the X(3872)

1) A CHROMOMAGNETIC MECHANISM FOR THE X(3872) RESONANCE.
By H. Hogaasen (Oslo U.), J.M. Richard (LPSC, Grenoble), P. Sorba (Annecy, LAPTH).
e-Print Archive: hep-ph/0511039

- Assume

\[ H_{SS} = - \sum_{i<j} C_{ij} \bar{\sigma}_i \cdot \bar{\sigma}_j \bar{\lambda}_i \cdot \bar{\lambda}_j , \]

- to be the leading mechanism for \((c\bar{q}c\bar{u})\).
- Adjust \(C_{ij}\) from known hadrons.
- Diagonalise this Hamiltonian.
Application to the X(3872)

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- Assume

\[ H_{SS} = - \sum_{i<j} C_{ij} \vec{\sigma}_i . \vec{\sigma}_j \tilde{\lambda}_i . \tilde{\lambda}_j , \]

to be the leading mechanism for \((cq\bar{c}\bar{u})\).
- Adjust \(C_{ij}\) from known hadrons.
- Diagonalise this Hamiltonian.
- good surprise A state comes with \(J^{PC} = 1^{++}\) with a mass near \(M \simeq m(D) + m(D^*)\),
- in the limit \(C(cq) = C(\bar{c}q)\), \exists eigenstate that is a pure colour
octet–octet \([c\bar{c}]_8[q\bar{q}]_8\), which hence cannot dissociate into \((c\bar{c})\)
and \((q\bar{q})\)
- The cross colour channel, \([c\bar{q}][q\bar{c}]\) contains of course a copious
singlet–singlet component, but is is entirely pseudoscalar–vector
and hence the corresponding decay is suppressed by phase-space.
Application to the X(3872)

- If $C(cq) \neq C(\bar{c}q)$, a small $[c\bar{c}]_1[q\bar{q}]_1$ singlet–singlet component appears, but restricted to \textit{vector–vector}, i.e., $J/\psi + \omega$.
- Due to isospin mixing ($m_u \neq m_d$), coupling to decay channels) a smaller $J/\psi + \rho^0$ also occurs, which, however, dominates the decay due to more favourable phase-space.
- This corresponds to the observed $J/\psi \pi^+\pi^-$ decay mode, and to the small width.
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- this corresponds to the observed $J/\psi \pi^+\pi^-$ decay mode, and to the small width.
- the second neutral (dominantly $I = 1$) and the charged partners, slightly higher but much broader are to be found.
- the charged $X^\pm$ probably suppressed in B decay, hence might be found better at collider than B factories
Other multiquarks?

- Not too many! Most of them very broad, as they dissociate into two colour singlets,
- $(b\bar{b}q\bar{q})$ analogue of $X(3872)$ expected,
- Favourable chromomagnetic effects in $(bc\bar{u}\bar{d})$,
- Large multiquark components in light scalar mesons.
Several interesting candidates for new type of hadrons in recent months

Most reliable, by far, in the heavy-quark sector.

Beware of cuts in the forward hemisphere and kinematical reflections
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Beware of cuts in the forward hemisphere and kinematical reflections.
Outlook, experimental aspects

- Charmonium family rather diverse
- Radial and orbital and spin degrees of freedom now identified
- Exotics also present

\[ X(3872) \]
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Outlook, theory aspects

- at least some X’s and Y’s well described as hybrids and multiquarks,
- no model yet got overall agreement
- colour gives a very rich dynamics
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