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The new hadrons: Molecules or tetraquarks?

C. Sabelli

Dipartimento di Fisica, Università di Roma "La Sapienza" - Piazzale A. Moro 2
I-00185 Rome, Italy

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Summary. — We briefly discuss some new hints about $X(3872)$ and $Y(4660)$, which can help to unravel the pros and cons of the molecular and tetraquark interpretations proposed in these years.

PACS 12.39.-x – Phenomenological quark models.
PACS 12.39.Mk – Glueball and nonstandard multi-quark/gluon states.
PACS 13.75.-n – Hadron-induced low- and intermediate-energy reactions and scattering (energy $\leq$ 10 GeV).

Prompt production of the $X(3872)$. – $X(3872)$ was first observed in B-meson decays by Belle and BaBar, in the $J/\psi\pi^+\pi^-$ invariant mass distribution at $\sim 3872\,\text{MeV}$, with a decay width smaller than the experimental resolution of $\sim 2.3\,\text{MeV}$. It was later confirmed by BaBar and in $p\bar{p}$ collisions by CDF and D0. The J^{PC} assignation is still controversial: in what follows we will assume $J^{PC} = 1^{++}$. The vicinity of the mass of the X to the $D^0\bar{D}^{0*}$ threshold suggested to identify the state with a $(D^0\bar{D}^{0*} + \bar{D}^0D^{0*})/\sqrt{2}$ S-wave molecule. This hypothesis is reinforced from the fact that X decays to $J/\psi\rho$ and $J/\psi\omega$ with the same strength [1]. This meson-meson bound state would have a tiny binding energy $\mathcal{E}_0 = (-0.25 \pm 0.4)\,\text{MeV}$, namely compatible with zero.

In a recent paper [2] we tested the molecular assignation on the prompt production mechanism. It seems at odds with common intuition that such a loosely bound molecule could be produced promptly in a high energy hadron collision environment. A recent analysis by CDF [3] allows indeed to distinguish between the fraction of X produced promptly and the one originated from B-decays: $\sigma(p\bar{p} \to X(3872) + \text{all})_{\text{prompt}} \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (3.1 \pm 0.7)\,\text{nb}$, for $p_T \geq 5\,\text{GeV}$ and $|y| \leq 0.6$. Using some bounds on the branching fraction [4], one obtains $33\,\text{nb} < \sigma(p\bar{p} \to X(3872) + \text{all})_{\text{prompt}} < 72\,\text{nb}$.To estimate an upper bound for the theoretical prompt production cross section

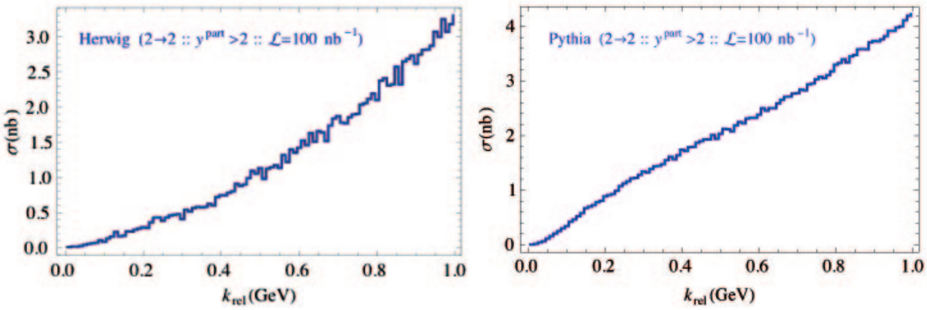

Fig. 1. – Left: the integrated cross section obtained with Herwig as a function of the relative momentum of the mesons in the $D^0\bar{D}^{0*}$ molecule. This plot is obtained after the generation of 55×10^9 events with parton cuts $p_\perp^{\rm part} > 2\,\text{GeV}$ and $y^{\rm part} > 6$. Right: same plot but using Pythia.

we made use of a Schwartz inequality:

$$
\begin{aligned}
(1) \qquad \sigma(p\bar{p} \to X(3872)) &\sim \left| \int \mathrm{d}^3\boldsymbol{k} \langle X | D\bar{D}^*(\boldsymbol{k})\rangle \langle D\bar{D}^*(\boldsymbol{k}) | p\bar{p}\rangle \right|^2 \\
&\simeq \left| \int_{\mathcal{R}} \mathrm{d}^3\boldsymbol{k} \langle X | D\bar{D}^*(\boldsymbol{k})\rangle \langle D\bar{D}^*(\boldsymbol{k}) | p\bar{p}\rangle \right|^2 \\
&\leq \int_{\mathcal{R}} \mathrm{d}^3\boldsymbol{k} |\psi(\boldsymbol{k})|^2 \int_{\mathcal{R}} \mathrm{d}^3\boldsymbol{k} |\langle D\bar{D}^*(\boldsymbol{k}) | p\bar{p}\rangle|^2 \\
&\leq \int_{\mathcal{R}} \mathrm{d}^3\boldsymbol{k} |\langle D\bar{D}^*(\boldsymbol{k}) | p\bar{p}\rangle|^2 \sim \sigma(p\bar{p} \to X(3872))^{\max},
\end{aligned}
$$

where $\boldsymbol{k}$ is the relative 3-momentum between the D mesons in their center-of-mass frame, $\psi(\boldsymbol{k})$ is some bound state wave function and $\mathcal{R}$ is the region were the wave function is appreciably different from zero. From the binding energy we can deduce the size of the molecule: $r_0 \sim \sqrt{1/2\mu\epsilon_0} \simeq 8\,\text{fm}$. Assuming a Gaussian wave function and using the minimal-uncertainty-principle relation we compute the spread of the relative 3-momentum $\Delta k \sim 1/2r_0 \simeq 12\,\text{MeV}$ around a central value $k_0 = \sqrt{\lambda(m_x^2, m_D^2, m_{D*}^2)}/2m_x \simeq 27\,\text{MeV}$. Thus $\mathcal{R} = [0, k_0 + \Delta k] \simeq [0, 35]\,\text{MeV}$. We recover what we expected: the two mesons inside the molecule must be almost collinear to account for such a small binding energy.

The matrix element $\langle D\bar{D}^*(\boldsymbol{k})|p\bar{p}\rangle$ can be computed using standard hadronization Monte Carlo programs like Herwig and Pythia, generating $2 \to 2$ QCD events with loose partonic cuts. Tuning our MC tools on the CDF data for $D^0 D^{*-}$ pair production, we obtain the differential distribution for the upper bound on the prompt production cross section of a $D^0\bar{D}^{0*}$ pair as a function of their relative 3-momentum k, see fig. 1. Integrating the distribution up to $k \simeq 35\,\text{MeV}$ we obtain $\sigma^{\rm th}_{\rm prompt} < 0.075\,\text{nb}$ with Herwig and $\sigma^{\rm th}_{\rm prompt} < 0.11\,\text{nb}$ with Pythia, both ~ 300 *times smaller* than the lower experimental limit $\sigma^{\rm exp}_{\rm prompt} > 33\,\text{nb}$. This result challenges the molecular interpretation of the X.

$Y(4660)$ and $Y(4350)$. – The Y resonances, $Y(4260)$, $Y(4350)$ and $Y(4660)$, are $J^{PC} = 1^{--}$ states produced via initial state radiation at the B-factories. The first

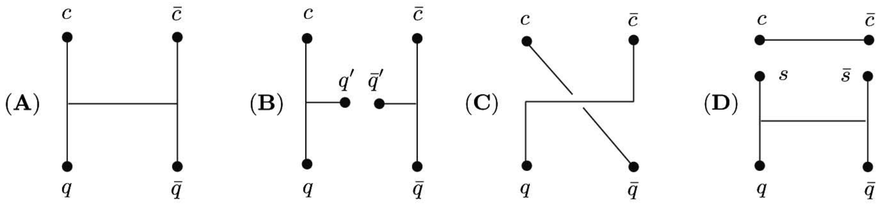

Fig. 2. – Phase space allows A $\to$ B ($Y \to \Lambda_c\bar{\Lambda}_c$), A $\to$ C ($Y \to D\bar{D}^*$), A $\to$ D ($Y \to \psi(2S)f_0(980)$).

decays mainly into $J/\psi\pi^+\pi^-$, while the other two into $\psi(2S)\pi^+\pi^-$. Since the $Y(4660)$ is above the threshold for the baryon-antibaryon decay, a scan was performed in this channel and found a peak at $\sim 4630\,\text{MeV}$. In [5] we reanalyzed the Belle data on $Y(4660) \to \psi(2S)\pi^+\pi^-$ [6] and $Y(4630) \to \Lambda_c^+\Lambda_c^-$ [7]. The two fits give consistent results, strongly supporting the hypothesis that the two structures are evidences of the *same resonance*, which we call Y_B ($M_{Y_B} = (4661 \pm 9)\,\text{MeV}$ and $\Gamma_{Y_B} = (61 \pm 23)\,\text{MeV}$). From the same fits we extract also: $\mathcal{B}(Y_B \to \Lambda_c^+\Lambda_c^-)/\mathcal{B}(Y_B \to \psi(2S)\pi^+\pi^-) = 25 \pm 7$. The Y_B shows a strong affinity to the baryon-antibaryon decay mode, which is typical of a $[cq][\bar{c}\bar{q}]$ tetraquark state. One can indeed describe the state as a diquark and an antidiquark attached at the end of a string which neutralizes their color, giving the "H"-shaped structure depicted in fig. 2 (A). The $\Lambda_c^+\Lambda_c^-$ decay is favored because it is realized breaking the string in one single point, fig. 2 (B), while the others proceed through the breaking in multiple points, fig. 2 (C-D). Furthermore we performed an analysis on the dipion invariant mass distribution which indicates the presence of the σ and $f_0(980)$ (famous tetraquark candidates in the light sector) as intermediate states in the decay $Y_B \to \psi(2S)\pi^+\pi^-$. This result is another indication of the tetraquark structure of this resonance.

The two diquarks must be in an odd orbital excitation to give odd parity. The spectrum of these orbitally excited states can be obtained using the relativistic string model derived by Selem and Wilczek in [8]. Two masses m_1 and m_2 are connected by a relativistic string with constant tension T, rotating with angular velocity ω. We consider the limit for equal and infinitely heavy masses M and obtain an analytic relation between the energy and the orbital angular momentum:

$$\mathcal{E} \simeq 2M + \frac{3}{(16\pi^2 M)^{1/3}}(\sigma\ell)^{2/3}, \tag{2}$$

where $\sigma = 2\pi T$. Using the string tension fitted from Regge trajectories $\sigma = 1.1\,\text{GeV}^2$, and the value of the diquark mass computed in [9] $M = 1933\,\text{MeV}$, one obtains $\mathcal{E} = 4311\,\text{MeV}$ for the $\ell = 1$ state, which we identify with the $Y(4350)$. Taking into account the absence of the decay $Y(4660) \to J/\psi\pi^+\pi^-$, we tentatively identify the $Y(4660)$ with a radial excitation of an $\ell = 1$ state, which should prefer to decay into charmonia with $n_r = 1$ ($\psi(2S)$), rather than $n_r = 0$ (J/ψ). The mass gap due to radial excitations of $\ell = 1$ states can be estimated from the experimental data in the bottomonium sector: $M_{\chi_b(2P)} - M_{\chi_b(1P)} \simeq 360\,\text{MeV}$. The mass of the the $\ell = 1$, $n_r = 1$ tetraquark would be $\simeq 4670\,\text{MeV}$, really close to the $Y(4660)$ mass.

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