The X(3872) at the TeVatron

G. Bauer
(Representing the CDF & DØ Collaborations)

Laboratory of Nuclear Science, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

Abstract. I report results on the X(3872) from the Tevatron. Mass and other properties have been studied, with a focus on new results on the dipion mass spectrum in X → J/ψπ⁺π⁻ decays. Dipions favor interpreting the decay as J/ψρ, implying even C-parity for the X. Modeling uncertainties do not allow distinguishing between S- and P-wave decays of the J/ψ-ρ mode. Effects of ρ-ω interference in X decay are also introduced.

The charmonium-like X(3872) stands as a major spectroscopic puzzle. Its mass and what is known of its decays makes c̅c assignments problematic. Exotic interpretations have been offered, notably that the X may be a D⁰-D̅⁰ "molecule" [1].

X(3872) → J/ψπ⁺π⁻ was confirmed by CDF [2] and DØ [3], and is copiously produced at Fermilab’s ¯pp collider—albeit with high backgrounds. Mass measurements are compared in Fig. 1 with an average of 3871.2 ± 0.4 MeV/c². DØ studied other X properties by comparing the fractions of X yield in various types of subsamples to the corresponding fractions for the ψ(2S) [3]. The results for 250 pb⁻¹ are summarized in Fig. 2 where the subsamples are the fraction of signal which have: a) p_T (J/ψππ) > 15 GeV, b) |y(J/ψππ)| < 1, c) cos(θπ) < 0.4 (π helicity angle), d) proper decay length ct < 100 µm, e) no tracks with ΔR < 0.5 around the candidate, f) cos(θµ) < 0.4 (µ helicity angle). In all cases the X results are compatible with those of the ψ(2S). CDF used the

FIGURE 1. LEFT: Summary of X-mass measurements compared to the D⁰-D̅⁰ and D⁺D̅⁻ thresholds. RIGHT: DØ’s comparison of X production/decay properties to that of the ψ(2S) [3]. The fraction of the yield surviving the listed cut is plotted (see text for descriptions).
The model also yields $^{3}S_{1}$ multipole expansion predictions for $C$-odd charmonia, and of $X \rightarrow J/\psi \rho$ for $L = 0$ and 1 using a relativistic Breit-Wigner with Blatt-Weisskopf factors ($R_{\rho} = 0.3$ and $R_{X} = 1.0$ fm).

Another property is the dipion mass spectrum. If the $X$ is a molecule, bound by an MeV or less, to be suppressed. It may, however, be sufficient to accommodate these features if the $X$ merely has a significant $c\bar{c}$ “core.”

Proper decay length $ct$ to quantify the fraction of $X$’s that come from $b$-hadrons, versus those that are promptly produced. Using 220 pb$^{-1}$, CDF finds the fraction of $X$’s from $b$-decays is $16.1 \pm 4.9 \pm 2.0\%$, in contrast to $28.3 \pm 1.0 \pm 0.7\%$ of $\psi(2S)$’s. The $X$ fraction is somewhat lower than the $\psi(2S)$’s, but within $\sim 2\sigma$. From these perspectives the $X$ is compatible with the $\psi(2S)$. The large $X$-production at the Tevatron is indicative to some of a charmonium character. Naïvely one expects production of a fragile $D^{0}\overline{D}^{0}$ molecule, bound by an MeV or less, to be suppressed. It may, however, be sufficient to accommodate these features if the $X$ merely has a significant $c\bar{c}$ “core.”

Another property is the dipion mass spectrum. If the $X$ has even $C$-parity, the dipions are (to lowest $L$) in a $1^{--}$ isovector state, and dominated by the $\rho_{0}$. An odd-$C$ state produces $0^{++}$ dipions, for which QCD multipole expansion predictions exist for $c\bar{c}$.

CDF used 360 pb$^{-1}$ ($\sim 1.3k$ $X$’s) to measure the $\pi\pi$-spectrum. The sample is divided into $m_{\pi\pi}$ “slices” and fitted for $X(3872)$ and $\psi(2S)$ yields. After modest efficiency corrections, the spectra of Fig. were obtained. The $\psi(2S)$ is a good reference signal and is well modeled by multipole predictions. Also in Fig. are multipole fits to the $X$ for the $C$-odd $c\bar{c}$ states. The $1P_{1}$ and $3D_{J}$ fits are unacceptable. The $3S_{1}$ is an excellent fit to the $X$, but no $3S_{1}$ $c\bar{c}$ is available for assignment in this mass region.

Earlier this spring CDF provided $J/\psi \rho$ fits using a simple non-relativistic Breit-Wigner sculpted by phase space. Good agreement was obtained (36% probability). About the same time Belle released new dipion data fit with a more sophisticated $\rho$ model, which included the effects of angular momentum $L$ in the $J/\psi-\rho$ system. The phase-space factor of the $J/\psi$ momentum in the $X$ rest-frame, $k^{*}$, generalizes to $(k^{*})^{2L+1}$, thereby turning off the mass spectrum at the upper kinematic limit ($k^{*} \rightarrow 0$) faster for $L = 1$ than for $L = 0$. Belle obtained a good fit for $S$-wave decay, but only a $0.1\%$ probability for $L = 1$. Thus, the latter case was strongly disfavored, and in conjunction with angular information, Belle argued for a $1^{++}$ assignment for the $X$.

The above CDF fit for $J/\psi \rho$ was implicitly for $L = 0$. A CDF fit using Belle’s $L = 1$ model also yields $0.1\%$ probability. The implication is, however, not robust.
Breit-Wigner formulations are often modified by Blatt-Weisskopf form factors \[10\]. The centrifugal modification to \((k^*)^{2L+1}\) tends to be too strong, and for \(L = 1\) it is multiplied by \(f_I(k^*) \propto (1 + R^2_{l} k^2)^{-\frac{1}{2}},\) where \(R_l\) is a “radius” of meson-\(i\). Specifically, CDF’s \(J/\psi \rho\) model is: \(dN/dm_{\pi \pi} \propto (k^*)^{2L+1} f_{I_X}(k^*) |B_\rho|^2\) for angular momentum \(L\). The \(\rho\) propagator \(B_\rho \propto \sqrt{m_{\pi \pi} \Gamma_\rho (m_{\pi \pi}) / [m_\rho^2 - m_{\pi \pi}^2 - i m_\rho \Gamma_\rho (m_{\pi \pi})]},\) where \(\Gamma_\rho (m_{\pi \pi}) = \Gamma \left[q^*/q_0^*\right]^3 \times [m_\rho / m_{\pi \pi}] [f_{i\rho}(q^*) / f_{i\rho}(q_0^*)]^2, q^*\) is the \(\pi\) momentum in the \(\pi \pi\) rest-frame, and \(q_0^* \equiv q^* (m_\rho).\) The \(\rho\) parameters \(m_\rho\) and \(\Gamma_0\) are taken from the PDG. The \(L = 0\) factor is \(f_{0\psi}(x) = 1.\) The \(f_{ii}\) factors require two uncertain parameters, \(R_X\) and \(R_\rho\). For light mesons, like the \(\rho,\) values \(\sim 0.3\) fm are usually found, whereas for charm mesons larger radii \(\sim 1\) fm are often used \[11\]. Choosing these values for \(R_\rho\) and \(R_X\), CDF obtains the fits in Fig. 2 (Right). The \(L = 0\) fit has an excellent probability of 55%. While the \(L = 1\) probability is not quantitatively as good, it is a respectable 7.7%. This \(P\)-wave fit is sensitive to the \(R_\rho\)’s, whereby the probability can be increased by lowering \(R_\rho\) and/or raising \(R_X\). We conclude that flexibility in the fit model can accommodate either \(L\).

Other modeling uncertainties may arise, for example, the effects of \(\rho-\omega\) interference. Belle reported \(X \to J/\psi \pi^+ \pi^- \pi^0,\) and interprets it as decay via a virtual \(\omega.\) As such, they find the ratio of \(J/\psi \omega\) to \(J/\psi \rho\) branching ratios \(R_{3/2}\) is \(1.0 \pm 0.5\) \[12\]. Although \(\omega \to \pi^+ \pi^-\) is nominally successful here, its interference effects may not be.

d\(dN_{2\pi}/d\omega m_{\pi \pi}\) is generalized by replacing \(|B_\rho|^2\) with \(|A_\rho B_\rho + e^{i\phi} A_\omega B_{\omega 2\pi}|^2\) where \(A_\rho\) and \(A_\omega\) are \(X\)-decay amplitudes via \(\rho\) and \(\omega,\) and \(\phi\) is the relative phase. The form for \(B_{\omega 2\pi}\) is identical to \(B_\rho\) except \(\rho\) quantities are replaced by \(\omega\) ones, including the \(\omega \to \pi \pi\) branching ratio. The ratio \(|A_\omega / A_\rho|\) is established by the relationship between \(R_{3/2}\) and the integrals of \(dN_{2\pi}/d\omega m_{\pi \pi}\) and \(dN_{3\pi}/d\omega m_{3\pi}\) for \(X \to J/\psi \pi^+ \pi^- \pi^0,\) where the latter is \(\propto |A_\omega B_{\omega 3\pi}|^2.\) The \(B_{\omega 3\pi}\) follows \(B_{\omega 2\pi}\) except the numerator contains \(\Gamma_{\omega 3\pi}(m).\) While \(\Gamma_{\omega 2\pi}(m)\) follows \(\Gamma_\rho (m),\) a different form for \(\Gamma_{\omega 3\pi}(m)\) is adapted from the SND experiment studying \(e^+ e^- \to \pi^+ \pi^- \pi^0\) \[13\]. They model \(\omega \to \pi^+ \pi^- \pi^0\) as virtual \(\rho \pi\) decays and use the \(\omega\) matrix-element \(|\vec{q}_{\pi^+} \times \vec{q}_{\pi} |^2,\) where \(\vec{q}_{\pi^+}\) are \(\pi^+/\pi^-\) momenta.

The integral of \(dN_{2\pi}/d\omega m_{\pi \pi}\) depends upon the phase, which is \(a priori\) unknown. As an illustration, \(|A_\omega / A_\rho|\) is determined assuming that \(\phi\) arises completely from \(\rho-\omega\) mixing, i.e. \(\phi = 95^\circ\) \[14\]. The \(dN_{2\pi}/d\omega m_{\pi \pi}\) decomposes into three parts: “pure” \(\rho\) and \(\omega\) terms, and an interference cross-term. In this model with \(R_{3/2} = 1.0,\) these fractions are, respectively, 71.0, 6.2, and 22.8% for \(S\)-wave decay, and 67.4, 8.7, 23.9% for \(P\)-wave. Fits with these fractions imposed are shown in Fig. 5 (Left). The \(S\)-wave probability has declined as the model peaks too much at high mass, but is still very good at 19%. Increasing the amount of high masses with interference improves the \(P\)-wave fit to 53%.

The \(L = 1\) fit is sensitive to \(\phi\) and \(R_X\) as is seen in the inset of Fig. 5. The dependence on \(R_\rho\) is relatively weak for both \(L\). The overall picture from these fits is insensitive to the \(\pm 1\sigma\) span of \(R_{3/2}\), as is seen in Fig. 3 (Right).

In summary, properties of \(X(3872) \to J/\psi \pi^+ \pi^-\) studied at the Tevatron are quite similar to those of the \(\psi(2S).\) There is no viable \(C\)-odd charmion assignment according to QCD multipole expansion fits to the \(\pi \pi\)-mass spectrum. Decay to \(J/\psi \rho\) provides good fits, irrespective of the \(c\bar{c}\) structure. This implies the \(X\) is \(C\)-even, in-line with Belle’s report of \(X \to J/\psi \gamma\) \[12\]. The effects of \(\rho-\omega\) interference are introduced, and can be quite important. This type of \(\rho-\omega\) modeling highlights that \(R_{3/2} \sim 1\) implies
the intrinsic amplitude for $X \to J/\psi \rho$ is actually significantly suppressed relative to $J/\psi \omega$ by virtue of the much greater phase space for $J/\psi \rho$ decay over $J/\psi \omega$. Given the modeling uncertainties governing the tails of the Breit-Wigners—especially if $\rho-\omega$ interference is in play—the CDF spectrum can be well described by $J/\psi \rho$ decay of either $L=0$ or $1$: such as from C-even charmonia (e.g. $1^{++}$ or $2^{-+}$) or by a $1^{++}$ exotic as preferred for a $D^0-\bar{D}^*0$ molecule.

REFERENCES

1. See for example: E.J. Eichten, K. Lane, and C. Quigg, hep-ph/0511179 and references therein.
2. D. Acosta et al. (CDF), Phys. Rev. Lett. 93, 072001 (2004).
3. V.N. Abazov et al. (DØ), Phys. Rev. Lett. 93, 162002 (2004).
4. G. Bauer (CDF), DPF ‘04, Riverside CA, 25-31 August 2004 [hep-ex/0409052].
5. K.-T. Chao, 2nd Workshop on Heavy Quarkonium, FNAL, 20-22 Sep. 2003 [www.qwg.to.infn.it/WS-sep03/WS2talks/prod/chao.ppt]; G. Bauer, hep-ex/0505083; C. Meng, Y.-J. Gao, K.-T. Chao, hep-ph/0506222; M. Suzuki, hep-ph/0508258.
6. CDF Note 7570 (7 April 2005) [www-cdf.fnal.gov/physics/new/bottom.html]; S. Nahn, APS/DPF Meeting, Tampa FL, 16-19 April 2005 [www-cdf.fnal.gov/physics/talks_transp/2005/aps_bphys_nahn.pdf]; A. Rakitin, Ph.D. Thesis, MIT (2005).
7. A. Abulencia et al. (CDF), FERMILAB-PUB-05/535-E, to be submitted to PRL.
8. T.M. Yan, Phys. Rev. D 22, 1652 (1980); Y.-P. Kuang et al., ibid D 37, 1210 (1988).
9. S. Olsen (Belle), APS/DPF Meeting, Tampa FL, 16-19 April 2005 [belle.kek.jp/belle/talks/aps05/olsen.pdf]; K. Abe et al. (Belle), Lepton-Photon ’05 [hep-ex/0505038].
10. J.M. Blatt and V.F. Weisskopf, *Theoretical Nuclear Physics*, John Wiley & Sons (1952).
11. For example: S. Kopp et al. (CLEO), Phys. Rev. D 63, 092001 (2001); H. Albrecht et al. (ARGUS), Phys. Lett. B 308, 435 (1993); D. Aston et al. (LASS), Nucl. Phys. B 296, 493 (1988).
12. K. Abe et al. (Belle), Lepton-Photon ’05, Uppsala, Sweden, 30 June-5 July 2005 [hep-ex/0505037].
13. M.N. Achasov et al. (SND), Phys. Rev. D 68, 052006 (2003).
14. $\Gamma_\rho / (m_\rho - m_\omega) \approx 2 \tan (95^\circ)$ [A.S. Goldhaber, G.C. Fox, and C. Quigg, Phys. Lett. B 30, 249 (1969)].