Observation of a narrow state $X(3872)$:

Abstract

Particle spectroscopy appears to be making a comeback with the recent observation of several unexpected narrow particles containing charmed quarks at the B factories. This analysis reports the first observation of one of these particles, the X(3872), at the Tevatron. The observation of this narrow state has invited speculation that an exotic form of matter made up of 2 quarks and 2 anti-quarks may have been observed.

In the 1960s the quark model, as proposed by Gell-man and Neéman in their "Eightfold Way", was very successful in explaining the large plethora of particles discovered in terms of families of particles called multiplets. The particles in a multiplet are related to each other and are composed of quarks (q) which at the time came in 3 types: up (u), down (d) and strange (s). They are described by an underlying mathematical symmetry called SU(3). Ordinary matter, comprising of protons and neutrons, only requires up and down quarks. Protons and neutrons are also baryons which are made up of three quarks (qqq). Mesons are made up of a quark and an anti-quark pair, $q\bar{q}$. In 1974, in what became known as the November revolution, a very narrow particle was simultaneously discovered at Brookhaven National Lab (BNL) on Long Island and at the Stanford Linear Accelerator Center (SLAC) in California. The BNL team, led by MIT, called their particle J and the SLAC team ψ and today it is known as the J/ψ. The mass of the J/ψ is 3097 MeV and its narrow width, less than 0.1 MeV, indicated a new form of matter. MeV is a unit of energy, the proton having the energy equivalent of about 1000 MeV. We now know that it is a meson comprised of a charmed quark and an anti-charmed quark pair, ($c\bar{c}$). The SU(3) symmetry had to be updated to SU(4) to accomodate the charmed quark. This new symmetry lead to the prediction of D meson states which are comprised of a charm quark and a $\bar{u}$, $\bar{d}$ or $\bar{s}$ quark. Eventually these D mesons were found, the D^0 ($c\bar{u}$) at 1864 MeV, the D^+ ($c\bar{d}$) at 1869 MeV and the D_s^+ ($c\bar{s}$) at 1969 MeV. Excited states of D mesons called D^* have also been found, for instance the D^{*0} ($c\bar{u}$) is at 2007 MeV.

A whole new spectroscopy arose with the discovery of the J/ψ called charmonium. It comprises a spectrum of excited states of the $c\bar{c}$ system which is well described by potential models to predict the masses of the states. Figure 1 shows our current understanding of the charmonium system. Each particle is described by quantum numbers J for its spin, P for parity and C for charge conjugation. The quantum numbers provide rules for which particles they can decay into. The first excited state, with similar quantum numbers to the J/ψ, is called the $\psi(2S)$ at a mass of 3686 MeV. The $\psi(3770)$, i.e. 3770 MeV, is above the $D\bar{D}$ threshold and hence it can decay strongly into $D^0\bar{D}^0$ or D^+D^- which gives it a larger width, 24 MeV, compared to the J/ψ and $\psi(2S)$. The D^0 and D^+ contain a c quark and the $\bar{D}^0$ and D^- contain a $\bar{c}$ quark and hence in the decay the number of c and $\bar{c}$ quarks are conserved.

An analogous system to charmonium is postronium, discovered by Martin Deutsch of MIT in 1951, which is an electron positron (e^-e^+) atomic system. Positronium also has excited states as does the hydrogen atom which comprises an electron orbiting a much

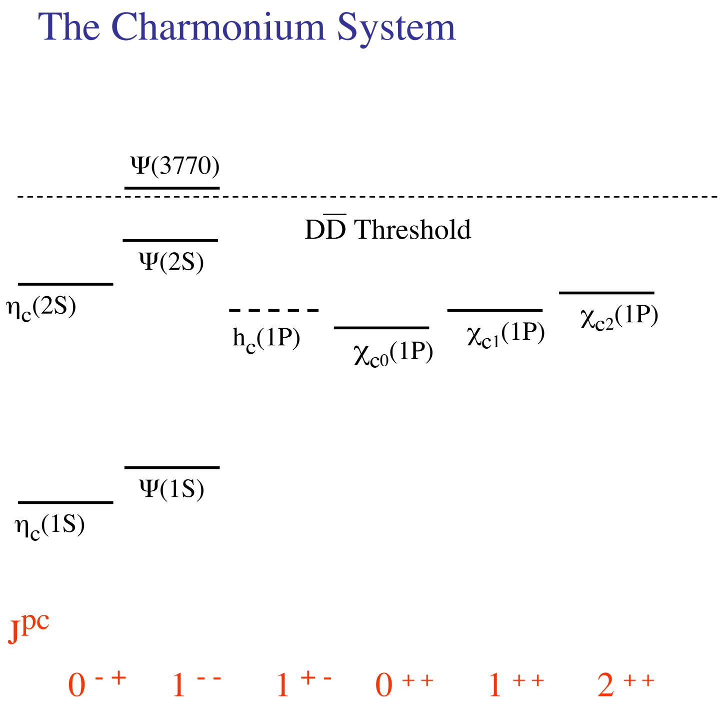

Figure 1: States of the charmonium system as a function of mass (vertical scale) and quantum numbers Spin Parity J^{PC} (horizontal scale)

heavier proton. Positronium is well described by Quantum Electrodynamics (QED) and charmonium is described by the strong interaction in terms of Quantum Chromodynamics or QCD. In QED the force is said to be mediated by the exchange of photons and in QCD this is done by exchanging massless gluons which have the additional property of interacting with themselves.

Earlier this year, the Belle Collaboration at the KEK electron-positron collider in Japan reported the observation of a very narrow state at 3872.0 ± 0.8 MeV decaying into $J/\psi\pi^+\pi^-$ which they called the $X(3872)$.

The CDF II experiment at Fermilab studies anti-proton proton collisions at $\sqrt{s} = 1.96$ TeV and triggers on J/ψs through their decays to $\mu^+\mu^-$. In this analysis J/ψs are combined with pairs of oppositely charged tracks which assumed to be pions and the invariant mass is calculated. Figure 2 shows the $J/\psi\pi^+\pi^-$ mass distribution after all selections have been made. A large peak for the $\psi(2S)$ is seen, and in addition a smaller peak at a $J/\psi\pi^+\pi^-$ mass of 3871.3 ± 0.8 MeV is observed. This in good agreement with the Belle result. Belle

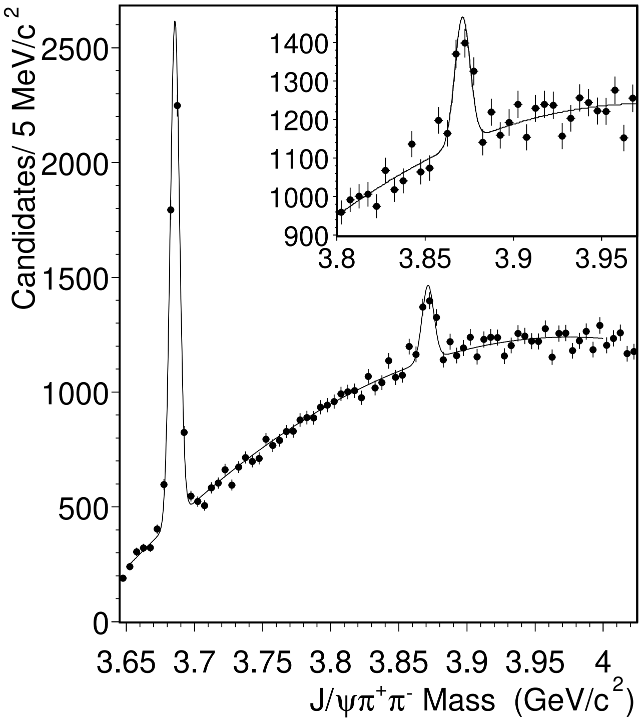

Figure 2: Mass distribution of the $J/\psi\pi^+\pi^-$ candidates. A large peak for the $\psi(2S)$ is seen and a signal near a mass of 3872 MeV is visible (enlargement shown in inset). The curve is a fit to the data using two Gaussians and a quadratic background to describe the data points.

observed 36 events on a very small background whereas we see 730 ± 90 events on a large background. The CDF II result is a solid confirmation on the existance of this new particle. Both experiments find a width consistent with their experimental resolutions.

A natural interpretation of this new particle would be a previously unobserved charmonium state, but there are no such states predicted to lie at or near the observed mass with the right quantum numbers to decay into $J/\psi\pi^+\pi^-$. For instance there are additional charmonium states expected to be associated with the $\psi(3770)$. However, the potential models, which give a good description of the other charmonium states, predict masses near 3810 MeV which is 60 MeV too low for this new state.

Within the context of QCD there are other possibilities. The quark model predicts that mesons, normaly made from a quark and and an anti-quark pair $(q\bar{q})$, can also be made by adding another quark anti-quark pair. This configuration, $(q\bar{q}q\bar{q})$, might suggest a pair of ordinary mesons in quark content. The near equality of the $X(3872)$ mass to the sum of the D^0 and D^{*0} masses suggests that the $X(3872)$ meson may be a deuteron-like "molecule" composed of a D and $\overline{D}^*$. This novel possibility has excited great interest in the $X(3872)$. In addition to exotic mesons states, $(q\bar{q}q\bar{q})$, exotic baryons can also be contructed in the quark model by adding a $q\bar{q}$ to the standard baryon, qqq, to make $qqqq\bar{q}$. These would be known as penta-quarks states where penta is greek for five. Earlier this year (2003) the $\Theta^+(1540)$ particle was discovered which is a clear candidate for a penta-quark state. The quark model has been with us for 40 years now and until this year there has been no clear experimental evidence for these exotic states. Whether the X(3872) is a new form of hadronic matter or a conventional $c\bar{c}$-state in conflict with theoretical models, the $X(3872)$ is an important object. We may, with further studies, be able to clearly distinguish it's true nature as a $q\bar{q}q\bar{q}$ or a $c\bar{c}$-state.