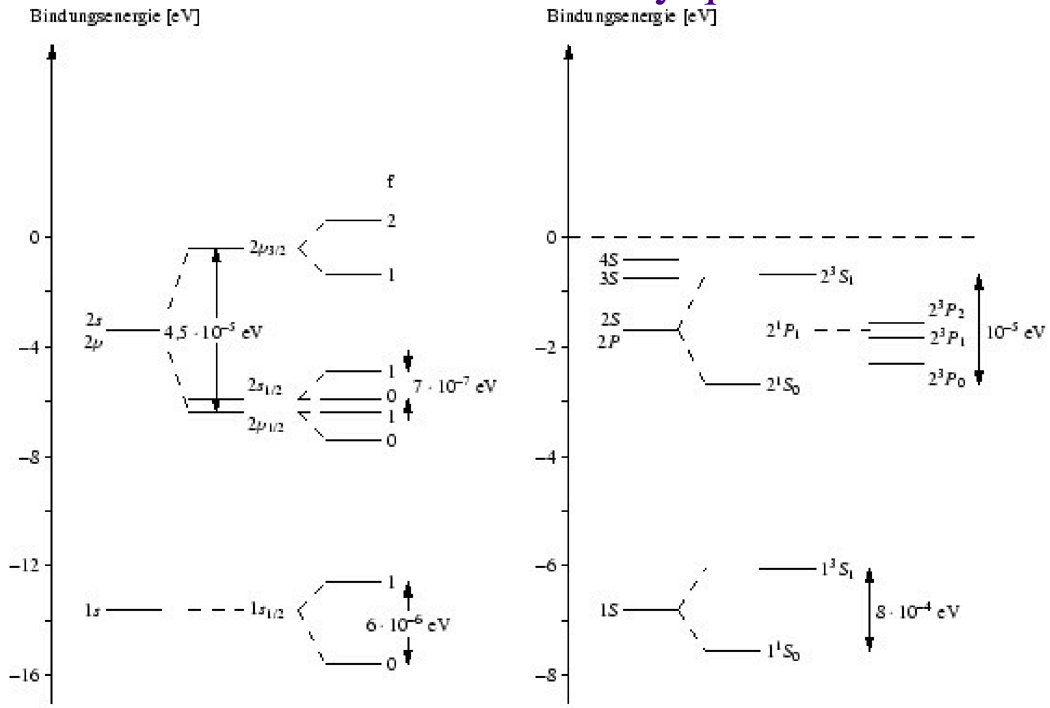
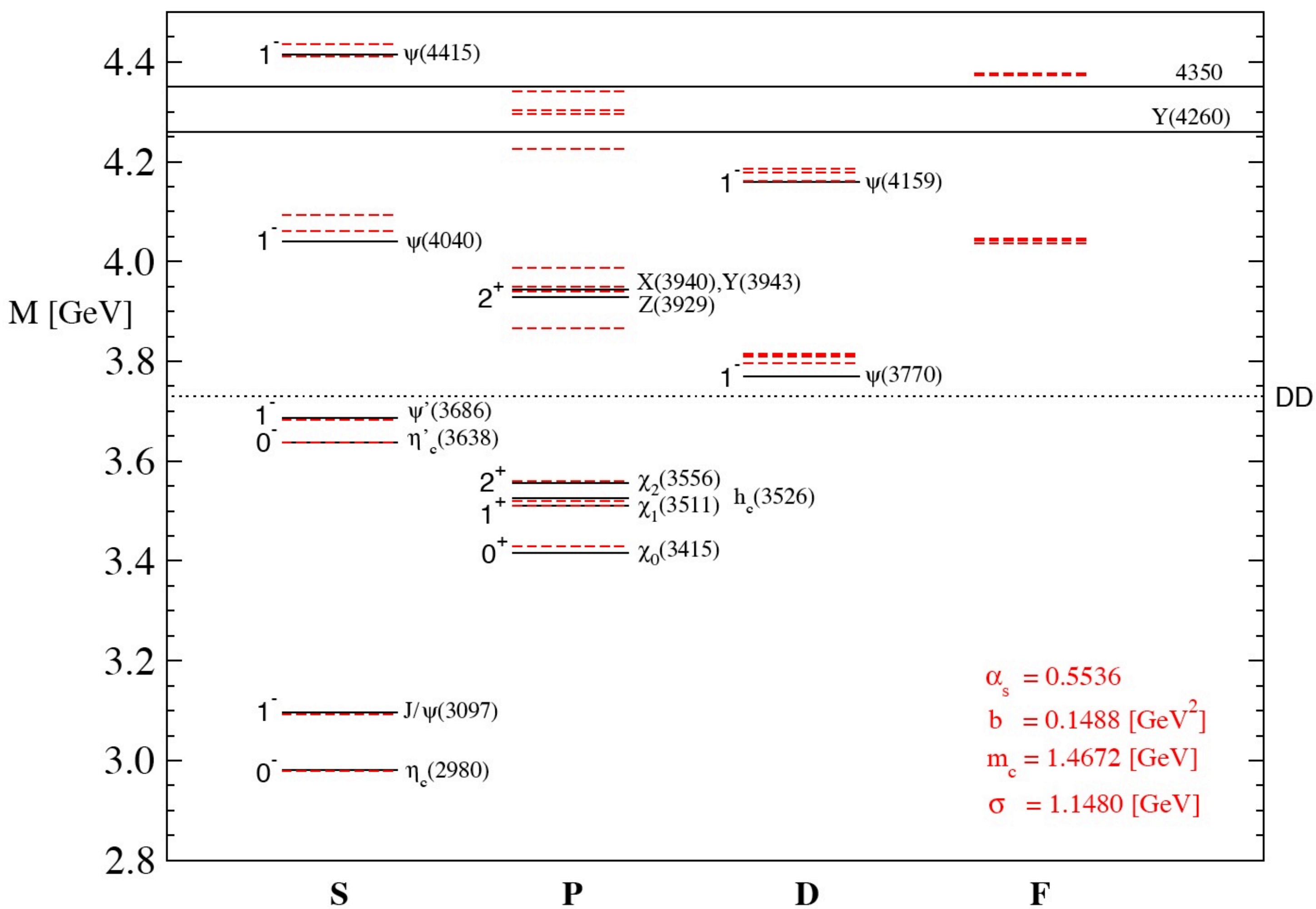
Mesons made of heavy quarks.



Energy levels of hydrogen and of positronium...

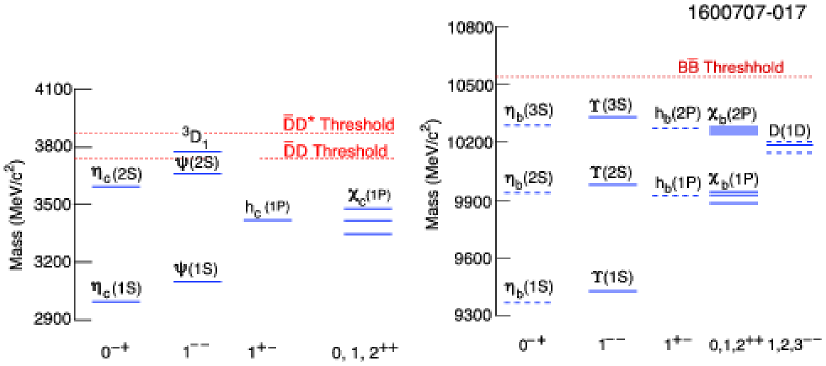


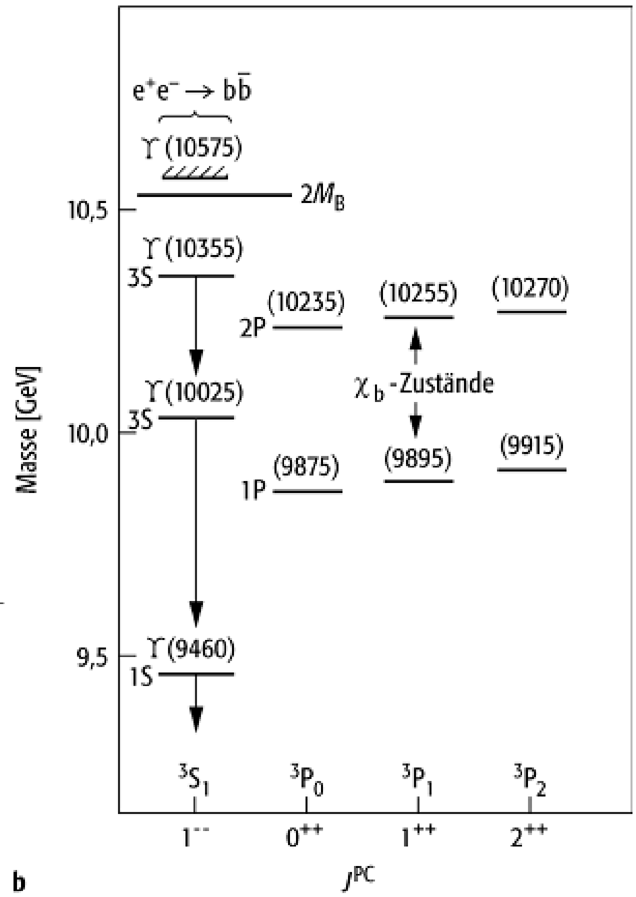
Bound states of the charm-anticharm system!

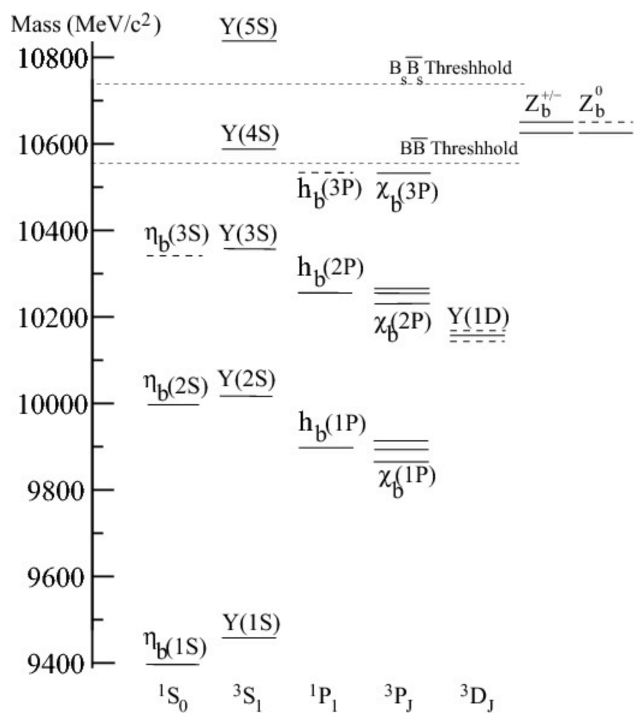
$$V_{c\bar{c}}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \kappa r + \frac{32\pi\alpha_s}{9m_c^2} f_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}\ , \quad \alpha_s = \frac{g^2}{4\pi}$$

Here, the first term is the “Coulomb” energy, with the strong coupling constant α_S instead of α of electrodynamics, the second term is the energy term linear in distance, which enforces confinement, and the third term contains spin-dependent terms to model the fine structure of the spectrum. The constant $\varkappa$ is the the so-called string tension. In the spectrum shown in the figure, the best fit to the experimental data with this spectrum is shown in red. It corresponds to an effective mass of the charm quark, $m_c = 1.46$ GeV/c^2, a coupling constant $\alpha_S = 0.55$, and a string tension (called "b" in the plot) of $\varkappa = 0.72$ GeV/fm --- meaning that an energy of 0.72 GeV is needed to separate the quark-antiquark pair by 10^{-15} meters.

The charm quark mass is about 1.29 GeV, the bottom quark mass about 4.18 GeV, and the top quark mass about 173 GeV. So “toponium” is beyond the reach of current accelerators, but both charmonium and bottomonium have been extensively studied.







Phenomenological fits to the meson masses use a simple idea such as $M = m_q + m_{anti\text{-}q} + \Delta$, where Δ is mainly a spin-spin interaction term.

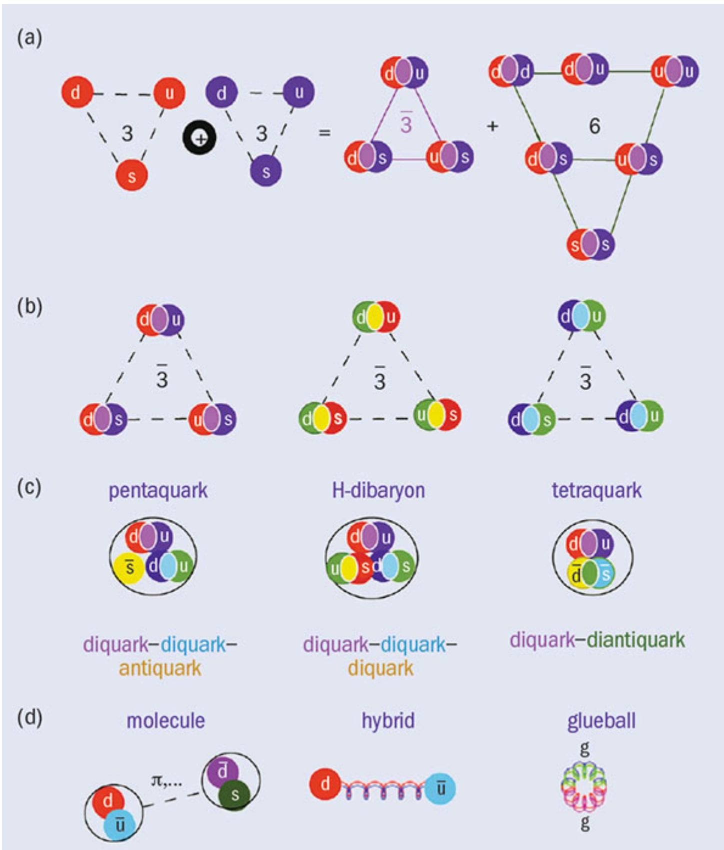
$q_i\bar{q}_j$	$J=0$	$J=1$
$\lvert u\bar{d}\rangle$	$\pi^+(140)$	$\rho^+(770)$
$2^{-1/2}\lvert d\bar{d}-u\bar{u}\rangle$	$\pi^0(135)$	$\rho^0(770)$
$\lvert u\bar{d}\rangle$	$\pi^-(140)$	$\rho^-(770)$
$2^{-1/2}\lvert d\bar{d}+u\bar{u}\rangle$	$\eta(549)$	$\omega(783)$
$\lvert u\bar{s}\rangle$	$K^+(494)$	$K^{*+}(892)$
$\lvert d\bar{s}\rangle$	$K^0(498)$	$K^{*0}(892)$
$\lvert \bar{u}s\rangle$	$K^-(494)$	$K^{*-}(892)$
$\lvert \bar{d}s\rangle$	$\bar{K}^0(498)$	$\bar{K}^{*0}(892)$
$\lvert s\bar{s}\rangle$	$\eta'(958)$	$\phi(1020)$

Table 02 Quark Pair and Mesons

$$
\begin{aligned}
V_{ij} = & -\frac{2\alpha_s}{3r} + \frac{\alpha_s}{3m_i m_j}\left[\frac{\boldsymbol{P}_i\cdot\boldsymbol{P}_j}{r} + \frac{(\boldsymbol{r}\cdot\boldsymbol{P}_i)(\boldsymbol{r}\cdot\boldsymbol{P}_j)}{r^3}\right] \\
& + \frac{\pi\alpha_s}{3}\delta^3(\boldsymbol{r})\left(\frac{1}{m_i^2}+\frac{1}{m_j^2}\right) \\
& + \frac{\alpha_s}{3m_i m_j}\left[\frac{8\pi}{3}\delta^3(\boldsymbol{r})\,\boldsymbol{s}_i\cdot\boldsymbol{s}_j + \frac{3(\boldsymbol{s}_i\cdot\hat{r})(\boldsymbol{s}_j\cdot\hat{r})-\boldsymbol{s}_i\cdot\boldsymbol{s}_j}{r^3}\right] \\
& + \frac{\alpha_s}{r^3}\left[\frac{\boldsymbol{r}\cdot\boldsymbol{P}_i\cdot\boldsymbol{s}_i}{m_i^2} - \frac{\boldsymbol{r}\cdot\boldsymbol{P}_j\cdot\boldsymbol{s}_j}{m_j^2}\right. \\
& \left. + \frac{2}{m_i m_j}\left(\boldsymbol{r}\cdot\boldsymbol{P}_i\cdot\boldsymbol{s}_j - \boldsymbol{r}\cdot\boldsymbol{P}_j\cdot\boldsymbol{s}_i\right)\right]
\end{aligned}
$$

Very complex potentials that are momentum-dependent can be generated from QCD itself, in various approximations...

Restricting strongly interacting particles just to states of three valence quarks, or a valence quark-antiquark pair, feels as if there is a lack of nature taking advantage of its own possibilities, given that we are dealing with the strongest force in nature. Thus, experimentalists have searched for more **exotic states,** predicted by some theorists, with larger numbers of valence quarks and antiquarks. Evidence of a few such states has gradually emerged. The surprisingly close similarity between the atom-atom potential and the nucleon-nucleon potential would suggest naively that hadronic equivalents of "diatomic molecules" should exist, albeit for a very, very short time.



Hypothetical exotic hadrons!

Is the deuteron really the only **di-baryon?**

Discovery of many multi-quark states!

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