Effective Field Theory Investigations of the "XYZ" Puzzle

Jorge Segovia

Physik-Department T30f, Technische Universität München, Germany

jorge.segovia@tum.de

T30f Theoretische Teilchen- und Kernphysik

Abstract

Quantum Chromodynamics, the theory of strong interactions, predicts several types of bound states. Among them are mesons (quark-antiquark) and baryons (quark-quark-quark), which have been the only states observed in experiments for years. However, in the last decade many states that do not fit this picture have been observed at B-factories (Belle, BES, and BaBar), at CLEO, and at LHC experiments. There is growing evidence that at least some of the new charmonium- and bottomonium-like states, the so-called "XYZ" mesons, are new forms of matter such as quark-gluon hybrids, mesonic molecules, and tetraquarks. Effective Field Theories (EFTs) have been constructed for heavy-quark-antiquark bound states, but the study of "XYZ" mesons within the same framework has not yet been done. The scope of this research project is the development of novel EFTs that, characterizing the conventional quarkonium states, facilitate also the systematic and model-independent description of the new exotic matter.

Introduction

The scientific community has witnessed what is called the golden age for heavy quarkonium physics, dawned a decade ago and initiated by the confluence of exciting advances in the development of theoretical approaches and an explosion of related experimental activity.

On the experimental side, everything started in 2003, while studying the reaction $B^+ \to K^+\pi^+\pi^- J/\psi$, an unexpected enhancement was discovered by Belle [1] in the $\pi^+\pi^- J/\psi$ invariant mass spectrum near $3872\,\mathrm{MeV}$. It was later confirmed by BaBar [2] in B-decays and by both CDF [3] and D0 [4] at Tevatron in prompt production from $p\bar{p}$ collisions.

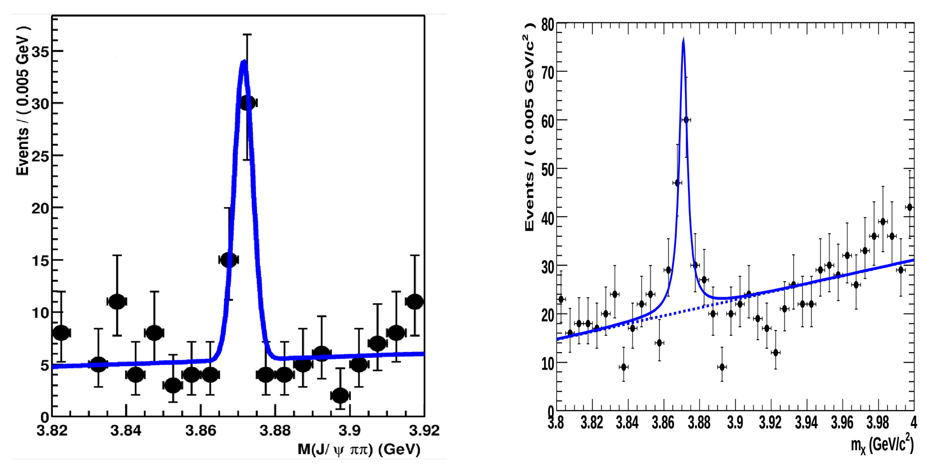

Figure 1: *Left panel* – Belle's data [1]; *Right panel* – BaBar's data [2].

Since then, many experiments around the world have joined the search and the number of new states has increased dramatically. More than a dozen charmonium- and bottomonium-like "XYZ" states have forced an end to the era when heavy quarkonium was considered as a relatively well-established bound system of a heavy quark and antiquark.

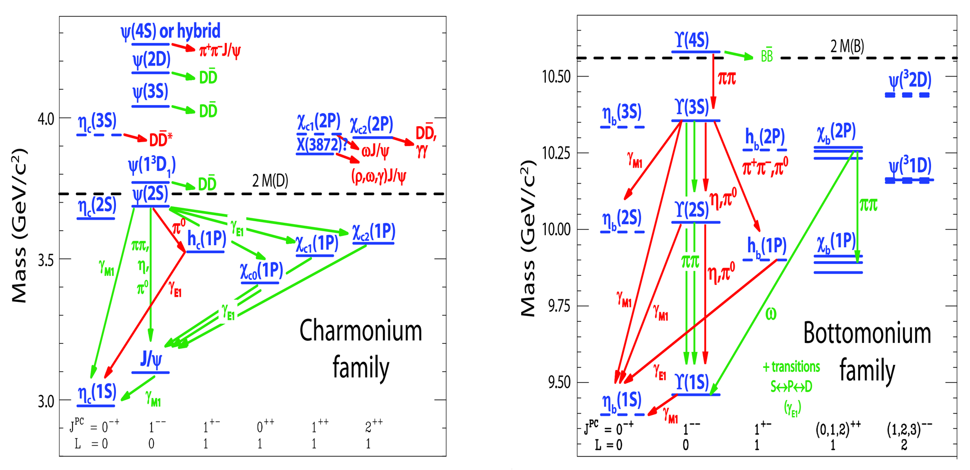

Figure 2: Modified versions of Figures shown in Ref. [5]. Well-established charmonium $(c\bar{c})$ and bottomonium $(b\bar{b})$ states which are mainly located below open-flavor threshold.

State	M (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment ($\#\sigma$)	Year	Status
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [1, 10] (12.8), BABAR [11] (8.6)	2003	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF [12–14] (np), DØ [15] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [16] (4.3), BABAR [17] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [18, 19] (6.4), BABAR [20] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [16] (4.0), BABAR [21, 22] (3.6)		
				$B \to K(\gamma\psi(2S))$	BABAR [22] (3.5)		
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [23] (8.1), BABAR [24] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [25] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [26] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\ (...)$	Belle [27] (5.0)		
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	BABAR [28] (np), Belle [29] (np)	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [30] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [31] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [32, 33] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [26] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [31] (5.0)	2008	NC!
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	BABAR [34, 35] (8.0)	2005	OK
					CLEO [36] (5.4)		
					Belle [37] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [38] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [38] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [33] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [39] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	BABAR [40] (np), Belle [41] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle [42, 43] (6.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [44] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [41] (5.8)	2007	NC!
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [45, 46] (3.2)	2010	NC!

Figure 3: Table taken from Ref. [6]. New unconventional states in the $c\bar{c}$ and $b\bar{b}$ sectors, ordered by mass.

New forms of matter such as quark-gluon hybrids, mesonic molecules, and tetraquarks have been proposed. Experiments focused on systematic studies of the "XYZ" states are needed and Europe is situated in a leading position with the current LHCb experiment at CERN and the promising Antiproton Annihilation at Darmstadt (PANDA) experiment at the Facility for Antiproton and Ion Research (FAIR).

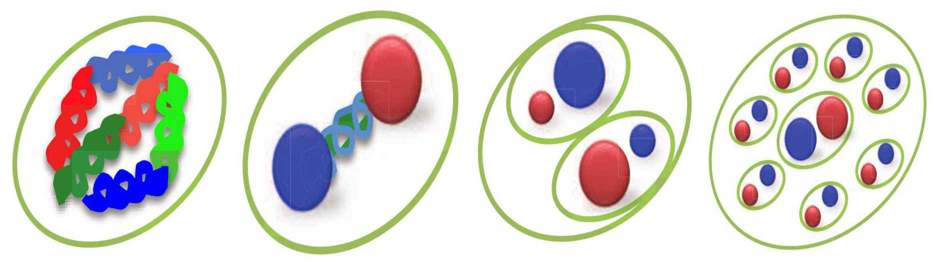

Figure 4: Some proposed new forms of matter beyond the quark model picture. Starting from the left, *Panel a* – A composite particle which consists solely of gluons; *Panel b* – A valence $Q\bar{Q}$ state whose exotic properties are due to gluonic excitations; *Panel c* – Shallow bound states of heavy-light mesons analogous to the deuteron; *Panel d* – A compact core of a valence $Q\bar{Q}$-pair surrounded by light mesons.

From a theoretical point of view, heavy quarkonium physics experienced a breakthrough with the development of Effective Field Theories. After the birth of nonrelativistic QCD (NRQCD) in 1986 [7, 8] and, in particular, of potential nonrelativistic QCD (pNRQCD) in 1998 [9, 10] one has been able to give a model-independent, QCD based approach to this field of research. Appropriate EFTs describing the quarkonium spectrum have been constructed successfully for states way below from threshold. Many of the new "XYZ" states are located close to or above threshold and, because the situation changes drastically, no EFT description has yet been constructed for most of these states.

Main Objectives

The aim of this research project is to work out a systematic, model-independent and QCD-based description of the "XYZ" states with the development of novel EFTs from the ones that we know at present. In order to do so, the following tangible objectives, which will be explained in more detail in the next section, must be completed:

1. In the determination of quark-gluon hybrids:
   (a) Determination of the $1/m^0$, $1/m^1$ and $1/m^2$ hybrid potentials at long distances within the framework of an Effective String Theory representation.
   (b) Determination of the $1/m^0$, $1/m^1$ and $1/m^2$ hybrid potentials at short distances within the framework of pNRQCD at weak coupling.
2. In the determination of mesonic molecules and tetraquarks:
   (a) Combined expansion of the QCD Lagrangian as a power series in $1/m$ and $1/N_c$ to organize in a natural way the different gauge-invariant-state contributions.
   (b) Identify nonperturbative contributions and apply different formalisms, like QCD's Dyson-Schwinger equations or QCD vacuum models, to calculate them.

Research methodology and approach

EFTs are the state-of-the-art tools for analysing physical systems that contain different separated energy scales. They constitute a suitable approach to compute physical observables in a particular energy region of a fundamental theory where some degrees of freedom decouple. Thus, calculations become easier and are systematically improvable.

The physical systems in which we are interested are the so-called heavy quarkonia, bound states of a heavy quark and a heavy antiquark. These systems are characterized by their nonrelativistic nature, *i.e.* the heavy quark bound-state velocity, v, satisfies $v \ll 1$. Moreover, at least, three widely separated scales appear: the heavy quark mass m (hard scale), the relative momentum of the bound state $p \sim mv$ (soft scale) and the binding energy $E \sim mv^2$ (ultrasoft scale). With $v \ll 1$, the following hierarchy of scales

$$m \gg p \sim 1/r \sim mv \gg E \sim mv^2$$

is fulfilled and this allows for a description in terms of EFTs of physical processes taking place at one of the lower scales. The existence of another scale, the QCD confinement scale $\Lambda_{\rm QCD}$, makes the procedure more intriguing since for energy scales close to $\Lambda_{\rm QCD}$, perturbation theory breaks down and one has to rely on nonperturbative methods. QCD vacuum models and QCD's Dyson-Schwinger equations are modern nonperturbative tools in which the supervisor and candidate are experts.

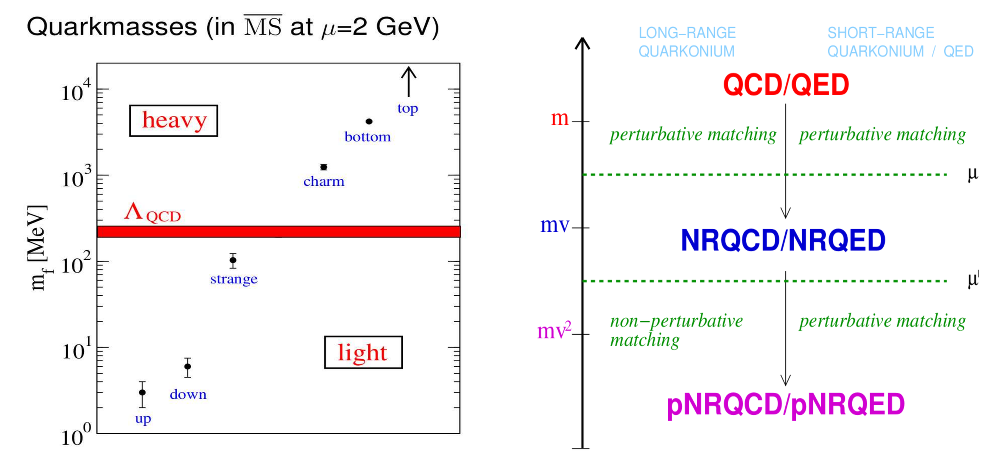

Figure 5: *Left panel* – Values of the quark masses and the QCD confinement scale $\Lambda_{\rm QCD}$; *Right panel* – Schematic view of the matching between QCD and the different EFTs for heavy quarkonium.

Quark-gluon hybrids

We consider first the case in which the dynamical degrees of freedom are only quarkonium and gluonic excitations (hybrids). At short distances, the spectrum of the hybrid energies is described in the leading multipole expansion of pNRQCD by the octet potential plus a mass scale, which is called gluelump mass [10, 11]. At large distances the energies rise linearly and the nonperturbative effects must be taken into account [12, 13].

Mesonic molecules and tetraquarks

The study within EFTs of "XYZ" states as multiquark systems requires the incorporation of light quarks as dynamical degrees of freedom. This not only incorporates new forms of matter, but also extra energy scales that intertwine with the ones already associated with the naive heavy quarkonium system. The nonrelativistic nature of the "XYZ" states still allows us to organize the QCD Lagrangian as a power series in $1/m$. In order to organize the different contributions, we propose to expand the NRQCD Lagrangian in terms of another parameter: the number of colours, N_c. EFTs that organize contributions of different physical origin have been successfully applied to the light quark sector [14].

Originality

The search of exotic matter is a topic that has fascinated all generations of nuclear and particle physicists since the establishment of QCD as the theory of the strong interaction. In this respect, Europe is situated in a privileged position for the next decade with two mayor experiments scheduled: LHCb@CERN and PANDA@GSI. In support of the experimental effort, we should also play a leading role in the theoretical counterpart. The work proposed in this project aims to develop a state-of-the-art theoretical tool able to turn the description of exotic matter from a qualitative perspective into a quantitative one.

References

[1] S. K. Choi et al. (Belle), Phys. Rev. Lett. **91**, 262001 (2003).
[2] B. Aubert et al. (BaBar), Phys. Rev. **D77**, 111101 (2008).
[3] D. Acosta et al. (CDF), Phys. Rev. Lett. **93**, 072001 (2004).
[4] V. M. Abazov et al. (D0), Phys. Rev. Lett. **93**, 162002 (2004).
[5] E. Eichten, S. Godfrey, H. Mahlke, and J. L. Rosner, Rev. Mod. Phys. **80**, 1161 (2008).
[6] N. Brambilla et al., Eur. Phys. J. **C71**, 1534 (2011).
[7] W. E. Caswell and G. P. Lepage, Phys. Lett. **B167**, 437 (1986).
[8] G. T. Bodwin, E. Braaten, and G. P. Lepage, Phys. Rev. **D51**, 1125 (1995), [Erratum: Phys. Rev. **D55**, 5853 (1997)].
[9] A. Pineda and J. Soto, Nucl. Phys. Proc. Suppl. **64**, 428 (1998).
[10] N. Brambilla, A. Pineda, J. Soto, and A. Vairo, Nucl. Phys. **B566**, 275 (2000).
[11] G. S. Bali and A. Pineda, Phys. Rev. **D69**, 094001 (2004).
[12] G. Perez-Nadal and J. Soto, Phys. Rev. **D79**, 114002 (2009).
[13] N. Brambilla, M. Groher, H. E. Martinez, and A. Vairo, Phys. Rev. **D90**, 114032 (2014).
[14] E. E. Jenkins, Phys. Rev. **D53**, 2625 (1996).

Acknowledgements

I am grateful for the supervision of Prof. Dr. Nora Brambilla and Prof. Dr. Antonio Vairo in the development of this project.