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Hot topics in hadron spectroscopy

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The modern theory of strong interactions is Quantum Chromodynamics (QCD), the quantum field theory of quarks and gluons based on the non-Abelian gauge group SU(3). It is part of the Standard Model of particle physics. QCD is well tested at high energies, where the strong coupling constant α_s is small and perturbation theory applies. In the low energy regime, however, QCD becomes a strongly coupled theory, many aspects of which are not understood. Some of the thriving questions are: How can we bring order into the rich and complex phenomena of low-energy QCD ? Are there effective degrees of freedom in terms of which we can understand the resonances and bound states of QCD efficiently and systematically ? Does QCD generate exotic structures so far undiscovered ? In order to answer these questions, dedicated experiments that test QCD in the non-perturbative regime and improve our limited understanding of these aspects of QCD are crucial. These measurements include the spectroscopy of QCD bound states, the search of new forms of hadronic matter, the study of nucleon structure and many more.

In this talk I present an overview of the experimental status of hadron physics, pointing out the open questions and how they will be addressed by future experimental facilities.

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[1] Speaker

1. Introduction

One of the most challenging and fascinating goals of modern physics is the achievement of a fully quantitative understanding of the strong interaction, which is the subject of hadron physics. Significant progress has been made over the past few years thanks to considerable advances in experiment and theory. New experimental results have stimulated a very intense theoretical activity and a refinement of the theoretical tools.

Still there are many fundamental questions that remain basically unanswered. Phenomena such as the confinement of quarks, the existence of glueballs and hybrids, the origin of the masses of hadrons in the context of the breaking of chiral symmetry are long-standing puzzles and present the intellectual challenges in our attempt to understand the nature of the strong interaction and of hadronic matter.

Hadron spectroscopy is one if the key experimental studies that will help us understand these fundamental questions.

1.1 The strong interaction and QCD

The modern theory of strong interactions is Quantum Chromodynamics (QCD), a quantum field theory of quarks and gluons based on the non-Abelian gauge group SU(3). It is part of the Standard Model of particle physics. QCD is well tested at high energies, where the strong coupling constant α_s is small and perturbation theory applies. In the low-energy regime, however, QCD becomes a strongly coupled theory, many aspects of which are not understood. Some of the central questions are: How can we bring order into the rich and complex phenomena of low-energy QCD ? Are there effective degrees of freedom in terms of which we can understand the resonances and bound states of QCD efficiently and systematically ? Does QCD generate exotic structures so far undiscovered ?

In order to deal with QCD in the non-perturbative regime, various theoretical frameworks have been developed, of which the best established are Lattice QCD (LQCD) and Effective Field Theories (EFT) [1].

Lattice QCD is an *ab initio* approach, in which the QCD equations of motion are discretized on a 4-dimensional space-time lattice and solved by means of large-scale numerical simulations on big computers. Over the past few years, LQCD has made enormous progress (e.g. gradual transition from quenched to unquenched calculations) and, thanks also to synergies with EFT (discussed below), many impressive results have been obtained with ever increasing precision.

Effective Field Theories exploit the symmetries of QCD and the existence of hierarchies of scales to provide effective Lagrangians that are equivalent to QCD for the problem at hand. We distinguish between EFT formulated in terms of quark-gluon degrees of freedom (e.g. Non-Relativistic QCD, NRQCD) and in terms of hadronic degrees of freedom (e.g. Chiral Perturbation Theory).

An additional framework within which non-perturbative problems are sometimes dealt with, even though not always rigorously justified in QCD, is represented by **potential models**. In this approach, bound systems of heavy quarks are treated in terms of non-relativistic potentials with forms that reproduce the asymptotic behaviours of QCD. Masses and widths of the bound states are obtained by solving Schrödinger's equation and can then be compared with experiment.

1.2 Experimental study of hadron physics

In order to answer the open questions, dedicated experiments that test QCD in the non-perturbative regime and improve our limited understanding of these aspects of QCD are crucial. These measurements include the spectroscopy of QCD bound states, the search of new forms of hadronic matter, the study of nucleon structure and many more.

Experimentally studies of hadron physics can be performed with different probes such as electrons, pions, kaons, protons or antiprotons. However the two main environments in which these studies have been carried out are e^+e^- and $\bar{p}p$ annihilation.

In **e^+e^- annihilation**, direct formation proceeds through an intermediate virtual photon and is therefore limited to the vector states ($J^{PC} = 1^{--}$). Other production mechanisms include photon-photon fusion, initial state radiation and *B*-meson decay. e^+e^- annihilation is characterized by low hadronic background and high discovery potential. The main disadvantage is that, as mentioned above, direct formation is limited to the vector states and this implies a limited mass and width resolution for the non-vector states.

In **$\bar{p}p$ annihilation**, thanks to the coherent annihilation of the three quarks in the proton with the three antiquarks in the antiproton, it is possible to form directly states with any (non-exotic) quantum number combination via intermediate states with the appropriate number of gluons. This makes it possible to achieve an excellent mass and width resolution for all states. $\bar{p}p$ annihilation is also characterized by a high discovery potential, but with a hadronic background that is higher than in e^+e^-. Exotic states can be produced in $\bar{p}p$ annihilation.

2. Search for exotics

One of the main challenges of hadron physics is the search for states beyond the simple quark-model picture of mesons. The most well known of such states are gluonic excitations, i.e. hadrons in which the gluons can act as principal components. These gluonic hadrons fall into two main categories: glueballs, i.e. states of pure glue, and hybrids, which consist of a $\bar{q}q$ pair and excited glue. The additional degrees of freedom carried by gluons allow these hybrids and glueballs to have exotic J^{PC} quantum numbers: in this case mixing effects with nearby $\bar{q}q$ states are excluded and this makes their experimental identification easier.

The spectrum of glueballs and hybrids can be calculated within the framework of various theoretical models and from Lattice QCD. The properties of these gluonic hadrons are determined by the long-distance features of QCD and their study will yield fundamental insight into the structure of the QCD vacuum.

So far, experimental searches for glueballs and hybrids have been carried out mainly in the mass region below 2.2 MeV/c^2, where mixing and overlap with conventional states makes their study more problematic. It would be interesting to extend the search to higher masses and, in particular, to the charmonium mass region, where light-quark states produce a structureless continuum and heavy-quark states are far fewer in number. Therefore, exotic hadrons in this mass region could be resolved and identified unambiguously.

In the remainder of this section I will report evidence of exotic hadrons in the light-quark sector: the $\pi_1(1400)$, the $\pi_1(1600)$ and the $f_0(1500)$, whereas in section 5 I will discuss some of the newly discovered states above open charm threshold.

2.1 The π_1(1400)

The first experimental report of a state with exotic quantum numbers came from the GAMS collaboration [2], which observed a $J^{PC}=1^{-+}$ state in the $\eta\pi^-$ system with a mass of approximately 1.4 GeV/c^2 using 40 GeV/c π^- to study the process $\pi^- p \rightarrow p\eta\pi^-$. A similar result was obtained by the E852 experiment, which also observed a state with the exotic quantum numbers $J^{PC}=1^{-+}$ and a mass of 1.37 GeV/c^2 using d 18 GeV/c π^- beam in the process $\pi^- p \rightarrow p\eta\pi^-$[3]. The VES collaboration obtained similar results using a 25 GeV/c pion beam [4], however they did not claim an exotic resonance, as they could not unambiguosly establish the nature of the exotic wave: the data could be fitted with a superposition of non-resonant amplitudes, so that the interpretation in terms of a new resonance was not mandatory.

The final confirmation for the existence of this exotic wave came from the Crystal Barrel experiment from analyses of the reactions $\bar{p}p \rightarrow \pi^-\pi^0\eta$ and $\bar{p}p \rightarrow 2\pi^0\eta$ [5]. The distribution of events in the Dalitz plot are poorly described if only conventional mesons are included in fit, but the addition of the exotic $\pi_1(1400)$ gives an excellent fit with deviations of the data from the final fit that are only statistical.

Thanks to the Crystal Barrel results, the existence of the $\pi_1(1400)$ is undoubted. What is still in question is its interpretation as a meson hybrid, since the value of the mass is much lower than theoretical predictions and the observation of a single decay mode is inconsistent with most models of hybrid decay. As a result there are still arguments as to wether it might be a dynamically generated resonance [6]. Other interpretations are also being considered [7].

2.2 The π_1(1600)

A second $J^{PC} = 1^{-+}$ exotic was observed by the E852 collaboration in the $\rho\pi$ [8] and $\eta'\pi$ [9] decay modes. The same state was also observed by the VES experiment in the $\rho\pi$, $\eta'\pi$ and $b_1(1235)\pi$ channels [10]. This new state has a mass of approximately 1600 MeV/c^2 and is called the $\pi_1(1600)$. The Crystal Barrel experiment confirmed the $\pi_1(1600)$ in the $b_1(1235)\pi$ final state in the reaction $\bar{p}p \rightarrow \omega\pi^+\pi^-\pi^0$ [11].

The most recent observation of the $\pi_1(1600)$ has been reported by the COMPASS experiment at CERN [12], [13]. They used a 190 GeV/c pion beam to study the process $\pi^- Pb \to \pi^-\pi^-\pi^+ Pb$. In their partial wave analysis of the 3-pion final state they observed the $\pi_1(1600)$ with a mass of (1660 ± 10 +0/-64) MeV/c^2 and a width of (269 ± 21 +42/-64) MeV/c^2, in good agreement with previous results.

On the other hand the $\pi_1(1600)$ was not observed by the CLAS experiment in 3-pion photoproduction at 6 GeV [14], meaning that this state is not strongly produced in photoproduction, or that it does not decay to 3 pions, or both.

The $\pi_1(1600)$ is less problematic then its predecessor, the $\pi_1(1400)$, since it has been observed by several experiments, in different production mechanisms and in different decay modes. Its mass and width are stable among the various experiments that have seen it.

2.3 The $f_0(1500)$

The isoscalar state $f_0(1500)$, which is now considered to be a scalar glueball candidate, was discovered by the Crystal Barrel experiment together with two other new states: the isovector $a_0(1450)$ and the isoscalar $f_0(1370)$ [15]. These discoveries were made in the study of $\bar{p}p$ annihilation at rest in the final states $\pi^0\eta\eta$, $\pi^0\pi^0\eta$ and $3\pi^0$. These discoveries were confirmed by OBELIX in the study of $\bar{p}p$ annihilation at rest [16] and by the CERN WA102 experiment in central production in pp collisions at the Omega facility [17].

The possible interpretation of the $f_0(1500)$ as a glueball candidate is not unambiguous, but rather it is done in relation to the identification of the ground-state scalar meson "nonet" of the standard quark model (meaning, of course, an SU(3) octet and a singlet). The PDG classification of the 0^{++} scalar mesons is tentative because there are more than 9 states:

- the $a_0(980)$ and $a_0(1450)$ isovectors,
- the $f_0(600)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ isoscalars,
- the $K^*_0(1430)$ and $K^*_0(1950)$ isodoublets.

However the $a_0(980)$, the $f_0(600)$ and the $f_0(980)$ are considered to be non - $\bar{q}q$ states and they are considered exotic candidates (multiquark states, $\bar{q}q$ bound states etc.). If we assume that the $f_0(1370)$, the $a_0(1450)$ and the strange $K^*_0(1430)$ are in the same SU(3) multiplet, all that is needed to complete the "nonet" is a single higher mass isoscalar, but theree are two: the $f_0(1500)$ and the $f_0(1710)$. Since LQCD calculations show that the lightest glueball is a scalar with a mass in the range 1.45 – 1.75 GeV/c^2, a possible solution is to include a glueball in the picture. Through a combined analysis of the complete set of two-body decays of the $f_0(1370)$, the $f_0(1500)$ and the $f_0(1710)$ into pseudoscalar mesons [18] it was possible to determine the mixing angles and the mass of the bare glueball. The mass was found to be $m_G = (1440 \pm 16)$ MeV/c^2. The physical states turned out to be:

$$
\begin{aligned}
f_0(1710) &= 0.39|\,gg\rangle + 0.91|s\bar{s}\rangle + 0.14|\,N\bar{N}\rangle \\
f_0(1500) &= -0.69|\,gg\rangle + 0.37|s\bar{s}\rangle - 0.62|\,N\bar{N}\rangle \\
f_0(1370) &= 0.60|\,gg\rangle - 0.13|s\bar{s}\rangle - 0.79|\,N\bar{N}\rangle
\end{aligned}
$$

where $\bar{N}N$ means $\bar{u}u$ + $\bar{d}d$. In this picture the $a_0(1450)$, $K^*_0(1430)$, $f_0(1370)$, $f_0(1710)$ would form the 0^{++} scalar "nonet", the $f_0(600)$, $f_0(980)$, $a_0(980)$ would be multiquark or $K\bar{K}$ states and the $f_0(1500)$ would be the scalar glueball. If this scenario is correct we can state that the $f_0(1500)$ is the ground-state glueball and that it was discovered by Crystal Barrel. There are, however, other possibilities: the $a_0(980)$, $K^*_0(1430)$, $f_0(980)$, $f_0(1500)$ could form the n=1 scalar "nonet", whereas the $a_0(1450)$, $K^*_0(1950)$, $f_0(1370)$, $f_0(1710)$ could form the n=2 scalar "nonet". It is clear that more data from dedicated experiments are needed to establish the existence of this and other glueball states.

3. Charmonium and bottomonium

The study of heavy quarkonium, i.e. the bound state of a heavy (c or b) quark and its antiquark, provides a powerful tool for the understanding of the strong interaction. The high quark mass makes it plausible to attempt a description of the dynamical properties of the $\bar{Q}Q$ system in terms of non relativistic potential models, in which the functional form of the potential is chosen to reproduce the asymptotic properties of the strong interaction. The free parameters in these models are to be determined from a comparison with the experimental data.

Now, more than thirty years after its discovery, heavy quarkonium continues to be an exciting and interesting field of research. The recent discoveries of new states, some of which expected ($\eta_c(2S)$, h_c, η_b, h_b, ...) and some totally unexpected ($X(3872)$ and all the new X, Y, Z states, have given rise to renewed interest in heavy quarkonium and stimulated a lot of experimental and theoretical activities.

The gross features of the spectra are reasonably well described by potential models, but these obviously do not tell the whole story: relativistic corrections are important (especially for charmonium), and other effects, such as coupled-channel effects, are significant and can considerably affect the properties of the $\bar{Q}Q$ states. To explain the finer features of the heavy quarkonium system, model calculations and predictions are made within various, complementary theoretical frameworks. Substantial progress in an effective field theoretical approach, called Non Relativistic QCD (NRQCD), has been achieved in recent years. This analytical approach makes it possible to expect significant progress in LQCD calculations, which have become increasingly more capable of dealing quantitatively with non-perturbative dynamics in all its aspects, starting from the first principles of QCD.

In the following I will report some recent results in charmonium and bottomonium spectroscopy, whereas the discussion of the new states above open charm threshold will be the subject of section 5.

3.1 The $\eta_c(2S)$

The first experimental evidence of the $\eta_c(2S)$ was reported by the Crystal Ball collaboration [19], but this finding was not confirmed in subsequent searches in $\bar{p}p$ or e^+e^- experiments. The $\eta_c(2S)$ was finally discovered by the Belle collaboration [20] in the hadronic decay of the B meson $B \to K + \eta_c(2S) \to K + (K_s K^- \pi^+)$ with a mass that was incompatible with the Crystal Ball candidate. The Belle finding was then confirmed by CLEO [21] and BaBar [22], which observed this state in two-photon fusion. The PDG [23] value of the mass is 3637 ± 4 MeV/c^2, corresponding to a surprisingly small hyperfine splitting of 48 ± 4 MeV/c^2, whereas the total width is only measured with an accuracy of 50 %. The study of this state has just started and all its properties need to be measured with improved accuracy.

3.2 The h_c(1P)

The $^1P_1$ state of charmonium, or h_c(1P), is of particular importance in the determination of the spin-dependent component of the $c\bar{c}$ confinement potential. In the non-relativistic potential model description the central potential is generally written as the sum of a Coulomb term with vector Lorentz structure (arising from one-gluon exchange) plus a confining term with scalar Lorentz structure [24]. For such a potential, the hyperfine splitting between spin-singlet and spin-triplet P-wave is very small (or vanishing). A significant deviation from this expectation could be evidence of an unexpected Lorentz structure, or for the existence of new effects, which are not included in non-relativistic potential model calculations.

The Fermilab experiment E760 reported an h_c candidate in the decay channel $J/\psi\pi^0$ [25], with a mass of 3526.2 ± 0.15 ± 0.2 MeV/c^2. This finding was not confirmed by the successor experiment E835, which, however, observed an enhancement in the $\eta_c\gamma$ final state with a mass of 3525.8 ± 0.2 ± 0.2 MeV/c^2[26]. The h_c was finally observed by the CLEO experiment [27] in the process $e^+e^- \rightarrow \psi(2S) \rightarrow h_c\ \pi^0$, with $h_c \rightarrow \eta_c + \gamma$, in which the η_c was identified via its hadronic decays. They found a value for the mass of 3524.4 ± 0.6 ± 0.4 MeV/c^2. Recently the BES III collaboration has reported a very nice h_c signal in the process $e^+e^- \rightarrow \psi(2S) \rightarrow h_c\ \pi^0$, with $h_c \rightarrow \eta_c + \gamma$, in with $\eta_c \rightarrow$ hadrons [28]. The PDG average for the h_c mass is (3525.41 ± 0.16) Mev/c^2 [23], corresponding to a hyperfine splitting $M(^3\mathrm{P}) - M(^1\mathrm{P})$ = (-0.10 ± 0.13) MeV/c^2, where $M(^3\mathrm{P})$ is the center of gravity of the ^3P_J states: $M(^3\mathrm{P})$ = (3525.3 ± 0.1) MeV/c^2 [23]. Thus, the hyperfine splitting for the P states is consistent with theoretical expectations.

3.3 Recent results in bottomonium spectroscopy

For the bottomonium system ($b\bar{b}$) the agreement between theoretical predictions and experimental findings should be better than for charmonium for several reasons. First of all the b quarks are heavier than the c quarks, therefore relativistic corrections are less important in bottomonium than in charmonium. Furthermore at this higher energy scale the QCD coupling strength α_s is smaller, which makes perturbative calculations more reliable. Finally, in the energy region of bottomonium the $Q\bar{Q}$ potential is dominated by the Coulomb term, so that uncertainties in the confinement term are less significant.

Even though bottomonium was discovered in 1977, the ground state spin-singlet **η_b(1S)** was found only recently by the BaBar collaboration in the radiative decay of the Υ(3S) [29] and Υ(2S) [30] in the process $e^+e^- \rightarrow \Upsilon \rightarrow \eta_b + \gamma$. The collaboration studied the photon energy spectrum and observed a peak at an energy of $(921.2^{+2.1}_{-2.8})$ MeV, corresponding to an η_b mass of (9391.1 ± 3.1) MeV/c^2, yielding a hyperfine splitting $M(\Upsilon(1S)) - M(\eta_b(1S))$ = (69.9 ± 3.1) MeV/c^2, in good agreement with LQCD calculations [31], but not with those of the constituent quark model (CMQ) [32]. The observation of the η_b(1S) is thus an important validation of LQCD predictions.

The Belle collaboration recently reported the observation of the **h_b(1P)** and **h_b(2P)** states of bottomonium [33] produced in the reaction $e^+e^- \rightarrow h_b(\mathrm{nP})\pi^+\pi^-$ using a 121.4 fb^{-1} data sample collected at energies near the Υ(5S). They measured masses $M(h_b(1\mathrm{P})) = (9898.3 \pm 1.1\ ^{+1.0}_{-1.1})$ MeV/c^2 and $M(h_b(2\mathrm{P})) = (10259.8 \pm 0.6\ ^{+1.4}_{-1.0})$ MeV/c^2, which correspond to P-wave hyperfine splittings of (1.6 ± 1.5) MeV/c^2 and $(0.5^{+1.6}_{-1.2})$ MeV/c^2, respectively. These hyperfine splittings are consistent with zero and in agreement with theoretical expectations. The h_b(1P) and h_b(2P) are observed with significances of 5.5σ and 11.2σ, respectively.

The BaBar collaboration had previously reported the results of a search for the h_b(1P), performed using 122 million Υ(3S) events in the decay: $\Upsilon(3\mathrm{S}) \rightarrow \pi^0 h_b(1\mathrm{P})$, with $h_b(1\mathrm{P}) \rightarrow \gamma\eta_b(1\mathrm{S})$ [34]. The experiment observed an excess of events above background in the distribution of the recoil mass against the π^0 at mass (9902 ± 4 ± 2) MeV/c^2. The width of the observed signal is consistent with experimental resolution and its significance is 3.1σ. The resulting hypefine splitting with respect to the center of gravity of the χ_b(1P) states is (2 ± 4 ± 2), consistent with zero and with model predictions [35], [36]. The mass values for the h_b(1P) measured by BaBar and Belle are in good agreement with each other.

4. Open charm mesons

Open charm mesons, consisting of a heavy and a light constituent, are very interesting objects for the understanding of the strong interaction, since they combine the aspect of the heavy quark as a static colour source on one side and the aspect of chiral symmetry breaking and restoration due to the presence of the light quark on the other side.

Based on earlier observations of low-lying D meson states, the phenomenological quark model was thought to be able to provide an accurate description of the excitation spectra of heavy-light systems. The experimentally observed spectrum of non-strange D mesons [37] was consistent with the expected pattern of states (although for some of the states the spin-parity assignment could not be given) and it was believed that the same model could predict also the unobserved D meson states with reasonable precision.

The situation changed drastically over the past nine years, with a series of unexpected discoveries of new states which did not fit in the quark model predictions. The first state to be discovered was the narrow D_s(2317), which was observed in e^+e^- annihilation by BaBar in the decay mode $D_s^+\pi^0$ [38] and shortly afterwards confirmed by CLEO [39] and Belle [40]. At the same time CLEO found a new, narrow state D_s(2460) [39] decaying to $D_s^{*+}\pi^0$. This state was subsequently confirmed by Belle [40] and BaBar [41] [42]. The width of both states is small, since the D_s(2317) lies below the DK threshold (hence it cannot decay by kaon emission), and the D_s(2460) lies below the D^*K threshold and, with $J^P=1^+$, it cannot decay by kaon emission either. The situation became even more complicated when BaBar discovered the D_{sJ}(2860) decaying to D^0K^+ and D^+K_S [43], Belle discovered the D_{sJ}(2710) decaying to D^0K^+ [44], and BaBar found a new, broad state D_{sJ}(3040) [45].

These unexpected discoveries attracted much interest in the hadron physics community, since the new states do not fit into the quark model predictions for heavy-light systems, in contrast to the previously known D meson states. A lot of theoretical activity is going on trying to understand the nature of these newly discovered mesons.

5. New states above the open charm threshold

The energy region above the $\bar{D}D$ threshold is rich in interesting new physics. In this region one expects to find the D-wave states. Of these only the 1^3D_1, identified with the ψ(3770) resonance, has been found. The J=2 states (1^2D_2 and 1^3D_2) are predicted to be narrow, because parity conservation forbids their decay to $\bar{D}D$. In addition to the D states, the radial excitations of the S and P states are predicted to occur above the open charm threshold. None of these states have been positively identified, with the possible exception of the χ_{c2}(2P), which has been observed with a mass of approximately 3930 MeV/c^2 (formerly known as the Z(3930)) [46], [47].

On the other hand a number of new states have recently been found at the B-factories (and confirmed by other e^+e^- machines and at the Fermilab Tevatron) whose nature is not yet understood. These states, which are produced through many different mechanisms (such as B-meson decay, Initial State Radiation (ISR), photon-photon fusion, double-charmonium), are usually associated with charmonium because they decay predominantly into charmonium states (such as the J/ψ or the ψ(2S)) and $\bar{D}$D, but their interpretation is far from obvious. In fact, some of them might be some previously unobserved form of hadronic matter, such as molecules, multiquark states or even charmonium hybrids. It is therefore understandable that these discoveries have stimulated a lot of theoretical and experimental activity and that they have played a significant role in determining a true renaissance of hadron physics.

More than ten such states have been discovered over the past few years. In the following I will briefly discuss three of them: the X(3872), the Y(4260) and the $X(4430)^{\pm}$.

5.1 The *X*(3872)

The X(3872) was discovered by Belle [48] in the hadronic decay of the B meson $B^{\pm}\to K^{\pm}(J/\psi\pi^+\pi^-)$, with $J/\psi\to\mu^+\mu^-$ or e^+e^-. The new state showed up as a peak in the ($J/\psi\pi^+\pi^-$) invariant mass spectrum and presented two striking features: it was extremely narrow ($\Gamma < 2.3$ MeV at the 90 % confidence level) and its mass (3872.0 ± 0.6 ± 0.5) MeV/c^2) was extremely close the D^0D^{0*} threshold. This state was subsequently confirmed by BaBar [49], CDF [50] and D0 [51]. As the first new state to be discovered the X(3872) is also the best studied, but, despite this, its nature is still a matter of debate. Subsequent to its discovery additional decay modes have been observed: $J/\psi\gamma$, $J/\psi\pi^+\pi^-\pi^0$ [52] and $\bar{D}^0D^0\pi^0$ [53] [54]. The decay into $J/\psi\gamma$ implies positive charge conjugation. An analysis by Belle of the $J/\psi\pi^+\pi^-$ decay strongly favors the quantum number assignment $J^{PC} = 1^{++}$ [52] while not excluding 2^{-+}, a conclusion which has been confirmed by an analysis by CDF [55]. Furthermore the $\pi^+\pi^-$ invariant mass distribution in the $J/\psi\pi^+\pi^-$ decay is strongly peaked at the ρ mass which, together with the observation of the $J/\psi\omega$ decay mode, would seem to imply isospin violation.

As we noted before, the exact nature of this state remains unknown: while the absence of radiative decays makes the conventional charmonium interpretation less likely, the closeness to the D^0D^{0*} threshold suggests that it might be a molecular or tetraquark state, but other interpretations are also possible [24].

5.2 The *Y*(4260)

This state was discovered by the BaBar collaboration using the ISR technique in the process $e^+e^- \to \gamma_{ISR}J/\psi\pi^+\pi^-$ [56] and subsequently confirmed by CLEO [57] and Belle [58]. It is a wide state, with a mass of (4263^{+8}_{-9}) MeV/c^2 and width of (95 ± 14) MeV [23]. Its production mechanism fixes the quantum numbers to be $J^{PC} = 1^{--}$. The absence of an available vector slot in the charmonium spectrum together with the absence of open charm decay modes seems to indicate that this is not a conventional $c\bar{c}$ state. One of the hypotheses which are being considered concerning the nature of the *Y*(4260) is that of a charmonium hybrid, since LQCD calculations predict that the lowest-lying charmonium hybrid should have a mass around 4200 MeV/c^2. Further studies are however needed to confirm this hypothesis.

5.3 The *X*(4430)$^\pm$

The *X*(4430)$^\pm$, formerly known as the *Z*(4430), is both the most controversial and the most exotic of the new states. It was discovered by Belle in the decay $B \to K\pi^\pm\psi(2S)$ [59] [60]. They observed a prominent peak in the $\pi^\pm\psi(2S)$ invariant mass distribution at a mass of approximately 4433 MeV/c^2 and a narrow width. However the BaBar collaboration failed to find any significant evidence of this state [61] and therefore some doubts remain about its true existence. If confirmed, this would be the first charmonium-like state having a non-zero electric charge and it would have an exotic structure, since the minimal quark content should be $(c\bar{c}u\bar{d})$.

6. Outlook and conclusions

Hadron physics continues to be an exciting field of research and, over the next few years, many experimental facilities will produce first-rate results: the BES III experiment is running at the Beijing Electron-Positron Collider, the LHC expreriments at CERN have been taking data for more than one year and have already shown the excellent quality of their hadron physics results. Concerning e^+e^- colliders: the Belle II and SuperB projects have both been approved and will continue to provide a wealth of results like their predecessors experiments Belle and BaBar. Finally Jefferson Lab is working towards its 12 GeV program, where, in addition to hadron structure, two experiments will produce outstanding hadron physics results: GlueX in Hall D and CLAS12 in Hall B.

Towards the end of the decade the lead will be taken by the $\bar{\text{P}}$ANDA experiment at FAIR, to which the remainder of this section will be dedicated.

6.1 The $\bar{\text{P}}$ANDA experiment at FAIR

The Facility for Antiproton and Ion Research (FAIR) will be built as a major upgrade of the existing GSI laboratory in Germany. It will provide antiproton beams of the highest quality in terms of intensity and resolution.

The $\overline{\mathrm{P}}$ANDA experiment (Pbar ANnihilations at DArmstadt) will use the antiprotons from the High-Energy Storage Ring (HESR) colliding with an internal proton target and a general purpose spectrometer to carry out a rich and diversified hadron physics program, of which spectroscopy will be a major part. The experiment is being designed to fully exploit the extraordinary potential arising from the availability of high-intensity, cooled antiproton beams. Significant progress beyond the present state-of-understanding of the field is expected thanks to improvements in statistics and precision of the data.

The main items in the $\overline{\mathrm{P}}$ANDA physics program are: the spectroscopy of QCD bound states, non-perturbative QCD dynamics, the study of hadrons modifications in nuclear matter, hypernuclear physics and nucleon structure.

6.1.1 The $\overline{\mathrm{P}}$ANDA detector

In order to carry out it physics program the $\overline{\mathrm{P}}$ANDA detector must satisfy a number of requirements: it must provide (nearly) full solid angle coverage, it must be able to handle high rates (2×10^7 annihilations/s) with good particle identification and momentum resolution for γ, e, μ, π, K and p. Additional requirements include vertex reconstruction capability, a pointlike interaction region, efficient lepton identification and excellent calorimetry (both in terms of resolution and of sensitivity to low-energy photons).

The antiprotons circulating in the HESR impinge on an internal hydrogen target (either pellet or cluster jet), while for the nuclear part of the experimental program, wire or fibers will be used. The apparatus consists of a central detector, dubbed the target spectrometer (TS), and a forward spectrometer (FS).

The TS, which will measure particles emitted at laboratory angles larger than 5°, will be located inside a solenoidal magnet that provides a field of 2T. Its main components will be a microvertex silicon detector, a straw-tube central tracker, an inner time-of-flight telescope, a cylindrical DIRC (Detector of Internally Reflected Light) for particle identification, an electromagnetic calorimeter consisting of $PbWO_4$ crystals, a set of muon counters and of multiwire drift chambers.

The FS will detect particles emitted at polar angles below 10° in the horizontal and 5° in the vertical direction. It will consist of a 2 T·m dipole magnet, with tracking detectors (straw tubes or multiwire chambers) before and after the magnet for charged particle tracking. Particle identification will be achieved by Čerenkov and time-of-flight detectors. Other components of the FS are an electromagnetic and hadron calorimeters.

All detector components are currently being developed as part of a very active R&D program.

6.1.2 Physics Performance

For many of the measurements that are part of the $\overline{\mathrm{P}}$ANDA physics program, the large hadronic background in $p\bar{p}$ annihilation represents a major challenge. The capability of observing a particular final state depends on the signal-to-background ratio. It is therefore necessary to test the capability to efficiently separate signal from background sources with cross sections that are orders of magnitude larger than the channels of interest. A full detector simulation has been developed to study physics channels of interest and the main sources of background, to assess the capability of background reduction at the required levels and to prove the feasibility of hadron spectroscopy studies in $\overline{\mathrm{P}}$ANDA.

In the following we will present the results obtained for the full simulation of some benchmark channels. A more complete discussion can be found in the $\overline{\mathrm{P}}$ANDA Physics Performance Report [1].

6.1.2.1 Particle decays with a J/ψ in the final state

The identification of states decaying into J/ψ is relatively clean due to the presence of a lepton-antilepton pair in the final state (l^+l^-). These channels can be used to study states, like the $\psi(2S)$, χ_{cJ}, $X(3872)$, $Y(4260)$, that contain a J/ψ among the decay products. These analyses rely on the positive identification of the lepton-antilepton pair (e^+e^- or $\mu^+\mu^-$) in the final state for the reconstruction of $J/\psi \to l^+l^-$, where the main background is represented by pairs of tracks, like $\pi^+\pi^-$, associated with large energy deposition in the electromagnetic calorimeter.

The event selection is based on topological cuts, particle identification and kinematic fitting. A resolution in the range 4 – 8 MeV/c^2 can be obtained on the J/ψ mass.

As a case study, the $J/\psi\pi^+\pi^-$ channel has been analyzed in some detail. This channel is particularly significant since many of the recently discovered states at the B-factories (such as, e.g., the $X(3872)$ and the $Y(4260)$) were observed in this decay mode. The $\overline{\mathrm{P}}$ANDA performance for this channel has been analyzed in detail through a complete simulation of the final state in the detector: the overall efficiency for the complete selection (including acceptance) has been found to be around 30 % over the region of interest (3.5 to 5.0 GeV). The main source of hadronic background for this channel comes from $\bar{p}p \to \pi^+\pi^-\pi^+\pi^-$, where two pions can be erroneously identified as electrons and contaminate the signal. At a center-of-mass energy of 4.26 GeV, the cross section for this process is of the order of few tens of μb [62], which is 10^6 times larger than the expected signal, estimated from Fermilab E835 results. The rejection power for this background is found to be of the order of 10^6 and the signal-to-background ratio is about 2, making this channel well identified in $\overline{\mathrm{P}}$ANDA.

6.1.2.2 Charmonium decays to 2 and 3 photons

One of the most promising channels for the observation of the h_c is the electromagnetic transition to the ground state via the decay $h_c \to \eta_c\gamma$, where the η_c can be detected through many decay modes. Among these, $\eta_c \to \gamma\gamma$ is characterized by a reasonably clean signature, due to the presence of two energetic photons in the detector with the η_c mass. The main disadvantage is the huge hadronic background coming from $\bar{p}p$ annihilation into channels containing multiple π^0s and ηs, that produce hard photons in the final state with no charged tracks. The simulation has shown that an event selection based on topological and kinematical cuts yields a signal efficiency of approximately 8 % (including detector acceptance) and a background suppression of the order of 10^6 or better. The production cross section observed by E835 [63], although with large uncertainties, combined with the present background suppression, yields an estimate of the order of 0.9 or more for the signal-to-background ratio and confirms the feasibility of this measurement with $\overline{\mathrm{P}}$ANDA.

6.1.2.3 Study of $h_c \rightarrow \eta_c\gamma \rightarrow 4K\gamma$

The process $\bar{p}p \rightarrow h_c \rightarrow \eta_c\gamma \rightarrow \phi\phi\gamma$ with $\phi \rightarrow K^+K^-$ has been studied as a benchmark channel with light hadrons in the final state. The main contribution to the background comes from the reactions $\bar{p}p \rightarrow 4K\pi^0$, $\bar{p}p \rightarrow \phi 2K\pi^0$, $\bar{p}p \rightarrow \phi\phi\pi^0$, with one photon from the neutral pion decay undetected. As usual, the selection is based on topological and kinematical cuts as well as particle ID. The overall efficiency of the event selection is of order of 25 %.

Since no experimental data is available for the three background cross-sections, the background contribution was estimated by means of Monte Carlo simulations using the Dual Parton Model generator (DPM). These simulations have shown that a signal-to-background ratio of 8 or larger can be obtained for each of the background channels.

Using this signal-to-background value it was possible to estimate the $\overline{\mathrm{P}}$ANDA sensitivity to the h_c width measurement. A few scans of the h_c have been simulated for different values of the $\Gamma(h_c)$. The expected shape of the measured cross-section is obtained from the convolution of the Breit-Wigner resonance curve with the normalized beam energy distribution plus a background term. With 5 days of data taking per point at the highest beam resolution ($\Delta p/p = 10^{-5}$, where p is the antiproton beam momentum) it will be possible to reconstruct the h_c resonance shape and to measure its witdth with an accuracy of the order of 0.2 MeV for $\Gamma(h_c)$ values in the range 0.5 – 1.0 MeV.

6.1.2.4 Study of $\bar{D}D$

The ability to reconstruct the $\bar{D}D$ final state is important for the major part of the $\overline{\mathrm{P}}$ANDA physics program dealing with topics such as the study of charmonium above open charm threshold, for open charm spectroscopy, the search for hybrids and CP violation studies. The study of the process $\bar{p}p \rightarrow \bar{D}D$ as a benchmark channel is important also to assess the capability to separate hadronic decay channels from the large hadronic background. Two benchmark channels have been studied in detail:

- $\bar{p}p \rightarrow D^+D^-$ (with $D^+ \rightarrow K^-\pi^+\pi^+$)
- $\bar{p}p \rightarrow D^{*+}D^{*-}$ (with $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$);

the first one was simulated at the $\psi(3770)$ and the second at the $\psi(4040)$ masses. We assume a conservative estimate for the charmonium production cross section above the open charm threshold to be of the order of 3 nb for D^+D^- and 0.9 nb for $D^{*+}D^{*-}$ production.

The event selection for D^+D^- is based on the detection of the charged tracks and the reconstruction of the D meson candidates. A kinematical fit of the two D candidates to the beam momentum-energy is applied and the events are then selected with a cut on the fit Confidence Level. A similar selection is done for $D^{*+}D^{*-}$, with an intermediate step for D^0 reconstruction.

The background was simulated using the DPM to produce inelastic reactions in $\bar{p}p$ annihilations. A background suppression of the order of 10^7 was achieved. A detailed study of specific background reactions was also performed, in particular the non-resonant production of $K^+K^-2\pi^+2\pi^-$, which has a cross-section that is 10^6 times larger than the D^+D^- signal. It was shown that a cut on the longitudinal and transverse momenta of the D mesons can reduce the background by a factor of 26, the remaining events leave a non-peaking background, part of which can be removed with a cut on the reconstruced decay vertex location, reaching a final signal-to-background ratio of the order of 1, with an overall signal efficiency of the order of 8 %.

With these assumptions, a conservative estimate of the number of reconstructed events per year of $\overline{\text{P}}$ANDA operation is of the order of 10^4 for D^+D^- and 10^3 for $D^{*+}D^{*-}$.

6.2 Conclusions

Hadron spectroscopy is an invaluable tool for a deeper understanding of the strong interaction and QCD.

Considerable advancement in our knowledge of hadron spectroscopy has been achieved over the past two decades thanks to many experiments at hadron machines and e^+e^- colliders, as well as tremendous progress in theory.

For the near and medium term future, first-rate results are expected from LHC and e^+e^- colliders (BES III, B-factories, Super Flavour Factories).

In the next years the $\overline{\text{P}}$ANDA experiment at FAIR will take the lead in hadron physics, exploiting antiproton beams of unprecedented quality to carry out high-precision, systematic measurements in spectroscopy and nucleon structure.

We can look forward to many exciting years of hadron physics !

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