Exploring QCD: from LEAR to GSI

T. Barnes

Physics Division, Oak Ridge National Laboratory
and
Department of Physics and Astronomy, University of Tennessee

Abstract

In this invited contribution I briefly review some of the principal topics in hadron spectroscopy that were studied at the CERN low-energy antiproton facility LEAR, from its beginnings in the early 1980s to the present. These topics include the nature of multiquark systems, the short-ranged nuclear force, and gluonic hadrons, including glueballs and hybrids. Lessons we have learned from the LEAR program that are relevant to the future GSI project are given particular emphasis.

Key words: QCD spectroscopy, antiproton, exotics, hybrids, glueballs, quarkonia

1 Introduction

The title suggested for this invited talk included the phrase “Testing QCD”. To me this implies a rather better theoretical understanding of low-energy QCD spectroscopy than we have at present. As this largely historical overview will show, experimental discoveries in this field have repeatedly surprised theorists, and the resonances found often bear only a passing resemblance to our predictions. In light hadron spectroscopy, we are still exploring unknown territory.

The fact that we have so much to learn from experiment is one of the great attractions of this field. Although the starting point of the QCD lagrangian is universally accepted, even our best theoretical methods (specifically lattice
gauge theory) currently involve uncontrolled approximations, and the resulting predictions need not closely resemble what is found experimentally in the real hadron spectrum. Progress in lattice gauge theory and in the development of models of hadrons continues to benefit from close comparisons to experiment.

Much of the recent experimental progress in hadron spectroscopy has come from nucleon-antiproton collisions, especially at LEAR. The parallel experimental efforts using meson beams, $e^+e^-$ and other initial states have as always been valuable as independent confirmations of discoveries, or for suggestions regarding interesting final states for detailed studies. In this review I will sketch the history of our ideas regarding hadron spectroscopy, first as it was understood at the beginning of the LEAR program, then how it developed and was modified by results from LEAR and elsewhere, and finally where we stand today. I will conclude with a few suggestions for interesting topics that might be addressed at the future GSI antiproton facility.

2 Classification of hadrons

Our general classification of hadrons as color-singlet states of quarks and gluons has not changed since the early days of QCD. The simplest such states are the conventional quark model $qqq$ baryons and $q\bar{q}$ mesons, and we have ca. $10^2$ examples of experimental resonances that appear to be well-described as such states.

In addition to these simplest possible color singlets, other combinations of quarks, antiquarks and gluons also span color singlets, and might in principle be expected to appear as resonances in the experimental light hadron spectrum. These include the $q^2\bar{q}^2$ multiquark states known as “baryonia”, pure glue basis states such as $gg$ and $ggg$ “glueballs”, and mixed quark-and-gluon states known as “hybrids”, which include $q\bar{q}g$ hybrid mesons and $qqqg$ hybrid baryons. Of course these simple basis states will mix when the quantum numbers allow, so that we expect the physical resonances to be strongly mixed linear combinations of such basis states. The level of configuration mixing and the types of basis state that best describe the physical resonances are at present open and poorly understood issues.
3 LEAR hadron physics goals

3.1 Baryonia: LEAR ab initio

The principal initial motivation for LEAR was to search for the novel “baryonium” $q^2\bar{q}^2$ mesons. These states had been studied in many models, such as the MIT bag model, quark potential models, color chemistry models, and so forth, and a very rich spectrum of discrete levels was predicted.

The purported connection of $q^2\bar{q}^2$ baryonium states to $p\bar{p}$ annihilation is quite interesting, because it introduces a crucial and still poorly understood topic, which is the nature of the short-ranged nuclear force. Progress in understanding this force should be a major goal of future studies in antiproton physics, for example at GSI. The argument leading to a strong coupling between $p\bar{p}$ annihilation and $q^2\bar{q}^2$ resonances was the belief that the short-ranged nucleon-nucleon repulsive core was due primarily to vector meson ($\omega$) exchange. This was discussed for example by Richard [1] at the 1982 Erice LEAR meeting. If this description is accurate, one can presumably similarly describe the corresponding $p\bar{p}$ $\omega$-exchange force after a G-parity transformation, and an attractive core is found which supports deeply bound $p\bar{p}$ states. (Hence the name “baryonia”.) The connection to $q^2\bar{q}^2$ requires a bit more imagination. If one takes a quark line diagram for $p\bar{p} \rightarrow p\bar{p}$ with $q\bar{q}$ meson exchange in t-channel, and deforms the exchange so the $q$ and $\bar{q}$ lines are widely separated, one sees intermediate $q^2\bar{q}^2$ states in s-channel. Thus one can argue that if the short-ranged nuclear force is indeed due to t-channel vector meson exchange, there should be deeply bound $p\bar{p}$ states with a strong coupling to $q^2\bar{q}^2$. Since there were many models that suggested a rich spectrum of discrete $q^2\bar{q}^2$ levels in the 1970s, a rather undermotivated identification of bound $p\bar{p}$ states with $q^2\bar{q}^2$ was suggested.

Even more remarkably, it was widely suggested (with little support from theory) that these light $q^2\bar{q}^2$ resonances might be very narrow ($\Gamma_{tot} = \text{few MeV}$), and that these narrow states might be evident for example in the total $p\bar{p}$ cross sections. Ambiguous evidence for narrow baryonium candidates such as the “S(1936)” was frequently cited in the literature of the early 1980s [2]. One of the clear experimental conclusions of the subsequent LEAR program was the absence of such narrow states [3].

Unfortunately the confining interaction required to give this discrete $q^2\bar{q}^2$ spectrum was a model artifact; $q^2\bar{q}^2$ states can in practice simply “fall apart” into two separate $q\bar{q}$ mesons when energetically allowed, and hence need not exist as resonances. This erroneous prediction of a rich spectrum of light multiquark resonances was referred to by Isgur as the “multiquark fiasco” [4].
We note in passing that for sufficiently large quark mass “heavy-light” $Q^2q^2$ bound states do lie below these fall-apart thresholds, and hence should exist as resonances [5]. However it is unclear whether $c$ quarks are sufficiently heavy to form such bound states; one might instead require a much more difficult study of the $b^2q^2$ system.

The fact that predictions of light $q^2q^2$ states relied on a meson-exchange model of short-ranged nuclear forces highlights the importance of understanding the physical mechanisms underlying these forces. An alternative description at the quark-gluon level, which has been confirmed by many independent theoretical calculations, finds instead that the nucleon-nucleon repulsive core is well described by the one-gluon exchange spin-spin contact interaction. If this picture is correct, there is no simple relation between the $pp$ and $p\bar{p}$ interactions, and there need not be deeply-bound $pp$ bound states. Evidently these different models of interhadron forces lead to very different predictions of the bound state spectrum. It is clearly of great importance to determine which mechanism, if either, is dominant at short distances. Studies of the reaction $p\bar{p} \rightarrow \Lambda\bar{\Lambda}$ at LEAR have attempted to clarify this issue, and the most recent results were presented at this meeting. Unfortunately the conclusions are rather ambiguous at present; neither meson exchange nor quark-gluon models in their present incarnations give a good description of the data [6]. This may not be surprising, since one would expect meson-exchange (e.g. kaon-exchange) to correctly describe the long-distance part of the interaction, but this picture should fail at sufficiently short distances where the baryon and antibaryon three-quark and three-antiquark wavefunctions experience considerable overlap.

3.2 Glueballs

Not long after the beginning of planning for the LEAR program, much interest arose in the possibility of observing gluonic excitations in the meson spectrum [7], in addition to the multiquark states that were the original motivation for LEAR. Theorists noted that color-singlet states could be formed in the pure glue sector from $|gg\rangle$, $|ggg\rangle$ . . . states, and in addition mixed quark-and-gluon color-singlet basis states such as $|q\bar{q}g\rangle$ were allowed. The associated resonances are now known as glueballs and hybrids respectively. Detailed predictions for the spectra of these states were published, most notably using the MIT bag model [8] and lattice gauge theory (LGT) [9].

Interest in glueballs at LEAR also arose from the experimental $J/\psi$ radiative decay program, which had identified the glueball candidates “$\upsilon$” (now the $\eta(1440)$, and excluded as a glueball due to its low mass) and the “$\theta$”, initially thought to be $2^{++}$ but now known as the $f_0(1710)$, and widely considered a scalar glueball candidate. It is amusing that LGT calculations at that time
Fig. 1. Dalitz plot of $p\bar{p} \rightarrow \pi^0\pi^0\pi^0$ showing the $f_0(1500)$ glueball candidate [11].

claimed $0^{--}$ and $2^{++}$ glueballs at masses of ca. 1420 and 1620 MeV respectively, consistent with these newly discovered states.

One might expect to find the most striking evidence of new states in the glueball sector, since these are the farthest removed physically from conventional $q\bar{q}$ states. In practice this does not appear to be the case. The theoretical “pure glue” glueball spectrum is now quite well understood from LGT studies [10], and is rather sparse at the energies of relevance to LEAR; the only glueball predicted to have a mass below 2 GeV is a scalar, at a mass of about 1.7 GeV. The next glueballs predicted with increasing mass are $0^{--}$ and $2^{++}$ states near 2.5 GeV; the first exotic encountered in the LGT glueball spectrum is a $2^{--}$ state, at a very high mass (near 4 GeV). As experimental studies of the light meson spectrum are almost exclusively concerned with the region below 2.5 GeV, the subject of glueballs specializes to the search for a single $I=0$ scalar state. Unfortunately, this sector is one of the most obscure in the light meson spectrum.

There are currently two candidates for the scalar glueball, the $f_0(1500)$ from LEAR and the $f_0(1710)$, originally reported in $J/\psi$ radiative decays.

The $f_0(1500)$ is clearly visible in the beautiful high-statistics $p\bar{p} \rightarrow 3\pi^0$ Dalitz plot shown in Fig.1, made famous by the Crystal Barrel Collaboration [11].
This state may be the single most interesting discovery of the LEAR hadron physics program. As an “extra” I=0 scalar state near 1.7 GeV it is a natural glueball candidate, and the width of ≈ 100 MeV appears anomalously small for a light $^3P_0$ $q\bar{q}$ quark model state.

There are problems however with identifying either the $f_0(1500)$ or the $J/\psi$-radiative state $f_0(1710)$ with the scalar glueball. Naively one would expect approximate SU(3) flavor symmetry in the decay couplings of a glueball, which should lead to relative PsPs couplings of $\pi\pi : KK : \eta\eta : \eta'\eta' = 3 : 4 : 1 : 0 : 1$. (These are branching fractions divided by phase space.) Since the observed branching fraction ratios are $B_{KK/\pi\pi}(f_0(1500)) = 0.19 \pm 0.07$ and $B_{\pi\pi/KK}(f_0(1710)) = 0.39 \pm 0.14$, neither state decays with the nearly equal $\pi\pi$ and $KK$ branching fractions expected for a glueball. This problem may be due to mixing between $q\bar{q}$ and $G$ basis states [12], or it may imply that there is strong momentum dependence in these decay couplings.

### 3.3 Hybrids

Shortly after interest arose in the glueball spectrum it was realized that a rather richer spectrum of $q\bar{q}g$ “hybrid meson” states should also exist. There are many more experimental opportunities to search for hybrids than glueballs because (light) hybrids span flavor nonets, and it was also found that the lightest hybrid multiplet includes very characteristic $J^{PC} = 1^{-+}$ exotic quantum numbers [13]. The bag model estimates for the mass of this light hybrid exotic were typically about 1.5 GeV. This work was followed by studies using the flux-tube model [14] and LGT [15], which find a rather higher mass of about 1.9-2.1 GeV for this $1^{-+}$ exotic.

The flux-tube model has also been applied to strong decays of hybrids [16], which leads to the well-known flux-tube selection rule that light hybrids typically decay preferentially into S+P final states, in which one final $q\bar{q}$ meson has an orbital excitation. (Note however that the present exotic hybrid candidates do not support this rule.)

Experimentally there has been great interest in searching for the very characteristic $J^{PC} = 1^{-+}$ exotics, especially with I=1 flavor. Two such states have been reported, a $\pi_1(1400)$ and a $\pi_1(1600)$. Note that both candidates are rather lower in mass than the LGT and flux-tube expectations of $M \approx 1.9-2.1$ GeV. The $\pi_1(1400)$ (first reported by VES and BNL in $\eta\pi$ [17] after a long history of studies of this channel) is the more controversial, since this is a rather weak, broad signal in a channel that is dominated by the $a_2(1320)$. This state has
Fig. 2. A difference Dalitz plot of $n\bar{p} \rightarrow \pi^+\pi^0\eta$ showing structures (upper panels) that are accounted for by assuming a broad $\pi_1(1400)$ exotic resonance (lower panels) [18].

apparently been confirmed in $p\bar{p}$ annihilation at LEAR by the Crystal Barrel Collaboration [18]; it is notable that the coupling of $p\bar{p}$ to this candidate exotic is quite large, which argues in favor of $p\bar{p}$ facilities as an approach for the study of exotic mesons. The second $J^{PC} = 1^{-+}$ exotic candidate is the $\pi_1(1600)$, also reported by VES and E852 [19], in the channels $b_1\pi$, $\eta\pi$ and $\eta'\pi$. The $\pi_1(1600)$ appears remarkably clearly in the recent analysis of the $\eta'/\pi^-$ channel by E852 [20], due largely to the weak coupling of $\eta'/\pi$ to other resonances in this mass region. (Fig.2 of this reference is our Fig.3; the $\pi_1(1600)$ is in panel c.) This very clear evidence for a $J^{PC}$-exotic is strong motivation for future searches for the flavor partners of this state, as well as the other $J^{PC}$ states expected near mass if this is indeed a light hybrid. The flux-tube model anticipates 72 approximately degenerate states in the lightest hybrid multiplet, and many of these should be narrow enough to be observable. If the partner states are not observed, the $\pi_1(1600)$ would appear doubtful as a hybrid candidate.
Fig. 3. The $\pi_1(1600)$ reported in $\pi^- p \rightarrow \eta' \pi^- p$ by the E852 Collaboration [20]. The exotic $1^{++}$ wave is shown in the bottom left panel.

3.4 Quarkonia

Although the study of conventional $q\bar{q}$ mesons does not carry the same excitement as the discovery of new types of states, the identification of higher-mass $q\bar{q}$ mesons ($q = u, d, s$) has nonetheless been one of the most important experimental activities at LEAR and other hadron machines over the previous two decades. The identification of any anomalous states will be much easier if we have a reasonably complete description of the background of “ordinary” $q\bar{q}$ mesons. Since non-$q\bar{q}$ mesons are expected to first appear in the mass range 1.5-2.0 GeV, identification of the conventional quark model states over this mass range is a correspondingly important exercise.

Many of these $q\bar{q}$ states were unknown or poorly established until the last decade, and much progress has been made recently. For example, of the 44 $n\bar{n}$ mesons ($n = u, d$) predicted to lie below 2.1 GeV (spanning the 1S, 2S, 3S, 1P, 2P, 1D and 1F $n\bar{n}$ multiplets), about 35 have now been reported. Recent discoveries include candidates for the 2P and 1F multiplets that lie in the crucial 1.5-2.0 GeV mass range. These multiplets are now experimentally
about 80% complete, which is comparable to how well we know the excited kaon spectrum in this mass range (ca. 16 of 22 states known). In comparison the \( s\bar{s} \) spectrum is a *terra incognita*, with only about 6 of these 22 states well established.

We do note that there is evidence of disagreement between theory and experiment in the light quarkonium spectrum, notably in radial excitations. One important discrepancy is in the prediction of the energy scale of radial excitations of \( q\bar{q} \) states. For example, Godfrey and Isgur [21] predicted that the 2P excitation of the light \( h_1(1170) \) should lie at 1.78 GeV, whereas the candidate reported recently by E852 is at 1.59 GeV [22]. The reports of possible hybrids near 1.4 and 1.6 GeV suggest that we may find a rich overpopulation of the meson spectrum relative to the predictions of the \( q\bar{q} \) quark model beginning at about this mass. High-statistics partial wave analyses will be important for the identification of conventional \( q\bar{q} \) mesons as well as the non-exotic hybrids, glueballs, multiquark systems, and mixing effects between these states that may be evident in this mass range.

4 From LEAR to GSI

To the extent that the intended purpose of LEAR was to identify new types of hadrons, it has been successful. We now have two glueball candidates, the \( f_0(1500) \) (from LEAR) and the \( f_0(1710) \), and two exotics, the \( \pi_1(1400) \) (confirmed by LEAR) and the \( \pi_1(1600) \). There is no clear evidence for multiquarks as originally proposed. We note in passing however that the \( f_0(980) \) and \( a_0(980) \) states were clearly observed at LEAR, for example in \( p\bar{p} \rightarrow \eta\pi\pi \), and are widely believed to have large multiquark components. The closely related and crucially important subject of the nature of short-ranged nuclear forces remains under investigation, for example using LEAR data on \( p\bar{p} \rightarrow \Lambda\bar{\Lambda} \).

Regarding glueballs and hybrids, the existing experimental candidates represent a rather thin and ambiguous beginning to what should eventually become a rich field of spectroscopy. Neither glueball candidate decays according to expectations for a flavor singlet, which suggests that mixing between glueball and \( q\bar{q} \) basis states may be very important. Of the 72 resonances expected in the lightest hybrid multiplet near 1.9 GeV, we have just two candidates for 1 exotic hybrid (the \( \pi_1 \) level), and in neither case do the reported decay modes agree with theoretical expectations for hybrids.

In conclusion, what we have from LEAR is “proof of principle”. An overpopulation of light scalars exists, giving us glueball and multiquark/molecule candidates, and \( J^{PC} \)-exotic mesons exist, giving us exotic hybrid candidates. However there is thus far little evidence for the partner states that should
also be present if these are indeed glueball and hybrid states. A primary task for GSI will be to confirm or refute the existing gluonic candidates, establish their strong branching fractions and other characteristic properties, and search for multiplet partner states with other flavors (u,d,s,c) [23] and $J^{PC}$ quantum numbers that must also exist if LEAR’s discoveries are indeed gluonic hadrons.

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