Status and plans for light hadron spectroscopy at Jefferson Laboratory [⋆]

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Abstract

Spectroscopy is a tool for identifying the relevant effective degrees of freedom in complex systems. As applied to Strong QCD, i.e. QCD in the low energy, confinement regime, we study the spectroscopy of light hadronic systems, including mesons and baryons. We review the progress in this field at Jefferson Laboratory, and discuss plans for the future, including the new experimental facility in Hall D.

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1 Introduction

A large part of the program at Jefferson Laboratory attempts to bring new understanding to QCD, the theory of the strong interactions. The spectroscopy program in particular tries to elucidate the appropriate degrees of freedom for describing QCD at low energies. We are particularly interested in states whose properties are not accountable within the quark model, and point to specific extensions which go beyond the quark model and help us learn about QCD more directly.

1.1 Spectroscopy and Degrees of Freedom in QCD

Spectroscopy is the study of particular quantum states, their energies and widths, and their decay schemes. Time and time again, from the hydrogen

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[⋆] Invited talk at the International Workshop on e^+e^- Collisions from ϕ to J/ψ (Novosibirsk, March 1999).

[1] Research supported by the National Science Foundation.

atom, to the shell and collective models of nuclear structure, and to the early days of particle physics and the quark model, this field has pointed the way to the underlying dynamics. The spectrum of states can, sometimes very intuitively, show directly the appropriate degrees of freedom for a very complex system. Once these degrees of freedom are known, effective theories can be formulated, and their properties compared to those in the more fundamental theory. Consequently, solutions of the fundamental theory must yield these effective degrees of freedom. One of my favorite examples of this is the transition from vibrational to rotational degrees of freedom as one increases the mass number in the even isotopes of Samarium. [1].

The quark model works very well as a description of both meson [2] and baryon [3] states. That is, it has been known for a long time that massive, weakly interacting, pointlike spin-$\frac{1}{2}$ quarks are the appropriate degrees of freedom for QCD at low energies for most of the known physical states. However, we know that QCD has other degrees of freedom as well, most notably those associated with the gluon field. The aim of much of the experimental and theoretical program today is to find states which violate the quark model and point to these new, possibly gluonic, degrees of freedom predicted by QCD. [4].

These new states can be identified either as an “overpopulation” of peculiar states, or as states with quantum numbers that are unequivocally the result of non-quark model degrees of freedom. The latter is only possible in meson systems where some quantum number combinations, such as $J^{PC} = 1^{-+}$, are impossible in the quark model. Furthermore, the baryon spectrum is *under*subscribed by the known states, and in fact it has been speculated that these missing states are a manifestation of non-quark model degrees of freedom. Both of these venues are being exploited at Jefferson Laboratory.

1.2 The CEBAF Accelerator Facility

The Continuous Electron Beam Accelerator Facility (CEBAF) is the accelerator complex at the heart of Jefferson Laboratory. Originally designed as a 4 GeV electron accelerator, producing CW beams with currents in excess of 100 μA, it is now clear that the facility can be straightforwardly upgraded to achieve higher energies. This is based on the performance of the superconducting RF system which has exceeded expectations. The accelerator has already delivered 5.5 GeV beam routinely, and an upgrade plan has been submitted to the US Department of Energy for an upgrade to 12 GeV.

For baryon spectroscopy, the lower beam energy is exactly what is needed. In this case, excited baryons with masses $M_B = \sqrt{s}$ are formed by the fusion of a high energy photon with a target proton or neutron, that is

$$\gamma p \to B \to X$$

where X represents some particular final state. For $M_B = 2$ GeV/c^2, one requires a 1.7 GeV photon. This can easily be produced using bremsstrahlung of an electron beam with a bit higher energy, and this is a mainstay of the currently operating CEBAF program.

Excited meson states are studied using peripheral production, that is,

$$\gamma p \to XN$$

where N represents a recoiling proton or neutron and the meson state X decays in some particular fasion. Somewhat higher energies are needed in this case, partly because of the additional energy needed to surpass threshold, but also to insure that the reaction is "peripheral" and does not include resonances that involve the recoil proton or neutron. This is the program that will be heavily exploited with the accelerator upgrade.

1.2.1 The CLAS and Photon Tagging systems in Hall B

The CEBAF Large Acceptance Spectrometer (CLAS) is a multiparticle detector, using various tracking and triggering devices in a toroidal magnetic field. An electron or photon beam can be deliveried down the axis of the toroid, impinging on one of a variety of targets. For the experiments I will discuss here, the target is liquid hydrogen and only photon beams are considered. The photons are produced in a bremsstrahlung tagging facility upstream of the hydrogen target. Photons are tagged with energies between 20% and 95% of the electron beam energy. Typically, tagged photon rates in excess of 10^7/sec are achieved in real running conditions.

2 Photoproduction Experiments in the CLAS

The original goals of the spectroscopy program for Jefferson Laboratory and CLAS were centered on the structure of baryons. This was necessitated, in large part, because of the restricted beam energy.

2.1 Baryon Spectroscopy

There is a large program in baryon spectroscopy [5] in CLAS including the reactions $\gamma p \to \pi N$, $\gamma p \to \eta p$, $\gamma p \to \eta' p$, $\gamma p \to \omega p$, and others. One experiment

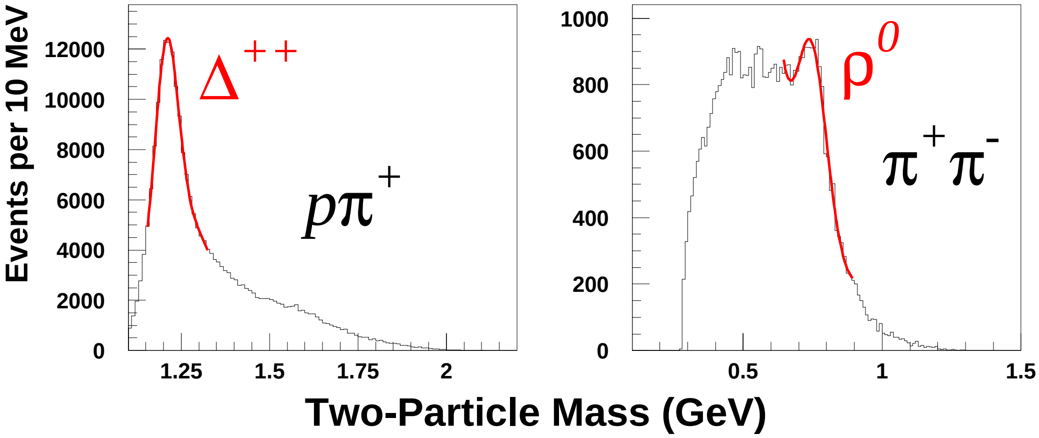

Fig. 1. Preliminary data from the CLAS detector on the reaction $\gamma p \to p\pi^+\pi^-$. It is clear that at least a subset of the data is dominated by $\Delta^{++}\pi^-$ and $p\rho^0$ quasi-two body production.

in particular [6] aims to address the problem of "missing baryons" [7] using the reaction

$$\gamma p \to B \to p\pi^+\pi^-$$

which is viewed as production of a baryon state B, followed by its decay to various quasi-two body final states such as $\Delta^{++}\pi^-$, $\Delta^0\pi^+$, or $p\rho^0$. Such a search is suggested by calculations which indicate that, in the quark model, the missing states have languished because they do not couple strongly to the πN channel [8] whereas most of the data acquired to date has used the $\pi^\pm N \to B$ reaction. These calculations also show, however, that there is no such accidental suppression in the γp production channel [9] or in various quasi-two body decay channels [10] such as the ones considered here.

Figure 1 shows some preliminary [11] results from a small subset of data on the reaction $\gamma p \to p\pi^+\pi^-$ already acquired in CLAS at Jefferson Lab. We plot the two-body invariant mass combinations for $p\pi^+$ and for $\pi^+\pi^-$. There are clear peaks showing the presence of $\gamma p \to \Delta^{++}\pi^-$ and $\gamma p \to p\rho^0$. These data are integrated over all photon energies in the tagging system, from 600 MeV up to 2.2 GeV. Deeper analysis shows that the relative amounts of these two quasi-two body reactions are very dependent on photon energy. In fact, one of the challenges of this analysis is to separate the diffractive production of $\gamma p \to \rho^0 p$ from the production of an intermediate baryon which then decays to $\rho^0 p$.

2.2 Meson Spectroscopy

A meson spectroscopy program is about to begin in the CLAS, using the presently available highest energy photons, with an 5.5 GeV photon energy. The CLAS is not particularly well suited to diffractive meson production, because the toroidal geometry tends to exclude particles in the forward direction. However, indications are that a subset of reactions may be investigated at some level, while we wait for higher energy electron beams and a suitable experimental facility.

3 Upgrade Plans for CEBAF

CEBAF consists of two parallel superconducting linacs, through which the electron beam is recirculated using two sets of semicircular arcs. The accelerating cavities are housed in “cryomodules” each achieving 20 MV of gain at the design gradient of 5 MV/m. There are twenty cryomodules in each linac and five sets of recirculation arcs, meeting the design beam energy of $5 \times 2 \times 20 \times 20$ MV or 4 GeV.

The key to the accelerator energy upgrade is that the superconducting cavities have performed well beyond specifications. The average gradient achieved before the cavity fails, typically because of field emission, is 8 MV/m. With some attention paid to the magnetic transport system, the accelerator can presently deliver 5.5 GeV rather routinely. A simultaneous upgrade of the accleration cavities and transport system is the basis of higher energies at CEBAF.

A development program is now in place to produce 80 MV cryomodules. This is based on various improvements in cavity design and seems to be quite feasible. New magnetic transport elements are being designed as well, and the goal is to deliver 12 GeV electrons sometime in the next several years. The plan is to build a new experimental hall, Hall D, on the other side of the laboratory, making use of an additional linac pass to achieve maximum energy.

4 The Hall D Experiment

A collaboration has formed to design, construct, and operate an experimental facility in the new hall. The overall physics objectives are based on photoproduction reactions on hydrogen and other targets, with high energy photons that may be linearly or circularly polarized. The central piece of experimental

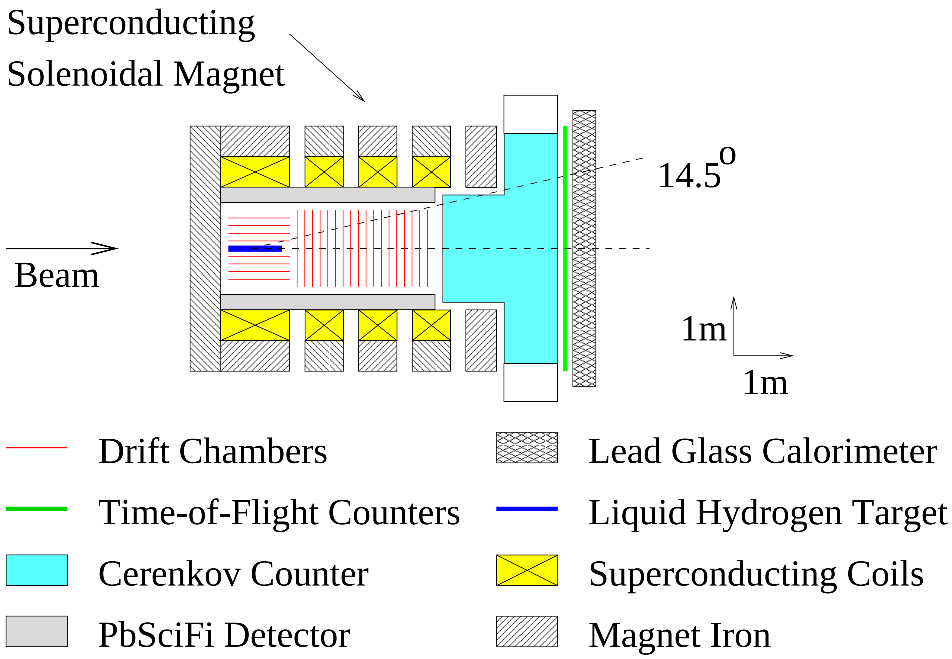

Fig. 2. Stage I configuration of the Hall D spectrometer

equipment is a multiparticle detector with a solenoidal magnetic field including both charged and neutral detection. A sketch of the apparatus, as it might appear in the first stage of experimentation, is shown in Fig. 2. At the present time, the collaboration includes over sixty physicists from fourteen institutions, and incorporates theorists as integral members as we identify and carry out the physics program. The spokesperson is Alex Dzierba from Indiana University.

A key aspect of the detector system will be a high rate, pipeline-based data acquisition system. This will allow a very unbiased sample of events to be accumulated. Along with the flat acceptance afforded by the solenoidal magnetic field and large coverage drift chambers and photon detectors, we will acquire a very large sample of events, comparable to that already obtained with pion beams. We argue, however, that the the spectrum that results from photon beams will be rather different giving us a new window on degrees of freedom in strong QCD.

Photon beams will be produced using tagged bremsstrahlung. Certainly, a large amount of physics can be done with an unpolarized photon source. However, it is straightforward to produce circularly polarized photons using a longitudinally polarized electron beam (already in operation at CEBAF), and we expect to begin operation with a coherent bremsstrahlung source based on a diamond crystal radiator. The latter not only allows linearly polarized photons, but also renders the source relatively monochromatic.

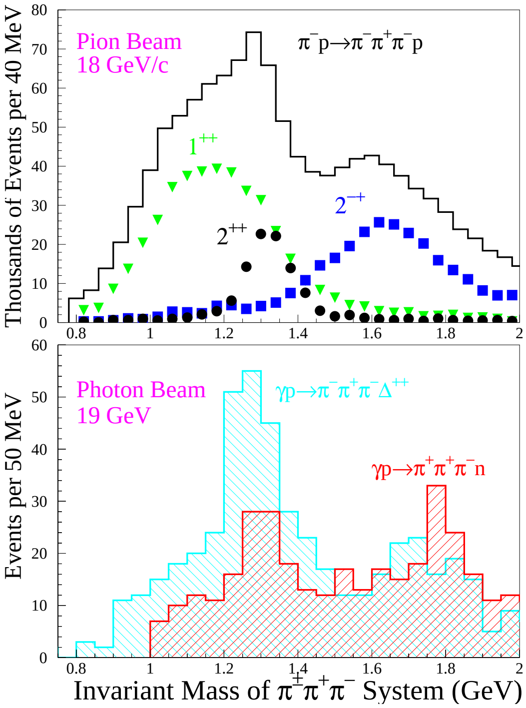

Fig. 3. Production of the $\pi^{\pm}\pi^{+}\pi^{-}$ system with pion and photon beams. Pion production, upper panel, is dominated by three meson excitations, namely $a_1(1260)$, $a_2(1320)$, and $\pi_2(1670)$. It also shows a very large number of events, and this allows the quantum numbers of these excitations to be identified using partial wave analysis. Photoproduction, with either positive or negative charge exchange, are seen to be different from pion production, even with severely reduced statistics. Furthermore, they are different from each other. Both reactions seem to show production of $a_2(1320)$ with little indication of the other two states seen in pion production. The reaction $\gamma p \to \pi^{+}\pi^{+}\pi^{-}n$ suggests a new narrow state at $\approx$ 1775 MeV.

4.1 Photoproduction of Mesons and Gluonic Excitations

Photoproduction has long been left out of the meson spectroscopy field [4] largely because of the scarcity of suitable beams. This is finally changing with the CEBAF upgrade. Still, a few experiments have been done and have yielded some tantalizing results. In addition, there is good theoretical motivation on a number of fronts.

It was originally pointed out [12] that photons present the only possible beam of spin-1 hadrons. Whereas the quark spin in pions are antialigned, the vector meson nature of a photon beam is a source of $q\bar{q}$ pairs with $S = 1$ and it is reasonable to assume that a different tower of excitations should be observed. These authors also pointed out that the decay modes of exotic mesons, based on the "flux tube" model, should be rather complicated.

Existing data already establish that a different meson excitation spectrum is observed with photon beams as compared to pion beams. Figure 3 shows this clearly. The upper panel shows a study [13] of the reaction $\pi^{-}p \to \pi^{-}\pi^{+}\pi^{-}p$. Note the vertical scale measures thousands of events per bin, and this level of statistics allows a detailed partial wave analysis of the angular distribution as a function of mass. The dominant meson excitations are shown to be the $a_1(1260)$ $(J^{PC} = 1^{++})$, the $a_2(1320)$ (2^{++}), and the $\pi_2(1670)$ (2^{-+}).

In contrast to pion production, photoproduction of the same, charged, three pion final state in the reactions $\gamma p \to \pi^-\pi^+\pi^-\Delta^{++}$ [14] and $\gamma p \to \pi^+\pi^+\pi^- n$ [15] are quite different. There are not enough events to carry out a full partial wave analysis, but the mass distribution indicates that the $a_2(1320)$ is produced, but not necessarily the $a_1(1260)$ or $\pi_2(1670)$. Furthermore, there is a strong suggestion of a new narrow state with mass ≈ 1775 MeV. An analysis of the angular distributions [16] indicates that the quantum numbers of this state are $J^P = 1^-$, 2^-, or 3^+.

Extending this data set, with high statistics and even, well understood acceptance, is a primary goal of the Hall D physics program. Furthermore, we will include states with neutral particles, that is π^0, η, and η', in search of more new states and measuring their decay branches. We are particularly interested in studying final states as suggested by the flux tube model, such as $\gamma p \to [b_1(1235)\pi]\, N$, in which there is already evidence of new excitations [17] based on a very limited amount of data.

It is of course important to identify the appropriate photon beam energy necessary to carry out this program. Once above threshold for a particular excitation mass M_X, the cross section for producing an exotic state seem to be relatively large, about the same as for $q\bar{q}$ states, based on specific [18] and general [19] grounds, and they do not fall very slowly with increased photon energy. One also wants to go high enough in energy so that resonances at the baryon vertex can be eliminated kinematically, but not so high that particle identification becomes difficult or expensive.

One measure is to go to energies high enough so that the the minimum momentum transfer from the photon to the meson system, $-t_{\rm min}$, is small enough so that one can integrate over enough of the differential cross section, which typically goes like $e^{-b|t|}$ with $b \sim 4/\mathrm{GeV}^2$. A simple analysis shows that with photons up to energies of 12 GeV, we will be able to copiously photoproduce meson excitations up to the $c\bar{c}$ threshold.

4.2 Strangeness Production and ϕ Physics

Photon beams are also a copious source of $s\bar{s}$ pairs, and we expect that a significant part of the research program in Hall D will exploit this. Possibilities include a detailed investigation of strangeonium, as well as photoproduction dynamics and decay of the ϕ meson.

Straneonium, bound states of $s\bar{s}$, are a particularly interesting system from the point of the quark model versus QCD, because the strange quark mass is close to the "natural" confinement scale of QCD. Despite this interest, however, spectroscopy of the $s\bar{s}$ system has been rather sparse [4], with most of the data coming from K^-p hypercharge exchange reactions. Much of the design effort for the Hall D detector is based on π/K discrimination so that reactions such as $\gamma p \to K^{\star}\bar{K}p \to KK\pi p$ can be thorougly studied.

Photoproduction of the ϕ meson itself has many interesting possibilities. There have been some studies using polarized photons [20,21] and there are clear indications of an interference of the P-wave ϕ with an underlaying S-wave [22,23] which may or not be resonant. Finally, studies of CP and CPT violation may be possible [24] using the correlated $K^0\bar{K}^0$ pairs from ϕ decay.

5 Conclusions and Future Plans

Data is presently being analyzed from the CLAS, and the results of various analyses on baryon spectroscopy should be available in the near future. A limited program of meson spectroscopy in the CLAS is just beginning, as the accelerator begins to deliver higher energy beams. A new program, focussing on meson spectroscopy, is beginning to take shape in Hall D. Formal collaboration meetings start in the Summer of 1999, and design reviews will begin in the Fall. We expect first data acquisition for physics to begin sometime in the first few years of the new millenium.

Acknowledgements

I would like to thank Nikolai Achasov for his kind invitation to join this workshop and to present this paper. I would also like to thank Alex Bondar, Simon Eidelman, and all the organizers for their warm hospitality and superb coordination. This was an outstanding conference.

References

[1] P.Stoler, et al., *Phys.Rev.* **155** (1967) 1334.

[2] S.Godfrey and N.Isgur, *Phys.Rev. D* **32** (1985) 189.

[3] S.Capstick and N.Isgur, *Phys.Rev. D* **34** (1986) 2809.

[4] S.Godfrey and J.Napolitano, *Rev.Mod.Phys.* **71** (October, 1999).

[5] See http://www.jlab.org/exp_prog/experiments/ for a complete listing of experiments, and other details about the Jefferson Laboratory program.

[6] Jefferson Laboratory experiment E93-033, J.Napolitano and D.Weygand, spokespersons.

[7] D.B. Lichtenberg, *Phys.Rev.* **178** (1969) 2197.

[8] S.Capstick and W.Roberts, *Phys.Rev. D* **47** (1993) 1994.

[9] S.Capstick, *Phys.Rev. D* **46** (1992) 2864.

[10] S.Capstick and W.Roberts, *Phys.Rev. D* **49** (1994) 4570.

[11] M.Klusman, Ph.D. Thesis, Rensselaer Polytechnic Institute (in progress)

[12] N.Isgur, R.Kokoski, and J.Paton, *Phys.Rev.Lett.* **54** (1985) 869.

[13] G.Adams, et al., *Phys.Rev.Lett* **81** (1998) 5760.

[14] G.Condo, et al., *Phys.Rev. D* **41** (1990) 3317.

[15] G.Condo, et al., *Phys.Rev. D* **48** (1993) 3045.

[16] G.Condo, et al., *Phys.Rev. D* **43** (1991) 2787.

[17] M.Atkinson, et al., *Z.Phys. C* **34** (1987) 157.

[18] A.Afanasev and P.Page, *Phys.Rev. D* **57** (1998) 6771.

[19] N.Isgur, hep-ph/9904494 (1999).

[20] J.Ballam, et al., *Phys.Rev. D* **7** (1973) 3150.

[21] M.Atkinson, et al., *Z.Phys. C* **27** (1985) 233.

[22] D.C.Fries, et al., *Nucl.Phys. B* **143** (1978) 408.

[23] D.P.Barber, et al., *Z.Phys. C* **12** (1982) 1.

[24] C.D.Buchanan, et al., *Phys.Rev. D* **45** (1992) 4088.