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Hadron Beams For Hadron Physics

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The 2002 NSAC Long Range Plan (LRP) characterized the Nuclear Physics agenda in the US in terms of five broad questions. These were:

- What is the structure of the nucleon?
- What is the structure of nucleonic matter?
- What are the properties of hot nuclear matter?
- What is the nuclear microphysics of the universe?
- What is to be the new Standard Model?

There are a number of scientific opportunities that can be addressed with experiments using secondary hadronic beams. A number of issues in the spectroscopy of baryons and mesons cry out for such beams. In the case of mesons, planned experiments in the search for exotics, such as at Jefferson Lab (JLab) with the GlueX detector, can be complemented by experiments using high-quality hadronic beams. The same is true of experiments in the light baryon sector, particularly regarding the search for 'missing' baryons. A number of rare symmetry violating processes that probe physics beyond the current standard model, and address questions regarding fundamental symmetries like CP, can be explored with high-quality hadron beams. In this note, the focus will be on one example of the physics that can be addressed with such beams, that of light baryon spectroscopy and the 'missing' baryons.

It has long been accepted that quantum chromodynamics (QCD) is the theory that describes the interactions between quarks and gluons. The way in which this theory leads to the hadrons that have been observed over the years has been a very difficult problem, with the only *ab initio* calculations that are completely based on QCD being lattice simulations. Some of these lattice simulations have suggested that the effective potential between a pair of quarks, or between a quark and an antiquark, is what has been termed 'linear + Coulomb' [1]. This means that the potential increases linearly with the separation of the quarks at large quark separation, and is Coulomb-like at small inter-quark separations.

Two broad research thrusts can be identified from these lattice studies. The more fundamental of the two is to identify the mechanism by which QCD gives rise to this potential. A number of hypotheses have been advanced, but a discussion of these is beyond the scope of this note. The second broad area of research is that of understanding as much of hadron phenomenology as possible in terms of such a potential. Put another way, given a potential suggested by lattice studies of QCD, can we understand the spectrum of observed hadrons, their interactions and their decays, as resulting from such a potential?

If this idea of an effective potential between pairs of quarks is applied to the light baryons, a spectrum results which, at present, is not completely consistent with experimental measurements. In particular, such approaches almost invariably predict the existence of a number of excited baryonic resonances that have not yet been identified in the various partial wave analyses carried out to find such resonances [2]. This is the so-called 'missing baryon problem'. It has been proposed that the solution to this problem lies in considering how the confirmed baryon resonances have been produced, predominantly in $N\pi$ scattering, and that the missing states couple weakly to that channel [3]. This proposed solution was subsequently confirmed by other authors [4].

Model calculations have subsequently suggested that missing resonances may be found in channels that do not include the $N\pi$ final state, such as $\Delta\pi$, $N\rho$, etc. [5], and a number of experiments have been proposed to explore such final states at JLab. It must be emphasized that the question of the missing states is of fundamental importance. While there are many experiments planned and being planned to explore the Q^2 evolution of baryon electromagnetic transitions, for instance, and to determine the 'onset of perturbative QCD' behavior in these form factors, such studies can only be carried out on the known resonances, and may improve our understanding of them. In addition, such studies may boost our confidence in our understanding of perturbative QCD. Furthermore, for most of the light

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baryons that are 'well known', properties such as helicity amplitudes and partial widths into a few decay channels, are only known to about 30%. For progress to be made in our understanding of the light baryon spectrum, more precise information is needed. However, none of these form factor studies will address the fundamental question regarding the relevant degrees of freedom inside a light baryon. If none of the missing baryons are found in the planned experimental searches (and accompanying analyses efforts), then our understanding of QCD in the confinement regime will have been found wanting.

There a number of other reasons for carrying out high-precision studies of the light baryons. One of these is the fact that the world around us is composed of baryons and any study of the nature of matter should include its most prevalent form. In addition, baryons are the simplest systems that manifest the non-Abelian nature of QCD. Furthermore, the constraints on constructing baryon multiplets are quite different from those for mesons: while mesons are thought to exist only in nonets, baryons are predicted to exist in 56-plets, 70-plets and 20-plets, and this rich structure needs to be confirmed with precise data.

The N^* program at Jefferson Laboratory (JLab) has been designed in part to provide answers to the question of the missing baryons, as well as provide the high precision data on the known baryons. The analysis required for the extraction of baryon properties from experimental data has led to the formation of the Excited Baryon Analysis Center (EBAC), with efforts there aimed at accomplishing the 2009 milestone for hadronic physics, *Complete the combined analysis of available data on single π, η, and K photoproduction of nucleon resonances and incorporate the analysis of two-pion final states into the coupled-channel analysis of resonances..*

The idea behind the coupled-channel analysis is that different channels feed into each other. This is illustrated in figure 1, where the initial state (on the left) consists of a photon and a nucleon. The final state may be $N\pi$ or $N\eta$, for example, but the intermediate state that provides the effect of 'rescattering', may be either of these two, along with any other accessible state such as $K\Lambda$, $K\Sigma$, $N\omega$, $\Delta\omega$ etc. If only a few channels are included in the coupled-channel

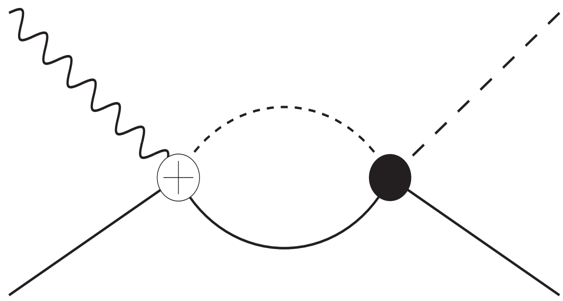

FIG. 1: Rescattering effects in a photoproduction process. The baryon and meson in the intermediate state are not necessarily the same as those in the final state.

analysis, this means that a scattering matrix like

$$\mathcal{T} = \begin{pmatrix} \mathcal{T}_{\gamma N\to\gamma N} & \mathcal{T}_{\gamma N\to\pi N} & \mathcal{T}_{\gamma N\to\eta N} & \mathcal{T}_{\gamma N\to\Lambda K} & \mathcal{T}_{\gamma N\to\Sigma K} & \mathcal{T}_{\gamma N\to\pi\pi N} \\ \mathcal{T}_{\pi N\to\gamma N} & \mathcal{T}_{\pi N\to\pi N} & \mathcal{T}_{\pi N\to\eta N} & \mathcal{T}_{\pi N\to\Lambda K} & \mathcal{T}_{\pi N\to\Sigma K} & \mathcal{T}_{\pi N\to\pi\pi N} \\ \mathcal{T}_{\eta N\to\gamma N} & \mathcal{T}_{\eta N\to\pi N} & \mathcal{T}_{\eta N\to\eta N} & \mathcal{T}_{\eta N\to\Lambda K} & \mathcal{T}_{\eta N\to\Sigma K} & \mathcal{T}_{\eta N\to\pi\pi N} \\ \mathcal{T}_{\Lambda K\to\gamma N} & \mathcal{T}_{\Lambda K\to\pi N} & \mathcal{T}_{\Lambda K\to\eta N} & \mathcal{T}_{\Lambda K\to\Lambda K} & \mathcal{T}_{\Lambda K\to\Sigma K} & \mathcal{T}_{\Lambda K\to\pi\pi N} \\ \mathcal{T}_{\Sigma K\to\gamma N} & \mathcal{T}_{\Sigma K\to\pi N} & \mathcal{T}_{\Sigma K\to\eta N} & \mathcal{T}_{\Sigma K\to\Lambda K} & \mathcal{T}_{\Sigma K\to\Sigma K} & \mathcal{T}_{\Sigma K\to\pi\pi N} \\ \mathcal{T}_{\pi\pi N\to\gamma N} & \mathcal{T}_{\pi\pi N\to\pi N} & \mathcal{T}_{\pi\pi N\to\eta N} & \mathcal{T}_{\pi\pi N\to\Lambda K} & \mathcal{T}_{\pi\pi N\to\Sigma K} & \mathcal{T}_{\pi\pi N\to\pi\pi N} \end{pmatrix}, \tag{1}$$

must be treated. The amplitudes along the first row of this matrix represent processes that will be measured at JLab, while those in the first column are the time-reversed versions, which can be obtained by application of time-reversal symmetry. Those on the second row, however, require experiments with pion beams, and while some data is available, most of these processes have not been measured. This means that there are few constraints on amplitudes in the second row, which will affect the reliability of any information extracted from such an analysis. The upshot of all this is that experiments with hadronic beams are required as input to the EBAC (or any other) analysis effort.

Assuming that the nuclear/hadronic community decides that experiments with hadronic beams should be a part of the nuclear physics portfolio, what would need to be done to take this from a 'wish' to a 'reality'? It must first be noted that after identifying the five important scientific questions, the 2002 LRP went on to make recommendations to the funding agencies regarding the resources needed to tackle these five questions:

- Increase support for facility operations;

- Increase investment in university research;
- Significantly increase funding for nuclear theory;
- RIA as highest priority for new construction;
- Immediate construction of underground science laboratory;
- Upgrade JLab.

The response of the agencies to these recomendations has been mixed. For instance, CD1 has been signed for the Jlab upgrade, but progress toward RIA and an underground science laboratory has not been as rapid. Of course, this response is in influenced by the fact that funding for research in nuclear physics is but a small component of the federal budget, and above all else, this dictates how the agencies respond to the priorities identified by the community.

For experiments with hadron beams, a number of options appear to exist at this time, or for the near future. The Fermilab Main Injector Particle Production Collaboration is one possibility, and two members of the community interested in baryon spectroscopy have recently joined that collaboration. There may be opportunities at J-PARC, but these have not been explored, and time may be running out on such opportunites. There has been a suggestion of secondary beams at JLab but, to the best of my knowledge, there has been no serious exploration of this possibility. There may even be the possibility of restarting such experiments at BNL. Ultimately, the science identified by the community will play a significant role in which one of these (or other) options is followed.

One important question is the projected cost of a facility for hadronic beams experiments, if this is what the community decides is essential. Alternatively, the cost of carrying out such experiments at an existing international facility must be determined. This latter option is very likely to be much cheaper than constructing a new facility on American soil, or even modifying an existing facility to add hadronic beams capabilities, but even so, the Program Manager of the DOE Medium Energy Program would need to be convinced that this is a high scientific priority. This will only happen if a significant portion of the hadronic community supports such an effort, and ensures that it is included in the LRP, either this time around or in the future. This means that it must be on the table for discussion at one or more of the town meetings that are organized as part of the long-range-planning exercise.

It is hard to envision what future, if any, there is for experiments with hadronic beams. One thing is clear, however. Since both funding agencies are 'proposal driven', funding for such experiments, eiher on the small scale (such as contributing to the MIPP collaboration), or on a larger scale (such as requesting a new, state-of-the-art facility) will only become available in response to a request from the community. Such a request must demonstrate first-rate science, as well as significant scientific opportunities that will be lost if such funding is not provided. The request must have not just the 'buy-in', but strong support from a significant portion of the nuclear physics community, and certainly must not appear to be the 'special interest' of a small group. Perhaps most importantly, the request must demonstrate clearly how the request ties in with the missions of the funding agencies, and the way in which nuclear science in the US will be strengthened if the request is funded.

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