Physics Opportunities with Meson Beams for EIC

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Abstract: Over the past two decades, meson photo- and electroproduction data of unprecedented quality and quantity have been measured at electromagnetic facilities worldwide. By contrast, the meson-beam data for the same hadronic final states are mostly outdated and largely of poor quality, or even non-existent, and thus provide inadequate input to help interpret, analyze, and exploit the full potential of the new electromagnetic data. To reap the full benefit of the high-precision electromagnetic data, new high-statistics data from measurements with meson beams, with good angle and energy coverage for a wide range of reactions, are critically needed to advance our knowledge in baryon and meson spectroscopy and other related areas of hadron physics. To address this situation, a state-of-the-art meson-beam facility needs to be constructed. The present letter summarizes unresolved issues in hadron physics and outlines the vast opportunities and advances that only become possible with such a facility.

Keywords:

Introduction: The CM energy range up to 2.5 GeV is rich in opportunities for physics with pion and kaon beams to study baryon and meson spectroscopy questions complementary to the electromagnetic programs underway at electromagnetic facilities. The White Paper [1] highlights some of these opportunities and describes how facilities with high-energy and high-intensity meson beams can contribute to a full understanding of the high-quality data now coming from electromagnetic facilities. We emphasize that what we advocate here is not a competing effort, but an experimental program that provides the hadronic complement of the ongoing electromagnetic program, to furnish the common ground for better and more reliable phenomenological and theoretical analyses based on high-quality data. A number of the topics mentioned in the White Paper are addressed in the summary of the recent DNP Town Meeting on QCD and Hadron Physics [2], which notes (on page 28) that meson beams are being considered.

The physics case for our program is aligned with Reaching for the Horizon: Long Range Plan for Nuclear Science [3]: ...a better understanding of the role of strange quarks became an important priority. Knowledge of the hyperon spectrum is an important component of this proposal. Overall, our knowledge of the hyperon spectrum is very poor; e.g., the empirical knowledge of the low-lying spectra of Λ and Σ hyperons remains very poor in comparison with that of the nucleon and, in the case of the Ξ hyperons, extremely poor. The structure of hyperon resonances cannot be understood without empirical determination of their pole positions and decays, which is the goal of the proposed experiments. The determination of the strange hyperon spectra in combination with the current measurements of the spectra of the charm and beauty hyperons at the LHCb experiment at CERN allows for a clearer understanding of soft QCD matter and the approach to heavy quark symmetry [4].

Opportunities with Meson Beams: Looking further down the road, we plan to take part in the future electron-ion collider (EIC) following the recommendation of the new Long-Range Plan Reaching for the Horizon: Long Range Plan for Nuclear Science [3]: RECOMMENDATION III: We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

An EIC will likely be one of the future large accelerator facilities for high-energy and nuclear physics [3]. The creation of a state-of-the-art hadron physics complex to study QCD at the deepest level with an EIC would provide the unique infrastructure for a meson-beam facility to complete our picture of the hadron spectrum of QCD at the same time. In addition, the presence of an electron beam at an EIC facility would permit a unique opportunity to measure the pion EM form factor directly using an electron-pion collider, although such a facility would present tremendous technical challenges. This is useful because the pion form factor serves as a paradigm for nonperturbative hadronic structure and is associated with chiral dynamics, gauge invariance, and perturbative QCD in a nontrivial fashion. Current methods to extract the form factor rely on extrapolation to the pion t-channel pole. Unfortunately, this procedure is not without ambiguity and remains controversial to this day.

The form factor is especially relevant in light of a more recent controversy concerning its approach to the expected perturbative QCD behavior. This issue is of fundamental importance since it questions the existence of perturbative QCD for exclusive processes [6]. Unfortunately, the experimental situation is confused, with the BaBar and Belle Collaborations obtaining results for...
$Q^2 |F_T(Q^2)|$ that appear to be in conflict \cite{7}.

**Spectroscopy of Hyperon Resonances**: Most of our current knowledge about the bound states of three light quarks has come from partial-wave analyses (PWAs) of $\pi N \rightarrow \pi N$ scattering. Measurements of $\pi N$ elastic scattering are mandatory for determining absolute $\pi N$ branching ratios. Without such information, it is likewise impossible to determine absolute branching ratios for other decay channels. A summary of resonance properties (pole positions (masses and widths), branching ratios, helicity couplings to $\gamma N$, etc.) is provided in the Review of Particle Physics (RPP) \cite{8}.

The information on resonance properties obtained from analyses of experimental data provides fundamental information about QCD in the nonperturbative region. A variety of quark models have been used to interpret these results. Dyson-Schwinger approaches provide a picture of baryons in terms of quarks and gluons by incorporating dynamical chiral symmetry. Results from lattice gauge theory calculations are constantly improving and are therefore becoming more relevant to experiment.

A comparison of the experimental results and models led to the well-known conundrum known as the “missing resonances” problem \cite{9}. Put simply, the models (and lattice-gauge calculations) predict far more states than are observed experimentally. These missing resonances, however, do not appear at all in the quark-diquark model. The reason for this, it is conjectured, is their weak coupling to the $\pi N$ channel, which supplies the bulk of our information about baryonic resonance states. A desire to test this hypothesis by looking for resonances in reactions that do not involve $\pi N$ in either the initial or final state was a major reason behind the construction of Hall B and the CLAS facility at JLab.

The world data on $\pi N \rightarrow \eta N$, $K\Lambda$, $K\Sigma$ were collected and date back to more than 20 or 30 years ago. In many cases, systematic uncertainties were not reported (separately from statistical uncertainties), and in many cases it is known that systematic uncertainties were underestimated. These problems of pion-induced reaction data have led to the emergence of many different analyses that claim a different resonance content. While many analyses agree on the 4-star resonances that are visible in elastic $\pi N$ scattering \cite{10}, there is no conclusive agreement on resonances that couple only weakly to the $\pi N$ channel.

Unlike in the cases described above, kaon beams are crucial to provide the data needed to identify and characterize the properties of hyperon resonances. The masses and widths of the lowest $\Lambda$ and $\Sigma$ baryons were determined mainly with kaon-beam experiments in the 1970s \cite{8}. First determinations of pole positions, for instance for $\Lambda(1520)$, were obtained only recently \cite{11}. An intense kaon beam would open a window of opportunity not only to locate missing resonances but also to establish properties including decay channels systematically for higher excited states.

In summary, better data from hadron-induced reactions will significantly contribute to answer the same fundamental questions that originally motivated the photoproduction program: the missing resonance problem, amplitudes for comparison with ab initio calculations, and low-energy precision physics. A program with hadron beams provides complementary information with large impact in the extraction of the amplitudes from observables. With a more precise knowledge of the amplitude it is expected that much-debated concepts, such as the aforementioned multiquark hypotheses, hadronic molecules, hybrid states, chiral symmetry restoration, chiral solitons, or string models, can be confirmed or ruled out.

**Meson Spectroscopy**: Although it was light hadron spectroscopy that led the way to the discovery of color degrees of freedom and Quantum Chromodynamics, much of the field remains poorly understood, both theoretically and experimentally \cite{12}. The availability of pion and kaon beams provide an important opportunity to improve this situation. Experimentally, meson spectroscopy can be investigated by using PWAs to determine quantum numbers from the angular distributions of final-state particle distributions. Such methods will be used to analyze data from future measurements at CLAS12. Pion beams with CM energies up to 5 GeV should be adequate for a complementary program. Such energies correspond to beam momenta of about 13 GeV/c. We note that meson beam experiments may not be ideal for the study of meson resonances; however, this approach has been taken at BNL and COMPASS and a closely related one is being pursued by the GlueX Collaboration. We therefore briefly review some of the open issues in light meson spectroscopy in this section.

**What is Needed for Hadron-Induced Reactions**: These measurements also have the potential to observe dozens of predicted (but heretofore unobserved) states and to establish the quantum numbers of already observed hyperon resonances listed in the RPP \cite{8}. Interesting puzzles exist for RPP-listed excited hyperons that do not fit into any of the low-lying excited multiplets, and these need to be further revisited and investigated. Excited $\Xi$s, for instance, are very poorly known. Establishing and discovering new states is important, in particular, for determination of the multiplet structure of excited baryons.

Our expertise says that is doable at JLab. The use 3-10 GeV protons from pre-booster or booster (which will be busy several minutes a day) to produce secondary charged meson beams will increase the efficiency of the EIC facility. One can roughly estimate that it will cost about 10% of the EIC cost.

**How it May Work**: What would be required to expand the scope of the EIC to include the production of secondary beams of pions and kaons, and what secondary fluxes might we expect? It’s useful to recall the projects that were proposed (both successfully and unsuccessfully) in the past to provide such beams.

**History**: Back in the 1980s, there were two proposals for kaon factories that failed to secure funding. The TRI-
UMF KAON factory [13][15] proposed to add an alternating series of three storage rings and two fast-cycling synchrotrons to the existing 150 $\mu$A, 0.5 GeV CW TRIUMF cyclotron. It would have provided 100 $\mu$A of 30 GeV protons (3 MW) to an experimental area with four production targets to provide a range of secondary meson beams, as well as a dedicated line for neutrino physics, for Cdn $700$M (1986 dollars), or about $1.1$ B in today’s (US) dollars. At the same time, a competing design at LAMPF called the Advanced Hadron Facility proposed to add a 1.2 GeV superconducting booster linac, which would have accepted 100 $\mu$A from the existing 0.8 GeV linac. The booster linac would have fed a 2 GeV compressor ring, followed by a 15 GeV booster ring and finally a 60 GeV main ring. This configuration allowed extraction of a short duty-factor neutrino beam and a high duty-factor beam for production of secondary particles. Both of these were (planned to be) MW-scale Kaon factories. Additionally, there was the the LAMPF II (AHF) proposal which described the 45-GeV version [16].

BNL successfully operated kaon beam lines at the 30 GeV AGS [17] for many years. Typical proton intensities of $6 \times 10^{12}$ protons per second were achieved with a 43% duty factor (DF), corresponding to almost 100 kW of average beam power.

Today the highly successful J-PARC facility [18][20] in Japan is the only Kaon factory in the world. It is a several-hundred kW proton accelerator with an extensive array of secondary kaon channels.

The EIC Booster: Several designs are under consideration for the EIC booster. Here we consider just one of these designs [21]. It envisions an 8 GeV (figure-8 shaped) booster of circumference 313.5 m producing a $\sim 1/4$ circumference, 260 ns-long spill every 2 s with a parabolic intensity distribution (the booster synchrotron magnets take 1 s to ramp up and 1 s to ramp down). The design intensity of $1 \times 10^{12}$ protons ($160$ nC) per spill corresponds to only about 0.6 kW, 2 orders of magnitude below the BNL AGS when it was serving kaon beamlines, and 3 orders of magnitude less than J-PARC [20]. The time-averaged current is only 80 nA.

It seems possible to consider flattening the distribution to 840 ns, or increasing the intensity a factor of 2-3 for modest additional investment. Much more expensive would be to increase the intensity significantly, or to slow-extract over (for example) 2 s every 3 s. While these changes would offer significant advantages, we take the position for the remainder of this manuscript that the booster parameters are frozen as described in Ref. [21], and then look to see what would need to be done on top of the existing design to satisfy the requirements for $\pi$ and K beams outlined above. Since the EIC booster would only inject to the main ring a small fraction of the time each day, we assume it could be made available for $\pi/K$ physics the rest of the time.

Stretcher: The nominal booster design has a duty factor of only 0.00005%, which makes it completely unsuitable for the physics experiments described earlier in this manuscript. Most experiments rely on detectors that are limited to instantaneous rates below a few MHz, so it’s better to have the same number of beam particles delivered with a lower instantaneous rate over a longer period of time than all at once in a short period of time. As noted, for example, in Ref. [22]. “In coincidence measurements the number of true events is proportional to the intensity but the number of random coincidence events (background) goes like the square of the peak current”. Without improving the duty factor of the nominal EIC booster there is no reason to proceed any further. Of course if the booster itself could be modified to provide slow extraction, a possibility mentioned above, that would be the most cost-effective solution to the duty-factor problem.

There is a solution to this seemingly fatal problem that does not involve making changes to the nominal booster design: adding a stretcher ring (see, for example, Ref. [23]). The nominal 8 GeV/c booster corresponds to a magnetic rigidity of 26.67 T-m. There are many stretcher configurations that could be used to provide nearly CW 100% duty factor beam in this situation. The simplest and most basic would be to extract the booster beam in a direction different than used to fill the EIC main ring, and fill exactly one turn of a stretcher ring over the 260 ns booster spill. That implies a booster ring with a radius of 12.3 m, and 39 one-meter-long dipole magnets of 4.3 T (fixed field) if half the circumference of the ring consisted of dipoles. While this is feasible, it would be more sensible to (for example) double the stretcher diameter, fill only half its circumference every spill, and halve the field to 2.16 T so resistive magnets could be used. In this mode, and with some flexibility in the bunch length, the planned booster tunnel would be about the right circumference to house the stretcher magnets. The stretcher magnet design could be the same or similar to that of the booster magnets.

Either way the beam could be extracted essentially CW with a good duty factor using the common technique of resonant slow extraction (see, for example [24]) while the booster magnets are ramping up and down. In this way, a time-average of $5 \times 10^{11}$ protons/s could be slow-extracted from the stretcher ring into a transfer line to a production target for secondary particles ($\pi/K$ in a dedicated hadron hall. Now we look to see what $\pi/K$ fluxes might be achieved with a CW proton beam of 80 nA.

Pion and Kaon Intensities: Given the conditions just established (80 nA CW, 8 GeV/c protons) we can estimate the fluxes of pions and kaons as a function of secondary particle momentum and secondary channel production angle. We first use the parametrizations of Sanford and Wang (SW) to estimate the number of pions [25] and kaons [26] generated at the production target per GeV/c per steradian per interacting proton. Then we use those results as input to the procedure described by Yamamoto [27], which includes the effects of secondary particle production efficiency and nuclear absorption cross
sections of the protons on different production targets, as well as solid angle, momentum acceptance, and decay factors for typical secondary-particle channels. This tells us what to expect for $\pi^\pm$ and $K^\pm$ fluxes at the end of the secondary particle beamline, again as a function of production angle, for a given production target and secondary-particle beamline. Yamamoto described the design of the KEK K2 channel for $1 \times 10^{12}$ protons at 12 GeV, which are similar conditions to the ones we're considering here.

It must be noted that the SW parametrizations [25, 26] used proton data between 10 and 30 GeV. We are outside this range for the 8 GeV case we’re considering here, which decreases the reliability of our predictions somewhat. For the production target and secondary beam channel we consider Yamamoto’s design [27] as the default: a 6 cm Pt production target, 30 m channel with 3.125 msr and $\Delta p/p=2\%$. This is a realistic design for our situation, and also makes it easier to benchmark our calculations against his.

Figure 1 shows the predictions of $\pi^\pm$ and $K^\pm$ production on beryllium per steradian per GeV/c per interacting proton for $5 \times 10^{11}$ protons/s CW at 8 GeV from the EIC booster and stretcher, based on the phenomenological fits of SW [25, 26]. Near production angles of $0^\circ$, and for $\pi/K$ momenta near 3 GeV/c, $\pi^\pm$ production rates are just under $1/\text{srr/(GeV/c)}$ per interacting proton, with $K^+$ rates about 30 times less than that, and $K^-$ rates another factor of 5 below that.

Much more interesting is to use this information to predict what fluxes of secondary particles could be expected for a specific choice of production target and realistic secondary beamline. Following the work of Yamamoto [27], the $\pi K$ yields $Y$ can be determined from the SW rates $d^2 N/(d\Omega dp) = (1/\sigma_a) d^2 \sigma/(d\Omega dp)$, the proton flux $F_1$ on the production target, the production efficiency $\eta$ for secondary particles per incident proton, the nuclear absorption cross section $\sigma_a$ associated with the protons on the production target, as well as the secondary channel characteristics: solid angle $d\Omega$, momentum bite $\Delta p/p$, momentum $p$, and decay factor $d$ according to

$$Y = F_1 \frac{\eta}{\sigma_a} \frac{d^2 \sigma}{d\Omega dp} \Delta \Omega (\Delta p/p) p d.$$  \hspace{1cm} (1)

We take an incident proton flux $F_1 = 5 \times 10^{11}$ protons/s CW at 8 GeV, a 6 cm Pt production target for which $\sigma_a = 1798$ mb, $\eta = 0.365$. We scale $\sigma_a$ and $\eta$ from the SW rates that were for a Be production target ($\sigma_a = 227$ mb and $\eta = 0.14$). The secondary channel is 30 m long with 3.125 msr and $\Delta p/p=2\%$. The decay factor $d$ is the probability the secondary particle of mass $M$, mean life $\tau$, and momentum $p$ survives a distance $x = 30$ m:

$$d(x) = \exp (-Mx/(p \tau \tau)).$$ \hspace{1cm} (2)

Following Yamamoto [27], we determine the production efficiency from the absorption lengths in Ref. [28] for protons, pions, and kaons. Although the absorption cross sections tabulated in Ref. [28] are at higher momenta than in our application, they are reasonably flat. This is also apparent from the corresponding plots of total cross sections (Figs. 51.6-51.9) in the RPP [3]. We determine the nuclear absorption cross section for the protons in the production target from Ref. [28] and note that Yamamoto [27] points out that it scales like $A^{2/3}$. For forward-angle production, 3 GeV/c pion fluxes of about 10 MHz are possible. Similarly, $K^+$ fluxes are an order of magnitude less, and $K^-$ fluxes are another order of magnitude below that.

These modest kaon fluxes would not inspire rare-decay experiments; however, they do seem well-suited to the physics program described earlier in this manuscript. At these $\pi/K$ rates, the beam can be directly counted, which offers important benefits to experimenters working with these beams. Although the low power associated with the proton beam (0.6 kW) is the root cause of the lower-than-ideal $\pi/K$ rates, it has a silver lining: it makes it much easier (and less expensive) to deal with the shielding, rad-hardening of magnets, activation issues, and cooling of the production target and surrounding region than has been the case with higher power beams [29, 31].

Secondary particle channels have been designed (see, for example [27, 32, 33]) at a number of different facilities that would serve the application described here as well. They employ one, usually two Wien filters [34] (crossed E and B field regions) to select either $\pi$ or $K$ beams.

**Summary:** The goals of current EM facilities would benefit greatly from having hadron-beam data of a quality similar to that of EM data. To this end, it is commonly recognized that a vigorous U.S. program in hadronic physics requires a modern facility with pion and kaon beams. A pion beam and a facility in which $\pi N$ elastic scattering and the reactions $\pi^- p \rightarrow K^0\Lambda$, $\pi^- p \rightarrow K^0\Sigma$, $\pi^- p \rightarrow K^+\Sigma^-$, and $\pi^+ p \rightarrow K^+\Sigma^+$ can be measured in a complete experiment with high precision would be very useful. Full solid angle coverage is required to study inelastic reactions such as $\pi^- p \rightarrow \eta n$, $\pi^+ p \rightarrow \pi^0\pi^+\pi^0$, or strangeness production (among many other reactions). Such a facility ideally should be able to allow baryon spectroscopy measurements up to center-of-mass energies $W$ of about 2.5 GeV, which would require pion beams with momenta up to about 2.85 GeV/c. The 2 GeV/c pion beam at J-PARC will allow baryon spectroscopy measurements up to $W \approx 2150$ MeV.

The White Paper [1] outlined some of the physics programs that could be advanced with a hadron-beam facility. These include studies of baryon spectroscopy, particularly the search for “missing resonances” with hadronic beam data that would be analyzed together with photo- and electroproduction data using modern coupled-channel analysis methods. A hadron beam facility would also advance hyperon spectroscopy and the study of strangeness in nuclear and hadronic physics.

At the end of the White Paper [1], there is a list of endorsers who have expressed support for the initiative described herein: 135 researchers from 77 institutes rep-
FIG. 1: Pion and Kaon production rates on beryllium per steradian per GeV/c per interacting proton for $5 \times 10^{11}$ protons/s CW at 8 GeV. The legend denotes different assumptions for the production angle.

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FIG. 2: Pion and Kaon rates that could be expected at the end of a 30 m-long channel with a solid angle of 3.125 msr and a momentum bite of 2% $\Delta p/p$. The production target is assumed to be 6 cm Pt. Decay along the length of the channel, as well as secondary particle production efficiency and nuclear absorption cross sections of the protons on the Pt target are also factored in to this prediction. The legend denotes different assumptions for the production angle.
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