Hadron Spectroscopy at J-PARC

Physics Overview

It is proposed to perform a program in meson and baryon spectroscopy at the new Japanese 50 GeV proton synchrotron, J-PARC. Secondary beams of protons, antiprotons, pions, and kaons would be used with momenta up to approximately 20 GeV/c. Heavy ions and polarized protons, if available, and low momentum polarized antiprotons (and protons) could also be used.

Quark inspired models of baryons and mesons have been quite successful at predicting the masses and properties of many of the observed hadron states and classifying them into multiplets. However, there remain a number of important open questions:

- Where do the gluonic degrees of freedom appear in the hadron spectrum? Are there hybrid mesons ($q\bar{q}g$) and baryons ($qqqg$) and glueballs (ggg), and what are their spectra?

- Where are the "missing" hyperon states? Based on the number of well established N^* and Δ^* resonances, many more Λ^*, Σ^*, Ξ^*, and Ω^* states are expected than have been observed.

- Are there "exotic" states of mesons and baryons ($q\bar{q}q\bar{q},\ qqqq\bar{q},\ qqqqqq$), and if so, what are their spectra?

- Much of the light quark (u, d, s) spectroscopy data are from the 1960's and 1970's, and the patterns of the observed resonances have been well studied. However, with the expected significant improvement in the knowledge of the hadron spectra, additional symmetries may become evident. These could point to new effective degrees of freedom. For example, is there parity doubling of the states? Is the quark-diquark or three quark picture for baryons more appropriate? What degrees of freedom are suggested by the spectra of hybrids, glueballs, and/or exotic states?

An important parameter in assigning states to multiplets is the electromagnetic coupling, $G_{\gamma NR}$, to the nucleon and resonant state. In most electro- and photo-production experiments, the product with a hadronic coupling is measured, $G_{\gamma NR} \times G_{HAD}$, since the resonance is usually observed via a strong decay channel (G_{HAD}). In contrast, hadro-production provides a product of hadronic couplings, $G_{HAD} \times G'_{HAD}$. Measurements of a couple reactions including elastic scattering are usually sufficient to determine G_{HAD}, and hence also $G_{\gamma NR}$. (The electromagnetic couplings can also be found in hadro-production experiments by observing the radiative decay of the resonance. However, the wealth of data expected from LEPS at SPring-8 and CLAS at JLAB should make the radiative decay data less important.) Thus, the measurements proposed here provide an important complement to the experiments at JLAB and SPring-8.

Pions up to a few GeV/c will be used to study N^* and Δ^* states in formation. Many such resonances are already well established as 3* (***) or 4* states with masses up to ~2500 MeV, as shown in the Particle Data Tables [1]. There are also a number of N^*'s and Δ^*'s classified as 1* or 2* requiring additional confirmation. Properties such as spin, parity, and branching ratios, and classification into multiplets are still required for many resonances as well. It is anticipated that much work will remain in this field of study by the time the proposed measurements would be performed, even with the wealth of new results from electro- and photo-production. Furthermore, the use of polarized targets and of a carbon rescattering polarimeter to measure the outgoing proton spin in some reactions is anticipated to significantly enhance the information available from the data.

A kaon beam of momentum up to 6 GeV/c would allow study of Λ^* and Σ^* states in formation, and Ξ^* and Ω^* resonances in production; the masses would range up to at least 2500 MeV. Assuming these baryons are formed of three quarks (u, d, s), then SU(3) provides the decomposition into multiplets to which these states will belong as $3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$. The decuplet contains a Δ^*, Σ^*, Ξ^*, and Ω^* state, while each octet contains a N^*, Σ^*, Λ^*, and Ξ^*, and the singlet is a Λ^*. Therefore, the number of baryon states should be in the ratio $N^* : \Delta^* : \Lambda^* : \Sigma^* : \Xi^* : \Omega^* = 2 : 1 : 3 : 3 : 3 : 1$. There are 14 N^*'s listed in the Particle Data Tables as 3* and 4* states, so the expected number and observed number of 3* and 4 * resonances is:

Resonance	Δ^*	Λ^*	Σ^*	Ξ^*	Ω^*
Expected #	7	21	21	21	7
Observed #	10	14	10	6	2

A good fraction of the missing states should be in the range of a 6 GeV/c kaon beam. On the other hand, if careful measurements fail to find a significant number of these missing states, and if it is concluded that the N^* states are not hybrid or exotic baryons, then important information will be gained about the effective degrees of freedom for baryon spectroscopy. Of course, the observation of hybrids or exotics will be very important as well. As noted in the pion beam case above, the addition of data from a polarized target will be very helpful for partial wave analyses of the data. However, in this case many of the hyperons are self analyzing via their weak decays, so a carbon rescattering polarimeter will not be as helpful.

As the mass of the resonant state increases, the density of states also grows. This makes the task of separating resonances and establishing their properties more difficult, and leads to the need for large numbers of events. In addition, certain reactions may be selective, making it easier to disentangle various states. For example, the $K^- p \rightarrow \pi^0 \Lambda^0$ and $\eta^0 \Sigma^0$ are both pure isospin-1, while $K^- p \rightarrow \eta^0 \Lambda^0$ is an isopin-0 reaction. In contrast, photo-production experiments usually give a mixture of isospin states. As another example, $s\bar{s}$ meson production should be suppressed in $\bar{p}p$ collisions based on the OZI rule, assuming small s-quark admixture in the proton wave function. This fact has been used to explain the lack of evidence for the $f_0(1710)$ meson in LEAR data [1,2]. The OZI rule would not suppress $f_0(1710)$ production with kaons. Thus, for both examples, kaon beam results will supplement and complement data from other accelerators.

The hyperon studies described above are all expected to occur with a K^- beam. However, searches for $qqqq\bar{q}$ states could be performed with a K^+ beam. Evidence for K^+N resonances (Z^*) was presented in the Particle Data Tables before the mid 1980's, but was then discontinued due to the lack of new data and the controversies surrounding the interpretation of the existing cross section and polarization results. A survey experiment with much improved statistics compared to those early data would hopefully resolve whether such "exotic" baryon resonances exist.

Antiprotons would be very useful for meson spectroscopy, as demonstrated by LEAR experiments. Mesons (and glueballs) with all quantum numbers can be produced, whereas other reactions are often limited. Even though large data samples were collected, the addition of $\bar{p}p$ measurements with a polarized proton target (and unpolarized antiproton beam) would be a valuable complement to the LEAR results. In particular, polarization data for the all neutrals final states $\bar{p}p \to \pi^0\eta^0, \pi^0\pi^0\pi^0, \omega^0\pi^0, \omega^0\eta^0$ would allow many ambiguities in present analyses to be resolved, yielding a better understanding of the meson spectrum.

At this time, it appears that an antiproton storage ring will be constructed at GSI, with momenta from approximately the top end of LEAR up to about 18 GeV/c. In addition to light quark states, open and hidden charm resonances could be produced and studied with high quality beams and a large general purpose detector. In general, antiproton beams at J-PARC would not be competitive with such a facility unless a similar one was constructed at Tokai.

A major exception to the previous statement may be the use of polarized antiproton beams. A scheme has been proposed [3] to scatter unpolarized antiprotons from a liquid hydrogen target and collect elastically scattered antiprotons at $t \cong -(0.1 - 0.2)\ \mathrm{GeV}^2/c^2$. The polarization of the antiprotons would be ~ 0.2, and the intensity would be roughly 2×10^{-4} times that of the incoming antiproton beam. These parameters apply in the momentum range of 0.4 – 1.8 GeV/c. The same process would also work at higher momenta with perhaps a smaller polarization (~ 0.1), but the data are few and have larger errors than the LEAR results, so detailed estimates cannot be made. Measurements to predict the polarized beam performance at these higher momenta could be done at the proposed spectrometer using an unpolarized antiproton beam incident on a polarized proton target. In any case, it is important to have as high intensity as possible for the incident unpolarized antiprotons.

Spin measurements may be very important in disentangling the quantum numbers of some resonances produced in $\bar{p}p$ interactions, as noted above. The polarized antiproton beam with a polarized target (or possibly the carbon rescattering polarimeter for the outgoing proton) could be employed. The low polarized beam intensity will require using this tool selectively at particular momenta of interest, carefully choosing spin observable(s) with optimum sensitivity to the expected quantum numbers. The polarized antiproton beam would then be complementary to the new GSI facility. At lower momenta, the spin observables in $\bar{p}p$ elastic and $\bar{p}n$ quasielastic scattering could be measured in order to determine the $\overline{N}N$ scattering amplitudes (see [3]). This will provide important new information on annihilation. At present, far too few spin observables have been measured to even attempt to obtain the amplitudes. Thus, a polarized antiproton beam would permit <u>unique</u> measurements in the GeV/c momentum range.

Information on the hadron spectrum in the Particle Data Tables comes from many types of measurements, including those with high momentum (≥ 10 GeV/c) beams of pions, kaons, and protons. These results typically complement data from electro- and photo-production, $\bar{p}p$ annihilation, and low momentum formation experiments. It is anticipated that such high momentum beams will have an important role also at the 50 GeV PS. For example, K and K^* mesons could be studied with a high momentum rf-separated kaon beam, with improved sensitivity to these states compared to pion or proton beams (since the incident kaon carries an s-quark). Such a kaon beam would be expected to have considerably higher intensity than a comparable one (OKA) at Serpukhov. Note that the known K^* mesons all fit into the expected multiplets, in contrast to other light mesons where a number of extra states exist. If the extra states correspond to hybrid or exotic mesons, these would also be expected for the K^*'s, and it would be important to search for them as well.

Specialized experiments, not related to spectroscopy, could be performed with polarized proton and heavy ion beams. Inclusive production of pions, η^0's, and K^0_s mesons at high x_F and moderate p_T with polarized protons have shown sizeable single spin asymmetries at 22 and 200 GeV/c and other momenta. The origin of these asymmetries is not known, but may be related to the transversity distribution function for the proton (see [4] for references). The proposed spectrometer and a 40 – 50 GeV polarized proton beam would be ideal to study a range of inclusive meson production asymmetries. For heavy ions, the large acceptance of the spectrometer should be very helpful to map out particle production as functions of beam and target nuclei, energy, and pseudorapidity. The spectrometer measurements would complement results from possible dedicated detectors for heavy ion interactions at J-PARC.

The Apparatus

The spectroscopy data from LEAR provide a standard for modern experiments. Samples of >100 K events per reaction and energy were shown necessary to unambiguously identify some states against sizeable backgrounds from other reactions. In order to achieve such samples in the hyperon measurements with reasonable run times, significantly higher kaon fluxes will be required than in previous kaon beams. Furthermore, the LEAR results show that the detector should cover nearly 4π solid angle and be capable of collecting data at several hundred Hz.

The detector should thus be a large acceptance, general purpose, magnetic spectrometer. The solid angle should be nearly 4π in order to achieve good acceptance, especially for multi-particle final states. The requirement of good rate capabilities is important to record high statistics data samples in reasonable running times. Triggering will also be important, for example to select Ξ^* and Ω^* hyperon candidate events from all K^-p interactions. The spectrometer should be designed to be compatible with a polarized target, which would greatly enhance the physics capabilities.

It is anticipated that the spectrometer construction might be staged. Initially, the magnet, tracking with some sort of wire chambers, electromagnetic calorimetry, and triggering would be essential. Particle identification with time of flight and RICH detectors would be highly desirable. Important upgrades would include a silicon tracker near the target to assist in identifying long lived particles, a carbon rescattering polarimeter over a portion of the acceptance, muon detectors, and perhaps hadron calorimetry (for neutrons and K_L's). It is hoped to reuse some components from a collider detector(s) to reduce the cost. The polarized target will be required early, though perhaps a couple years after startup.

Two beams are expected to deliver particles to the spectrometer. One would have a maximum momentum about 6 GeV/c with electrostatic separators for pions, kaons, protons, and antiprotons. The origin of this beam should be a target in the high intensity primary A line, probably from the T_1 target. This requirement is driven by the need for high intensity kaon and antiproton beams. It should be designed so that it can also be configured as the polarized antiproton beam. Good shielding will need to be provided to minimize the flux of kaon and pion decay products (muons, electrons, photons) from reaching the spectrometer. Wire chambers and/or scintillation hodoscopes and a Cerenkov counter will be required near the target to record the particle trajectory and type.

The second beamline should permit transport of primary heavy ion beams and perhaps a portion of the polarized proton beam. It should be configurable as a secondary beam as well, probably from the SM1 target, to provide pions, rf-separated kaons, and antiprotons. The kaon and antiproton fluxes will be limited by the SM1 target thickness, which must be kept reasonably thin due to the planned shielding. A secondary target in the B line might be sufficient for some of the high momentum pion experiments, and also for the location of the septum magnet for the polarized or heavy ion beams.

Funding

It is planned to request funding for construction of the beamlines and some polarized proton beam hardware from the US Department of Energy (DOE). This would include the cost to manufacture the special radiation-hard magnets near the production targets, and to build or refurbish other dipoles, quadrupoles, separators, and snake magnets. It is also expected to work with DOE laboratories to obtain any useful existing magnets and separators for these beams.

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