Strange Hadron Spectroscopy with Secondary $\mathbf{K}_L$ Beam at GlueX

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Abstract: This White Paper summarizes unresolved issues in hadron physics and outlines the vast opportunities and advances that only become possible with the KL facility. This KL facility would revolutionize our understanding of bound-systems containing strange quarks, providing the long sought, quality experimental data to reach deeper into the strange quark sector. This will enable the tremendous recent progress in spectroscopy in both theory and experiment with electromagnetic beams to continue into a new frontier.

I. THEORETICAL MOTIVATION FOR EXPERIMENTAL DETERMINATION OF THE SPECTRA OF STRANGE HADRONS USING A $\mathbf{K}_L$ BEAM AND THE GLUEX DETECTOR

The experiment [1] will measure both differential cross sections and self-analyzed polarizations of the Λ, Σ, Ξ, and Ω hyperons. These new data will significantly constrain the partial wave analyses for the extraction of the properties and pole positions of the strange hyperon resonances. They will finally determine the orbitally excited multiplets in the spectra of these hyperons, which with the exception of the Λ remain very poorly known. Comparison with the corresponding multiplets in the spectra of charm and bottom hyperons will illuminate the approach to heavy flavor symmetry and eventually the accuracy of QCD based calculations.

The proposed facility will have a defining impact in the strange meson sector through measurements of the final state $K\pi$ system up to 2 GeV invariant mass by determination of pole positions and widths of all $K^*(K\pi)$ P-wave resonances. It will settle the question of the possible existence or nonexistence the of scalar meson $K_0^*(700)$ (κ). This resonance would be the strange counterpart of the σ (or $f_0(500)$) meson, which is now rather well established from πN scattering. Knowledge of the resonance spectra of the strange hyperons is a crucial ingredient in strange resonance enhancements in relativistic heavy ion collisions.

The physics case for the experiments is aligned with the 2015 Long Range Plan for Nuclear Science: "....a better understanding of the role of strange quarks became an important priority" [2]. 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 will provide an understanding of soft QCD matter and the approach to heavy quark symmetry. In the spectrum of the Λ hyperon only the lowest negative parity doublet and the positive parity singlet are well established, but their structure remains unsettled. In the spectra of the Σ and Ξ hyperons only the lowest decuplet states $\Sigma(1385)$ and $\Xi(1530)$ are well established. It is a priority determine whether the indication for several low lying negative parity Σ hyperon around 1500 MeV are real.

The mass of the lowest positive-parity resonance in the spectrum of Σ hyperons is experimentally known, but their structure is not. In the case of the Ξ hyperon, the lowest positive-parity resonance remains unobserved. To settle the nature of these hyperon resonances, their main decay modes have to be determined by experiment. Heavy quark symmetry provides a powerful tool for analyzing the structure of strange hyperons by comparison to the corresponding heavy flavor hyperons. Heavy quark symmetry is a consequence of the fact that the strength of quark spin-orbit couplings scale with the inverse of the constituent mass. In the case of the hyperons, this implies that the spin-orbit splittings in the hyperon spectra decrease with increasing quark mass. In the case of hyperons with light and heavy quarks this implies that the heavy quark spin decouples from that of the light quarks. Heavy quark

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symmetry suggests, that the ratio of the sizes of such spin-orbit splittings in the corresponding multiplets in the spectra of the strange, charm and beauty hyperons should approximately correspond to the ratio of the inverses of the corresponding constituent quark (or approximately) meson (K, D, B) masses. Where the spin-orbit splittings conform to this scaling law the implication is that the quark structure of the corresponding hyperon resonances in the different flavor sectors are similar.

Given hyperons with only one light flavor quark shall be exceptionally important to compare the spin-orbit splittings between the Ξ hyperons in the different flavor sectors, once these are determined experimentally. Hitherto the comparable splittings are only known for the lowest negative parity doublets in the strange, charm and beauty hyperon spectra, with two light-flavor and only one single heavy quark.

Current QCD lattice calculations are able to give good qualitative information on the structure of the hadron spectra, but still are computational constrained to unphysically large pion mass values.

The application to baryons is far more limited. In an approach in which the excited-state hadrons are treated as stable particles, a spectrum of baryons at least as rich as that of the quark model has been revealed and evidence has been presented for "hybrid" baryon states, beyond those of the quark model, in which gluon degrees of freedom are essential. Notably, this picture extends to the spectrum of the Λ, Σ, Ξ, and Ω states where the counting of states reflects $SU(6) \times O(3)$ symmetry.

The calculations for the baryon sector are incomplete, in that the momentum-dependent scattering amplitudes characterizing multi-hadron states have not been extracted. In comparison with the calculations for mesons cited above, the challenges are more computational than theoretical or conceptual. The first direct calculation of the $I = 3/2$ $N\pi$ system in the P-wave has now been performed and reveals a Breit-Wigner description of the amplitude commensurate with a phenomenological description of the $\Delta(1232)$ resonance. According to the general trend in lattice QCD, it is likely that the progress made in the meson sector will be reflected for the case of baryons in the coming years. Quantitative first principle lattice calculations with the physical pion mass of the positive parity resonances beyond the lowest decuplet states do, however, remain beyond reach for the time being. This emphasizes the need for phenomenological determination of the strange hyperon spectra at GlueX in parallel with the current work at LHCb at CERN.

II. EXPERIMENTAL DETAILS

The tertiary neutral kaon beam to be used for these experiments will consist of four main components:

- In the first stage, 12 GeV electrons will scatter in a copper radiator (10% X_0) inside the Compact Photon Source (CPS), thereby generating an intense beam of untagged bremsstrahlung photons.
- In the second stage, the photon beam will interact with a Be target located 67 m downstream of the CPS. Directly behind the Be target there will be collimation and a sweep magnet to strongly enhance the relative contribution of neutral kaons transported along the beam line.
- In the third stage a flux monitor will register in-flight decays of the K_L over a 2 m path length.
- In the fourth and final stage, the momentum-tagged K_L (via time-of-flight) will interact with the existing GlueX liquid hydrogen target modified to accept a larger diameter target cell.

A brief overview of each of these components is provided below, together with an overview of the experimental conditions that this facility will be able to provide. Further details of the devices and experimental conditions can be found in the proposal and supplemental materials to PAC46 [1].

CPS: The CPS design combines in a single properly shielded assembly all elements necessary for the production of the intense photon beam, such that the overall dimensions of the setup are limited and the operational radiation dose rates around it are acceptable. The CPS with a weight of 100 t is to be located in the Hall D tagger vault, 11 m downstream of the current radiator. Consequently, the Hall D tagger does not need to be modified to implement the CPS. The CPS will contain a 10% X_0 radiator capable of handling up to 60 kW of power deposited from the 12 GeV electron beam. The enclosed magnet will enable the CPS to concurrently serve as the beam dump for the primary electron beam. The active elements will be surrounded by sufficient shielding for radiation protection. At the full 60 kW beam operation, the dose rates will be comparable to nominal conditions in the vault.

Be target: The K_L will be produced with forward emission kinematics in the interaction of the photon beam with a Be target. Be is used because lighter element provide higher photoproduction yield per unit radiation length. The Be-target will be a cylinder of 6 cm diameter and 40 cm length. The Be will be surrounded radially and downstream by a tungsten absorber with an overall length of 70 cm and an outer diameter of 75 cm. This will be surrounded by lead (diameter 100 cm, length 130 cm) and then a 10 cm shell of borated polyethylene. The weight of the Be-target assembly is 14.5 t. Changeover from the photon to K_L beamline and vice versa is expected to take about half a year or less , and thus should fit well into beam breaks of the current CEBAF schedule. Water cooling will be required to dissipate the 6 kW deposited by the photon beam. Directly downstream of the target there will be a magnet with a field integral of 0.8 $T \cdot m$ to clean up the charged particle component from the beam.

Flux Monitor: In order to normalize the cross section of the recorded data, the K_L flux will be determined with a relative precision of better than 5% by a dedicated Flux Monitor (FM). This device will measure pairs of charged decay products from the in-flight decay of the K_L. The K_L flux will be measured upstream of the GlueX detector, using the Hall D pair spectrometer as shielding against decays that have occurred further upstream. The fiducial volume will encompass the 2 m downstream of the Pair Spectrometer. The FM will consist of tracking devices directly before and after a solenoid magnet and will be surrounding by scintillating endcaps. A potential extension of the system would further increase performance by instrumenting the inner wall of the magnet and add a start counter surrounding the beamline. Detailed studies indicate that a statistical precision to measure the K_L flux of 1% is achievable in less than one day.

CryogenicTarget: The existing GlueX liquid hydrogen cryogenic target will be used and modified to accept a larger diameter target cell. The radius of the kapton cell will be increased from 2 cm to 6 cm and the length will increase from 30 cm to 40 cm, corresponding to a volume of 1.1 liter. There will be cooperation with the JLab Target Group to investigate alternative materials and construction techniques to increase the strength of the cell and to enable operation with both LH_2 and LD_2.

Beam Luminosity/Background: Detailed simulation studies of the beam properties have been performed. The main mechanism of K_L production in this energy range is via ϕ-meson photoproduction. Total and differential cross sections including angular distributions of intermediate decays have been taken into account, as well as absorption in the target and surrounding shielding. The K_L flux incident upon the cryogenic target will increase with momentum and reach a broad plateau at about 4 GeV/c, beyond which the flux will drop rapidly. Due to the contribution of hyperons, the flux of K^0 will be larger than that of the $\overline{K^0}$ by about 30%. In total about 1×10^4 K_L /s will be incident on the cryogenic target.

Beam background from muons, neutrons and photons have been studied. Most muons are produced in the photon dump and will be swept out of the K_L beamline; thus, they are not inherently a significant background for the measurement. Detailed studies show that they are also not a significant radiation load outside of the shielding. The neutron and gamma flux along the beamline and the neutron dose rate in the experimental hall from scattered neutrons and gamma were determined using the MCNP6 N-Particle (MCNP) Transport code. The neutron dose rate calculated is 0.11 ± 0.04 $mrem/h$, which is acceptable by RadCon. The neutron flux on the face of the LH_2/LD_2 cryogenic target is 1.7×10^4 $n/(s \cdot cm^2)$. This flux peaks at about 400 MeV and drops exponentially to 10 GeV. The flux is not sufficient to provide a significant background in the case of np or nd interactions in the cryogenic target.

The momentum of the K_L beam will be measured using time-of-flight (TOF) - the time between the accelerator bunch (RF signal from CEBAF) and the reaction in the LH_2/LD_2 target as detected by the GlueX spectrometer. Since the accelerator signal has a time resolution of about 1 ps, the TOF resolution will be defined by GlueX. With a beam bunch separation of 64 ns, there will be no bunch misidentification for momenta above about 320 MeV/c. The beam momentum resolution will vary from about 1.5% at 1 GeV/c to 5% at 2 GeV/c, corresponding to a W resolution of better than 30 MeV over this momentum range. At higher momenta, exclusive reconstruction of final states will enable ΔW to be limited to about 30 MeV by exploiting over-constraints in the event reconstruction.

Summary: The current KLF proposal has been tested in four international workshops with more than 100 talks given, supporting the KLF physics program [3–6]. Currently this proposal is signed by 200 physicists from 61 institutions of 20 countries, with some distinguished world experts in the field. It is the largest collaboration ever to submit a proposal to the JLab PAC. The submitted proposal reflects the collective wisdom of the broad community.

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