**Proposal to the Q-PAC at RCNP for the LEPS detector**

# Measurement of the $\Lambda$-N Interaction with a Deuterium Target

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Beam Time requested: 90 days
Beam Conditions: 1.5-2.4 GeV circularly polarized
Detector: standard forward-angle detector with neutron detectors
Target: $LD_2$ 15-cm long

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**Summary of Proposal**

This proposal is to measure the $\gamma d \rightarrow K^+ \Lambda n$ reaction where the $\Lambda$ and the neutron are detected in the LEPS detector (modified for neutron detection). The goal of the experiment is to extract the $\Lambda$-n scattering length by comparing theoretical predictions for the invariant mass of the $\Lambda$-n system with experimental measurements (when cut above the Fermi momentum for a neutron in deuterium). In addition, circular polarization of the photon beam will polarize the $\Lambda$, providing an asymmetry (as a function of the $\Lambda$-n invariant mass) which can be compared with theoretical models with different values for the spin-triplet and spin-singlet amplitudes.

In order to measure the neutron, additional detectors (plastic scintillator bars) will be added to the LEPS spectrometer after the TOF wall. This will be a straightforward modification to the existing support structure for the TOF wall, and will not require expensive modifications. The neutron detectors already exist, along with phototubes and electronics for the readout. Neutron energies will be calculated from their velocity measured by time-of-flight along the 4 meter path from the target.

Calculations for this reaction have been published [1] and can be applied to the LEPS kinematics. In this publication, they considered also polarized target observables. Once the polarized HD target is available, this would be a natural extension to the proposed measurements. However, a polarized target is not necessary to complete the goal of the present proposal.

In addition to the proposed measurement, other measurements that would benefit from neutron detection (such as $\Theta^+$ production followed by decay to $K^+ n$) could also be analyzed from the same data set. Hence the proposed experiment, with the detection of neutrons, will provide a new capability for LEPS experiments.

## Detailed Description of the Proposed Research

## 1. Objectives and Impacts of the Λ-N Experiment

The ΛN scattering length has been of interest to theorists for many years in order to expand our understanding of baryon-baryon dynamics. In particular, the existence of hypernuclei have led to a quantitative understanding of the Λ-nucleus potential, including the spin and tensor couplings [2]. It is natural to extend this to scattering of the Λ with free nucleons, yet available data do not allow a reliable determination of the spin-triplet and spin-singlet scattering parameters [1]. Now, calculations of photoproduction of the $K^+\Lambda$ reaction on the deuteron followed by final state interactions with the spectator nucleon [1] predict observables with a sensitivity to the ΛN force.

In addition, lattice QCD calculations (PACS-CS Collaboration) have been used to predict the ΛN force directly from QCD [3]. The results show a repulsive core, which is strong for the spin-singlet case and weak for the spin-triplet case, and has a slight attractive region at medium distances. Data is necessary to provide tests of these calculations of the ΛN force.

As a final motivation, the binding energies of Λ hypernuclei for the four-baryon systems ${}^4_\Lambda He$ and ${}^4_\Lambda H$ show a significant mass differences (after correction for the known mass differences of the core nuclei, ${}^3He$ and ${}^3H$). This indicates a charge asymmetry of the Λ-p and Λ-n interactions that is far greater than the difference between the charge-symmetric n-p and n-n forces. The measured values for $B_\Lambda({}^4_\Lambda H)$ and $B_\Lambda({}^4_\Lambda He)$ are shown in Table 1 (copied from Ref. [2]). This question of isospin asymmetry can only be understood in detail from Λ-N scattering data.

Table 1: Binding energies of the $A = 4$ Λ-hypernuclei, corrected for the binding of the ${}^3H$ and ${}^3He$ core binding energies, demonstrating the charge asymmetry of the Λ-n and Λ-p interactions.

| Hypernucleus | $J^\pi$(gs) | $B_\Lambda$ (MeV) |
|---|---|---|
| ${}^4_\Lambda H$ | $0^+$ | $2.04 \pm 0.04$ |
| ${}^4_\Lambda He$ | $0^+$ | $2.39 \pm 0.03$ |

Hence, data on both Λ-p and Λ-n scattering at the same kinematics is desirable. The former can be measured by hadronic reactions such as $pp \to K^+\Lambda p$ at COSY, but the latter is more difficult to access since it requires a neutron beam (or deuteron target). The measurement of the charge asymmetry is more easily determined from photoproduction on the deuteron, where the Λ can be produced on either the proton or the neutron in a nearly symmetric fashion.

Here we propose an experiment using the LEPS detector at SPring-8 that includes neutron detectors to measure the Λ and the neutron directly at forward angles. The produced kaon can be determined from the missing mass spectrum of the ΛN system. The ΛN force is most apparent when the Λ and the neutron have low relative momentum, *i.e.* an invariant mass near zero. This requirement is most easily imposed when the neutron is directly detected at forward angles. In addition, it is known from CLAS data [4] that the polarization transfer of the photon spin to the $\Lambda$ is large for circular polarization and forward production angles. By reversing the photon polarization at LEPS, the spin-triplet and spin-singlet forces can, in principle, be separated.

The resulting data will provide a useful constraint for theorists to test various $\Lambda$N scattering interactions. This will be the first time that photoproduction has been used to access observables that are sensitive to the $\Lambda$N force, hence demonstrating a new capability. With help from theorists, this experiment will lead to new constraints on the $YN$ interaction, which is one of the primary goals of nuclear physics.

## 2. Theoretical Predictions of $K^+\Lambda$ production

The theoretical situation for $NY$-scattering was summarized in three talks presented at the recent HYP-X international conference. The first talk was given by Prof. Rijken, who uses a SU(3) unitary model to do a unified fit to both $NN$ and $NY$ scattering data. The second talk was by Haidenbauer, who uses a different model fit to hyperon production data at COSY (Julich). The third talk was by Nemura, who uses results from Lattice Gauge calculations to extract the wave functions of the baryons on the lattice and converts these to scattering potentials. Papers from the latter two talks will be briefly reviewed next. The bottom line is that there is significant theoretical interst in the $YN$ scattering potential, and new data is needed to constrain the fits in these three models.

The calculation done by Haidenbauer [1] is most relevant for this proposal. In Ref. [1], they explicitly considered the $\gamma d \to K^+\Lambda n$ reaction and conclude that it is sensitive to the $\Lambda n$ scattering length. They use a dispersion integral method to factorize the left-hand singularities from the eleastic amplitude, leaving a term that is weakly dependent on the invariant mass of the $\Lambda n$ system. To extract the low-energy scattering parameters, they use a specific model for kaon photoproduction (KAON-MAID) to produce the $\Lambda$ followed by their $\Lambda n$ scattering calculation. The results are summarized by Ref. [1] where they say "An important kinematical constraint for the reaction $\gamma p \to K^+\Lambda n$ is the limitation of the kaon angle to very forward or very backward directions because only then a separation of the spin-singlet and spin-triplet states is possible". In other words, the kinematics of the LEPS detector is ideally suited for a study of the $\Lambda n$ scattering potential, since only in these kinematics can one separate the two contributions of spin states. They suggest to use a polarized target for this separation, but in fact it is also possible to do this with circularly polarized beam.

As shown by CLAS data, there is almost complete transfer of polarization to the $\Lambda$ in kaon photoproduction reactions. Hence, the $\Lambda$ will be polarized either parallel or anti-parallel to the beam momentum, depending on the projection of the circular polarization. One can also measure the $\Lambda$ polarization in the final state (due to its weak decay), which allows a separation of the spin-singlet and spin-triplet. Unfortunately, the proposed experiment will not have sufficient statistics to measure the $\Lambda$ polarization in the final state. However, future proposals to use the HD target and/or the LEPS2 detector (with larger acceptance to allow measurements of the $\Lambda$

polarization) are possible. Even if the spin-states cannot be separated, the database for $\Lambda n$ scattering has so few entries (only 38 data points) the proposed measurement is still valuable.

The calculations of Ref. [1] show that the scattering observables are most sensitive to the $\Lambda n$ force when the invariant mass of the $\Lambda n$ system is low (within 10 MeV/$c^2$ of threshold).

## 3. Objectives of the Λ-N Measurement

The goal of this experiment is to extract the scattering length of the Λ-N force. This low-energy scattering parameter is the most important part of the Λ-N scattering potential. To measure this, the Λ and the neutron must have a small *relative* momentum, corresponding to an invariant mass of the Λ-N pair within about 10 MeV/c$^2$ of threshold (based on the above calculations).

The experimental objective is to measure neutrons in coincidence with Λ particles at forward angles in the LEPS spectrometer. The neutrons must have a momentum above the Fermi momentum for deuterium, showing that a final-state interaction has taken place. The missing mass of the Λ-N system should be the kaon mass, to cleanly identify the exclusive reaction.

For a cut on the neutron momentum above the Fermi momentum tail, the invariant mass of the Λ-N system will be calculated. The shape of this mass spectrum will be compared with that predicted by theoretical models with different Λ-N scattering lengths. In addition, we will form a ratio (an asymmetry) of events with the circular polarization in each of the two projections, as a function of the Λ-N invariant mass, and this asymmetry will be compared with theoretical predictions with different values of the spin-triplet and spin-singlet scattering force.

## 4. Neutron Detection using Plastic Scintillators

The neutron detectors will be plastic scintillator bars with cross sections of 10 cm by 10 cm. Such detectors have been used extensively at IUCF for the $(p, n)$ reacction to investigate Gamov-Teller strength in nuclei, and also at the LEGS experiment at Brookhaven Lab to study the GDH sum rule. Hence, this style of neutron detection is well understood and calibrations of neutron detection efficiency are documented in the literature.

Ohio University owns 16 neutron bars, with phototubes at both ends. These bars were used at the LEGS experiment, and will be shipped to SPring-8 for installation at LEPS. In addition, there are many neutron bars, some long and some short, already at SPring-8, originally from the TAGX collaboration. The TAGX group has been contacted and has given permission for these bars to be mounted on the LEPS detector. Electronics for readout of the bars will be done using fastbus, which has 96 inputs per board. Spare TDC and ADC modules are currently available for use at LEPS and can easily be incorporated into the data acquisition stream.

The neutron bars will be installed at the LEPS facility immediately behind the TOF counters. The TOF counters serve as a veto of charged particles, allowing clean

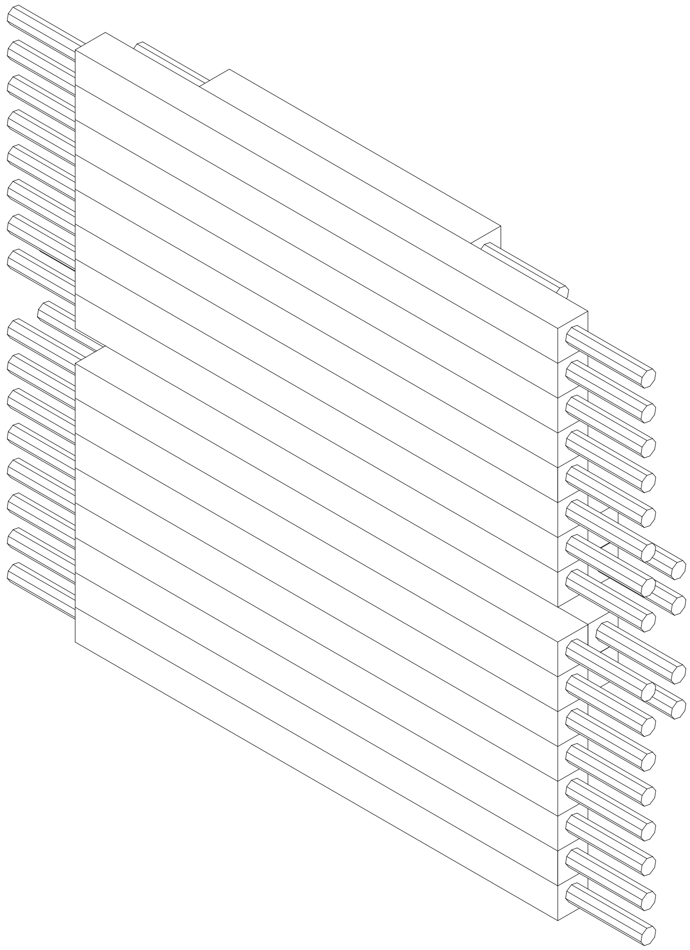

Figure 1: Schematic diagram of the neutron detector configuration that will be placed after the TOF bars at LEPS.

neutron identification. The TOF counters ride on a moveable cart and a horizontal shelf will be mounted just above the wheels on the TOF cart. The neutron bars will be stacked vertically (with the length of the bars horizontal), up to just below the beam height. and then a gap at beam height, allowing an opening for the photon beam to continue to the beam dump. Long horizontal bars will again be stacked vertically above the beam level. Depending on the exact support structure, which will require some engineering design, there are enough neutron bars for two layers deep, giving a 10-20% efficiency (depending on the neutron momentum, see below). A preliminary drawing of this configuration is shown in Fig. 1.

Neutrons can be distinguished from photons based on their time-of-flight. Photons will travel at the speed of light, whereas neutrons will travel much slower. A typical neutron momentum expected from Λ-N scattering is about 1 GeV/c, corresponding to a $\beta$ of about 0.60. Over a 4-meter flight path, a neutron of this speed will take about 5 ns longer than a photon. Using the RF time as a start time, the neutrons are easily separated from coincident photons. Photons from room background, mostly

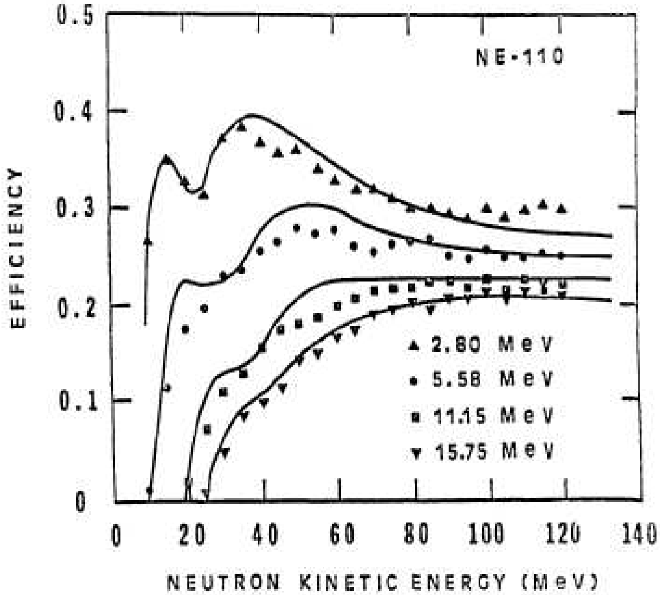


Figure 2: Neutron detector efficiency, measured by the Kent State group, for plastic scintillator bars with the same dimensions and orientation to the neutron source as for the proposed measurments.

associated with the beam dump, will cause accidental coincidences, but the rate is not expected to be high. These accidentals can be subtracted in the usual way (by measuring the coincidences with out-of-time beam buckets.

The resolution of the neutron velocity (energy) depends on the timing resolution of the neutron detectors. A typical resolution, corrected for pulse height, is about 0.1-0.2 ns (greater than the TOF counters due to the greater width of the neutron bars). However, resolution is not a big issue, since detection of the $\Lambda$ uniquely identifies the production of strangeness. The associated $K^+$ can be seen in the missing mass of the $\Lambda$-n system, and background from $K^*$ and 3-body $K\pi\Lambda$ production is expected to be small. Knowledge of the neutron angle constrains the kinematics and simulations indicate that $K\pi\Lambda$ production can be separated using a combination of missing mass and missing energy.

Even though the neutron efficiency is well-known for plastic scintillator bars, as shown by Fig. 2 from Ref. [7], it is easy to calibrate directly using the deuteron breakup reaction. Deuteron breakup has two-body kinematics, and so the neutron mass forms a strong peak in the spectrum of missing mass of the proton. Since the neutron direction and velocity are known from the proton, we know where the neutron should hit in the scintillator bars. The deuteron photodisintigration cross section is large, and so the neutron rate will be sufficient to get a high-statistics calibration of the neutron efficiency at the kinematics of deuteron breakup. Extrapolation to other neutron energies will be done by calculating the efficiency of these scintillators from standard codes and normalizing the absolute efficiency from deuteron breakup.

Because of past experience with neutron detection by one of the spokesman and others on this proposal, this technical aspect of the proposal is not a problem. Neutron detection will enhance the capabilities of the LEPS detector and can be used for many other physics investigations other than the one proposed here (such as $\Sigma^- \to n\pi^-$ detection or possibly for $\Theta^+ \to nK^+$ decays).

## 5. Experimental method and apparatus

This measurement is ideally suited to the forward angles measured by the LEPS detector and the highly polarized photon beam available at BL33 at SPring-8. The LEPS detector has been described elsewhere [5] and is unnecessary to repeat here.

The only changes from the standard LEPS setup are:

1. large plastic scintillator bars need to be installed just behind the TOF wall.

2. the electronics needs to be updated to read out the ADC and TDC signals from the neutron bars.

Describe the configuration of the bars and their readout here.

The target for this experiment will be the 15-cm long liquid deuterium (LD2) vessel. Because the cross sections are small, the target length should be as long as possible. The vertex reconstruction for two-particle decays provides good enough resolution to cleanly separate the target from the start counter.

## 6. Beam Time Request

The photon beam flux with the standard laser is known to be about $20^5$ Hz per 0.1 GeV bin in the region from 1.5-2.4 GeV. The cross section in the region from 1.5-2.0 GeV is about 0.5 $\mu$b in $\cos\theta$ bin $-1 < \cos\theta < -0.6$. for forward-angle $\Lambda$'s (backward angle $K^+$). Taking a cone of polar angle 20°, the solid angle is about 72 sr. Finally, the area number density of deuterium nuclei for the 15 cm LD2 target is about $6\times10^{23}$ per cm$^2$. Putting these numbers together, the average count rate is:

$$R \;=\; (2\times10^5/sec)(6\times10^{23}/cm^2)(0.5\times10^{-30}cm^2$$

or about 0.06 counts per second assuming 100% efficiency.

Of course, the detector is not 100be less. In particular, the efficiency to detect both decay products from the $\Lambda$ going at 0° into the LEPS solid angle is about 5% (based on g3leps simulations, see LEPS Technical Note 36), and decreases as the $\Lambda$ angle increases. This detection efficiency includes effects from the the lead blocker bar and the hole for the pair-produced electrons at 0°. Finally, there is the beam transport factor, trigger efficiency and the deadtime of the data acquisition system. Taking these effects into account, we expect about than 0.001 count/second averaged over the entire solid angle, per 0.1 GeV bin of the photon beam. Neutron detection efficiency will be about 10efficiencies as described in the previous section. This efficiency can be increased by adding more layers of plastic scintillators, but this would require additional funding.

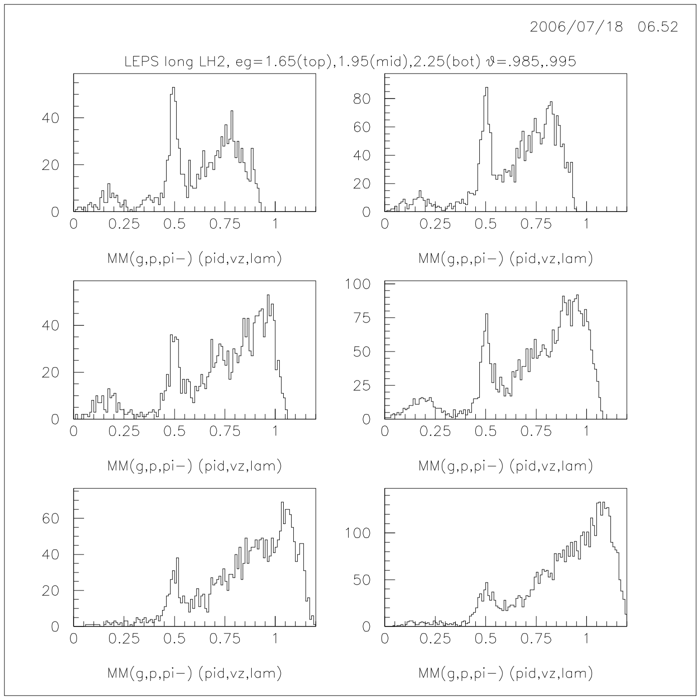


Figure 3: The $\Lambda$ missing mass for different beam energies (1.65, 1.95, and 2.25 GeV from top to bottom) and two angle bins (left: $\cos\theta_{LAB} = 0.985$, right: $\cos\theta_{LAB} = 0.995$).

The background for $\Lambda$ detection is shown in Fig. 3 (see also Ref. [6]) and is minimal at lower photon energies. In order to fit the peak cleanly, with this signal/noise ratio, we need about 200 counts in the peak to obtain a statistical precision in the peak fit of about 7%.

For an expected rate of 0.0001 counts/sec/bin for the average bin, about 8 counts per day can be obtained, or 25 days to get 200 counts for each polarization direction, for a total of 50 days. However, in some bins (especially at higher energy), the count rate will be lower by about factor of about 2. So we request a total of 90 calendar days of running for the full kinematic coverage.

Another way of estimating the beam time request is to look at the number of counts in LEPS Technical Note 36. These data for forward-angle detection of the $\Lambda$ where taken with a total photon flux of $3.2 \times 10^12$ photons from the long LH2 target run. For a tagger rate of 1 MHz (over the whole photon energy range), in one hour we get $3.6 \times 10^9$ photons. Hence, we need about 1000 hours (about 40 days) to get equivalent statistics. Since we plan to combine all events into a single angle bin (there were six angle bins for the TN36 analysis), this gives about a factor of about five. Doubling the time period gives a factor of 10, which provides the factor necessary to account for the neutron detection efficiency (about 10%).

Hence we estimate a need for 80-90 days of full-time running. The actual length of the run may be longer, due to downtime for maintenance and so on.

## 7. Experimental Schedule

It is desirable for the experiment to be scheduled in the summer, when classes are not in session in the USA. This will allow for a long visit by the spokesman during the run. It might also be desirable to schedule the experiment to run in 2012 when K. Hicks will be on sabbatical.

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