Letter of Intent for

Study of Exotic Hadrons with $S = +1$ and Rare Decay $K^+ \to \pi^+ \nu \overline{\nu}$ with Low-momentum Kaon Beam at J-PARC

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Abstract

This is a Letter of Intent for a new experimental program in J-PARC, combining the topics of "Hadron Physics" and "Kaon Physics" by using the large solenoidal spectrometer of the BNL-E949 experiment and with a low-momentum DC-separated K^+ beam. The exotic Θ^+ baryon resonance at 1540 MeV/c^2 is studied with the reaction $K^+n \to \Theta^+ \to K^0p$ followed by $K^0 \to \pi^+\pi^-$. A new measurement of the branching ratio for the rare decay $K^+ \to \pi^+\nu\bar{\nu}$ is performed with K^+ decays at rest; we observe more than 50 $K^+ \to \pi^+\nu\bar{\nu}$ events in the Standard Model and measure the branching ratio with a precision $\leq$20%. We plan to move the E949 detector from BNL to SPring-8 first, use it for the experiments at LEPS2 until around 2012 or 2013, and then move the detector to J-PARC for the experiments in this Letter. A low-momentum and separated K^+ beam, such as the K0.8 line operated in lower momentum, is suitable for the Θ^+ experiment. A K^+ beam line incorporating two stages of DC separation is indispensable for the $K^+ \to \pi^+\nu\bar{\nu}$ experiment, and we consider to construct a new K^+ beam from the T2 target of A-line in future.

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1 Introduction

After the original Letter of Intent(LoI) [1] for the $K^+ \to \pi^+\nu\bar{\nu}$ experiment at J-PARC was submitted in December 2002, there were big and unexpected changes, summarized below, in the context and situation of the experiment. We therefore decided to submit the revised LoI, this document, as a combined experimental program of "Hadron Physics" and "Kaon Physics" by using the spectrometer that has been used for the E949 experiment at the AGS accelerator of Brookhaven National Laboratory(BNL). Many new collaborators joined this LoI. The contact person was changed to T.Nakano (RCNP).

- The existence of an exotic baryon resonance [2], the Θ^+, was reported by the LEPS experiment [3] at SPring-8 in the invariant nK^+ mass spectrum from the reaction $\gamma n \to K^+K^-n$ inside Carbon nuclei. Many experiments reporting the existence followed; there were also a large number of experiments that have failed to find this state. In particular, the CLAS experiment in Jefferson Lab was unable to confirm [4] their original observation with less statistics [5].
  - In order to resolve the possible existence, an LoI to use the existing separated K^+ beam (LESB3) and the E949 detector to search for the Θ^+ [6], as an s-channel resonance $K^+n \to \Theta^+ \to K^0p$ with $K^0 \to \pi^+\pi^-$, was submitted to BNL in August 2004. Though the Program Advisory Committee(PAC) encouraged [7] the preparation and submission of a proposal, due to the cancellation of the RSVP project [8] at BNL-AGS in August 2005, it got difficult to realize the experiment at BNL.
- BNL-E949 analyzed the data in 2002, which was with the first 20% of the running approved by DOE-OHEP, and published the results on $K^+ \to \pi^+\nu\bar{\nu}$ [9], $K^+ \to \pi^+\gamma\gamma$ [10] and $\pi^0 \to \nu\bar{\nu}$ [11] in 2004-2005. The collaboration waited for funding of the remaining beam hours in their proposal but, after the cancellation of RSVP, BNL officially discontinued the experiment.
- The CKM experiment at Fermilab, which intended to study $K^+ \to \pi^+\nu\bar{\nu}$ with K^+ decays in flight for the first time and had been given Stage-1 scientific approval in June 2001, was not approved because the P5 Subpanel of HEPAP, in September 2003, did not recommend proceeding with CKM [13]. The collaboration prepared another $K^+ \to \pi^+\nu\bar{\nu}$ experiment at Fermilab with reduced costs, but the proposal was disapproved by the PAC in April 2005.
- The NA48 collaboration at CERN started new efforts to do a $K^+ \to \pi^+\nu\bar{\nu}$ experiment at the SPS accelerator with K^+ decays in flight [14]; this proposal, named P326 or NA48/3, is described in Section 3.3.2.

2 Exotic Hadrons with $S = +1$ (pentaquark)

2.1 Motivation

During the past three years there have been many experiments reporting the existence of an exotic baryon, the Θ^+ [3] [15] [16] [17] [18]. It is observed in the kaon-nucleon system with baryon number one, strangeness plus one, and positively charged (Fig. 1 shows the first claimed observation). It is, therefore, manifestly exotic composed of five quarks, $ud\ ud\ \overline{s}$. Unfortunately, there are also a large number of experiments that have failed to find this state. In addition, the positive evidence, although relatively numerous, suffers from limited statistics and systematics, although efforts are underway to remedy this situation. A careful examination of older K^+n cross-section data [19], including the charge exchange channel, indicates a total width of at most a few MeV for the Θ^+ [20].

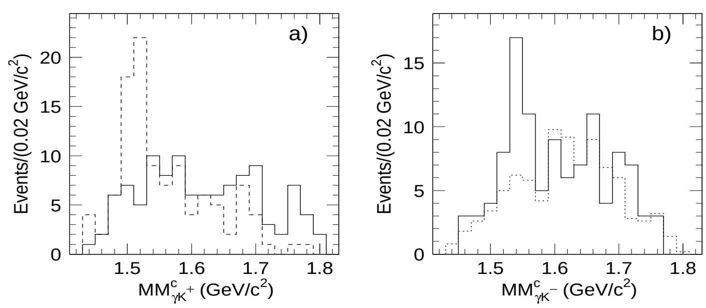

Figure 1: Corrected missing mass recoiling from γK in $\gamma n \to K^+K^-n$: (a) recoil from γK^+ showing a peak for the $\Lambda(1520)$ and (b) recoil from γK^- showing purported Θ^+ signal (from [3]).

The possible existence of such exotic states has been the subject of much theoretical speculation [21]. This has involved quark and bag models, and SU(3) chiral soliton models especially the $\overline{10}$ representation. In fact, the mass such an isosinglet member has been predicted to be 1540 MeV, the reported Θ^+ mass. Such an antidecuplet would contain nucleon, sigma and cascade states, the exotic component being a double negative charged cascade, $dd\ ss\ \overline{u}$ as well as a positively charged cascade, $uu\ ss\ \overline{u}$. Although there have been some claims for the observation of these others members of the antidecuplet, the evidence is poor. To say the least, the situation with regard to exotics is murky and in need of clarification. Several searches for the Θ^+ have proved negative. Moreover, as shown in Fig. 2, those experiments which have seen the Θ^+ do not find a consistent value for its mass and there are also problems with the extracted width. Finally, imposing consistency with old but precise measurements of the charge exchange cross-section requires the Θ^+ to have a width of 1-2 MeV. Fig. 3 shows the best of the old measurements along with theoretical estimates of the Θ^+ contribution under various assumptions for the width. The problem of "fitting in" the Θ^+ is compellingly illustrated by the Argand diagrams shown in Fig 4 [22] [23]. It should be recalled that a resonance, such as the Θ^+, should traverse a complete circle on such a plot.

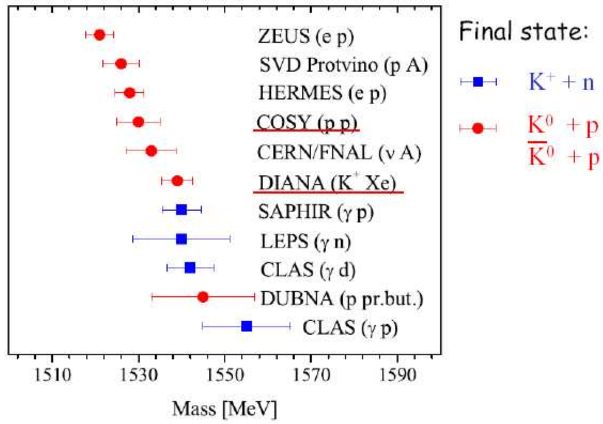

Figure 2: Mass of Θ^+ extracted from various purported observations.

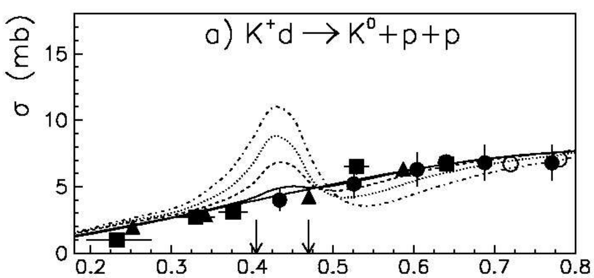

Figure 3: Consistency of previous charge exchange data with the Θ^+ (from [18]).

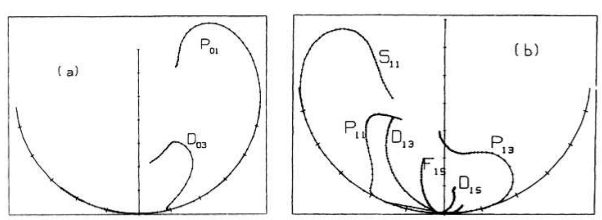

Figure 4: Argand diagrams: (a) Isoscalar partial waves, (b) isovector partial waves (from [22]). The hash marks are separated by 50 MeV increments in T_{lab}.

The key to resolving the possible existence of any of these types of exotics is the Θ^+. To this end it is proposed to use a low-momentum K^+ beam and the 4π detector at J-PARC to search for the Θ^+ as an S channel resonance. If it exists as proposed, it should be produced with millibarn cross-sections and be readily observable at J-PARC.

2.2 Scientific Goals and Merits

It is evident that if the Θ^+ exists it should be strongly coupled to the kaon nucleon system. As such it seems prudent to search for this resonant state with K^+'s and neutrons. It is fortuitous that such a target, detector and analysis system all can be adopted from the E949 experiment at the BNL-AGS. Both of the expected cross sections for the production of Θ^+ and $\Lambda(1520)$ are very large around 25-100 mbarns. The rates will therefore also be very large. As explained in the latter sections there are a variety of search techniques that will be utilized. The pacing reaction will involve seeing both the K^0 decay and the proton from the Θ^+. **The aim is to clearly observe the Θ^+ and determine its width if it exists and, if not, to set a meaningful limit on its properties.**

3 Rare Decay $K^+ \to \pi^+ \nu\bar{\nu}$

3.1 Motivation

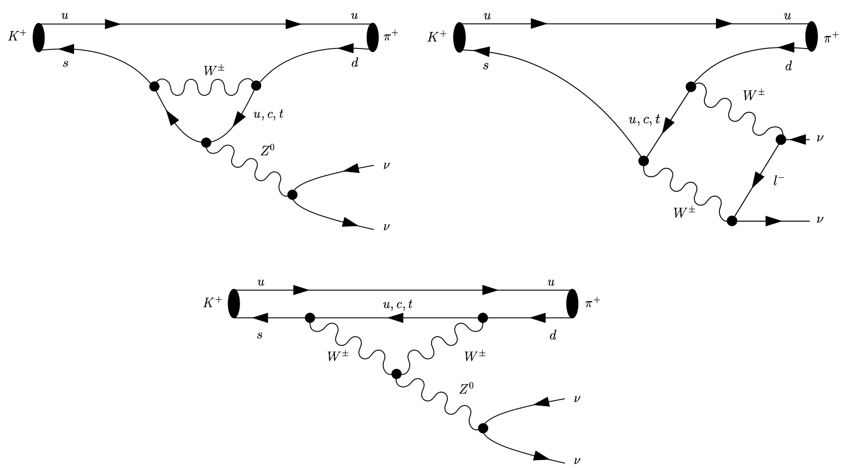

Figure 5: Penguin and box diagrams for $K^+ \to \pi^+ \nu\bar{\nu}$ in the Standard Model (from [24]).

The $K^+ \to \pi^+ \nu\bar{\nu}$ decay is a process of flavor-changing neutral current from strange-quark to down-quark and is induced in the Standard Model (SM) of particle physics by the loop effects of W and Z bosons in the form of penguin and box diagrams (Fig. 5). The decay is sensitive to top-quark effects and provides an excellent route to determine the absolute value of the quantity λ_t:

$$\lambda_t \equiv V_{ts}^* \cdot V_{td} = A^2 \lambda^5 \cdot (1 - \rho - i\eta) \tag{1}$$

in the Kobayashi-Maskawa matrix [25], where A, λ, ρ and η are the Wolfenstein parameterization [26]. Long-distance contributions to the decay are evaluated to be small [27] [28], and the hadronic matrix element is extracted from the $K^+ \to \pi^0 e^+ \nu$ decay; the theoretical uncertainty of the branching ratio $B(K^+ \to \pi^+ \nu\bar{\nu})$ is now controlled to $\pm 6\%$ from the charm-quark contribution in the Next-to-Next-to-Leading order QCD calculations performed recently (and would be improved by an increased accuracy on the charm mass in future) [29]. With the constraints on ρ-η (and λ_t) from other Kaon and B-meson experiments the SM predicts $B(K^+ \to \pi^+ \nu\bar{\nu})$, which is proportional to $|\lambda_t|^2$, to be $(0.80 \pm 0.11) \times 10^{-10}$ [29]. The large part of the error in the prediction is from the ρ-η constraints, not from the theoretical uncertainty.

3.1.1 $K^+ \to \pi^+ \nu\bar{\nu}$ beyond the Standard Model

New physics beyond the SM could affect $B(K^+ \to \pi^+ \nu\bar{\nu})$ [24] [30] [31] [32] [33]. For example, new effects in supersymmetric models are induced through diagrams with new particles such as charged Higgs or charginos and stops replacing the W boson and quark in Fig. 5. By making a comparison between the results from K decays and B decays, it

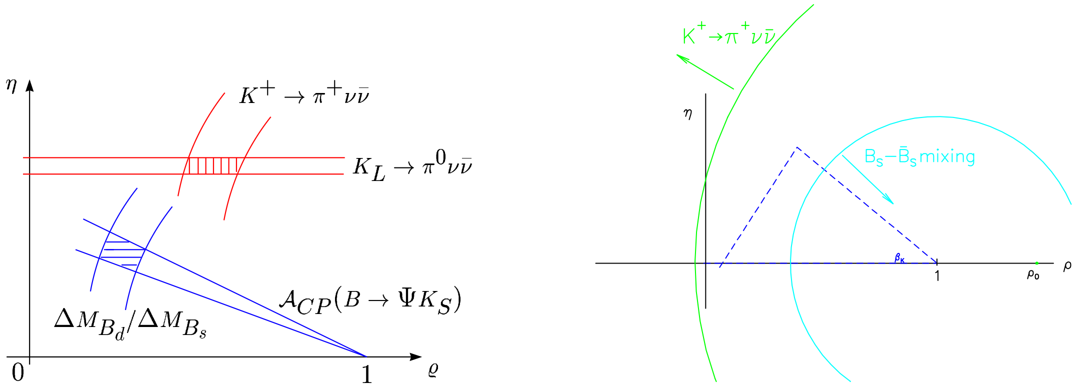

Figure 6: (Left) Schematic determination of (ρ, η) from the B system (horizontally hatched) and from $K \to \pi\nu\bar{\nu}$ (vertically hatched) (from [33]). (Right) Schematic appearance of new physics in "$K^+ \to \pi^+\nu\bar{\nu}$ vs $B_S - \overline{B_S}$ mixing ".

can be tested whether the source of CP violation is only from the phase of Kobayashi-Maskawa matrix elements or not. Fig. 6(left) shows a possible future comparison between $K \to \pi\nu\bar{\nu}$ branching ratios and theoretically-clean B-physics observables in the presence of new physics [33]; the (ρ, η) determined by the $|\Delta B| = 2$ mixing processes could be different from the (ρ, η) by the $|\Delta S| = 1$ rare decays [34]. The presence of new physics could spoil the unitarity-plane consistency of $K^+ \to \pi^+\nu\bar{\nu}$ and $B_S - \overline{B_S}$ mixing, which was recently measured at Tevatron [35], as shown in Fig. 6(right).

3.2 Scientific Goals and Merits

Theoretical predictions give impetus for a precise measurement of the branching ratio for the rare $K^+ \to \pi^+\nu\bar{\nu}$ decay. The primary goal of kaon physics in this LoI is to **observe more than 50 $K^+ \to \pi^+\nu\bar{\nu}$ events** and **measure the branching ratio with a precision $\leq$ 20%**. $|\lambda_t|$ is determined with a precision $\leq 10\%$, which enables us to search for new physics beyond the SM by making a comparison between the results from K decays and B decays.

The high-intensity proton beam available at J-PARC is suitable for studying quark-flavor physics through rare processes of 10^{-10} or less, such as the $K^+ \to \pi^+\nu\bar{\nu}$ decay. The experimental methods proposed in this LoI are the ones already established by the experiments E787 [36] and E949 [37] for $K^+ \to \pi^+\nu\bar{\nu}$ at BNL-AGS, which is the world's highest-intensity proton accelerator before J-PARC. We have had plenty of experience with the methods through E787 and E949 for nearly 20 years and are confident that we achieve the physics results proposed in this LoI.

3.3 Review of Other Experiments

Fig. 7 shows the progress in the search and measurement of $K^+ \to \pi^+\nu\bar{\nu}$ [38].

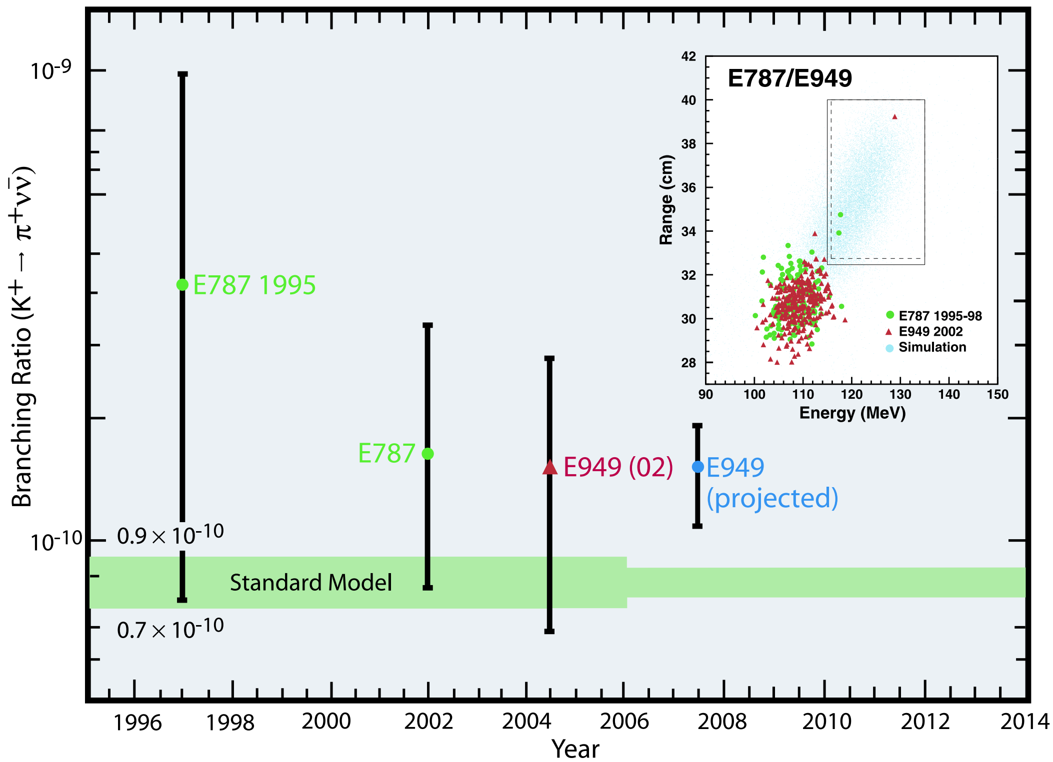

Figure 7: History of the study of $K^+ \to \pi^+\nu\bar{\nu}$ [38], with the plot [9] of E949-'02+E787 at the top right. "E949(02)" represents the branching ratio by combining the E949 and E787 data sets; "E949(projected)" represents the measured central value with the precision expected to E949 after running for 60 weeks. Recent results from Tevatron on $B_S - \overline{B_S}$ mixing are not properly taken care of to the SM prediction in this plot.

3.3.1 BNL Experiments E787 and E949

E787 measured the charged track emanating from K^+ decays at rest. The first evidence for $K^+ \to \pi^+\nu\bar{\nu}$ [39] was reported from the 1995 data set. Final results from E787 on $K^+ \to \pi^+\nu\bar{\nu}$ [40] were published in 2002; the total for the combined data set was two signal events in the pion momentum region examined, $211 < P < 229\text{MeV}/c$. The branching ratio for the $K^+ \to \pi^+\nu\bar{\nu}$ decay was $1.57^{+1.75}_{-0.82} \times 10^{-10}$. Although the results were consistent with the SM prediction, the possibility of a larger-than-expected branching ratio gave further impetus for measurements.

The E949 experiment continued the study at AGS. 65-Tera(10^{12}) protons per 4.1-sec spill were extracted from AGS every 6.4 sec to the kaon-production target. The detector operated well at fluxes nearly twice as high as those typical of E787; the sensitivity was however comparable to the achievement of E787 due to limited beam hours of AGS for E949. In the data set for 12 weeks in 2002 with the upgraded detector, an additional event near the upper kinematic limit for $K^+ \to \pi^+\nu\bar{\nu}$ was observed. Combining the E949 and E787 data sets, the branching ratio $B(K^+ \to \pi^+\nu\bar{\nu}) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$, in the 68% confidence interval including statistical and systematic uncertainties, was obtained by a likelihood ratio technique based on the three observed events (Fig. 7, top right) [9]. The estimated probability that background alone gave rise to the three events (or to any more signal-like configuration) was 0.001. The upper limit for $B(K^+ \to \pi^+\nu\bar{\nu})$ was $< 3.22\times10^{-10}$, from which a model-independent bound on $K_L^0 \to \pi^0\nu\bar{\nu}$: $B(K_L^0 \to \pi^0\nu\bar{\nu}) < 4.4 \times B(K^+ \to \pi^+\nu\bar{\nu}) < 1.4 \times 10^{-9}$ (Grossman-Nir limit [41]) was extracted.

3.3.2 CERN proposal P326(NA48/3)

P326 (or called NA48/3 because this is a new initiative of people in the NA48 collaboration, which has performed the experiments on CP violation with K_+^0/K_S^0 and K^+/K^-) [14] is to measure the in-flight $K^+ \to \pi^+\nu\bar{\nu}$ decay at CERN-SPS with an un-separated K^+ beam of 75GeV/c. The proposed experiment aims to collect about 80 $K^+ \to \pi^+\nu\bar{\nu}$ events for a 10^{-10} branching ratio, with a signal to background ratio of 10:1 in two years of data taking. The proposal [42] was submitted and presented at the CERN SPSC meeting in September 2005, and the R&D's were endorsed by CERN Research Board on December 2005. They seek the full approval by the end of 2006.

3.4 Anticipated Experimental Programs

With the same solenoidal magnetic spectrometer for $K^+ \to \pi^+\nu\bar{\nu}$, many medium-rare K^+ decay modes for studying chiral dynamics in low-energy QCD (e.g. Chiral Perturbation Theory (ChPT) [43] and large-N_c QCD [44]) can be measured simultaneously. Table 1 is a list of the physics of kaon decays from the E787 and E949 experiments; most of these are three- or four-body decays to the final states consisting of π^+, μ^+ and γ (including the γ's from π^0) [3]. These decay modes can be measured with better sensitivities by the experiment proposed in this LoI, and possible CP and T violations in the correlation of momentum vectors in the final states can be pursued. This would potentially be a new experimental program of J-PARC that both particle and nuclear physicists are interested in.

[3]Reconstructing electron tracks from kaon decays at rest is not easy, because they could start showering in the stopping target before entering the spectrometer.

decay mode	result	year	physics
$K^+ \to \pi^+ \nu\bar{\nu}$	observed	2004	SM flavor dynamics
$K^+ \to \pi^+ f$	limit	2004	familon [45], beyond the SM
$K^+ \to \pi^+ H$, $H \to \mu^+\mu^-$	limit	1989	SM light Higgs
$K^+ \to \pi^+ \gamma\gamma$	observed	1997	ChPT
$K^+ \to \pi^+ \mu^+\mu^-$	observed	1997	ChPT
$K^+ \to e^+ \nu \mu^+\mu^-$	limit	1998	ChPT
$K^+ \to \mu^+ \nu\gamma$	measured	2000	ChPT
$K^+ \to \pi^+ \pi^0 \gamma$	measured	2000	ChPT, analysis in progress
$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$	limit	2001	SM, initial search
$K^+ \to \mu^+ \pi^0 \nu\gamma$			ChPT, analysis in progress
$K^+ \to \pi^+ \gamma\gamma$ ($P_{\pi^+} > 213\mathrm{MeV}/c$)	limit	2005	ChPT
$K^+ \to \pi^+ \gamma$	limit	2005	Noncommutative theories [46]
$\pi^0 \to \nu\bar{\nu}$	limit	2005	properties of neutrinos

Table 1: Physics of kaon decays from E787 and E949.

4 Experimental Methods

4.1 Low-momentum K^+ beam

Slow-extracted proton beam of 30 GeV can produce enough number of K^+'s. The low-momentum kaons of less than 700 MeV/c, which is set to be below the threshold for hyperon production in the material for slowing them, should be delivered to the experiment. For the Θ^+-production experiment described in the next section the K^+ momentum has to be around 475 MeV/c; we would also run with a K^- beam for crosschecks with the $\Lambda(1520)$ production. An 800 MeV/c separated kaon beam at J-PARC (Fig. 8, left), called K0.8, is proposed by J.Doornbos (TRIUMF) [47]. The K0.8 line, designed as a branch of the K1.1 line (Fig. 8, right) proposed for strange nuclear experiments, coincides up to the third dipole magnet (B3) with the first stage of electrostatic (DC) particle separation in K1.1, and the B3 magnet bends 50 degrees clockwise. The length of the beam is 19.0 meters, and the total angle-momentum acceptance is 6 msr·% $\Delta p/p$. The K^+ flux of a few MHz with a K^+/π^+ ratio of more than 2 is expected even though K0.8 is single-stage separated. Such a kaon beam, operated in lower momentum, is suitable for the Θ^+ experiment.

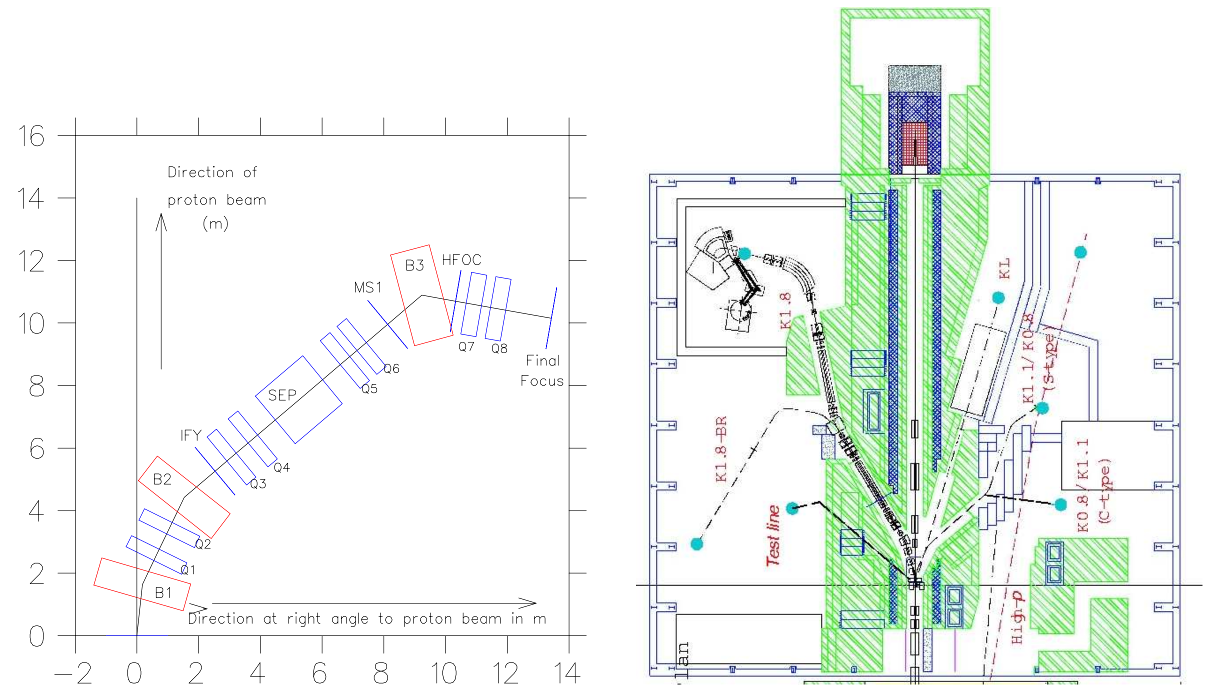

Figure 8: Left: layout of an 800MeV/c beam for J-PARC [47]. Right: layout of the K-Hall. "K1.1" is to the right in this figure.

A K^+ beam line incorporating two stages of DC separation is indispensable for the $K^+ \to \pi^+\nu\overline{\nu}$ experiment in order to reduce the pion contamination and thereby the background due to beam pions scattered into the detector. A good example is the LESB3 channel [48] for E787-E949 at the AGS; the beam line provides a flux of $\sim 5\times10^5 K^+$/Tera-protons on the production target with a K^+/π^+ ratio of > 3. The channel views the 6-cm long platinum production-target at 0 degree and is 19.6 m long, including a 2.6-m drift from the last quadrupole magnet to the final focus at the center of the detector (Fig. 9). We consider to construct a new two-stage separated K^+ beam from the T2 target of A-line in future.

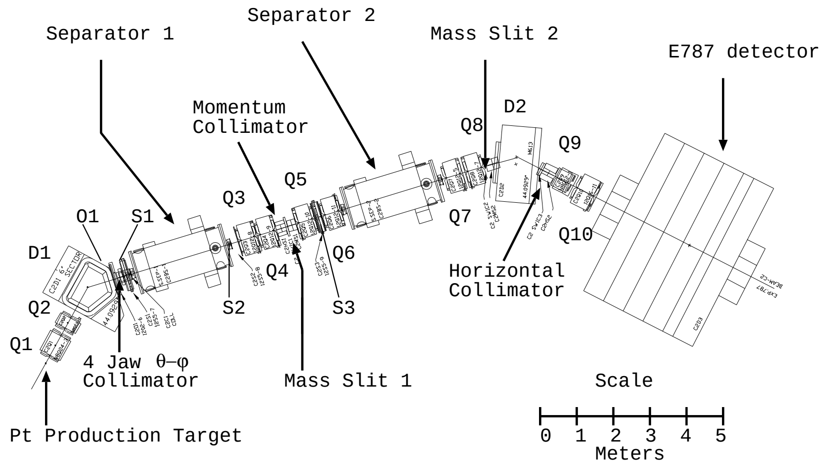

Figure 9: Layout of the LESB3 channel at BNL-AGS [48].

4.2 Beam Transportation and Target

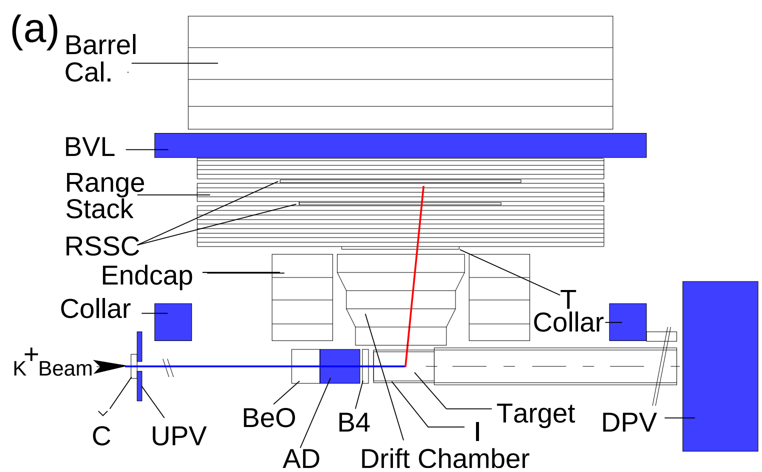

Figure 10: Schematic side view of the upper half of the E949 detector. Č: Čerenkov counter and B4: energy-loss counters.

Kaons from the beam line are detected and identified by a Fitch-type Čerenkov counter [49], multi-wire proportional chambers and an energy-loss counter (Fig. 10). These counters are also used to remove backgrounds from multiple beam particles. After being slowed by a BeO degrader [4], approximately 25% of the incident kaons come to rest in an active stopping target; the remainder are lost or scattered out in the degrader. In the Θ^+-production experiment, the degrader will be removed and the K^+ beam of 475 MeV/c hits the target directly.

The E949 target (Fig. 11) consists of plastic scintillating-fibers. Neutrons supplied by the carbon in the scintillating fibers are used for the $K^+n \rightarrow \Theta^+$ reaction. The target provides initial tracking of the stopping kaon and its decay/reaction products, including low energy protons from the $\Theta^+ \rightarrow K^0p$ decay. A delayed coincidence requirement (typically > 2 nsec) of the timing between the outgoing pion and the incoming kaon in the target guarantees that the kaon actually decays at rest, and removes contributions from beam pions that are scattered into the detector and from kaons that decay in flight.

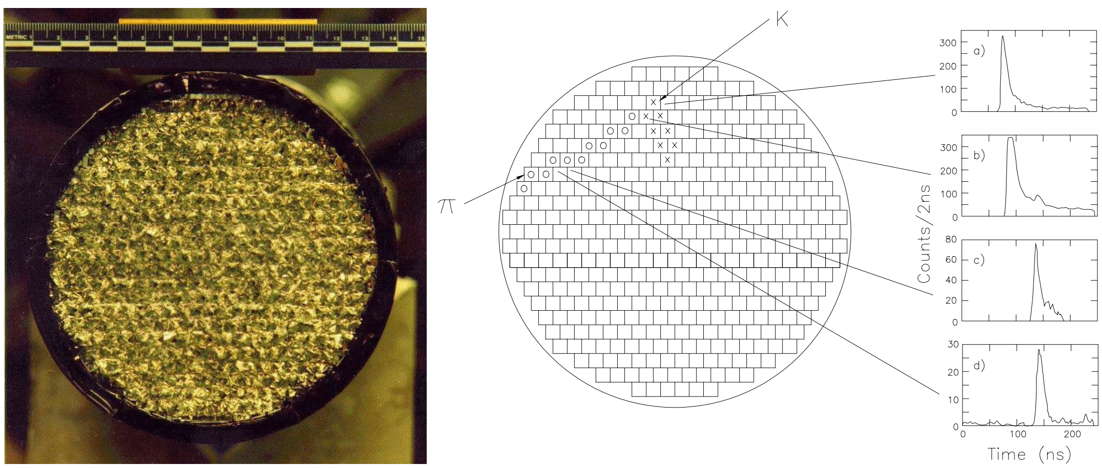

Figure 11: Left: end view of the active stopping target of E949. Right: kaon decay at rest to pion in the target.

4.3 Detector

The stopping target is located at the center of the E949 detector [50] (Fig. 12). Particles emanating from the target were measured in a solenoidal spectrometer with a 1.0-T field directed along the beam axis. The magnet is large enough to contain all the active components within the yoke and coils; the inner volume of the E949 detector is 2.2m long and 3.0m in diameter. We plan to move the E949 detector from BNL in the U.S. to SPring-8 in Japan at first and to move the detector to J-PARC later for the experiment. The schedule is described in Section 7.

The charged particles passed through a layer of trigger scintillators surrounding the target and a cylindrical low-mass central drift-chamber [51] and lost energy in an array of

[4]BeO is a material with high density to slow kaons and with a low average atomic number to minimize their multiple Coulomb scattering.

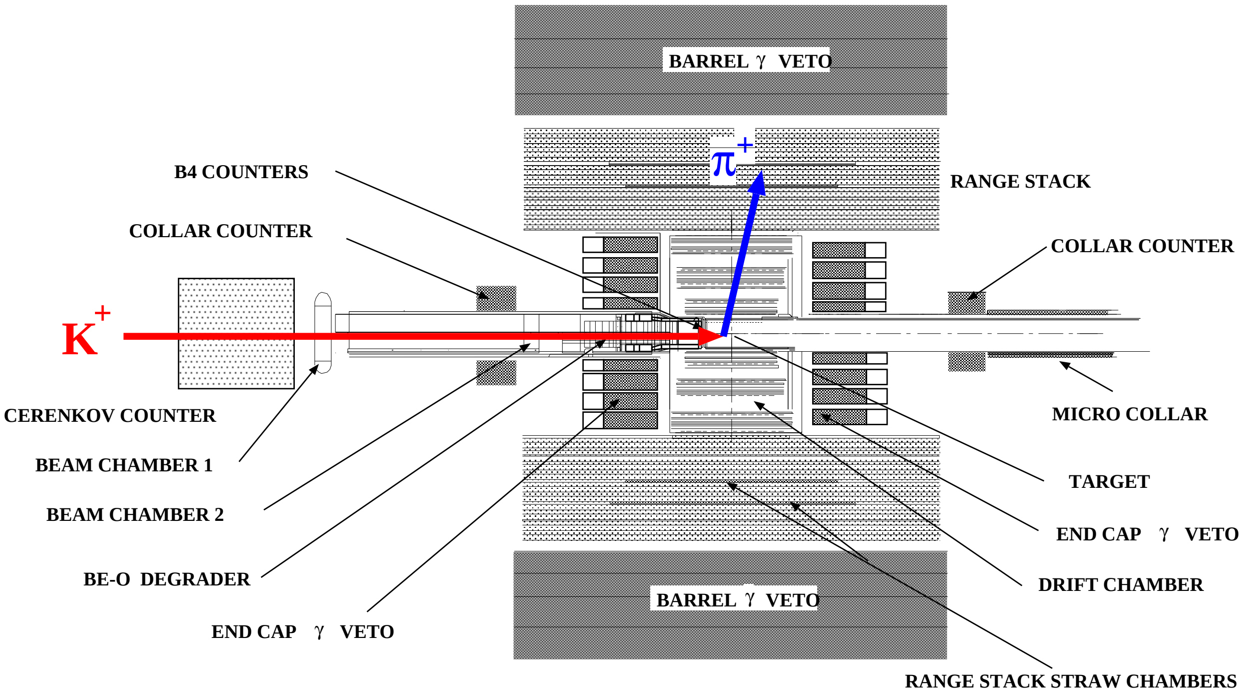

Figure 12: Schematic side-view of a solenoidal magnetic spectrometer.

plastic scintillators called the "Range Stack (RS)". The drift chamber provides tracking information for momentum determination; the RS provides a measurement of range and kinetic energy of the π^+ track which comes to rest in it. The RS in the E949 detector is segmented into 24 azimuthal sectors and 19 radial layers. The RS counters in the first layer define the solid angle acceptance of 2π for the π^+ track in the RS. Two layers of low-mass tracking chambers were embedded within the RS to help range measurement. The RS counter in the sector and layer where the π^+ track comes to rest is called the "stopping counter". Scintillation light is brought out of the magnet at the upstream and downstream ends of the detector by ultraviolet-transmitting acrylic lightguides and is read out by phototubes. The output pulse shapes of the RS counters are recorded by 500-MHz sampling transient digitizers (TDs) [52]. In addition to providing precise time and energy information for reconstructing the π^+ track, the TDs enables us to observe the $\pi^+ \to \mu^+\nu$ decay at rest and the subsequent $\mu^+ \to e^+\nu\bar{\nu}$ decay in the RS stopping counter, and to remove muon and positron tracks as well as the π^+ tracks that decay in flight or undergo nuclear interaction before it comes to rest in the RS.

A hermetic calorimeter system surrounding the central region is designed to detect photons and all decay products (except for ν) from $K_{\pi 2}$ and other decay modes. Good resolution for timing and energy is critical for reducing acceptance loss by the accidental hits in a high counting-rate environment. The barrel calorimeter, which is a cylindrical detector located immediately outside the RS, covers about two thirds of the solid angle. Two endcap calorimeters and additional calorimeters for filling minor openings along the beam direction, as well as any active parts of the detector not hit by the π^+ track, are also used for detecting extra particles. In E949, the barrel calorimeter consists of sampling showercounter modules constructed of alternating layers of lead and plastic-scintillator sheets totaling 14.3 radiation lengths, and the endcap calorimeters [53] consisted of undoped-CsI crystals (with 13.5 radiation lengths), which are read out by fine-mesh phototubes in the 1.0-T field into 500-MHz TDs based on charged coupled devices (CCDs) [54]. Plastic scintillating-fibers of the target are also read out by the CCD-based TDs.

The end view of the E949 detector and the two $K^+ \to \pi^+\nu\bar{\nu}$ signal events are shown in Fig 13. In the E787 and E949 experiments, in order to estimate the background to $K^+ \to \pi^+\nu\overline{\nu}$ from the Charge Exchange reaction in the target: $K^+n \ \to \ K^0p$ followed by $K^0_L \to \pi^+\ell^-\nu_\ell$, the information on the production points and the momentum vector of K^0 was obtained from real data by measuring the $K^0_S \to \pi^+\pi^-$ events. We have confirmed that multi charged-tracks from a single event can be reconstructed in the detector, which is crucial to observe the $\Theta^+ \ \to \ K^0p$ decay.

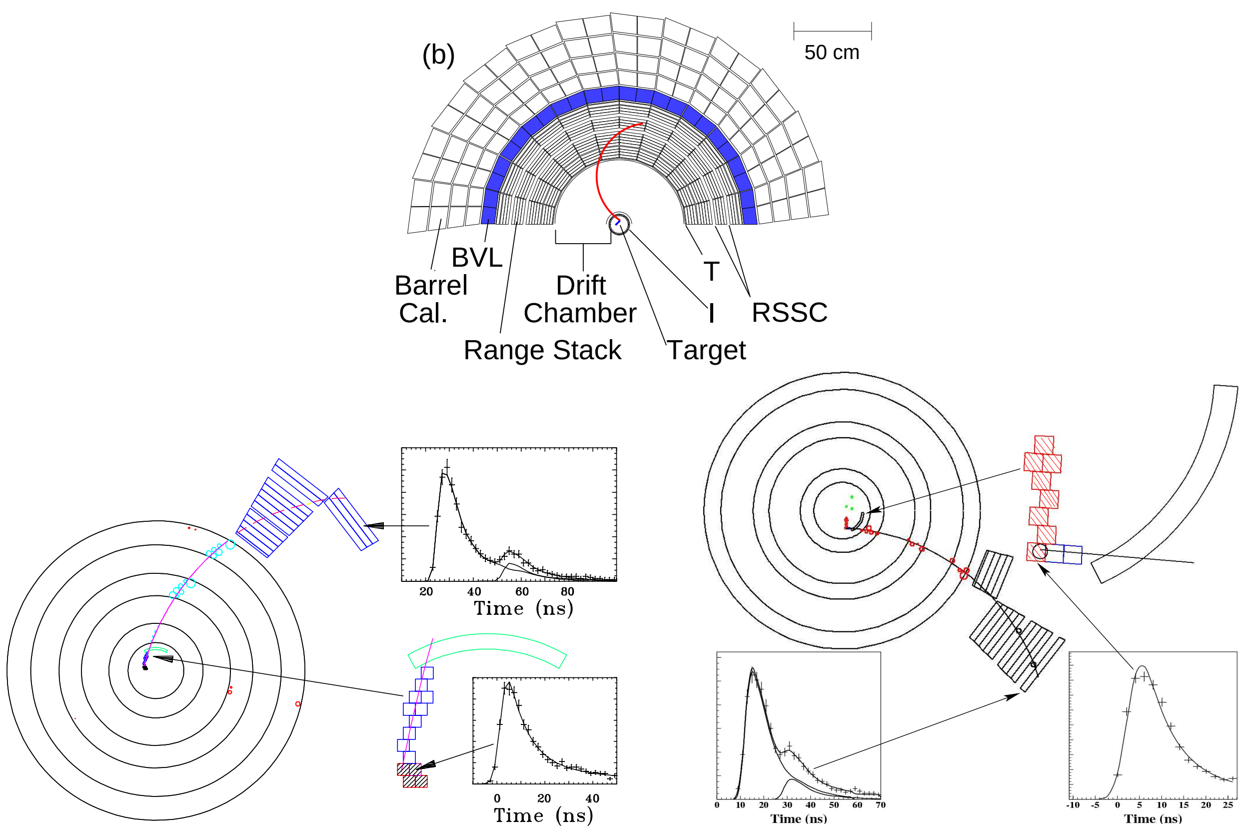

Figure 13: Top: schematic end view of the upper half of the E949 detector. Bottom: displays of the two $K^+ \to \pi^+\nu\bar{\nu}$ events [39] [40].

5 Prospects for Exotic Hadrons with $S = +1$

5.1 Experimental Concept

It is proposed to produce the Θ^+, if it exists, as an S channel resonance in a formation experiment utilizing a separated K^+ beam of low-momentum. Thus far only one experiment, DIANA [15], claims to have observed the Θ^+ in formation with a tagged K^+ beam. Fig. 14 shows the K^0p effective mass spectrum from $K^+Xe \rightarrow K^0pXe$ events in their Xenon bubble chamber. Note that the statistics are rather small and also that the signal is much less significant before implementing the cuts to suppress the effects of reinteractions in the Xe nucleus.

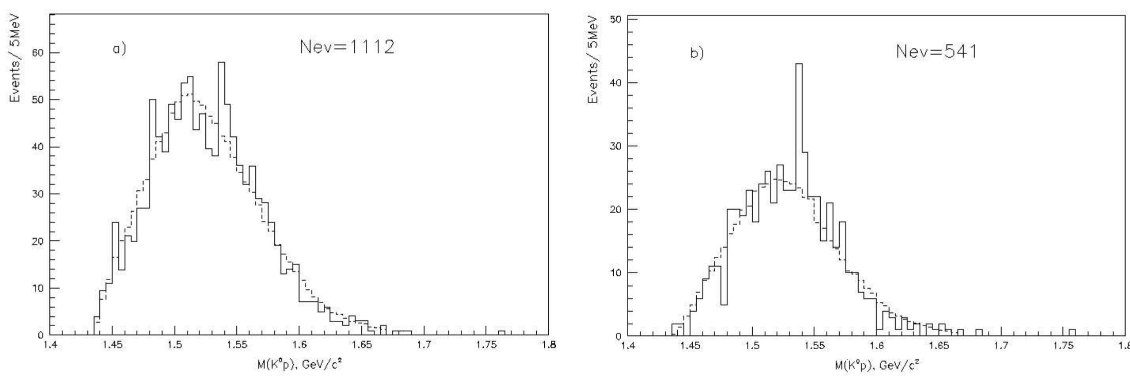

Figure 14: - Effective mass of K^0p from [15]. Reaction was $K^+Xe \rightarrow K^0pXe$: spectra (a) for all measured events and (b) for events passing additional cuts aimed at suppressing K^0 and proton reinteractions in nuclear matter.

In the experiment being considered here, the statistics would be enormously enhanced over those of [15], and the nuclear medium would be much smaller (by using C instead of Xe).

The reaction is:

$$K^+n \quad \rightarrow \quad \Theta^+ \quad \rightarrow \quad K^0p \qquad with \quad K^0 \quad \rightarrow \quad \pi^+\pi^- \tag{2}$$

where the neutrons are supplied by the carbon in the E949 scintillator target.

In essence, the K^+ meson loses energy in the target (acting in the accustomed manner) until its energy matches that of the Θ^+ resonance whereupon there is an excess of events in the reaction (2) and a consequent reduction, as the K^+energy becomes lower and is again non-resonant. The preferred manner to measure this reaction is to observe both the final state proton and the two-pion decay of the K^0 and to examine the effective mass of these particles. If the Θ^+ exists, one should see an excess of such events at the Θ^+ mass. This distribution should be unaffected by the Fermi motion but sensitive to rescattering in the target and to the acceptance and detection efficiency of the detector. A second and complementary method consists of observing the pions from the K^0 decay and measuring this production rate as a function of position in the target. Again, one should see an increase in the yield as the K^+ loses energy in the target and at some point encounters the Θ^+ resonance. This distribution is, however, affected by the Fermi motion of the struck neutron in the target, the precision of the incoming K^+ momentum, and any straggling in the target as well as the aforementioned detector efficiencies. The uncertainties introduced by the Fermi motion can be partially ameliorated via the missing mass technique successfully implemented in the photoproduction studies in [3].

The effectiveness of these techniques can be ascertained by running a K^- beam into the same target and apparatus and studying the well established $\Lambda(1520)$ resonance, which has a similar mass and decay modes but opposite strangeness to the Θ^+. In this instance, the reaction is

$$K^-p \quad \rightarrow \quad \Lambda(1520) \quad \rightarrow \quad \overline{K^0}n \qquad with \quad \overline{K^0} \quad \rightarrow \quad \pi^+\pi^- \tag{3}$$

which is very analogous to reaction (2) and

$$K^-p \quad \rightarrow \quad \Lambda(1520) \quad \rightarrow \quad \Sigma^0\pi^0 \qquad with \quad \Sigma^0 \quad \rightarrow \quad \gamma\Lambda \tag{4}$$

$$K^-p \quad \rightarrow \quad \Lambda(1520) \quad \rightarrow \quad \Lambda\pi^+\pi^- \tag{5}$$

One utilizes the effective mass technique for the $\Lambda(1520)$ in reaction (4) and (5) since one will observe and measure all the particles from its decay. One can then compare the properties of this resonance, in particular the mass width, with the accepted values. By again just measuring the pions from K^0 decay, reaction (3) and investigating the distribution of the position of the K^0 decays along the target length, one can look for an excess of events due to the S channel production of this Λ resonance. One should see it if this technique works and thus be able to determine the effects of the Fermi motion. This is slightly different from (2) in that the proton can be either in the carbon nucleus or exist as free hydrogen. Again the missing mass technique should aid in unraveling the effects of Fermi motion especially since in this case one knows the answer.

How either of these methods succeeds or fails depends on the details that we will address in the next subsections.

5.2 Target and Detector

The target consists of 5 mm-square plastic scintillating-fibers (413 fibers in total) of 310 cm length. The scintillator is PVT with a density of 1.032 gm/cm^{3}and a hydrogen to carbon ratio of $\sim$1.1 : 1. Impacted by an incoming kaon of momentum 475 MeV/c, the active fiducial length of target of 25 cm will span a mass region for the Θ^+ from 1550 to 1520 MeV/c^2, encompassing the reported values for the Θ^+ mass. The yield of events per millibarn per 25 cm of target per pulse is therefore

$$Y \quad = \rho \times l \times \sigma \times N_A \times F_K \times f_n \quad = 1.032 \times 25 \times 10^{-27} \times 6.022{\cdot}10^{23} \times 2.8{\cdot}10^4 \times 6/13.1 \tag{6}$$

and is 200/mb/pulse where the last factor is the fraction of neutrons in the scintillator target.

This experiment will use the E949 detector. The detector has been described in the previous section. In this proposed experiment, the degrader would be removed. A trigger sensitive to charge-exchange events was created by E787 and tested in this detector in 1997, and was used to provide data for a master thesis: "Low Energy (K^+,^{12}C) Charge Exchange Cross Section Measurements"[55]. A typical charge-exchange event is shown in Fig 15. The K^0 mass resolution observed was $\sim$5 MeV rms as seen in Fig 16. The acceptance of the target/trigger counter combination for charge exchange events is shown in Fig 17.

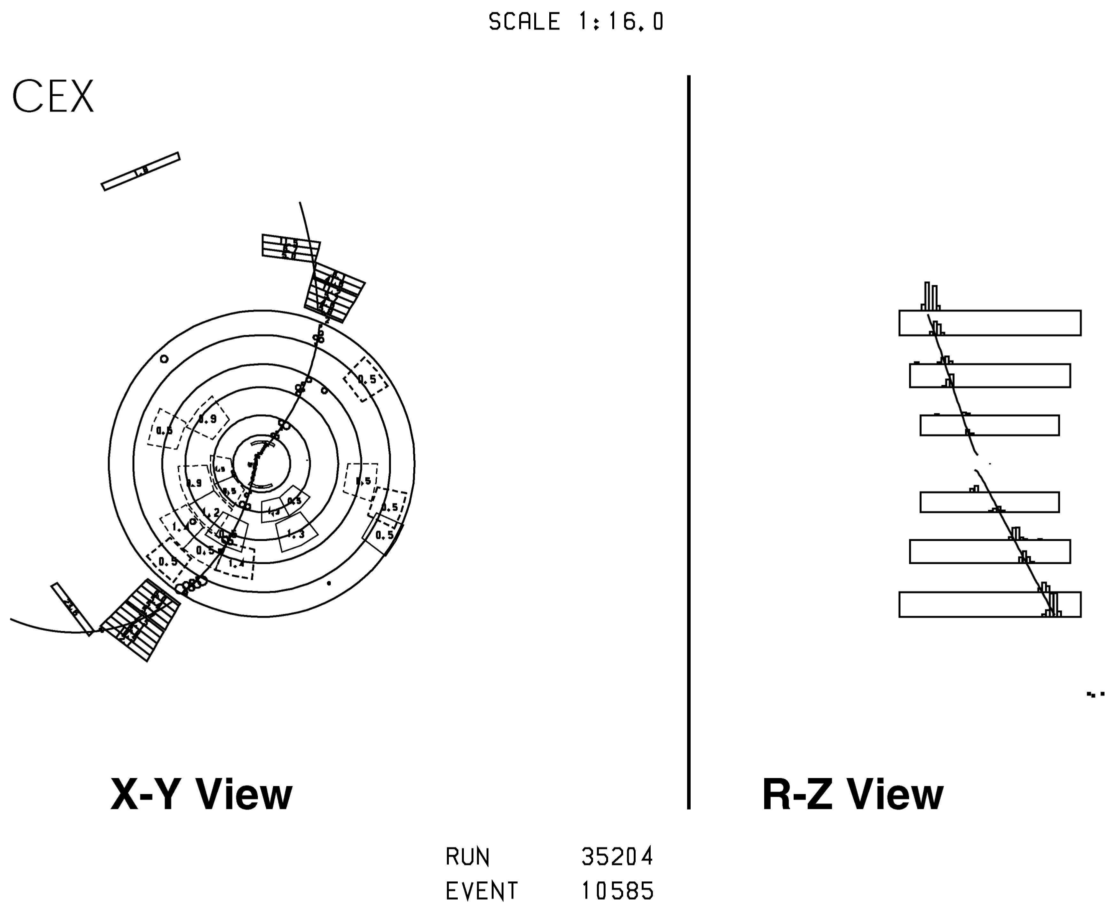

Figure 15: End and side view of charge exchange event in E787.

5.3 Expected Yields

The expected cross section for the Θ^+ can be estimated from the resonant Breit-Wigner expression:

$$\sigma_{BW}(E) \quad = \frac{(2J+1)}{(2S_1+1)(2S_2+1)} \frac{\pi}{k^2} B_{in} B_{out} \frac{\Gamma^2}{(E-M)^2 + \Gamma^2/4} \tag{7}$$

where k is the momentum in the CMS system, S_1 and S_2 are the incident spins, Γ is the width of the resonance, and B_{in} and B_{out} are the branching ratios into initial and final

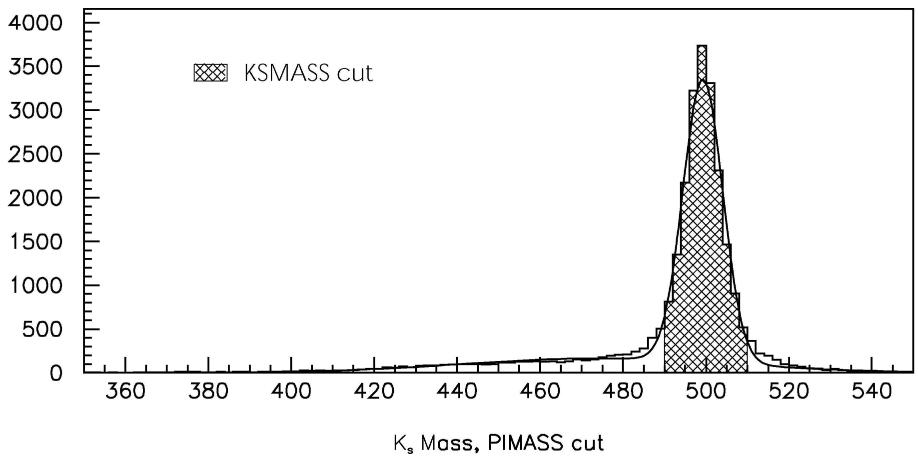

Figure 16: $\pi^+\pi^-$ effective mass from Ng thesis.

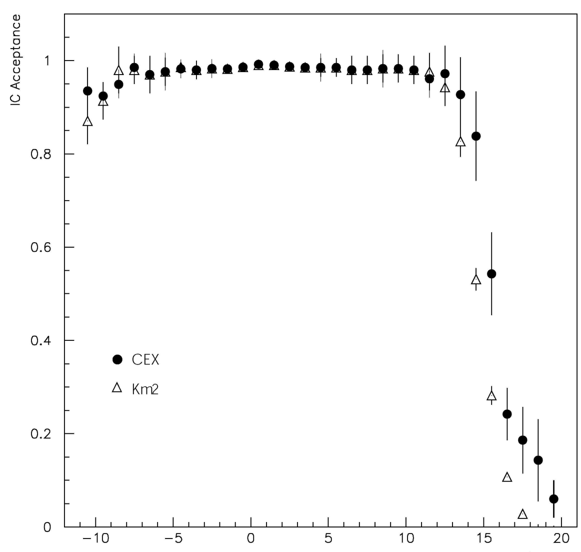

Figure 17: Acceptance of E787 target and trigger counters for charge exchange and $K^+ \to \mu^+\nu$ events.

channels with J=1/2. In this case $S_1 = 0$, $S_2 = 1/2$, and $B_{in} = B_{out} = 1/2$, and this reduces to

$$\sigma_{BW}(E) \quad = \frac{\pi}{4k^2} \frac{\Gamma^2}{(E-M)^2 + \Gamma^2/4} \tag{8}$$

At the resonance E = M, the cross section is therefore $\sigma_{BW}(M) = \pi/k^2 = 16.8$ mb and the integrated cross section is $\int \sigma dE = \pi/2k^2 \;\times \Gamma = 26.4 \times\Gamma$ mb/MeV. For a width of $\Gamma = 1$ MeV, which is the present estimate [56], this gives a value of 26.4 mb.

The charge exchange cross section (2) has been measured in the incoming K$^+$ momentum range of 200-700 MeV/c to smoothly rising as is evident in Fig. 3. At 475 MeV/c it is 4 mb with no evidence for any resonant formation. Thus, one should plan on the production of 4 mb x 200 events/mb/pulse = 800 events/pulse over the whole target for the charge exchange cross section. If the Θ^+exists there should be an excess of events of at least an equal magnitude.

The situation for observing the $\Lambda(1520)$ appears also to be quite favorable. The cross section for its production with K$^-$ is of the order of 100 mb! Its width has been accurately measured to be $\Gamma = 15.6 \pm 1.0$ MeV and the major branching ratios are:

- $N\bar{K}$ (45%), of which one half is $n\overline{K^0}$ and the remaining one half is pK^-,
- $\Sigma\pi$ (42%), of which one third is $\Sigma^0\pi^0$, another one third is $\Sigma^-\pi^+$, and the remaining one third is $\Sigma^+\pi^-$,
- $\Lambda\pi\pi$ (10%), of which one half is $\Lambda\pi^+\pi^-$.

The present strategy is to utilize the $\Sigma^0\pi^0$, where one observes the Λ and gamma rays, and probably the $\Lambda\pi^+\pi^-$ channels in investigating the effectiveness of observing the $\Lambda(1520)$ in the effective mass distribution of the observed particles. As noted earlier, this is independent of the Fermi momentum of the struck proton. We would also look in the $n\overline{K^0}$ channel as mentioned above.

5.4 Requests to the K^+ Beam and the Beamtime

This experiment was originally planned at BNL-AGS, where the low energy separated beam III (LESB III)[48] successfully delivered 13.5×10^6 K^+'s at 710 MeV/c per spill with 4.5×10^{13} protons on target. By running this experiment parasitically with the polarized proton program at RHIC in BNL, the AGS could still deliver 10^{12} protons per pulse to the production target and therefore 3×10^5 K^+'s per pulse. Scaling to 475 MeV/c this implies $F_K = 2.8 \times 10^4$ K^+'s, which was more than adequate for the experiment. From the preliminary estimates we expect that, at J-PARC, the execution of this experiment will require hundreds of hours of running time if the intensity is in the same order as in AGS.

6 Prospects for $K^+ \to \pi^+\nu\bar{\nu}$

The π^+ momentum from $K^+ \to \pi^+\nu\bar{\nu}$ (Fig. 18) is less than 227MeV/c. The major background sources of $K^+ \to \pi^+\pi^0$ ($K_{\pi2}$, 21.2%) and $K^+ \to \mu^+\nu$ ($K_{\mu2}$, 63.5%) are two-body decays and have monochromatic momentum of 205MeV/c and 236MeV/c, respectively. The region "above the $K_{\pi2}$" between 211MeV/c and 229MeV/c has been adopted for the search. Background rejection is essential in this experiment, and the weapons for redundant kinematics measurement, μ^+ rejection, and extra-particle and photon veto are employed. Each weapon should have a rejection of $10^5 \sim 10^6$, and reliable estimation of these rejections using real data is the key of the experiment.

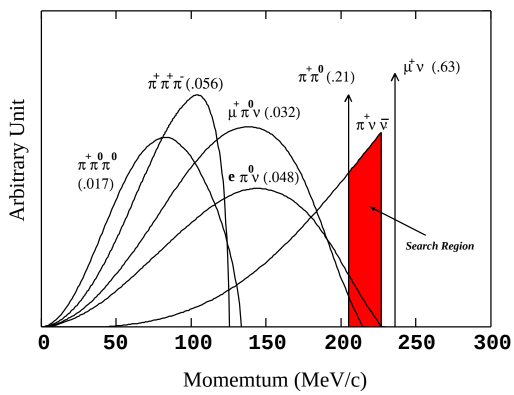

Figure 18: Momentum spectrum of the charged particles from K^+ decays at rest.

There are two approaches for the precise measurement of $K^+ \to \pi^+\nu\bar{\nu}$. One is a brand-new method with K^+ decays in flight, with much better acceptance than previously achieved [5], by the CERN P326(NA48/3) collaboration. This LoI takes the other and conservative approach - i.e. to push ahead with an experiment with K^+ decay at rest in the style of E787-E949. An unbeatable merit is, we can make very realistic estimation of the sensitivity, acceptance and background level from the experiences of E787-E949 for many years; the real data, analysis codes and Monte Carlo simulations are available. A big issue is whether the beam line and detector can be improved further to compete with the in-flight decay experiment.

6.1 Requests to the Accelerator

A typical machine cycle of the 50GeV Synchrotron at J-PARC is to accelerate 200-Tera protons every 3.42 sec (Fig. 19), which means the average current is 9.5 μA. Slow-extracted proton beam (0.7-sec spill, with the duty factor of 0.20) is transported to the Experimental Hall. The beam energy at the initial operation phase (Phase 1) of the Synchrotron will be 30 GeV.

[5] To be fair, it should be mentioned that the in-flight technique is not yet proved for the $K^+ \to \pi^+\nu\bar{\nu}$ experiment.

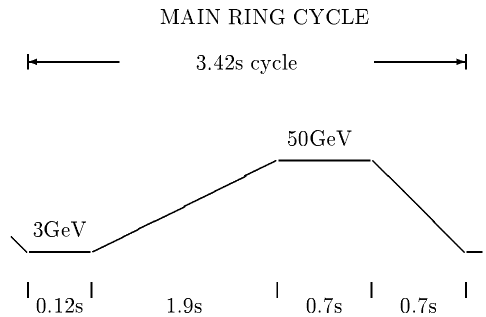

Figure 19: Typical machine cycle of the 50GeV Synchrotron for slow extraction.

It must be pointed out that the slow-extraction described above is unoptimized for any particle-nuclear experiment with time-coincidence techniques [57]. Table 2 shows a comparison of the PS operation between the AGS (optimized to the E949 experiment) and the J-PARC Synchrotron. While the amount of protons per spill available at J-PARC is ×3 larger, the instantaneous proton rate in the spill is ×18 higher than AGS, due to the poor duty cycle of J-PARC Synchrotron, and is hardly ever tolerable by taking into account the acceptance loss due to accidental hits.

PS operation		AGS for E949	J-PARC Phase 1	
proton energy	GeV	24	30	
protons on Tgt	10^{12}/spill	65	200	× 3.1
machine cycle	sec	6.4	3.42	× 1/1.87
average current	μA	1.63	9.5	× 6
slow extraction	sec	4.1	0.7	× 1/6
duty factor		0.64	0.20	× 0.31
instantaneous rate	10^{12}/sec	16	286	× 18

Table 2: Comparison of the PS operation between the AGS to the E949 experiment and the J-PARC 50GeV Synchrotron.

We therefore request, for the $K^+ \to \pi^+ \nu \overline{\nu}$ experiment, a longer spill length and high duty factor to the operation of the Synchrotron rather than upgrading the proton energy to 40 GeV or 50 GeV [6]. It has been suggested that the duty-cycle can be improved from 0.20 to 0.39 (1.7-sec spill every 4.42 sec) when the Synchrotron is operated at 30 GeV [59].

[6] There is no significant change to the K^+ yields below 1 GeV/c between the proton energies of 30 GeV and 50 GeV [58].

6.2 Requests to the Beam Line

To reduce the pion contamination and the background to $K^+ \to \pi^+\nu\bar{\nu}$ due to beam pions scattered into the detector, a K^+ beam line with a high K^+/π^+ ratio (> 3) should be constructed. The K^+ momentum must be low (600-800 MeV/c). Right now we are investigating the optimization of the kaon beam line for $K^+ \to \pi^+\nu\bar{\nu}$ based on the experience of E787 and E949. An idea is a shorter beam line with lower K^+ momentum.

- The counting-rates in the most subsystems related to the beam analysis and photon veto analysis in the E787 and E949 detectors were proportional to the incident kaons, not to the kaons at rest in the target [60]. That means, with the same incident flux and by lowering the beam momentum (and reducing the amount of material in the degrader), the kaon stopping fraction increases while accidental hits decrease [7].
- There is already an optics design of a 550 MeV/c two-stage separated K^+ beam called "K550" by J. Doornbos (TRIUMF) [61] [8]. K550 has a twice as high solid angle and momentum acceptance as LESB3 and the same beam purity. In contrast to the stopping fraction of 0.26 for 730-MeV/c kaons by the LESB3 (19.6m), the stopping fraction for 550-MeV/c kaons by the K550 (14.7m) is 0.40 and is 50% better.
- To handle lower-momentum kaons, the beam line should have shorter length. There are many difficulties, in the real case, in constructing a shorter K^+ beam line with high solid angle as K550 to the current Experimental Hall: heat capacity of the vacuum duct, radiation hardness and stability of the magnets and separators, radiation shield of the experimental area etc. We are making a preliminary optics design of the K^+ beam line for $K^+ \to \pi^+\nu\bar{\nu}$ within these constraints.

6.3 Detector and Experiment

The goal of the new experiment is to collect more than 50 $K^+ \to \pi^+\nu\bar{\nu}$ events in the SM from K^+ decays at rest. In other words, the single-event sensitivity proposed by E949 should be improved, by a factor of at least 5, to 2×10^{-12} in the environment that the instantaneous rate is higher.

In this subsection, we discuss an experiment based on incremental improvements of the E949 methods. We expect to achieve the goal by optimizing the Synchrotron operation and the K^+ beam line, improving the detector, and relaxing selection criteria ("cuts") in the analysis.

- Running mode ($\times 1.5$):

[7] Also, using additional proton intensity to extend the spill length without increasing the instantaneous rate raises the number of kaon decays per hour without impacting the acceptance.

[8] The K550 was originally designed for E949 as a replacement of the present line LESB3 at AGS.

- stopping fraction and duty factor (×1) [9] and
- beam hours of ~ 3 years (×1.5).

- New, rate-capable detector (×2).

- Re-optimization of the detector and analysis (×2):
  - S/N=5 by relaxing the TD cuts identifying π^+ with the $\mu^+ \to e^+$ chain etc. (×1.2),
  - brighter detector and better energy resolution (×1.4), and
  - pipeline trigger, faster DAQ etc (×1.2).

Major upgrades of the stopping target and the RS of the current E949 detector to achieve better resolutions and rate capabilities are the key, and ideas are:

- more segmentation ("chopping") of the RS scintillators by at least four,
- brighter plastic scintillators to get more light outputs, and
- RS readout with wavelength-shifting fibers or readout directly in the magnetic field [62], with advanced phototubes or photodiodes, for better light-collection.

In addition, beam counters with better segmentation, a new Silicon-strip energy-loss counter (for better dE/dx measurement and K^+/π^+ separation) [63] in the beam line, and new calorimeters, with fast response, to the subsystems close to the beam line are being considered. Waveform digitizing, as well as the trigger, DAQ and monitor systems, will be developed based on modern technologies [64]. A design of a prototype 500-MHz waveform digitizer is made by the KEK Electronics group.

[9] We hope for keeping the beam conditions to be comparable to E949 by a duty factor of at least 0.5 or a K^+ beam line with a better stopping fraction.

7 Time Schedule: Programs at SPring-8 and J-PARC

We plan to move the E949 detector from BNL in the U.S. to SPring-8 in Japan first and use it as a main detector of the second Laser-Electron Photon beam line (LEPS2) for Hadron Nuclear experiments. If the LEPS2 project proceeds as currently planned, the E949 detector will be taken apart at BNL in 2007 and moved to SPring-8 in 2008. After reassembling and commissioning, which will take about a year, the detector will be used until around 2012 or 2013 for the experiments at LEPS2 in SPring-8. We hope the construction of the new K^+ beam line will be made so that we can move the detector to J-PARC right after the termination of the usage at LEPS2.

There are several advantage for using the E949 detector at LEPS2 first. There are considerable overlaps between the collaborators in this LoI and the LEPS2 collaborators. The detector and analysis system will be kept literary alive until the K^+ beam become available at J-PARC while providing many young scientists with opportunities to learn about the detector system. Some of the readout electronics will be replaced by using the vastly improved modern technology. We also expect some of the upgrades of the E949 detector for the $K^+ \to \pi^+ \nu \bar{\nu}$ experiment (Section 6.3) would be made in advance during the experiments at LEPS2.

A New Spectrometer

We also seek a stopped kaon experiment for $K^+ \to \pi^+ \nu\bar{\nu}$ with new techniques. A concept of "higher-field ($\geq$2.0-T) spectrometer" (with a superconducting solenoidal magnet) has been discussed by E787 collaborators [65]. The merits are:

1. Improved π^+-momentum resolution.
2. "Compact detector": since the curvature of the π^+ tracks get smaller, the size of the drift chamber, RS and magnet is reduced.
3. "Fiber Stack": since the size of the RS is small, finer RS segmentation (in particular to the region where the π^+ track comes to rest) with plastic scintillating-fibers can be realized, which makes the RS tracking easier and a loss of $\pi - \mu - e$ decay acceptance due to accidental hits in the stopping counter smaller.
4. "Crystal Barrel": since the detector is compact, the size of the calorimeter system surrounding the central region is also reduced; the barrel calorimeter located immediately outside the RS can be made of fully-active scintillating crystals (undoped-CsI or faster ones), rather than sampling shower-counters, and achieve much-improved photon detection.

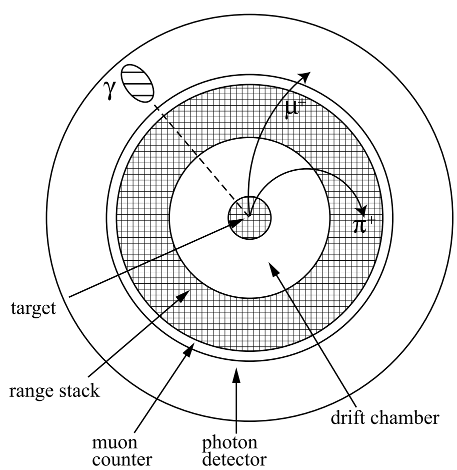

Figure 20: Schematic endview of a new spectrometer.

Fig. 20 shows a schematic endview of a new spectrometer being considered. While π^+ tracks are contained in the RS region, μ^+ tracks from $K_{\mu 2}$ (with a larger curvature) pass through the RS and hit the muon counter, which makes the online μ^+ rejection easier. The barrel calorimeter detects photons as well as μ^+ tracks. Higher counting-rates in the compact detector is overcome by the much finer segmentation (than the E949 detector) in all the subsystems.

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