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Search for Θ^+ in $K_L p \to K^+ n$ reaction in KLF at JLab

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The possibility of the existence of multiquark hadrons made of 4-quarks for mesons and 5-quarks for baryons was predicted by Gell-Mann [*Phys. Lett.* **8**, 214 (1964)]. The renewed interest for the search for exotic pentaquark states was initiated by the paper by Diakonov, Petrov, and Polyakov [*Z. Phys. A* **359**, 305 (1997)]. The 2003 experimental reports on the observation of Θ^+ pentaquark with $uudd\bar{s}$ quark content created a great excitement and many following experiments have reported its observation [K. H. Hicks, *Eur. Phys. J. H* **37**, 1 (2012)]. After high-statistics experiments at JLab, which did not confirm previous claims by the CLAS collaboration, the community concluded that the Θ^+ pentaquark either does not exist at all or has an extremely small cross-section, making it currently unobserved. There were different review papers on this subject, questioning the existence of Θ^+ or trying to explain the reasons why reaching a conclusion based on production experiments is challenging [M. Amaryan, *Eur. Phys. J. Plus* **137**, 684 (2022)]. To address the challenge of minimal 3-body final states, a formation experiment with a projectile-kaon beam is proposed. In the following, we discuss how the Θ^+ could be observed in the $K_L p \to \Theta^+ \to K^+ n$ reaction in the KLF experiment at JLab [M. Amaryan *et al.* [KLF Collaboration], arXiv:2008.08215 [nucl-ex]].

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1. Introduction

QCD gives rise to the hadron spectrum[1] and many $q\bar{q}$ and qqq have been observed.[2] However, the $q\bar{q}q\bar{q}$ and $qqqq\bar{q}$ and other many-quark states are not forbidden either. Recently, LHCb collaboration claims evidence for four hidden-charm $qqqq\bar{q}$ states near open-charm decay thresholds for $\Sigma_c^+\bar{D}^0$ and $\Sigma_c^+\bar{D}^{*0}$ in $\Lambda_b \to J/\psi p K^-$ decays.[3] Nevertheless, although there is no doubt about LHCb observations, these states are not manifestly multi-quark states and there is a room that their flavor can be explained by three quarks. In the light quark sector, there is a clearly exotic $\Theta^+(uudd\bar{s})$ state, yet to be unequivocally observed and identified. This particle, along with other members of $\bar{10}$ has been proposed in Ref. 4 with a mass of $M_{\Theta^+} = 1.53\,\mathrm{GeV}$ and a width less than 15 MeV. The mass splitting of members of the $\bar{10}$ was also discussed in Ref. 5. Due to relatively low mass and simple decay channels to K^+n or K^0p it has attracted attention of many experimental collaborations at different facilities worldwide (see, for instance, review papers[6,7]). The initial experimental evidence for Θ^+ was presented by the LEPS Collaboration at SPring-8[8] and the DIANA Collaboration from ITEP.[9] Subsequently, several experimental groups declared the observation of Θ^+ but later retracted their claims. However, there are still persistent claims from other groups, maintaining the existence of Θ^+ in an inconclusive status. Luckily there is a unique possibility to use intensive incoming kaon beams to observe it in formation experiments in a 2-body reaction free from reflections of other states simultaneously produced in a many-body final states.

2. KLF Experiment in Hall D at JLab

The K-Long project, led by the K-Long Facility (KLF) Collaboration, has been approved for a 200-day run. This project requires the establishment of a secondary K_L beamline in Hall D at Jefferson Lab. Boasting a flux of $10^4\,\mathrm{K_L/s}$ on a physics target three orders of magnitude higher than previously achieved at SLAC (refer to Ref. 10 and citations therein) the KLF experiment stands out as a unique facility. The KLF has been specifically mentioned in the Department of Energy Office of Science Long-Range Plan (LPR2023) as the future physics program in Hall D with the GlueX setup.[11]

By conducting scattering experiments on both proton and neutron targets, the K-Long Facility will distinguish itself as the world's first secondary neutral kaon beam facility with a sufficiently high beam intensity to elucidate all Σ^* and Λ^* resonances up to $M = 2500\,\mathrm{MeV}$ in formation reactions using precise partial wave analysis (PWA) to determine the pole positions and the widths of these resonances. While proton accelerators produce neutral kaons with significantly higher intensity, the simultaneous generation of orders of magnitude more neutrons restricts their utility to the search for rare decays, as seen in KOTO experiment at J-PARC,[12] rather than for spectroscopy. This capability is achievable only with the high-intensity $I = 5\,\mu\mathrm{A}$ electron beam of CEBAF at JLab, which is uniquely capable of delivering a beam with a 64 ns (or even 128 ns) bunch separation by running it in storage ring mode.

Table 1. The list of reactions which allow to study some of hyperon resonances.[10]

Hyperon	Reaction
Σ^*	$K_L p \to \pi\Sigma^* \to \pi\pi\Lambda$
Λ^*	$K_L p \to \pi\Lambda^* \to \pi\pi\Sigma$
Ξ^*	$K_L p \to K\Xi^* \to \pi K\Xi^*$
Ω^*	$K_L p \to K^+K^+\Omega^*$

The KLF experiment aims to uncover "missing" hyperons[13] through reactions, exemplified in Table 1. Additionally, strange-meson spectroscopy will be performed to determine pole positions in the I = 1/2 and 3/2 channels.

Besides the ordinary hyperons composed of 3-quarks, the KLF experiment may also observe the exotic Θ^+ pentaquark, located at the apex of the anti-decuplet, $\overline{10}$, triangle. Furthermore, the experiment is sensitive to the observation of the exotic Ξ^+, positioned in the lower right corner of the $\overline{10}$ triangle, in the reaction $K_L p \to K_S \Xi^+$, as was noticed in Ref. 14. It is also designed to detect another exotic state, Ξ^{--}, situated in the lower left corner of the $\overline{10}$ triangle, within the reaction $K_L p \to K^+K^+K^+\Xi^{--}$. The 4 π acceptance of the GlueX setup is well suited to serve a purpose.

Hall D is acquiring a new basic equipment for the KLF project[10]: the Compact Photon Source (CPS) situated in the Tagger Hall, the Kaon Production Target (KPT) located in the Collimator Cave, and the Kaon Flux Monitor (KFM) positioned in the Experimental Hall just in front of the GlueX spectrometer. A schematic view of the setup, including the GlueX spectrometer, is presented in Fig. 1. According to the current schedule, the KLF experiment will build all beamline components in 2024, install them in 2025, and start data collection in 2026.

Figure 2 shows that the KLF simulations for the KLF kaon and neutron flux at 12 GeV (left) agree reasonably well with the K_L and neutron spectra measured

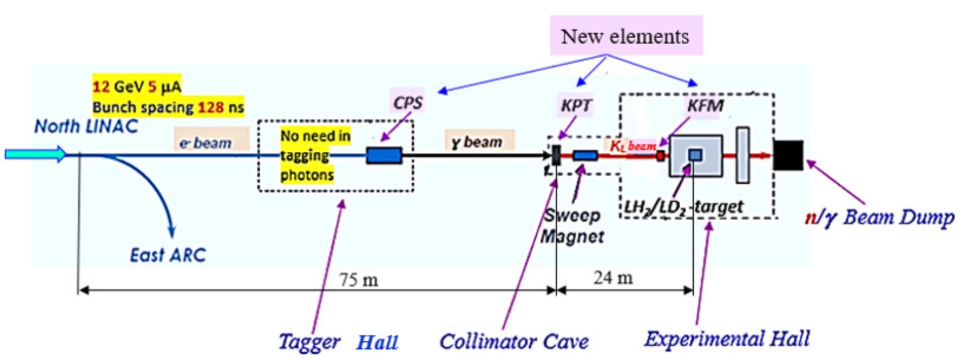

Fig. 1. Schematic view of the KLF beam line in JLab Hall D with the production chain $e \to \gamma \to K_L$. The main components are the CPS, KPT, sweep magnet, and KFM. The beam goes from the left to the right.[10]

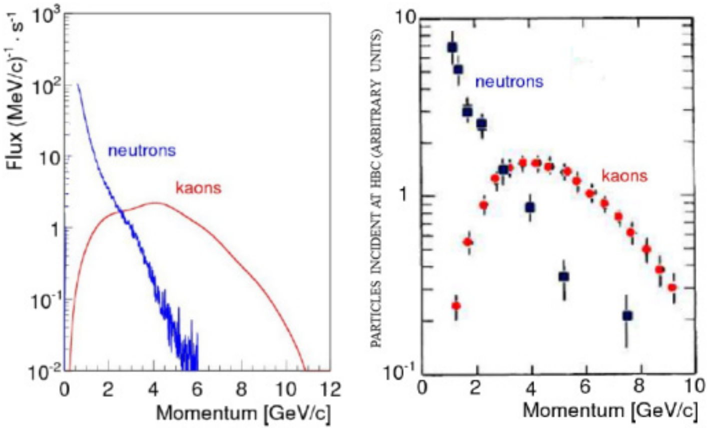

Fig. 2. (Color online) Left: Rate of K_L (red) and neutrons (blue) on the LH_2/LD_2 cryogenic target of Hall D at 12 GeV/c as a function of their generated momenta, with a total rate of 1×10^4 K_L/sec and 6.6×10^5 n/sec, respectively.[10] Right: Experimental data from SLAC measurements using a 16 GeV electron beam.[21]

by SLAC at 16 GeV[21] (right). The low momenta $(0.3 - 0.6\,\text{GeV/c})$ distribution is shown in Fig. 3.

The momentum of a K_L beam will be measured using time of flight (TOF), specifically the time between the accelerator bunch (CEBAF RF signal) and the reaction in the cryogenic target LH_2 (LD_2), as detected by the GlueX spectrometer. The TOF resolution is the quadratic sum of the accelerator time and GlueX spectrometer time resolutions. Given the excellent time resolution of the accelerator signal, on the order of a few picoseconds, the TOF resolution will be predominantly determined by the GlueX detector. In our calculations, we utilized the currently achieved Start Counter time resolution of 250 psec to illustrate the beam momentum resolution versus the kaon momentum (Fig. 4).

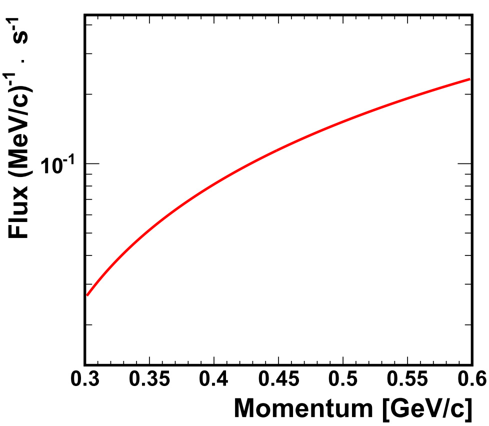

Fig. 3. Rate of K_L on the LH_2/LD_2 cryogenic target of Hall D for low momenta $(0.3 - 0.6\,\text{GeV/c})$.

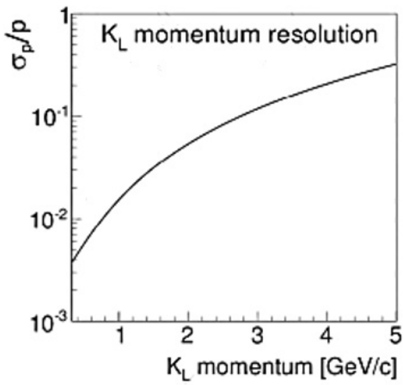

Fig. 4. Momentum resolution (σ_p/p) as a function of the initial kaon momentum.[10]

3. Expected Statistics for the Reaction $K_L p \to \Theta^+ \to K^+ n$

Utilizing a modified Partial Wave Analysis (PWA), Arndt and co-workers conducted a re-analysis of the existing KN database.[15] The aim was to investigate the impact of a narrow state on the fit of $K^+ - N$ observables.[16] The study revealed that the presence of a Θ^+ in the P_{01} ($J^P = 1/2^+$) state, the mass of $\sim$1545 MeV and with a width of $\Gamma(\Theta^+) \leq 0.5$ MeV, is conceivable (refer to Fig. 1(b) in Ref. 16).

The charge–exchange reaction $K^+ Xe \to K^0 p Xe'$ was investigated using the data of the DIANA experiment.[17] Using the ratio between the numbers of resonant and non-resonant charge–exchange events in the peak region, the intrinsic width of this baryon resonance is determined as $\Gamma(\Theta^+) = 0.34 \pm 0.10$ MeV.

Using Chiral Soliton approach, the decay width for $\Theta^+ \to NK$ was studied in the context of the LEPS and DIANA experiments. When the LEPS value of the Θ^+ mass[8] was used, then $\Gamma(\Theta^+) = 0.5 \pm 0.1$ MeV.[18]

In our study, we will consider the width of $\Gamma(\Theta^+) = 0.4$ MeV.

Authors in Ref. 19 revisited the low-energy $K^+ N$ elastic scatterings in the context of the in-medium quark condensate with strange quarks. There it described the KN amplitudes using chiral perturbation theory and fixed the low-energy constants appearing in the amplitudes by existing KN scattering data. It allows to determine a non-resonant background cross-section estimation for the reaction $K_L p \to K^+ n$ (Fig. 5). Then the total cross-section for the kaon beam momentum in the laboratory frame $p_{K_L} = 0.440$ GeV/c, which corresponds to $M_{\Theta^+} = 1.54$ GeV, is equal to $\sigma_{bkgd} = 3$ mb.

The momentum resolution for p_{K_L} at 440 MeV/c is $\sigma_p/p = 6 \times 10^{-3}$ (Fig. 4), which is extremely important factor in a search for a resonance with a very narrow width.

Using Eq. (1) from Ref. 17 and Eq. (3) from Ref. 20, one can get a number of events in the peak as

$$N_{\text{peak}} = \frac{\Gamma(\Theta^+)\ \pi\sigma_0 N_{bkgd} B_i B_f}{2\sigma_{bkgd}\Delta m_0} = 18,000\,\text{events}, \tag{1}$$

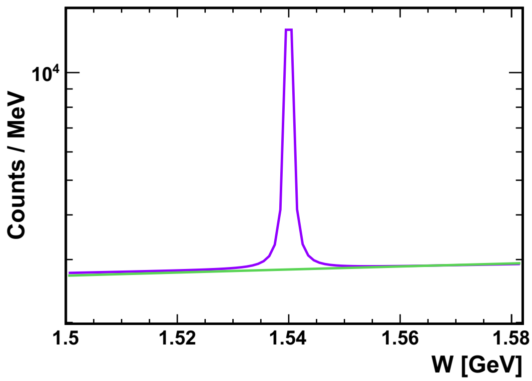

Fig. 5. (Color online) Expected number of events in reaction $K_L p \to K^+ n$ as a function of W. The background for $K_L p \to K^+ N$ (solid green curve) was simulated based on the prediction of the model.[19] The number of events in the peak for 100 days of running (purple solid curve) is estimated to be about 10,000 events (see text for details).

where N_{bkgd} corresponds to statistics during 100 days of the KLF running period ($N_{bkgd} = 5 \times 10^3$ events), Δm_0 is the Θ^+ mass resolution corresponding to σ_p/p and $\Delta m_0 = 1\,\text{MeV}$, branching ratios B_i and B_f into the initial and final channels of Θ^+ according to the Breit–Wigner form (see Eq. (1) from Ref. 20) and $B_i = B_f = 1/2$. The σ_0 is a geometrical factor calculated as in Eq. (2) from Ref. 20

$$\sigma_0 = \frac{2J+1}{(2s_{K_L}+1)(2s_p+1)}\,\frac{4\pi}{k^2} = 68\,\text{mb}, \tag{2}$$

where k is the center-of-mass momentum of the neutral kaon beam ($k = 0.268\,\text{GeV/c}$), s_{K_L} ($s_{K_L} = 0$) and s_p ($s_p = 1/2$) are incident spins, and J ($J = 1/2$) is the spin of the Θ^+ P_{01} resonance.

Finally, with all these calculations, we arrive at the number of events of the resonance of Θ^+ in a 1 MeV bin of the square root of the invariant energy $W = s^{1/2}$, which is equal to the invariant mass of the two-body K^+N system. Thus, in 100 days of running of KLF it is expected to observe 18,000 events with the acceptance and efficiency correction, it ends up to 10,000 events of the Θ^+ formation or an impressive amount of 100 events per day. The corresponding graph is presented in Fig. 5. It must be mentioned that the statistics at KLF will exceed those obtained by the DIANA experiment[17] by ∼50 times.

4. Discussion and Outlook

In summary, according to our estimation, about 10,000 exotic events Θ^+ will be observed in a 100 days of running KLF. It is worth to mention that here we will measure not the invariant mass of K^+n system, but rather the W of the initial state for this reaction benefiting from the extraordinary momentum resolution below 1 MeV of the incoming neutral kaon momenta in the region of interest.

Another proposal is developed, but not yet approved by J-PARC PAC, to find the Θ^+ in the reaction $K^+ d \to K^0 pp$ in $p_{K^+} = 0.5\,\mathrm{GeV/c}$ in J-PARC.[22] The most prominent advantage of the reaction $K_L p \to K^+ n$ is that we can clearly test whether Θ^+ exists or not in direct formation of Θ^+ without reflections from alternative resonances created in other combinations of the final state. The large acceptance Hyperon Spectrometer, which consists mainly of a time projection chamber and a 1 T superconducting magnet, will exclusively measure the decay products of $\Theta^+ \to K^0 p$ and $K^0 \to \pi^+\pi^-$ decay. Although, a very interesting proposal, the final state is still a 3-body and one has to do model dependent calculations of the final-state interaction (FSI),[24,25] accurately take into account Fermi motion effects and avoid reflections from the combinatorial background.

By comparing different reactions to directly measure the formation of the Θ^+ it becomes clear that the unique way to make a formation of the Θ^+ without any other associated particles is in reactions $K_L p \to K^+ n$ or $K_L p \to K_S p$. However, in the latter case the strangeness is not fixed due to the presence of both K^0 and $\bar{K}^0$ in the wave function of neutral kaons.

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