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High-precision three-dimensional field mapping of a high resolution magnetic spectrometer for hypernuclear spectroscopy at JLab

Yuu Fujii [a,*], Osamu Hashimoto [a,1], Toshinobu Miyoshi [a,2], Satoshi N. Nakamura [a], Atsushi Ohtani [a,3], Yuichi Okayasu [a,4], Masamichi Oyamada [a], Yosuke Yamamoto [a], Seigo Kato [b], Jumei Matsui [c], Katsuhisa Sako [c], Paul Brindza [d]

[a] Department of Physics, Tohoku University, Sendai 980-8578, Japan
[b] Department of Physics, Faculty of Science, Yamagata University, Yamagata 990-8560, Japan
[c] Mitsubishi Electric Corporation Energy & Industrial System Center, Kobe 652-8555, Japan
[d] Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

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ABSTRACT

The High Resolution Kaon Spectrometer (HKS), which consists of two quadrupole magnets and one dipole magnet, was designed and constructed for high-resolution spectroscopy of hypernuclei using the $(e, e'K^+)$ reaction in Hall C, Jefferson Lab (JLab). It was used to analyze momenta of around 1.2 GeV/c K^+ s with a resolution of 2×10^{-4} (FWHM). To achieve the target resolution, a full three-dimensional magnetic field measurement of each magnet was successfully performed, and a full three-dimensional magnetic field map of the HKS magnets was reconstructed. Using the measured field map, the initial reconstruction function was generated. The target resolution would be achieved via careful tuning of the reconstruction function of HKS with the $p(e, e'K^+)\Lambda, \Sigma^0$ and $^{12}C\,(e, e'K^+)^{12}_{\Lambda}\,B_{g.s.}$ reactions. After tuning of the initial reconstruction function generated from the measured map, the estimated HKS momentum resolution was 2.2×10^{-4} (FWHM).

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1. Introduction

A traditional magnetic spectrometer with a well-defined focal plane needs only one-dimensional position measurement for momentum analysis (e.g., the split-pole [1] or the so-called "hardware" spectrometer). However, a highly sophisticated magnet design is required to minimize aberration, and thus, it is difficult to have a large solid angle. In contrast to "hardware" spectrometers, modern magnetic spectrometers (e.g., the Superconducting Kaon Spectrometer (SKS) [2]) have a rough focal plane and a large solid angle; moreover, the shape of the magnet is relatively simple. Because the optics of these spectrometers includes highly complicated higher-order aberrations, not only the positions but also the angles of the particles should be measured; the momentum vectors of the particles at the reaction point would be reconstructed using these quantities. Therefore, such spectrometers are known as "software" spectrometers. Owing to recent advancements in computing power and the development of sophisticated simulation techniques, the reconstruction function can be deduced using a simulation based on a three-dimensional magnetic field map. Therefore, it is important to develop a procedure for generating a three-dimensional magnetic field map from magnetic field values at discrete spatial points.

The High Resolution Kaon Spectrometer (HKS) was designed and constructed to have a momentum resolution of 2×10^{-4} (FWHM) for high-resolution (sub-MeV) spectroscopy of hypernuclei using the $(e, e'K^+)$ reaction in JLab [3,4]. HKS was designed as a quadrupole–quadrupole–dipole (QQD)-type normal conducting spectrometer to satisfy the following requirements.

- Central momentum of 1.2 GeV/c to accept kaons from hypernuclear production.
- Momentum resolution of 2×10^{-4} (FWHM) to achieve a missing mass resolution of $\leq$ 0.5 MeV (FWHM).

* Corresponding author. Tel.: +81 22 795 6787; fax: +81 22 795 6455.
E-mail address: fujii@lambda.phys.tohoku.ac.jp (Y. Fujii).
[1] Deceased.
[2] Present address: Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan.
[3] Present address: Shimadzu Corporation, 1 Nishinokyo Kuwabara-cho, Nakagyo-ku, Kyoto 604-8511, Japan.
[4] Present address: Japan Synchrotron Radiation Research Institute, 1-1-1 Kouto, Sayo, Sayo-gun, Hyogo 679-5198, Japan.

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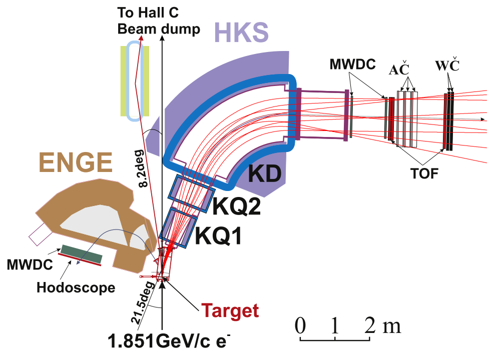

Fig. 1. Schematic top view of the experimental setup of JLab E01-011. A 1.851 GeV electron beam was irradiated onto an experimental target located at the entrance of a charge separation dipole. Unscattered electrons were bent by the charge separation dipole, and bent back to the Hall C standard beam dump by two beam line dipoles (only the first dipole is shown). Photons from the bremsstrahlung directly went through the Hall C beam dump. Scattered electrons were bent toward the left and entered the Enge spectrometer. Scattered kaons were bent toward the right and entered HKS. The following types of detectors were employed: MWDC (multi-wire drift chambers for particle tracking), TOF (scintillator hodoscopes for time-of-flight measurement), AČ (aerogel Cherenkov detectors for pion rejection), and WČ (water Cherenkov detectors for proton rejection).

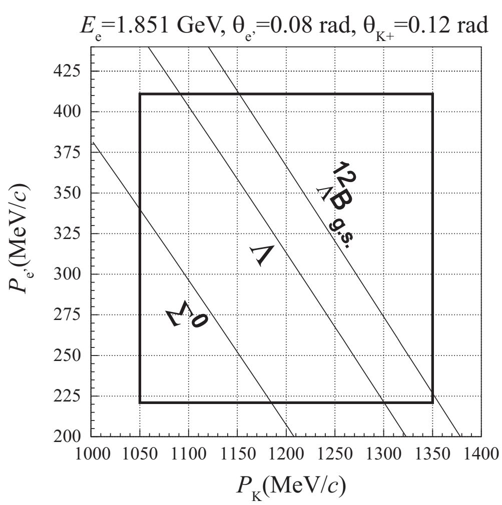

Fig. 2. Momentum correlation between a scattered kaon (P_K) and an electron ($P_{e'}$) from Λ, Σ^0, and $^{12}_{\Lambda}B_{g.s.}$ production via the $(e, e'K^+)$ reaction in the JLab E01-011 kinematics with the following parameters: beam energy (E_e=1.851 GeV), electron scattering angle ($\theta_{e'}$ = 0.08 rad) and kaon scattering angle (θ_{K^+} = 0.12 rad) with the beam direction. The momentum acceptances of the existing electron detection arm (Enge) and HKS are shown as a rectangle. HKS was designed to have a momentum acceptance of 1.2 GeV/c ± 12.5% to accept kaons from hypernuclear production in coincidence with electrons accepted by the electron detection arm.

- Large solid angle up to 30 msr without a charge separation dipole magnet in front of it, to maximize hypernuclear yield.
- Momentum acceptance of 300 MeV/c (1.2 ± 0.15 GeV/c), matching that of the electron detection arm, as shown in Fig. 2. Hyperons (Λ, Σ^0) and hypernucleus ($^{12}_{\Lambda}$ B) are covered by the momentum acceptances of the kaon and electron spectrometers, respectively.
- Shorter path length (< 10 m) to minimize kaon loss due to kaon decay in flight ($c\tau$=3.6 m).

The QQD-configuration also has the advantage of flexible focusing, which makes it compatible with different experimental configurations.

Diagrams of the quadrupoles (KQ1 and KQ2) are shown in Fig. 3, and the parameters are listed in Table 1. Similarly, a diagram of the dipole (KD) is shown in Fig. 4, and the parameters are listed in Table 2. These were designed to fit the experimental setup such that they do not interfere physically with the photon line, beam line, and electron detection arm, as shown in Fig. 1. Thus, KQ1 and

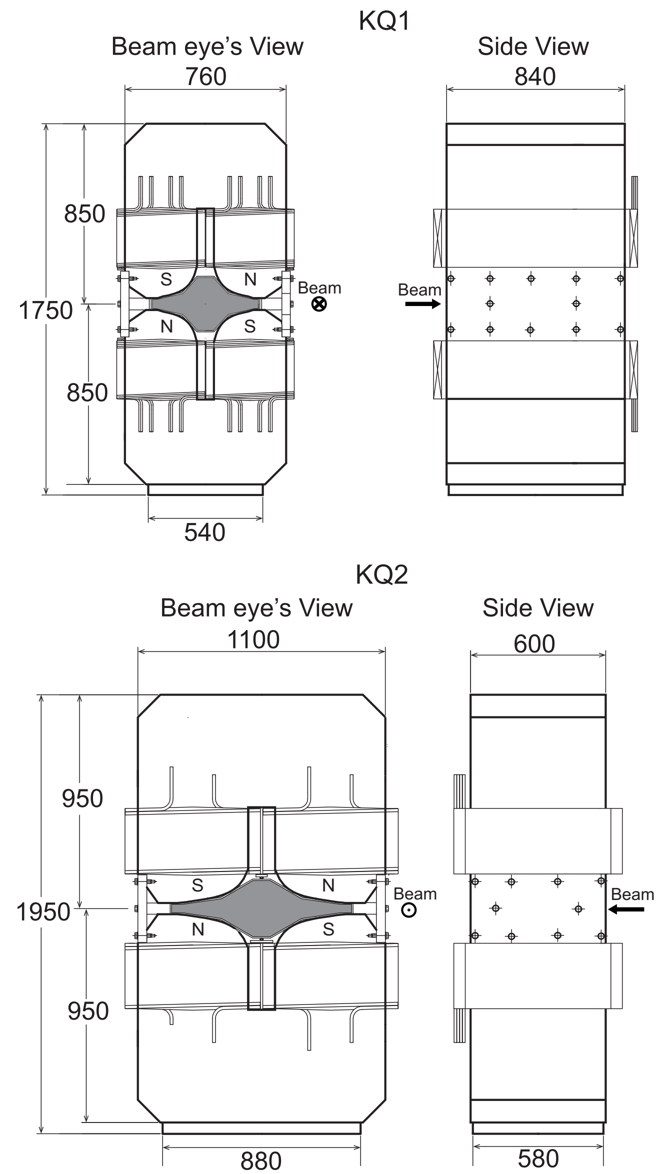

Fig. 3. Diagrams of KQ1 (top panel) and KQ2 (bottom panel) magnets (units, mm). The iron specification is SUY-1 (JIS C 2504). The cross-section of the vacuum chamber is also shown, and the vacuum area is shaded in gray.

Table 1
Parameters of KQ1 and KQ2 magnets.

Parameters	KQ1	KQ2
Bore radius (mm)	120	145
Pole length (mm)	840	600
Effective width (mm)	500	800
Number of turns	256	320
Field gradient (T/m)	5.78 (max 6.60)	−3.40[a] (max −4.19)
Current (A)	585 (max 875)	363 (max 450)
Total magnet weight (t)	8.2	10.5

[a] Negative values denote reversed polarity with respect to KQ1, i.e., vertical focusing.

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