Active canceling of stray-mangnetic field for PMTs of S-2S water Čerenkov detector

T. Gogami,[1,*] S. Kanatsuki,[1] T. Nagae,[1] and T. Nanamura[1]

[1] *Department of Physics, Kyoto University, Kyoto 606-8502, Japan*

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We plan to perform Ξ^- hypernuclear spectroscopy with a new magnetic spectrometer, S-2S via the (K^-,K^+) reaction at J-PARC. A water Čerenkov detector which detects a Čerenkov radiation with photo multiplier tubes (PMT) is needed to be installed near by S-2S to minimize a loss of K^+ by decay. Therefore, there is a considerable strength of stray-magnetic field from the S-2S dipole magnet on the PMTs, which causes a critical PMT-gain reduction. We studied a bucking-coil implementation on the PMTs in order to actively vanish the stray-magnetic field on the PMTs. As a result, the bucking-coil method was able to recover the PMT-gain up to the original gain in a similar strength of magnetic field in S-2S, and thus it allows us to maintain an on-line separation capability between K^+s and background protons by our water Čerenkov detector.

I. INTRODUCTION

We are planning to perform a spectroscopic experiment of Ξ^- hypernuclei via the (K^-,K^+) reaction (J-PARC E05 experiment [1]) at K1.8 beam line in Hadron experimental hall in J-PARC [2]. There is no clear observation of Ξ^- hypernculei up to now, although it would be significant inputs for further understanding of the strong interaction between baryons with a strangeness degree of freedom. In order to observe Ξ^- hypernuclei with sufficient significance, we are constructing a new magnetic spectrometer, S-2S for K^+ detection, which possesses high momentum resolution of $\Delta p/p \simeq 5 \times 10^{-4}$ in FWHM. Thus, the Ξ^- hypernulcear structures are expected to be investigated with an energy resolution of a few MeV (FWHM), owing to a combined optical systems between the K1.8 beam line spectrometer [2] and S-2S.

S-2S is designd to detect particles with the momenta of 1.2–1.6 GeV/c, and the solid angle at 1.3 GeV/c is approximately 60 msr. We estimated that protons and π^+s are detected as major background particles in S-2S. Counting rates for protons and π^+s were estimated by a Monte Calro simulation (Geant4 [3]) with a particle generator based on JAM code [4]. As a result, it is estimated that the counting rates for protons, K^+s, and π^+s are 150, 1, and 20, respectively for an expected beam intensity of 10^6 K^-/spill. These background particles are planned to be rejected at a trigger level (on-line) by using a combination of two types of Čerenkov detectors with radiation media of purified water (refractive index of $n = 1.33$) and aerogel ($n = 1.05$). π^+s are planned to be rejected by an existing aerogel Čerenkov detector, which was used in the previous Λ hypernulcear experiments with a magnetic spectrometer, SKS at J-PARC. On the other hand, we developed a water Čerenkov detector for a proton rejection, and the latest prototype is expected to achive our goal of > 90% proton-rejection capability maintaining a K^+ survival ratio of > 95% at the trigger level [5].

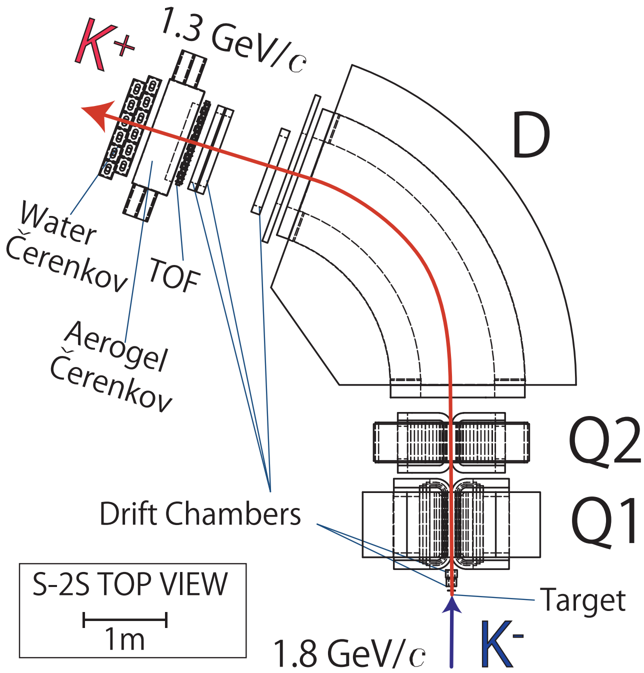

FIG. 1. A schematic drawing of S-2S top view. S-2S consists of two quadrupole magnets (Q1, Q2), one dipole magent (D), and particle detectors. K^+s with the momentum of 1.2–1.6 GeV/c are measured in S-2S.

Figure 1 shows a schematic drawing of S-2S top view. S-2S consists of two quadrupole (Q1, Q2) magnets, one dipole (D) magnet, and particle detectors. K^- beams at 1.8 GeV/c are impinged on a target, and generated K^+s are measured in S-2S. For particle tracking, two drift chambers are in between a target and Q1 magent, and three drift chambers are at the downstream of D magnet. A layer of time-of-fight (TOF) detector, which is made of 18 segments of plastic scintillation counters, is right behind the most downstrem drift chamber for data-taking trigger and off-line particle identification (PID). Aerogel

* *Present Address: Research Center for Nuclear Physics, Osaka University, Osaka 567-0047, Japan*

and water Čerenkov detectors are at the downstream of TOF detector for both on-line and off-line PID.

These particle detectors are desinged to be installed near the S-2S magnets in order to minimize a loss of K^+ by decay. Therefore, it is expected that there is considerable strength of magnetic field from the dipole magnet at around the particle detectors with photo multiplier tubes (PMT) such as the TOF and Čerenkov detectors. The magnetic field especially in parallel to an axis of PMT is expected to reduce a PMT gain. For instance, a PMT gain of Hamamatsu H7195 [6] was reduced by 60% in the case of a magnetic field of 5 G in parallel to the PMT axis [7]. On the other hand, the gain reduction by the magnetic field of 5 G in perpendicular direction with respect to the PMT axis was found to be only about 5%. The gain reduction would be predominantly caused by a reduction of probability that a photoelectron reaches the first dynode from the photocathode in a PMT. Such gain reduction is a critical issue particularly for the Čerenkov detectors because the light yield of Čerenkov radiation is rather smaller than that of scintillation.

We measured a stray-magnetic field of the S-2S dipole magnet, and it was found that there is the magnetic field of $B_x \simeq 1$ G, $B_y \simeq 5$ G and $B_z \simeq 8$ G at maximum at around PMTs of the particle detectors, where the x, y and z-coordinates are defined in Fig. 2. The axis of PMT attached on the water Čerenkov detector is in parallel to the y-axis although that of the aerogel Čerenkov detector is in parallel to the x-axis. Therefore, we need to reduce the stray-magnetic field at around PMTs particularly for the water Čerenkov detector. There are two major ways to prevent the magnetic field from acting on the PMT gain reduction. One is an installation of magnetic-field shield by using high-permeability material such as iron. The other is a bucking-coil implementation on PMT which actively cancels the stray-magnetic field [7]. We are considering installations of both methods to avoid the PMT-gain reduction which would cause deteriorations of particle-detection efficiency and background-suppression capability in S-2S. In the present paper, studies of the bucking-coil implementation on a PMT (Hamamatsu H11284-100UV [6]), which will be used for the water Čerenkov detector in S-2S, are presented.

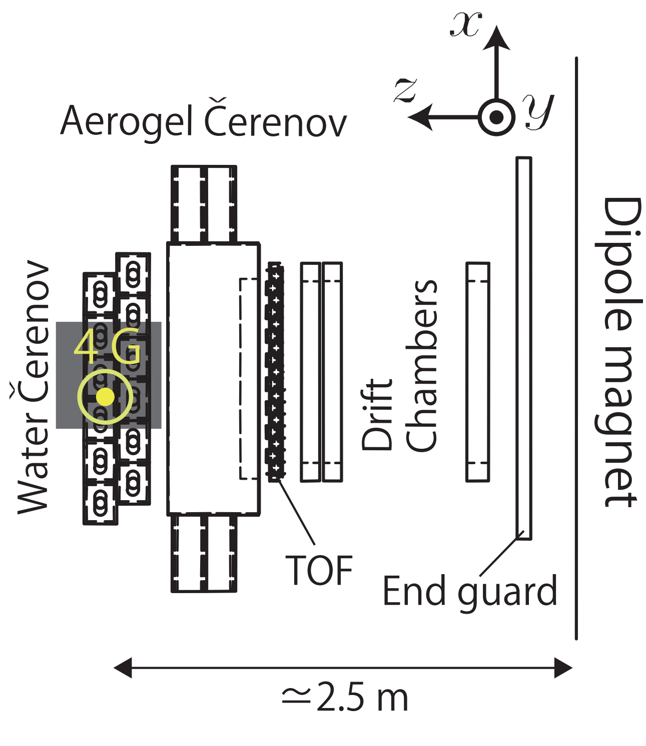

FIG. 2. A schematic drawing of the S-2S downstream particle detectors. The water Čerenkov detector is palnned to be installed 2.5 m away from the S-2S dipole magnet, and the stray-magnetic field in parallel to the PMT axis (B_y) was measured to be ≤ 4 G there.

II. EFFECT OF MAGNETIC FIELD ON H1128-100UV PMT

There were $(B_x, B_y, B_z) \simeq (1\,\text{G}, 4\,\text{G}, 4\,\text{G})$ at maximum at positions for PMTs of the water Čerenkov detector as shown in Fig. 2. Thus, we studied a performance of H11284-100UV PMT under an environment with a magnetic field ranging from 0 to 10 G, and the results are described in this section.

A. Experimental Setup

In order to generate a uniform-magnetic field around a PMT, we constructed a Helmholtz coil with a radius of 400 mm and 100 turns of cables in total. An H11284-100UV PMT was attached on one side of a segment of the water Čerenkov detector with optical coupling grease (BC-630 [8], $n = 1.465$), and an LED (light emitting diode) light was attached on the other side. A container of the water Čerenkov detector, of which basic design is similar to the latest prototype as reported in [5], was filled by pure water (purified water Clean & Clean [9], electrical conductivity of ≤ 0.1 mS/m at 25°C, $n = 1.33$). The H11284-100UV PMT, which was attached on the water Čerenkov detector, was inserted into a center volume of the Helmholtz coil to yield the magnetic field of ≤ 10 G in a parallel direction with respect to the PMT axis. Figures 3 and 4 show a schematic drawing and a photograph of the experimental setup, respectively.

B. Magnetic field generation

The magnetic field of the Helmholtz coil (radius of 400 mm, $50 + 50 = 100$ turns of cables) with several settings of currents was measured by a Hall probe. An

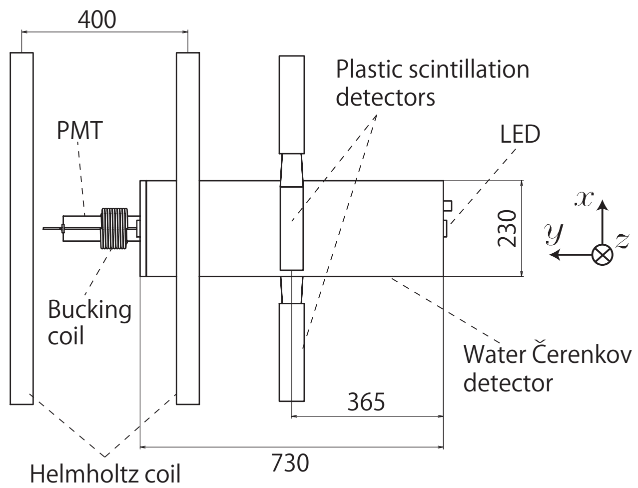

FIG. 3. A top-view schematic drawing of an experimental setup of the bucking-coil test. An H11284-100UV PMT, which was attached on one side of a segment of the water Čerenkov detector, was installed in a center volume of Helmholtz coil. An LED light was attached on the other side of the PMT. The water Čerenkov detector was sandwiched by two plastic-scintillation detectors which were used as trigger counters to take data with cosmic rays. A 20-turn bucking coil was started winding at 30 mm apart from the PMT photocathode. All dimensions are in mm.

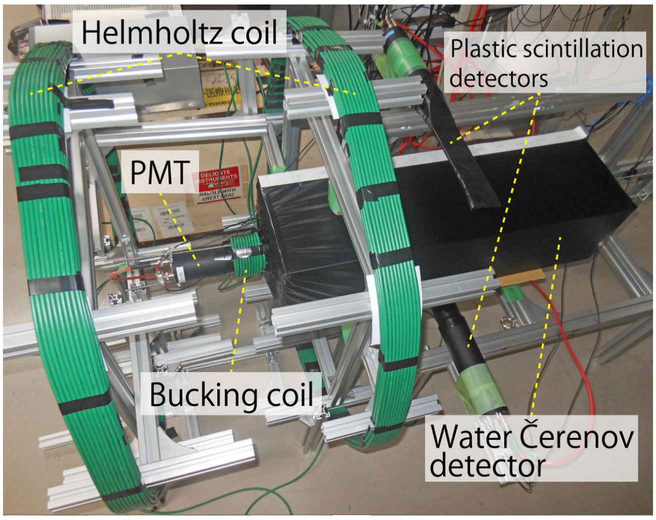

FIG. 4. A photograph of an experimental setup of the bucking-coil test.

obtained relation between the current and B_y (the coordinates are defined in Fig. 3) at the center position of the Helmholtz coil is shown in Fig. 5, and a result of fitting to these data with a linear function is represented by a solid line. The Helmholtz coil was able to generate 11.5 G at the current of 10 A. The uniformity of B_y and the other components of magnetic field ($B_{x,z}$) in a central volume of $200^x \times 200^y \times 100^z$ mm^3, where the PMT was installed,

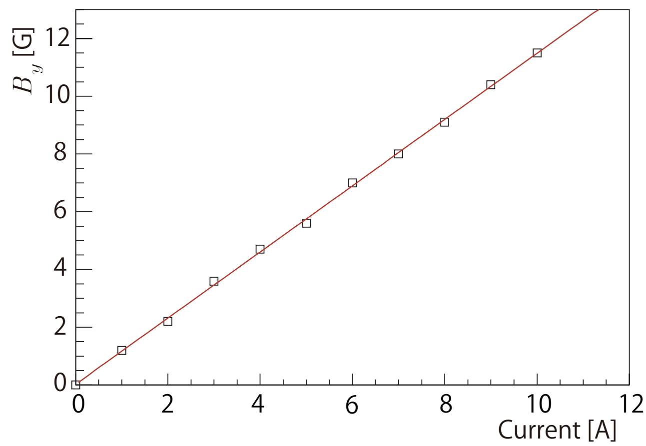

FIG. 5. A measured relation between the current and B_y at the center position of the Helmholtz coil we constructed.

were measured as

$$\frac{\Delta B_y}{B_y} \leq 1\%, \tag{1}$$

$$\frac{B_{x,z}}{B_y} \leq 3\%. \tag{2}$$

The above performance of the Helmholtz was adequate to investigate an effect of the magnetic field on the PMT.

C. Gain Reduction of PMT

In order to study the gain reduction of a H11284-100UV PMT due to the magnetic field, charge information was taken by a ADC (Hoshin C009 [10]) with a data-taking trigger synchronized with the LED light. The number of photons generated with the LED light was adjusted by controlling widths and frequencies of rectangular pulses input to the LED. Obtained ADC histograms at the supplied-high voltage of -2100 V for the PMT in the cases of $B_y = 0$, 3, 5, 8 and 10 G are shown in Fig. 6. The ADC histograms were fitted by Gaussian functions as represented by dashed lines in Fig. 6. The obtained mean values were normalized to unity at $B_y = 0$ G (relative gain), and they are plotted in Fig. 7 ($\theta = 0$ deg; the magnetic field was yielded in parallel to the PMT axis). For a comparison, the relative gains when the magnetic field was yielded in perpendicular to the PMT axis were also plotted ($\theta = 90$ deg). It was found that the gain of H11284-100UV PMT at -2100 V was reduced by approximately 70% when the magnetic field of 5 G was yielded in parallel to the PMT axis. On the other hand, the gain reduction is only about 5% for the the magnetic field of 5 G in perpendicular to the PMT axis, which is consistent with the case of Hamamatsu H7195 PMT [7].

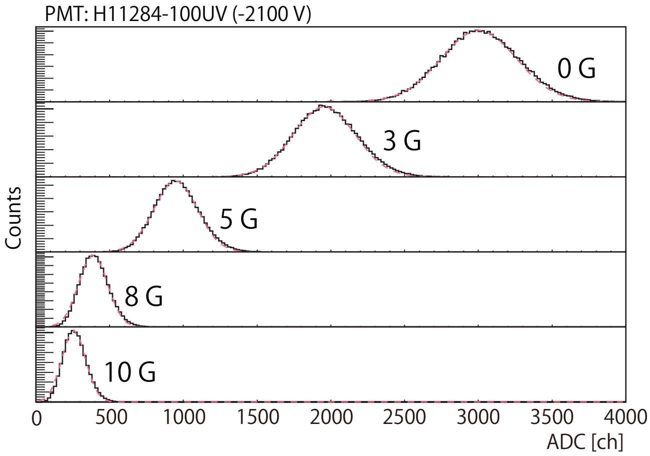

FIG. 6. ADC histograms of H11284-100UV PMT at the supplied high voltage of −2100 V when the magnetic field of $B_y = 0$, 3, 5, 8 and 10 G was yielded.

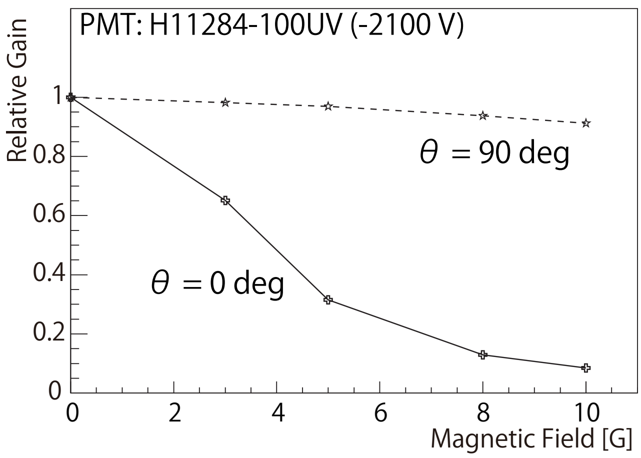

FIG. 7. Relative gains of H11284-100UV PMT at −2100 V when the magnetic field of 0, 3, 5, 8 and 10 G was yielded in parallel ($\theta = 0$ deg) and perpendicular ($\theta = 90$ deg) to the PMT axis.

III. MAGNETIC FIELD CANCELING BY BUCKING COIL

As shown in the previous section, a magnetic field particularly in parallel to the PMT axis causes a considerable PMT-gain reduction. In an experiment with S-2S, the gain reduction would be caused due to a stray-magnetic field from the S-2S dipole magnet, and it directly deteriorate a separation capability between K^+s and protons by the water Čerenkov detector. We plan to cancel the stray-magnetic field by adopting a bucking-coil method which is the way to cancel the magnetic field localy and actively by installing a coil on a PMT. In this section, studies for implementation of a bucking coil on the PMT of our water Čerenkov detector are described.

A. PMT-gain recovery with bucking coil

The experimental setup is the same as shown in Figs. 3 and 4. A bucking coil which starts from closer to the PMT photocathode is more effective in order to ease an effect of gain reduction due to a magnetic field as reported in [7]. For our water Čerenkov detector, however, a bucking coil was started winding 30 mm away from the PMT photocathode because of a PMT-support structure. The number of turns for the bucking coil was 20 in this test, although it can be varied to be less or more. An LED was used as a light source, and a data-taking trigger was synchronized with the LED light as represented in Sec. II C. Figure 8 shows measured relative gains of the H11284-100UV PMT as a function of the bucking-coil current for $B_y = 3$, 5, 8 and 10 G. The relative gain at $B_y = 5$ G, which is larger than the maximum magnetic field at around PMTs of the water Čerenkov detector, was able to be recovered to be $\simeq 1$ by the 20-turn bucking coil with the current of 4.5 A.

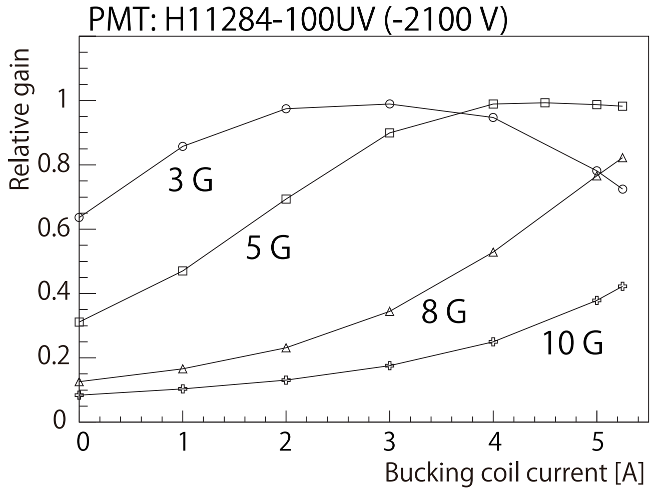

FIG. 8. Relative gains of an H11284-100UV PMT (−2100 V) as a function of the bucking-coil current for $B_y = 3$, 5, 8 and 10 G. The relative gain at $B_y = 5$ G, which is larger than the maximum magnetic field at around PMTs of the water Čerenkov detector in S-2S, was able to be recovered up to $\simeq 1$ by the 20-turn bucking coil with the current of 4.5 A. The bucking coil was started winding 30 mm away from the PMT photocathode.

B. Cosmic-ray test

A capability of gain recovery with the 20-turn bucking coil was attempted to be confirmed by a cosmic-ray test in which a Čerenkov radiation was detected by the PMT. The experimental setup is the same as shown in Sec. III A (Figs. 3 and 4), but the trigger condition was changed to a coincidence between two plastic scintillation counters.

Figure 9 shows ADC spectra in the cases of:

(a) $B_y = 0$ G and the bucking current of 0 A ($I_B = 0$ A),

(b) $B_y = 5$ G and $I_B = 0$ A,

(c) $B_y = 5$ G and $I_B = 4.5$ A (cf. Fig. 8).

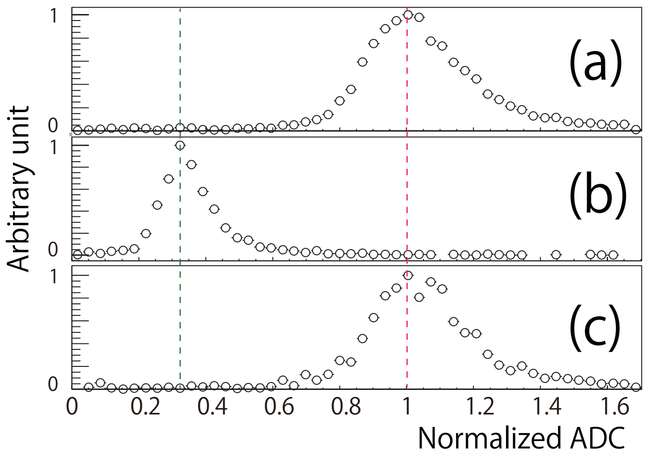

FIG. 9. Normalized ADC spectra in the cases of (a) $(B_y, I_B) = (0\text{ G}, 0\text{ A})$, (b) $(B_y, I_B) = (5\text{ G}, 0\text{ A})$, and (c) $(B_y, I_B) = (5\text{ G}, 4.5\text{ A})$.

An ordinate axis for each spectrum was normalized so as to make the maximum bin unity. Moreover, abscissa axes were normalized to make a peak position of (a) unity.

Squares of residuals for spectra of (a)-(b) and (a)-(c) were calculated, and obtained spectra are presented in Fig. 10 (top: $(\mathrm{b}-\mathrm{a})^2$, bottom: $(\mathrm{c}-\mathrm{a})^2$). The square of residual becomes zero if two spectra are the exactly same. An integrated charge by a signal of Čerenkov radiation was reduced by approximately 70% in the case of (b) as shown in a top panel of Fig. 10. On the other hand, the square of resudual for (a)-(c) distributes around zero as shown in a bottom panel of Fig. 10, and it indicates the gain was able to be recovered by the bucking-coil implementation on PMT. The above results are consistent with the studies by the LED light as described in Sections II C and III A.

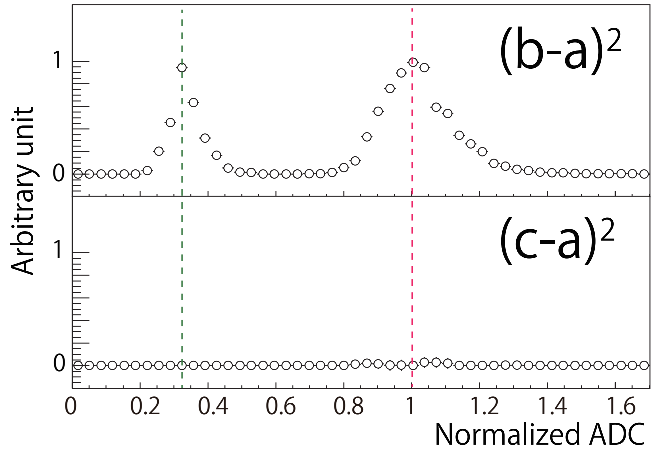

FIG. 10. Spectra of squares of residuals for (a)-(b) and (a)-(c). If two spectra is the exactly same, the square of residual becomes zero. An integrated charge by a signal of Čerenkov radiation was reduced by approximately 70% in the case of (b) as shown in a top panel ($(\mathrm{b}-\mathrm{a})^2$). On the other hand, the $(\mathrm{c}-\mathrm{a})^2$ spectrum distributes around zero, and it indicates the gain was able to be recovered by the bucking-coil implementation on PMT.

IV. CONCLUSION

We are constructing a new magnetic spectrometer, S-2S for a K^+ detection to observe Ξ^--nucleus buond system with an energy resolution of a few MeV (FWHM) via the (K^-,K^+) reaction at J-PARC. A water Čerenkov detector, which detects Čerenkov radiations by photomultiplier tubes (PMT), is needed to be installed approximately 2.5 m away from the S-2S dipole magnet in order to minimize a loss of K^+ by decay. It was found that there is a stray-magnetic field of ≤ 4 G in parallel to the PMT axis at positions of PMTs of the water Čerenkov detector. The magnetic field would cause a PMT-gain reduction which directly deteriorates a capability of particle separation between K^+s and background protons with the water Čerenkov detector. We are considering to avoid the PMT-gain reduction by installing a magnetic-field shield and a bucking coil. In this paper, we reported studies of the bucking-coil implementation on a Hamamatsu H11284-100UV PMT which will be used for the water Čerenkov detector.

We measured a gain reduction of the PMT in a magnetic field ranging from 0 to 10 G. It was found that the PMT gain was reduced by approximately 70% for the magnetic field of 5 G in parallel to the PMT axis. On the other hand, the magnetic field of 5 G in perpendicular to the PMT axis reduced the PMT gain by only about 5%, which is negligibly small.

A bucking coil made of 20 turns of cables was implemented on the PMT in the present study. The gain recovery by the 20-turn bucking coil was measured in the magnetic field of 5 G in parallel to the PMT axis, which is larger than the maximum stray-magnetic field around PMTs of the water Čerenkov detector in S-2S. The bucking coil started 30 mm away from the PMT photocathode to avoid a physical interference with a PMT-support structure of our water Čerenkov detector although a bucking coil which starts nearer by the photocathode was found to be more effective in the old published study. As a result, it was found that the PMT gain was able to be recovered up to the original gain even in an environment of the magnetic field of 5 G in parallel to the PMT axis by using the 20-turn bucking coil with the current of 4.5 A.

We plan to use one power supply for all of bucking coils on the PMTs of water Čerenkov detector. However, the number of turns of each bucking coil can be adjusted to ease an effect of the stray-magnetic field at each PMT position. Consequently, the bucking-coil implementation on the PMTs of our water Čerenkov detector is expected to allow for clean separation between K^{+}s and background protons in S-2S.

ACKNOWLEDGMENT

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