Magnetic field measurement of the S-2S D1 electromagnet

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Contents

• Introduction
  ▫ Spectroscopy of Ξ-hypernuclei
  ▫ Development of S-2S

• S-2S D1 magnetic field measurement
  ▫ Instruments
  ▫ Basic characteristics of S-2S D1
  ▫ Field mapping

• Improvement of calculated magnetic field map
• Momentum resolution of S-2S
Study of Xi-hypernuclei

- **What can we know from Ξ-hypernuclei?**
  - baryon-baryon interaction (Ξ-N, Λ-Λ)
  - role of multi-strangeness system in NS core

- **Spectroscopic study via the $^{12}$C(K-,K+) reaction**
  - BNL-E885 experiment
    - Suggested existence of $^{12}_Ξ$Be
    - Estimated $V_Ξ$ and $dσ/dΩ$
      - $V_Ξ \sim -14$ MeV
      - $dσ/dΩ = 89 \pm 14$nb/Sr ($θ<8°$)
  - J-PARC E05 pilot run (2015)
    - SKS was used as the spectrometer for K+
    - Better missing mass resolution achieved
    - Observe significant excess in bound region

P. Khaustov et al., PRC 61 (2000) 054603
Why do we aim for better resolution?

- To observe $\Xi$-hypernuclear state definitely as peak(s) in missing mass spectra
- To resolve excited states of $\Xi$-hypernuclei
  - Key to verify shell model and baryon-baryon interaction model
  - $\Delta E < 2$ MeV is essential

Calculated spectra for various interaction

$^{12}\Xi(\Xi^-K^+)^{12}\text{Be}$ production cross section calculated with DWIA (for ESC08a interaction)

J-PARC E05 with S-2S

- New spectrometer S-2S (Strangeness -2 Spectrometer)
  - Consists of two Q magnets and D magnet
  - Acceptance $\sim 60$ msr
  - Momentum resolution $\Delta p/p = 6 \times 10^{-4}$ (FWHM)
  → better missing mass resolution and statistics

$K^+ \sim 1.4$ GeV/c

$1.8$ GeV/c $K^-$

$\Delta p/p = 1.0 \times 10^{-3}$
S-2S Q1, Q2 magnet

Q1 (vertical focus)
Maximum gradient: 8.7 [T/m]
aperture: 31 [cm]
weight: 37 [Ton]
$W \times H \times L: 2.4 \times 2.4 \times 0.88$ [m$^3$]

Q2 (horizontal focus)
Maximum gradient: 5.0 [T/m]
aperture: 36 [cm]
Weight: 12 [Ton]
$W \times H \times L: 2.1 \times 1.54 \times 0.5$ [m$^3$]
S-2S D1 magnet

Max current: 2500 [A]
1.475 [T]
Central momentum:
1.38 [GeV/c]
Pole gap:
800 × 320 × 3650 [m³]
weight: 86 [Ton]

End guard: reducing leakage magnetic field

2015.9 @ KEK
Purpose of magnetic field measurement

- In experiments with S-2S, we analyze K+ momentum using calculated magnetic field map
  - Measurement for actual setup is difficult
- Error of magnetic field may make resolution worse.

Measured map \[\text{compare}\] Calculated map

Improving calculated map

Evaluating momentum resolution of S-2S
Instruments
Field mapping system
Field mapping system

Mover
Range: $1000 \times 450 \times 130$ mm

3-axis hall probe
(Lake shore MMZ-2508-UH)

Limit switch
Field mapping system: side view
Field mapping system: side view

- Frame (top)
- Frame (bottom)
- Mover control box
- Gauss meter
- Base plate
Field mapping system: side view
Control of instruments

- Connecting hall probe, mover, NMR probe with PC
- Using excel-VBA macro
Control of instruments

- Connecting hall probe, mover, NMR prove with PC
- Using excel-VBA macro

① list up points we want measure
Control of instruments

- Connecting hall probe, mover, NMR prove with PC
- Using excel-VBA macro

<table>
<thead>
<tr>
<th>x [mm]</th>
<th>y [mm]</th>
<th>z [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.75</td>
<td>38.69</td>
<td>0.04</td>
</tr>
</tbody>
</table>

① list up points we want measure

② push button: start to measure

測定開始時刻 2016/12/25 10:56
測定終了時刻 2016/12/25 11:51
Control of instruments

- Connecting hall probe, mover, NMR prove with PC
- Using excel-VBA macro

1. List up points we want to measure
2. Push button: start to measure
3. Operate mover and probe and record field value
operation characteristics S-2S D1 magnet and measuring system
Long-term stability

- From excitation @1500A, we had taken NMR data for about 90 minutes. (every 30 seconds)
  
  Time dependence of NMR value @1500A

- 10 minutes after excitation, NMR value becomes very stable. (σ = 1.6μT)
Excitation and hysteresis curve

- Changing current and taking value of NMR
  - 0A → 300A → 500A → ⋅⋅⋅ → 2500A (UP)
  - 2500A → 2300A → ⋅⋅⋅ → 500A → 0A (DOWN)
  - 0A → 1100A → 1500A → 2000A (UP2)

NMR value of “UP2” correspond with “UP” within 0.05 %.
→ hysteresis effect is enough small.
How long should we wait to take data?

- When the mover move, the position of hall probe may oscillate and therefore measured magnetic field will oscillate.
- @1500A
- Moving x ± 5 cm, y ± 5cm, z ± 5cm (and composition of these shift)
  - read hall probe value every 200ms
  - during 12 seconds from moving.
- When we wait two seconds, magnetic field vary within 0.05%.

Magnetic field value normalized by average of last 2 seconds
S-2S D1 magnetic field map measurement
Overview of measurement

- **Area**: $800 \times 320 \times 1700 \text{ mm}^3$ (DS), $400 \times 320 \times 1100 \text{ mm}^3$ (US)
- **Mesh size**: $50 \times 20 \times 50 \text{ mm}^3$
- **Current**: 1000A, 1500A, 2000A, **2500A**

By on central orbit

![Diagram showing measured area and NMR probe](image)

- **Z** axis
- **Z = 0**
- **Z = -3650**

Calculated vs. measured

- **BY [T]**
  - 0
  - -0.2
  - -0.4
  - -0.6
  - -0.8
  - -1
  - -1.2
  - -1.4
  - -1.6

- **Z [mm]**
  - -6000
  - -4000
  - -2000
  - 0
  - 2000
Transformation between coordinates

- Measured data
  - \((x,y,z), (b_x,b_y,b_z)\)
- Calculated data
  - \((X,Y,Z), (B_x,B_y,B_z)\)
- Transformation measured data \((x, y, z, b_x, b_y, b_z)\) to \((X,Y,Z), (Bx,By,Bz)\)
  - Decision 9 parameters by survey and fitting to reproduce symmetry.
  - (position shift : \(\delta x, \delta y, \delta z\) mover tilt : \(\delta \Phi x, \delta \Phi y, \delta \Phi z\) probe tilt \(\delta \theta x, \delta \theta y, \delta \theta z\))
- position \((x,y,z) \rightarrow (X,Y,Z)\)
  - Position of origin
  - Mover tilt
    \(\rightarrow \delta X < 0.1 \, [\text{mm}]\)
- Magnetic field \((b_x,b_y,b_z) \rightarrow (B_x,B_y,B_z)\)
  - Probe tilt
  - NMR correction
    \(\rightarrow \Delta \theta = 0.002 \, [\text{rad}]\)
Error evaluation

- **Error from hall probe** $\sigma_{\text{Hall}}$
  - Using data of same point stopping probe
- **Error from position precision** $\sigma_{\text{mover}}$
  - Using data of same point moving probe
- **Error from size of hall elements** $\sigma_{\text{size}}$
  - Hall element is 750μm-radius disk
  - Calculated $\frac{\partial B}{\partial x}$ from measured result and propagation
- $\Delta B^2 = \sigma^2_{\text{Hall}} + \sigma^2_{\text{mover}} + \sigma^2_{\text{size}}$
  - For $\Delta B$, $\sigma_{\text{size}}$ is dominant.

<table>
<thead>
<tr>
<th>成分</th>
<th>$\sigma_{\text{Hall}}$ [mT]</th>
<th>$\sigma_{\text{mover}}$ [mT]</th>
<th>$\sigma_{\text{size}}$ [mT]</th>
<th>$\Delta B$ [mT]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_X$</td>
<td>0.03</td>
<td>0.01</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>$B_Y$</td>
<td>0.03</td>
<td>0.02</td>
<td>&lt;1.6</td>
<td>1.6 (near pole end), 0.20 (others)</td>
</tr>
<tr>
<td>$B_Z$</td>
<td>0.03</td>
<td>0.1</td>
<td>&lt;1.4</td>
<td>1.4 (near pole end), 0.22 (others)</td>
</tr>
</tbody>
</table>
Improvement of calculated magnetic field
Calculated magnetic field

- Calculate by OPERA-3D/TOSCA
- modeling: made according to drawing, vertical symmetry
- BHcurve: base is pure iron: tune to reconstruct Q1 magnet

- Mesh size
  - yoke: 30 mm, area (particle passing): 20 mm
  - others: 100 mm
Compare with calculated field

- \( \text{DB}_Y = (\text{B}_Y \text{ measured}) - (\text{B}_Y \text{ calculated}) \)
  - Trend a: wide DBY distribution near pole end (\( \sigma = 2.8 \text{ mT} \))
  - Trend b: narrow DBY distribution in other area (\( \sigma = 0.7 \text{ mT} \))
Which region of BH curve we tune?

- There is large difference near end guard
  - On Iron, $B>1.8$ T, $(H>10000)$
  - Tune BH curve in this region
Tuning BH curve (1)

- Changing slope of BH curve ($\mu$) to 75%, comparing original.
  - Scaling with central magnetic field
  - Different trend in inner of magnet, similar trend near end guard.
  - Dividing BH curve between yoke and end guard.

![BH curve](image)

Before change

After change

![DBY on central orbit](image)

DBY on central orbit

Before - After

End guard
Tuning BH curve(2)

- Changing BH curve of end guard, compare with measured one.
  - BH curve of SS400 is best.
    - Checking drawings, actually end guard was made of SS400.
    - We use this calculated magnetic field.

![BH curve graph](image)

![DBY on central orbit graph](image)
Compare with calculated field again

- Distribution of $DB_Y = (BY\ measured) - (BY\ calculated)$ became narrow.
  - Near pole end: $\sigma = 1.3\ mT$ (before: $2.8\ mT$)
  - Other area: $\sigma = 0.4\ mT$ (before: $0.7\ mT$)
    - Comparable to measurement errors: $\sigma = 1.6\ mT, 0.2\ mT$
  - Reducing position dependence is effective.

**DB\_Y distribution**

**DBY on central orbit**
Evaluating momentum resolution of S-2S
Method of evaluation

Event generation map

$\textbf{Bgen}$

Analysis map

$\textbf{Bana}$

K⁺ event generation

$P_0 = 1.3 \text{ GeV/c}$

$\theta_{K⁺} < 10°$

Trajectory information
(resolution 0.3 mm)

Reconstructing momentum

Momentum resolution

$R = \text{Width of } (P - P_0)/P_0$

$\textbf{Bgen} : \text{tuned map} + \text{measured map}$

$\textbf{Bana1} := \textbf{Bgen} \ (\text{ideal})$

$\textbf{Bana2} : \text{original map}$

$\textbf{Bana3} : \text{tuned map fluctuated by errors}$
Momentum resolution with errors

- Analysis map and momentum resolution

<table>
<thead>
<tr>
<th></th>
<th>Bana1</th>
<th>Bana2</th>
<th>Bana3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>$5.3 \times 10^{-4}$</td>
<td>$5.3 \times 10^{-4}$</td>
<td>$5.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Delta p_{\text{center}}$ [MeV/c]</td>
<td>-0.2</td>
<td>-1.0</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

- Difference of Bana has little effect.
  - Considering BL product
  - whole D magnet: 5.7 [Tm], near end guard: 0.6 [Tm]
Summary

• We are preparing spectroscopy of $\Xi$-hyper nuclei with S-2S
• We constructed field mapping system and get magnetic field map.
  ▫ Measurement errors $<$ 1.6 [mT]
• We improve calculated magnetic field map
  ▫ BH curve of end guard was different $\rightarrow$ modified
  ▫ Calculated map is consistent with measured one in measurement errors.
• Evaluating momentum resolution of S-2S
  ▫ $5.5 \times 10^{-4}$ for 1.3GeV K+ from simulation
  ▫ We are waiting for confirmation in actual experiment!
My feelings and advice

• **Instruments**
  ▫ Because this hall probe is long, handling and alignment is troublesome.
  ▫ Limit switch is important (both software and hardware).
  ▫ If leakage magnetic field is large (~100 mT), hardware limit of mover will work by mistake.

• “If you use calculated magnetic field, is magnetic field measurement essential?”
  ▫ If you are sure that modeling and BH curve is right, you don’t need to measure magnetic field map in detail.
  ▫ Points on symmetry plane or points characterizing the magnet (e.g. central orbit of D magnet) have priority.
backup
Standard and resolution of survey

- We set two theodolite and level on standard line.
- Move probe to see marking in center of theodolite and record value of mover moved.
- We could resolve 25μm → angular resolution ~ 0.01 deg.

Probe almost fixed this two point

189.5 mm

X standard (336mm from pole tip, 20mm from End guard)

Y standard (S-2S center)

Z standard (2m height)
Flow chart of control macro
Example of result: main components

- Fitting $B_Y$ with Enge function

$$f(Z) = \frac{1}{1 + e^{p(Z-s)}} : \text{ } p(x) \text{ polynomial}$$

Position of effective edge
$s = 67.3 \pm 0.4 \text{ [mm]}$

Effective edge of calculated map:
$s = 67.4 [\text{mm}]$
Confirm Maxwell equations

- div $B$ and components of rot $B$ is distributed around 0
  - Fulfill Maxwell equations

measured
Calculated: one example of ideal magnetic field
Picture of dead hall probe