Study of Λ-n Interaction via FSI in γ+d Reaction

- Feasibility in the NKS2 Experiment -

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Motivation

• Study of nuclear force with strangeness
  • Hypernuclear experiment
    • Hadronic reaction
      • CERN-PS, BNL-AGS, KEK-PS, DAΦNE, J-PARC
    • Electro-Magnetic reaction
      • JLab, MAMI
    • Heavy ion reaction
      • GSI, BNL-RHIC, CERN-LHC
  • Hyperon-nucleon scattering
    • $\Lambda$-$p$ at Fermi Lab, $\Sigma$-$p$ at J-PARC
    • How about hyperon-$n$ elastic scattering?

The first observation of a hypernucleus.
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      \(\rightarrow\) Experimentally difficult

- We need the other data to understand NN, YN, YY force
How to Measure $\Lambda n$ Interaction

- Using FSI in $\gamma$+$d$ reaction for $K^+$+$\Lambda$ production
How to Measure Λn Interaction

- Using FSI in $\gamma + d$ reaction for $K^+ + \Lambda$ production
How to Measure Λn Interaction

- Using FSI in $\gamma+d$ reaction for $K^++\Lambda$ production

$\gamma + p \rightarrow K^+ + \Lambda$

$\Lambda n$ interaction in Final State Interaction (FSI)
How to Measure Λn Interaction

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The other capability is $K^- + d \rightarrow \gamma + \Lambda + n$, but........
FSI Effect in the $K^+$ Cross-section

- The shape of the curves
  - Enhancement in forward $K^+$
  - Variations: order of 10%
- Highly accurate measurements are required
  - In order to be able to distinguish among different potential models

Preceded Experiment

- JLab Hall C E91-016
  - $A(e,e'K^+)\Lambda n$ reaction
  - $A = {^1H, ~^2H, ~^3He, ~^4He}$
  - $Q^2=0.35$ (GeV/c)$^2$, $W = 1.91$ GeV

### DETECTOR STACKS:

#### TRACKING / TIMING:
1. DRIFT CHAMBERS
2. HODOSCOPES

#### PARTICLE ID:
3. GAS CERENKOV
4. LEAD GLASS CALORIMETER
5a. ACRYLIC CERENKOV (SOS)
5b. AEROGLASS CERENKOV (SOS)

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**Fig. 6.** (Color online) Effects of including FSI for the fits to the $H$, have $A^3H$, $A^2H$, and $A^4H$ targets at one kinematic setting ($\Delta E, x, Q^2$) obtained in Fig. 3. Simulated quasifree reactions include both the respective model cross section and the respective enhancement factors $\sigma_H$ and $\sigma_A$. The respective cross sections are given by $\sigma_H \equiv \frac{\sigma_H}{\sigma_A}$, for which this experiment is not able to distinguish directly the contributions of either $H$ or $A$. The respective ratio of the fit parameters $R$ is given by $R \equiv \frac{\sigma_H}{\sigma_A}$, for which this experiment is not able to distinguish directly the contributions of either $H$ or $A$. The model cross sections are then multiplied by the respective enhancement factors $\sigma_H$ and $\sigma_A$ for the simulated contributions (yellow). Vertical dot-dashed lines are as in Fig. 3.

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Scattering length $a = -2.68$ [fm] (from Nijmegen 89) Effective range $r = 2.91$ [fm] (from Nijmegen 97f) are fixed for estimation.

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Analysis of the $\Lambda p$ final-state interaction in the reaction $p + p \rightarrow K^+(\Lambda p)$

F. Hinterberger$^{1, a}$ and A. Sibirtsev$^{2, a}$

2.2 Final-state interaction

In the Watson-Migdal approximation [38–40] the FSI is taken into account by introducing a FSI enhancement factor $|C_{\text{FSI}}|^2$,

$$\frac{d^2\sigma}{d\Omega_{K}dM_{\Lambda p}} = |M|^2 |C_{\text{FSI}}|^2 \Phi_3,$$

where now $M$ is a pure production matrix element and the FSI amplitude $C_{\text{FSI}}$ depends on the internal momentum $q$ of the $\Lambda p$ subsystem. It converges to 1 for $q \rightarrow \infty$ where the $S$-wave FSI enhancement vanishes.

$$C_{\text{FSI}} = \frac{q - i\beta}{q + i\alpha} \left|\frac{C_{\text{FSI}}}{\sqrt{q^2 + \alpha^2}}\right|^2.$$

The potential parameters $\alpha$ and $\beta$ can be used to establish phase-equivalent Bargmann potentials [44, 45]. They are related to the scattering lengths $a$, and effective ranges $r$ of the low-energy $S$-wave scattering

$$\alpha = \frac{1}{r} \left(1 - \sqrt{1 - 2r/a}\right), \quad \beta = \frac{1}{r} \left(1 + \sqrt{1 - 2r/a}\right).$$

The $\Lambda p$ system can couple to singlet $^1S_0$ and triplet $^3S_1$ states. Near production threshold the singlet-triplet transitions due to the final-state interaction cannot occur. Therefore, the contributions of the spin-singlet and spin-triplet final states can be added incoherently. Taking the spin-statistical weights into account the unpolarized double differential cross-section may be written as

$$\frac{d^2\sigma}{d\Omega_{K}dM_{\Lambda p}} = \Phi_3 \left[0.25 |M_+|^2 \frac{q^2 + \beta^2}{q^2 + \alpha^2} + 0.75 |M_-|^2 \frac{q^2 + \beta^2}{q^2 + \alpha^2}\right].$$

This equation leaves six free parameters, the singlet and triplet potential parameters $\alpha_+$, $\beta_+$, $\alpha_-$, $\beta_-$ and the production matrix elements $|M_+|$ and $|M_-|$. Instead of the parameters $\alpha_+$, $\beta_+$, $\alpha_-$ and $\beta_-$ one can equally well use the singlet and triplet scattering length and effective-range parameters $a_\pm$, $r_\pm$, $a_\pm$, and $r_\pm$. The functional dependence on the invariant mass $M_{\Lambda p}$ can be evaluated by inserting the corresponding expression for the internal momentum $q$ of the $\Lambda p$ system,

$$q = \sqrt{M_{\Lambda p}^2 - (m_\Lambda + m_p)^2} \sqrt{M_{\Lambda p}^2 - (m_\Lambda - m_p)^2}.$$
Enhancement Factors of Λn FSI

\[ |C_{\text{FSI}}|^2 = \frac{q^2 + \beta^2}{q^2 + \alpha^2}. \]
\[ \alpha = \frac{1}{r} \left(1 - \sqrt{1 - 2\frac{r}{a}}\right), \quad \beta = \frac{1}{r} \left(1 + \sqrt{1 - 2\frac{r}{a}}\right). \]

Note: It is assumed that the production matrix of single and triplet are the same.
NKS2 Experiment

(The recent results will be shown in Parallel 2b by H. Kanda)
Photon Beam Line
in Research Center of Electron Photon Science (ELPH), Tohoku Univ.

Stretcher-Booster (STB) Ring
Max $E_e = 1.2$ GeV

After repairing
Max $E_e = 1.3$ GeV

Sweep magnet
NKS2

2nd experimental hall in ELPH
Photon Beam Line
in Research Center of Electron Photon Science (ELPH), Tohoku Univ.

Tagged Photon Rate: 1-3 MHz
Duty Factor: ~85%

Scattered electron $E_{e'} = 1/3 - 1/12$ of $E_e$
The NKS2 Experiment

- Tagged photon beam
  - $E_\gamma = 0.80$-1.08 GeV

- Liquid D$_2$ or H$_2$ target

- Magnetic spectrometer
  - Tracker
    - Two drift chambers
    - Charged particle momentum, trajectory, and decay vertex
  - Hodoscopes
    - Plastic scintillator + PMT
    - Time-Of-Flight (TOF)
    - Particle identification combined with momentum
  - Electron Veto

- Acceptance
  - Covering large kinematic region including forward angle
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Particle Identification

![Particle Identification Diagram](image)

- Momentum $\times$ charge sign [GeV/c]
- Inverse velocity $(1/\beta)$ [c$^{-1}$]

Diagrams show the relationship between momentum and inverse velocity for various particles, including $p$, $D$, $\pi^+$, and $\pi$.
Particle Identification

- Momentum \times charge sign [GeV/c]
- Inverse velocity \(1/\beta\) [c\(^{-1}\)]
- Mass squared [GeV\(^4/c^2\)]

Counts

- \(\pi\)
- \(P\)
Feasibility in NKS2
Feasibility Study by a Simulation

- FSI affects to cross section
  - Using effective range approximation
    - Large in low relative momentum region
    - How looks like in K and Λ distribution ($p$ and $\theta$)?
- Acceptance
  - $K^+$ single, and $K^+ + \Lambda$ coincidence
- Study by a Monte-Carlo simulation
  - GEANT4 based
  - $\gamma + d \rightarrow K^+ + \Lambda + n$
    - Kaon-MAID: $\gamma + p \rightarrow K^+ \Lambda$
    - Applying the effect of Fermi motion inside of deuteron
- New $K^+$ ID detector
  - same acceptance with current outer hodoscopes
$K^+$ angle vs. $K^+$ momentum

$E_\gamma = 800-900$, 900-1000, 1000-1100, 1100-1200, 1200-1300 [MeV]

2 or more tracks required

relative momentum 0-100 MeV/c

relative momentum 100-200 MeV/c

relative momentum 200-300 MeV/c

$K^+$ angle with respect to the gamma beam (Lab.) [rad]

$K^+$ momentum (Lab.) [MeV/c]
**K⁺ Single Measurement (MC studied)**

- 2 track trigger requested
- Geometrical acceptance for $K^+$:
  - ~20-30% (varied by relative momentum)
  - note: ~1-2 % for $K^+ + \Lambda$
- If requesting of < 3% error
  - in each 100 MeV step of $E_\gamma$ bin
  - total number of $K^+$ event: ~50000

Enhancement factor: effective range approximation for $\Lambda n$ FSI (S-wave, low energy)
K\(^{+}\) Single Measurement (MC studied)

- 2 track trigger requested
- Geometrical acceptance for K\(^{+}\):
  - \(\sim 20-30\%\) (varied by relative momentum)
  - note: \(\sim 1-2\%\) for K\(^{+}\)+Λ
- If requesting of < 3\% error
  - in each 100 MeV step of E\(\gamma\) bin
  - total number of K\(^{+}\) event: \(\sim 50000\)
K$^+$ Single Measurement (MC studied)

- 2 track trigger requested
- Geometrical acceptance for K$^+$:
  - ~20-30% (varied by relative momentum)
  - note: ~1-2 % for K$^+$+Λ
- If requesting of < 3% error
  - in each 100 MeV step of Eγ bin
  - total number of K$^+$ event: ~50000

Beam time estimated: ~150 days for each D$_2$ and H$_2$ target
It is realistic in ELPH
Summary

• $\Lambda n$ interaction via FSI effect
  • $\gamma + d \rightarrow K^+ + \Lambda + n$ and $\gamma + p \rightarrow K^+ + \Lambda$

• NKS2 experiment
  • NKS2 spectrometer covers forward angle region
  • Liquid Deuterium and Hydrogen target
  • Strangeness photo-production near the threshold

• Feasibility of measurements of the $\Lambda n$ interaction
  • Studied by the MC simulation based on GEANT4
    • $K^+$ single measurement
      • ~20-30% geometrical acceptance (for $\Lambda n$ relative momentum <300 MeV/c)
      • ~150 days of beam time for 50000 event
    • $K^+$ $\Lambda$ coincidence measurement
      • ~1-3% geometrical acceptance (for $\Lambda n$ relative momentum <300 MeV/c)
      • Capability of the complete measurement of kinematics
      • $\Lambda$ recoil polarization may give us more information
      • need helps of theoretical study
      • single/triplet separation?
Backup
are lengths and effective-range parameters are listed in Table 2. Here the statistical weights 0.25 the singlet contribution dominates, and a large variation of the \( |M_s|^2 \) is much larger than the triplet one, \( |M_t|^2 \). The results from the Nijmegen model are denoted as Nijm D [17], Nijm F [18] and Nijm a-f [20]. The NSC available meson exchange potential model predictions are not fit the FSI enhancement of the missing-mass spectrum measured in the total-cross-section and missing-mass spectrum measured in the production matrix elements of \( \Lambda p \) singlet and triplet state are varied by model.
### Effective Range and Scattering Length for an interaction

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<th>(r_s) [fm]</th>
<th>(a_t) [fm]</th>
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