Possibilities for large acceptance nucleon polarimetry & $(\gamma,NN)$ revisited

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Recent work on large acceptance nucleon polarimetry

-> Useful in next generation SRC experiments?

Revisit some ($\gamma$,NN) results
EDPOL2: CB@MAMI

- EDPOL2 Run completed Aug ’17
- 10cm liquid deuterium target
- \[ d(\gamma pn) \ n(\gamma \pi^0) n \ n(\gamma \eta) n \]

\[ n(\theta,\phi) = n_0(\theta) \{1 + A(\theta)[P_y \cos(\phi) - P_x \sin(\phi)] \} \]
Expected statistical accuracy for $D(\gamma,pn)$

Proton polarization

$\theta_{cm} = 90^\circ$

$D(\gamma,pn)$

Evolution of $D(\gamma,pn)$ with photon energy (GeV)

CB@MAMI (projected)
$\theta_N$ bin of $\pm 10^\circ$
EDPOL1 CB@MAMI – hydrogen target

- EDPOL1 – no MWPC.
- Geant4: New classes: Parameterise $p^{-12}\text{C}$ scattering data (+SAID PWA for QF NN)

**FIG. 3** (color online). $C_x^*$ excitation functions for $\vec{\gamma}p \rightarrow \pi^0\vec{p}$ (black circles) for fixed pion polar angles $\theta_{cm}$. Previous data came from JLab [2] (magenta triangles). The PWA solutions shown are SAID CM12 [36] (cyan long-dash line), SAID SN11 [37] (green short-dash line), BnGa2011-2 [38] (solid red line), and MAID07 [39] (violet dash-dotted line).
d(γ, pn) with CLAS@JLAB

- CLAS start counter as analysing medium
- Two **proton** final state
  - Incident neutron vector from kinematics & intercept of scatter track with SC
  - Scatter vector from CLAS drift chambers

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**g13 Experiment@CLAS**
Liq D₂ target 40 cm long
Circular (g13a) 20 triggers
Linear (g13b) 30 triggers

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Analysis of Zachariou (Edinburgh)
• Next step with CLAS data $A(\gamma,\text{NN})$

Physics -> Test Glauber predictions, HHC in medium, .. (more?)
Evolution of transferred/induced nucleon polarisation with $A, E_{\gamma}$
Analysing powers may cancel to first order in ratios of targets ✓
Glue-X possibilities?

• Use in future experiments at CLAS12, .. ?

Wide range of kinematic variables ($Q^2, \omega, x..$) in one experiment ✓
Gives access to neutron (as well as proton) polarisation ✓
Transferred polarisation (likely) only measurable transverse to the nucleon scatter plane ✗

• Worth the effort? Need steer from theory

$$\frac{P_x}{P_z} = -\frac{2M_p}{(E + E')\tan(\theta/2)} \frac{G_E^P(Q^2)}{G_M^P(Q^2)}$$
(γ,NN) revisited
Q distribution sensitive to

- Relative pair momentum (s-wave, p-wave, d-wave)
- Final state of (A-2) nucleus
- Contributing shells – e.g. (1s)(1p) narrower and at higher Q than (1p)^2

True for mean field. SRC nucleons?
$^{12}\text{C}(\gamma,\text{pn})$ – high Q excess

- Clear excess at high Q over mean field (selecting $(1p)^2$ knockout)
- Excess rather uniform for different photon energy ranges, kinematics (different reaction mechanisms, different nucleon energies, different phase space)
- Is comparison possible with the new more detailed theories?
- Can other processes fool us? e.g. 2N+FSI

**Figure 10.** Recoil momentum distributions for $^{12}\text{C}(\gamma,np)$ for $E_{\gamma} \leq 40$ MeV presented as a ratio to the $2N$ knockout MC predictions. The plot shows data from the kinematic regions I (squares), II (triangles), and III (circles) described in the text. The solid line shows the ratio of the pair momentum distribution obtained with SRC's to that calculated without SRC’s for $^{16}\text{O}$ [8]. The dotted (dashed) lines show the ratio of the $P_{\gamma}$ distribution predicted using Hartree-Fock (Woods-Saxon) wave functions (with no SRC’s) to that using HO.
Photoinduced 3-nucleon knockout $^{12}\text{C}(\gamma,\text{ppn})$

- Comparison with Valencia model
  - Suggestion of direct 3-nucleon knockout (3N) contribution
  - Significant 2N+FSI and QF$_\pi$ +($\pi$,2N)

All include kinematic cut to suppress contribution of QF$_\pi$
• Recoil nucleon polarimetry may be possible – is it worthwhile?

• The $A(\gamma,NN)$ MAMI data may be worth revisting given the exciting advances in theory in recent years.

• Other ongoing studies - subthreshold Kaon photoproduction from nuclei.
• We are also looking at possibilities for sub-threshold Kaon photoproduction. Kaon has large mean free path – less sensitive to FSI.
Need forward angle Kaon detection (new weak sub-cluster method)
Possibility to tag isospin of struck nucleon?
\[ \gamma + p \rightarrow K^+ \Sigma^0 \] (tag with gamma from sigma decay, or proton pi0)
\[ \gamma + n \rightarrow K^+ \Sigma^- \] (Tag with pi- or neutron)
• Ratio of these reactions above and below the fermi surface?
TABLE I. Ratio $a_0:a_1:a_2$ obtained from fitting the $^{12}\text{C}(\gamma,\text{n})$ and $^{12}\text{C}(\gamma,\text{p})$ recoil momentum spectra with the combination $\sum_L a_L F_L(P)$ for two excitation regions of the residual nucleus and $E_\gamma$ regions below and through the $\Delta$ resonance. Errors in the fitted parameters are shown in brackets.

<table>
<thead>
<tr>
<th></th>
<th>$E_\gamma$</th>
<th>$E_X\leq3$ MeV</th>
<th>$3\leq E_X \leq 9$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\gamma,n)</td>
<td></td>
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</tr>
<tr>
<td>150–200</td>
<td>0.35(±0.02): 0.02(±0.13): 0.63(±0.07)</td>
<td>0.20(±0.01): 0.53(±0.13): 0.27(±0.07)</td>
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<tr>
<td>200–500</td>
<td>0.37(±0.01): 0.01(±0.10): 0.62(±0.05)</td>
<td>0.22(±0.01): 0.43(±0.08): 0.35(±0.04)</td>
<td></td>
</tr>
<tr>
<td>(\gamma,p)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150–200</td>
<td>0.11(±0.02): 0.59(±0.29): 0.30(±0.18)</td>
<td>0.06(±0.01): 0.54(±0.17): 0.40(±0.12)</td>
<td></td>
</tr>
<tr>
<td>200–500</td>
<td>0.15(±0.02): 0.16(±0.17): 0.69(±0.09)</td>
<td>0.06(±0.01): 0.62(±0.09): 0.32(±0.05)</td>
<td></td>
</tr>
</tbody>
</table>
Nucleon scattering and polarisation

\[ n(\theta,\phi) = n_o(\theta) \{ 1 + A(\theta) [P_y \cos(\phi) - P_x \sin(\phi)] \} \]

Number of nucleons scattered in the direction \( \theta, \phi \)

Polar angle distribution for unpolarised nucleons

x and y (transverse) components of nucleon polarisation

Analysing power of scatterer
The CB proton polarimeter

Data

G4 total

G4 no nuclear int

Proton scattering angle in graphite

4cm Thick Graphite Cylinder
Outer radius 97mm
40cm downstream of target

Graphite tube
Inner radius 60mm
Outer radius 95mm
Length 20cm

\[
\frac{N^+ (\phi'_p) - N^- (\phi'_p)}{N^+ (\phi'_p) + N^- (\phi'_p)} = C_x' P^c_{\gamma} A \sin \phi'_p
\]
$C_x$ - transferred poln. from circ. pol $\gamma$ : $p(\gamma,\pi^0)p$

$E_\gamma = 425$ MeV

$E_\gamma = 475$ MeV

$E_\gamma = 550$ MeV

$E_\gamma = 650$ MeV

$E_\gamma = 750$ MeV

$E_\gamma = 850$ MeV

$E_\gamma = 975$ MeV

$E_\gamma = 1225$ MeV

$E_\gamma = 1300$ MeV

Pion angle in CM (Deg)
\[ p(\gamma, \eta)p \ C_{x'} \]

*Next steps*  
\[ O_x, T, P \] also \[ p(\gamma, 2\pi) \] and \[ p(\gamma, \pi\eta) \] channels
The Crystal Ball and TAPS

**Crystal Ball**
- 672 NaI Crystals
- Stops: Protons $\sim 420$ MeV
- Chrg. $\pi$ $\sim 240$ MeV
- Kaons $\sim 341$ MeV
- Muons $\sim 233$ MeV

**TAPS**
- 384 BaF$_2$ crystals
- Stops: Protons $\sim 360$ MeV
- Chrg. $\pi$ $\sim 180$ MeV
- Kaons $\sim 280$ MeV

Particle-ID detector
EDPOL1 with CB@MAMI

Data
G4 total
G4 no nuclear int

Proton scattering angle in graphite

\( \chi^2 / \text{ndf} = 8.812 / 9 \)

\( p^0 = 0.0525 \pm 0.0068 \)
G4 – Stationary proton target: \( p(\gamma,\pi^0)p \)

Input \( A=1 \), \( Cx'=1 \), \( P\gamma(\text{circ})=1 \) into simulation.

Polarimeter efficiency \( \sim 3\% \) (probability to get a "good" scatter event).

Dilution \( \sim 20\% \).

Realistic event distribution – based on SAID PWA.
G4 – typical \((n,p)\) charge exchange: \(p(\gamma,\pi^+)n\)

- \((n,p)\) charge exchange
- Polarimeter efficiency \(\sim 1\%\)
- No multiple scattering peak

Dilution \(\sim 25\%\)
### Count rate estimate – as per PAC proposal

- **γ-flux**: $1.2 \times 10^5 \, \text{s}^{-1} \, \text{MeV}^{-1}$
- **target nuclei**: $2.1 \times 10^{23} \, \text{nuclei/cm}^2$
- **Meson det. eff**: $\pi^0 \sim 80\%$, $\eta \sim 35\%$
- **DAQ live**: $\sim 70\%$
- **Polarimeter efficiency**:
  - Prot: $3\%$
  - Neut: $1\%$ (G4)
- **$d\Omega_{avg}$ for $\theta_{\pi} \pm 10^0$**: $\sim 2 \, \text{sr}$
- **Beamtime**: 950 hours (inc. TO)

**Analyzing power**

- Prot: $\sim 0.2$
- Neut: $\sim 0.1$

**$d\sigma/d\Omega_{avg}$**

- For $\pi$: $3 \, \mu\text{b/sr}$
- For $\eta$: $0.7 \, \mu\text{b/sr}$
- For $D(\gamma,pn)$: $0.3 \, \mu\text{b/sr}$

**No. of analyzable nucleon scatters**

$$= \frac{d\sigma}{d\Omega_{avg}} \times \frac{d\Omega_{avg}}{\gamma} \times \text{nuclei} \times \text{daq} \times \text{pol eff} \times \text{meson eff} \times \text{beamtime}$$

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma:O_x/T$</th>
<th>$\sigma:C_x^I$</th>
<th>$\sigma:P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p(\gamma,p^0)p$</td>
<td>0.06</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>$n(\gamma,\eta)n$</td>
<td>------</td>
<td>0.2</td>
<td>0.14</td>
</tr>
<tr>
<td>$p(\gamma,\pi^+)n$</td>
<td>0.21</td>
<td>0.09</td>
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<td>$p(\gamma,\eta)n$</td>
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<td>0.1</td>
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For 400 hours errors would be a factor 1.55 larger

- $\Delta C_x = \sqrt{(2/A^2N)}$
- $\Delta O_x = 2/\sqrt{(A^2N)}$
- $E_{\gamma}$ bin $\pm 25$ MeV
- $\theta_{\pi/N}$ bin $\pm 10^0$
Analysing powers for $^{12}\text{C}(n,p)$ scattering

- Previous polarimeters (e.g. Yerevan) use $^{1}\text{H}(n,p)$ analysing powers for $^{12}\text{C}(n,p)$.
- Supported by recent RCNP measurements, older Saclay data, A1 at MAMI

Wakasa et. al. NIM A547 (2005) 269
NPOL3 at RCNP Cyclotron

Saclay measurements

Model (based on $^{1}\text{H}(n,p)$ Experiment $\text{CH}_2(n,p)$
$T_n \sim 400$ MeV