Compton Scattering from $^{3,4}$He using an Active Target

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Collaboration
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Obtaining the Nucleon Scalar Polarisabilities

- Differential cross section for Real Compton Scattering (RCS) on the nucleon sensitive to $\alpha$ and $\beta$

$$\sigma(\omega, \theta) = \sigma_{\text{Born}}(\omega, \theta) - \omega\omega'(\omega')^2 \frac{e^2}{m} \left\{ \frac{\alpha + \beta}{2} (1 + \cos \theta)^2 + \frac{\alpha - \beta}{2} (1 - \cos \theta)^2 \right\} + \text{higher order terms}$$

- Higher order terms contain spin polarisabilities
  
  See talk Mainz Compton programme: E.J. Downie, Friday.

- To date most of the measurements are on the proton
  
  Free proton target, relatively straightforward interpretation of data

- **Neutron data very sparse by comparison**

- $\alpha_n$ from EM scattering of thermal n from E-field of heavy nucleus
  
  ...uncertainties open to question

- Bulk of neutron polarisability info. comes from Compton on $^2\text{H}$ target

- Either quasi-free $^2\text{H}(\gamma,\gamma'n)$ scattering
  
  Or coherent $^2\text{H}(\gamma,\gamma)$
  
  Interpretation more complicated than in proton case.

- Other light nuclei possible “neutron targets”...$^3\text{He}$, $^4\text{He}$, $^6\text{Li}$
New MAX-lab Measurements of $^2$H(\(\gamma,\gamma\))

\[ \alpha_n = 11.1 \pm 1.8 \text{(stat)} \pm 0.2 \text{(BSR)} \pm 0.8 \text{(th)} \]
\[ \beta_n = 4.1 \mp 1.8 \text{(stat)} \pm 0.2 \text{(BSR)} \mp 0.8 \text{(th)}, \]

With new MAX-lab data

\[ \alpha_n = 11.55 \pm 1.25 \text{(stat)} \pm 0.2 \text{(BSR)} \pm 0.8 \text{(th)} \]
\[ \beta_n = 3.65 \mp 1.25 \text{(stat)} \pm 0.2 \text{(BSR)} \mp 0.8 \text{(th)}. \]

- Isoscalar polarisabilities. Subtract proton contribution to obtain neutron value
- Benefit from Thompson term in cross section
- Need very good \(\gamma\) energy resolution to separate non-coherent from coherent

Proton Values

\[ \alpha_p = 10.65 \pm 0.35 \text{(stat)} \pm 0.2 \text{(BSR)} \pm 0.3 \text{(th)} \]
\[ \beta_p = 3.15 \mp 0.35 \text{(stat)} \pm 0.2 \text{(BSR)} \mp 0.3 \text{(th)}, \]

D.L. Hornidge et al. PRL84(2000),2334
M. Lundin et al. PRL90(2003),192501

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Alternative Neutron Target $^3$He (or $^4$He...)

- Advantages of $Z = 2$ compared to $Z = 1$
  - Larger cross section...scales $\sim Z$ at $\omega \sim 120$ MeV
  - Larger sensitivity to polarisabilities (interference Thompson term)
- Binding energy of $^3,^4$He higher than $^2$H...can separate coherent elastic events with poorer energy resolution compared to $^2$H experiment
- He scintillates: can be used in a high-rate active target.
  - Experiment A2-01/13
    - “Compton Scattering on the He Isotopes with an Active Target”
- Theoretical treatment becomes more complicated as number of nucleons increases
  - HB$\chi$PT treatment of Compton scattering on $^3$He: D.Shulka, A. Nogga & D. Phillips Nucl. Phys, A819 (2009), 98
  - Further development (Griesshammer, Phillips and Strandberg)
- As yet no $\chi$EFT calculation of $^4$He (or $^6$Li)
- $^4$He would give a different isospin combination
- $^6$Li($\gamma,\gamma$)...HIGS data up to 60 MeV, MAX-lab data 60 – 100 MeV
Theoretical Calculations $^3\text{He}(\gamma,\gamma)^3\text{He}$

**Sensitivity to $\alpha_n$**

- Full $\mathcal{O}(e^2Q)$ calculation
- Calculation @ $\omega = 60, 80, 100, 120$ MeV
- HB$\chi$PT NLO, $\omega < m_\pi$
- $\Delta$ contributions not considered
- Sensitivity of $\sigma(\theta)$ to $\alpha_n$ and $\beta_n$
  - Increasing with increasing $E_\gamma$
  - $\sigma(\theta)$ insensitive to $\beta_n$ at $\theta_\gamma \sim 90^\circ$

**Sensitivity to $\beta_n$**

- Full $\mathcal{O}(e^2Q)$ calculation
- Calculation @ $\omega = 60, 80, 100, 120$ MeV
- HB$\chi$PT NLO, $\omega < m_\pi$
- $\Delta$ contributions not considered
- Sensitivity of $\sigma(\theta)$ to $\alpha_n$ and $\beta_n$
  - Increasing with increasing $E_\gamma$
  - $\sigma(\theta)$ insensitive to $\beta_n$ at $\theta_\gamma \sim 90^\circ$
Recent Development of $^3$He(γ,γ) χEFT Theory

H. Griesshammer, D. Phillips and B. Strandberg
Extension of Shukla at al. to include dynamical Δ terms

- Extend calculation beyond pion threshold?
- Sensitivity to polarisability increases with energy
- Theoretical interpretation more complicated above π threshold
- Opening of π⁰ channel can obscure Compton experimental signal

See also at CD2015

χEFT Treatment of Compton Scattering on $^1$H, $^2$H, $^3$He...
See talks J. McGovern, H. Griesshammer
The Active Target @ MAX-lab

- The Active Target is a detector of charged reaction products
- He gas scintillator: pressure 20 bar

**AT – Tagger Coincidence**

- Fast scintillation signal
- High rate capability
- Full intensity $\gamma$ beam
- Good timing resolution
- Clean coincidence with photon tagger

Graph showing coincidence time with mean and RMS values:
- Entries: 5811942
- Mean: 56.48 ns
- RMS: 15.17 ns

Graph showing time resolution with $\sigma = 1.15$ ns.
Comparison Measured AT energy response to MC Simulation

\[ ^4\text{He}(\gamma,n) \text{ measured at MAX-lab} \]
Active Target +
Nordball Time-of-Flight Array
Tagged photon beam
\[ E_\gamma = 10 - 65 \text{ MeV} \]

Correlation of AT total energy with TOF in external liquid scintillators
\[ \theta_n = 30, 60, 90 \text{ deg.} \]

The prominent “banana” is from \[ ^4\text{He}(\gamma,n \, ^3\text{He}) \]
Correlations between AT & external counters well reproduced by Geant-4 MC simulation
He is a linear scintillator: light output depends on energy only
A New $^{3,4}$He Compton Experiment at Mainz

The Glasgow/Mainz Photon Tagger

- Electron beam energy 180 – 1604 MeV, CW operation.
- Broad band (5 – 95% of $E_0$) Glasgow/Mainz photon tagging spectrometer
- In operation since ~1990, upgraded 2007
- Tagged photon rate: 2.5 MHz per 10 MeV wide bin of photon energy
- Plan to increase tagged beam intensity by a factor 5-10...new high-rate focal plane detector

- Use active target to detect $^3$He ions
  Target Thickness $^3$He: 0.075 g/cm²
- Crystal Ball & TAPS $4\pi$ calorimeter to detect scattered photons
- Measure range $\omega = 80 – 200$ MeV

Experiment A2-01/13
“Compton Scattering on the He Isotopes with an Active Target”
Mk3 He Active Target for Mainz

Scintillation detected by 64 SiPMT situated inside pressure vessel

- Measure $\gamma + ^3\text{He} \rightarrow \gamma + ^3\text{He}$
- $^3\text{He}$ detected in AT
- $\gamma'$ detected by CB or TAPS
- Coherent Compton cross section small
- How clean is the Compton signal?

Simulate the combined response of the AT + CB/TAPS for:
  i. Coherent Compton scattering $^3\text{He}$
  ii. Quasi-free $\gamma + ^3\text{He} \rightarrow \gamma\text{NX}$
  iii. $\gamma + ^3\text{He} \rightarrow \text{ppn} \ldots$ neutron (could mimic $\gamma$ in CB)
  iv. Coherent and QF $\pi^0$ production
The Simulated $^3$He(\(\gamma,\gamma\)) Signal

Compare measured AT kinetic energy with missing energy obtained from 4-momenta of initial \(\gamma\), target $^3$He and final $\gamma'$

\[
E_{\text{miss}} = (P_\gamma + P_{\text{targ}} - P_{\gamma'}) \rightarrow E - M_{^3\text{He}}
\]

Select Compton signal by cut on elastic scattering energy region in Crystal Ball or TAPS

Beam Energy
- 120 MeV
- 160 MeV
- 200 MeV
Simulated $^3\text{He}(\gamma,\gamma)$ Signal and Background

\[ E_{\text{balance}} = E_{\text{miss}} - E_{\text{AT}} \]

A: AT $E_{\text{balance}}$ signal for various reaction channels,
Elastic $\gamma$ energy range selected

B: Detection efficiency of corresponding reaction channels after selection coherent $E_{\text{balance}}$ peak and $T_{\text{AT}} > 1.0$ MeV

Events generated For these reaction channels

- $\gamma + ^3\text{He} \rightarrow \gamma + ^3\text{He}$
- $\gamma + ^3\text{He} \rightarrow \gamma + n + p + p$
- $\gamma + ^3\text{He} \rightarrow \gamma + p + d$
- $\gamma + ^3\text{He} \rightarrow p + p + n$
- $\gamma + ^3\text{He} \rightarrow \pi^0 + ^3\text{He}$
- $\gamma + ^3\text{He} \rightarrow \pi^0 + n + p + p$
- $\gamma + ^3\text{He} \rightarrow \pi^0 + p + d$
Projected Statistical Uncertainty $\omega = 120$ MeV

Projected uncertainties $\omega = 115 - 125$ MeV

Uncertainties
- 200 hrs of beam
- Statistical 4-7% most angles at current beam intensity
- Statistical uncertainties factor $\sim 2$ smaller with increased beam intensity
- Systematic uncertainties beam flux, target thickness $\sim 3\%$
- Systematic uncertainty QF Compton subtraction: to be determined

Analyze data in 10-MeV wide bins covering $\omega = 80 - 200$ MeV
In total $\sim 100$ data points
Degree of Constraint on \( \alpha^n, \beta^n \)

Estimate of \( \alpha^n, \beta^n \) based on \( \chi \text{EFT} \) fit to \( \gamma + d \to \gamma + d \) (Griesshammer et al.)

Units \( 10^{-4} \text{ fm}^3 \), with Baldin Sum Rule constraint

\[
\begin{align*}
\alpha_n &= 11.55 \pm 1.25 \text{(stat)} \pm 0.2 \text{(BSR)} \pm 0.8 \text{(th)} \\
\beta_n &= 3.65 \mp 1.25 \text{(stat)} \pm 0.2 \text{(BSR)} \mp 0.8 \text{(th)}.
\end{align*}
\]

29 + 23 new coherent deuteron Compton scattering points

Factors affecting accuracy of extracted \( \alpha^n, \beta^n \) from \( \gamma + ^3\text{He} \to \gamma + ^3\text{He} \)

- Absolute normalisation of differential cross section
  - Target thickness, photon flux
  - Uncertainty \( \sim 3\% \)
- Uncertainty from background subtraction (mainly at forward angle)
  - To be determined
- Fit to differential cross section \( \sigma(\omega, \theta) \)
  - Statistical uncertainties \( 2 - 4\% \) at \( \omega = 120 \text{ MeV} \) (with FPD upgrade)
  - Data at 80, 90, 100, 110, 120, 150, 160, 170, 180, 190, 200.... MeV
  - \( \sim 100^3\text{He} \) data points

**GOAL**

- Reduce statistical uncertainty in extraction of \( \alpha, \beta \) by a factor 2
- Theoretical interpretation uncertainty to be determined
- \(^4\text{He} \) expect similar “stat” uncertainty
- \( \chi \text{EFT} \) analysis not developed

Useful extra from \( \Sigma \) asymmetry? Used to separate \( \alpha^p, \beta^p \)

\[
\sigma_{\text{perp}} - \sigma_{\text{para}} : \alpha \cos^2(\theta), \sigma_{\text{perp}} - \sigma_{\text{para}} : \beta
\]
Summary

- The AT will be used at Mainz in conjunction with CB/TAPS to measure Compton scattering on He isotopes
  Experiment A2-01/13
  “Compton Scattering on the He Isotopes with an Active Target”
- Geant-4 simulations of AT + CB/TAPS suggest that clean separation of coherent Compton from background processes is possible
- 9-10 angle-point Compton differential cross section 10 MeV bin $\omega$ ($\delta\sigma(\theta) \sim 4 - 7\%$) possible in ~200 hr. Reduce statistical uncertainties by factor ~2 with new high rate tagger
- Targeted statistical uncertainty in neutron scalar polarisabilities reduced by factor ~2
- Extend $\chi$PT calculations on $^3$He($\gamma,\gamma$):
  George Washington, Ohio U., Manchester and Glasgow
- AT also suitable for coherent $\pi^0$ measurements on He isotopes...
  Mainz LOI A2-03 Hornidge et al. S-wave $n\pi^0$ amplitude $\chi$PT

Thanks for your attention
Signal for Coherent $\pi^0$ Production

Coherent $\pi^0$ Signal

Compare AT energy with that obtained from $\pi^0$ 4-momentum

$T_{\text{miss}} = (P_\gamma + P_{\text{targ}} - P_{\pi^0}) \rightarrow T$

$\omega_{\text{miss}} = T_{\text{miss}} - T_{\text{AT}}$

Select coherent $\pi^0$ signal by cut on:

$-2 < \omega_{\text{miss}} < 1 \text{ MeV}$

$T_{\text{AT}} > 1 \text{ MeV}$

$M_{\pi^0 2\gamma}$ in CB/TAPS
Backup Slides
Relative wealth of $^1\text{H}(\gamma,\gamma)$ differential cross section data, largely from Mainz.

Recent $\chi$EFT analysis
McGovern et al. EPJ A49(2013),12

$$\alpha_p = 10.65 \pm 0.35{\text{(stat)}} \pm 0.2{\text{(BSR)}} \pm 0.3{\text{(th)}}$$

$$\beta_p = 3.15 \mp 0.35{\text{(stat)}} \pm 0.2{\text{(BSR)}} \mp 0.3{\text{(th)}}$$

(BSR = Baldin Sum Rule)
Mainz work continues: proton spin polarisabilities

No free neutron target...use $^2\text{H}$, $^3\text{He}$...
Limited data set for $^2\text{H}(\gamma,\gamma)$
(Illinois, MAX-lab, SAL)

Neutron scalar polarisabilities poorly determined relative to proton
Neutron-proton differences relatively small...and potentially very interesting
But...we are a long way from quantifying these differences
Neutron Compton Scattering

- Quasi free $d(\gamma, \gamma'n)p$ measured at Mainz and SAL: determine $\alpha - \beta$
- Proton: interference between Thompson term in Born amplitude & non-Born amplitude containing the polarizabilities.
- Neutron: Thomson amplitude vanishes
- Mainz experiment $200 - 400$ MeV
  \[ \alpha_n = 12.5 \pm 1.8 \text{(stat)} \pm 1.1 \text{(th)} \]
  \[ \beta_n = 2.7 \pm 1.8 \text{(stat)} \pm 1.1 \text{(th)}, \]
- Theoretical uncertainty may be underestimated
- Alternative: coherent $^2H(\gamma, \gamma)^2H$
- Isospin averaged polarisabilities.
- Subtract proton contribution
- Benefit from Thompson term in cross section
- Need very good $\gamma'$ energy resolution to separate non-coherent
- Up to now all “neutron” Compton measurements on $^2H$

K. Kossert et al., PRL88, 162301 (2002)

An Active Target for $\gamma$+He $\rightarrow$ $\gamma$+He

Monte Carlo Simulation
Scintillation light transport
Position dependence of signal
Fold with calculated energy loss

He target is also detector of
Photo reaction products
Low energy recoil He ions detected
Coincidence with CB & TAPS
Compton Cross Section Measurement at Mainz

- 855 MeV electron beam, $\omega = 46 - 795$ MeV, $\delta \omega \sim 2$ MeV
- 1 MHz rate per tagger channel @ 120 MeV,
- 50% tagging efficiency (4mm collimator)
- Incident photon rate $0.25 \times 10^6$ per MeV

Active Target (AT) sits directly in beam at centre of CB
Remove PID and MWPC
AT insensitive to electrons generated by photon beam and to low energy background in general

- $4\pi$ electromagnetic calorimeter CB + TAPS
- Good angle and energy resolution
- AT makes primary trigger (good timing). $\sim 10$ kHz rate
- Coincidence rate $< 1$ kHz
- Demand $\geq 1$ cluster coincidence with CB or TAPS

Record Compton, $\pi^0$, $\eta$ photoproduction.
Best AT signal where recoiling He ion stops in target gas
Around 70% of started $^3$He Compton events registered within the coherent-elastic region by the AT-CB combination.

Acceptance has some angle dependence.

Small AT signal amplitude at $\theta < 20^\circ$.

Potential background contamination any channel which produces neutral.

Below $\pi^0$ threshold quasi-free Compton is the main source of background.

Breakup channels (producing neutron):
- higher cross section
- neutron efficiency 20-30% CB
- neutron pulse height in CB or TAPS much lower than scattered photon

$E_\gamma = 115 - 125$ MeV
\[ \omega = 115-125 \text{ MeV} \]
Be Window Effects
PRELIMINARY
Nucleon Scalar Polarisabilities

- Electric Polarisability $\alpha$
- Magnetic Polarisability $\beta$

- Pion cloud

- Nucleon is pretty “stiff”
  Polarisabilties come in units of $10^{-4}$ fm$^3$
- How to access: nucleon Compton Scattering incident real photon
  $\omega \sim 100 - 200$ MeV