MEASURING THE NEUTRON SPIN-POLARIZABILITIES USING COMPTON SCATTERING OFF POLARIZED ^{3}HE AT HIγS

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The High Intensity Gamma Source (HIγS) at the Duke Free Electron Laser Laboratory (DFELL) has created an opportunity to measure the spin polarizabilities of the neutron using polarized Compton scattering from a polarized ^{3}He target. An experiment is being planned to measure the spin-dependent asymmetries from Compton Scattering from circularly polarized photons from a high-pressured polarized ^{3}He gas target at quasi-elastic kinematics. The scattered photon and the recoil neutron will be detected in coincidence. The proposed beam energy is 140 MeV. We present the motivation and preliminary design of this experiment.

1. Introduction

Nucleon polarizabilities are a set of fundamental quantities that characterize the response of nucleons in an external electromagnetic field. These quantities can be accessed through low-energy Compton scattering experiments. Compton scattering from nucleons at low energy is specified by low-energy theorems up to and including terms linear in energy. These terms are completely determined by the static properties of the nucleon, i.e. the nucleon charge, mass and its anomalous magnetic moment.

The electric (α) and magnetic (β) scalar polarizabilities describe the the response of the nucleon to external electric and magnetic fields. These polarizabilities enter into second-order in photon energy. At third order four new parameters, γ_1 to γ_4, appear [1]. These additional polarizabilities, which are known as the spin polarizabilities, do not have an intuitive physical

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interpretation, but are just as fundamental as the electric and magnetic polarizabilities. The closest analogy in classical physics one can make to spin polarizabilities is the parameters that determine Faraday rotation in which the linear polarization of incoming light is rotated through a spin-polarized medium.

2. Low Energy Compton Scattering

Polarizabilities can be extracted from the low-energy Compton scattering cross-section on a nucleon $d\sigma/d\Omega = (\omega'/\omega)^2|T|^2/(8\pi M)^2$ where ω and ω' are the incident and scattered photon energies in the lab frame and M is the mass of the target nucleon. The scattering amplitude, T, for this cross-section in the center-of-mass frame (where $\omega = \omega'$) can be written

$$
\begin{aligned}
T = {} & A_1(\omega,\theta)\vec{\epsilon}'^* \cdot \vec{\epsilon} + A_2(\omega,\theta)\vec{\epsilon}'^* \cdot \hat{k}\vec{\epsilon}\cdot\hat{k}' + \\
& iA_3(\omega,\theta)\vec{\sigma}\cdot(\vec{\epsilon}'^* \times \vec{\epsilon}) + iA_4(\omega,\theta)\vec{\sigma}\cdot(\hat{k}' \times \hat{k})\vec{\epsilon}'^* \cdot \vec{\epsilon} + \\
& iA_5(\omega,\theta)\vec{\sigma}\cdot\left[(\vec{\epsilon}'^* \times \hat{k})\vec{\epsilon}\cdot\hat{k}' - (\vec{\epsilon}\times\vec{k'})\vec{\epsilon}'^* \cdot \vec{k}\right] + \\
& iA_6(\omega,\theta)\vec{\sigma}\cdot\left[(\vec{\epsilon}'^* \times \hat{k}')\vec{\epsilon}\cdot\hat{k} - (\vec{\epsilon}\times\vec{k})\vec{\epsilon}'^* \cdot \vec{k'}\right]
\end{aligned} \tag{1}
$$

where ϵ and ϵ' are the photon polarization direction vectors for the incident and scattered photons respectively, k and k' are the momentum direction vectors for the incident and and scattered photons respectively and σ is the target polarization direction vector. It is a convention to separate the pion-pole part of the amplitude from what is known as the 'regular' part of the contributions from the structure functions. When this is done the spin-dependent structure functions can be written out to third order in ω [10]

$$
\begin{aligned}
A_3(\omega,\theta)_{c.m.} = {} & \left[Q(Q+2\kappa) - (Q+\kappa)^2\cos\theta\right]\frac{e^2}{2M_N^2}\omega \\
& +4\pi\left[\gamma_1 - (\gamma_2 + 2\gamma_4)\cos\theta\right]\omega^3 + \mathcal{O}\left(\omega^4, \frac{1}{M_N^3}\right)
\end{aligned} \tag{2}
$$

$$
A_4(\omega,\theta)_{c.m.} = -\frac{(Q+\kappa)^2 e^2}{2M_N^2}\omega + 4\pi\gamma_2\omega^3 + \mathcal{O}\left(\omega^4, \frac{1}{M_N^3}\right) \tag{3}
$$

$$
A_5(\omega,\theta)_{c.m.} = \frac{(Q+\kappa)^2 e^2}{2M_N^2}\omega + 4\pi\gamma_4\omega^3 + \mathcal{O}\left(\omega^4, \frac{1}{M_N^3}\right) \tag{4}
$$

$$
A_6(\omega,\theta)_{c.m.} = -\frac{(Q+\kappa)^2 e^2}{2M_N^2}\omega + 4\pi\gamma_3\omega^3 + \mathcal{O}\left(\omega^4, \frac{1}{M_N^3}\right) \tag{5}
$$

where Q is the nucleon charge and κ is the anomalous magnetic moment of the nucleon. The amplitudes A_1 and A_2 are excluded because they lack spin-polarizability terms. For each structure function the leading order terms in the ω expansion are given by model-independent Born contributions for scattering from a spin 1/2 particle with an anomalous magnetic moment and are fixed by low-energy theorems of current algebra. Higher order terms in ω, which also contain the spin-polarizabilities, are model dependent quantities and the comparison between experiment and theory should test the validity of these approaches.

3. Previous Measurements of the Polarizabilities

While no complete set of measurements exist for the spin-polarizabilities, two linear combinations of the spin-polarizabilities have been determined. The first is $\gamma_0 = \gamma_1 - \gamma_2 - 2\gamma_4$, known as the forward polarizability, and the second is $\gamma_\pi = \gamma_1 + \gamma_2 + 2\gamma_4$, known as the backward polarizability. The backward polarizability of the neutron has been determined from unpolarized Compton scattering on deuterium and the best value is $\gamma_\pi^n = (58.6 \pm 4.0) \times 10^{-4}$ fm^4 [2].

The forward polarizability can be determined by the Gell-Mann, Goldberger and Thirring (GGT) Sum Rule [4]

$$\gamma_0 = \frac{1}{4\pi^2} \int_{\nu_0}^{\infty} \frac{d\omega}{\omega^3} [\sigma_-(\omega) - \sigma_+(\omega)], \tag{6}$$

where ν_0 is the pion production threshold and $\sigma_-(\omega)$, $\sigma_+(\omega)$ are the total photo-absorption cross-section for the total helicity of the photon-nucleon system to be 1/2 and 3/2 along the photon momentum direction, respectively. For the neutron, based on multi-pole analysis of the photo-pion production data, the best value for the forward polarizability is $\gamma_0 \; -0.38 \times 10^{-4}$ fm^4 [5].

4. Planned Experiment at HIγS

The planned experiment is a double-polarization scattering experiment of circularly polarized photons from a polarized ^{3}He target [12]. The scattered photons and the knockout neutrons will be detected in coincidence. Two configurations of the target polarization, parallel and perpendicular to the incident photon beam in the reaction plane, will be measured. These have been shown by calculations by two independent groups [6,7] to be sensitive to the spin-polarizabilities. These measurements, when combined with measurements of the forward and backward polarizabilities, provide a data set from which unique values of the four spin-polarizabilities can be extracted. This experiment will be performed at the High-Intensity Gamma Source (HIγS) which is a part of the Duke Free Electron Laser Laboratory (DFELL). The HIγS program uses Compton backscattering of UV-FEL light from electrons in the DFELL storage ring to provide circularly polarized photons with high intensity and narrow energy spread. It is possible, with planned future upgrades, the DFELL will have the capability to deliver up to 2×10^8 photons/sec at photon energies of 120-140 MeV with an energy spread of 10 MeV to the HIγS program by the time this experiment begins.

The target to be used will be a high-density gas target polarized by spin-exchange with optically polarized rubidium vapor. Such systems have been used in previous experiments and have shown to have polarizations of 40-50% [9]. The photons can be detected by a Neutral Meson Spectrometer (NMS) which consist of two sets of 60 cesium-iodide photon calorimeters each with a bismuth germinate converter. For coincident measurements, a set of BC-505 liquid scintillators used at HIγS previously, known as the 'BLOWFISH' detector [3], will be used to detect neutrons. The set-up for this proposed experiment is shown in Figure 1.

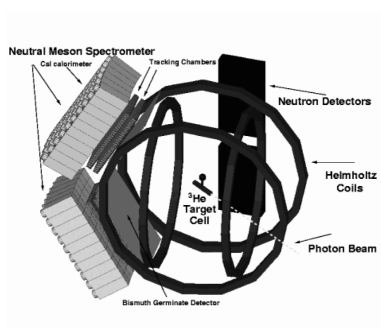

Figure 1. The proposed target and detector for measurement of the neutron spin-polarizabilities. The Helmholtz coils are used to create the magnetic field for the polarized ^{3}He target.

Initial estimates of the statistical error on the knockout neutron measurement compared with calculations by Judith McGovern [6,8] for the asymmetries show that a strong statement can be made about the four spin-polarizabilities using this kind of experiment. With a target density

6.25×10^{21} atoms/cm and and photon flux of 2×10^8 photons/sec, a target polarization of 45%, neutron detection efficiency of 25% and beam time of 500 hours in each polarization configurations a determination of γ_1, γ_3 and γ_4 for the first time can be made to a statistical precision of 0.9, 0.6 and 0.6, respectively, in the units of 10^{-4} fm^4. Given the predicted smallness of γ_2 value, the proposed experiment will provide a statistical error of 1.5, again in units of 10^{-4} fm^4, in the determination of the neutron γ_π and the neutron γ_0.

In addition to the neutron knockout measurement, one can measure the photon scattering from the ^{3}He nucleus at elastic kinematics which has an order of magnitude greater improvement in the size of the cross-section. No calculation has been completed for extracting the spin-polarizabilites for the neutron from ^{3}He nucleus, but reliable calculations should be available in the near future [11]. The elastic kinematics will be taken simultaneously with the quasi-elastic and causes no additional complications with the experiment.

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