INCLUSIVE QUASIELASTIC AND DEEP INELASTIC SCATTERING OF POLARIZED ELECTRONS BY POLARIZED $^3$He

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Abstract
A comprehensive treatement of the theoretical approach for describing nuclear effects in inclusive scattering of polarized electrons by polarized $^3$He is presented.

1. Introduction
The advent of new experimental facilities, allowing systematic measurements with polarized $^3$He and polarized electrons beams, are substantially increasing the amount of information on the electromagnetic properties of the neutron, in a wide range of the kinematical variables. As is well known, polarized $^3$He represents a good candidate as an effective neutron target [1]. The effects of nuclear structure, however, have to be carefully investigated in order to reliably extract information on the neutron from the data both in the quasielastic (qe) [2,3] and in the deep inelastic [4] region. In what follows, we will illustrate how the proton contribution affects the extraction of the neutron elastic form factors [5-7] and spin structure functions [8].

2. The polarized inclusive cross section
The inclusive cross section describing the scattering of a longitudinally polarized lepton of helicity $h = \pm 1$ by a polarized hadron of spin $J = 1/2$, is given in one photon exchange approximation by [1a]

$$\frac{d^2\sigma(h)}{d\Omega_2 d\nu} \equiv \sigma_2(\nu, Q^2, \vec{S}_A, h) = \frac{4\alpha^2}{Q^4} \frac{\epsilon_2}{\epsilon_1} m^2 L^{\mu\nu}W_{\mu\nu} = \frac{4\alpha^2}{Q^4} \frac{\epsilon_2}{\epsilon_1} m^2 \left[ L^{\mu\nu}_s W^s_{\mu\nu} + L^{\mu\nu}_a W^a_{\mu\nu} \right]$$

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where \( L^{\mu\nu}_{s(a)} \) and \( W^{s(a)}_{\mu\nu} \) are the symmetric (s) (antisymmetric (a)) leptonic and hadronic tensors, respectively. The antisymmetric hadronic tensor is given by

\[
W_{\mu\nu}^a = i\epsilon_{\mu\nu\rho\sigma} q^\sigma V^\rho
\]

where \( V^\rho \) is a pseudovector that can be expressed as follows

\[
V^\rho \equiv S_A^\rho \left( \frac{G_1^A}{M_A} + (P_A \cdot q \ S_A^\sigma - S_A \cdot q \ P_A^\sigma) \right) \left( \frac{G_2^A}{M_A} \right)
\]

In the above equations, the index \( A \) denotes the number of nucleons composing the target; \( G_1^A \) and \( G_2^A \) are the polarized structure functions; \( k_{1(2)}^i \equiv (\epsilon_{1(2)}, \bar{k}_{1(2)}) \) and \( P_A^\rho \equiv (M_A, 0) \) are electron and target four-momenta; \( q^\mu \equiv (\nu, \bar{q}) \) is the four-momentum transfer, \( Q^2 = -q^2 \); \( g_{\mu\nu} \) is the symmetric metric tensor, \( \epsilon_{\mu\nu\rho\sigma} \) the fully antisymmetric tensor and \( S_A^\mu \) the polarization four-vector (in the rest frame \( S_A^\mu \equiv (0, \bar{S}_A) \)).

The antisymmetric hadronic tensor, \( W_{\mu\nu}^a \), is constrained to the very general expression (2) by invariance principles (Lorentz, gauge, parity and time reversal invariance); moreover the antisymmetric tensor \( \epsilon_{\mu\nu\rho\sigma} \) in Eq.(2) cancels out any contribution to \( W_{\mu\nu}^a \) arising from possible terms proportional to \( q^\mu \) \( (\epsilon_{\mu\nu\rho\sigma} q^\sigma q^\beta = 0) \) in \( V^\sigma \). This fact has to be carefully taken into account once a model is adopted for obtaining the polarized structure functions [6].

The polarized structure functions \( G_1^A \) and \( G_2^A \) have to be obtained by expressing them in terms of the components of \( W_{\mu\nu}^a \). Thus, assuming in the rest frame of the target the z-axis along the momentum transfer (\( \bar{q} \equiv \bar{u}_z \)), and using Eq.(3), one has (cf. Refs.[6,7])

\[
\frac{G_1^A}{M_A} = -i \left( \frac{Q^2}{|q|^2} \frac{W_0^a}{S_{Ax}} + \frac{\nu}{|q|^2} \frac{W_1^a}{S_{Ax}} \right) \quad \frac{G_2^A}{M_A^2} = -i \frac{1}{|q|^2} \left( \frac{\nu}{|q|^2} \frac{W_0^a}{S_{Ax}} - \frac{W_1^a}{S_{Ax}} \right)
\]

It should be pointed out that in Ref.[1a] \( G_{1(2)}^A \) have been obtained by another procedure, namely using the components of the pseudovector \( V^\sigma \), Eq.(3); in this case one has

\[
\frac{G_1^A}{M_A} = \frac{(V \cdot q)}{|q|S_{Az}} \quad \frac{G_2^A}{M_A^2} = \frac{V_0}{|q|S_{Az}}
\]

Given the form (3) for \( V^\sigma \), Eq.(4) are totally equivalent to Eq.(3). However, such an equivalence will not hold if a term proportional to \( q^\mu \) is explicitly added to the r.h.s. of Eq.(3), since Eq.(4) will be unaffected by the added term, whereas Eq. (5) will be; therefore \( G_1^A \) and \( G_2^A \) obtained from Eq.(3) will not be correct in this case [6].

After contracting the two tensors in Eq.(3) one has

\[
d^2\sigma(h) = d\Omega_2 d\nu = \Sigma + h \Delta
\]

where \( \Sigma \) and \( \Delta \) describe the unpolarized and the polarized scattering, respectively. The polarized term is

\[
\Delta = \sigma_{Mott} 2 \tan^2 \frac{\theta_e}{2} \left[ \frac{G_1^A(Q^2, \nu)}{M_A} (\bar{k}_1 + \bar{k}_2) + \frac{G_2^A(Q^2, \nu)}{M_A^2} (\epsilon_1 \bar{k}_2 - \epsilon_2 \bar{k}_1) \right] \cdot \bar{S}_A
\]

Experimentally one measures the following asymmetry

\[
A = \frac{\sigma_2(\nu, Q^2, \bar{S}_A, +1) - \sigma_2(\nu, Q^2, \bar{S}_A, -1)}{\sigma_2(\nu, Q^2, \bar{S}_A, +1) + \sigma_2(\nu, Q^2, \bar{S}_A, -1)} = \frac{\Delta}{\Sigma}
\]
In order to obtain the theoretical asymmetry, one has to introduce some approximations; in particular, till now, the Plane Wave Impulse Approximation (PWIA) has been adopted. Within such a framework the polarized structure functions \( G^A_1 \) and \( G^A_2 \) are given by (cf. Refs.[6-7] for the qe case and [8-9] for the deep inelastic one)

\[
\frac{G^A_1(Q^2, \nu)}{M_1} = \sum_{N=p,n} \int dz \int dE \int d\bar{p} \frac{1}{E_p M} \left\{ \hat{G}^N_1(z, \nu, Q^2) \left[ M P^N_\parallel (|\bar{p}|, E, \alpha) + -|\bar{p}| \left( \frac{\nu}{|q|} - \frac{|\bar{p}| \cos \alpha}{M + E_p} \right) \mathcal{P}^N(|\bar{p}|, E, \alpha) \right] - \frac{Q^2}{|q|^2} L^N \right\} \delta \left( z + \frac{M^2 - p \cdot p}{2M \nu} - \frac{q \cdot p}{M \nu} \right)
\]

\[
\frac{G^A_2(Q^2, \nu)}{M_1} = \sum_{N=p,n} \int dz \int dE \int d\bar{p} \frac{1}{E_p M} \left\{ \left[ \hat{G}^N_1(z, \nu, Q^2) \left( E_p P^N_\parallel (|\bar{p}|, E, \alpha) - \frac{|\bar{p}|^2 \cos \alpha}{M + E_p} \mathcal{P}^N(|\bar{p}|, E, \alpha) \right) \right] - \frac{\nu}{|q|^2} L^N \right\} \delta \left( z + \frac{M^2 - p \cdot p}{2M \nu} - \frac{q \cdot p}{M \nu} \right)
\]

where \( E \) is the removal energy, \( p \equiv (M_1 - \sqrt{(E + M_A - M)^2 + |\bar{p}|^2}, \bar{p}) \), \( E_p = \sqrt{M^2 + |\bar{p}|^2} \) and \( \hat{G}^N_1(2, \nu, Q^2) \) are the nucleon structure functions to be used in the energy transfer region considered (cf. Sects. 4 and 5, below). The function \( L^N \) is

\[
L^N = \left[ \hat{G}^N_1(z, \nu, Q^2) \mathcal{H}^N_1 + |q| \frac{\hat{G}^N_2(z, \nu, Q^2)}{M} \mathcal{H}^N_2 \right]
\]

where \( \mathcal{H}^N_1 \) and \( \mathcal{H}^N_2 \) are proper combinations of \( P^N_\parallel (p, E, \alpha) \) and \( P^N_\perp (p, E, \alpha) \) [6], and \( \mathcal{P}^N(p, E, \alpha) = \cos \alpha P^N_\parallel (p, E, \alpha) + \sin \alpha P^N_\perp (p, E, \alpha) \). The quantities \( P^N_\parallel (p, E, \alpha) \) and \( P^N_\perp (p, E, \alpha) \), already used in a previous paper of ours [5], are related to the elements of the 2x2 matrix, representing the spin dependent spectral function of a nucleon inside a nucleus with polarization \( S_A \). The elements of this matrix are

\[
P_{\sigma, \sigma', \nu}(\bar{p}, E) = \sum_{J=1} N \left\langle \bar{p}, \sigma; \psi_{A-1}^J | \psi_{JM} \right\rangle \left\langle \psi_{JM} | \psi_{A-1}^J; \bar{p}, \sigma' \right\rangle \delta(E - E_{A-1}^J + E_A)
\]

where \( |\psi_{JM}\rangle \) is the ground state of the target nucleus polarized along \( S_A \), \( |\psi_{A-1}^J\rangle \) is an eigenstate of the \((A-1)\) nucleon system, \( |\bar{p}, \sigma\rangle_N \) is the plane wave for the nucleon \( N \equiv p(n) \).

### 4. The asymmetry in the quasielastic region

As is well known, the experiments in the qe region [2,3] are aimed at investigating the neutron elastic form factor. In this kinematical region, the nucleon structure functions \( \hat{G}^N_1(2, \nu, Q^2) \) are related to the Sachs electromagnetic form factors \( G^N_E \) and \( G^N_M \) as follows

\[
\hat{G}^N_1(z, \nu, Q^2) = -\frac{1}{\nu} \delta \left( z - \frac{Q^2}{2M \nu} \right) \frac{G^N_M}{2} \frac{(G^N_E + \tau G^N_M)}{(1 + \tau)}
\]

\[
\hat{G}^N_2(z, \nu, Q^2) = \frac{1}{\nu} \delta \left( z - \frac{Q^2}{2M \nu} \right) \frac{G^N_M}{4} \frac{(G^N_M - G^N_E)}{(1 + \tau)}
\]

with \( \tau = Q^2/(4M^2) \).
Fig. 1. The asymmetry corresponding to $\epsilon_1 = 574\text{ MeV}$ and $\theta_e = 44^\circ$, vs. the energy transfer $\nu$ calculated by Eqs. (10) and (11) (solid line) and using the spin-dependent spectral function of Ref.[5]; the dotted (dashed) line represents the neutron (proton) contribution. The nucleon form factors of Ref.[10] have been used and the experimental data are from Ref.[2]. The arrow indicates the position of the $q_e$ peak. (After Ref.[6])

By substituting Eqs.(13) and (14) in Eqs.(9) and (10) one obtains the expressions of $G_{A1}^{T}(Q^2,\nu)$ given in Ref.[6]. Present experimental results aim at measuring the quantities $R_{AT}^{L}$ and $R_{AT}^{T}$, given by

$$R_{AT}^{L}(Q^2,\nu) = 2 \sqrt{2} |q| \left( \frac{G_{1}^{A}(Q^2,\nu)}{M_{A}} + \nu \frac{G_{2}^{A}(Q^2,\nu)}{M_{A}^2} \right) = -i 2 \frac{W_{12}^{0}}{S_{Ax}}$$

$$R_{AT}^{T}(Q^2,\nu) = -2 \left( \frac{G_{1}^{A}(Q^2,\nu)}{M_{A}} - \nu \frac{G_{2}^{A}(Q^2,\nu)}{M_{A}^2} \right) = i 2 \frac{W_{12}^{0}}{S_{Ax}}$$

The interest in these quantities is due to the fact that $R_{AT}^{L}$ and $R_{AT}^{T}$, at the top of the $q_e$ peak, are proportional to $(G_{M}^{n})^2$ and $G_{E}^{n} G_{M}^{n}$, respectively, provided the proton contribution can be disregarded [2,3].

In Fig. 1 the asymmetry, measured by the MIT-Caltech collaboration [2], corresponding to $\epsilon_1 = 574\text{ MeV}$ and $\theta_e = 44^\circ$ and averaged over three different values of the polarization angles around $\theta^* \approx 90^o$, $(\cos \theta^* = \vec{S_A} \cdot \hat{q})$ is shown together with the neutron (dotted line) and proton (dashed line) contributions. It is worth noting that, in these kinematical conditions, the measured asymmetry reduces to $R_{TL}^{L}$ only at the top of the $q_e$ peak ($A_{exp}^{q_e} \propto R_{TL}^{L}$). Therefore, as previously explained, one could have access to $G_{E}^{n} G_{M}^{n}$, provided the proton contribution can be disregarded; but unfortunately, it is shown that this not the case, for the proton contribution is relevant at the top of the $q_e$ peak. A comparison with the experimental value obtained after averaging over the polarization angle and over a 100 MeV interval for the energy transfer yields

$$A_{exp}^{q_e} = 2.41 \mp 1.29 \mp 0.51 \% \; MIT - Caltech^2$$

$$A_{th}^{q_e} = 1.65 \% \; (3.74 \%)$$

The theoretical value in the brackets is obtained without averaging over the energy, i.e. at $\nu = \nu_{peak}$.

In correspondence to a different choice of kinematical variables, $\epsilon_1 = 574\text{ MeV}$ and $\theta_e = 51.1^\circ$, only one experimental point has been obtained, just for the asymmetry

$$A_{exp}^{q_e} = 4$$

Fig. 2. The total asymmetry at the top of the $q_e$ peak, vs. $Q^2$, for $\theta_e = 75^\circ$ and $\beta = 95^\circ$, using Eqs. (10) and (11). The Galster form factors [11] have been used. The curves in the lower part of the figure represent the corresponding proton contributions. (After Ref.[6])

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nucleon form factors of Ref.[11] have been used. Obtained in Ref.[7], where a spin-dependent Faddeev spectral function for finding a polarization angle \( \beta \) vanishing the proton contribution. As a matter of fact, it turns out that it is possible to minimize or even make asymmetry is sizeable. However, as shown in Refs. [5,6], one can minimize or even make asymmetry and the proton contribution are shown in Fig. 2 for different values of \( G_{M} \) for the analysis of DIS (see, e.g., Refs.[9,14]).

The results presented in Fig. 1 show that the proton contribution to the measured asymmetry is sizeable. However, as shown in Refs. [5,6], one can minimize or even make asymmetry and the proton contribution are shown in Fig. 2 for different values of \( G_{M} \) for the analysis of DIS (see, e.g., Refs.[9,14]).

It should be pointed out that our results are only slightly different from the ones obtained in Ref.[7], where a spin-dependent Faddeev spectral function for \( ^3He \) and the nucleon form factors of Ref.[11] have been used.

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In the Bjorken limit ($\nu/|\vec{q}| \to 1$, $Q^2/|\vec{q}|^2 \to 0$), the asymmetry reduces to

$$A_{||} = 2x \frac{g_1^A(x)}{F_2^A(x)}$$

and $g_1^A$ becomes a function of $g_1^N$ only; namely it reads as follows

$$g_1^A(x) = \sum_N \int_x^A dz \frac{1}{z} g_1^N \left( \frac{x}{z} \right) G^N(z),$$

with the spin dependent light cone momentum distribution for the nucleon given by

$$G^N(z) = \int dE \int d\vec{p} \left\{ P_{||}^N(p, E, \alpha) - \left[ 1 - \frac{p_{||}}{E_p + M} \right] \frac{\vec{p}}{M} P^N(p, E, \alpha) \right\} \delta \left( z - \frac{p^+}{M} \right)$$

where $p^+ = p^0 - p_{||}$ is the light cone momentum component.

The $^3\text{He}$ asymmetry (Eq. (13)) and the SSF $g_1^3$, Eq. (22), calculated in the Bjorken limit using the SSF $g_1^N$ of Ref.[15], are shown in Figs. 3a and 3b, respectively. We would like to stress the following point: the non vanishing proton contribution to the asymmetry shown in Fig. 3a hinders in principle the extraction of the neutron structure function from the $^3\text{He}$ asymmetry. It can be seen from Fig. 3b that for $0.01 \leq x \leq 0.3$ the neutron contribution, $g_1^{3,n}$, differs from the neutron structure function $g_1^n$ by a factor of about 10%; since this factor is generated by nuclear effects, one might be tempted to consider it as the theoretical error on the determination of $g_1^n$; however, it should be recalled that the difference between $g_1^n$ and $g_1^{3,n}$ is in principle model dependent through the way nuclear effects are introduced and the specific form of $g_1^n$ used in the convolution formula. In order to investigate in detail such a question, Eq. (22) has been extensively analysed in Refs.[8,9], where it has been shown that a factorized formula for $g_1^n$ (see Ref.[16] for the qe region) represents a reliable approximation of the Eq. (22) at least for $x \leq 0.9$. The factorized formula can be heuristically obtained by expanding $\frac{1}{z} g_1^N \left( \frac{x}{z} \right)$ in Eq. (22) around $z = 1$ and by disregarding the term proportional to $P^N$ in Eq. (23), which gives anyway a very small contribution, being of the order $|\vec{p}|/M$. Thus one has

$$g_1^3(x) \approx 2p_p g_1^p(x) + p_n g_1^n(x)$$

where $p_p$ and $p_n$ are the effective nucleon polarizations, produced by the $S'$ and $D$ waves in the ground state of $^3\text{He}$, and given by

$$p_N = \int dE \int d\vec{p} P_{||}^N(p, E, \alpha)$$

Our calculations yield $p_p = -0.30$ and $p_n = 0.88$ in agreement with world values $p_p = -0.028 \pm 0.004$ and $p_n = 0.86 \pm 0.02$ reported in Ref.[16]. In Fig. 4, the relevant nuclear effects, due to the effective nucleon polarizations induced by $S'$ and $D$ waves, are illustrated through the comparison between the free neutron structure function and the quantity

$$g_1^n(x) = \frac{1}{p_n} \left[ g_1^3(x) - 2p_p g_1^p(x) \right]$$

calculated using the convolution formula for $g_1^3(x)$. It can be seen that the two quantities are very close to each other, differing, because of binding and Fermi motion effects, by at most 4%. Such a small difference is rather independent of the form of any well behaved $g_1^N$ [8], and therefore Eq. (24) can be considered a workable formula for extracting $g_1^3(x)$ from the experimental $g_1^3(x)$. 
Fig. 3a. The $^3$He asymmetry [Eq. (21)] calculated within the convolution approach [Eq. (22)] (full line). Also shown are the neutron (short–dashed line) and proton (long–dashed line) contributions. (After Ref.[8])

Fig. 3b. The SSF $g_{1}^{3}$ of $^3$He (full line); also shown are the neutron (short–dashed line) and proton (long–dashed line) contributions. The dotted curve represents the free neutron structure function $g_{1}^{n}$. The difference between the dotted and short–dashed lines is due to nuclear structure effects. (After Ref.[8])

Fig. 4. The free neutron structure function $g_{1}^{n}$ (dotted line) compared with the neutron structure function given by Eq. (26) (dashed line). The difference between the two curves is due to Fermi motion and binding effects. The SSF $g_{1}^{N}$ of Ref.[15] has been used. (After Ref.[8])
6. Summary and conclusion

The analysis of the asymmetry, based on the correct expression of $G_1^A$ and $G_2^A$ given by Eqs.(11) and (12), respectively, has put in evidence: i) the relevance of the proton both in the $q_e$ [6,7] and the DIS regions [8,9], ii) the possibility of selecting a polarization angle, which leads at $q_e$ peak to an almost vanishing proton contribution for a wide range of the kinematical variables [6], and therefore making feasible the analysis of the sensitivity of the asymmetry to the electric neutron form factor; iii) the reliability of the factorized formula, represented by Eq.(24), for extracting $g_1^n(x)$ from the experimental $g_3^L(x)$.

Calculations of the final state effects are in progress.

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