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Manifestation of mixed symmetry components in the $^{3}\overrightarrow{\mathrm{He}}(\vec{e},e'p)pn$ reaction

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Abstract

The $A_{x,z}$-asymmetries of the $^{3}\overrightarrow{\mathrm{He}}(\vec{e},e'p)pn$ reaction have been calculated using different models of the *NN*-interaction which provide analytic representation of the solutions of the Faddeev equations. Strong sensitivity to the mixed symmetry components was discovered at $P_r \sim 20-60$ MeV/c. In the quasi-elastic region at $P_r \sim 0$ a large asymmetry is found to be model-independent and arises from the FSI of the spectator nucleons. © 1998 Elsevier Science B.V. All rights reserved.

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Recently the possibility of examining the ^{3}He wave function (WF) in $^{3}\overrightarrow{\mathrm{He}}(\vec{e},e'p)pn$ reaction was shown [1]. However, the sensitivity of $A_{x,z}$-asymmetries to the mixed symmetry component (S') and their dependence upon the models of strong interaction was not investigated. Also, it is not evident why such a large asymmetry was obtained in [1] at low (and zero) recoil momenta (P_r) (see Fig. 3 in [1]), without final state interactions (FSI). Since the protons in the main full symmetric configuration (S) are ''not polarized'', the PWIA-asymmetry should be very close to zero at low P_r (see below).

In this letter we will show that the large asymmetry at low P_r arises due to FSI inside spectator *pn*-pair. Moreover, this asymmetry at $P_r \sim 0$ is model-independent and may be used for the calibration of the measurements. Also we will investigate the sensitivity of asymmetries to the mixed symmetry components and different nuclear models, for which solutions of Faddeev equations with different *NN*-potentials will be used.

The S-state part of the three-body wave function (WF) may be represented [2] as:

$$\Psi(^{3}\mathrm{He})_{S-wave} = -\Psi^{s}\xi^{a} + \Psi'\xi'' - \Psi''\xi'. \qquad (1)$$

Here Ψ^{s} is the fully symmetric space S-wave component, accounting for $\sim 90\%$ of WF^{2}. Ψ', Ψ'' are the space S'-components with mixed symmetry, which indicate the deviation from the full symmetry state due to spin-momentum correlations and account for $\sim 2\%$ of the WF^{2}. The spin-isospin pieces of the WF are the fully antisymmetric ξ^{a} and the mixed symmetry ξ', ξ'' configurations. The S'-components are intriguing objects: i) their probability is strongly

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correlated with binding energy [3] as $P_{S'} \sim E_B^{-2.1}$; ii) they do not exist for the deuteron; iii) for ^{3}He they have [2] $P_{S'} \sim 1-2\%$, while for ^{4}He we can expect their strong suppression ($P_{S'} < 0.1\%$) due to the higher binding energies.

In addition to S- and S'-components, the ^{3}He WF contains P- and D-waves. The P-state probabilities are extremely small [2] ($\sim 0.1\%$) and we will not discuss them here. Various D-wave components with a total probability estimated [2] at $P_D \sim 8\%$ arise due to the tensor part of the NN-forces and become important only at high P_r (see, for instance, [1,4,5]).

For the $(e,e'p)$ channel in quasi-elastic kinematics: $\nu \sim \epsilon_3 + (m^2 + \boldsymbol{q}^2)^{1/2} - m$ (m is nucleon mass, $q = (\nu, \boldsymbol{q})$ is 4-momentum of the photon and ϵ_3 is the binding energy) proton-pole diagrams with either singlet or triplet spectator pn-pairs will dominate at low P_r. Their amplitudes are determined by two vertices $G_{t,s}$ of the ^{3}He break up with pn-pairs in the triplet ($^3\text{He} \to p + \{pn\}_t$) and singlet ($^3\text{He} \to p + \{pn\}_s$) spin states [4]:

$$G_t = (\Psi^s - \Psi'')/\sqrt{2}\,; \quad G_s = -(\Psi^s + \Psi'')/\sqrt{2}\,. \tag{2}$$

Thus, it is only owing to the S'-component that the vertices (2) are not the same.

For the main S-configuration the amplitude for production of a singlet pn-spectator pair corresponds to absorption of the photon by a proton whose spin is oriented opposite to the nuclear spin direction, while for the amplitude with a triplet spectator pn-pair another proton with its spin along the nuclear one will absorb the virtual photons. In PWIA the squares of these amplitudes (for polarized ^{3}He) will have the same magnitude, but opposite signs. As a result, PWIA asymmetries of the $^3\overrightarrow{\text{He}}(\vec{e},e'p)pn$ reaction calculated on the basis of only full symmetric configuration will be equal to zero. This reflects the fact that the protons in the S-configuration of ^{3}He WF are ‘‘not polarized’’. So, at low P_r the asymmetries in PWIA may arise only due to S'-component and we can expect their strong sensitivity to the mixed symmetry configuration. However, the magnitudes of $A_{x,z}$ should be very small, since the admixture of S' is not more than 2%.

Using the explicit form of the $^3\text{He} \to p + \{pn\}_{s,t}$ vertices [4] with polarized ^{3}He, nuclear electromagnetic (EM) currents of the proton-pole diagrams with singlet ($J_\mu^{(0)}$) and triplet ($J_\mu^{(1)}$) spectator pn-pairs may be represented (without re-scattering):

$$J_\mu^{(1)} = G_t\left[\overline{U}(p)F_\mu(\hat{p}' + m)(\gamma_\alpha + p'_\alpha/2m)\gamma_5 U_S(T)\right] \times \left[\overline{U}(p_1)(\gamma_\alpha - k_\alpha/2m)C\overline{U}^T(n)\right], \tag{3}$$

$$J_\mu^{(0)} = G_s\left[\overline{U}(p)F_\mu(\hat{p}' + m)U_S(T)\right] \times \left[\overline{U}(p_1)\gamma_5 C\overline{U}^T(n)\right]. \tag{4}$$

Here $p'(p)$ is the momentum of the observed proton before (after) photoabsorption; T and S are the target momentum and spin vectors while p_1 and n are the momenta of the un-observed proton and neutron: $q + T = p + p_1 + n$. The center of mass and relative momenta of the spectator pn-pair have the form: $P_r = p_1 + n$, $k = (p_1 - n)/2$ (in the lab. frame $\boldsymbol{P}_r = -\boldsymbol{p}'$). Furthermore, F_μ is the $\gamma p' p$-vertex, $\gamma_{\mu,5}$ are 4×4 Dirac matrices, $\hat{p} = \gamma_\mu p_\mu$; $U(p)$ is a bi-spinor and C is the matrix of charge conjugation.

The EM tensor of ultra-relativistic polarized electrons has the form:

$$l_{\mu\nu} = l_{\mu\nu}^{(0)} + \lambda l_{\mu\nu}^{(S)};$$

$$l_{\mu\nu}^{(S)} = 2i\varepsilon_{\mu\nu\gamma\delta} q_\gamma k_{1\delta},$$

$$l_{\mu\nu}^{(0)} = 2\left(k_{1\mu}k_{2\nu} + k_{2\mu}k_{1\nu}\right) + q^2 g_{\mu\nu}$$

where $k_{1(2)}$ is the momentum of initial (final) electron, $q = k_1 - k_2$, and $\lambda = 1(-1)$ corresponds to the initial electron polarization along (opposite) to its 3-momentum.

Taking the squares of (3),(4), using $\Sigma U_S(T)\overline{U}_S(T) = (\hat{T} + M_T)(1 - \gamma_5\hat{S})$ and considering low P_r (in quasi-elastic kinematics the relative momenta k will be small too: $\boldsymbol{k}^2 \sim \frac{3}{4}\boldsymbol{P}_r^2 - \boldsymbol{P}_r\boldsymbol{q}$), and neglecting the terms of order $(P_r/m)^3, (k/m)^3$, we get a factorized equation for the asymmetry of the exclusive $^3\overrightarrow{\text{He}}(\vec{e},e'p)pn$ reaction:

$$A = \kappa_p(P_r) \times A^{\vec{e}\vec{p}}\left(\boldsymbol{S}, q^2, \nu\right). \tag{5}$$

Here $A^{\vec{e}\vec{p}}(\boldsymbol{S}, q^2, \nu)$ has the meaning of the ‘‘quasi-free proton asymmetry’’:

$$A^{\vec{e}\vec{p}}\left(\boldsymbol{S}, q^2, \nu\right) = \frac{l_{\mu\nu}^{(S)} Sp\left\{(\hat{p}' + m)\hat{S}\gamma_5 \overline{F}_\nu(\hat{p} + m)F_\mu\right\}}{l_{\mu\nu}^{(0)} Sp\left\{(\hat{p}' + m)\overline{F}_\nu(\hat{p} + m)F_\mu\right\}}, \tag{6}$$

while $\kappa_p(P_r)$ may be called the ''effective proton polarization'' in $^3\overrightarrow{\mathrm{He}}$:

$$\kappa_p(P_r) = \{G_s^2 - G_t^2\}/\{G_s^2 + 3G_t^2\}. \quad (7)$$

Substituting (2) into (7), we see the quasi-elastic PWIA asymmetry of the $^3\overrightarrow{\mathrm{He}}(\vec{e},e'p)pn$ reaction are proportional to the admixture of the mixed symmetry configuration:

$$\kappa_p(P_r)_{\mathrm{PWIA}} \sim \Psi''/\Psi^s \ll 1. \quad (8)$$

The exact ''covariant PWIA'' calculations of the asymmetry are given in Fig. 1 by the dashed-dotted curves 1 and 2 for the Reid Soft Core (RSC) and the Yamaguchi-Tabakin (Y-T) potential, respectively. Without S'-components all PWIA calculations are equal to zero. So, the PWIA asymmetry is very sensitive to S'-components, but its small value (1 – 3%) reflects insignificant ''proton polarization'' (8).

Now let us examine what transpires when FSI is taken into account. At low P_r and high q the major FSI will be between the spectator nucleons, since their relative momenta k will be small due to energy-momentum conservation, while the relative momentum of the struck proton ($|\boldsymbol{p}| \sim |\boldsymbol{q}|$) with respect to the spectator pn-pair will be large enough, so that their interaction may be neglected (at least [1] at $P_r < 0.2\,\mathrm{GeV/c}$). Thus, accounting for the FSI in the spectator pn-pairs of the $^3\mathrm{He} \to p + \{pn\}_{s,t}$ vertices in this particular case simply corresponds to replacing the functions $G_{s,t}$ in Eq. (7) by the re-normalized [4] ones $G_{s,t}^{(+)}$, including additionally the loops with half-off-shell amplitudes $f_{s,t}(\boldsymbol{k}',\boldsymbol{k},E_k)$ of the elastic pn-scattering in the $^1S_0$- and $^3S_1$-states:

$$G_{s,t}^{(+)}(P,k) = \int d^3\boldsymbol{k}' \left\{ \delta(\boldsymbol{k}-\boldsymbol{k}') + \frac{1}{2\pi^2}\frac{f_{s,t}(\boldsymbol{k}',\boldsymbol{k},E_k)}{\boldsymbol{k}'^2-\boldsymbol{k}^2-i\epsilon} \right\} \times G_{s,t}(\boldsymbol{P},\boldsymbol{k}'), \quad (9)$$

First let us consider $P_r \sim 0$ (which means $|\boldsymbol{k}| \sim 0$). In this case the Migdal-Watson approximation [6] for the FSI of spectator nucleons will be available and the ''re-normalized'' vertex $G_{s,t}^{(+)}$ has the factorized form: $G_{s,t}^{(+)}(\boldsymbol{P},\boldsymbol{k}) = G_{s,t}(\boldsymbol{P},\boldsymbol{k}) \times \Delta_{s,t}(\boldsymbol{k}^2)$ with $\Delta_{s,t}(\boldsymbol{k}^2) \sim (\boldsymbol{k}^2/m + \epsilon_0^{s,t})^{-1}$ for the ''scattering length'' approximation ($\epsilon_0^{s(t)}$ is the virtual (real) level in the singlet (triplet) pn-pair). As a result of

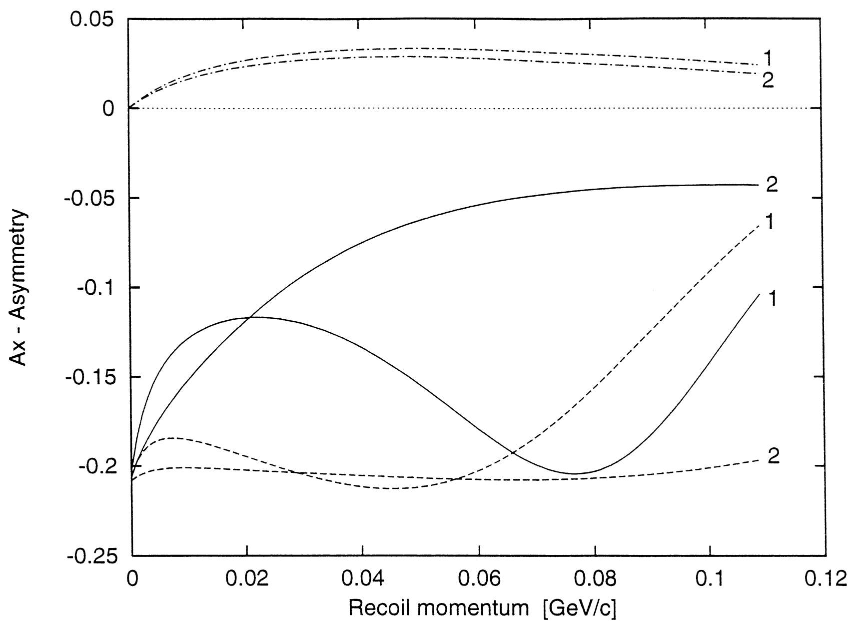

Fig. 1. The A_x-asymmetry of the $^3\overrightarrow{\mathrm{He}}(\vec{e},e'p)pn$ reaction for the Raid Soft Core potential (curves 1) and the Yamaguchi-Tabakin one (curves 2) in the collinear kinematics at $E_e = 0.88$ GeV/c and $|\boldsymbol{q}| = 0.4$ GeV/c as a function of P_r. Solid (dashed) curves reflect total calculations with $S+S'$ (S) configurations.

the strong differences of the singlet and the triplet *pn*-interaction at low energies, the main contributions in the numerator and denominator of Eq. (7) will be from Ψ^s, which will be cancelled in the ratio. So, due to the FSI between spectator nucleons the effective ''proton polarization'' will be very close to 1 ($\epsilon_0^s/\epsilon_0^t \ll 1$) at $P_r \sim 0$ and it will not depend upon the ^{3}He structure:

$$\kappa_p(P_r \to 0)_{\mathrm{PWIA+FSI}} \sim 1 - 4\epsilon_0^s/\epsilon_0^t. \qquad (10)$$

According to Eqs. (5), (6), (10), quasi-elastic asymmetries at $P_r = 0$ will be rather large (very close to the asymmetries on the free polarized proton), and practically model-independent. Thus, the polarized ^{3}He-target is a simple polarized proton target (10) if $P_r \to 0$, the same as for the $^3\overrightarrow{\mathrm{He}}(\vec{e},e'p)d$ reaction [5], except that the sign of $A_{x,z}$ in the three-body channel will be opposite. So, the asymmetry near zero recoil momentum may be used for the calibration of measurements. With increasing P_r the relative momentum $|\boldsymbol{k}|$ will quickly increase and exact Eq. (9) should be used in (7).

The asymmetry calculated according to Eqs. (3), (4) on the basis of $S + S'$ components with exact accounting of FSI inside spectator system via Eq. (9) is shown in Fig. 1 for the RSC (Y-T) potential by the solid curve 1 (2), while the same calculation, but on the basis of only the *S*-component, are given by the dashed curve 1 (2). The same NN-potentials were used to calculate the half-off-shell *pn*-amplitudes in (9), as were used in the Faddeev equations for the bound-state vertices. We see that at $P_r = 0$ there is no sensitivity of A_x to the mixed symmetry components nor to the choice of *NN*-potentials. At $P_r = 20 - 60$ MeV/c the differences of $^1S_0 - {}^3S_1$ FSI and the contribution of S'-components become comparable and their interference decreases the asymmetry considerably. It is interesting that at $P_r < 60$ MeV/c asymmetries calculated without S' for different potentials (RSC and Y-T) practically coincide. This means that the Migdal-Watson factorization is valid for $G_{s,t}^{(+)}$ up to $P_r \sim 60$ MeV/c. Then the nuclear structure will be cancelled in the ratio for $\kappa_p(P_r)$ when neglecting the S'-components, and the asymmetry is determined only by the low-energy behaviour of the singlet/triplet *pn*-interaction, which is the same for any realistic potentials. The presence of mixed symmetry components prevents the nuclear structure cancellation and changes results for various potentials in different amounts. The A_z-asymmetry has the same shape and sensitivity to S' but a factor of two smaller magnitude and we will not show it here.

In Fig. 2 the same calculations of the asymmetry

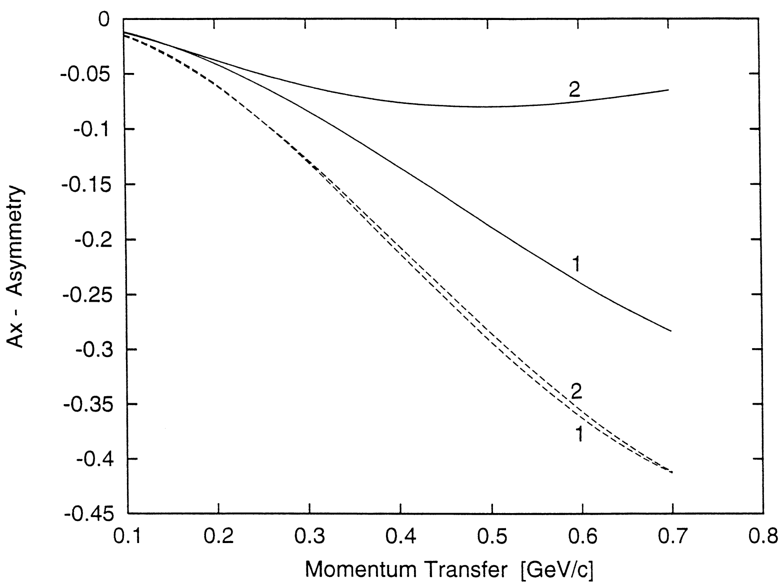

Fig. 2. The same like in Fig. 1, but as a function of $|\boldsymbol{q}|$ at $P_r = 0.04$ GeV/c.

at $P_r = 40$ MeV/c are plotted against the 3-momentum transfer $|\boldsymbol{q}|$. There is a strong sensitivity of A_x to the S'-component, which increases with $|\boldsymbol{q}|$, while the asymmetry does not depend upon the model of the full symmetric configuration, when neglecting the S'-component.

The comparison of the exact calculations with the corresponding results obtained on the basis of the factorized form (5) shows that they deffer by about of 1% at $P_r < 100$ MeV/c and can not be distinguished in Fig. 1,2. So, simple analytical, factorized representation (5) of the asymmetry in terms of the ''quasi-free proton asymmetry'' (6) and ''effective proton polarization'' (7), together with vertex re-normalization (9), is a good approximation in the quasi-elastic region at high $|\boldsymbol{q}|$ and small P_r.

To summarize, the $A_{x,z}$-asymmetries in collinear kinematics of the three-body $(e,e'p)$ break up of the polarized ^{3}He-target by polarized electrons appear to be very sensitive to the mixed symmetry component at $P_r \sim 20-60$ MeV/c. In addition, the dependence of the asymmetry on the S'-component admixture strongly increases with increasing momentum transfer, while the calculations without S' are model independent at $P_r < 60$ MeV/c. A large asymmetry of the $^3\overrightarrow{\text{He}}(\vec{e},e'p)pn$ reaction at $P_r \sim 0$ arises only due to the FSI of spectator nucleons: (i) its value is determined by only the difference of the low energy singlet/triplet pn-interaction, and (ii) it does not depend on the nuclear structure. The asymmetry is model-independent near zero recoil momentum and its value may be used for the calibration of measurements. Finally, a factorized form of the asymmetry for $^3\overrightarrow{\text{He}}(\vec{e},e'p)pn$ reaction in the quasi-elastic region was obtained.

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References

[1] J.M. Laget, Phys. Lett. B 276 (1992) 398.
[2] Ch. Hajduk et al., Nucl. Phys. A 337 (1980) 13.
[3] J.L. Friar et al., Phys. Lett. B 161 (1985) 241.
[4] S.I. Nagorny et al., Phys. of Atomic Nuclei 57 (1994) 940.
[5] S.I. Nagorny, W. Turchinetz, Phys. Lett. B 389 (1996) 429.
[6] K.M. Watson, Phys. Rev. 88 (1952) 1163; A.B. Migdal, JETP 1 (1955) 2.