ELSEVIER

19 December 1996

PHYSICS LETTERS B

Physics Letters B 389 (1996) 429–432

Manifestation of small nuclear components and current structure in the $^3\vec{\mathrm{He}}(\vec{e}, e'd)p$ reaction

S. Nagorny [a,1], W. Turchinetz [b]

[a] *Department of Physics and Astronomy, Vrije Universiteit, de Boelelaan 1081, 1081 HV Amsterdam, The Netherlands and NIKHEF, P.O. 41882, 1009 DB Amsterdam, The Netherlands*

[b] *Bates Linear Accelerator Center, Laboratory for Nuclear Science, Massachusetts Institute of Technology, P.O. 846, Middleton, MA 01949, USA*

Received 18 April 1996
Editor: W. Haxton

Abstract

The sensitivity of the $^3\vec{\mathrm{He}}(\vec{e}, e'd)p$ reaction to the nuclear and current structure has been investigated. It has been shown that $(e, e'd)$ channel provides information about the small S'- and D-components in the ^{3}He wave function, and also about isoscalar/isovector structure of the nuclear electromagnetic current. Moreover, the effects from nuclear dynamics and reaction mechanisms may be separated in special kinematics.

PACS: 25.30.Fj; 25.10.+s; 21.30.-x; 21.45.+v
Keywords: Polarized electrons; Polarized ^{3}He; Asymmetry; Mixed symmetry components; D-waves; Current conservation; Isoscalar current; Isovector current

Recently the possibility of examining the ^{3}He wave function (WF) in the reactions $^3\vec{\mathrm{He}}(\vec{e}, e'p)d$ and $^3\vec{\mathrm{He}}(\vec{e}, e'p)pn$ was shown [1]. However, the sensitivity of asymmetries to the mixed symmetry components (S') and the spin-observables for the $^3\vec{\mathrm{He}}(\vec{e}, e'd)p$ channel had not been investigated. We will show here that i) this single reaction provides information on both the small S'- and D-components in the ^{3}He WF, and ii) the $(e, e'd)$ channel is a source of information about isoscalar/isovector pieces of two-body electromagnetic (EM) currents [2] at low recoil momentum (P_r), since one-body mechanisms are strongly suppressed near the deuteron pole [2,3]. In the $(e, e'p)$ channel the two-body currents become manifest only at high P_r which makes it difficult to investigate them [4].

The S-state part of the three-body wave function (WF) may be represented [5] as:

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

Here Ψ^s is the fully symmetric space S-wave component, accounting for $\sim 90\%$ of WF [5]. Ψ', Ψ'' are the space S'-components with mixed symmetry, which indicate the deviation from full symmetry state due to the spin-momentum correlations and account for $\sim 2\%$ of WF [5]. The spin-isospin pieces of the WF are the fully antisymmetric ξ^a and the mixed symmetry ξ', ξ'' configurations [5]. The S'-components are intriguing objects: i) their probability is strongly

[1] Permanent address: National Scientific Center "KFTI", Kharkov 310108, Ukraine.

PII 0370-2693(96)01308-1

correlated with binding energy [6] as $P_{S'} \sim E_B^{-2.1}$; ii) they do not exist for the deuteron; iii) for ^{3}He they have [5] $P_{S'} \sim$ 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 [5] ($\sim 0.1\%$) and we will not discuss them here. Various D-wave components with a total probability estimated [5] at $P_D \sim 8\%$ arise due to the tensor part of the NN-forces and become important only at high P_r.

The cross-section for the $\vec{e} + {}^3\vec{\mathrm{He}} \rightarrow e' + p + d$ reaction has the general form [1,4]:

$$d^3\sigma = d^3\sigma_0\{1 + SA^0 + \lambda(A_e + SA)\}. \tag{2}$$

$d^3\sigma_0$ is the unpolarized cross section, S is the spin of the target and λ is the helicity of the electrons. A^0, A_e indicate the asymmetries produced by the polarization of only the target or only the beam, while A is the asymmetry when both the beam and the target are polarized. We will concentrate on the latter case where only two asymmetries $A_{x,z}$ ($S_x \perp \boldsymbol{q}$ and $S_z \parallel \boldsymbol{q}$) are not equal to zero in coplanar geometry:

$$A_{x,z} = \frac{d^3\sigma(\lambda = 1; S) - d^3\sigma(\lambda = -1; S)}{d^3\sigma(\lambda = 1; S) + d^3\sigma(\lambda = -1; S)}. \tag{3}$$

We will use a relativistic gauge invariant approach [7–10] which allows us to combine the requirements of covariance and current conservation with accounting of nuclear structure, final state interaction (FSI) and meson exchange current (MEC) [8,10]. But in this letter we shall restrict our examination to the minimal set of diagrams (Fig. 1), providing i) nuclear current conservation [2] and ii) a good enough description of the unpolarized cross sections for two-body photo- [2,11] and electro- [2] disintegration of ^{3}He. The details of calculations were given earlier [2,11]. The first diagram in Fig. 1a with the proton pole corresponds to the plane-wave impulse approximation [2,9]. The diagram with the deuteron pole corresponds to the quasi-deuteron model (QDM) [2], while the third diagram with the ^{3}He-pole is a part of FSI [2,9,12], stipulated by the pole piece of the $pd \rightarrow pd$ T-matrix [2,11]. The last (contact) diagram in Fig. 1a provides conservation of the isoscalar current [2]. Its amplitude is determined [2,7] by the Ward-Takahashi identities and the structure of the ^{3}He $\rightarrow pd$ vertex. The physical sense of the various contact diagrams is to provide an accounting of the interaction current [7,8] (it is MEC [8] in a meson theory) in a form consistent with nuclear dynamics [9,10] on the each level of consideration: pole-set of diagrams, one-, two-loop-sets and so on. For each of the diagrams in Fig. 1a the internal state of pn pair before and after the photoabsorption is the same: spin = 1 and isospin = 0. Thus, the isospin of pn-pair does not change during photoabsorption [2] and in this sense this current (Fig. 1a) may be called an isoscalar current.

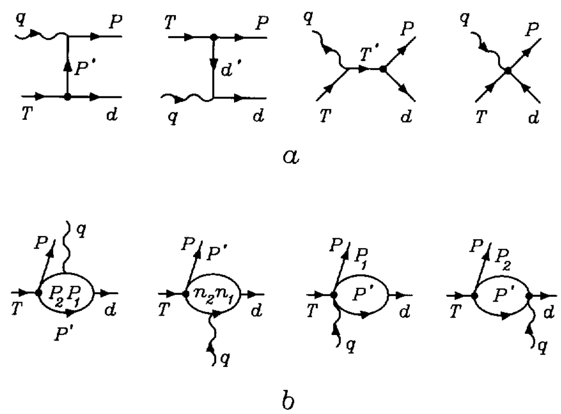

Fig. 1. Minimally necessary set of covariant diagrams providing conservation of the isoscalar (a) and isovector (b) currents.

The isovector current is given by the totality of diagrams in Fig. 1b. In this case the internal state of pn-pair before and after photoabsorption is different [2]: spin = 0 (isospin = 1) before the photoabsorption and spin = 1 (isospin = 0) after it; hence in this case the isospin of the pn-pair changes during the photoabsorption and this piece of the full current may be called an isovector current. The diagrams in Fig. 1b are gauge invariant themselves [2], since this is a purely transverse transition: ${}^1S_0 \rightarrow {}^3S_1 - {}^3D_1$. For numerical calculations we have used ^{3}He Faddeev WF's [5] for the Reid potential.

Although only the full currents in Fig. 1 are conserved, for the processes with virtual photons (contrary to the real photoabsorption) the amplitude of each diagram is gauge independent [2] and we can suppress the contributions of separate diagrams by special choice of kinematic conditions. For the $(e, e'p)$ reaction in quasi-elastic kinematics "on the proton": $\nu \sim -q^2/2m$ (where $q = (\nu, \boldsymbol{q})$ is 4-momentum of photon and m is nucleon mass) the first diagram in Fig. 1a will dominate [2] at low P_r. Its amplitude may be factorized exactly [9], and at low P_r, where only the S-wave part of the vertex $^3\text{He} \to pd$ is retained, all information about nuclear dynamics will be cancelled in the ratio (3). Then the asymmetries will be given [1] by only the proton's EM form factors and the reaction $^3\vec{\text{He}}(\vec{e}, e'p)d$ provides no information on the S'-components, which manifest themselves only at small P_r. In this case the polarized ^{3}He is a simple polarized proton target [4]. Clearly, in the main S-wave configuration two protons are in a spin singlet state and the orientation of neutron spin coincides with the nuclear spin. But the deuteron may be produced only due to the pn-pair when the proton spin direction coincides with the neutron spin orientation and, as a result, coincides with nuclear spin. Then, the proton which absorbs the virtual photon in $^3\text{He}(\vec{e}, e'p)d$ channel at low P_r has selected spin orientation - opposite to the nuclear spin.

For the $(e, e'd)$ reaction in quasi-elastic kinematics "on the deuteron": $\nu \sim -q^2/2M_d$ (M_d is the deuteron mass) it is the deuteron pole which is near the "physical" region and at low P_r the contributions of one-body mechanisms will be strongly suppressed [2,3]. Now the full amplitude will define both the isoscalar and isovector transitions, which are determined by two different amplitudes G_t and G_s of the ^{3}He three-body virtual break up with production of pn-pairs in the triplet ($^3\text{He} \to p + \{pn\}_t$) and singlet ($^3\text{He} \to p + \{pn\}_s$) spin states [2]:

$$G_t = \frac{\Psi^s - \Psi''}{\sqrt{2}}; \quad G_s = -\frac{\Psi^s + \Psi''}{\sqrt{2}}. \tag{4}$$

Due to the interference of the isoscalar and isovector transitions the cancellation of the nuclear dynamics in formula (3) is impossible, and in accordance with (4) the asymmetries in the $^3\vec{\text{He}}(\vec{e}, e'd)p$ channel will be sensitive to the S'-components.

In Fig. 2 the asymmetries $A_{x,z}$ for the $^3\vec{\text{He}}(\vec{e}, e'd)p$ channel are plotted as functions of P_r for the colinear kinematics [13]: E_e = 380 MeV and $|\boldsymbol{q}|$ = 420 MeV/c. The large effects from S'- and D-components arise in the different regions of P_r.

There is a general reason for the strong sensitivity of asymmetries, up to a change of their signs, when switching on and off the D-waves. Indeed, for the

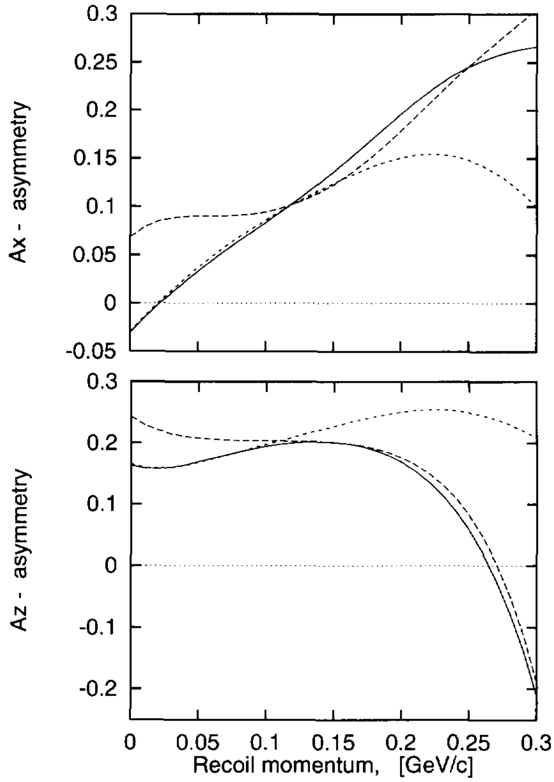

Fig. 2. Asymmetries as a functions of recoil momenta at Q = 0.420 GeV/c. The solid curves correspond to the full calculations including S-, S'- and D-states, while the long(short)-dashed ones represent the results without $S'(D)$-components.

D- components the orbital angular momentum $L = 2$ couples with the total nucleons spin $S = 3/2$ to the nuclear spin $J = 1/2$. So, in the case of D-waves the spin of all nucleons are dominantly oriented opposite to the nuclear spin, while for the S-state the spin of neuteron and one of the protons are oriented along the nuclear spin. Therefore, the triplet pn-pairs in the S- and D-states have different spin orientation in relation to the nuclear spin direction and, as a result, their contributions to the asymmetries will have opposite signs.

We see also that at 100 MeV/c $< P_r <$ 120 MeV/c there is practically no sensitivity of either asymmetry to the S'- and D-components. Thus, this interval of recoil momenta may be used for examining the isoscalar/isovector current structure. It is evident that this interval is practically model independent, as it is determined only by the composition of the partial waves in the momentum distribution functions which are very similar for different realistic potentials [3]

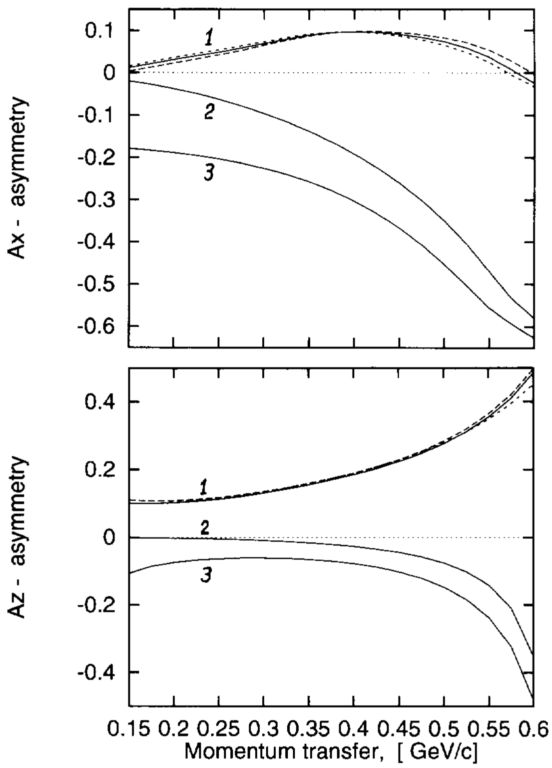

Fig. 3. Asymmetries as functions of momentum transfer at P_r = 0.110 GeV/c. The solid curve 1, short- and long-dashed curves are the calculations on the basis of the total conserved nuclear isoscalar + isovector current. But the solid line 1 reflects the results which were obtained with the full ^{3}He WF, including S-, S'- and D-states, while the long(short)-dashed lines correspond to the calculations without $S'(D)$-components. The solid curve 2 (3) is the calculation with the full ^{3}He WF, but on the basis of only deuteron-pole diagram (conserved isoscalar current).

up to 0.3 GeV/c.

In Fig. 3 the asymmetries $A_{x,z}$ for the $^3\vec{\mathrm{He}}(\vec{e},e'd)p$ reaction are plotted as functions of 3-momentum transfer at P_r = 110 MeV/c. Clearly, in this special kinematics the effects from nuclear dynamics and current structure are separated, since: 1) there is no sensitivity of $A_{x,z}$ to the small nuclear components (solid line 1, long- and short-dashed curves practically coincide) and 2) there is strong sensitivity of the both asymmetries to the structure of the nuclear current (compare solid curves 1, 2 and 3). The difference between curves 1 and 3 shows us the contribution of the isovector current, while the difference between curves 2 and 3 indicates the deviation from the QDM due to the FSI + contact current, and thus the role of isoscalar current conservation.

To summarize, spin asymmetries in the exclusive two-body $(e,e'd)$ channel of quasi-elastic scattering of polarized electrons on a polarized ^{3}He target i) appear to be very sensitive to both the small S'- and D-components, and ii) they also allow us to examine the isoscalar/isovector current structure. So, $^3\vec{\mathrm{He}}(\vec{e},e'd)p$ reaction may be a source of information about the isovector form factor of the two-nucleon system, since we deal with bound states of pn- system before and after the photoabsorpthion.

For the $(e,e'd)$ channel, even at low virtuality, as well as for the $(e,e'p)$ reaction at high P_r, the contributions from the three last diagrams in Fig. 1a are comparable [2]. So, it is important not only to take QDM, FSI and MEC into account, but it is also necessary to coordinate them exactly in the full nuclear amplitude due to the current conservation. The sensitivity of the asymmetries to different NN-potentials and the estimation of two-loop corrections, corresponding to the regular part of $pd \to pd$ T-matrix, will be the subject of future work.

This work was supported by the US Department of Energy (D.O.E.) under Grant DE-FG05-90ER40570. We would like to thank J.-M. Laget for stimulating discussions, critical reading of this manuscript and useful comments. S.N. is very grateful to MIT staff for their hospitality during the preparation of this paper.

References

[1] J.-M. Laget, Phys. Lett. B 276 (1992) 398.
[2] S.I. Nagorny et al., Phys. of Atomic Nuclei 57 (1994) 940.
[3] E. Van Meijgard and J.A. Tjon, Phys. Rev. C 42 (1990) 96.
[4] S.I. Nagorny et al., Proc. of National Conf. on Phys. of Few- Body and Quark-Hadron Systems, Kharkov, Ukraine (1992) p. 163.
[5] Ch. Hajduk et al., Nucl. Phys. A 337 (1980) 13; A.V. Blinov et al., Nucl. Phys. A 451 (1986) 701.
[6] J.L. Friar et al., Phys. Lett. B 161 (1985) 241.
[7] S.I. Nagorny et al., Sov. J. Nucl. Phys. 49 (1989) 465.
[8] S.I. Nagorny et al., Sov. J. Nucl. Phys. 53 (1991) 228.
[9] S.I. Nagorny et al., Phys. Lett. B 316 (1993) 231.
[10] S.I. Nagorny, 14th- Int. Conf. on Few-Body Problems, New-Port, USA (1994) p. 615.
[11] S.I. Nagorny et al., Sov. J. Nucl. Phys. 55 (1992) 1325.
[12] F.M. Renard et al., Nuovo Cimento 38 (1965) 565, 1688.
[13] C. Tripp et al., Phys. Rev. Lett. B 76 (1996) 885.