Physics Letters B 276 (1992) 398–402
North-Holland

PHYSICS LETTERS B

The $^3\overrightarrow{He}$ ($\vec{e}$, e′p) reactions and the components of the ^{3}He wave function

Jean-Marc Laget
Service de Physique Nucléaire, Centre d'Etudes de Saclay, F-91191 Gif-sur-Yvette, France

Received 19 September 1991; revised manuscript received 9 December 1991

Spin observables in exclusive and semi-inclusive quasi-elastic scattering of polarized electrons on a polarized ^{3}He target provides us with a powerful way to disentangle the dominant components of its wave function. However, the contributions of Final State Interactions and Meson Exchange Currents are sizeable for large values of the missing momentum, in the kinematical domain covered by the present generation of electron accelerators (virtual photon momentum of the order of 500 MeV/c). They become small when the momentum of the virtual photon is larger than 1 GeV/c.

Exclusive quasi-elastic electron scattering on few nucleon systems has already provided us with the strongest and the more direct constraints on their wave functions. Provided that Final State Interactions (FS) and Meson Exchange Currents (MEC) are fully taken into account, the analysis of the ^{3}He(e, e′p)D, ^{3}He(e, e′p)np and D(e, e′p)n reactions has led to their determination up to momentum of the order of 600 MeV/c (see ref. [1] for a review). However, in Plane Wave Impulse Approximation (PWIA) the unpolarized cross sections are directly proportional to the sum of the square of the S and D-waves. To go further, spin transfer coefficients proportional to the interference between these two waves should be determined. It is the aim of this letter to investigate to what extent the various S and D components of the ^{3}He wave function can be disentangled by the study of the $^3\overrightarrow{He}$($\vec{e}$, e′p) and $^3\overrightarrow{He}$($\vec{e}$, e′pn) reactions, and what is the size of the corrections.

The general expression of the cross section, of the (e, e′N) reaction induced by a polarized electron on a spin $\frac{1}{2}$ (nucleon or ^{3}He for instance) polarized target, can be cast in the form

$$\frac{d\sigma(h,\boldsymbol{S})}{d\Omega_e dE_e d\Omega_N dp_N} = \frac{d\sigma^0}{d\Omega_e dE_e d\Omega_N dp_N} \times [1+\boldsymbol{S}\cdot\boldsymbol{A}^0 + h(A_e + \boldsymbol{S}\cdot\boldsymbol{A}')] , \quad (1)$$

where h is the helicity of the electron, $\boldsymbol{S}$ the spin of the target, σ^0 the unpolarized cross section [2], $\boldsymbol{A}^0$ the target asymmetry when the beam is unpolarized, A_e the electron asymmetry when the target is unpolarized and $\boldsymbol{A}'$ the spin transfer asymmetry when both the beam and the target are polarized.

In a reference frame where the quantization axis Z lies along the direction of the virtual photon, the X axis lies in the nucleon emission plane (which also contains the virtual photon) and the Y axis is normal to the nucleon emission plane, the cartesian components of the spin transfer asymmetries take the following expressions:

$$\sigma^0 A'_Y = -\sqrt{\frac{-q^2\epsilon(1-\epsilon)}{2\omega^2}}\,\sigma'_{TL}(Y)\sin\phi , \quad (2)$$

$$\sigma^0 A'_{X,Z} = -\sqrt{\frac{-q^2\epsilon(1-\epsilon)}{2\omega^2}}\,\sigma'_{TL}(X,Z)\cos\phi + \sqrt{1-\epsilon^2}\,\sigma'_{TT}(X,Z) , \quad (3)$$

where ω, q^2 and ϵ are respectively the energy, the squared mass and the polarization of the virtual photon. The azimuthal angle ϕ is the angle between the electron scattering plane and the nucleon emission plane. The various transverse–transverse ($\sigma'_{\rm TT}$) and transverse-longitudinal ($\sigma'_{\rm TL}$) interference cross sections are related to the cartesian components of the nuclear current ($\boldsymbol{J}$, J_0) and the cartesian components (σ_X, σ_Y, σ_Z) of the Pauli spin matrix $\boldsymbol{\sigma}$ in the following way:

$$\sigma'_{\rm TL}(Y)=2A\,{\rm Im}\langle J^*_X\sigma_Y J_0\rangle\omega/|\boldsymbol{k}|\,, \tag{4}$$

$$\sigma'_{\rm TL}(X,Z)=-2A\,{\rm Im}\langle J^*_Y\sigma_{X,Z} J_0\rangle\omega/|\boldsymbol{k}|\,, \tag{5}$$

$$\sigma'_{\rm TT}(X,Z)=-2A\,{\rm Im}\langle J^*_Y\sigma_{X,Z} J_X\rangle\,, \tag{6}$$

where A is a phase space factor, where $\boldsymbol{k}$ is the three-momentum of the virtual photon and where the brackets stand for a shorthand notation for the average over the initial polarizations and the sum over the final polarizations (see ref. [2]). The components of $\boldsymbol{A}^0$ exhibit similar forms, which are not given here.

In an actual experiment, the X axis usually lies in the electron scattering plane: terms quadratic in sin ϕ and cos ϕ appear when the target asymmetries are expressed in this new frame.

In coplanar geometry (where the emitted nucleon lies in the electron scattering plane), $A'_Y=A^0_X=A^0_Z=0$ and only $A'_X\neq 0$ and $A'_Z\neq 0$. In PWIA $A^0_Y=0$, but $A^0_Y\neq 0$ only if FSI or MEC are taken into account: the simultaneous use of polarized target and beam is mandatory to disentangle the various components of the wave function, in kinematics where FSI and MEC contributions are small.

In collinear kinematics, where the nucleon is emitted along the direction of the virtual photon, A'_X depends only on the transverse–longitudinal interference $\sigma'_{\rm TL}(X)$ whereas A'_Z depends only on the transverse–transverse interference $\sigma'_{\rm TT}(Z)$, for symmetry reasons. This makes more easy the analysis of each spin observable: for instance, MEC contribute mainly to the transverse part of the nuclear current, but very weakly to the longitudinal one.

This appears clearly in fig. 1, where the three target asymmetries which do not vanish in collinear kinematics, are plotted against the momentum $P_{\rm R}$ of the deuteron emitted in the $^3\overrightarrow{\rm He}(\vec{\rm e},{\rm e'p}){\rm D}$ reaction. The incoming electron energy and the virtual photon three-momentum are respectively kept constant at the values $E=880$ MeV and $|\boldsymbol{k}|=400$ MeV/c, typical of the present generation of high duty factor electron accelerators (MIT-Bates, Mainz, NIKHEF, ...). If only the S-wave part of the $\langle ^3{\rm He}|{\rm D}\rangle$ overlap integral is retained, it factorizes in PWIA and the asymmetries depend only on the nucleon form factors and trivial kinematical factors [3]. When the D-wave part is also retained, their shape changes significantly and reflects the main features of the three-nucleon wave function: at $|\boldsymbol{P}_{\rm R}|=0$ the D-wave is vanishing and does not contribute; around $|\boldsymbol{P}_{\rm R}|=380$ MeV/c the S-wave exhibits a node and the two curves cross; in between, the two components interfere. Above 250 MeV/c, FSI and MEC contribute significantly and make difficult a reliable determination of the high momentum components of the D-wave. As expected, the contribution of MEC is larger in A'_Z, which depends only on the transverse components of the current. The asymmetry A^0_Y, which can be measured when the electrons

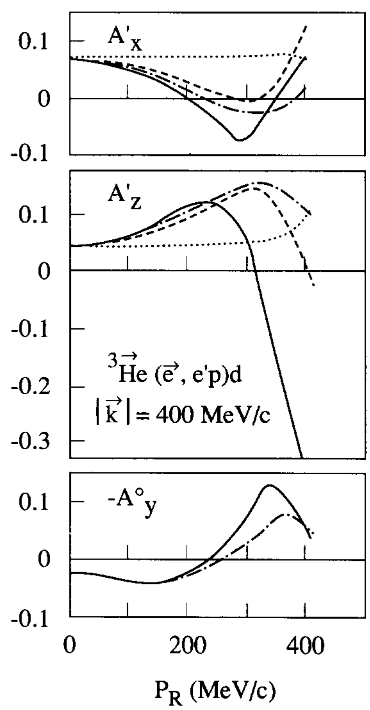

Fig. 1. The three target asymmetries, which do not vanish in collinear kinematics, are plotted against the momentum $P_{\rm R}$ of the deuteron recoiling in the reaction $^3\overrightarrow{\rm He}(\vec{\rm e},{\rm e'p}){\rm D}$. The incoming electron energy is 880 MeV. The dotted lines and dashed lines correspond to the PWIA when only the S-wave or both the S- and D-waves are respectively taken into account. The dash-dotted lines include FSI, while the full lines include also MEC.

are not polarized but the target is polarized, vanishes in PWIA and provides us with a direct measure of FSI and MEC.

They have already been an essential ingredient in the analysis of the unpolarized cross sections, and the corresponding model has already been described elsewhere [4]: let me recall its main features. It uses the expansion, up to and including terms of order $1/m^3$, of the elementary operators. All the amplitudes corresponding to one and two active nucleons are taken into account. The wave functions of ^{3}He and deuterium are respectively the solution [5] of the 18 channel Faddeev equations and the solution [6] of the Schrödinger equation for the Paris potential. Both pion and rho exchange are considered in the MEC amplitude, while the FSI amplitude employs the numerical values of the nucleon half off-shell scattering amplitudes corresponding to the Paris potential. Both FSI and MEC amplitudes involve a sixfold integral which is performed numerically. Besides a trivial dependence on the nucleon form factors, these amplitudes depend also on a transition form factor: when the momentum of the exchanged virtual photon increases, they decrease faster than the quasi-free amplitude. It is therefore mandatory to work at high momentum transfer to avoid strong FSI and MEC corrections.

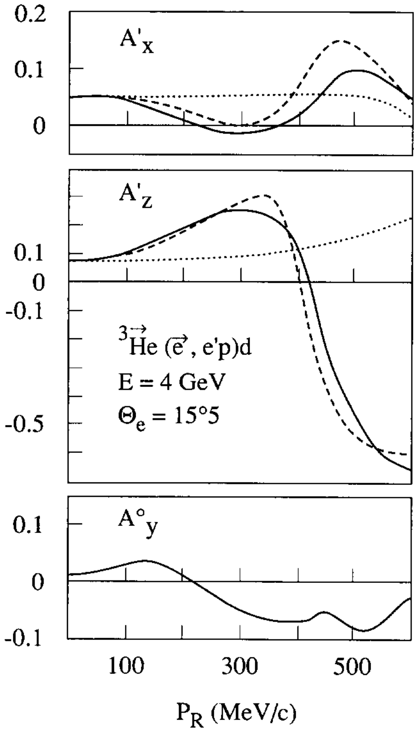

Fig. 2. The same as in fig. 1, but when the momentum of the virtual photon ranges from $|\boldsymbol{k}| = 1.15$ GeV/c (at $P_R = 0$) to 2.5 GeV/c (at $P_R = 600$ MeV/c).

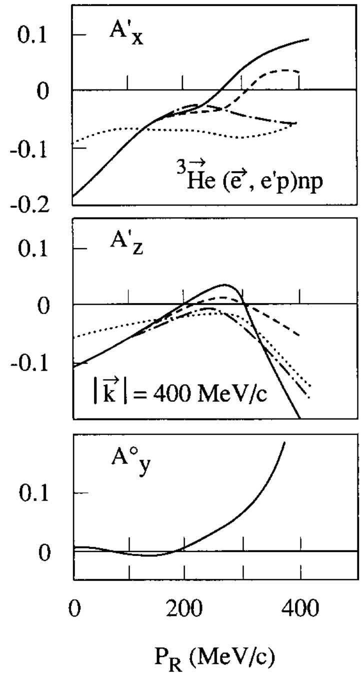

Fig. 3. The three target asymmetries, which do not vanish in collinear kinematics, are plotted against the average value of the momentum of the pn pair recoiling in the reaction $^3\vec{\text{He}}(\vec{e}, e'p)pn$. The kinematics is the same as in fig. 1. The dotted lines, the dash-dotted and the dashed lines correspond to the PWIA when only the $^1S_0$-wave, the $^1S_0$- and $^3S_1$-waves, and the S- and D-waves are respectively taken into account. The full lines include also FSI and MEC. Their relative importance is not shown – it is similar as fig. 1.

This point is illustrated in fig. 2, which again shows the variations of the three asymmetries, of the $^3\vec{\text{He}}$ $(\vec{e}, e'p)$D reaction, which do not vanish in collinear kinematics. Now the three momentum of the virtual photon exceeds 1 GeV/c: it ranges from $|\boldsymbol{k}| = 1.15$ to 2.5 GeV/c. The energy of the incoming electron is $E = 4$ GeV and the electron scattering angle is $\theta_e = 15.5°$: a kinematics which could be typically achieved at CEBAF in the future.

The study of the semi-inclusive reaction

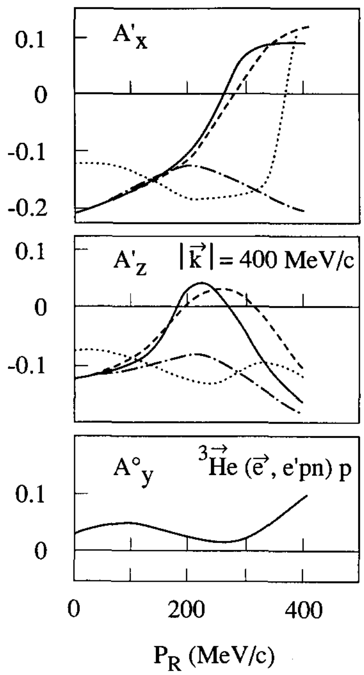

Fig. 4. The same as in fig. 3, but for the exclusive reaction $^3\overrightarrow{\mathrm{He}}(\vec{e}, e'pn)p_s$, when $p_s=0$ (disintegration of a pn pair at rest).

^{3}He(e, e'p)np has revealed a broad structure which dominates the continuum. To date it is the most convincing evidence for two body correlations in the ground state of the three-nucleon system [7]. It is mainly due to the disintegration of a proton–neutron pair mostly at rest in ^{3}He. As can be seen in fig. 3, each spin observable exhibits a different sensitivity to the $^1S_0$ and the $^3S_1 \leftrightarrow {}^3D_1$ components of the relative wave function of the active proton–neutron pair. The kinematics is the same as in fig. 1: for such a low value of the photon momentum, FSI and MEC are again sizeable.

However, in such a semi-inclusive experiment the cross sections have been integrated over the motion of the center of mass of the active pair: the result not only depends on the properties of the wave function of the pair, but also on the properties of the wave function of spectator nucleon. To go further, spin observables should be determined in the exclusive reaction $^3\overrightarrow{\mathrm{He}}(\vec{e}, e'pn)p_s$, when the momentum of the spectator nucleon p_s is vanishing: fig. 4 shows their values in such a disintegration of a proton–neutron pair really at rest in ^{3}He. The kinematics is the same as in figs. 1 and 3. The sensitivity to the D-wave is larger and the FSI and MEC contributions are smaller than in the semi-inclusive case.

All these examples concern collinear kinematics. Another way of varying the recoil momentum is to fix the kinematics of the electron and to perform an angular distribution of the emitted nucleon. If the nucleon detector is symmetric around the direction of the virtual photon (toroidal detector [8] for instance), the integration over the azimuthal angle kills all the contributions proportional to odd powers of $\cos\phi$ and $\sin\phi$: the integrated sideways asymmetry depends only on a transverse-longitudinal interference, while the longitudinal asymmetry depends only on a transverse–transverse interference, as in collinear kinematics. On the other hand, this integration enhances the acceptance of the experimental set-up: this is very important when dealing with the high momentum components of the nuclear wave function.

To summarize, spin transfer asymmetries in exclusive quasi-elastic scattering of polarized electrons on a polarized ^{3}He target appear to be very sensitive to the various components of its wave function and could provide us with a powerful way to disentangle them. However, care must be taken of FSI and MEC contributions. In the kinematical range accessible to the present generation of high duty factor electron machines, they are small only for low values of the missing momentum: above $|\boldsymbol{P}_R| = 250$ MeV/c they prevent to map out the high momentum components of the wave function in a reliable way. To achieve this goal, one must increase the value of the momentum transfered by the virtual photon: above $|\boldsymbol{k}| = 1$ GeV/c, the contribution of FSI and MEC become small enough to make less model dependent the determination of the wave function. While the corresponding measurements could be started with the existing continuous electron beams, one will have to wait for facilities like CEBAF to fully exploit their richness.

References

[1] J.M. Laget, in: Modern topics in electron scattering, eds. B. Frois and I. Sick (World Scientific, Singapore, 1991) p. 290.
[2] J.M. Laget, in: New vistas in electronuclear physics, eds. E.L. Tomusiak, H.S. Caplan and E.T. Dressler (Plenum, New York, 1986) p. 361.

[3] S. Boffi et al., Nucl. Phys. A 476 (1988) 617;
A. Picklesimer and J.W. Van Orden, Phys. Rev. C 40 (1989) 290.
[4] J.M. Laget, Phys. Lett. B 199 (1987) 493.
[5] Ch. Hajduk and P.U. Sauer, Nucl. Phys. A 369 (1981) 321.
[6] M. Lacombe et al., Phys. Lett. B 101 (1981) 139.
[7] C. Marchand et al., Phys. Rev. Lett. 60 (1988) 1703.
[8] C. Papanicolas et al., Nucl. Phys. A 497 (1989) 509c.