High Proton Momenta and Nucleon-Nucleon Correlations in the Reaction ^{3}He(*e*, *e*′*p*)

C. Marchand, M. Bernheim, P. C. Dunn,[a] A. Gérard, J. M. Laget, A. Magnon, J. Morgenstern, J. Mougey,[b] J. Picard, D. Reffay-Pikeroen, S. Turck-Chieze, P. Vernin, M. K. Brussel,[c] G. P. Capitani,[d] E. De Sanctis,[d] S. Frullani,[e] and F. Garibaldi[e]

Service de Physique Nucléaire–Haute Energie, Centre d'Etudes Nucléaires de Saclay, 91191 Gif-sur-Yvette Cedex, France

(Received 8 June 1987; revised manuscript received 15 January 1988)

Electron-scattering cross sections for the reaction ^{3}He(*e*,*e*′*p*) have been measured for recoil momenta between 300 and 600 MeV/*c* and for missing energies up to 90 MeV. Proton momentum distributions in ^{3}He, corrected for final-state–interaction and meson-exchange effects, have been obtained from 318 to 600 MeV/*c* for the *pd* channel and from 290 to 515 MeV/*c* for the *ppn* channel. Explicit evidence for nucleon-nucleon correlations is presented.

PACS numbers: 25.30.Fj, 21.30.+y, 21.40.+d, 25.10.+s

It has recently[1] become feasible to solve the nonrelativistic nuclear few-body problem with consistency and precision with use of realistic nucleon-nucleon (*NN*, *NNN*) potentials. The short- to medium-range properties of these potentials govern the strength of *NN* correlations and high-nucleon-momentum ($k \geq k_F$) components in nuclei. The (*e*,*e*′*p*) reaction can be used advantageously to probe these features,[2] since the simply interpreted plane-wave impulse approximation (PWIA) can be applied to guide the analysis and can be safely corrected for higher-order effects such as final-state interactions and meson-exchange currents.

We report in this Letter a study of the reaction ^{3}He(*e*,*e*′*p*) performed under conditions which emphasize the interaction of the electron with nucleons correlated in pairs in the ground state; the interaction in this sense mimics the two-nucleon absorption of virtual photons. Evidence for this appears in both the kinematical and dynamical aspects of the reaction.

Our measurements were made at the Saclay Linear Accelerator. Scattered electrons and ejected protons were analyzed with the 900 and 600 spectrometers, respectively, of the HE1 experimental area.[3] Particles were detected by a set of two multiwire proportional chambers, each with horizontal and vertical wires, permitting a complete reconstruction of the particle trajectories. Coincidence events were localized in a 3-ns time-of-flight window. An average beam current of 7 μA passed through a gaseous ^{3}He target (7 atm at 21 K). The empty-target background was measured and always resulted in less than a 1% contribution to the counting rate. Target thickness, detection efficiency, and solid angle determinations were checked with procedures described by Marchand *et al.*[4]

The electron kinematics [*e* (incident energy) = 560 MeV, *e*′ (scattered energy) = 360 MeV, $\theta_{e'} = 25°$] were kept constant during the experiment. The angular distribution of the ejected proton was measured in nearly coplanar kinematics at five angles, $\theta_{p'} = 45°$, 60°, 90.5°, 112°, and 142.5°. The full data set spans a range of recoil momentum P_R from 300 to 600 MeV/*c* and missing energy E_m ($E_m = M_P + M_R - M_{^3\mathrm{He}}$) from 0 to 90 [$M_R$ denotes the invariant mass of the recoiling (*np*) system], covering both the *pd* and most of the *ppn* breakup channels (Fig. 1). All data presented have been corrected for radiative effects, following de Calan and Fuchs[5]

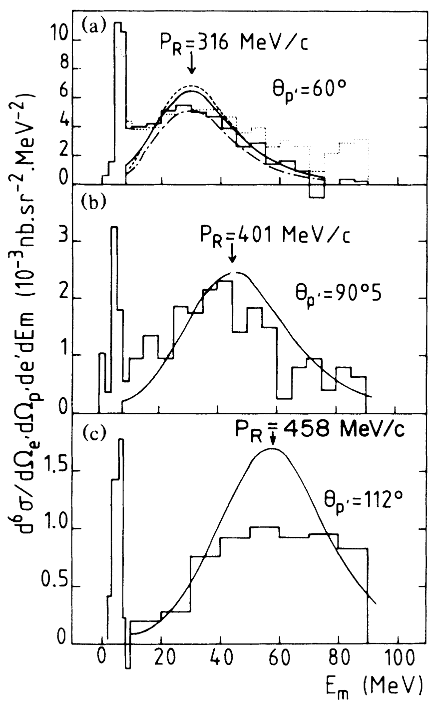

FIG. 1. Cross sections for the reaction ^{3}He(*e*,*e*′*p*) vs missing energy E_m. Dotted (solid) histograms show data before (after) radiative corrections. Curves are theoretical predictions. [Simple PWIA, dashed line; distorted-wave impulse approximation, dot-dashed line; distorted-wave impulse approximation + MEC, solid line.] Arrows locate values of $(E_m)_c$ which correspond to the indicated p_R (see text).

TABLE I. Measured cross sections (pb MeV^{-1} sr^{-2}) for the reactions $^3He(e,e'p)d$ and $^3He(e,e'p)pn$. Kinematics: $e=560$ MeV, $e'=360$ MeV, $\theta_{e'}=25°$. The errors indicate statistics only; systematic uncertainties are $\leq 7\%$. Values in parentheses are estimates of (extrapolated) strength (see text). For complete results see Ref. 7.

$\theta_{p'}$ (deg)	$^3He(e,e'p)d$ $\frac{d^5\sigma}{d\Omega_{e'}d\Omega_{p'}de'}$	$^3He(e,e'p)np$ $\int_{\Omega_p,\text{fixed}}\frac{d^6\sigma}{d\Omega_{e'}d\Omega_{p'}de'dE_m}dE_m$
45	63.9 ± 6.0	240 ± 17
60	46.9 ± 3.4	218 ± 14
90.5	12.2 ± 2.0	101 ± 8
112	6.7 ± 1.3	59 ± 5 (70)
142.5	2.3 ± 1.6	30 ± 5 (40)

for the discrete *pd* breakup and Borie and Drechsel[6] for the continuum *ppn* channel (Table I).

The missing-energy resolution, about 1.5 MeV FWHM, allowed a clear separation of the *pd* and *ppn* breakup channels. This can be seen in Fig. 1. The sharp peak at the left of each spectrum is the two-body breakup peak, whose missing energy is 5.5 MeV. To its right, above 7.7 MeV, is the three-body (*ppn*) breakup continuum. This continuum exhibits a broad peak which, after radiative corrections [see Fig. 1(a)], falls to zero at higher E_m. The peak shifts to higher missing energies with increasing recoil momentum in a characteristic fashion, as $(E_m)_c \approx P_R^2/4M_P$. Its significance is clear simply from this behavior, because this energy, $(E_m)_c$, corresponds to the breakup by the incident electron of a nucleon-nucleon (*NN*) pair whose center of mass is at rest inside the ^3He nucleus. The peak width reflects the motion of that center of mass. The peak thus signifies the absorption of virtual photons on nucleons correlated in pairs, as in the electrodisintegration of deuterons. It is notable that the peak dominates the reaction $^3He(e,e'p)$ for recoil momenta exceeding 300 MeV/*c*.

A simple and intuitive interpretation of the $(e,e'p)$ cross section is given via the PWIA wherein the cross section factorizes:

$$\frac{d^6\sigma^{\text{PWIA}}}{d\Omega_{e'}d\Omega_{p'}de'dE_m}=p'^2\frac{dp'}{dE_m}\sigma_{ep}S(p,E).$$

σ_{ep} is the (off shell) electron-proton cross section,[8] and $S(p,E_m)$ is the so-called proton spectral function, which gives the probability of our finding a proton of momentum p in the nucleus with a separation energy corresponding to E_m. p' denotes the momentum of the ejected proton. The proton momentum distribution is obtained by the integration of $S(p,E_m)$ over E_m: $n(p) = \int S(p,E_m)dE_m$. In PWIA, $p=p_R$, and $\int_0^\infty 4\pi n(p) \times p^2 dp = Z$. For ^3He, $n(p)$ has two components: $n_2(p)$ for the two-body breakup and $n_3(p)$ for the continuum three-body breakup.

Laget[9] has improved on the PWIA by incorporating contributions from final-state interactions (FSI) and meson-exchange currents (MEC). The curves in Fig. 1 show his calculated cross sections for the continuum breakup channel as a function of missing energy. The accord with the data confirms in the dynamics what was suggested by the kinematics; in the calculations most of the calculated strength arises from the electron's interaction with nucleons correlated in pairs in the ^3He ground state. MEC, although appreciable, do not [Fig. 1(a)] play the major role and in fact tend to be canceled by FSI.

Figure 2 displays cross sections for the two-body breakup channel, the curves showing that FSI and MEC effects tend to cancel below $p=400$ MeV/*c*. However,

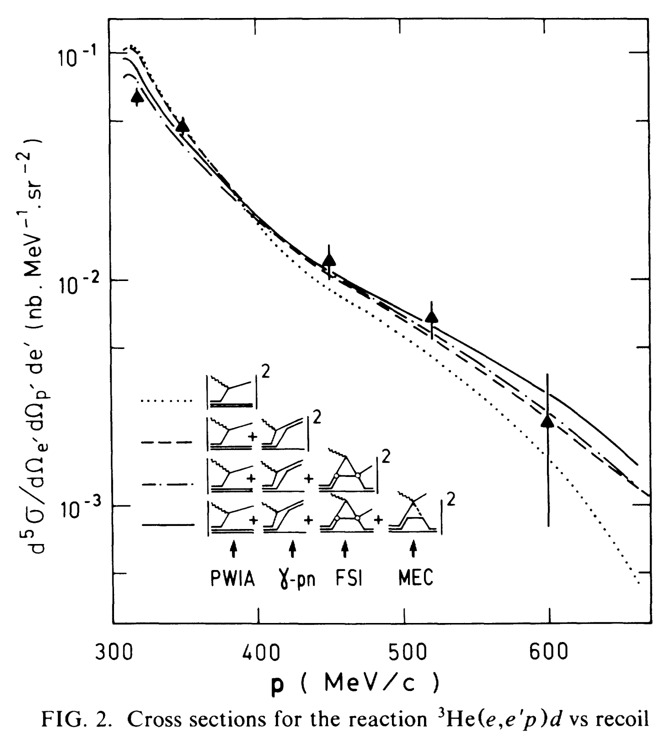

FIG. 2. Cross sections for the reaction $^3He(e,e'p)d$ vs recoil momentum. Solid curve signifies calculation (Ref. 9) with MEC and FSI, based on ^3He wave function of Ref. 10; other curves show partial calculations (see inset).

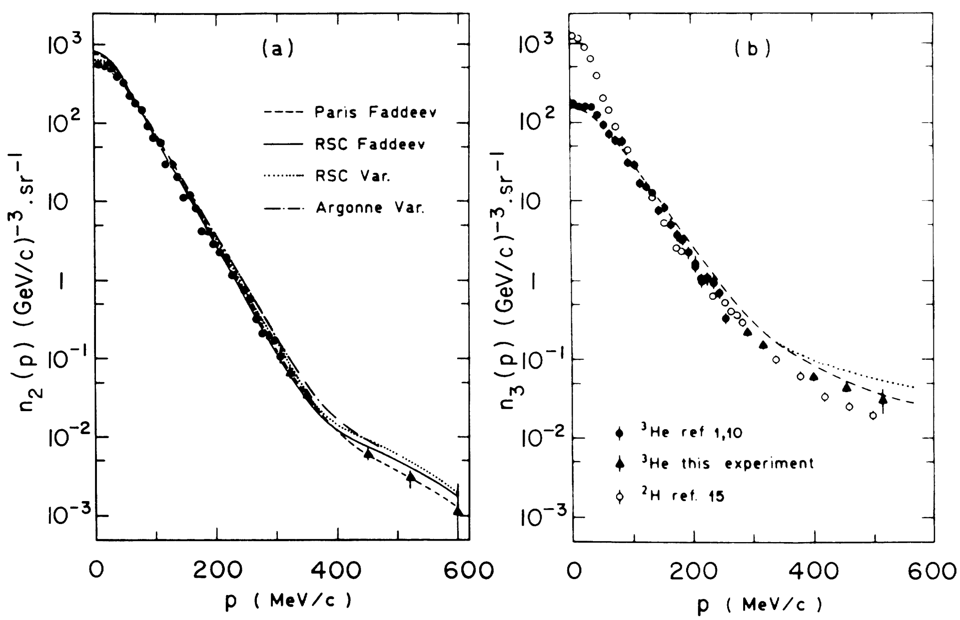

FIG. 3. Proton momentum distributions from the reactions (a) ^{3}He$(e,e'p)d$ and (b) ^{3}He$(e,e'p)np$. (b) shows also the distribution from the electrodisintegration of ^{2}H (Ref. 12). The curve for Ref. 13 up to 300 MeV/c overlaps the Paris-Faddeev curve.

above 500 MeV/c, corrections[9] to PWIA exceed 40%, principally arising from the coupling of the virtual photon to a proton of a correlated np pair (see inset). This is an effect analogous to the three-body breakup result discussed above, the difference being only that no dissociation of the interactive pair occurs, and it is the spectator proton which is detected. Such a process has been directly observed in a ^{3}He$(e,e'd)$ experiment by Keizer *et al.*,[11] and is well reproduced by the model.

Momentum distributions can be extracted from the measured cross sections in the PWIA context if MEC and FSI are taken into account. This has been done by our correcting the measured cross sections by the difference between a full calculation, including meson exchange and FSI, and the PWIA calculation. The corrections are relatively insensitive to the choice of the ^{3}He wave function. We thus arrive at "experimental" momentum distributions: $n_2(p)$ for $318 \le p \le 600$ MeV/c, and $n_3(p)$ for $290 \le p \le 515$ MeV/c. Values are shown in Table II, and are plotted in Fig. 3 with similarly modified data of Jans *et al.*[14] The error bars reflect the statistical uncertainties in the experimental data alone.

Also shown in Fig. 3 are curves from calculations of Meier-Hajduk *et al.*,[15] who solve the Faddeev equations numerically in momentum space with Reid soft-core (RSC) and Paris potentials, and Ciofi degli Atti, Pace, and Salme[16] and Schiavilla, Pandharipande, and Wiringa,[13] who solve the nonrelativistic Schrödinger equation variationally. The former use the RSC potential and a trial wave function expanded on a harmonic-oscillator basis; the latter use the Argonne + Model-VII potential, including three-body forces and a correlated Jastrow-type trial wave function.

Figure 3(b) shows the continuum proton momentum distribution $n_3(p)$. For the two data points beyond p $=400$ MeV/c, an extrapolation (assuming a Gaussian shape) of the measured cross sections above $E_m=90$ MeV was made in order to recover strength experimentally inaccessible (about a 10% correction; see Fig. 1). The theory curves tend to be above the experimental points at high momentum, but further study of the PWIA and corrections to it in the continuum is desirable before we draw definitive conclusions. However, we remark in passing that a renormalization of the calculations by a factor $1+[p/(285\ \text{MeV}/c)]^{2.5}$, cited by Sick, Day, and McCarthy[17] to remove the disagreement between the PWIA and measured ^{3}He(e,e') *inclusive* cross sections, would completely destroy the overall agreement observed here. The disagreement for the inclusive experiment[17] is therefore probably due to defects in the PWIA rather than to a lack of high-nucleon-momentum components in the ^{3}He ground-state wave function.

In order to obtain a different perspective, in Fig. 3(b)

TABLE II. Proton momentum distributions n_2 and n_3 in (GeV/c)$^{-3}$ sr^{-1}. For other information, see caption for Table I.

p	$n_2(p)$	$\langle p \rangle$	$n_3(p)$
318	67 ± 5	290	220 ± 16
350	35.9 ± 2.3	315	151 ± 10
450	6.1 ± 1.2	400	57 ± 7
521	3.1 ± 0.9	455	35 ± 3 (42)
600	1.13 ± 1.5	515	21 ± 4 (29)

we have also displayed the proton momentum distribution for the deuteron.[12] Corrections to the PWIA were applied as before. The similarity of the ^{3}He and ^{2}H distributions at high momenta (where the ^{3}He/^{2}H ratio is close to the number of $T=0$ np pairs in ^{3}He, i.e., $\frac{3}{2}$) suggests that the higher-momentum components in ^{3}He are governed by NN correlations, an interpretation consistent with and reinforcing our interpretation of the continuum bump of Fig. 1. In the deuteron, the D state dominates the wave function for $p \gtrsim 0.3$ GeV/c. The diminishing slope of the ^{3}He data (Fig. 3) above 0.3 GeV/c is reminiscent of this effect.

It is difficult to choose between the theoretical curves of Fig. 3. They all fit the data quite well. Although the Faddeev–Paris-potential calculation appears to follow the data better above 300 MeV/c, it is too high for momenta close to zero for $n_2(p)$, a consequence of the underbinding of ^{3}He. It is unclear whether it would be above the high-momentum data, as are the other curves, if renormalized (e.g., by the addition of three-body forces) to fit better at zero. At 500 MeV/c, the Faddeev-RSC calculation exceeds that of the Faddeev-Paris result by about 25%, deriving from the larger D-state component in the RSC ^{3}He wave function.[10]

To summarize, our study of the reaction ^{3}He $(e,e'p)$ associates the high-nucleon-momentum components (≥ 300 MeV/c) in the ^{3}He wave function with the absorption of virtual photons on nucleons correlated in pairs in the ^{3}He ground state. Overall agreement between theory and experiment for momentum distributions obtains. No obvious anomaly appears at high momentum in either the two- or three-body breakup channels. Further refinements of the reaction theory relating to the final-state continuum are needed before we evaluate the discrepancies that remain between theory and experiment.

[a]Present address: Bates Linear Accelerator Center, Middleton, MA 01949.

[b]On leave at CEBAF, Newport News, VA 23606.

[c]Permanent address: Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801.

[d]Permanent address: Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, 00044 Frascati, Italy.

[e]Permanent address: Laboratori di Fisica and Istituto Nazionale di Fisica Nucleare, Sezione Sanità, Istituto Superiore di Sanità, 00161 Roma, Italy.

[1]For example, Few-Body Syst., Suppl. 2 (1987), and Nucl. Phys. **A463**, Nos. 1,2 (1987).

[2]S. Frullani and J. Mougey, *Advances in Nuclear Physics*, edited by J. W. Negele and E. Vogt (Plenum, New York, 1984), Vol. 14.

[3]Ph. Leconte *et al.*, Nucl. Instrum. Methods **169**, 401 (1980).

[4]C. Marchand *et al.*, Phys. Lett. **153B**, 29 (1985).

[5]C. de Calan and G. Fuchs, Nuovo Cimento **38**, 1594 (1965).

[6]E. Borie and D. Drechsel, Nucl. Phys. **A167**, 369 (1971).

[7]C. Marchand *et al.*, Centre d'Etudes Nucléaires de Saclay Report No. CEA-N 2528, 1987 (to be published).

[8]T. de Forest, Nucl. Phys. **A392**, 232 (1983).

[9]J. M. Laget, Phys. Lett. **151B**, 325 (1985); J. M. Laget, Few-Body Syst., Suppl. 1, 271 (1986); J. M. Laget, in *New Vistas in Electronuclear Physics*, edited by E. Tomusiak *et al.* (Plenum, New York, 1986), p. 361.

[10]Ch. Hajduk and P. U. Sauer, Nucl. Phys. **A369**, 321 (1981).

[11]P. H. M. Keizer *et al.*, Phys. Lett. **157B**, 255 (1985).

[12]M. Bernheim *et al.*, Nucl. Phys. **A365**, 349 (1981); S. Turck-Chieze *et al.*, Phys. Lett. **142B**, 145 (1984).

[13]R. Schiavilla, V. R. Pandharipande, and R. B. Wiringa, Nucl. Phys. **A449**, 219 (1986).

[14]E. Jans *et al.*, Phys. Rev. Lett. **49**, 974 (1982); E. Jans *et al.*, Nucl. Phys. **A475**, 687 (1987).

[15]H. Meier-Hajduk *et al.*, Nucl. Phys. **A395**, 332 (1983).

[16]C. Ciofi degli Atti, E. Pace, and G. Salme, Phys. Lett. **141B**, 14 (1984).

[17]I. Sick, D. Day, and J. S. McCarthy, Phys. Rev. Lett. **45**, 871 (1980).