Mechanism of the Reaction ^{4}He$(e,e'd)^2$H

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The cross section for the ^{4}He$(e,e'd)^2$H reaction has been measured as a function of the four-momentum transfer q at a missing momentum of 125 MeV/c. The data show that this reaction cannot be described as quasielastic knockout of a deuteron. In a microscopic description of the $(e,e'd)$ cross section, assuming a direct knockout mechanism, the q dependence reflects the p-n relative wave function in ^{4}He. However, even a calculation in this framework using a realistic ^{4}He wave function does not describe the data, indicating that other reaction mechanisms play a non-negligible role.

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Single-nucleon densities $\rho_1(\mathbf{r})$ within the nucleus have been extensively investigated by stripping and pickup reactions as well as knockout reactions. In particular the $(e,e'p)$ reaction proved to be very instrumental to study these densities [1-4]. In contrast, information about nucleon correlations, i.e., the two-nucleon density function [5] $\rho_2(\mathbf{r}_1,\mathbf{r}_2)$, is very scarce. The $(e,e'd)$ reaction can yield information on this two-nucleon density function. Indeed, the d-^{4}He momentum distribution in the ground state of ^{6}Li could be determined using the ^{6}Li$(e,e'd)$ reaction [6]. Since ^{4}He is a very dense and tightly bound nuclear system, where the effect of correlations will be relatively large and for which extensive microscopic calculations are available [7-9], we also studied the ^{4}He$(e,e'd)^2$H reaction.

Although the electromagnetic interaction mainly takes place with a single nucleon, the momentum-transfer dependence of the ^{6}Li$(e,e'd)^4$He(g.s.) cross section was observed [6,10], after correcting for distortion effects, to be the same as that of elastic electron scattering from a free deuteron. This indicates that the "deuteron cluster" in ^{6}Li can be quantitatively regarded as a (quasi)free deuteron. In view of the tight binding (small size) of ^{4}He and the small binding (large size) of a free deuteron it is certainly not obvious that the ^{4}He$(e,e'd)^2$H reaction can likewise be described in terms of a quasielastic-scattering mechanism.

In this Letter we present the results of a measurement of the ^{4}He$(e,e'd)^2$H cross section as a function of the four-momentum transfer q and compare the obtained data with the results of both a quasielastic and a microscopic approach to describe the ^{4}He$(e,e'd)^2$H reaction.

The ^{4}He$(e,e'd)$ experiment was performed at the NIKHEF-K electron-scattering facility [11] at an incident electron energy of 460 MeV with beam currents between 5 and 15 μA. A cryogenic target system [12] was used at an operating temperature of 20 K and a pressure of 400 kPa, resulting in a target density of 10 mg/cm^3. The effective length of the target, viewed by the spectrometers at 90°, amounts to 2.3 cm. The target thickness, which varies as a function of the dissipated power, could be related within an accuracy of 2% to measurements of the elastic-electron-scattering cross section by use of the simultaneously measured proton singles rates (see also Ref. [12]). The measurements were performed at a fixed d-d center-of-mass energy of 35 MeV, keeping the missing-momentum acceptance region $100 < p_m < 150$ MeV/c constant. The values of the four-momentum-transfer squared q^2 were 1.75, 2.49, 3.36, and 4.79 fm^{-2}. An excitation-energy spectrum for $q^2 = 1.75$ fm^{-2} is shown in Fig. 1. The measured cross sections are shown in Fig. 2. The systematical error on these cross sections is smaller than 7%.

Assuming quasielastic knockout and only an S-wave component in the ^{4}He$\rightarrow d+d$ vertex, the coincidence

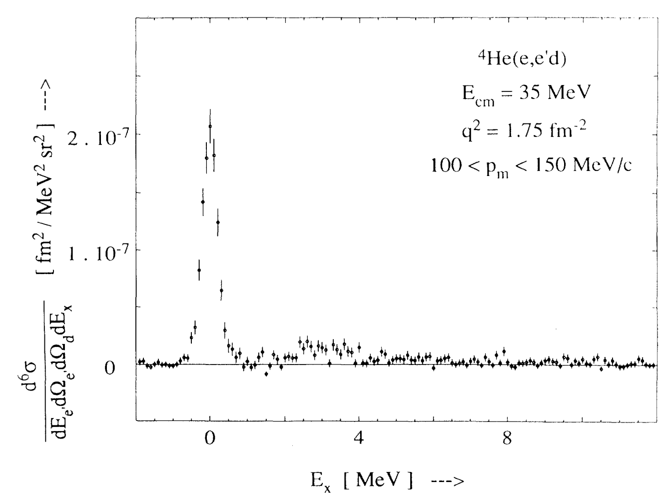

FIG. 1. Excitation-energy spectrum of the ^{4}He$(e,e'd)$ reaction.

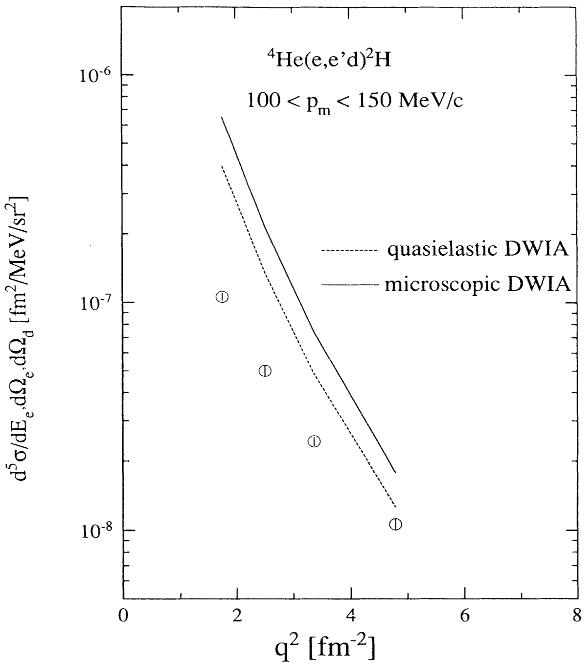

FIG. 2. Measured cross sections for the reaction ^{4}He($e,e'd$)^{2}H as a function of the momentum-transfer squared. The dashed curve is the result of the quasielastic-scattering calculation; the solid curve is the result of the microscopic calculation. Both curves have been corrected for distortion effects (see text).

cross section can, in analogy to the $(e,e'p)$ reaction, be factorized in the plane-wave impulse approximation (PWIA) as [13,14]

$$\frac{d^6\sigma}{d\mathbf{e}'d\mathbf{p}}=K\sigma_{ed}S(E_m,\mathbf{p}_m)\,, \tag{1}$$

where $\mathbf{e}'$ is the momentum of the scattered electron, $\mathbf{p}$ that of the outgoing deuteron, K a kinematical factor, S the spectral function [15], and σ_{ed} the electron-deuteron cross section. Final-state-interaction (FSI) effects can be approximated by replacing $S(E_m,\mathbf{p}_m)$ with the distorted spectral function $S^D(E_m,\mathbf{p}_m,\mathbf{p})$.

If the reaction proceeds via quasielastic knockout, the cross section as a function of q should follow the free-electron-deuteron cross section. We first focus on this aspect. The measured ^{4}He($e,e'd$)^{2}H cross sections are compared in Fig. 2 with the predicted behavior of $K\sigma_{ed}$. For the calculation of the spectral function we used the d-d bound-state wave function (BSWF) of Ref. [9], which results from a variational calculation with the Reid soft-core potential. Although the d-d center-of-mass energy is kept constant, the predicted behavior had to be corrected for FSI effects, as the angle between $\mathbf{p}$ and $\mathbf{p}_m$ changes. These were calculated with the factorized $(e,e'X)$ distorted-wave impulse approximation code PEEP [16], using the mentioned BSWF [9], and a d-d optical potential constructed by a double-folding procedure, using the Jeukenne-Lejeune-Mahaux effective nucleon-nucleon interaction [17,18]. The strength of this optical potential was adjusted to describe measured d-d elastic cross sections [19]. The FSI reduces the spectral function at $p_m=125$ MeV/c with a factor of 3.1 for the lowest value of q^2, and a factor of 2.1 for the highest value of q^2.

The conclusion from the above comparison is that the measured cross sections cannot be described using the free-electron-deuteron cross section. Because this cross section depends on the relative wave function of the p-n pair inside the deuteron [20,21], the reason may be that in the ^{4}He($e,e'd$)^{2}H reaction the electron is scattered from a p-n pair that is smaller than a free deuteron, as the size of ^{4}He is smaller than that of a free deuteron. Therefore we will now consider a microscopic treatment of the ^{4}He($e,e'd$)^{2}H reaction, in which such features are accommodated.

We describe the interaction of the electron with the nucleus ^{4}He as the sum of the one-body interactions with the nucleons. Taking for simplicity only charge interaction into account the transition matrix element for the ^{4}He($e,e'd$)^{2}H reaction in the PWIA contains the factor

$$M_{fi}=\langle\phi_d(\mathbf{r}_1-\mathbf{r}_2)\phi_d(\mathbf{r}_3-\mathbf{r}_4)e^{-i\mathbf{p}_m\cdot(\mathbf{r}_1+\mathbf{r}_2)/2}e^{i(\mathbf{p}_m+\mathbf{q})\cdot(\mathbf{r}_3+\mathbf{r}_4)/2}|\sum_{i=1}^{4}e_iF_p(q)e^{i\mathbf{q}\cdot\mathbf{r}_i}|\Psi_{^4\mathrm{He}}\rangle\,, \tag{2}$$

where r_i indicates the position of nucleon i, and e_i is its charge, while the proton form factor $F_p(q)$ reflects the finite size of the proton (we have only sketched the transition matrix element and left out details on quantum numbers). The internal deuteron wave function is denoted with ϕ_d and the fully antisymmetrized ^{4}He wave function with Ψ. The sixfold $(e,e'd)$ cross section can be written in terms of M_{fi} as

$$\frac{d^6\sigma}{d\mathbf{e}'d\mathbf{p}}=K\sigma_{\mathrm{Mott}}|M_{fi}|^2\,. \tag{3}$$

We can obtain a qualitative idea of the effects caused by the difference between the p-n pair in ^{4}He and the p-n pair in a free deuteron by writing the wave function of ^{4}He as a product of a deuteron wave function and an overlap wave function between a deuteron and ^{4}He [9]. This overlap function can be written as a product of a bound-state wave function and an internal wave function of the p-n pair. If one takes only S-wave components into account and neglects antisymmetrization the sixfold $(e,e'd)$ coincidence cross section can then be easily rewritten as

$$\frac{d^6\sigma}{d\mathbf{e}'d\mathbf{p}} = K\sigma_{\text{Mott}}|\langle\phi_d(\mathbf{r})|F_p(q)e^{i\mathbf{q}\cdot\mathbf{r}/2}|\phi_{pn}(\mathbf{r})\rangle|^2 S(E_m,\mathbf{p}_m)\,, \quad (4)$$

where $\phi_{pn}(\mathbf{r})$ is the internal wave function of the p-n pair inside ^{4}He, with $\mathbf{r}$ the relative coordinate of the p-n pair, while $S(E_m,\mathbf{p}_m)$ contains the BSWF. From Eq. (4) it can be seen that if $\phi_{pn}(\mathbf{r})$ is equal to the internal wave function of a free deuteron $\phi_d(\mathbf{r})$ (the quasielastic-scattering assumption), the transition form factor

$$|\langle\phi_d(\mathbf{r})|F_p(q)e^{i\mathbf{q}\cdot\mathbf{r}/2}|\phi_{pn}(\mathbf{r})\rangle|$$

reduces to the deuteron charge form factor and Eq. (1) is recovered. Hence one would expect that if $\phi_{pn}(\mathbf{r})$ has a smaller radial extension than $\phi_d(\mathbf{r})$, the transition form factor has a shallower dependence on q^2.

The ^{4}He$(e,e'd)^2$H cross section has been calculated according to Eqs. (2) and (3), using full ^{2}H and ^{4}He wave functions including D-wave components and antisymmetrization. The ^{4}He wave function was calculated in the method called amalgamation of two-body correlation into the multiple-scattering process [22], where the correlations between the nucleons due to a Reid soft-core V8 model nucleon-nucleon potential are included in the trial wave functions in terms of two-body correlation wave functions. Different on-shell and off-shell two-body correlation functions are taken into account in this model.

The measured cross sections are compared with the ones calculated in this microscopic model in Fig. 2. Since in Eq. (2) the relative motion of the two deuterons in the final state is described as a plane wave, we corrected for distortion effects as described before.

The data are not described by the microscopic model either. In fact, the dependence on q^2 of the microscopic description does not differ much from the quasielastic-scattering description. An explanation for this surprising result is given in Fig. 3, where the deuteron charge form factor is compared to the charge transition form factor (only S-wave components taken into account). At $q^2=0$ the derivative of the latter is smaller than that of the deuteron charge form factor, which is caused by the smaller rms radius of the p-n pair inside ^{4}He. Also, the absolute normalization of the transition form factor at $q^2=0$ is not equal to unity, since the overlap of the p-n pair in ^{4}He and the free deuteron is not perfect. However, at high q^2 the behavior of both form factors is almost equal. Apparently the relative nucleon-nucleon wave function at short distances is not influenced by the presence of the other nucleons in ^{4}He.

The basic conclusions derived from Fig. 3 are not influenced by including D-wave components: They increase the absolute value of the cross section, but hardly change the dependence on q^2.

Compared to the data, not only the dependence on q^2, but also the absolute magnitude is off (see Fig. 2). The difference in absolute magnitude between the two calculations has two origins: About half is due to the difference between the deuteron form factor and the transition form factor (see Fig. 3), while the other half is due to an interference effect that results from the inclusion of the D states in both ^{2}H and ^{4}He. This interference is clearly not taken into account in the factorized quasielastic description.

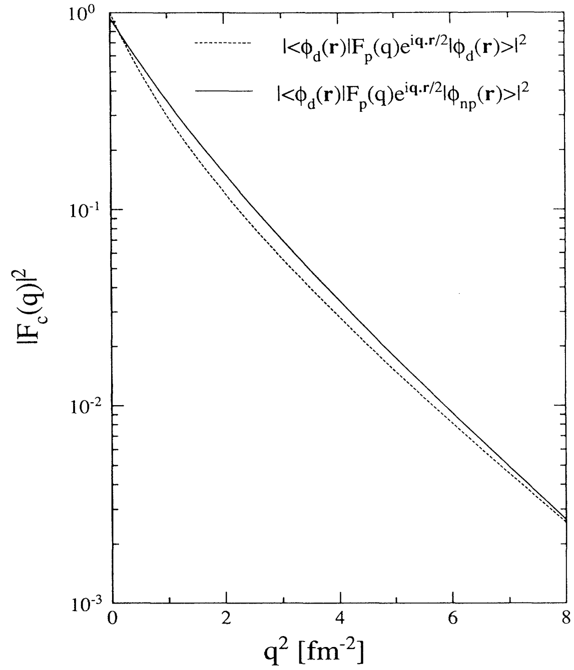

FIG. 3. Comparison of the deuteron (monopole) charge form factor with the transition form factor of Eq. (4) (only S-wave components taken into account).

Therefore the question is what causes the discrepancy between the microscopic ^{4}He$(e,e'd)^2$H calculations and the data. One can claim that the ^{4}He wave function used is not perfect, as, for instance, the binding energy of ^{4}He is not reproduced correctly, which may be related to the neglect of a three-nucleon interaction. However, this probably cannot explain the large discrepancy, since the calculated p-t and d-d momentum distributions [9] are not so much different from the variational calculations of Ref. [8], in which a three-nucleon interaction is included. In fact, use of the d-d wave function of Ref. [8] instead of that of Ref. [9] in a quasielastic-scattering calculation yields cross sections that are only (10–20)% lower. Antisymmetrization, where the recoil deuteron is detected and the momentum transfer is given to the undetected deuteron, is taken into account by using the completely antisymmetrized ^{4}He wave function. Anyway, this is only a small effect in our kinematics. Since our data are primarily longitudinal ($>95\%$), we also do not believe that the assumption of charge scattering only influences our results significantly. The calculation of the FSI effects with an optical potential introduces some uncertainties, but calculations with different optical potentials that give acceptable descriptions of the measured d-d elastic scattering [19] indicate that this influences mainly the absolute magnitude (by up to 30%) and hardly the dependence on q^2 (less than 10%).

The fact that both the calculated absolute magnitude and the shape are quite far from the data indicates, in our opinion, the contribution of another (destructively interfering) reaction mechanism. Calculations by Keizer *et al.* [23] for the ^{3}He$(e,e'd)$ reaction, which include the effects of two-body currents and final-state interactions beyond elastic rescattering, suggest that these effects may indeed reduce the cross sections. Since our data were taken in mainly longitudinal kinematics, large effects from two-body currents are not expected. The discrepancy may be due to the influence of final-state interactions of the type $(e,e'p)(p,d)$. However, if this would explain the discrepancy, it is not clear why the role of these two-step processes is not visible in the ^{6}Li$(e,e'd)^4$He(g.s.) reaction.

In summary, we have shown that it is not allowed to extract cluster spectroscopic information from a cluster knockout reaction just using a free-projectile-cluster interaction, since the relative wave function of the nucleons in the cluster may change during the reaction. With a microscopic direct knockout model, which takes this change into account, the ^{4}He$(e,e'd)^2$H cross section as a function of q^2 could still not be described. It seems that other reaction mechanisms play a non-negligible role.

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