Reaction ^{6}Li$(e,e'd)^4$He and the α-d Momentum Distribution in the Ground State of ^{6}Li

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The α-d momentum distribution in the ground state of ^{6}Li has been measured in parallel kinematics with the reaction ^{6}Li$(e,e'd)^4$He in the momentum range $0 < p_m < 270$ MeV/c. The reaction can be described by a direct coupling of the virtual photon to a deuteron in ^{6}Li. The results agree well with the predictions of a three-body αNN model of ^{6}Li.

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Correlations between nucleons bound in a nucleus play an important role in nuclear physics, e.g., in alpha decay and in pion absorption. Although single-nucleon densities have been studied extensively with stripping and pickup reactions and more recently with the $(e,e'p)$ reaction,[1] little is known about two- (or more-) nucleon density functions. Some information has been obtained from knockout reactions with hadrons, especially from the (p,pd) reaction.[2] However, the results of such experiments are hard to interpret because of both uncertainties in the reaction mechanism and distortion effects in the entrance and exit channels.[3] Electron-induced knockout reactions, like $(e,e'd)$, suffer from fewer uncertainties because the electromagnetic interaction which drives the reaction is known, and the only important distortion effects occur between the hadronic particles in the final state.

The only $(e,e'd)$ measurements with a reasonable energy resolution have been performed on ^{6}Li at Saclay[4] and on ^{3}He at the National Instituut voor Kernfysica en Hoge-Energiefysica Sektion K (NIKHEF-K).[5] However, the energy of the outgoing deuterons in the ^{6}Li experiment was rather low, resulting in large rescattering effects, and only a limited momentum range was investigated. In the experiment reported here we have studied the reaction ^{6}Li$(e,e'd)^4$He at higher deuteron energies with good resolution over a large momentum interval and have compared the extracted α-d momentum distribution with model predictions.[6]

The ^{6}Li nucleus is an excellent candidate for such a comparison because the tight binding of ^{4}He and the small separation energy between the α and the deuteron in ^{6}Li suggest a description of this nucleus as an α-d cluster or as an αpn three-body system. In either approach the Pauli principle plays an important role. In cluster models antisymmetrization leads to an effective α-d wave function that has a $2S$ form, i.e., a wave function that possesses a node, independent of whether the relative-motion wave function is chosen to have $1S$ (no node) or $2S$ character before antisymmetrization.[7] Likewise, three-body models of ^{6}Li, which go beyond cluster-model and resonating-group work[7,8] in that the dynamics are not reduced to effective two-body dynamics, predict an effective S-wave α-d wave function of the $2S$ form.[9–11] The structure of this wave function is reflected in the α-d momentum distribution in ^{6}Li. Thus a determination of this distribution constitutes a test of three-body models of ^{6}Li.

If one assumes that the virtual photon couples quasielastically to the deuteron[5] and that one can neglect the D-wave component in the $^6\mathrm{Li}\rightarrow \alpha + d$ vertex,[6,9,11] the coincidence cross section for the $(e,e'd)$ reaction in the plane-wave impulse approximation (PWIA) can be written[12] as

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

where $\mathbf{e}'$ is the momentum of the outgoing electron, $\mathbf{p}$ is the momentum of the outgoing deuteron, K is a kinematical factor, and σ_{ed} is the elastic electron-deuteron cross section, corrected for the (small) off-shell effects according to the current-conservation prescription of de Forest.[13,14] The dependence of the cross section on σ_{ed} will be discussed below. The spectral function $S(E_m,p_m)$ is the probability of finding a deuteron with energy $-E_m$ and momentum p_m in the target nucleus. For a transition to a bound state one can define the momentum density distribution $\rho(p_m) = \int_{\Delta E_m} S(E_m, p_m) dE_m$, which is the Fourier transform of, in our case, the effective α-d wave function $\Psi_{\alpha\text{-}d}(R)$:

$$\rho(p_m) = \left| \int e^{-i\mathbf{p}_m \cdot \mathbf{R}} \Psi_{\alpha\text{-}d}(R) d\mathbf{R} \right|^2, \tag{2}$$

where R is the α-d relative coordinate.

Inclusion of the interaction between the deuteron and the α particle in the final state can be incorporated approximately by the change of ρ in Eq. (2) into the distorted momentum distribution $\rho^D(\mathbf{p}_m, \mathbf{p})$, which now also depends on the momentum of the outgoing deuteron. The distortions can be described by replacement of the plane wave for the deuteron, which is used in Eq. (2), by an optical-model wave function.

The ^{6}Li$(e,e'd)$ experiment was performed at the NIKHEF-K electron accelerator. The experimental setup, which includes two magnetic spectrometers, was the same as has been used for $(e,e'p)$ experiments.[15] Identification of the outgoing deuterons and rejection of other particles was accomplished by pulse-height discrimination in two scintillators behind the multiwire drift chambers in the focal plane of the hadron spectrometer. The target was a self-supporting foil of thickness 13.0 mg/cm^2, enriched to 98.7% in ^{6}Li. The energy of the incoming electrons was 480 MeV. The range in missing momentum covered in the experiment was $-50 < p_m < 270$ MeV/c, with parallel kinematics ($\mathbf{p} \parallel \mathbf{q}$, $p_m = p - q$). The outgoing deuteron energy was such as to yield an α-d center-of-mass energy $E_{\text{c.m.}}$ of 45 MeV for the data with p_m up to 120 MeV/c, 55 MeV for $120 < p_m < 230$ MeV/c, and 70 MeV for $120 < p_m < 270$ MeV/c.

The data analysis included subtraction of accidental coincidences and unfolding of the radiative tail (see Ref. 15 for details). An E_m spectrum for $80 < p_m < 120$ MeV/c is shown in Fig. 1. Except for the peak corresponding to the ground state of ^{4}He, the spectrum is consistent with zero up to the breakup threshold of ^{4}He. The resolution is 250 keV, which is almost completely due to variation in energy loss in the target. The momentum distribution for the transition to the ground state of ^{4}He is shown in Fig. 2. The curves are the results of calculations in which we used the "repulsive" α-d wave function of Parke and Lehman.[11] (Using the "attractive" wave function of Ref. 11 gives an almost equivalent, though slightly poorer, description.) The PWIA curve shows a maximum at $p_m = 0$ and a minimum (at $p_m = 145$ MeV/c) characteristic of a 2S-type wave function. The other curves are the results of distorted-wave impulse-approximation (DWIA) calculations for the relevant deuteron energies. Because our data were obtained at different values of $E_{\text{c.m.}}$, we used the global optical-model parameter set of Hinterberger *et al.*[16] As can be seen from the difference between the PWIA and DWIA curves, distortion effects are relatively small at low p_m. This can be understood from the fact that the data at small p_m are sensitive mainly to the wave function at large values of R, where the optical-model potential (OMP) is weak. However, at larger p_m the minimum which exists in the PWIA curve is almost completely filled in because the contributions from the nuclear interior, which are responsible for the minimum, are strongly suppressed by the absorptive part of the OMP. The overall agreement in shape between the data and the DWIA calculation is rather good. It seems that a little more strength around $p_m = 0$ is needed in the calculation. In this region use of a different OMP changes the calculated cross sections by only a few percent, while in the

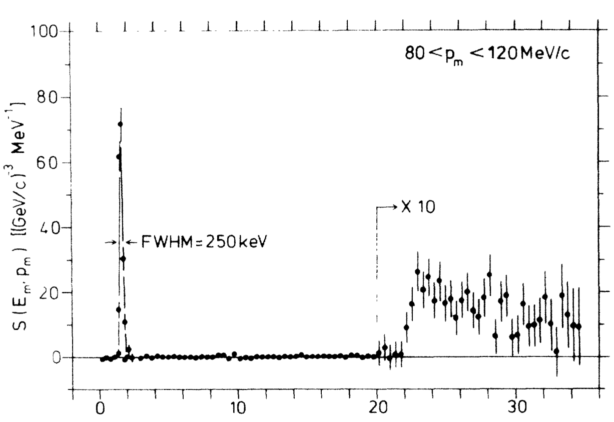

FIG. 1. Missing-energy spectrum of the ^{6}Li$(e,e'd)$ reaction.

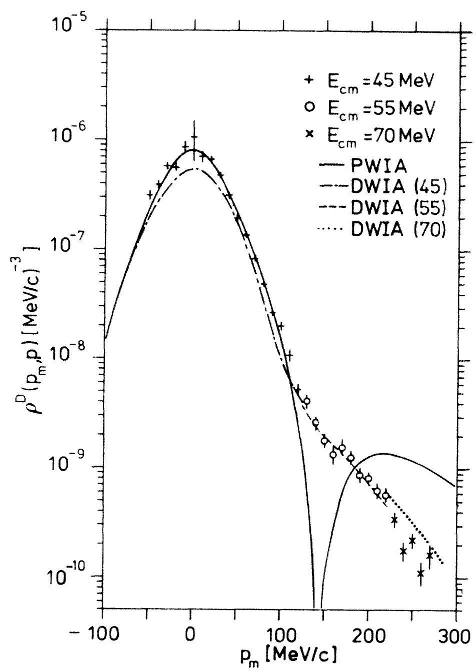

FIG. 2. Measured momentum distribution for the reaction ^{6}Li$(e,e'd)^4$He(g.s.) compared with the results of DWIA calculations, which use the "repulsive" wave function of Ref. 11. DWIA curves are for the indicated center-of-mass energies. Each datum point represents an average over a 10-MeV/c bind.

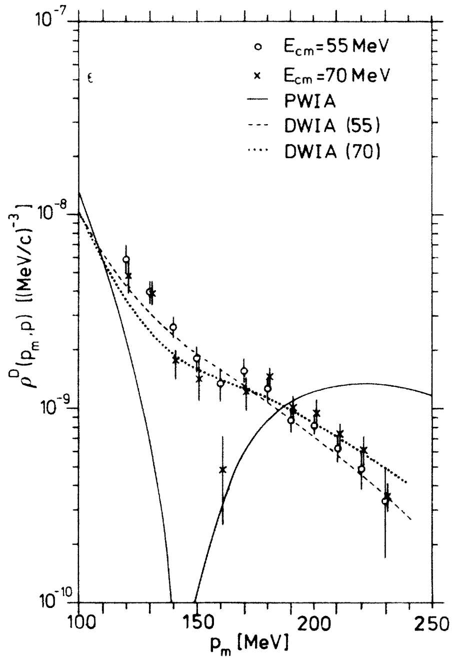

FIG. 3. Momentum distribution for the reaction ^{6}Li$(e,e'd)^4$He(g.s.) for $120 \leq p_m \leq 230$ MeV/c, measured at two α-d center-of-mass energies. DWIA curves are for the indicated center-of-mass energies. Each data point represents an average over a 10-MeV/c bin.

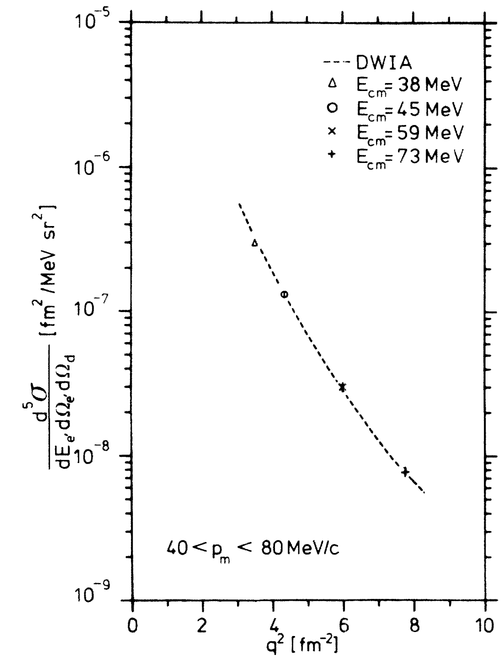

FIG. 4. Measured cross sections for the reaction ^{6}Li$(e,e'd)^4$He(g.s.) as a function of the momentum transfer squared. The dashed curve indicates the expected behavior (normalized at the highest q) of the cross section for direct deuteron knockout, corrected for distortion effects.

high-p_m region it yields effects of up to 30%.

The α-d probability in the ground state of ^{6}Li from the three-body calculations is $P = 0.616$ (Ref. 11). The data yield $P = 0.73$, which was obtained by integration of the measured momentum distribution (extrapolated to infinity) after correction of it for distortion effects. The statistical and extrapolation uncertainty is 0.03. The uncertainty due to target thickness, solid angle, etc., is about 0.04. The uncertainty from the description of the distortion effects with the optical model is estimated to be 0.07. Values of P from the ^{6}Li(p,pd) reaction[2] obtained by normalization of a calculated momentum distribution at $p_m = 0$ to the data range from 1.08 to 1.35.

In order to investigate the region of the minimum more thoroughly, data for $120 < p_m < 230$ MeV/c were obtained as well for $E_{\mathrm{c.m.}} = 70$ MeV, in which case the distortion effects are expected to be smaller than for $E_{\mathrm{c.m.}} = 55$ MeV. The two data sets are compared in Fig. 3. Although the separate data points exhibit overlapping error bars, the higher-$E_{\mathrm{c.m.}}$ data tend towards the PWIA curve, i.e., the 70-MeV points are systematically lower at $p_m \sim 160$ MeV/c and higher at $p_m \sim 200$ MeV/c, in agreement with the DWIA calculations.

It should be mentioned that the data cannot be described by assumption of a $1S$-type α-d wave function, because a $1S$ wave function yields a momentum distribution that decreases smoothly at $p_m \sim 150$ MeV/c, in contrast with the data, which show a change of slope (Figs. 2 and 3). It should be noted that in the reaction ^{6}Li$(p,pd)^4$He the various distortions completely hide the $1S$ or $2S$ character of the α-d wave function.[3] Clearly, the $(e,e'd)$ reaction has the advantages that the electron can probe the nuclear interior and that only one distorting interaction is present.

We explicitly checked the assumption that the coincidence cross section follows σ_{ed} as a function of q [Eq. (1)]. Therefore data were taken for four values of q between 370 and 550 MeV/c, with p_m kept constant at 60 MeV/c. The measured cross sections are compared with $K\sigma_{ed}$ in Fig. 4. The change of the coincidence cross section by a factor of nearly 40 is, within the error bars (< 10%), accounted for by the change in σ_{ed} (of a factor of 10) and K over this range of q. Since $E_{\mathrm{c.m.}}$ changes with q (because p_m is kept constant and $\mathbf{p} \parallel \mathbf{q}$), the distortions change also, but this change is not large at this value of $p_m (\sim 30\%)$. The curve for $K\sigma_{ed}$ includes a correction for this effect. The variation in σ_{ed} is almost completely due to its Coulomb part, as the kinematics of our data points were such that the transverse contribution is $\sim 15\%$ at the highest-q point and much less for the other points. It is hard to imagine that a different reaction process would yield the observed q dependence. For instance, sequential knockout $(e,e'p)(p,d)$ is expected to follow approximately $K\sigma_{ep}$, which changes by only a factor of 5 in the q range of our data points. Thus it can be concluded that the $(e,e'd)$ reaction on ^{6}Li proceeds primarily via quasielastic deuteron knockout, akin to what has been found for the ^{3}He$(e,e'd)$ reaction.[5]

In summary, the reaction ^{6}Li$(e,e'd)^4$He allows one to determine the α-d momentum distribution in the ground state of ^{6}Li. The reaction can be described by a direct coupling of the virtual photon to a deuteron in ^{6}Li. A three-body model for ^{6}Li gives a good description of the data. The data clearly illustrate the $2S$ character of the α-d relative wave function, as required by antisymmetrization.

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[1]L. Lapikás, Nucl. Phys. **A434**, 85C (1985).

[2]P. Kitching *et al.*, Phys. Rev. C **11**, 420 (1975); W. Dollhopf *et al.*, Phys. Lett. **588**, 425 (1975); D. Albrecht *et al.*, Nucl. Phys. **A338**, 477 (1980).

[3]R. E. Warner *et al.*, Nucl. Phys. **A422**, 205 (1984), and **A443**, 64 (1985).

[4]J. P. Genin *et al.*, Phys. Lett. **52B**, 46 (1974).

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

[6]C. T. Christou *et al.*, Phys. Rev. C **31**, 250 (1985).

[7]Yu. A. Kudeyarov, V. G. Neudatchin, S. G. Serebryakov, and Yu. F. Smirnov, Yad. Fiz. **6**, 1203 (1967) [Sov. J. Nucl. Phys. **6**, 876 (1968)]; I. V. Kuryumov, V. G. Neudatchin, and Yu. F. Smirnov, Phys. Lett. **31B**, 426 (1970); Yu. A. Kudeyarov, I. V. Kerdymov, V. G. Neudatchin, and Yu. F. Smirnov, Nucl. Phys. **A163**, 316 (1971).

[8]Y. C. Tang, K. Wildermuth, and L. D. Pearlstein, Phys. Rev. **123**, 548 (1961).

[9]D. R. Lehman and M. Rajan, Phys. Rev. C **25**, 2743 (1982).

[10]D. R. Lehman, Phys. Rev. C **25**, 3146 (1982).

[11]W. C. Parke and D. R. Lehman, Phys. Rev. C **29**, 2319 (1984).

[12]S. Frullani and J. Mougey, Adv. Nucl. Phys. **14**, 1 (1985).

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

[14]R. Ent, NIKHEF-K Report No. 85-15, 1985 (unpublished).

[15]L. Lapikás and P. K. A. de Witt Huberts, J. Phys. (Paris) **45**, C4-57 (1984).

[16]F. Hinterberger *et al.*, Nucl. Phys. **A111**, 265 (1968).