Deuteron Formation in the Reaction $^{12}$C($e,e'd$)$^{10}$B$^{-1}$

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In the reaction $^{12}$C($e,e'd$)$^{10}$B the lowest-lying $T=1$ state in $^{10}$B is found to be as strongly excited as the $T=0$ ground state of $^{10}$B, although the transition to the $T=1$ state is isospin forbidden for direct deuteron knockout. A mechanism integration of a $p$-$n$ pair in a relative $T=1$ state into a deuteron is proposed to explain this result. This new proposed mechanism is consistent with both the observed purely transverse character of the transition and the momentum-transfer dependence of the cross section.

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In this Letter we report on a measurement of the reaction $^{12}$C($e,e'd$) leading to the residual $^{10}$B nucleus in its ground and low-lying excited states, with a surprising result. The results of the previous measurements on the $^3$He($e,e'd$)$^4$H and the $^6$Li($e,e'd$)$^4$He(g.s.) reactions$^{1,2}$ could be described well by assuming that the reaction proceeds via direct, quasielastic knockout of a deuteron. The momentum-transfer ($q$) dependence of the process is the same as that for the elementary electron-deuteron cross section $\sigma_{ed}$. Therefore it is surprising that we found the $0^+$, $T=1$ state at an excitation energy of 1.74 MeV in $^{10}$B to be strongly excited in the $^{12}$C($e,e'd$) experiment, since the transition to this state is isospin forbidden for a direct knockout process. Because the strength of this transition is of similar magnitude as that for the transitions to the ground and first excited states in $^{10}$B, which are the strongest isospin-allowed transitions, it seems unlikely that the two-step process $^{12}$C($e,e'p$)$^{10}$B is the dominant process. Hence another reaction mechanism is needed to explain this result.

This mechanism could be the integration of a $p$-$n$ pair into a deuteron. If an electron is scattered from a deuteron, there is a possibility that the deuteron breaks apart and that the $p$-$n$ system ends up in a relative $^1S$ state, which is only slightly bound. The strength of this breakup channel may even be comparable to that of the elastic channel.$^3$ Reversing this process, it is possible, if an electron is scattered from a $p$-$n$ pair in a relative $^1S$ state inside a nucleus, that this $p$-$n$ pair is emitted as a real deuteron. This "deuteron-integration" mechanism, which involves both spin and isospin flip of the $p$-$n$ pair, might be responsible for the strong excitation of the $^1P=1$ state in the reaction $^{12}$C($e,e'd$)$^{10}$B. The occurrence of such a deuteron electrointegration process is very interesting, as this would mean that one could obtain information on correlated $p$-$n$ pairs in a relative $^1S$ state inside a nucleus. In this Letter an investigation of the mechanism of the reaction $^{12}$C($e,e'd$)$^{10}$B,1.74 MeV is described.

Within the one-photon-exchange approximation and with the restriction to the case where the momentum $p$ of the outgoing deuteron is parallel to the momentum transfer $q$ (parallel kinematics), the ($e,e'd$) coincidence cross section can be expressed$^4$ in terms of two structure functions $W_L$ and $W_T$:

$$
\frac{d^6\sigma}{d\omega d^2p} = K\sigma_{Mott} \frac{q^2}{q_0^2} [W_L(\omega,q^2,p) + e^{-1}W_T(\omega,q^2,p)]
$$

(1)

where $e'$ is the momentum of the outgoing electron, $K$ is a kinematical factor, $\sigma_{Mott}$ is the Mott cross section, $q^2$ is the squared four-momentum transfer, and $\omega$ is the electron energy loss, while the virtual-photon polarization parameter $\epsilon$ is given by

$$
\epsilon = \left[ 1 + \frac{2q_0^2}{q^2} \tan^2 \left( \frac{\theta_e}{2} \right) \right]^{-1}
$$

(2)

with $\theta_e$ the electron-scattering angle.

With only an $S$-wave component in the $A \to (A-2)$ $+d$ vertex,$^5,6$ the quasielastic $A(e,e'd)A-2$ coincidence cross section can be factorized in the plane-wave impulse approximation$^7$ as

$$
\frac{d^6\sigma}{d\omega d^2p} = K\sigma_{ed} S(E_m,p_m),
$$

(3)

where the spectral function $S(E_m,p_m)$ is the nuclear structure part, i.e., the probability of finding a deuteron with binding energy $E_m$ and momentum $p_m$ in the target.
nucleus, and $K_{\sigma d}$ is the reaction mechanism part, with $\sigma_{\sigma d}$ describing the electron-deuteron scattering cross section. Final-state-interaction effects between the outgoing deuteron and the residual nucleus can be approximated by replacing $S(E_m, p_m)$ with the distorted spectral function $S_0(E_m, p_m, p)$. The electron-deuteron scattering cross section can be written generally as

$$\sigma_{\sigma d}(q) = \sigma_{\text{Mot}} q^{-2} \left[ |F_L(q^2)|^2 + e^{-1} |F_T(q^2)|^2 \right].$$

For quasielastic deuteron knockout $F_L$ and $F_T$ are the known longitudinal and transverse form factors of the deuteron. For the case of the deuteron-integration process we assume a description similar to Eq. (3), now taking for $\sigma_{\sigma d}$ the electron-deuteron integration cross section, which, assuming validity of time invariance, is the same, apart from spin factors, as the electron-deuteron disintegration cross section. By describing the reaction in this way we implicitly treated the $\alpha-p$ pair as a quasibound singlet deuteron. We have studied the mechanism of the $^{12}$C($e,e'd$) coincidence reaction in two ways: (I) The longitudinal-transverse character has been investigated by performing measurements at constant $(\alpha, q)$ but different incoming electron energy $E_0$ and electron-scattering angle $\theta_e$. (II) The behavior of the coincidence cross section as a function of $q$ has been investigated by changing the value of $q$.

The $^{12}$C($e,e'd$) experiment was performed at the NIKHEF-K electron scattering facility. With use of a 15.9-mg/cm$^2$ carbon target a (typical) missing-energy resolution of 200 keV (FWHM) was achieved. All measurements were performed in parallel kinematics (pLq), which means that in the $q$ check the distortions change as the $^{10}$B-$d$ center-of-mass energy $E_{\text{c.m.}}$ changes. In the $LT$ check $E_{\text{c.m.}}$ was kept fixed at 52 MeV. For kinematical reasons the missing-momentum region was different in the two cases, i.e., $35 < p_m < 85$ MeV/c ($p_{m,\text{central}} = 60$ MeV/c) and $70 < p_m < 130$ MeV/c ($p_{m,\text{central}} = 100$ MeV/c), respectively. Further kinematical information is given in Table I. The data were analyzed as described in Refs. 2 and 10. An excitation-energy spectrum is shown in Fig. 1. The $3^+$ ground state of $^{10}$B, the first-excited $1^+$ state at $E_x = 0.72$ MeV, and the $0^+$, $T = 1$ state at 1.74 MeV can be seen clearly.

To check the $L/T$ behavior of the reaction $^{12}$C($e,e'd$)$^{10}$B$_{1.74}$ MeV, a Rosenbluth separation has been performed: the measured cross sections at $p_m = 60$ MeV/c (see Table I) were divided by $K_{\sigma d} (q^2/\alpha)^2$, which, according to Eq. (1), yields the sum $W_L + e^{-1} W_T$. This sum is plotted as a function of $e^{-1}$ in Fig. 2. A linear least-squares fit to the data gives $W_L = (-0.2 \pm 0.4) \times 10^{-10}$ (MeV/MeV) and $W_T = (1.2 \pm 0.2) \times 10^{-10}$ (MeV/MeV). Thus the data indicate within the uncertainties a purely transverse process. Since the center-of-mass energy $E_{\text{c.m.}}$ was kept fixed in our kinematics, and the distortions are not expected to be very different for $W_L$ and $W_T$, this conclusion is not influenced by distortion effects. The purely transverse character of the reaction is consistent with an explanation in terms of the deuteron-integration mechanism. The results of the $LT$ check speak against a two-step reaction mechanism because the process $(e,e'n)(p,d)$ is not expected to be a purely transverse process, since the reaction $(e,e'p)$ has a predominantly longitudinal character, and we do not see how the $(p,d)$ part can change this character significantly. The $(e,e'n)(n,d)$ process would be purely transverse, but in our kinematics the $(e,e'n)$ cross section is much smaller than that for $(e,e'p)$. It should be mentioned that for the first two isospin-allowed transitions we found $W_L$ values significantly different from zero, indicating the expected difference in reaction mechanism.

The second check is to investigate whether the $q$ dependence of the cross section follows that of the deuteron electrodissintegration cross section. This was done by taking data for three values of $q^2$, and by keeping $p_m$ constant at 100 MeV/c. The $q$ behavior of the measured $^{12}$C($e,e'd$)$^{10}$B$_{1.74}$ MeV cross section and that of the deuteron-electron scattering is shown in Fig. 3. It is seen that the splittings in the $3^+$ and $1^+$ states are in fair agreement with the deuteron-electron scattering cross section.

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**FIG. 1.** Excitation-energy spectrum of the reaction $^{12}$C($e,e'd$)$^{10}$B. Labels indicate $J^T, T$. **TABLE I.** $^{12}$C($e,e'd$) kinematics.
eson disintegration cross section are compared in Fig. 3. We used calculations by Fabian and Arenhövel,12 which include meson-exchange currents and ground-state isobar components for the deuteron disintegration process. These calculations give a good description of the measured deuteron disintegration cross sections in the $q$ range of the present experiment.4 The calculated cross sections have been integrated over the energy region 0–3 MeV above threshold, because the major contribution of the $^1S_p-n$ state is expected to be concentrated below 3 MeV above threshold. We explicitly calculated the effect of the changing final-state interaction, due to different values of $E_{c.m.}$, by using the factorized distorted-wave impulse approximation (DWIA) code PEEP.13 The global optical-model parameter set of Hinterberger et al.14 and an $l=0$ bound-state wave function of the Woods-Saxon type were used to estimate these distortion effects for $p_m \approx 100$ MeV/c. The differences in final-state interaction are taken into account in the calculated disintegration cross section. As can be seen in Fig. 3 the variation in measured coincidence cross sections is a factor of $5.9 \pm 1.2$, which agrees well with the variation in the calculated deuteron disintegration cross section of $6.2 \pm 0.3$, where the uncertainty is due to distortion effects. The choice of the integration interval of 0–3 MeV above threshold has little influence (<1%) on this factor.

In hadron-induced deuteron-knockout experiments a mechanism where the hadronic particle changes a $p-n$ ($S=0$, $T=1$) pair into a deuteron can also take place. In the reaction $^{12}$C($p,d) ^{10}$B, the excitation of the $^{10}$B$_{1s,1s,1s}$ MeV state indeed can be described reasonably well by such a mechanism.15 However, these data do not exclude other mechanisms, since the general trend of the experimental cross sections also can be reproduced with a constant $p-d$ cross section, independent of the momentum transfer $q$.

In summary, we have found evidence that the $0^+$, $T=1$ state at 1.74 MeV excitation energy in $^{10}$B is excited in the reaction $^{12}$C($e,e'd) ^{10}$B at 1.74 MeV as a function of the momentum transfer squared. The dashed curve indicates the behavior (normalized at the lowest $q^2$) of the calculated deuteron disintegration cross section.

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