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Deuteron Formation in the Reaction $^{12}C(e,e'd)^{10}B_{T=1}$

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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 $^3He(e,e'd)^1H$ and the $^6Li(e,e'd)^4He(g.s.)$ 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 σ_{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 $^{12}C(e,e'p)(p,d)^{10}B$ 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 unbound. 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 $T=1$ 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 $\mathbf{p}$ of the outgoing deuteron is parallel to the momentum transfer $\mathbf{q}$ (parallel kinematics), the $(e,e'd)$ coincidence cross section can be expressed[4] in terms of two structure functions W_L and W_T:

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

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

$$\epsilon = \left[1+\frac{2\mathbf{q}^2}{q^2}\tan^2\left(\frac{\theta_{e'}}{2}\right)\right]^{-1} \quad (2)$$

with $\theta_{e'}$ the electron-scattering angle.

With only an S-wave component in the $A \rightarrow (A-2)+d$ 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

$$\frac{d^6\sigma}{d\mathbf{e}'d\mathbf{p}} = K\sigma_{ed}S(E_m,\mathbf{p}_m), \quad (3)$$

where the spectral function $S(E_m,\mathbf{p}_m)$ is the nuclear structure part, i.e., the probability of finding a deuteron with binding energy E_m and momentum $\mathbf{p}_m$ in the target

nucleus, and $K\sigma_{ed}$ is the reaction mechanism part, with σ_{ed} describing the electron-deuteron scattering cross section. Final-state-interaction effects between the outgoing deuteron and the residual nucleus can be approximated by replacing $S(E_m,\mathbf{p}_m)$ with the distorted spectral function $S^D(E_m,\mathbf{p}_m,\mathbf{p})$. The electron-deuteron scattering cross section can be written generally as

$$\sigma_{ed}(q)=\sigma_{\text{Mott}}\frac{q^2}{\mathbf{q}^2}[|F_L(q^2)|^2+\epsilon^{-1}|F_T(q^2)|^2]. \quad (4)$$

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 σ_{ed} 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.[8] By describing the reaction in this way we have implicitly treated the *p-n* 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 $(\omega,\mathbf{q})$ 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.[9] 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 ($\mathbf{p}\|\mathbf{q}$), 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.

TABLE I. $^{12}C(e,e'd)$ kinematics.

p_m (MeV/c)	E_0 (MeV)	ϵ^{-1}	q^2 (fm^{-2})	$E_{\text{c.m.}}$ (MeV)
60	313	3.93	4.45	52
60	337	3.02	4.45	52
60	406	2.00	4.45	52
60	466	1.64	4.45	52
100	481	1.27	2.29	40
100	481	1.43	3.30	52
100	481	1.57	4.07	61

To check the L/T behavior of the reaction $^{12}C(e,e'd)^{10}B_{1.74\,\text{MeV}}$, a Rosenbluth separation has been performed: the measured cross sections at $p_m=60$ MeV/c (see Table I) were divided by $K\sigma_{\text{Mott}}q^2/\mathbf{q}^2$, which, according to Eq. (1), yields the sum $W_L+\epsilon^{-1}W_T$. This sum is plotted as a function of ϵ^{-1} in Fig. 2. A linear least-squares fit to the data gives $W_L=(-0.2\pm0.4)\times10^{-10}$ (MeV/c)$^{-3}$ and $W_T=(1.2\pm0.2)\times10^{-10}$ (MeV/c)$^{-3}$. 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[11] 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 $(e,e'p)(p,d)$ 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 electrodisintegration 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 $^{12}C(e,e'd)^{10}B_{1.74\,\text{MeV}}$ cross section and that of the deu-

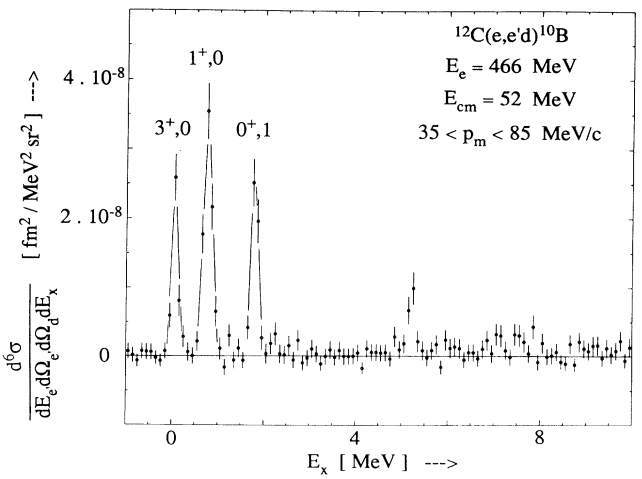

FIG. 1. Excitation-energy spectrum of the reaction $^{12}C(e,e'd)^{10}B$. Labels indicate J^π, T.

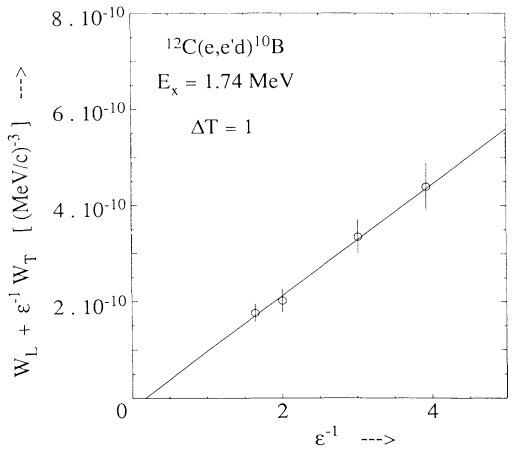

FIG. 2. Rosenbluth plot for the reaction ^{12}C(e, $e'd$)^{10}B$_{1.74\,\mathrm{MeV}}$. The solid line represents the best straight-line fit to the data.

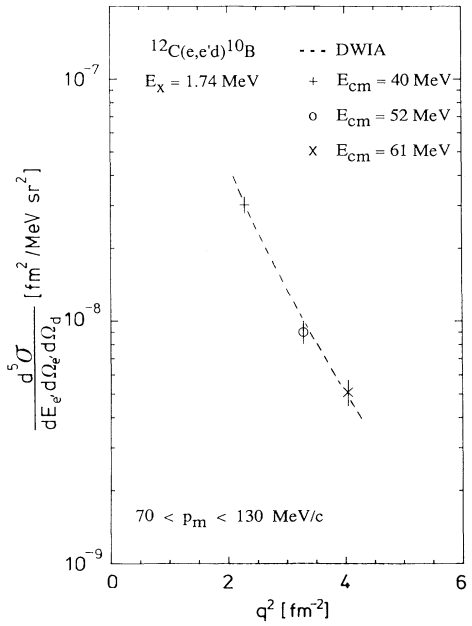

FIG. 3. Measured cross section for the reaction ^{12}C(e, $e'd$)^{10}B$_{1.74\,\mathrm{MeV}}$ as a function of the momentum transfer squared. The dashed curve indicates the behavior (normalized at the lowest q^2) of the calculated deuteron disintegration cross section.

teron 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 $E_{\mathrm{c.m.}}$, 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 $p_m \cong 100$ 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 ± 1.2, which agrees well with the variation in the calculated deuteron disintegration cross section of 6.2 ± 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,pd)^{10}B, the excitation of the ^{10}B$_{1.74\,\mathrm{MeV}}$ 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,$e'd$) through the mechanism of deuteron integration. If further theoretical study about the possible contributions of two-step processes indeed supports the dominance of the proposed deuteron-integration mechanism, we may, by use of this reaction, be able to investigate correlated p-n pairs in ^{12}C which are not in a deuteron quantum state, and thus to obtain complementary information about correlations in the ^{12}C nucleus. The prospect then would be application of this method to other nuclei as well.

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