Reaction (d_{pol}, ^{2}He) at Intermediate Energies

C. Ellegaard, C. Gaarde, T. S. Jørgensen, and J. S. Larsen
Niels Bohr Institute, DK-2100 Copenhagen, Denmark

C. Goodman
Indiana University, Bloomington, Indiana 47405

I. Bergqvist, A. Brockstedt, and P. Ekström
University of Lund, S-22362 Lund, Sweden

M. Bedjidian, D. Contardo, J. Y. Grossiord, and A. Guichard
Institut de Physique Nucléaire, Université Lyon, F-69622 Villeurbanne Cedex, France

D. Bachelier, J. L. Boyard, T. Hennino, J. C. Jourdain, and M. Roy-Stephan
Institut de Physique Nucléaire, Université de Paris-Sud, F-91406 Orsay Cedex, France

and

P. Radvanyi and J. Tinsley
Laboratoire National Saturne, F-91191 Gif-sur-Yvette, France
(Received 31 March 1987; revised manuscript received 1 July 1987)

We have succeeded in measuring at 0° and small angles the energy spectra for the (d,$2p[^1S_0]$) reaction (with the two protons in the singlet S state) at 650 MeV and 2 GeV. It is demonstrated that the reaction is a one-step process that can be used to study isospin-spin excitations. The Δ excitation is very clearly observed. A shift down in energy of the Δ peak from the proton to the ^{12}C target is observed. The experiments are performed with a tensor-polarized beam and the tensor analyzing power for the reaction $p(d_{pol},{}^2\mathrm{He})n$ at 2 GeV is given.

PACS numbers: 25.45.−z, 13.75.Cs, 24.70.+s

The (d_{pol},$2p$) reaction with the two protons in the relative singlet S state and performed with a tensor-polarized deuteron beam is a unique tool for the study of spin phenomena.[1] It is a charge-exchange reaction with spin transfer, and by a simple measurement of relative yields in the three-spin projections of the deuteron, the tensor analyzing power can be measured. This corresponds to information that can be obtained only in an (n_{pol},p_{pol}) reaction, i.e., an experiment where the polarization of the outgoing particle is also determined.

We see interesting perspectives in the use of the (d_{pol},$2p[^1S_0]$) reaction to study not only β^+ strength distributions but also ionic modes at larger momentum transfers, e.g., in the quasielastic region. An experiment is underway to study the spin structure of the Δ excitation through the (d_{pol},$2p[^1S_0]$) reaction on the proton and on nuclear targets.

As a background for these perspectives we shall in this Letter show results that allow us to conclude that (i) the reaction is a one-step process; (ii) the polarization signal is large, emphasizing the difference between transverse and longitudinal response; (iii) the distortion factor is "normal"—it is in between that for the (p,n) and (^{3}He,t) reactions, in spite of the fact that the ejectile system is unbound; and (iv) the Δ excitation of the proton can be described as the elementary $NN \to N\Delta$ cross section times the square of the d-$2p[^1S_0]$ form factor.

We have performed the (d,$2p$) experiments at bombarding energies of 650 MeV and 2 GeV at the Laboratoire National Saturne using the magnetic spectrometer SPES4,[2] to detect—with a certain efficiency—both of the outgoing protons. With a solid angle of $\Delta\Omega = 1.7° \times 3.4°$ and a momentum range $\Delta p/p \simeq 7\%$ the spectrometer itself selects events where the two protons have small relative momentum. The protons are recorded in two sets of drift chambers 1 m apart[3] so that the momentum vectors can be determined and the momentum transfer in the (d,$2p$) reaction can be defined.

Single protons from breakup of the deuteron have about the same momentum distribution as the protons from the $2p$ system and these very abundant breakup protons give a severe background especially at $\theta = 0°$. It is therefore essential to have fast coincidence conditions on the top two protons from the (d,$2p$) reaction. This is achieved in SPES4 by the requirement of coincidence between two out of twelve plastic scintillators placed in an intermediate focus 16 m from the target as well as in two of thirteen placed just behind the drift chambers, 35 m from the target. In the off-line analysis it has then been possible to put 1–2-nsec (FWHM) time windows on the $2p$ signals. With these conditions clean spectra can be obtained with $(2-5)\times 10^9$ beam particles/sec and with target thicknesses of 15–50 mg/cm^2 at forward angles and 200 mg/cm^2 for $\theta \gtrsim 5°$.

 © 1987 The American Physical Society

In Fig. 1 we show the distribution of the relative momentum of the two protons. Also given in the figure is the calculated distribution for the singlet S state. The observed shape is to a very large extent determined by the properties of the SPES4 spectrometer. Too large an angle between the two particles prohibits their getting through the aperture, while too large a relative momentum will bring them outside the momentum range of the spectrometer. The setup is ideal for the selection of the singlet S state; in fact, the contribution from the ^3P state is less than 1%. We shall, in the following, use the notation $(d,{}^2\mathrm{He})$ to emphasize that the ejectile system really is the $^1S_0$ state.

The spectra obtained on a number of target nuclei do support the assumptions made above, that the $(d,{}^2\mathrm{He})$ reaction is indeed a simple one-step process. The spectra with ^{12}C and ^{40}Ca as targets are very similar to the (p,n) spectra on the same $T=0$ targets at similar momentum transfers.[4]

The reaction $p(d,{}^2\mathrm{He})n$ is an important test case for the understanding of the reaction mechanism. In Fig. 2 we show a spectrum for the proton as the target obtained as the difference between CH_2 and C spectra. In addition to the peak corresponding to the $p\rightarrow n$ transition we see the excitation of the Δ^0 resonance. Also shown in the figure is the spectrum from the carbon target, and, as for the proton, the response to the $(d,{}^2\mathrm{He})$ probe is concentrated in two regions of the spectrum.

The measured q dependence of the cross section for the reaction $p(d,{}^2\mathrm{He})n$ is given in Table I together with calculated numbers obtained in the impulse approximation. The reaction is described in terms of the spin part of the charge-exchange NN amplitudes and a form factor for the d-^{2}He system. Following the notation of Ref. 1 we write

$$d\sigma/dt=\tfrac{1}{3}\{(|\beta|^2+|\epsilon|^2+|\gamma|^2)|S^-(t)|^2+|\delta|^2|S^+(t)|^2\}. \quad (1)$$

β and ϵ are the spin-transverse, δ the spin-longitudinal, and γ the spin-orbit amplitudes. The $S^{\pm}$ are linear combinations of form factors for the transitions from ^3S and ^3D of the deuteron to the ^1S $2p$ state; $S^+=S_0({}^3S\rightarrow{}^1S)+\sqrt{2}S_D({}^3D\rightarrow{}^1S)$ and $S^-=S_0-(1/\sqrt{2})S_D$. With these combinations the longitudinal and transverse contributions separate as shown in (1).

In general the form factor depends on momentum transfer $\mathbf{q}$ and relative momentum $\mathbf{k}$ of the two protons in the final state, $S(\mathbf{q},\mathbf{k})$. It is calculated from wave functions for the deuteron and the $2p$ system:

$$S(\mathbf{k},\mathbf{q})=\int \psi_{2p}(\mathbf{k},\mathbf{r})e^{i\mathbf{q}\cdot\mathbf{r}/2}\psi_d(\mathbf{r})d^3r, \quad (2)$$

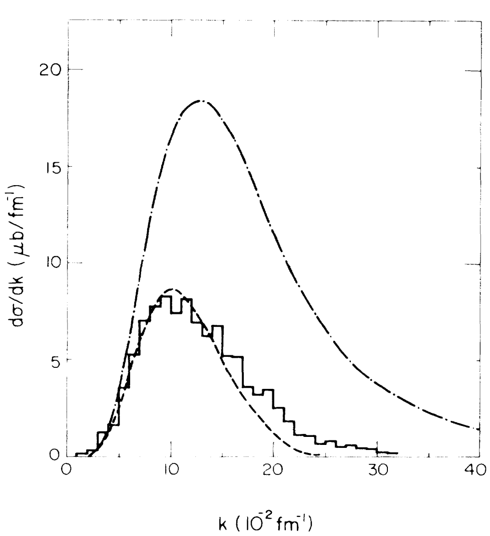

FIG. 1. Spectrum of the relative momentum of the two protons in the reaction $p(d,2p)n$ at 2 GeV with an aperture of $1.7°\times3.4°$ around $\theta=2.2°$. The dashed and dot-dashed curves are calculated spectra for the $^1S_0$ diproton state, following the two protons in a Monte Carlo simulation constrained by the aperture only (dotted-dashed) and the aperture plus spectrometer (dashed).

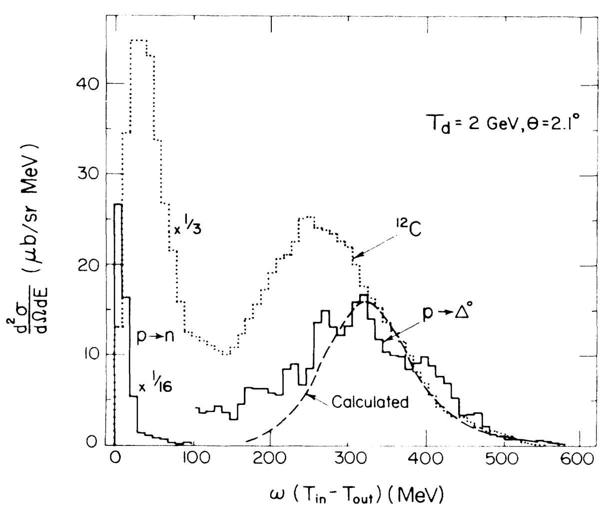

FIG. 2. Spectra for the reaction $(d,{}^2\mathrm{He})$ at 2 GeV. The proton spectrum is obtained as a difference between spectra from CH_2 and C targets. The spectra are pieced together from spectra at seven different magnetic field settings and are shown with a 10-MeV binning. The cross-section scale is obtained from the $p\rightarrow n$ transition (15% uncertainty). The calculated spectrum for the $p\rightarrow\Delta^0$ transition is obtained in a one-pion-exchange approximation as the $NN\rightarrow N\Delta$ amplitude multiplied by the d-^{2}He form factor.

or more specially for $S^+(\mathbf{k},\mathbf{q})$,

$$S^+(\mathbf{k},\mathbf{q}) = \langle 2p;k \,|\, j_0(\mathbf{q}\cdot\mathbf{r}/2) \,|\, d;{}^3S_1\rangle + \sqrt{2}\langle 2p;k \,|\, j_2(\mathbf{q}\cdot\mathbf{r}/2) \,|\, d;{}^3D_1\rangle. \quad (3)$$

The deuteron wave function is obtained from the parametrized form of the Paris potential,[8] including the D state. For the $2p$ system we have calculated the wave function from an interaction parametrized as a sum of three Yukawa potentials (Reid)[9] and the Coulomb potential, with the constraint that the experimental scattering length is reproduced.

The k dependence of the cross sections is directly given by spectra as shown in Fig. 1. Experimentally we observe that at a given bombarding energy the spectra all have the same shape, i.e., independent of target and momentum transfer. The k dependence is really determined by properties of the spectrometer. We can therefore integrate over k and get an effective form factor only depending on q. This is already implied in Eq. (1) as the k dependence of S^2 is suppressed.

The results in Table I are obtained in three independent runs with $\theta \simeq 2°$ ($q \simeq 0.6$ fm^{-1}) as the common angle. We follow the cross section over three decades and we see that the impulse approximation as expressed in Eq. (1) describes the data all the way out to $q \simeq 2.2$ fm^{-1}.

We shall illustrate the type of information contained in the polarization data by discussing the tensor analyzing power for the reaction $p(d_{\text{pol}},{}^2\text{He})n$ at 2 GeV. The quantity measured in the present setup is

$$M = \rho_{20}\tfrac{1}{2}(T_{20} + \sqrt{6}T_{22}\cos 2\phi) \simeq \rho_{20}\frac{1}{\sqrt{2}}\frac{[2(\beta^2+\gamma^2)-\epsilon^2]S^{-2} - \delta^2 S^{+2}}{(\beta^2+\gamma^2+\epsilon^2)S^{-2} + \delta^2 S^{+2}}, \quad (4)$$

where $T_{2\mu}$ are components of the tensor analyzing power and ρ_{20} (=0.60) the beam polarization. The dependence on ϕ, the angle between the beam polarization axis (normal to the momentum) and the normal to the scattering plane comes from the finite-size aperture ($\cos 2\phi$ is given in Table I). In Eq. (4) we have also given the result for M in the impulse approximation expressed as in Eq. (1), in terms of the charge-exchange spin amplitude.[10] To simplify the expression $\cos 2\phi$ is taken as equal to 1 in (4). We see from Fig. 3 that we have a very large polarization signal, dominated by the transverse amplitudes around $q \simeq 0.8$ fm^{-1} and becoming mostly longitudinal for $q \simeq 2$ fm^{-1}. We also see that the impulse approximation seems to work out to $q \simeq 2$ fm^{-1}, but that a significant deviation is observed at 2.4 fm^{-1}. The spin amplitudes are not well known at 1 GeV. The values used in the calculated curve in Fig. 3 are based on model extrapolations.[7]

We can also calculate the cross section for the reaction $p(d,{}^2\text{He})\Delta^0$ in the plane-wave impulse approximation,

$$d^2\sigma/dt\,dm^{*2} = \tfrac{1}{3}(m_d/m_p)^2(d^2\sigma/dt\,dm^{*2})(np \to p\Delta^0)\,|S^+(t)|^2, \quad (5)$$

written in an invariant form as the cross section for the $NN \to N\Delta$ transition multiplied by the square of the d-^{2}He form factor. We have seen that such an approach gives a very reasonable description for the corresponding reaction $p({}^3\text{He},t)\Delta^{++}$.[11] There we described the elementary excitation as one-pion exchange with a cutoff mass of $\Lambda \simeq 0.7$

TABLE I. Data for $p(d,{}^2\text{He})n$ at 2 GeV, normalized at $\theta = 2.1°$ ($q = 0.64$ fm^{-1}) to $(d\sigma/d\Omega)(\text{lab}) = \frac{1}{3}\{(\beta^2+\epsilon^2+\gamma^2)S^{-2} + \delta^2 S^{+2}\}(dt/d\Omega)/S^2$ ($q=0$). The effective form factors can be parametrized as $S^-/S_0 = 1.25\exp(-1.36q) - 0.25\exp(-8.0q)$ and $F = (S^+/S^-)^2 = \exp(0.26q^2)$, where q is given in inverse femtometers. The NN amplitudes are from Refs. 5–7. The values for $\cos 2\phi$ are based on a calculation following the two protons through the spectrometer.

q (fm^{-1})	$\cos 2\phi$	$(d\sigma/d\Omega)$(lab) (mb/sr)	$(d\sigma/d\Omega)$(calc) (mb/sr)
0.16	−0.28	44 ± 5	44
0.64	0.86	7.5	7.5
0.81	0.92	4.1 ± 10%	4.1
1.29	0.96	0.85 ± 10%	0.92
1.56	0.98	0.41 ± 10%	0.43
1.71	0.98	0.27 ± 10%	0.28
1.86	0.98	0.16 ± 10%	0.18
2.15	0.99	0.091 ± 10%	0.084
2.44	0.99	0.052 ± 10%	0.040

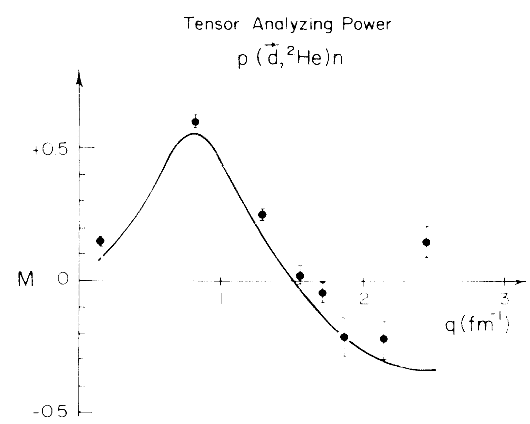

FIG. 3. Experimental and calculated (solid curve) values at 2 GeV for the quantity $M = \rho_{20}\frac{1}{2}(T_{20} + \sqrt{6}T_{22}\cos 2\phi)$ (see text). For $\theta \gtrsim 3°$ ($q \gtrsim 1$ fm^{-1}), $\cos 2\phi \simeq 1$ (see Table I) and M becomes proportional to A_{yy}. The NN amplitudes are from Ref. 7.

GeV/c, a value that consistently accounts for all the available $p \rightarrow \Delta^{++}$ cross-section data.[12] The result for the $p(d,{}^2\mathrm{He})\Delta^0$ reaction displayed in Fig. 2 shows that a very satisfactory description is obtained with the same parameters. We note that in using S^+ we have implied that the spin structure of the excitation is pionlike. In a way we do not lean as much on the plane-wave approximation as in the (^{3}He,t) case. Since we normalize to the $p \rightarrow n$ transition we only assume the same distortion for the $p \rightarrow \Delta^0$ transition.

We now turn to the ${}^{12}\mathrm{C}(d,{}^2\mathrm{He})$ data. The ratio of zero-degree cross sections for the Gamow-Teller transition to the ^{12}B ground-state relative to the $p(d,{}^2\mathrm{He})n$ transition may be written

$$R=\frac{(d\sigma/dt)({}^{12}\mathrm{C}\rightarrow{}^{12}\mathrm{B})}{(d\sigma/dt)(p\rightarrow n)}=\frac{\frac{1}{3}N}{\frac{1}{3}}\,\frac{\{\beta^2+\epsilon^2+\delta^2\}}{\{\beta^2+\epsilon^2+\delta^2\}}\,\frac{S_0^2(q\simeq 0)}{S_0^2(q\simeq 0)}\,\frac{B(\mathrm{GT})}{3}=N\frac{0.91}{3}.$$

Here we have expressed the result in terms of a distortion factor N and the ratio of B(GT) values in an eikonal approximation. Experimentally this cross-section ratio is well determined. With CH_2 targets the ratio is obtained from areas of peaks (corrected for efficiency) in the same spectrum. We find $N=0.39$ and 0.31 at 650 and 2000 MeV, respectively. The corresponding distortion factors in the (p,n) and (^{3}He,t) reactions on ^{12}C are found to be $N=0.65$ and 0.46 for (p,n) at 200[13] and 800 MeV[14] and $N=0.34$ and 0.21 for (^{3}He,t) at 600 and 2000 MeV.[15] Typical error bars on all these N values are 15%.

Another interesting feature illustrated in Fig. 2 is the shift of 65 MeV between the Δ peak for the proton and the ^{12}C targets. A similar shift is also seen in the (^{3}He,t) reaction.[16] We note that in both reactions a model of quasifree Δ production only accounts for half the observed shift.

We have in this paper demonstrated that the $(d,{}^2\mathrm{He})$ reaction at intermediate energies can be described in the impulse approximation. With a tensor-polarized beam detailed information on the spin structure of the excitation can be obtained. This seems especially promising for an understanding of the nature of the Δ excitation.

We acknowledge stimulating discussions with Colin Wilkin and the enthusiastic support from the staff of Laboratoire National Saturne. This work was supported by the Danish and Swedish Natural Science Research Councils.

[1]V. Bugg and C. Wilkin, Nucl. Phys. **A467**, 575 (1987), and Phys. Lett. **152B**, 57 (1985); C. Wilkin and D. V. Bugg, Phys. Lett. **154B**, 243 (1985).

[2]E. Grorud *et al.*, Nucl. Instrum. Methods **188**, 549 (1981).

[3]M. Bedjidian *et al.*, Nucl. Instrum. Methods (to be published).

[4]C. Gaarde, in *Proceedings of the Niels Bohr Centennial on Nuclear Structure 1985, Copenhagen, Denmark, May 1985*, edited by R. Broglia, G. B. Hagemann, and B. Herskind (North-Holland, Amsterdam, 1985), p. 449.

[5]B. E. Bonner *et al.*, Phys. Rev. Lett. **41**, 1200 (1978).

[6]D. V. Bugg and C. Wilkin, private communication.

[7]H. Esbensen, private communication.

[8]M. Lacombe *et al.*, Phys. Lett. **101B**, 139 (1981).

[9]R. V. Reid, Jr., Ann. Phys. (N.Y.) **50**, 411 (1968).

[10]J. Arvieux *et al.*, Phys. Rev. Lett. **50**, 19 (1983).

[11]C. Ellegaard *et al.*, Phys. Lett. **154B**, 110 (1985).

[12]V. Dmitriev, O. Sushkov, and C. Gaarde, Nucl. Phys. **A459**, 503 (1986).

[13]T. N. Taddeucci *et al.*, Nucl. Phys. **A469**, 125 (1987).

[14]N. S. P. King *et al.*, Phys. Lett. B **175**, 279 (1986).

[15]I. Bergqvist *et al.*, Nucl. Phys. A (to be published).

[16]D. Contardo *et al.*, Phys. Lett. **168B**, 331 (1986).