Measurement of vector–tensor spin-transfer observables for the reaction $\text{H}(\vec{p}, \vec{d}) \pi^+$ between 580 and 1300 MeV

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Abstract

The three polarization tensor components of the deuteron produced in the $\text{H}(\vec{p}, \vec{d}) \pi^+$ reaction have been measured for the first time. The experiment was performed using a vertically polarized proton beam produced by the SATURNE accelerator. The deuteron polarization was measured with the POLDER polarimeter. The three polarizing powers $t_{00}^{00}$, $t_{00}^{20}$ and $t_{00}^{22}$ and the three spin-transfer observables $t_{11}^{00}$, $t_{11}^{20}$ and $t_{11}^{22}$ have been extracted at a proton kinetic energy of 580 MeV over a wide angular range and at two fixed center-of-mass angles, 132° and 151°, between 800 and 1300 MeV. The six observables, calculated in the C.M. helicity frame, have been compared with predictions of the most refined partial-wave analyses and also with the predictions of a theoretical coupled-channel model which includes the NN–N reaction. The comparison between the data and the theory/partial-wave analyses shows some discrepancies which get worse with increasing proton energy. Adding these data to the world database should improve significantly future partial-wave analyses. The $A_{10}$ analyzing power has also been measured over the same kinematical range. The partial-wave analysis predictions are in good agreement with this observable. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The NN–πNN system has been extensively studied in the intermediate energy domain during the last 30 years both experimentally and theoretically [1]. The interest in understanding this basic system is due to the fundamental role played by the absorption or emission of a pion which could be extended to more complicated systems. Furthermore, the understanding of πNN systems can also be useful for other processes like photo- and electro-disintegration of the deuteron [1].

The H(p,d)π⁺ reaction is of particular interest because the production of a pion takes place in a two-body process. This reaction is dominated at medium energies by the excitation of a Δ resonance in the intermediate state. Other nucleon excitations like the Roper resonance play a role at higher energies.

Several theoretical approaches have been developed to describe the H(p,d)π⁺ reaction (see Ref. [1] for details). The Coupled Channels Model (CCM) [2] is based on the calculation of two coupled scattering amplitudes NN→NN and NN→NΔ via static potentials. The π production results from Δ decay. The Pion–Nucleon–Nucleon Approach (PNNA) is based on the resolution of the Fadeev three-body equations [3,4] which provide a unitary framework for two-body processes in the πNN system (NN→NN, πd→πd and pp→dπ). The most sensitive inputs are the tNN two-body amplitudes in the P33 and P11 channels associated with the excitation of the Δ and the Roper resonances. Many predictions have been made in the energy range of the Δ excitation and comparison with the data tests the physics ingredients. For example, discrepancies between experimental spin observables and theoretical calculations have pointed out problems with the spin-triplet strength [5]. However the lack of multi-pion production in these models restricts the predictions to relatively low energies. Some relativistic models have been tested either at low energy, under 800 MeV [5], or at high energy, above 1300 MeV [6], but not in our region of interest between 800 and 1300 MeV due to the lack of data. Theoretical predictions of the model of Niskanen [2] will be compared to the present data although part of our energy range of interest is well above the Δ resonance.

Alternatively, the six complex spin amplitudes of the reaction H(p,d)π⁺ can be extracted from existing data through an amplitude analysis. For example, new spin observables related to deuteron polarization measurements between 470 and 580 MeV have allowed a first reconstruction of these amplitudes [7]. However this approach is restricted to the energy range where enough data exist. Another approach is to use a partial wave expansion where the amplitudes are identified by their spin and angular momentum. Several partial-wave analyses have been carried out during the last 15 years [8,9], most recently by the Virginia group [10,11]. Such analyses extract, from a minimization procedure, the first 15 partial waves (for J ≤ 5) from the pion threshold up to about 1380 MeV. Two different sets of amplitudes have been obtained [12]. The first one (SP96) comes from a study of the energy dependence of the H(p,d)π⁺ data up to 1380 MeV proton energy. The second set (C500) results from a combined analysis of the NN→NN, πd→πd and H(p,d)π⁺ reactions. In this article we will compare
our data with these two versions, especially between 800 and 1300 MeV where only a few observables have been measured up to now.

Another goal of this experiment is related to the search for possible structures often suggested in these processes. In the region between 800 and 1300 MeV, several authors have seen hints of structures in the ratio $\sigma(30^\circ)/\sigma(0^\circ)$ [13] and in the deuteron vector polarization $it_{11}$ [14] around $\sqrt{s} \approx 2.37$ GeV. Part of our experiment was dedicated to the measurement of the analyzing power $A_{10}$ around 90° between 1000 and 1300 MeV and the results have already been published [15]. Indeed, the measured energy dependence of $A_{10}$ exhibits a small bump located at 2.37 GeV. Several interpretations such as possible threshold effects (like $N-\Delta$ with $L = 2$ [16] or $N-N^*$ (1440 MeV) intermediate states) have been mentioned [13]. The interference of several amplitudes could also generate structures but very precise partial-wave analyses are needed to support or rule out such explanations. The relatively small width of the structure compared to the $\Delta$ or Roper resonances could also be in favor of a dibaryon resonance with an exotic (six quark) structure [17]. However, additional and very precise measurements are needed for a definitive statement. This experiment provides new measurements of the energy dependence of various observables and should help in this attempt.

A large set of spin observables for the $H(p,d)\pi^+$ reaction has been measured in the past [12]. The analyzing power $A_{10}$ of the $pp \rightarrow d\pi^+$ reaction and the analyzing power $iT_{11}$ in the inverse reaction $\pi^+d \rightarrow pp$ (which is equal to $it_{11}$, the deuteron vector polarization in $pp \rightarrow d\pi^+$) has already put constraints both on the models and on the partial-wave analyses. Since these two observables have been measured intensively only below 800 MeV proton energy, additional experimental data in a large angle/energy range are necessary to improve partial-wave analyses between 800 and 1300 MeV.

Several experiments aiming at measuring polarization transfer coefficients have also been carried out; these measure the polarization of a recoil particle for reactions induced by polarized beams on unpolarized targets (at PSI, TRIUMF, LAMPF and SATURNE) or induced by unpolarized beams on polarized deuteron targets (at TRIUMF and St Petersburg). The observables measured are mainly related to vector-to-vector spin-transfer coefficients $K_{NN}$, $K_{SL}$, $K_{SS}$ [18,19]. Other experiments have measured experimental quantities combining the analyzing powers of the polarimeters and the $H(p,d)\pi^+$ spin-transfer observables like $K_{LS}$ [20], $K_{SS}$ [21] and also the vector-to-tensor $t_{12}^{11}$ spin-transfer observable [7]. All these measurements are concentrated around the $\Delta$ excitation between 470 and 800 MeV.

Polarimeters previously used to measure deuteron polarization had high sensitivity to the vector components but not to the tensor components [22]. One experiment involved the inverse reaction, and the polarization of the recoil proton was measured [19].

The experiment described in this article is the first to determine separately the three tensor components of the deuteron polarization. Using the proton beam of SATURNE, polarized normal to the reaction plane, and the polarimeter POLDER [23], based on the analyzing reaction $H(d,2p)n$ [24,25], six new transfer observables, the three polarizing powers $t_{20}^{00}$, $t_{00}^{00}$ and $t_{00}^{00}$ (the tensor polarization of the deuteron induced by an unpolarized beam) and the three spin-transfer observables $t_{20}^{11}$, $t_{11}^{11}$, and $t_{12}^{11}$ have been measured. The
knowledge of the three tensor components allows us to express the observables in the center-of-mass frame where theoretical and partial-wave predictions are usually given. Moreover this experiment provides the first double-spin measurement in the energy range between 800 and 1300 MeV where the lack of data has prevented a precise determination of the partial waves.

Various constraints have fixed the specific angle and energy ranges. For example, the range in deuteron kinetic energy between 175 and 500 MeV was imposed by the POLDER polarimeter. Since one goal of this experiment was the search for possible structures in the new observables, excitation functions were measured between 800 and 1300 MeV at two different center-of-mass angles (132° and 151°). Data have also been obtained at 580 MeV in order to increase the angular domain of existing data and to compare with partial-wave predictions which are well established at this energy. In addition, the analyzing power $A_{10}$ has been measured as a by-product of this experiment.

Section 2 is devoted to the description of the experimental setup. The data handling is described in Section 3 and the extraction of the observables is detailed in Section 4, as well as the calibration data used for this analysis. Section 5 gives the relations between the deuteron polarization and the $H(p, d)\pi^+$ observables. In Section 6, the measured values of the $H(\pi, d)\pi^+$ observables are compared with the predictions of the available partial-wave analyses and with the model of Ref. [2]. A summary and comments on future prospects are given in Section 7. Additional details can be found in Ref. [26].

2. Experimental setup

The experiment used polarized protons with a vector polarization $i\rho_1^y (= |P_y|/\sqrt{2}$, with $P_y \leq 1$) perpendicular to the reaction plane. The SATURNE accelerator delivered about $2-5 \times 10^{10}$ protons per pulse in two different states of polarization. The protons polarized normal to the scattering plane were incident on a primary liquid hydrogen target 11 cm long. The deuterons produced in the reaction $H(p, d)\pi^+$ were selected using the SPES1 magnetic spectrometer. The polarization of the deuterons was measured by the POLDER polarimeter placed at the focal plane of the spectrometer. In this section we detail the experimental setup (see Fig. 1) as well as the electronics and data acquisition system.

2.1. High energy proton polarimeter

At Saturne, depolarizing resonances are crossed in a controlled way during beam acceleration, so that the beam polarization depends on the extracted proton energy. The polarization of the incident protons is measured for each incident energy after extraction from the accelerator. The beam line polarimeter is based on the measurement of the left-right asymmetries in elastic pp scattering from a CH$_2$ target [27]. Depending on the energy of the incident protons, typical polarizations of $P_y = 70-80\%$ are obtained with uncertainties of about 2%.
2.2. SPES1 spectrometer

The deuterons produced in the $^3$He$(p,d)^3$He reaction are selected in momentum using the SPES1 spectrometer. The momentum dispersion of the spectrometer (12.37 cm/% at the focal plane) and the POLDER target size allow the selection of a small momentum acceptance ($\lesssim 1\%$). A Monte Carlo code was used to calculate the corresponding
center-of-mass angles after taking into account the energy losses of both the proton and deuteron in the primary LH$_2$ target.

Two different setups were used to stop the proton beam after the target. For laboratory angles greater than 13$^\circ$ the protons were focused into a Faraday cup. For smaller angles (corresponding to higher backward center-of-mass angles) the proton beam was stopped in a uranium block before the SPES1 magnets.

2.3. POLDER polarimeter

An extensive description of POLDER (see Fig. 1) can be found in Ref. [23]. The calibration data between 175 and 500 MeV used during this experiment are reported there and only minor changes have been made for the H($\bar{p}$,$\bar{d}$)$\pi^+$ setup.

The POLDER polarimeter is based on the charge exchange reaction H(d,2p)n which provides large figures of merit for tensor observables over a wide energy range. The two protons are selected in low relative energy configurations (see Refs. [23–25]). This quasi-two-body kinematics allows POLDER to cover about 20–25$^\circ$ around the beam direction with almost 100% efficiency.

Two scintillators S$_1$ and S$_2$ placed 70 and 25 cm upstream of the secondary POLDER target are 2.4 and 1.2 mm thick, respectively, and 8 and 7 cm in diameter. They are used to measure the number of deuterons incident on the secondary target. Six plastic scintillators (TOF), 3.5 cm wide and 1.2 mm thick, are placed at the exit of the SPES1 spectrometer, 4.5 m upstream of the POLDER target. Two multi-wire proportional chambers, 84 and 38 cm upstream of the secondary target, are used to reconstruct the trajectory of the deuterons. These MWPC have three detection planes (rotated by 120$^\circ$ relative to each other). Each plane consists of 156 wires spaced 1.27 mm apart. The argon–isobutane–freon magic gas mixture yields efficiencies of about 100% when 2 planes out of 3 are required. The associated electronics used during this experiment is based on a delay line read-out. In the most demanding conditions (large secondary beam intensities or high background levels in the experimental area), the overall tracking efficiency was about 95%. A third MWPC, installed behind the second hodoscope, was used for off-line alignment of detection elements.

The POLDER target, where the H(d,2p)n reaction takes place, is cylindrical, 16 cm long and 10.2 cm in diameter. The target cell is made of mylar 170 $\mu$m thick, mounted on a ring of aluminum located upstream. The entrance and exit windows of the vacuum chamber which contains the target cell are 50 and 100 $\mu$m thick, respectively. The temperature of the liquid hydrogen (19 K) is controlled by a monitoring system measuring the absolute pressure.

Protons from the H(d,2p)n reaction were detected in two hodoscopes placed after the target, as shown in Fig. 1. Their distances to the target center varied with incident deuteron energy in the ranges 50–70 cm and 150–210 cm for the first and second hodoscopes, respectively [23]. POLDER thus covers a momentum transfer range $q$ to the neutron of 0–300 MeV/c with good efficiency almost independent of the deuteron beam energy. The hodoscopes are formed of two planes providing $x$ and $y$ information;
each consisted of 24 bars of plastic scintillator optically coupled to phototubes on one side only. The thickness of the scintillators, 0.2 cm for the first and 1 cm for the second hodoscope, is kept small to reduce the detection of neutral particles and the reaction rate in the detectors. The dead area between adjacent bars is minimized (200 μm, to be compared to their widths, 1.1 cm and 3.5 cm, in the first and second hodoscopes). Typically a 90% detection efficiency for two-proton events is achieved. The information from the bars fired in the two hodoscopes allows the determination of the particle trajectories, and thus the angular information necessary for data binning. The first hodoscope is rotated by 45° to remove ambiguities in their reconstruction.

At the present energies, the characteristics and kinematics of the H(d,2p)n reaction allow discrimination between good events and events arising from other parasitic reactions. Indeed the simple condition that two (charged) particles be detected in the hodoscopes at small relative angles and with velocities close to that of the incident beam, with a deuteron identified in the scintillators S1 and S2, is sufficient. The velocity of the detected particles is obtained by measuring the time of flight between the S2 start detector and the second hodoscope.

2.4. Electronics and data acquisition

The four signals coming from the phototubes (PMT) connected to the scintillators S1 and S2 are amplified and sent into a constant fraction discriminator (CFD). The coincidence of the four logic signals gives the first level trigger for particles incident on the target. This signal is recorded in a scaler to give the total number of incident particles for each polarization state. It is also scaled down to allow the recording of Beam Sampling events (BS) ("beam" here means the particles incident upon POLDER). The four individual analog signals are encoded by a charge to digital converter (QDC) and used for deuteron identification.

In the hodoscopes, the analog signals associated with the hit bars are amplified and sent into a CFD. The threshold of the CFD is set close to the electronic noise of the PMT in order to ensure 100% detection efficiency for the protons. The charge exchange trigger (CE) is enabled when (1) the multiplicity M is three or greater in each hodoscope, and (2) an S1S2 signal is recorded within the 60 ns timing gate.

The signals corresponding to the BS and CE triggers are used to start the acquisition system and to block further acquisition for roughly 1 ms. Thus the dead time is exactly the same for the BS and CE events and for the scaled number of incident deuterons. This means that no dead time correction is needed in the deuteron polarization analysis.

Time information is encoded by a time to digital converter (TDC). The common start of the TDC’s is given by the S1S2 coincidence signal with one phototube selected for time reference. The signals coming from each end of the MWPC delay lines (six signals per chamber) are also recorded to determine the position of the particles.

The beam structure of SATURNE consisted of D.C. bursts 500 ms long separated by a gap of 1.5 s during which all scaler information relative to the previous burst was recorded. The scalers contained the burst number and its polarization state, the number
of events of each type, and the number of incident particles (with and without deadtime) measured during that burst. Finally, the counting rates of the detectors monitoring the proton beam intensity were also recorded with and without dead time. The typical dead time was 5–15% and it was measured with a precision of better than 1%. It enters in the analysis of the $A_{y0}$ analyzing power data only.

3. Data analysis

3.1. Deuteron selection

The experimental measurements took place at backward angles ($\geq 110^\circ$ for the high energy measurements between 800 and 1300 MeV), far away from 70° where the $pp$ elastic and $H(p,d)\pi^+$ kinematics overlap. The only physical background arises from the detection of protons from the three-body reactions $pp \rightarrow pn\pi^+$ and $pp \rightarrow pp\pi^0$ which have large cross-sections over a broad phase space. Under these operating conditions the proton counting rates never exceeded the deuteron counting rate from the $H(p,d)\pi^+$ reaction by more than a factor of two.

The angular dispersion of the scattered deuteron is constrained by the SPES1 spectrometer to a full width of about 2.7°. Deuterons are identified by time of flight selection between the TOF hodoscope and $S_2$. Only the two central bars of the hodoscope are selected for analysis; these correspond to 95% of the deuterons of interest. The time difference over the 4.5 m flight path ranged between 8 and 14 ns with a full width half maximum (FWHM) of about 1.5 ns. The two-dimensional spectrum in Fig. 2 shows the quality of the $p/d$ discrimination.

The second tool to discriminate between deuterons and protons is the measurement of
the energy loss in the scintillator $S_1$. This information is particularly useful in rejecting events with two particles in coincidence within a window of 100 ns. These events represent about 20% of the CE events but less than 1% of the BS events.

The location of the particle in the MWPC is obtained by measuring the propagation times of the signal along the delay lines. The difference of times gives the relative position of the particle, while the sum, constant for good events, is used to reject a few percent of the events associated with multi-hits in the MWPC. A deuteron spot, $\pm 3$ cm in $x$ and $\pm 2$ cm in $y$, is selected at the secondary target. It defines a momentum acceptance of 0.5%. Note that the extraction of the polarization observables is not sensitive to inefficiencies in the deuteron selection.

3.2. Selection of the charge exchange events

The selection of the CE events requires a careful analysis of the hodoscope data to remove background, mostly associated with random coincidences. Coincidences between two beam particles are removed using the front detectors; the signature is two particles detected in the MWPC but false QDC information. Coincidences between one beam particle and noise in the hodoscope are eliminated using the TDC data. This background is partly due to the high noise level in the experimental area and partly to the electronic noise of the PMT’s.

The proton track reconstruction requires an algorithm to correctly correlate the cells hit in $H_1$ with those in $H_2$. This algorithm is based on the search for the best alignment between the vertex (V) and the cells hit in each hodoscope ($H_1$ and $H_2$). Because of the poor resolution in the vertex position along the target axis, the vertex is approximated by the intercept of the deuteron trajectory with the $z = 0$ plane (target center). The first proton is defined as the one that minimizes the angle $\alpha$ between the vectors $VH_1$ and $VH_2$ drawn from the vertex to the hit positions in $H_1$ and $H_2$, with the condition that $\alpha$ be smaller than $\alpha_{\text{max}} \simeq 3.5^\circ$. The second track is defined similarly from the remaining hit cells. The event is accepted if both alignment angles satisfy $\alpha \leq \alpha_{\text{max}}$, which represent about 90% of the detected events (see Fig. 3, where the vertical line at about $3.5^\circ$ corresponds to $\alpha_{\text{max}}$). A simulation of this algorithm showed that the pp pair angles are properly reconstructed even with trajectory ambiguities.

For the remainder of the analysis, in order to avoid any binning problems in the data, the proton positions are randomized inside the elementary cells (crossing of $x$ and $y$ bars).

Once the hit bars have been identified in this way, the TDC information can be corrected as a function of the hit position. In practice this is done only on a subset of events with resolved trajectory ambiguities, that is, for events with hit bars separated by at least two bars on all hodoscope planes. Since only one end of a bar is coupled to a PMT, the time information is largely dependent on the time of propagation of the light along the plastic bar (5 ns for $H_2$ and 1.6 ns for $H_1$). The shift can be corrected using information about the fired bar in the other plane. The width of the time distribution is lowered by about 40% by this procedure and typical time resolutions of about 1.5 and
2 ns (FWHM) have been achieved for $H_1$ and $H_2$.

For polarization measurements it is essential to preserve a cylindrical symmetry in the detection setup. Both protons are thus required to pass a cone test ensuring that the proton position in $H_1$ lies within a circle of radius 8.8 cm centered on the (extrapolated) deuteron position on $H_1$, and the proton position in $H_2$ lies within a circle of radius 35.8 cm centered on the (extrapolated) deuteron position in $H_2$. These circles have to be entirely contained within the hodoscope. The same cuts are applied to the calibration data in order to have exactly the same solid angle in the measurement of the efficiency in the $H(\vec{p}\vec{d})\pi^-$ and calibration experiments.

### 3.3. Efficiency measurement

The measured polarimeter efficiency for the $H(d,2p)n$ reaction is given by

$$\epsilon_{\text{meas}}(q, \phi) = \frac{N_{\text{CE}}(q, \phi)}{N_d},$$

where $N_d$ is the number of deuterons:

$$N_d = \frac{N_{\text{BS}}^{\text{cuts}}}{N_{\text{BS}}}N_{\text{inc}},$$

$N_{\text{BS}}$ is the number of raw BS events, $N_{\text{BS}}^{\text{cuts}}$ is the number of BS events passing all cuts (deuteron identification, MWPC efficiency and cylindrical symmetry) and $N_{\text{inc}}$ is the number of incident particles.

The measured efficiency depends on the momentum $q$ transferred to the neutron in the $H(d,2p)n$ reaction. It is related to the angle $\theta$ of the center of mass of the two protons which is approximated by the average of the proton angles. These are defined as the angles between the deuteron trajectory and the vectors $VH_1$ and $VH_2$. The azimuthal angle $\phi$ for the protons is calculated similarly.
The measured efficiency also changes with the relative energy $E_{\text{rel}}$ in the two-proton C.M. system which depends on the angle between the two protons and the energies of the individual protons:

$$E_{\text{rel}} \simeq \frac{1}{2} T_d (1 - \cos \theta_{\text{rel}}).$$

(3)

This approximation is valid since, most of the time, the protons share the deuteron energy about equally. Furthermore, it has been shown [23,25] that a precise knowledge of the proton energies is not required for polarimetry applications of the $H(d,2p)\pi^+$ reaction. The efficiency is calculated for 0–5 MeV relative energies, yielding large analyzing powers. It is measured with an overall accuracy of about 1%.

4. Calculation of the deuteron tensor polarization

The three tensor components $t_{ij}^d$ of the polarization of the deuterons are obtained by comparing the results of the present experiment with the calibration results. To determine the components of the deuteron polarization, the measured efficiency $\epsilon_{\text{meas}}$ is compared with the general expression for the polarized efficiency of the CE reaction:

$$\epsilon_{\text{pol}}(q, \phi) = k \epsilon_0(q) \left( 1 + t_{20}^d T_{20}(q) + 2 \cos(\phi) i T_{11}(q) + 2 \cos(2\phi) t_{22}^d T_{22}(q) \right).$$

(4)

Here the $T_{ij}$ are the analyzing powers of the charge exchange reaction and $\epsilon_0$ is the unpolarized efficiency. These quantities have all been determined in the calibration experiment (see Section 4.1): $q$ is the momentum transfer to the neutron and $\phi$ is the azimuthal angle of the detected “particle” (see Fig. 4). The $t_{ij}^d$ are the vector ($i = 1$) and tensor ($i = 2$) polarization of the deuteron. The vector analyzing power $i T_{11}$ of the charge exchange reaction was measured to be zero in the calibration experiment and thus no vector polarization $i t_{11}^d$ of the deuteron could be obtained. The three tensor coefficients $t_{20}^d$, $t_{21}^d$ and $t_{22}^d$ are extracted through a $\chi^2$ minimization procedure, performed over all the $(q, \phi)$ bins.

Fig. 5 shows the polarized efficiency deduced from the fitting procedure and compared to the measured one. We will discuss in the following the origin of the normalization factor $k$ in relation (4), and the different systematic errors associated with the extraction of polarization coefficients. The final uncertainties obtained on the $H(p,d)\pi^+$ observables will be discussed in Section 5.

4.1. Polarimeter calibration

The calibration experiment was done with the polarized deuteron beam of SATURNE at ten energies between 175 and 500 MeV. The unpolarized efficiency $\epsilon_0$ and the analyzing powers $i T_{11}$, $T_{20}$, $T_{21}$ and $T_{22}$ were extracted (see Ref. [23] for details). Two main changes were made in the POLDER set-up for the H(p,d) reaction.
Fig. 4. Definition of the different helicity frames used in the analysis. The $y$ axis is always perpendicular to the reaction plane ($y = k_{in} \times k_{out}$). The helicity frame is rotated when passing through SPES1. The deuteron polarization is usually measured in the helicity frame of the secondary beam after the spectrometer. The two final protons are measured in the POLDER polarimeter at angles ($\theta, \phi$).

Fig. 5. (left) Typical results for the $\phi$ asymmetries of the measured (polarized) efficiency $\epsilon_{\text{meas}}(q, \phi)$ obtained during the $H(p,d)\pi^+$ experiment, shown for several $q$ bins. They are used to extract the deuteron polarization coefficients. (right) The measured (polarized) efficiency $\epsilon_{\text{meas}}(q, \phi)$ integrated over $\phi$ plotted versus the momentum transfer $q$ (solid curve) and the unpolarized efficiency $\epsilon_0(q)$ (dashed curve). The data on the integrated polarized efficiency are compared to the unpolarized efficiency to extract the $t_{20}'$. 
Fig. 6. Analyzing powers and (unpolarized) cross section for the H(d,2p)n reaction obtained with the polarimeter POLDER during the calibration at a deuteron kinetic energy of 300 MeV.

Since, in the calibration experiment, deuterons came directly from the accelerator, no particle identification for the incoming particles was needed. The TOF detectors were not used and the S1 scintillator was thinner. The deuteron energies at the POLDER target were corrected accordingly. A different set of MWPC’s was used during the calibration experiment. They were composed of only two planes with individual wire readout allowing the detection of multi-hit events.

Fig. 6 shows typical results for the (unpolarized) cross-section (the basic ingredient in $\epsilon_0(q)$) and the different analyzing powers in POLDER. Since $T_{21}$ is about half the size of $T_{22}$, the errors for the $T_{21}$ component of the deuteron polarization are larger than for the $T_{22}$ component. The cross-section decreases rapidly for $q$ above 200 MeV/c, and the $T_{20}$ analyzing power, rather flat up to 150 MeV/c, crosses zero around 200 MeV/c.

The H($\bar{p},d$)$\pi^+$ experiment was performed at energies which do not exactly match the calibration energies. The unpolarized efficiencies and the analyzing powers have been deduced from the calibration data using an interpolation in energy with a parametrization of the form $f(E) = a + b/E + c/E^2$. This shape is in accordance with experimental results and with a simulation of the polarimeter response using the theoretical cross sections of Ref. [24]. The result of the interpolation is shown in Fig. 7 for several $q$ bins between 37.5 and 237.5 MeV/c over the energy range covered by the H($\bar{p},d$)$\pi^+$ experiment. The extrapolation to energies below 175 MeV is not used in the analysis.
Fig. 7. The interpolation curves for the unpolarized efficiency $\varepsilon_0$ and for the tensor analyzing powers are shown with the calibration data points measured at six energies. The discontinuities are due to different hodoscope positions. The energies used during the H($\bar{p},d$) experiment are all above 175 MeV.

4.2. Errors on the deuteron polarization

Errors in $\varepsilon_{\text{meas}}$

Most of the cuts applied to the raw data to eliminate background are unambiguous and loose enough not to generate uncertainties in the resulting observables. This is not the case for the maximum value $\alpha_{\text{max}}$ chosen to remove the ambiguity in the individual proton trajectories (see Section 3.2). This cut can change slightly the resulting values of the deuteron polarization; the $\alpha_{\text{max}}$ parameter was varied over $\pm 1.5^\circ$ to estimate the resulting error in the efficiency. Also the randomization of the impact position of the protons inside the elementary cells of the hodoscopes led to small variations in the results. Finally some ambiguity in the values of the calculated vertex of the reaction along the $z$ axis led us to introduce an uncertainty in the positions of the hodoscopes of $\pm 0.5$ cm for the positions 1 and 3 and $\pm 1$ cm for the position 2, and corresponding errors in $\varepsilon$.

In summary, the errors on the efficiency used in the minimization procedure are

$$\Delta \varepsilon(q, \phi) = \sqrt{\sigma_{\text{stat}}(q)^2 + \sigma_{\text{syst}}(q, \phi)^2}.$$ (5)
where the statistical and systematic errors have been combined quadratically. The 
\( \sigma_{\text{syst}}(q, \phi) \) results from the quadratic summation of the systematic uncertainties 
described above. The corresponding contribution to the error in the deuteron polarization \( \Delta t^d_{ij} \) is determined by the minimization procedure.

**Errors on the calibration data**

The values of the unpolarized efficiency \( \varepsilon_0 \) and the analyzing powers \( T_{ij} \) determined in the calibration experiments have associated errors which also affect the polarization results. The procedure used to determine this error was to perform a \( \chi^2 \) minimization and to vary \( \varepsilon_0 \) and \( T_{ij} \) within their error bars. This allows us to estimate systematic errors \( \Delta t^c_{ij} \) due to the calibration uncertainties.

Systematic errors coming from the interpolation procedure for the unpolarized ef- ficiency \( \varepsilon_0 \) are estimated by comparing the deuteron polarizations \( t^d_{ij} \) obtained using the parametrization \( f(E) = a + b/E + c/E^2 \) to the values obtained through a linear interpolation. The resulting systematic errors \( \Delta t^\text{int}_{ij} \), which are upper limits, contribute only at energies far from calibration energies.

**Determination of the normalization factor \( k \)**

Different POLDER target operation conditions prevailed during the \( \text{H}(\vec{p}, \vec{d})\pi^+ \) and calibration experiments. The pressure in the liquid hydrogen target used as reference was 350±50 mbar during the calibration experiment to be compared to 1120 mbar for the \( \text{H}(\vec{p}, \vec{d})\pi^+ \) experiment. This induced a change of the target density and a small deformation of the entrance window. These two effects lead to a normalization factor \( k \sim 0.948 \pm 0.003 \). Moreover, the presence of additional material (TOF detectors and a thicker scintillator for \( S_1 \) ) increased the probability that particles identified as deuterons would break up before the POLDER target; this reduces the efficiency in the \( \text{H}(\vec{p}, \vec{d})\pi^+ \) experiment by about 1% compared to the calibration.

The final normalization factor used in the analysis is \( k = 0.940 \pm 0.005 \). The error in the \( k \) factor leads to a systematic error \( \Delta t^k_{ij} \) in the deuteron polarization.

**5. Extraction of the \( \text{H}(p,d)\pi^+ \) observables**

The observables of the reaction \( \text{H}(\vec{p}, \vec{d})\pi^+ \) can be calculated from the three tensor components of the deuteron polarization \( t^d_{20}, t^d_{21} \) and \( t^d_{22} \) measured in POLDER, through the relations

\[
\begin{align*}
  t^d_{20}(\alpha_p) &= t^{00}_{20} + 2t^{11}_{11}t^{11}_{20}, \\
  t^d_{21}(\alpha_p) &= t^{01}_{21} + t^{11}_{11}(t^{11}_{21} - t^{11}_{2-1}), \\
  t^d_{22}(\alpha_p) &= t^{02}_{22} + t^{11}_{11}(t^{11}_{22} + t^{11}_{2-2}).
\end{align*}
\] (6)
where the $r_{2i}^d(\alpha_p)$ are the deuteron polarizations deduced from the minimization procedure for the two proton polarization states $\alpha_p$ ($ir_{11}^p(\alpha_p) = P_p/\sqrt{2}$ with $P_p > 0$ for $\alpha_p = 2$ and $P_p < 0$ for $\alpha_p = 3$).

The polarizing powers $r_{2i}^{t0}(i = 0, 1, 2)$ are pure real quantities while the vector-to-tensor spin-transfer coefficients $r_{2i}^{t1}(i = -2, 0, 2)$ are pure imaginary quantities. The errors coming from the normalization factor $k$ ($\Delta r_{ij}^{t0}$) and from the interpolation in energy of $\varepsilon_0$ ($\Delta r_{ij}^{t0}$) affect only the $r_{22}^{t0}$ polarization coefficients in the minimization procedure. They are added linearly. The $r_{21}^{t1}$ and $r_{22}^{t2}$ polarization parameters are deduced from the asymmetries and are insensitive to normalization problems.

The 2% error coming from the uncertainty in the measurement of the incident proton polarization is also included in the errors on the spin-transfer observables together with the uncertainty in the incident deuteron polarization during the calibration experiment (about 3% including statistical and systematic errors). The other errors ($\Delta r_{ij}^{t}$ and $\Delta r_{ij}^{al}$) are added quadratically and affect all observables.

The polarization of the deuteron is measured in the helicity frame in POLDER. However it is useful to express the polarization observables of the reaction $H(p, d)\pi^+$ in the center-of-mass frame (C.M.) to compare the data with the theoretical predictions and phase-shift analyses (see Fig. 4). The $z$ axis is defined as to be along the momentum of the final particle (here the deuteron). The transformation from the C.M. to the Laboratory frame (Lab) consists of a rotation of the spin around the $y$ axis ($y = k_{in} \times k_{out}$) by an angle $\omega = \theta_{CM} - \theta_{Lab}$. The relativistic derivation of $\omega$ yields

$$\cos(\omega) = \cos(\theta_{CM}) \cos(\theta_{Lab}) + \gamma_{CM} \sin(\theta_{CM}) \sin(\theta_{Lab}),$$

$$\sin(\omega) = m_dE_d \left[ \sin(\theta_{CM}) \sin(\theta_{Lab}) - \gamma_{CM} \cos(\theta_{CM}) \cos(\theta_{Lab}) \right].$$

Moreover, the SPES1 spectrometer induces after the primary target a precession of the spin around the $y$ axis (aligned with the magnetic field of the dipole) while the $z$ axis of the helicity frame rotates with the momentum of the particle. This results in a rotation of the spin by an angle $\eta = \gamma\theta_d G_d$, where $\gamma$ is the Lorentz factor, $\theta_d = 97^\circ$ is the rotation angle in the spectrometer and $G_d = g_d - 1 = -0.143$, where $g_d$ is the $g$-factor of the deuteron.

Finally, the deuteron polarization coefficients $\tilde{r}_{k, q}^{d, q'}$ can be expressed in terms of the polarization coefficients $r_{k, q}^{d}$ in the POLDER frame as

$$\tilde{r}_{k, q}^{d, q'} = \sum_{q''} d_{q''}^{q''}(-\omega + \eta) r_{k, q}^{d},$$

where the $d_{q''}^{q''}$ are reduced rotation matrices [28].

6. Experimental results

Data were taken first at five different angles at 580 MeV in the region of the $\Delta$ excitation where the partial-wave amplitudes are supposedly well known. A second set
of data provides the energy dependence of the $H(p,d)\pi^+$ observables between 800 and 1300 MeV where the partial-wave analyses are only slightly constrained by existing data.

In the following we will compare the present results to the partial-wave analyses of Refs. [10,11]. The two different sets of parameters for the partial amplitudes, called SP96 and C500, have been determined from the same experimental database. The main differences between the two sets come from the additional constraints given by the coupled channels in the C500 analysis, where a $K$ matrix formalism is used [11]. The NN elastic scattering data are used to determine some elements of the $K$ matrix, while the other matrix elements are determined from a fit to $\pi d \leftrightarrow \pi d$ and the $H(p,d)\pi^+$ reaction data. In the more conventional SP96 analysis [10], the partial amplitudes are obtained using only the $H(p,d)\pi^+$ database. The first approach (C500) should improve the determination of the partial waves at higher energies between 800 and 1300 MeV where the data are rare for the $H(p,d)\pi^+$ reaction [11]. At 580 MeV, both predictions give exactly the same results.

The present data set will also be compared to the theoretical predictions of the coupled channels model (CCM) of Niskanen [2]. It includes, in addition to the direct production of a pion from nucleons, the production of a pion from $NN$ admixture [29]. These additional components dominate $NN$ inelasticities above 400 MeV and the procedure gives a good description of the energy dependence of the $I=1$ NN phase shifts. The resulting amplitudes $a_2$ and $a_6$, coming from the initial $^1D_2$ and $^3F_3$ NN states, dominate the $H(p,d)\pi^+$ cross-section in the $\Delta$ resonance region. The model includes also $s$-wave rescattering of the pion from the second nucleon. The momentum dependence is a phenomenological fit to on-shell $\pi N$ scattering [30] parametrized by a monopole form factor with $A = 830$ MeV.

6.1. Measurement of the $A_{y0}$ analyzing powers

The analyzing power $A_{y0}$ is given by:

$$A_{y0} = \frac{1}{P_y} \left( \frac{N^{d}(2) - N^{d}(3)}{N^{d}(2) + N^{d}(3)} \right),$$

where $N^{d}(2)$ and $N^{d}(3)$ are the numbers of deuterons for up and down proton polarization states, corrected for the acquisition dead time.

The results are listed in Table 1 and plotted in Fig. 8. At 580 MeV, our data are in good agreement with previous data from Refs. [19,31,33] and with the partial-wave predictions. The main difference, about 5 to 10% at 125$^\circ$ is not significant and we can consider these results as a test of the consistency of our analysis.

At higher energy, the data are sparse [34–39] but the comparison between our data and the prediction of the C500 version of the partial-wave analysis exhibits good agreement, especially at 132$^\circ$. A discrepancy can be observed mainly at 151.5$^\circ$ where the analyzing power varies rapidly with angle. In particular, the small structure predicted by the C500 partial-wave prediction does not seem to be supported by the data. $A_{y0}$ was measured
Table 1
Measured values of the analyzing power \( A_{y0} \), given in terms of the kinematic variables of the \( H(p,d)\pi^+ \) reaction

<table>
<thead>
<tr>
<th>( T_p ) (MeV)</th>
<th>( \theta_{lab} ) (deg.)</th>
<th>( \theta_{CM} ) (deg.)</th>
<th>( T_d ) (MeV)</th>
<th>( A_{y0} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>580</td>
<td>10.6</td>
<td>74.6</td>
<td>312.4</td>
<td>0.335 ± 0.015</td>
</tr>
<tr>
<td></td>
<td>11.2</td>
<td>80.7</td>
<td>298.8</td>
<td>0.323 ± 0.017</td>
</tr>
<tr>
<td></td>
<td>11.4</td>
<td>84.1</td>
<td>292.3</td>
<td>0.313 ± 0.013</td>
</tr>
<tr>
<td></td>
<td>11.2</td>
<td>124.2</td>
<td>211.3</td>
<td>0.425 ± 0.010</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td>140.5</td>
<td>182.4</td>
<td>0.446 ± 0.011</td>
</tr>
<tr>
<td>800</td>
<td>13.2</td>
<td>130.8</td>
<td>257.4</td>
<td>0.248 ± 0.009</td>
</tr>
<tr>
<td></td>
<td>9.2</td>
<td>151.6</td>
<td>211.6</td>
<td>0.240 ± 0.008</td>
</tr>
<tr>
<td></td>
<td>3.4</td>
<td>170.0</td>
<td>188.8</td>
<td>0.112 ± 0.012</td>
</tr>
<tr>
<td>900</td>
<td>15.5</td>
<td>112.3</td>
<td>348.5</td>
<td>0.055 ± 0.009</td>
</tr>
<tr>
<td></td>
<td>13.9</td>
<td>132.4</td>
<td>277.4</td>
<td>0.130 ± 0.016</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>151.2</td>
<td>228.7</td>
<td>0.195 ± 0.008</td>
</tr>
<tr>
<td>1000</td>
<td>14.7</td>
<td>132.8</td>
<td>299.5</td>
<td>0.063 ± 0.009</td>
</tr>
<tr>
<td>1100</td>
<td>15.5</td>
<td>132.3</td>
<td>325.9</td>
<td>0.001 ± 0.008</td>
</tr>
<tr>
<td></td>
<td>11.1</td>
<td>151.8</td>
<td>257.1</td>
<td>0.145 ± 0.008</td>
</tr>
<tr>
<td>1200</td>
<td>16.2</td>
<td>132.1</td>
<td>346.8</td>
<td>−0.056 ± 0.008</td>
</tr>
<tr>
<td></td>
<td>11.7</td>
<td>151.7</td>
<td>271.3</td>
<td>0.059 ± 0.008</td>
</tr>
<tr>
<td>1300</td>
<td>16.8</td>
<td>131.9</td>
<td>373.0</td>
<td>−0.141 ± 0.013</td>
</tr>
</tbody>
</table>

Column 1: proton incident energy (MeV), column 2: laboratory angle (deg.), column 3: C.M. angle (deg.), column 4: deuteron kinetic energy (MeV). The errors include statistical and systematic contributions.

During the same experiment [15] between 800 and 1300 MeV at 2(\( u_d \) ≃ −0.17 GeV^2) (corresponding to C.M. angles between 75 and 110°) and with small energy steps. These data showed some evidence of a bump located around 90° which is qualitatively reproduced by the C500 partial-wave analysis [40]. The fact that, experimentally, no structure has been found at 151.5° could be explained by the fact that some of the partial amplitudes dominating around 90° may vanish at larger angles. Indeed a careful study of the predictions of C500 shows that the two structures predicted by the C500 partial-wave analysis (at 90° and 151.5°) may not have the same origin.

The \( A_{y0} \) observable is rather well reproduced by the CCM model of Ref. [2] at 580 MeV. The overall height of \( A_{y0} \), in particular its dip at 90°, is governed by the interplay of rescattering and direct production of \( s \)-wave pions. The experimental forward–backward asymmetry of \( A_{y0} \) is not easy to reproduce; it results from the interference of different tensor-coupled initial states (i.e., \( a_4 \) and \( a_5 \) from the \( 3P_2 \) and \( 3F_2 \) initial states) with each other and with uncoupled triplets. Rescattering of the \( d \)-waves may have to be included to improve the agreement with the data. At higher energies the \( s \)-wave rescattering parametrization may not be valid any more with the onset of the \( N^*(1535) \) resonance effects. This problem could be responsible for the large discrepancies observed in \( A_{y0} \) between 800 and 1300 MeV. Relativistic effects must also be considered.
Fig. 8. The analyzing power $A_{y0}$ obtained at 580 MeV and between 800 and 1300 MeV at 130 and 150$^\circ$. The curves correspond to the phase-shift analyses of Ref. [10,11] (SP96: dashed curve, C500: solid curve), and the theoretical prediction of the NN-N4 model of Niskanen [2] (dotted curve). Our data (black squares) are also compared to previous data from Refs. [19,31,33] at 580 MeV and from Refs. [34–39] at higher energies.

6.2. Results for the spin-transfer observables

The three polarizing powers and the three spin-transfer coefficients are listed in Tables 2 and 3, where the observables are expressed in the POLDER and C.M. frames. The errors include all statistical and systematic uncertainties.

Fig. 9 presents the 580 MeV data. The correlation parameter $A_{yy}$ has also been calculated from the polarizing powers $t_{20}^0$ and $t_{22}^0$ through the relation

$$1 + 3A_{yy} = \sqrt{2} t_{20}^0 + 2\sqrt{3} t_{22}^0.$$  

(10)

Since $A_{yy}$ is symmetrical around 90$^\circ$, the 124.2$^\circ$ and 140.5$^\circ$ data can be compared directly to existing data around 55$^\circ$ and 40$^\circ$ [31]. Very good agreement is found for these observables.

The data obtained for the three polarizing powers are in very good agreement with existing data and are well reproduced by the partial-wave predictions. At this energy the SP96 and C500 predictions are very similar. Indeed, the main contribution to the cross section comes from the $a_2$ amplitude which corresponds to an N4 excitation with $L = 0$. It has been noticed [4] that the three tensor polarizing powers, which are proportional to $|a_2|^2$, should not be very sensitive to minor partial amplitudes. The very good agreement
Table 2
Measured values of the polarizing powers and the spin-transfer coefficients expressed in the POLDER frame

<table>
<thead>
<tr>
<th>$T_p$</th>
<th>$\theta_{lab}$</th>
<th>$\theta_{CM}$</th>
<th>$T_d$</th>
<th>$P_{10}^{00}$</th>
<th>$P_{11}^{00}$</th>
<th>$P_{12}^{00}$</th>
<th>$t_{11}^{11}$</th>
<th>$t_{11}^{11} - t_{11}^{1-1}$</th>
<th>$t_{11}^{11} + t_{11}^{1-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>580</td>
<td>10.6</td>
<td>74.6</td>
<td>312.4</td>
<td>0.820 ± 0.036</td>
<td>0.001 ± 0.027</td>
<td>-0.806 ± 0.019</td>
<td>0.045 ± 0.020</td>
<td>-0.350 ± 0.041</td>
<td>-0.109 ± 0.029</td>
</tr>
<tr>
<td>11.2</td>
<td>80.7</td>
<td>298.8</td>
<td>0.880 ± 0.059</td>
<td>0.464 ± 0.060</td>
<td>-0.838 ± 0.041</td>
<td>0.025 ± 0.042</td>
<td>-0.247 ± 0.090</td>
<td>-0.091 ± 0.062</td>
<td></td>
</tr>
<tr>
<td>11.4</td>
<td>84.1</td>
<td>292.3</td>
<td>0.670 ± 0.033</td>
<td>0.484 ± 0.026</td>
<td>-0.760 ± 0.018</td>
<td>0.049 ± 0.018</td>
<td>-0.096 ± 0.039</td>
<td>-0.058 ± 0.027</td>
<td></td>
</tr>
<tr>
<td>11.2</td>
<td>124.2</td>
<td>211.3</td>
<td>-0.910 ± 0.063</td>
<td>0.245 ± 0.027</td>
<td>-0.056 ± 0.021</td>
<td>-0.103 ± 0.017</td>
<td>-0.349 ± 0.040</td>
<td>0.119 ± 0.031</td>
<td></td>
</tr>
<tr>
<td>8.5</td>
<td>140.5</td>
<td>182.4</td>
<td>-1.029 ± 0.063</td>
<td>-0.021 ± 0.034</td>
<td>-0.010 ± 0.028</td>
<td>0.034 ± 0.021</td>
<td>-0.471 ± 0.052</td>
<td>0.045 ± 0.043</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>13.2</td>
<td>130.8</td>
<td>257.4</td>
<td>-0.763 ± 0.055</td>
<td>-0.021 ± 0.039</td>
<td>0.097 ± 0.027</td>
<td>-0.058 ± 0.024</td>
<td>-0.243 ± 0.061</td>
<td>-0.096 ± 0.042</td>
</tr>
<tr>
<td>9.2</td>
<td>151.6</td>
<td>211.6</td>
<td>-0.801 ± 0.064</td>
<td>-0.211 ± 0.031</td>
<td>-0.012 ± 0.024</td>
<td>0.100 ± 0.019</td>
<td>-0.233 ± 0.046</td>
<td>-0.016 ± 0.035</td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>170.0</td>
<td>188.8</td>
<td>-0.181 ± 0.071</td>
<td>-0.345 ± 0.054</td>
<td>-0.091 ± 0.044</td>
<td>0.117 ± 0.032</td>
<td>-0.365 ± 0.081</td>
<td>-0.158 ± 0.067</td>
<td></td>
</tr>
<tr>
<td>900</td>
<td>15.5</td>
<td>112.3</td>
<td>348.5</td>
<td>-0.778 ± 0.053</td>
<td>0.345 ± 0.046</td>
<td>-0.008 ± 0.024</td>
<td>-0.171 ± 0.030</td>
<td>-0.041 ± 0.075</td>
<td>-0.033 ± 0.039</td>
</tr>
<tr>
<td>13.9</td>
<td>132.4</td>
<td>277.4</td>
<td>-0.854 ± 0.074</td>
<td>-0.040 ± 0.045</td>
<td>0.116 ± 0.029</td>
<td>-0.071 ± 0.028</td>
<td>-0.175 ± 0.072</td>
<td>-0.044 ± 0.047</td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td>151.2</td>
<td>228.7</td>
<td>-0.867 ± 0.070</td>
<td>-0.218 ± 0.035</td>
<td>0.058 ± 0.025</td>
<td>0.071 ± 0.024</td>
<td>-0.178 ± 0.057</td>
<td>0.067 ± 0.041</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>14.7</td>
<td>132.8</td>
<td>299.5</td>
<td>-0.706 ± 0.046</td>
<td>0.020 ± 0.030</td>
<td>0.088 ± 0.019</td>
<td>-0.130 ± 0.021</td>
<td>-0.162 ± 0.048</td>
<td>-0.067 ± 0.031</td>
</tr>
<tr>
<td>11.0</td>
<td>155.3</td>
<td>325.9</td>
<td>-0.631 ± 0.040</td>
<td>0.079 ± 0.027</td>
<td>0.083 ± 0.016</td>
<td>-0.219 ± 0.026</td>
<td>-0.055 ± 0.059</td>
<td>-0.109 ± 0.036</td>
<td></td>
</tr>
<tr>
<td>11.1</td>
<td>151.8</td>
<td>257.1</td>
<td>-0.625 ± 0.052</td>
<td>-0.161 ± 0.056</td>
<td>0.074 ± 0.038</td>
<td>-0.090 ± 0.040</td>
<td>-0.201 ± 0.107</td>
<td>-0.191 ± 0.073</td>
<td></td>
</tr>
<tr>
<td>12.0</td>
<td>162.1</td>
<td>346.8</td>
<td>-0.423 ± 0.042</td>
<td>0.080 ± 0.029</td>
<td>0.087 ± 0.015</td>
<td>-0.338 ± 0.023</td>
<td>-0.144 ± 0.057</td>
<td>-0.085 ± 0.030</td>
<td></td>
</tr>
<tr>
<td>11.7</td>
<td>151.7</td>
<td>271.3</td>
<td>-0.504 ± 0.050</td>
<td>-0.223 ± 0.053</td>
<td>0.080 ± 0.035</td>
<td>-0.200 ± 0.038</td>
<td>-0.098 ± 0.100</td>
<td>-0.009 ± 0.066</td>
<td></td>
</tr>
<tr>
<td>1300</td>
<td>16.8</td>
<td>131.9</td>
<td>373.0</td>
<td>-0.190 ± 0.066</td>
<td>0.009 ± 0.071</td>
<td>0.105 ± 0.035</td>
<td>-0.398 ± 0.068</td>
<td>-0.092 ± 0.171</td>
<td>-0.311 ± 0.085</td>
</tr>
</tbody>
</table>

Kinematical variables such as the proton incident energy, laboratory angle, C.M. angle, and deuteron kinetic energy are also given.
Table 3
Same as Table 2 for the polarizing powers and the spin-transfer coefficients expressed in the C.M. frame

<table>
<thead>
<tr>
<th>$T_P$</th>
<th>$\theta_{\text{lab}}$</th>
<th>$\theta_{\text{CM}}$</th>
<th>$T_d$</th>
<th>$\rho_{30}^0$</th>
<th>$\rho_{21}^0$</th>
<th>$\rho_{22}^0$</th>
<th>$\rho_{20}^0$</th>
<th>$\rho_{21}^1$</th>
<th>$\rho_{21}^1 - \rho_{21}^0$</th>
<th>$\rho_{21}^1 + \rho_{21}^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>580</td>
<td>10.6</td>
<td>74.6</td>
<td>312.4</td>
<td>-0.365 ± 0.036</td>
<td>0.903 ± 0.024</td>
<td>-0.322 ± 0.023</td>
<td>0.187 ± 0.027</td>
<td>0.133 ± 0.028</td>
<td>-0.225 ± 0.032</td>
<td></td>
</tr>
<tr>
<td>11.2</td>
<td>80.7</td>
<td>98.8</td>
<td>-1.151 ± 0.077</td>
<td>0.801 ± 0.043</td>
<td>-0.009 ± 0.046</td>
<td>0.112 ± 0.058</td>
<td>0.139 ± 0.062</td>
<td>-0.162 ± 0.069</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.4</td>
<td>84.1</td>
<td>292.3</td>
<td>-1.209 ± 0.033</td>
<td>0.553 ± 0.023</td>
<td>0.007 ± 0.022</td>
<td>0.029 ± 0.025</td>
<td>0.118 ± 0.028</td>
<td>-0.041 ± 0.029</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.2</td>
<td>124.2</td>
<td>211.3</td>
<td>0.443 ± 0.040</td>
<td>-0.098 ± 0.028</td>
<td>-0.608 ± 0.040</td>
<td>0.065 ± 0.021</td>
<td>0.386 ± 0.040</td>
<td>-0.018 ± 0.027</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.5</td>
<td>140.5</td>
<td>182.4</td>
<td>0.155 ± 0.045</td>
<td>0.524 ± 0.039</td>
<td>-0.494 ± 0.038</td>
<td>-0.220 ± 0.034</td>
<td>0.255 ± 0.041</td>
<td>0.252 ± 0.039</td>
<td></td>
<td></td>
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<td>0.217 ± 0.040</td>
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<td>-0.214 ± 0.033</td>
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<td>-0.045 ± 0.046</td>
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<td>-0.007 ± 0.065</td>
<td>0.158 ± 0.168</td>
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for these observables is a good consistency check giving confidence in our analysis.

At 580 MeV some measured spin-transfer coefficients show discrepancies at backward angles with existing partial-wave analyses although the overall angular dependence is roughly reproduced. This is not surprising since such data, which are very sensitive to interference terms between the dominating $a_2$ amplitude and minor partial wave amplitudes, did not exist when the partial wave analyses were done. A comparison between our data and those of Ref. [7] is also inconclusive since their polarimeter is mostly sensitive to the $t_{22}$ component of the deuteron polarization.

Another consistency check can be made using the exact relationship [32] between $A_{y0}$ and $t_{11}^{20}$ at 90° ($t_{11}^{20}(90°) = -A_{y0}(90°)$). From the partial-wave predictions of $A_{y0}$ at 90° (which fit the existing data for this observable), one can calculate $t_{11}^{20}(90°) \approx -0.34$. This value is shown in Fig. 9 (open triangle) together with our data around 80° and the phase-shift analysis predictions. This comparison may suggest that $t_{11}^{20}$ has a sharper
angular dependence than the one predicted by the phase-shift analyses.

The results at higher energies are plotted in Figs. 10 and 11. At these energies the SP96 and C500 analyses exhibit large differences. In particular C500 predicts some structures, for proton energies between 1100 and 1300 MeV, in \( t_{11}^{21} \) at 132° and in \( t_{20}^{10} \) and \( t_{22}^{11} \) at 151°. This feature may be related to the \( A_{10} \) and \( H_{11} \) [40] energy dependences. The energy dependence of the data appears to be smoother than the C500 calculations (see for example \( t_{22}^{11} \) at 132°) and it could be in favor of the SP96 predictions.

In view of the small number of points measured and their accuracy, no firm conclusion can be drawn at this stage concerning the existence of narrow energy structures. It will be interesting in the future to perform a new partial-wave analysis including our results and see if the structures expected by the C500 analysis remain. Indeed some of the partial amplitudes (like \( a_1 \) and \( a_4 \) coming from \( 3P_1 \) and \( 3P_2 \) initial states) deduced from
Fig. 11. Results for the polarizing powers and the spin-transfer coefficients at $\theta_{CM} = 151^\circ$, expressed in the center of mass frame. The curves are as in Fig. 10.

the C500 partial-wave analysis have been predicted with a strong unexpected energy dependence at about 1250 MeV where only little data existed up to now.

Fig. 9 exhibits also a good overall agreement between our 580 MeV data and the predictions of the CCM model [2]. A rather large discrepancy is observed near 120$^\circ$ in the $t_{22}$ observable. As this observable is dominated by the $a_2 \left( ^2D_1 \right)$ partial amplitude, it should be well predicted and no explanation of this disagreement has yet been found. The same problem can be seen in the wrong angular dependence of $A_{yy}$ as compared to the data (see Fig. 9). This seems to be a peculiarity of the CCM model since both the data and the partial-wave analyses agree at this energy. For the spin-transfer coefficients ($t_{20}^{II}$, $t_{21}^{II}$ and $t_{22}^{II}$) it has been shown [4] that they are related to spin-triplet partial-waves (like $A_{v0}$) and the good agreement between the model and the data seems to validate the CCM model at 580 MeV for these waves.

At higher energies, the comparison of the CCM model with the present $A_{v0}$ accurate data shows the limitation of the model which predicts too strong an energy dependence
for almost all observables compared to the data. This trend was already observed for $A_{y0}$ between 547 and 800 MeV [38]. The large discrepancy observed, for the $t_{11}^{11}$ observable, can be related to the $A_{y0}$ discrepancy, the partial amplitudes involved being the same.

7. Summary and conclusion

We have reported the results of an experiment performed at SATURNE to measure tensor polarization observables in the reaction $H(p,d)\pi^+$. An angular distribution was measured at 580 MeV and excitation functions at two different center-of-mass angles (132 and 151°) were measured for proton kinetic energies between 800 and 1300 MeV.

The spin-transfer observables have been deduced from the measurement of the tensor polarizations of the recoil deuterons for two different states of polarization of the incident protons. This experiment is the first one able to extract the six $H(p,d)\pi^+$ observables associated with the tensor deuteron polarization measurements with a proton beam polarized normal to the reaction plane. It has thus been possible to convert the data to the center-of-mass frame in order to compare with theory and partial-wave analyses.

Measurements in a new energy range up to 1300 MeV, where the number of partial amplitudes increases significantly and knowledge of them is still poor, increase significantly the available data base.

The data have been compared with the predictions of two partial-wave analyses [10, 11] and the NN–N\(\Delta\) model of Ref. [2]. For the partial-wave predictions the differences observed between the two versions SP96 and C500 give us some insight into the importance of the constraints from NN elastic scattering. At 580 MeV it has been shown that the analyzing powers $t_{00}^{00}$, $t_{20}^{00}$, and $t_{22}^{00}$, which are sensitive in first order to the dominant partial amplitude $a_2$, are well reproduced by the partial-wave predictions. However some discrepancies were observed for the spin-transfer coefficients $t_{20}^{11}$, $t_{21}^{11}$, and $t_{22}^{11}$, and the amplitude determination could be improved in the future by using the present data set.

Between 800 and 1300 MeV our data set permits a significant improvement of the experimental knowledge of the reaction $H(p,d)\pi^+$ in increasing by a factor of three the number of existing measured observables. The comparison between our data and the two predictions of the partial-wave analyses show that some qualitative agreement is obtained. However our data provide a good opportunity to improve the quality of the partial wave determination for both analyses. They also offer an opportunity to learn about physical mechanisms such as $\Delta$-production with high angular momentum, the excitation of the Roper resonance, and the existence of possible dibaryons.

In this article we have also presented precise new data on the analyzing power $A_{y0}$. These data are in very good agreement with the C500 version of the partial-wave analysis (except at 151°). A similar agreement was previously observed for data obtained by our collaboration on the analyzing power $A_{y0}$ for C.M. angles near 90° in the same energy range [40].

We have mentioned that there are several indications of a structure in the data near...
\( \sqrt{s} \approx 2.37 \text{ GeV} (T_p \approx 1150 \text{ MeV}) \). At present the best experimental signatures have been obtained in the \( it_{11} \) observable [14] and in \( A_0 \) near 90° [15]. No strong evidence is seen in the tensor \( H(\bar{p}, \bar{d}) \pi^+ \) observables. A careful analysis of the partial waves involved for the different observables measured up to now could pin down the partial amplitudes responsible for these structures. For example, the contribution of the \( a_0 \) partial amplitude is supposed to be larger for the \( it_{11} \) observable than for the tensor observables. From an experimental point of view, very precise data on the vector polarizing power \( it_{11} \) and the vector spin-transfer coefficient \( K_{NN} \) between 1000 and 1300 MeV would be important to confirm this structure.

Acknowledgements

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References

[12] Partial-wave analysis of Refs. [10,11] and the corresponding databases can be viewed at the WWW site http://clsaid.phys.vt.edu/