Vector analyzing power at $\theta_{lab} = 18°$ for the $^2H(\vec{p},n)2p$ reaction at 21.3 MeV

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The vector analyzing power $A_y(E_n)$ for the breakup reaction $^2H(\vec{p},n)2p$ at laboratory angle $\theta_n = 18°$ has been measured for $E_p = 21.3$ MeV as a function of neutron energy. The experimental $A_y(E_n)$ values are compared with the predictions of various three-nucleon Faddeev calculations.

I. INTRODUCTION

Three-body interaction observables have been the subject of extensive measurement[1,2] and calculation[3] in recent years, not only for what such investigations might reveal about two nucleon forces, and especially their off-shell behavior, but also in the hope of gaining information on specifically three-body forces. Numerical calculations based on the Faddeev equations using realistic separable S-wave N-N potentials have been relatively successful in fitting N-d observables for the elastic channel.[4] While the amount and variety of data available for the breakup channel are comparatively small, they are generally predicted less accurately.[5] Of the different quantities which can be measured for the breakup channel, the first and second order polarization observables, such as analyzing powers, polarization transfer coefficients, etc., are of particular interest because they are expected to contain more information about the dynamics of three-body breakup reactions than do the cross sections.[6] At this laboratory, we have undertaken a series of proton-deuteron breakup experiments, some of the results of which have been reported earlier.[7–9] In Ref. 7, values for the polarization transfer coefficient $K_y^{y'}(E_n)$ for the $^2H(\vec{p},\vec{n})2p$ reaction at $E_p = 20.4$ MeV were reported for $\theta_n = 18°$. In the same paper, values of the analyzing power for the continuum neutrons, $A_y(E_n)$ at $\theta_n = 18°$, which came as a by-product of the $K_y^{y'}(E_n)$ measurement, were also presented. The $K_y^{y'}(E_n)$ results were compared with the predictions of a Faddeev calculation, done with the code of Jain and Doolen,[10] which used realistic N-N potentials, but only for the S-wave interaction. Since higher partial waves were not included in the calculation, it could not generate a nonvanishing theoretical prediction for $A_y(E_n)$. Bruinsma and Van Wageningen[11] have reported detailed calculations based on the Faddeev formalism, using a separable interaction which included P waves and tensor forces. More recently Stolk and Tjon[12] also reported calculations based on a perturbative method, using the Reid soft core potential. While both of these calculations gave $K_y^{y'}$ predictions in rough qualitative agreement with the experimental $K_y^{y'}$ values, the predictions for A_y were not in agreement with the measured A_y values. Since the latter were the by-product of another experiment, it seemed prudent to attempt a careful, direct measurement of A_y. The results of that new measurement are reported here.

II. EXPERIMENTAL DETAILS

The experiment was performed at the Texas A&M cyclotron neutron facility,[13] and made use of the polarized beam provided by an atomic beam polarized ion source.[14] The energy-analyzed proton beam was transported to the experimental area where it passed through a high-pressure liquid-nitrogen-cooled deuterium gas target of thickness 6.3 cm. The target cell had entrance and exit windows of 2.5 cm diameter made of Havar. The energy loss in the gas was $\simeq 0.5$ MeV, and the mean proton energy in the target was 21.3 MeV. Immediately after the target, the beam was deflected magnetically through 90° and collected in a heavily shielded Faraday cup. The beam polarization was vertical and could be reversed at the source. It was monitored continuously by measuring the asymmetry of p-^{4}He elastic scattering in a ^{4}He gas polarimeter located upstream of the target. The average beam polarization p_y was 0.653 ± 0.012 based on analyzing power values given by the p-^{4}He phase shifts.[15] The breakup neutrons from the reaction passed through a collimator channel at angle $\theta_n = 18°$, formed by the poles of two transverse-field spin-precession magnets, described elsewhere.[13] The neutrons were detected in a cylindrical NE102 scintillator of diameter 5 cm and length 7.5 cm, placed coaxially on the 18° collimator axis, 4.5 m from the neutron production target. An identical scintillator detector placed on the 0° collimator axis provided a determination of run-to-run normalization factors, which were also determined independently by the integrated secondary electron emission current from a thin foil traversed by the beam upstream of the target. The data were acquired with an on-line computer, which recorded the time of flight, t, from the neutron production target to the detector [measured relative to the cyclotron radio frequency (rf) period] and the proton recoil pulse height, H. Runs were taken in four stage cycles with the beam polarization being altered in the sequence ↑↓↓↑, so as to minimize the effect of any long term drifts in the system. Background runs in the same sequence were made with the gas target cell empty.

The analyzing power $A_y(E_n)$ was calculated from the measured asymmetry $\epsilon(E_n)$ in the normalized yields of breakup neutrons with incident beam polarization p_y up and down, through use of the relationship $A_y(E_n) = \epsilon(E_n)/p_y$. Two-dimensional plots of the time of flight versus pulse height for both full and empty target runs are shown in Fig. 1. Two consecutive rf periods are

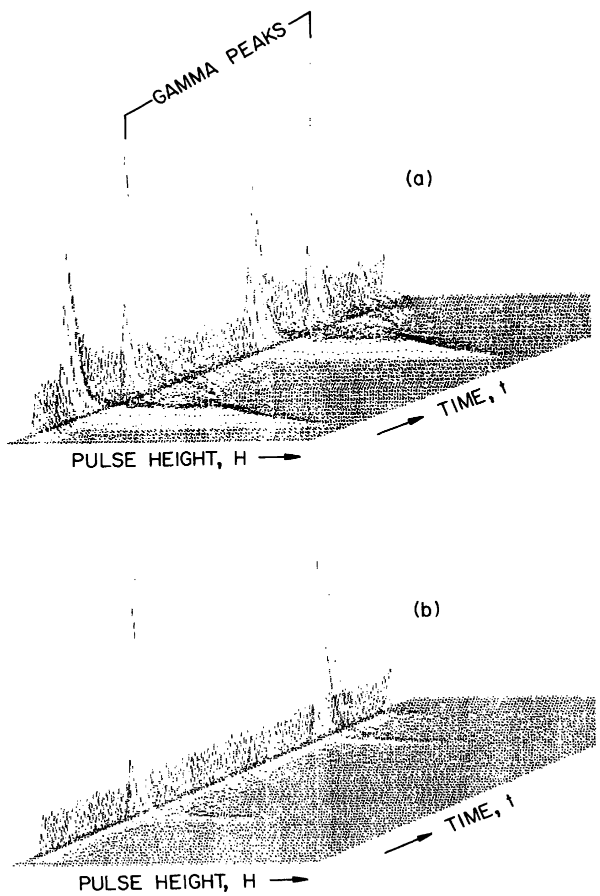

FIG. 1. Plots of pulse height (H) vs time of flight (t) for two consecutive rf cycles: (a) with deuterium gas in the target; (b) with target cell empty.

included. Note that increasing neutron energy in Fig. 1(a) goes with decreasing t value. The presence of the peak caused by gamma rays from the target windows, seen in both spectra, serves two very useful purposes. It provides a convenient means for energy calibration, and its presence is crucial for detection of small time drifts from run to run. Compensation for these is made off-line before several runs of identical spin mode are summed. It can be seen in Fig. 1(a) that the continuum spectrum is abruptly cut off at the high energy end (smaller t values). Uncompensated time shifts of even a fraction of a channel would produce spurious asymmetries for this rapidly falling part of the spectrum. In the lower energy part of the continuum, however, where the cross section varies slowly, such time shifts have a negligible effect.

With proper setting of pulse height thresholds, the background-subtracted spin up and spin down time spectra were transformed into continuum energy spectra with bins of equal width $\simeq 1$ MeV. The asymmetries $\epsilon(E_n)$, where E_n is the mean energy of the bin, were then obtained from the numbers of counts $N\uparrow$ and $N\downarrow$ in the bins of the spin-up and spin-down spectra, respectively, with the formula $\epsilon(E_n)=(N\uparrow-N\downarrow)/(N\uparrow+N\downarrow)$. The choice of the pulse height threshold used in the off-line analysis was of some importance, particularly in the analysis of the low energy portion of the continuum, because the background of small pulses was large [see Fig. 1(b)]. This threshold was set high enough to limit the target-empty background contribution to the analyzed spectra to a small fraction (less than 4% in the lowest energy portion of the spectrum).

As noted by others,[16] the accuracy of this single detector technique depends on the reproducibility of beam current integration and on stable beam axis alignment from run to run. In particular, beam movement may occur when the switch from spin-up to spin-down mode is accomplished by reversal of the solenoid current in the strong-field ionizer of the source, as was done in this experiment. The 0° breakup neutron spectra served as a very important means for off-line checks and the elimination of false instrumental asymmetries. Measurements of the analyzing power for a continuum are subject to errors due to "binning" effects,[17] i.e., errors associated with the selection of a discrete number of channels while summing. Such errors were minimized in the conversion from time spectra to energy spectra by division of the latter into bins of equal energy width and by appropriate sharing of the contents of time channels which straddled energy bin boundaries. The choice of energy bin width was influenced by the average energy loss of beam in the target and by the need to obtain reasonable statistical accuracy for each bin. The effect of small variations in the low energy limit for the binning of the spectrum was also investigated and found to be unimportant. No corrections for multiple scattering have been made to the data since such corrections should be very small.

III. RESULTS AND DISCUSSION

The resulting values for the analyzing power are shown in Fig. 2. For each point, the vertical bar shows the statistical error and the horizontal bar shows the energy bin used. The sign of p_y has been chosen to be positive when $\vec{p}_y$ is along $\hat{k}_{in}\times\hat{k}_{out}$, where $\hat{k}_{in}$ and $\hat{k}_{out}$ are the incident beam direction and the direction of the detected particle, respectively, in accordance with the Basel convention. These results are not in agreement with the previously published values,[7] but are in considerably better agreement with the exact calculations of Bruinsma and Van Wageningen[11] and the perturbative calculations of Stolk and Tjon[12] for n-d breakup at 22.7 MeV, which are also shown in Fig. 2. The suspected errors in the A_y values of Ref. 7 are attributed to the inferior beam monitoring system used at the time, plus the fact that the experiment was designed to measure $K_y^{y'}$ and not optimized for the measurement of A_y.

Bruinsma and Van Wageningen used Doleschall's method of angular momentum decomposition[18] and solved exactly the Alt-Grassberger-Sandhas form[19] of the Faddeev equations. The calculation included a number of different rank-one charge independent separable interactions. The dotted line in Fig. 2 shows the result for an s-wave interaction plus a ${}^3S_1$-${}^3D_1$ tensor force, while the solid line shows the result of a calculation which included

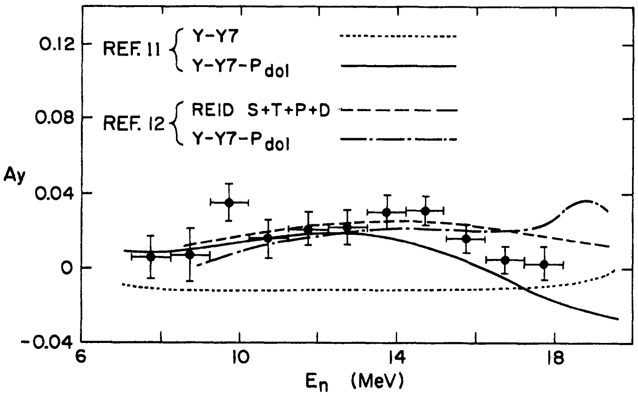

FIG. 2. Vector analyzing power A_y for the reaction ^{2}H($\vec{p}$,n)pp at $\theta_n = 18°$ as a function of neutron energy. Results are compared with the predictions of theoretical calculations. The labels for the curves are those used by the authors of Refs. 11 and 12.

S- and *P*-wave interactions together with the $^3S_1$-$^3D_1$ tensor force. The results shown actually are from an updated calculation by Bruinsma,[20] and are different from those reported in Ref. 11. Stolk and Tjon performed calculations using both the full Reid soft core interaction (dashed line) and a separable potential (dot-dashed line), by solving the Faddeev equations exactly for the *s*-wave parts of the two nucleon *T* matrix while treating the higher order partial waves perturbatively to first order. The substantial discrepancy between the dotted curve and the experimental results may be ascribed to the omission of *P*-wave interactions in the calculations. It is well known that for kinematically complete situations, vector analyzing power values are strongly dependent upon *P*-wave interactions. Up to about 13 MeV, the other three calculations agree very well with the experimental results. At higher energy, both the dashed and solid curves are in fairly good qualitative agreement with the trend of the experimental points, but gradually deviate from the data in opposite directions. Some of the difference in the high energy region between the calculated curves and the experimental points is attributable[11,12(a)] to the difference in incident energy, 21.3 MeV for the experiment vs 22.7 MeV for the calculations. The abrupt bump at the highest energy part of the dot-dashed curve is in sharp contrast with the smooth behavior shown by the experimental points. It should be noted that this is the region of the p-p final state interaction (FSI) and that Coulomb effects were neglected in the calculations which were done for the case of n-d breakup. A more valid comparison with the experimental results would be possible if the Coulomb interaction had been included properly in the calculation.

Both the calculated and observed analyzing power values are rather small. Given the experimental uncertainty of the present data, it is not possible to arrive at definitive conclusions about the relative validity of the perturbative and the exact calculations. The bump in the p-p FSI region of the Y-$Y7$-$P_{\rm dol}$ perturbative calculation may indicate, however, that it is not adequate for calculation of the observable A_y. It is worth noting that in both calculations involving the Y-$Y7$-$P_{\rm dol}$ potential, the *P*-wave interaction used is that of Doleschall.[18] Since the global data base for nucleon-nucleon phase shifts has undergone significant changes in the recent past, it would be desirable to have theoretical calculations based on more current *P*-wave phase shifts. It might also be interesting to explore the effect of the *D* state ($Y7$ indicates 7% *D* state) in the interaction potential. Such theoretical effort would stimulate further experiments aiming for much better accuracy. In addition, the existing calculations predict large and significantly different values, particularly in the FSI region, for tensor analyzing powers in the n-d breakup channel, where further experimental effort could yield interesting results.

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