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ARTICLES

Measurement of the longitudinal analyzing power for noncoplanar *p-d* breakup

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First measurements of the longitudinal analyzing power A_z for noncoplanar *p-d* breakup at E_p=9 MeV in four kinematically complete configurations are presented. The measurements are compared with Faddeev calculations obtained with the Bonn B nucleon-nucleon interaction and the 2π-exchange Tucson-Melbourne three-nucleon force. The measured analyzing powers and the corresponding theoretical predictions are very small in magnitude and compatible within the error bars of the data. Because of the smallness of A_z, the expected enhanced sensitivity to three-nucleon force effects is not seen in this low energy region. [S0556-2813(96)02510-1]

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I. INTRODUCTION

There is currently a great deal of interest in understanding the nature of nuclear three-body forces [1,2]. It is now generally believed that three-body forces are needed to reproduce the observed ^{3}H and ^{3}He binding energies [3]. Sophisticated theoretical models have been developed which make quite definite predictions concerning the form and to some extent the strength of these interactions. However, it has proved to be difficult to identify experiments which are sensitive to the nature of the three-body interactions.

It seems reasonable to suppose that proton- (or neutron-) induced deuteron breakup may be a good system for the study of three-body force effects. In simple terms, the thinking is that three-body forces may couple strongly to particular three-nucleon configurations. The breakup reactions then offer the possibility of detecting these special configurations since, with three independent particles in the final state, one can explore a very broad range of kinematic conditions and observables. Of course, for this to be successful, one needs to identify particular experimental conditions which lead to a reasonable level of sensitivity to three-body forces.

In this paper we will report the results of some new measurements of *p-d* breakup with polarized protons at E_p = 9 MeV. This experiment was undertaken in response to the suggestion in Ref. [4] that certain polarization observables for *p-d* breakup may have an enhanced sensitivity to nuclear three-body forces. The experiments proposed in Ref. [4] involve obtaining polarization measurements for breakup reactions with ''noncoplanar'' kinematics. This requires the detection of two (or more) particles in the final state with detectors separated in azimuthal angle by an amount $\Delta\phi$ other than 0° or 180°, so that the momentum of particle 2 does not lie in the plane formed by the beam direction and the momentum of particle 1.

The use of noncoplanar geometry opens the possibility of measuring a new class of polarization observables which, under ordinary conditions (reactions with two-body final states and breakup reactions with coplanar geometry), are required by conservation of parity to be zero. It is these new observables which, according to the arguments of Ref. [4], are thought to have possible enhanced sensitivity to the presence of three-body forces. An example of such an observable is the analyzing power for longitudinally polarized protons.

In this paper we present the first measurements of the longitudinal analyzing power for proton-induced deuteron breakup. We also report the first Faddeev calculations of this observable. Theoretical predictions with and without three-body forces will be presented and will be compared with the measurements.

The experiments and calculations were performed by the Wisconsin and Cracow/Bochum groups, respectively. Because the work was done simultaneously, neither group had knowledge of the other's results prior to completion of the work.

The outline of the paper is as follows. Section II contains a brief review of the theoretical background along with discussion of the choice of reaction kinematics. In Sec. III we describe the experiment in detail and present the experimental results. Section IV contains a brief description of the Faddeev calculations. Comments on the comparison between theory and experiment are given in Sec. V, along with a few concluding remarks.

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II. THEORETICAL BACKGROUND

The arguments leading to the conclusion that the longitudinal analyzing power may be sensitive to the presence of three-body forces are given in Ref. [4]. The idea is based on the observation that three-body potentials involve spin operators of a type not allowed for ordinary two-body interactions. These operators transform as vectors under rotations of the spatial coordinates but are even with respect to parity inversion, and so we say that they are axial vector in nature. It is argued in Ref. [4] that, in contrast to ordinary two-body interactions, the axial-vector operators couple strongly to states of ''unnatural parity'' [states with parity $(-1)^{L+1}$ where L is the total orbital angular momentum of the system], for example, even parity P states.

The problem then becomes one of trying to identify observables that are sensitive to the presence of unnatural parity states. What one needs to find are observables that have significant contributions from interference between the relatively large natural parity amplitudes and the presumably smaller unnatural parity amplitudes. The arguments given in Ref. [4] suggest that this may be the case for the longitudinal analyzing power. Although these arguments are somewhat tenuous, we believe that the concept is deserving of further study both experimentally and theoretically.

One question that needs to be addressed before undertaking an experiment is how to choose the reaction kinematics to maximize the desired effects. Following Ref. [4] we describe the three-nucleon system by employing Jacobi coordinates,

$$\mathbf{x}=\mathbf{r}_2-\mathbf{r}_3 \tag{1}$$

and

$$\mathbf{y}=\tfrac{1}{2}(\mathbf{r}_2+\mathbf{r}_3)-\mathbf{r}_1 \tag{2}$$

The reaction kinematics may be specified in the c.m. frame in terms of the momenta $\mathbf{k}_x$ and $\mathbf{k}_y$ conjugate to these coordinates. The momenta of the individual particles are then given by

$$\mathbf{k}_1=-\mathbf{k}_y\,, \tag{3}$$

$$\mathbf{k}_2=\tfrac{1}{2}\mathbf{k}_y+\mathbf{k}_x\,, \tag{4}$$

$$\mathbf{k}_3=\tfrac{1}{2}\mathbf{k}_y-\mathbf{k}_x\,. \tag{5}$$

It is shown in Ref. [4] that the product of the cross section and the longitudinal analyzing power can be conveniently expressed in terms of the ''bipolar harmonics,''

$$B^M_{l_x l_y,L}(\hat{\mathbf{k}}_x,\hat{\mathbf{k}}_y)\equiv\sum_{\lambda_x\lambda_y}\langle l_x\lambda_x,l_y\lambda_y|LM\rangle Y^{\lambda_x}_{l_x}(\hat{\mathbf{k}}_x)Y^{\lambda_y}_{l_y}(\hat{\mathbf{k}}_y), \tag{6}$$

by an equation of the form

$$\sigma A_z=\sum_{\beta\beta' l_x l_y L} C^{\beta\beta'}_{l_x l_y L}B^0_{l_x l_y,L}(\hat{\mathbf{k}}_x,\hat{\mathbf{k}}_y). \tag{7}$$

It is further shown that this expansion involves only bipolar harmonics for which l_x+l_y+L is odd. This expression allows one to understand the kinds of kinematic angular dependences that can occur for the analyzing power.

To use this result one must incorporate the fact that the breakup state contains two indistinguishable protons. For our purposes it is convenient to assign labels 2 and 3 to the protons and let particle 1 be the neutron. With this choice, interchanging the protons is accomplished by reversing the direction of $\mathbf{x}$. We now define $\mathbf{S}_x$ to be the sum of the two proton spins,

$$\mathbf{S}_x$$

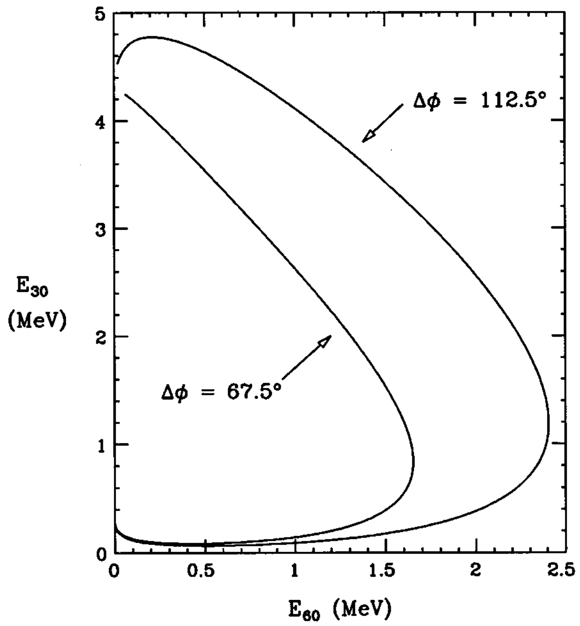

FIG. 1. Calculated kinematic loci for *p-d* breakup at $E_p = 9$ MeV. The protons emerge at $\theta_1 = 30°$ and $\theta_2 = 60°$ in the laboratory frame and are separated in azimuthal angle by an amount $\Delta\phi$.

III. DESCRIPTION OF THE EXPERIMENT

A. Apparatus and procedures

The *p-d* breakup reaction was initiated with polarized protons obtained from the University of Wisconsin crossed-beam polarized ion source [5]. The beam was accelerated to just above 9 MeV with a tandem electrostatic accelerator, momentum analyzed with a 90° deflection magnet, and then transported to a 1 m diameter scattering chamber.

The breakup reactions were initiated on a deuterium gas target. Figure 3 shows the geometry of the interaction region at the center of the chamber. The incident beam entered the chamber, which was filled with deuterium gas, through a 0.76 μm thick Ni foil, located 51.3 mm upstream of the center of the interaction region. This foil isolated the beam line vacuum from the chamber which was maintained at a pressure of 26.6 kPa. The beam was collimated with a circular aperture 1.5 mm in diameter located 13.4 mm upstream of the center of the interaction region. Since the events of interest involve coincidence detection of outgoing protons at 30° and 60° in the laboratory, the interaction region is the region of gas which can be viewed from both angles. This region was 13.6 mm in length and was defined at the upstream end by a 3.0 mm diameter circular aperture and at the downstream end by a 3.5 mm i.d. exit tube. The beam energy at the center of the interaction region was 9.00 ± 0.02 MeV.

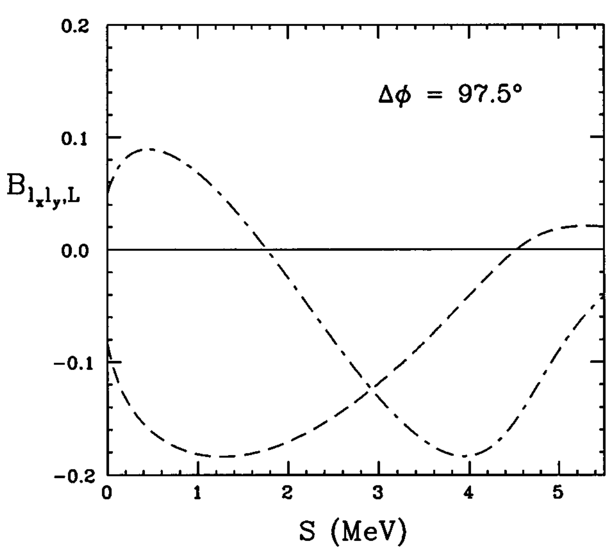

FIG. 2. Bipolar harmonic functions for $\Delta\phi = 97.5°$. The dashed and dot-dashed curves show the functions of Eqs. (9) and (10), respectively.

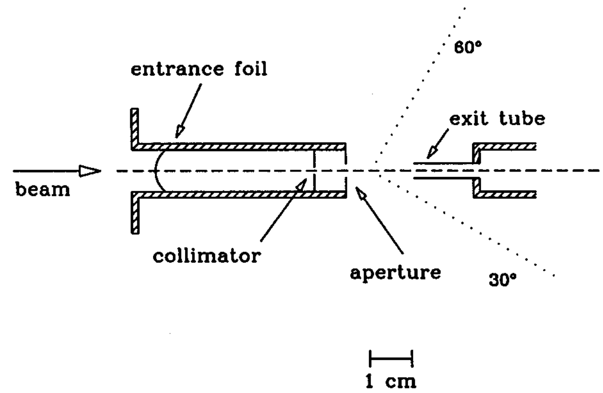

FIG. 3. Schematic diagram of the interaction region. The incident beam is represented by the dashed line. The dotted lines indicate the line of sight from the center of the interaction region to detectors located at 30° and 60°. In the actual setup, the detectors are located at various azimuthal angles.

Charged particles from elastic scattering and breakup were detected with silicon surface barrier detectors located 15 cm from the center of the interaction region. The detectors were 13.8 mm in diameter and were collimated with 11.9 mm diameter circular apertures.

Eight detectors were used in all, four at 30° and four at 60°. Coincidence events were recorded for each of the 16 30°/60° pairs. The polar and azimuthal angles of each detector are given in Table I. The 60° detectors were located to the left and right of the beam 7.5° above and below the horizontal plane, while the 30° detectors were basically above and below the beam, 15° to either side of the vertical plane. In this way the coincident detector pairs were sepa-

TABLE I. Detector locations.

Detector	θ (deg)	ϕ (deg)
1	60	7.5
2	60	172.5
3	60	187.5
4	60	352.5
5	30	75.0
6	30	105.0
7	30	255.0
8	30	285.0

rated in azimuthal angle by 112.5°, 97.5°, 82.5°, or 67.5°.

In order to protect the detectors against the damaging effects of deuterium gas, the detectors were contained in sealed cans filled with air at 26 kPa. Since deuterium readily diffuses through the polyvinyl chloride tubes that were used to carry the detector cables to the outside world, it was necessary to continually flow fresh air into the cans. A feedback system kept the pressure inside the cans equal to the deuterium pressure (to within ± 1 kPa), which allowed the use of very thin entrance windows.

To reach the detectors, reaction products needed to pass through 15 cm of deuterium gas, the 0.5 μm thick Ni entrance window, and about 3 mm of air, corresponding to an energy loss of roughly 320 keV for 1 MeV protons.

Signals from the detectors were processed with conventional electronics and recorded event by event. The detectors were operated in conjunction with commercial timing preamps. Information on the arrival time of the detected particle was obtained by employing timing filter amplifiers and constant-fraction discriminators. The event trigger required a signal in any of the four 30° detectors in coincidence with (within ± 60 nsec of) any of the four 60° detectors. Precise relative timing information was recorded using an eight-channel time-to-digital converter (TDC). A common TDC start signal was derived from the overlap coincidence circuit and the eight stop signals were obtained from the eight individual detectors. All eight channels were read and recorded for each event.

Linear energy signals from the preamps were amplified and fed into an eight-channel integrating analog-to-digital converter (ADC). All eight ADC channels were read and recorded for each event.

To measure the analyzing power A_z one uses protons polarized along the direction of the incident beam. For this coincidences involving elastic protons or recoil deuterons from elastic scattering in both detectors.

To remove the accidental coincidences, two-dimensional ''accidentals'' spectra were generated by selecting events that fell more than 10 nsec from the true peak in the time difference spectrum. After applying the approprite normalization factor, the accidentals spectrum was then subtracted from the coincidence energy spectrum. The normalization factor for each detector pair was determined by requiring that regions of the subtracted spectrum well away from the kinematic locus should have, on the average, zero counts.

Figure 6 shows an example of an accidental-subtracted spectrum. We find that after removal of the accidentals, the remaining events mainly lie along the curve expected for *p*-*d* breakup. The window drawn in Fig. 6 shows our calculation of the expected location of these events. In this calculation we start with the proton energies predicted from the reaction kinematics, subtract the calculated energy loss in the gas and the detector entrance foil, and then predict the channel numbers based on the measured detector gain (as deduced from the positions of the elastic scattering peaks and the measured zero-energy channel). The window shown in Fig. 6 includes events within 200 keV of the expected curve.

The final step in the analysis is to extract the analyzing power of the breakup events. As the data are analyzed, the events are sorted into groups based upon the distance of the measured energy from the expected kinematic curve. Group A corresponds to the range 0–100 keV, group B to the range 100–150 keV, group C to the range 150–200 keV, and group D to the range 200–300 keV. Within each group, events were sorted into bins as a function of S. Each bin is defined by a set of coordinate values E_{60} and E_{30}, which locate the center of the bin. The individual events are then each assigned to the closest bin.

IV. FADDEEV CALCULATIONS

We now compare our experimental results to theoretical predictions based on rigorous solutions of the $3N$ Faddeev equations using the Bonn B [7] NN interaction. Neglecting the long-range Coulomb force and assuming that only pairwise NN interactions are active we solved the Faddeev equation

$$T = tP + tPG_0T, \tag{14}$$

where G_0 is the free three-body propagator and P denotes a sum of cyclic and anticyclic permutations of three nucleons. The two-body off-shell t matrix t is generated from the Bonn B potential using the Lippmann-Schwinger equation. From T the breakup transition operator U_0 follows by quadrature:

$$U_0 = (1+P)T. \tag{15}$$

In order to check the expected enhanced sensitivity of A_z to the three-nucleon force (3NF) as presented in Sec. II we included, in addition to the Bonn B NN interaction, the presently most elaborate Tucson-Melbourne (TM) three-nucleon force [8,9]. This requires an extended formalism [10]. We introduce the operator

$$t_4 = V_4 + V_4G_0t_4$$

driven by the three-nucleon interaction V_4. The transition operator U_0 contains then a new term T_4 in addition to T. Both

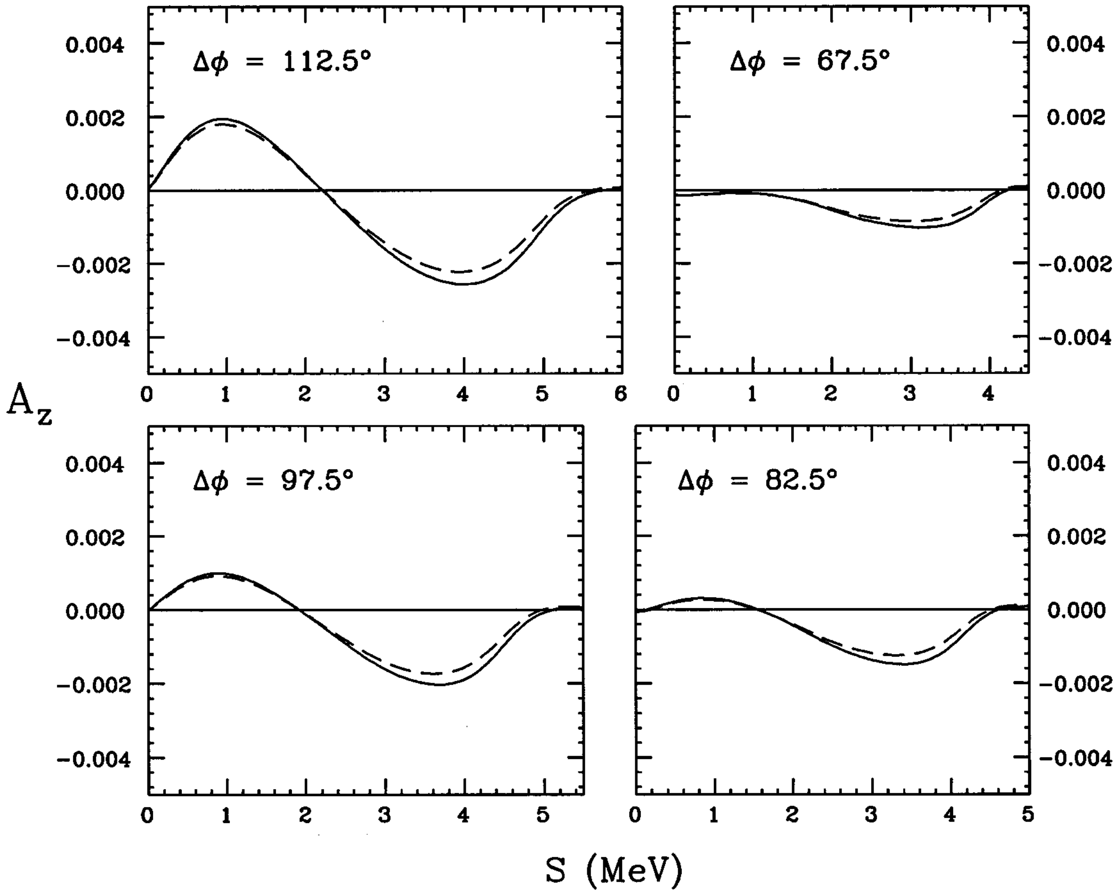

FIG. 8. Theoretical predictions of the longitudinal analyzing power A_z as a function of distance along the kinematic locus. The dashed and solid lines correspond to Bonn B and Bonn B + TM 3NF calculations, respectively.

resulting effects of the π-π TM 3NF for 3N breakup significantly. Therefore the 3NF effects obtained in the present work with $\Lambda_\pi = 5.8\mu$ should be regarded as an overestimate.

V. CONCLUSIONS

In Fig. 8 we show our theoretical predictions for the longitudinal analyzing power A_z for all four kinematic configurations. In agreement with the measurements, we see that the theoretical predictions are very small in magnitude. In all four configurations studied and for all values of the arc length S the longitudinal analyzing power A_z does not exceed 0.003 in magnitude. Including the 3NF increases A_z but only by 10–15%.

It is interesting to note that the calculated A_z values are qualitatively similar to the function $B^0_{22,1}$ of Eq. (10) (see Fig. 2). It might also be noted that in some regions of the S curve not covered by the present experiment the effects of the TM 3NF are of the order of 25%. However, the smallness of the observable A_z at this energy will hardly allow an experimental test of this prediction.

Based on our current experience, we believe that experiments to measure A_z with statistical accuracies of ± 0.001 or better are perfectly feasible. In particular, significant gains in coincidence counting rates can be achieved by using detectors that cover a larger fraction of the available solid angle. It therefore seems likely that one could obtain statistically significant nonzero measurements of A_z. Such an experiment would be a useful test of our understanding of the 3N system.

On the other hand, observing the effects of three-body forces at this energy does not appear to be possible. In order to check the expectations concerning the enhanced sensitivity of the longitudinal analyzing powers to a 3NF and in order to perform more stringent tests of present day 3NF models one should perform such breakup measurements at higher energies. For a general overview of recent results in the 3N continuum and proposals of experiments of various types we refer to Ref. [16].

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