MEASUREMENT OF THE CROSS SECTION AND $A_{yy}$ TENSOR ANALYZING POWER FOR THE $^1\text{H}(\bar{d},\text{pp})n$ REACTION IN THE SYMMETRIC CONSTANT RELATIVE ENERGY GEOMETRY

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We measured the tensor analyzing power $A_{yy}$ for the $^1\text{H}(\bar{d},\text{pp})n$ reaction in the Symmetric Constant Relative Energy (SCRE) geometry. The measurement will provide relatively precise data to compare with three-body Faddeev calculations. A more detailed discussion of the theoretical motivation for the experiment is found in the 1986 IUCF Scientific and Technical Report.1

The SCRE geometry is characterized primarily by the equal energy sharing of the three nucleons in the center-of-mass system.2 In addition, the protons emerge symmetrically with respect to, and outside of, the plane defined by the deuteron polarization axis. Tensor polarization of the deuteron beam along this axis will yield a measurement of the $A_{yy}$ tensor analyzing power. The one remaining free parameter is the angle of the outgoing neutron to the incoming beam direction, $\alpha$. Measurements made with polarized beam for a variety of values of $\alpha$ will yield angular distributions of the cross section and tensor analyzing power.

The experiment was kinematically complete, simultaneously measuring of the scattering angles and energies of both outgoing protons. Data was acquired over the range $72^\circ \leq \alpha \leq 180^\circ$ using large area detectors. Because of the low coincident rate, it was possible to acquire data simultaneously over a large range of $\alpha$, thus making maximal use of the available running time to improve the statistical precision of the measurement.

Plastic scintillators were used for event definition, particle identification (time-of-flight vs. detected energy) and energy measurement. The detected particle energy resolution was 2.5% , and was monitored by observing the width of the $d+^{12}\text{C}$ elastic scattering group. The pulse height of this group was used as the monitor of the gain of the photomultiplier and amplification system. The scintillators were segmented on either side of the beam into four units (labelled A through D) to reduce the singles rates in the phototubes. The front face of each scintillator measured 7.62 cm by 7.62 cm (see Fig. 1). They were 5.08 cm thick and attached at the side to a 2.54 cm long light guide. The light guide was in turn attached in each case to a 5.08 cm diameter phototube. Both the scintillator and the light guide were tapered as shown in Fig. 1. This taper allowed the scintillators to be positioned so that their side faces were perpendicular to a line to the target. This scheme limited the number of events that escaped through the side of one of the scintillators.

The scattering angles of the protons were measured with two-dimensional delay-line wire chambers. These were fabricated for this experiment and had an active area of 24 cm by 32 cm with a wire spacing of 4 mm. The wire spacing was chosen to allow an opening angle of approximately 0.5° per wire. This corresponded with the uncertainty of the beam-spot position on target and was smaller than the minimum angular binning size of the analysis. The two planes are named the $\theta$ and the $\phi$ planes in reference to the polar angles to which they most nearly correspond.
Figure 1. Sketch of the one of the plastic scintillators used for particle energy and time-of-flight measurements. The taper allowed the scintillators to stack together while facing the target. Paths of incident particles are shown to indicate their relative flight-paths.

The proton target was composed of a 5.78 mg/cm$^2$ thick CH$_2$ film to provide a localized source point for good definition the scattering angles. The target was placed in the beamline vacuum and the illuminated portion was shifted periodically as hydrogen was lost from beam heating of the film. The scattered particles passed through a Kapton window and atmospheric pressure Helium to the chambers and the scintillators. The total distance travelled by the outgoing particles was 59 cm.

The wire chamber location of a detected particle was calculated by taking the difference of the time-of-arrival of the signals from the ends of the delay lines. Early stops (events with multiple particle strikes in a given chamber) were eliminated during replay by examining the sum of the time-of-arrival of the signals. For a single-particle event, the sum was equal to a constant value to within the span of the drift-time in the chamber. The timing information gained from the scintillators (with a resolution of about 200 ps) was used as the reference for the wire chambers.

The experimental support apparatus was designed to rigidly hold the detector stacks, vacuum system and target chamber at their required positions. The structure was connected to rest of the beamline via standard HV vacuum connections and was supported on I-beam rails by screw-mounted feet. The apparatus was optically aligned with the remainder of the beamline.

Concern over wire chamber dead-time due to high deuteron singles rates from the $^1$H(d,d)$^1$H reaction prompted us to stop them with a 1.91 cm aluminum plate. The maximum scattering angle for these deuterons is 30° so the plate was mounted to stop all particles with scattering angles of less than that value. This led to the restriction on values of $\alpha$ greater than 72°.
The nominal (and maximum allowable) luminosity on target for the experiment was 7.5 nA \cdot mg/cm^2 because of excessive computer dead-time. Other rate-limiting factors were considered, including wire chamber dead-time, wire chamber cathode leakage current, random event rate and scintillator singles rates (relating to sagging of the dynode chain). All but the cathode leakage current operated close to their limits.

Wire chamber dead-time (as crudely measured by the fraction of early stops to the sum of early stops plus events in the good events peak) ran approximately 8% at the nominal luminosity. The computer dead-time averaged over the experiment to 12%. The random event rate was measured apart from the aquisition run and found to be greater than 15:1. The scintillator singles rates were monitored during the data acquisition runs to assure that the phototube bases were operating well below saturation.

The experiment generated data comprised of scintillator energy values and times, wire chamber times, a coincidence register and numerous scalers. The analysis was divided into three stages with the first consisting of tape compression, particle identification and wire chamber sum checks. The second divided the data into software bins associated with specific \( \alpha \) angle ranges. The size of the software bins was chosen to reflect the cross section and expected rate of change of the tensor analyzing power.

In addition to the nominal SCRE data, we also sorted bins with the same scattering angles rotated about the beam direction by an angle \( \phi \). This information was used to improve the precision of the tensor analyzing power determinations. The improvement of the error in the analyzing power points varied from 1.0 to 4, depending on the range of \( \phi \) could be covered with the scintillator geometry.

The third stage of the analysis sorted the data in each directional bin into a two-dimensional energy spectrum, comparing the energies of the two detected protons. The kinematics of the reaction demands that the proton energies lie in an energy locus which is symmetric about the equal-energy line. Figure 2 is one such locus for \( \alpha = 153^\circ \) with

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**Figure 2.** Kinematic energy locus for the \( \alpha=153^\circ \) angle cut. Shown are the SCRE analysis slice and the SCRE point.
the SCRE point shown. The locus was divided into segments of about 5 MeV across along the locus. Each segment was defined by a centerline and width. The width at the SCRE point was chosen to maximize the precision of the analyzing power without compromising its accuracy by introducing data from nearby locus points. Widths for other locus points were chosen with the additional concerns of locus curvature and cross section.

Each segment was displayed as a one-dimensional histogram of counts vs distance along the centerline of the segment. An example is shown in Fig. 3. The peaks (the areas where the locus intersected the segment) were summed with the subtraction of either no background or a flat background. The choice of background varied with the value of $\alpha$, and depended upon the proximity and relative cross sections of the two intersected portions of the locus. The uncertainty in the value of the resulting analyzing powers due to the background subtraction was included in the error bars.

![Figure 3. One-dimensional projection of the slice from Figure 2. The SCRE portion is shown, along with the sum limits. The upper limit was chosen to minimize the effect of the high-energy portion of the locus which has a large negative analyzing power.](image)

The resulting SCRE $A_{yy}$ analyzing powers are compared with various Faddeev calculations in Fig. 4. All of these calculations were done for the d+n system to avoid the difficulties associated with the Coulomb interaction. These calculations can be divided into two groups. The calculations labelled 'perturbative' were conducted by calculating the S-wave portion of the two-nucleon wave functions exactly and higher orders perturbatively.\textsuperscript{3,4} The other calculations were done with all included orders treated exactly but using separable potentials.\textsuperscript{5,6} Particular care was taken in the derivation of the H.P. separable Paris potential to obtain valid off-shell properties.

It is unclear whether any of the above methods is intrinsically superior on physical grounds, however the calculation with the separable Paris potential seems to do a better overall job of describing the data than the rest. At the same time, the angular region near $\alpha = 120^\circ$ contains a minimum due to the interference of several large amplitudes. In this region, the perturbative calculations appear to have the relative phases of the amplitudes correct, since the sharp rise in the tensor analyzing power is reproduced.
The analysis of the non-SCRE portions of the data yielded one surprise. Specifically, $A_{yy}$ was large and negative for a narrow portion of the locus centered on the opposite side of the SCRE point. This feature existed for all of those loci for whom this portion of the locus was available for analysis ($144^\circ \leq \alpha \leq 180^\circ$). Figure 5 shows the value of the analyzing power along the $\alpha = 168^\circ$ locus. The geometry for this area in the $\alpha = 180^\circ$ locus is within $0.5^\circ$ of the geometry where the neutron stops in the center-of-mass and the two protons emerge parallel to the x-axis (transverse to the beam and perpendicular to the direction of polarization).

In conclusion, the new large-area detector design has yielded measurements for a large range of $\alpha$ with errors small enough to evaluate the various three-body calculations for a kinematic regime far from that usually encountered in p+d elastic scattering. In this regime, the calculations exhibit a sensitivity to the method of calculation and the quality of the off-shell amplitudes. When sufficient care is taken with the description of the off-shell effects, a valid description of the three-body breakup is attainable.

![Tensor Analyzing Power $A_{yy}$, 95 MeV](image)

**Figure 4.** Preliminary values of the $A_{yy}$ Tensor Analyzing Power in the SCRE geometry as described in the text. The calculations by Tjon are all perturbative approximations to the indicated potentials. The other two are separable versions of a phenomenological potential by Doleschall and the Paris potential.
Figure 5. Preliminary values of the $A_{yy}$ Tensor Analyzing Power along the $\alpha=168^\circ$ kinematic energy locus. The analyzing powers are plotted as a function of the distance along the locus in MeV where the zero value is defined as the SCRE point. Positive values of the distance indicate points clockwise from the SCRE point and vice-versa for negative values. The point at 44 MeV is that opposite the SCRE point. Note the large negative analyzing power over the narrow range in energy near this point.