A $^2H(n,p)2n$ Experiment to Measure Accurately the Neutron-Neutron Scattering Length

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Summary

The neutron-neutron (n-n) scattering length a_{nn} is a parameter that represents the strength of the *n-n* interaction at low energies. It can be compared with the proton-proton (*p-p*) scattering length a_{pp} to investigate the charge-symmetry breaking in nuclear forces. The difference a_{pp}-a_{nn} is a measure of the mass difference of the up and down quarks and therefore it is of fundamental interest. Experiments to determine a_{nn} use mainly one of two deuteron reactions: π^--*d* capture or *n-d* breakup. For both of these deuteron reactions, a_{nn} is extracted by analysis of the cross-section data. However, the experimental values of a_{nn} from the two reactions disagree. What is more confusing than this discrepancy is that significantly different values for a_{nn} are reported from similar $^2H(n,p)2n$ experiments. This problem must be resolved before the differences between π^--*d* and *n-d* reactions can be addressed further.

In the past, the proton spectra from $^2H(n,p)2n$ experiments were analyzed using simplified nuclear force models to extract the value of a_{nn}. Published data from $^2H(n,p)2n$ experiments have been re-analyzed recently at Triangle Universities Nuclear Laboratory (TUNL) using a realistic nucleon-nucleon (NN) potential. In that work the 3N continuum Faddeev equations were solved rigorously using the meson-exchange based Bonn B NN potential. The comparisons between the published data and the new calculations showed that the differences persist in a_{nn} values from various $^2H(n,p)2n$ data. This project proposed a new $^2H(n,p)2n$ experiment to clarify this inconsistent experimental situation.

This project is a collaborative research effort between the principal investigator at NC A&T State University (A&T) and Drs. Howell, Tornow, and Walter at Duke University and TUNL. Tasks necessary to develop the $^2H(n,p)2n$ experiment included: computer simulation, target development, magnetic spectrometer testing, detector design and construction, and data acquisition development. The work of this project included activities at both A&T and TUNL. This work relates to TUNL's long-term interests and continuing contributions in the study of few-body nuclear systems. TUNL is an official Inter-institution Research Institute of the UNC system jointly staffed by Duke University, the University of North Carolina at Chapel Hill and North Carolina State University. Through this work, NC A&T State University, a Historically Black University, has become an active participant in the research program at TUNL. The formation of the A&T/TUNL collaboration has been an important step in the research program development of the Department of Physics, and this work has provided opportunities for physics majors at A&T to participate in forefront nuclear physics research.

In our work to date, we have localized the a_{nn} value to be between 16.5 and 18.5 fm. We have encountered disagreement between our measured cross section data and our theoretical Monte Carlo simulations for the experiment. We also have identified a significantly low sensitivity level of the FSI peak versus a_{nn} for the realistic finite geometry of our experiment. We plan to continue the work of measuring precisely the proton energy spectrum from the $^2H(n,p)2n$ reaction. We have acquired skill and expertise in the use of an Enge magnetic spectrometer in measurements of neutron induced reactions. We must explore different experimental arrangements to reduce the finite geometry effects that reduce sensitivity to measure a_{nn}. We also must resolve the issue of normalization between data and theoretical simulations.

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Introduction

The neutron-neutron (n-n) scattering length a_{nn} is a parameter that represents the strength of the n-n interaction at low energies. It can be compared with the nuclear part of the proton-proton (p-p) scattering length a_{pp} in considering the charge symmetry of nuclear forces. Charge symmetry refers to the equality of the n-n force and p-p force. The determination of charge-symmetry breaking (CSB) from low-energy nucleon-nucleon (NN) scattering experiments has been a controversial issue, but it has been accepted that charge symmetry is broken in the $^1S_0$ NN scattering. The difference a_{pp}-a_{nn} is a measure of the mass difference of the up and down quarks and therefore it is of fundamental interest [Mi9O]. The recommended value for a_{pp} obtained from p-p scattering and corrected for electromagnetic effects is [Ma89]

$$a_{pp} = -17.3 \pm 0.4 \text{ fm} .$$

The value of a_{nn} is much more difficult to determine, since a suitable free neutron target is not available. Experiments to determine a_{nn} have been performed using pion-deuteron (π^--d) capture reactions or neutron-deuteron (n-d) breakup reactions. In these deuteron reactions two neutrons with low relative momentum interact strongly in the final state: $\pi^- + d \rightarrow n+n+\gamma$ and $n+d \rightarrow n+n+p$. Currently, the recommended value for a_{nn} associated with results from a number of π^--d experiments is [Ma89]

$$a_{nn} \quad = -18.5 \pm 0.3 \text{ fm} .$$

However, results of n-d experiments give different values for a_{nn}. It should be understood why these two deuteron reactions give different a_{nn} values.

There are a number of possible contributors to the discrepancies: (1) problems with the π^--d data, (2) problems with the analyses of the nd data, and (3) problems with the nd data. Uncertainties in the analyses of π^--d capture data are sufficiently small and under control that they can be confidently excluded from adding significantly to the discrepancies. The theoretical treatment of the π^--d capture reaction is well established, and the uncertainties due to model dependencies in the value of a_{nn} determined from the analyses of π^--d capture data have been thoroughly studied [Gi75, De79]. Two quite different theoretical approaches were applied in the analyses of the π^--d data that give the most accurate values of a_{nn}. Both techniques resulted in a theoretical uncertainty of about ±0.3 fm [Gi75, De79, Ga79]. For these reasons, recent efforts have concentrated mainly on the above three issues. The first two have been addressed in recent studies. The results of a new π^--d capture measurement [Ho98] confirm the values obtained in earlier studies [Ga79, Sc87] and greatly reduce concerns about the quality of the π^--d data. The second possible problem was investigated in the re-analysis of nd breakup data by Tornow *et al.* [To93]. In nd breakup experiments, the value of a_{nn} is determined by fitting the enhancement in the cross section at the end of the proton-energy spectrum of the $^2H(n,p)2n$ reaction for proton emission angles near zero degrees [Ha77, Sh73]. The n-d breakup process at low energies is complicated and requires a rigorous solution of the three-nucleon problem for reliable interpretation of data. Furthermore, the nucleon-nucleon (NN) potential model used to describe the two-nucleon subsystem must be realistic, i.e., it must have a physically creditable form and must give a good description of two-nucleon data. These conditions were not met in the early analyses [Ha77, Sh73] and there lies the concerns. Even in the instances when the Faddeev equations were solved to give exact solutions to the three-nucleon problem, over simplified NN potential models were used to make the calculations practical with the limited computer resources available at that time. The customary approach was to use separable NN potentials that acted only in the S-wave angular-momentum state. The values of a_{nn} obtained using these analysis tools varied greatly among experiments as is exemplified by the results of Haight *et al.* [Ha77] and Shirato *et al.* [Sh73]. A brief description of the work of Tornow *et al.* [To93] follows.

Tornow *et al.* at TUNL have revisited published work on a_{nn} measurements from $^2H(n,p)2n$ experiments and have re-analyzed data using a realistic nucleon-nucleon potential in three- nucleon calculations [To93,Wi88]. In their work the 3N continuum Faddeev equations were solved rigorously using the meson-exchange based Bonn B NN potential [Ma89] with angular momentum states of quantum number $j \leq 3$. To quantify the sensitivity of the *n-n* interaction in the final state to a_{nn}, they performed a series of calculations using a charge-symmetric version of the Bonn B potential in which the $^1S_0$ force component was modified. This modification to the $^1S_0$ force component of the potential is achieved by adjusting the σ-meson coupling constant to give a particular a_{nn} value in the range -12 fm to -24 fm. A set of 3N breakup amplitudes was generated for each value of a_{nn} at several incident neutron energies. From the breakup amplitudes, proton energy spectra were calculated for all proton emission angles of interest. Calculated proton-energy spectra are shown in Figure 1 for three values of a_{nn} for a proton emission angle of $\theta_p = 4°$ and an incident neutron energy of 14.1 MeV. It is the peak at the high end of the spectrum that is sensitive to changes in a_{nn}, as can be seen from the dispersion in the curves in Fig 1. The enhanced region is due to the *n-n final-state interaction (FSI),* and the height of the peak is a measure of a_{nn}.

The new analysis by Tornow *et al.* [To93] of reported cross-section data for the $^2H(n,p)2n$ reaction eliminated the inadequacies of the theory used to obtain a_{nn} from the proton-energy spectrum. However, their results cast strong doubt on the quality of the reported data. As expected, their results differed from the original analyses. What were not anticipated were the large differences between the new a_{nn} values and the original ones, and the large dispersion in the values of a_{nn} obtained in the new analysis for the different data. For example, they obtained an a_{nn} value of -22.08 ± 1.47 fm from the experiment of Haight *et al.* [Ha77] as opposed to the reported value of -23.2 ± 3.6 fm. Also, they obtained an a_{nn} value of -16.00 ± 0.59 fm from the experiment of Shirato *et al.* [Sh73] as opposed to the reported value of -18.31 ± 0.22 fm. The data of Haight *et al.* [Ha77] and Shirato *et al.* [Sh73] are shown in figures 2 and 3, respectively, in comparison to the new calculation of Tornow *et al.* [To93]. The a_{nn} values are significantly different from each other, and they are not in agreement with π^--d capture results. The inconsistency in a_{nn} values from similar $^2H(n,p)2n$ experiments is confusing and suggests opposite effects of charge-symmetry breaking. The a_{nn} value from the data of Haight *et al.* suggests the *nn* force is stronger than the *pp* force, while the a_{nn} value from the data of Shirato *et al.* suggests the *nn* force is weaker than the *pp* force. These results strongly suggest that there are problems with the experimental data.

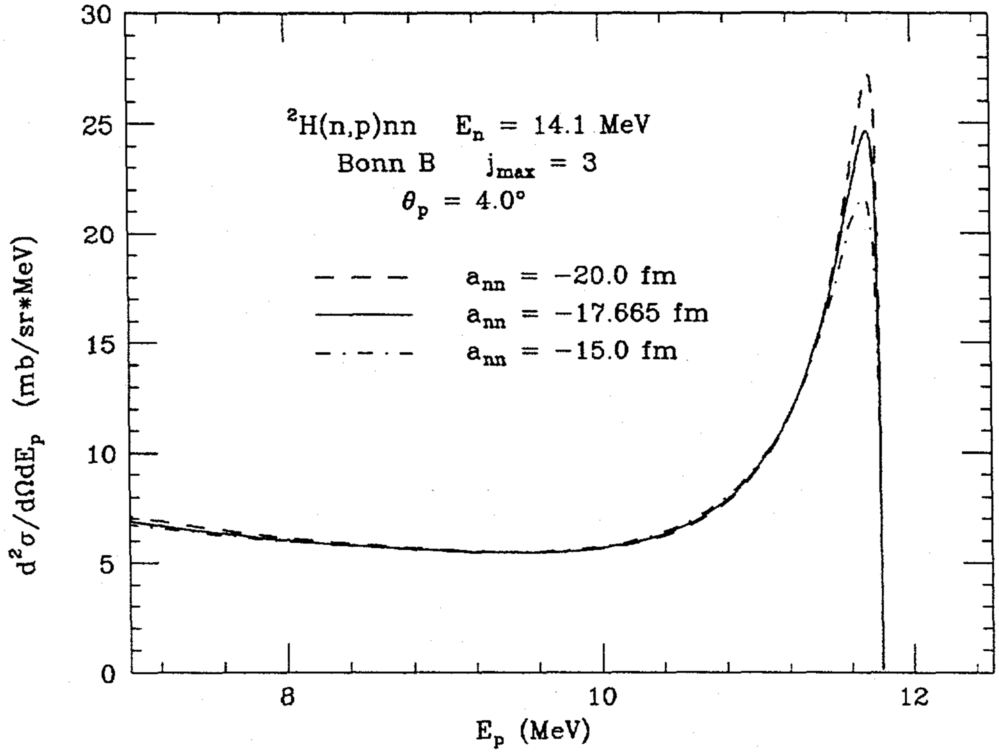

FIGURE 1: Rigorous point-geometry 3N calculations of proton energy spectra for the $^2H(n,p)2n$ reaction at an incident neutron energy of 14.1 MeV and a laboratory proton emission angle of 4.0°.

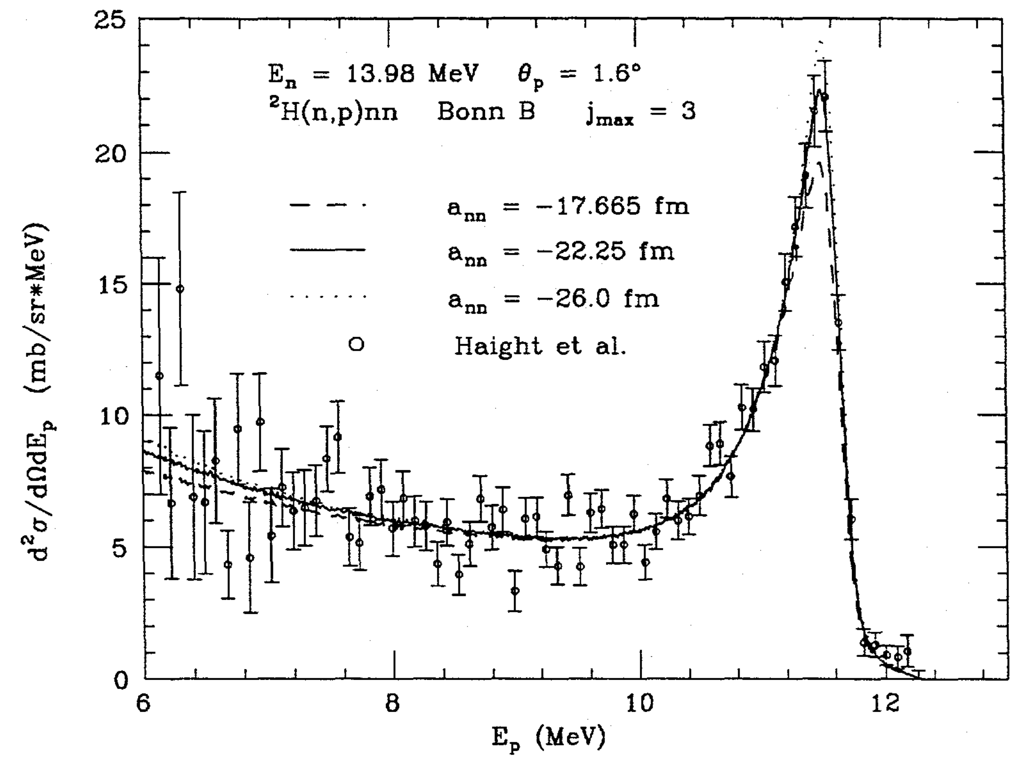

FIGURE 2: New analysis of Tornow *et al.* [To93] on data of Haight *et al.* [Ha77].

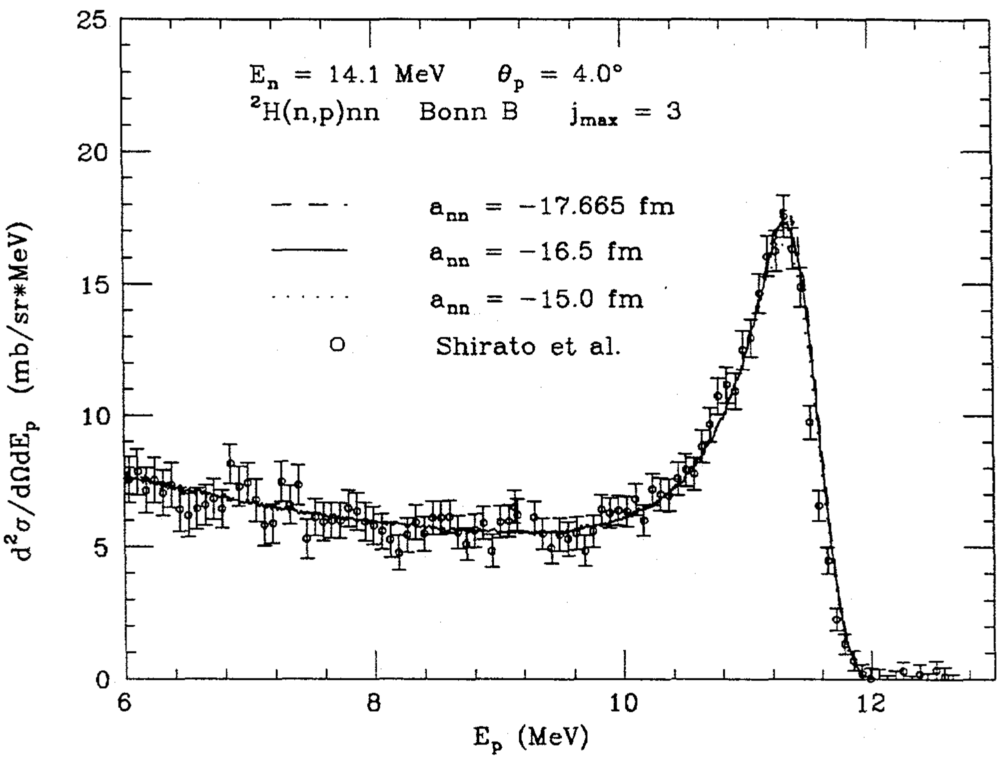

FIGURE 3: New analysis of Tornow *et al.* [To93] on data of Shirato *et al.* [Sh73].

Project Description

The goal of the present work is to clarify the inconsistencies in the values of a_{nn} obtained from the $^2H(n,p)2n$ reaction. To this aim we are making new cross-section measurements of the $^2H(n,p)2n$ reaction for emission of the protons near zero degrees. The proton-energy spectrum will be analyzed to determine a_{nn} using the same theoretical calculations employed in the work of Tornow *et a*l. [To93]. All measurements will be conducted at the tandem-accelerator facility at TUNL. The experiment will be done at a neutron incident energy of 14 MeV. The energy choice was made based on the observation that most data for this reaction were taken for neutron energies around 14 MeV and for the pragmatic reasons that neutron beams with energies between 8 and 15 MeV are routinely delivered at TUNL. A description of the experimental design is given below.

The neutrons are produced with the $^2H(d,n)$ reaction. The production target is a 3.1-cm long cell filled with 4.0 atm of deuterium. The deuteron beam that drives the source reaction is stopped in the 5.1-mm thick gold endcap of the production cell. The cell is electrically isolated to permit direct beam-current measurements and charge integration. The neutrons emerging from the source reaction near zero degrees bombard the 3-mg/cm^2 CD_2 foil. The protons from the nd breakup reaction emitted near zero degrees are analyzed by momentum in the TUNL Enge Split-pole Magnetic Spectrometer [Ch94]. The energy acceptance of the spectrum in our energy range is about 4 MeV, and the magnetic field in the spectrometer is set to analyze protons with energies between 8 and 12 MeV in our measurements.

The Enge split-pole spectrometer is designed especially for use with the tandem accelerator [En67], and it is capable of a momentum resolution of 2 x 10^{-4}. The main features of the spectrometer [En79] are given in Table I and an illustration of the spectrometer is shown in figure 4. The Enge split-pole spectrometer is designed to accept charged particles within a solid angle of 8-12 msr (millisteradians), depending upon momentum. However, the resolution deteriorates rapidly above 2 msr. To obtain optimal momentum resolution with the TUNL Enge Spectrometer, a high-resolution position detector is needed. A drift chamber [Be77,Hy84,Sc86,Sj84] located in the focal plane will provide position information with a resolution fully compatible with the split-pole magnet.. A new multi-wire proportional counter (MWPC) position-sensitive detector [Ha96,Ha97] has been developed specifically for use as the focal plane detector for the TUNL Enge spectrometer. A schematic diagram of this detector is shown in Figure 5.

The MWPC detector package consists of four detector planes: two drift chamber planes, a single-wire proportional counter, and a plastic scintillator. The two drift chamber planes are position-sensitive sections for particle position measurements, the single-wire proportional counter is for energy loss measurement, and the plastic scintillator is for total energy measurement. The position measurements are produced from TAC (time-to-amplitude converter) signals generated from right and left timing signals out of a drift chamber planes. The pulse-height measurement in the proportional counter was used in combination with the pulse-height from the scintillator and the position measurements in the drift chambers to identify the particle type from the scattering experiment. This particle ID feature of the detector will be used in our work to distinguish between protons and deuterons. The position measurements in the drift-chamber planes will be used to determine the horizontal component of the particle trajectory. From two position measurements with the MWPC, the angle of the particle's trajectory can be determined. Having the particle's trajectory angle at the focal plane will allow operation of the Enge spectrometer with a large angular acceptance. This feature is very important to increase the accumulation rate of data without degradation of the momentum resolution.

Figure 6 is a schematic drawing of the scattering chamber. The neutron gas cell was attached to the beam lime and protruded into the scattering chamber inside a chamber insert. The target rod used initially was made of lead as were the target holders, and a lead sleeve was inserted in the chamber exit port.

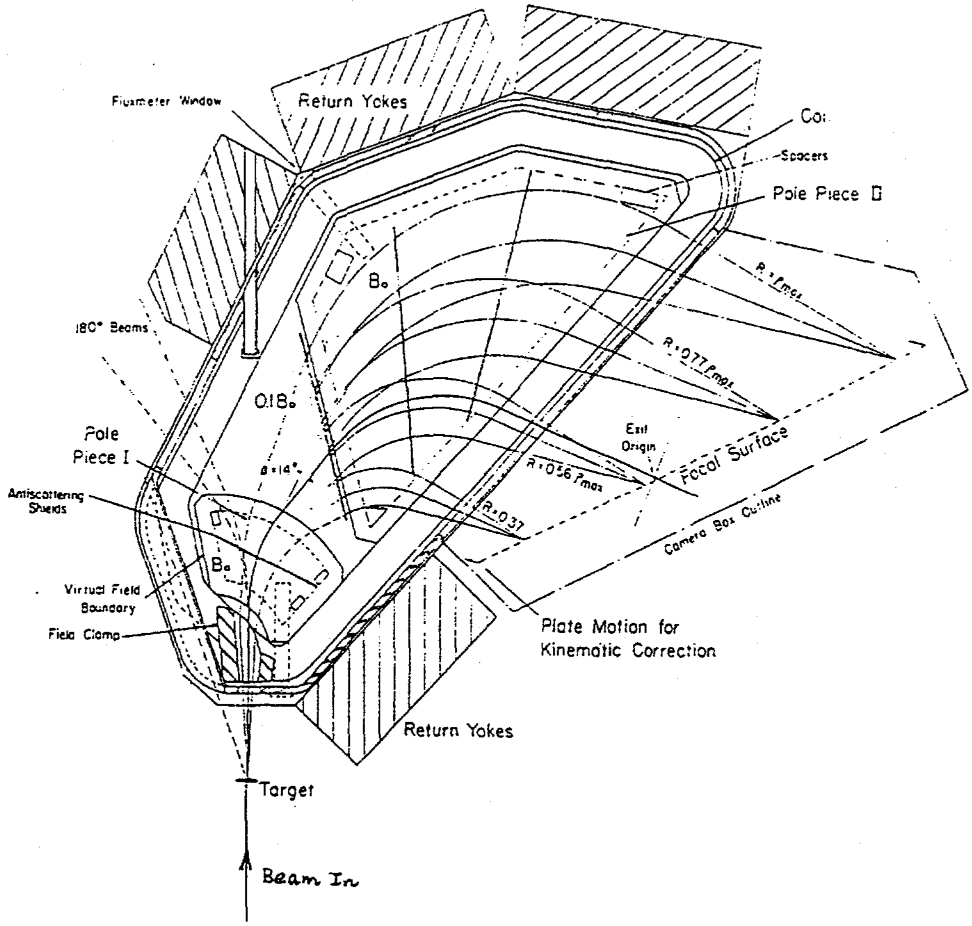

FIGURE 4: Top view of the split-pole spectrometer

Table I Features of the Enge Split-pole Spectrometer

Bending angle	114°
Range, p_{max}/p_{min}	2.8
Mean radius, ρ_0	0.6 m
Magnification, M_x	0.3
Air gap, d	3.8 cm
Vert. Magnif., M_y	4.0
Solid angle	2 msr (high resolution)
	8-12 msr (max)
Dispersion, $D=\Delta x/\Delta\rho$	1.9
Resolving power, $p/\Delta p$	4500

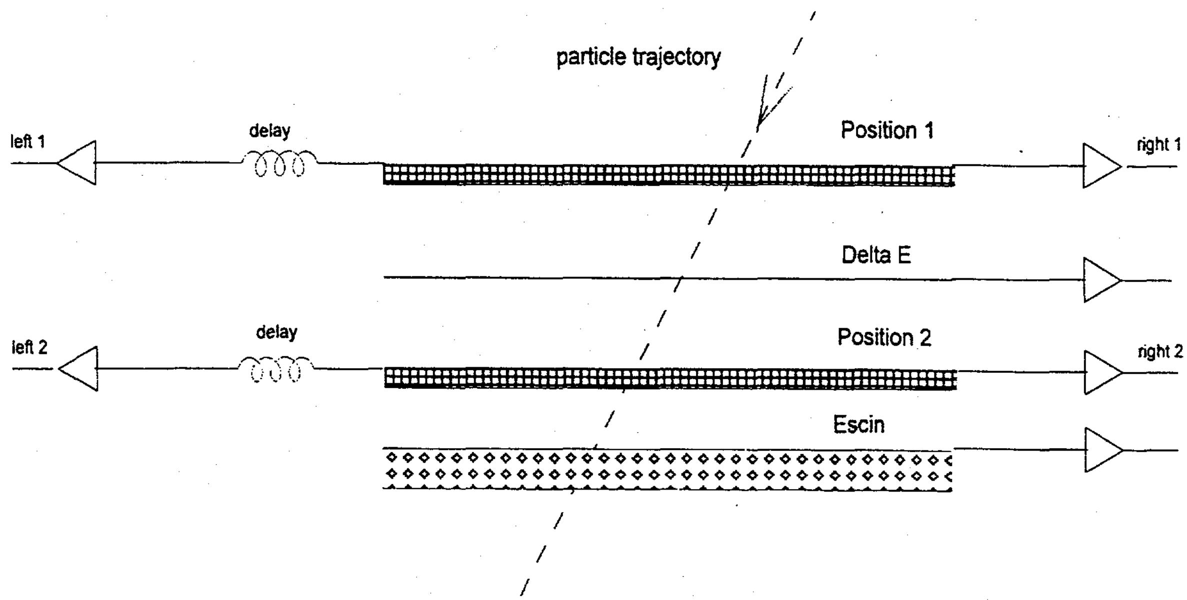

FIGURE 5: Schematic diagram of the multi-wire proportional counter (MWPC) position-sensitive detector for the TUNL Enge split-pole magnetic spectrometer.

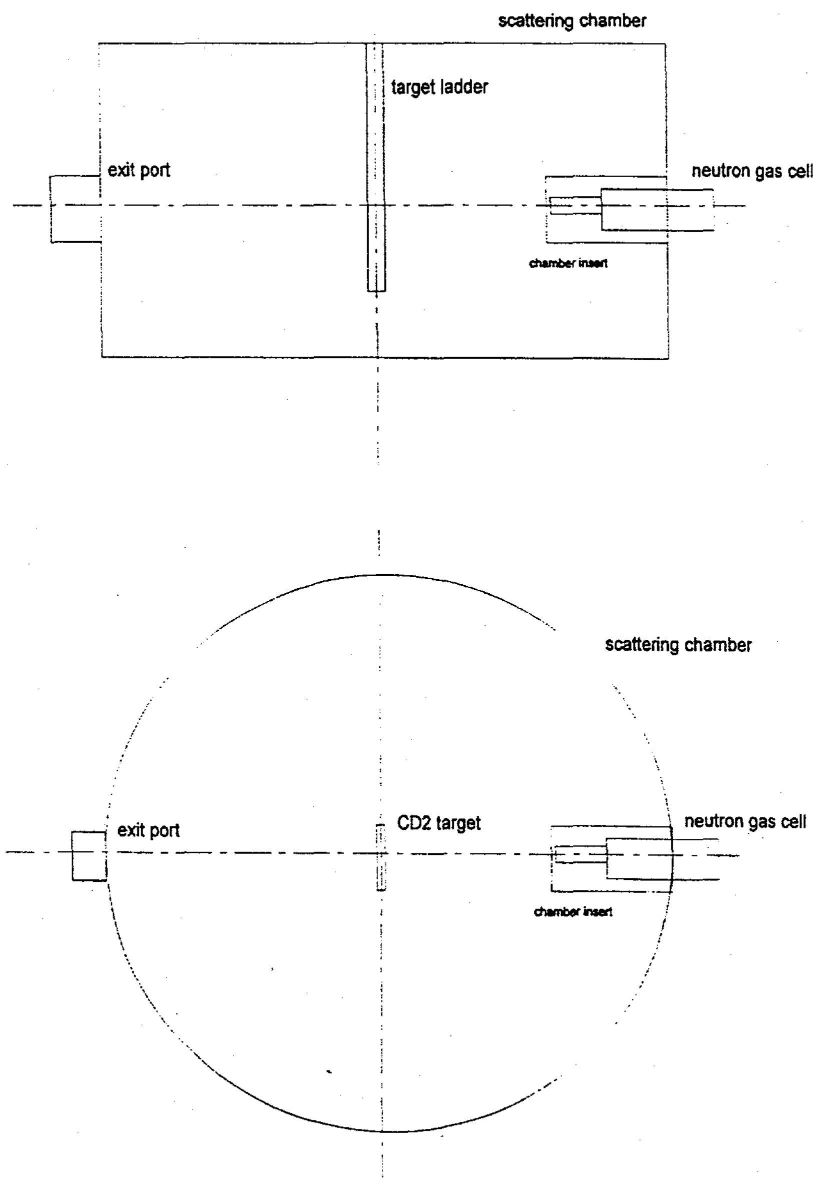

FIGURE 6: Schematic diagram of the scattering chamber.

Project Impact on NC A&T

This project is a collaborative research effort between the principal investigator at NC A&T State University (A&T) and Drs. Howell, Tornow, and Walter at Duke University and TUNL. Tasks necessary to develop the $^{2}H(n,p)2n$ experiment included: computer simulation, target development, magnetic spectrometer testing, detector design and construction, and data acquisition development. The work of this project included activities at both A&T and TUNL. This work relates to TUNL's long-term interests and continuing contributions in the study of few-body nuclear systems. TUNL is an official Inter-institution Research Institute of the UNC system jointly staffed by Duke University, the University of North Carolina at Chapel Hill and North Carolina State University. Through this work, NC A&T State University, a Historically Black University, has become an active participant in the research program at TUNL. The formation of the A&T/TUNL collaboration has been an important step in the research program development of the Department of Physics, and this work has provided opportunities for physics majors at A&T to participate in forefront nuclear physics research. A brief overview of the University and the Department of Physics is given in the appendices.

Student development in physics is enhanced substantially when the individual is involved actively in research. A key objective for the A&T/TUNL collaboration and the proposed work has been to develop and to train undergraduate physicists. Undergraduates at A&T have been involved in the research activities at the University during the academic year and at TUNL during the summer months. Undergraduates from A&T involved in this work interact with graduate students, researchers, and professors from three major universities, and therefore this work provided to A&T undergraduate students excellent research experience as well as career exposure to graduate programs in physics. Bryan Tuttle participated in the project for two summers at TUNL, graduated from A&T in physics in 1998, and is now working as a geophysicist for Western Geophysical/Baker Hughes Corporation. Andre Burton participated in experiments for two summers at TUNL and helped to set up the detector-testing laboratory in the A&T Physics Department. Andre is a graduating senior and will be entering graduate school to pursue a Ph.D. in Medical Physics. Necota Staples has participated in experiments at TUNL over the past summer and current academic year, where he has maintained and assembled detectors and fabricated targets. We are seeking support for Necota for the upcoming summer at TUNL.

The principal investigator expects to build a long-term scientific relationship with TUNL. The $^{2}H(n,p)2n$ experiment is part of a larger research program at TUNL to refine the understanding of the NN force and to maintain a leadership role in the study of few-nucleon systems. TUNL is a nationally recognized research facility and has been successful with its teaching laboratory operating structure. The laboratory is well staffed and is accessible to its researchers in a very "hands-on" mode of operation. As a result, the principal investigator has been able to build a professional and scientific foundation through this project and through TUNL, and he has become proficient in the experimental operations of low energy nuclear physics. This Department of Energy (DOE) grant is the first major award to the principal investigator, and the $^{2}H(n,p)2n$ project has involved significant skills development and R&D (research and development) effort to understand the problem and associated issues of measurement. Figure 7 shows the TUNL layout and Table II lists some of the technical proficiencies achieved by the principal investigator through this project.

Triangle Universities Nuclear Laboratory

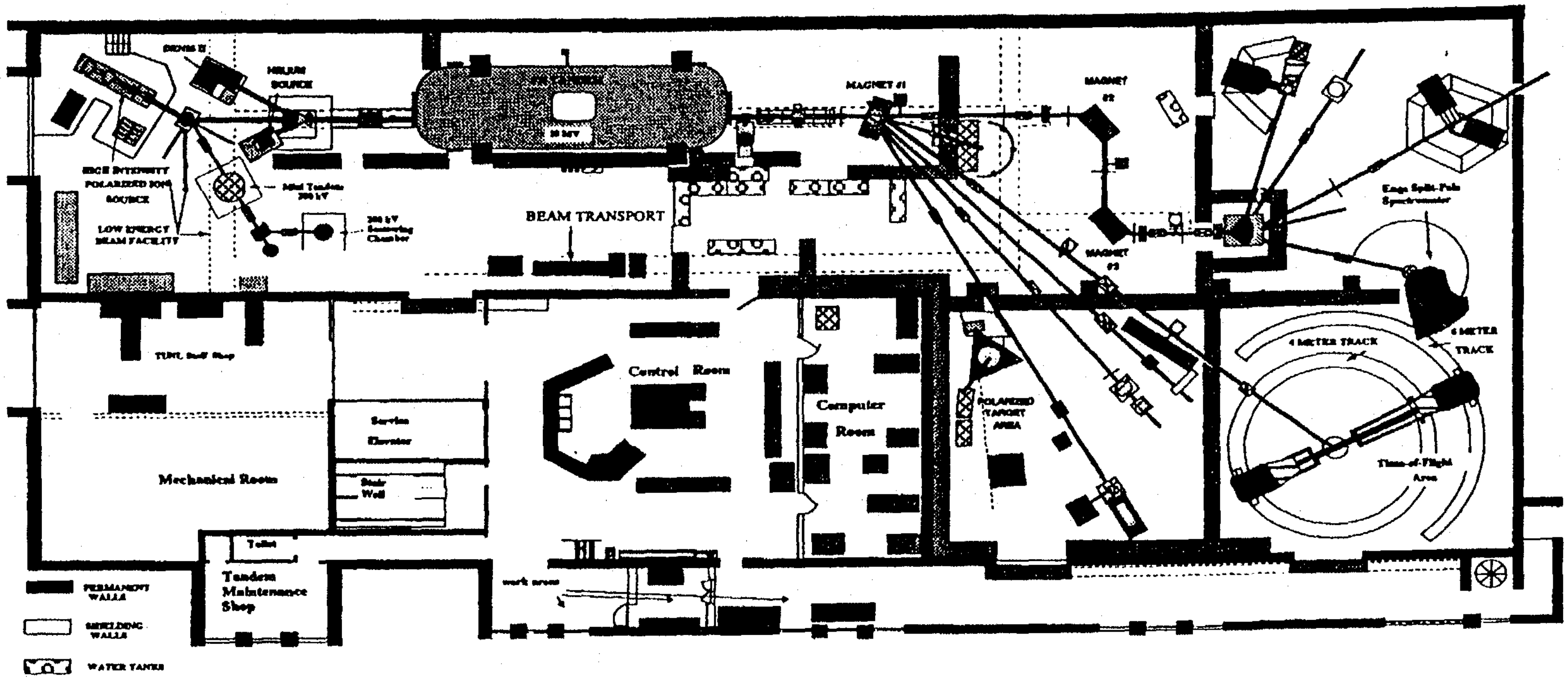

FIGURE 7: Layout of Triangle Universities Nuclear Laboratory. The Enge split-pole magnetic spectrometer used in the present work is located in the target area shown at the right-center of the diagram.

Table II Technical Proficiencies Obtained by P/I Through the $^2H(n,p)2n$ project.

Technical proficiency	Comments
Operation of the Direct Extraction Negative Ion Source (DENIS)	Startup, control, shutdown, and repair
FN Tandem Operation	Startup, control, shutdown
90-90 magnet and controls; beamline vacuum systems	Beamline setup and beam tuning
Solid and gas target development	CD2, Au, Al and other solid targets; Deuterium gas cell targets
Target chamber development	Target-holding hardware design and fabrication
Neutron shielding	
Gas detector development and operation	Setup, control, and repair
Gas detector electronics and signal processing	
Enge Split-pole Magnetic Spectrometry	
Data Acquisition Systems: Hardware and software	Setup, operations, and control
Run low-energy nuclear scattering experiments	
Data Analysis	Software development; Physical interpretation

The principal investigator is able to run experimental shifts independently, and has been involved also in other experiments in the A&T/TUNL collaboration. The hardware and software developed from the $^2H(n,p)2n$ experiment also will contribute general support to the experimental programs at TUNL and the expertise gained by the principal investigator in this effort should lead to other collaborative research opportunities.

The principal investigator (P/I) began his academic career as an Assistant Professor in the Department of Physics at North Carolina A&T in Fall, 1992. In the fall of 1994 the P/I was appointed interim chairperson and brought stability and growth to the Department of Physics. During this time, the P/I revised the curricula and enhanced the course offerings for the department's physics programs. In 1995 the P/I was appointed permanent chairperson and developed the department's research infrastructure, lead the department to increased levels of research activity and funding, and graduated the largest classes of majors. In 1996 the P/I secured UNC System approval to establish a M. S. program in Physics at NC A&T. The first student in the M. S. program in Physics graduated in May, 1998 and is now working as a geophysicist at Western Geophysical/Baker Hughes in Houston, Texas. In the spring of 1997 the P/I earned tenure and the Associate Professor rank, and at the beginning of the 1998 academic year, the P/I was promoted to Associate Dean for Research and Graduate Programs in the College of Arts and Sciences at NC A&T.

Research and Development Activities

The objectives of this research are to make a precise measurement of the proton energy spectrum from the $^2H(n,p)2n$ reaction and to extract very accurately the value of a_{nn} from these measurements. The breakup reaction will be induced with 14-MeV neutrons, and the proton energy spectrum will be measured near 0° using an Enge split-pole magnetic spectrometer. The data will be analyzed using the Bonn B and other realistic NN potentials (like the Argonne, Nijmegen, and Paris potentials) in rigorous Faddeev calculations. The results will establish a firm experimental value of a_{nn} measured in *n-d* breakup reactions for comparison with a_{nn} measured in the π^--*d* capture reaction. To determine a_{nn} to within ±0.3 fm from the $^2H(n,p)2n$ reaction requires that the absolute cross section of the proton energy spectrum be measured to an accuracy of about ±1%.

A detailed study of the systematic effects is a central aspect of the experimental work of this project and constitutes a large part of the experimental effort to achieve the desired accuracy. In particular, the Enge split-pole magnetic spectrometer is a relatively new instrument at TUNL, and expertise had to be achieved by the principal investigator in its operations and in its use in measurement of neutron-deuteron reactions. In addition, a new multi-wire proportional counter (MWPC) position-sensitive detector, developed specifically for use as the focal plane detector for the Enge spectrometer by Dr. Art Champagne of the UNC-Chapel Hill group, has been essential to this project. Assisting in the R&D and characterization activities of the Enge spectrometer and the MWPC detector have been central to the efforts of the principal investigator toward achieving a measurement of the proton energy spectrum from the $^2H(n,p)2n$ reaction.

The following is a chronology of activities in which the P/I was engaged to accomplish the R&D background and skills to measure the a_{nn} parameter from a $^2H(n,p)2n$ experiment.

CHRONOLOGY:

1995 - 96: Exploring and testing position-sensitive solid state detectors
Solid state detector setup and test
Participation in UNC-Chapel Hill Enge Group runs
Data Acquisition coding and electronics
Enge magnet control systems R&D involvement

Enge vacuum and rotation control systems operation
Sliding seal scattering chamber
DENIS: proton beam extraction
Accelerator operation
Exploring and testing scintillating paddle position-sensitive detector
Proton-proton elastic scattering

1996 - 97: Exploring vertical drift chamber (VDC) detector (loaned by Oak Ridge Nat'l Lab)
Set up detector test area at NCA&T; Test VDC detector
Participation in neutron time-of-flight (NTOF) group runs
Target hardware design and fabrication
Participation in UNC-Chapel Hill Enge Group runs
Assist in development of multi-wire proportional counter (MWPC) by UNC-Chapel Hill Enge Group
Experimentation with prototype MWPC
MWPC detector electronics and gas-handling system operations
Enge vacuum, magnet, and control systems operations
Data acquisition hardware and software operations
DENIS: proton beam extraction
Operation of the FN Tandem Accelerator
Proton-proton elastic scattering and reaction kinematics
Analytical evaluation Enge magnetic focusing system

1997-98: Participation in neutron time-of-flight (NTOF) group runs
Participation in UNC-Chapel Hill Enge Group runs
Development runs with MWPC detector; Itemization of detector problems
Participated in realignment of high-energy beamline and 90-90 magnet system
Participated in 70-70 magnet system alignment
Performance testing of new MWPC detector with UNC-Chapel Hill Group
Proton-proton elastic scattering experiments using Enge and MWPC detector
MWPC detector efficiency measurements and energy calibration runs
Installation of deuterium gas cell and neutron-proton elastic scattering runs
Neutron-deuteron breakup development runs using Enge and MWPC detector
Systematic studies of $^{1}H(n,p)$ and $^{2}H(n,p)2n$ reactions: target thickness, aperture size, and kinematic effects
Production runs on $^{1}H(n,p)$ and $^{2}H(n,p)2n$ reactions
Monte-Carlo simulations of $^{1}H(n,p)$ and $^{2}H(n,p)2n$ experiments including Enge magnetic focussing features

1998-99: Participation in neutron time-of-flight (NTOF) group runs
Production runs on $^{2}H(n,p)2n$ reaction
Data acquisition and data analysis code development and enhancements
Thin target preparation; Shielding against neutron-proton background
Data analysis and cross section extraction
Finite geometry analysis of $^{1}H(n,p)$ and $^{2}H(n,p)2n$ experiments
Monte-Carlo simulation using 3N Faddeev calculations with Bonn B potential

Preliminary measurements and interpretation

Examination of Results

We aim to make a precise measurement of the neutron-neutron scattering length a_{nn} from the neutron-deuteron (n-d) reaction $n+d \rightarrow n+n+p$ in a kinematically incomplete geometry. The energy distribution of the protons near $\theta_p=0°$ are observed from this n-d breakup reaction $^2H(n,p)2n$ for En=14MeV. The experiment is intended to resolve the inconsistency of a_{nn} values from similar experiments performed near 14 MeV [Ha77, Sh73], after re-analysis of the data using a realistic nucleon-nucleon potential in three-nucleon calculations [To93, Wi88]. Improved performance of the TUNL Enge Spectrometer and significant design changes in the focal plane detector [Ha97] have enabled us to have several development runs to study the systematic effects of the experiment and a few production runs to obtain proton spectra from the $^2H(n,p)2n$ reaction.

Proton Spectrum Measurements

We originally observed the nn FSI peak from the ^{2}H(n,p)2n reaction for En=14MeV and at $\theta_p=0°$ using a thick CD_2 solid target with a thickness of 14.4 mg/cm_2. Protons from the reaction were analyzed by the Enge spectrometer and the analyzed particles were position-detected by the focal plane detector. Figure 8 is a sample position histogram of the detected protons measured by the Position 1 detector. In this figure, the foreground and the background measurements are overlaid. The background spectrum was observed to not be flat as we anticipated, therefore modest shielding was added inside the scattering chamber to reduce background counts from expected sources of n-p background counts.

Figure 9 is a sample position histogram when a thinner CD_2 target of 3mg/cm^2 was used. The thin CD_2 target was made using the method of Bartle and Meyer [Ba73]. Figure 10 is the background subtracted proton spectrum. A narrower FSI peak is observed at the end of the spectrum for the thinner target, however two spurious peaks became obvious in the spectrum as well. We recognized that there were some electronic noise problems in the detector producing the spurious peaks and this had to be remedied in the data analysis. Also other sources of n-p background counts persisted, therefore a large effort to develop shielding for the inside of the Enge spectrometer and for the inside of the scattering chamber was undertaken.

Carbon shielding was used inside the Enge, as carbon has a large negative Q-value for n-p scattering and its cross section is at threshold near 14 MeV. Also lead shielding lined with carbon was used in the scattering chamber in such a way as to channel reaction particles into the Enge while reducing the neutron flux striking nearby surfaces. A proton energy spectrum measurement made following the shielding effort produced a cleaner spectrum. Also measured was the yield from n-d elastic scattering and the average n-d elastic differential scattering cross section value was determined for the aperture used from known n-d angular distributions [BNL62]. The absolute cross section for the proton energy spectrum for the ^{2}H(n,p)2n reaction was obtained by comparison to the n-d elastic scattering cross-section. Figure 11 is the absolute cross section of the proton energy spectrum measurement from the ^{2}H(n,p)2n experiment.

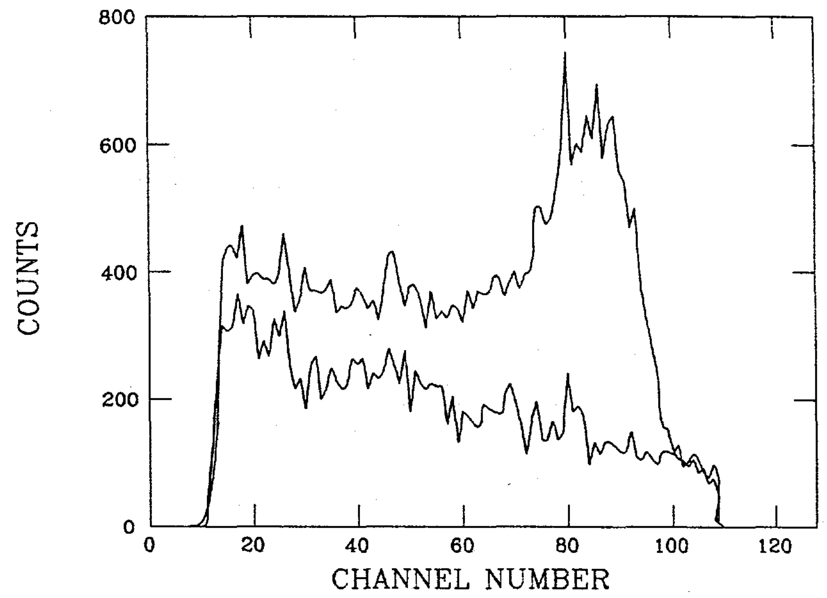

FIGURE 8: Position spectrum of protons measured (Detector #1) in foreground (top) and normalized background (bottom) of the $^{2}H(n,p)2n$ reaction for a thick CD_2 target foil of 14.4 mg/cm^2.

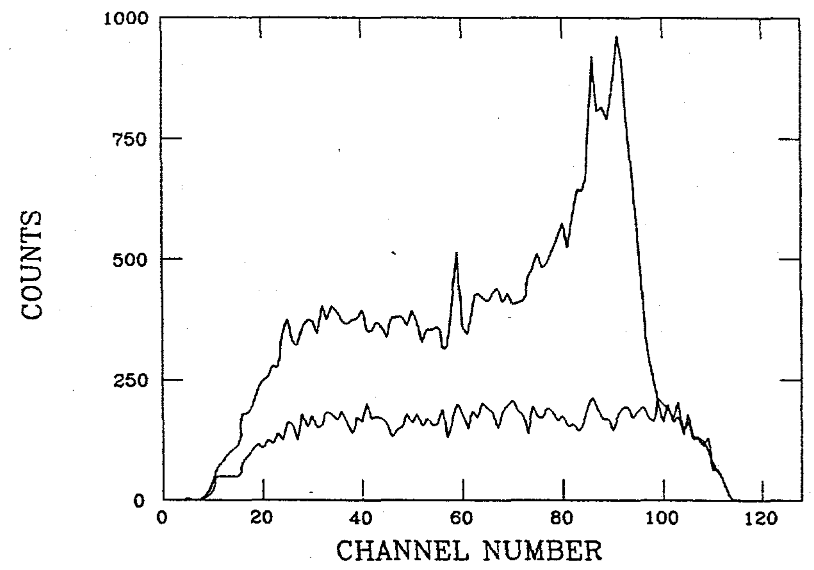

FIGURE 9: Position spectrum of protons measured in (Detector #1) foreground and background (normalized) of the $^{2}H(n,p)2n$ reaction using a thinner CD_2 target foil of 3 mg/cm^2.

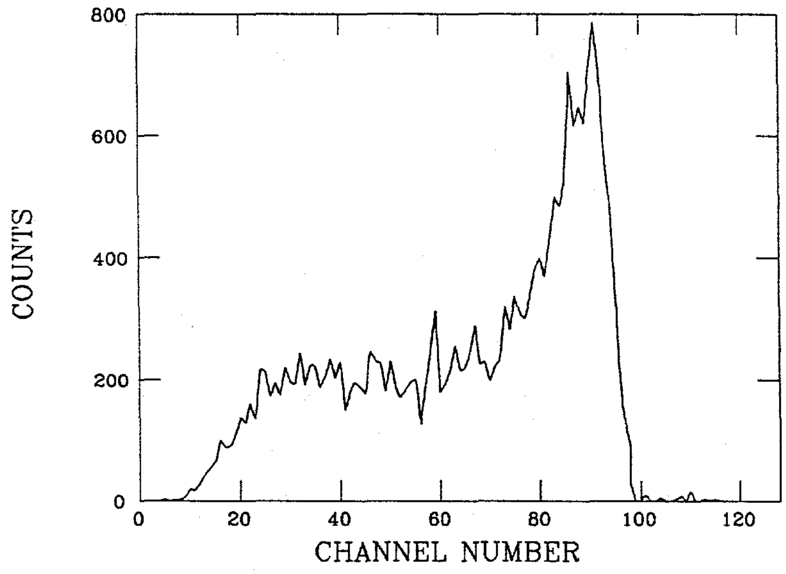

FIGURE 10: Background subtracted position spectrum of protons from the $^{2}H(n,p)2n$ reaction for the 3 mg/cm^2 thick CD_2 target foil.

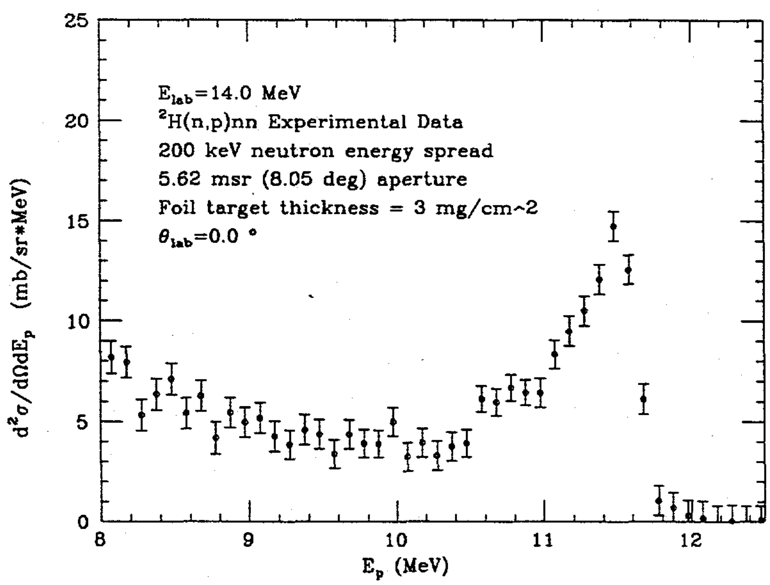

FIGURE 11: The absolute cross section of the proton energy spectrum measurement from the $^{2}H(n,p)2n$ experiment.

Monte Carlo Simulation of Data

The Monte Carlo simulation techniques used in this work is similar to that of Tornow *et al.* [To93,To96a,To96b]. The experimental details for a realistic Monte Carlo simulation (finite geometry) of our experiment is given in Figure 12. The target size was 1 cm and the aperture was 0.939 cm high by 3.322 cm wide. The gas cell to target distance was 11.24 cm and the target to aperture distance was 23.49 cm. Theoretical point-geometry proton spectra were taken from cross-section libraries generated for a range of values for a_{nn} at the incident-neutron energies and breakup proton angles of interest [To93,To96b] and used as input for our Monte Carlo simulations. Figure 13 is a comparison of Monte Carlo simulations of the ^{2}H(n,p)2n experiment for point and finite geometry. As can be seen in this figure, the effect of the finite geometry, which include target size and aperture size, in a real experiment is to reduce the cross section by a factor of 2.

Figure 14 is a comparison of Monte Carlo simulations of the ^{2}H(n,p)2n experiment for different a_{nn} values. Figure 15 is a comparison of the FSI peak sensitivity versus a_{nn} for point and finite geometry simulations for our experimental conditions. The FSI peak sensitivity for finite geometry for this experiment is reduced by a factor of 4 from that for point geometry as shown in figure 15.

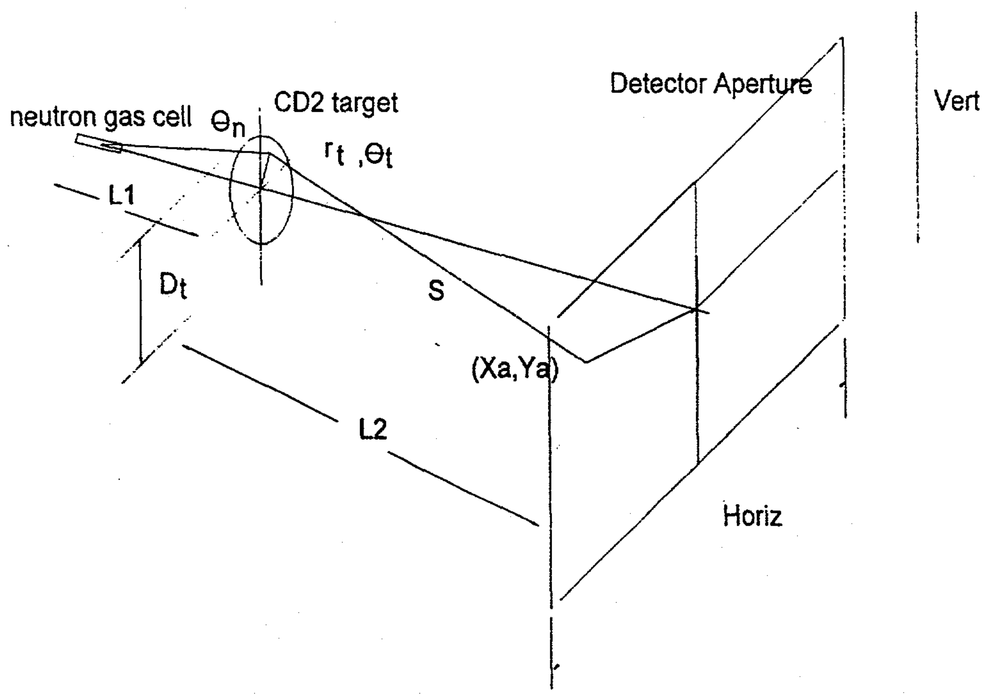

FIGURE 12: Schematic diagram of experimental layout for finite geometry Monte Carlo simulations of the ^{2}H(n,p)2n experiment.

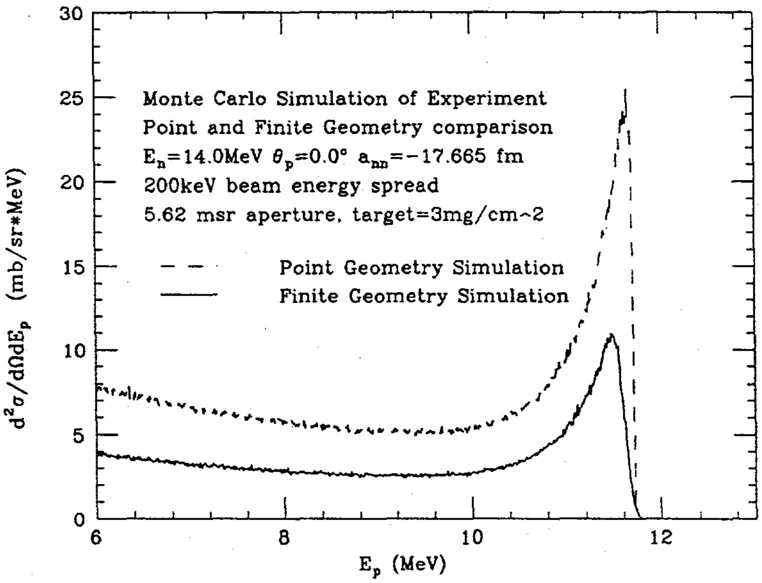

FIGURE 13: Point and finite geometry comparison of Monte Carlo simulations of the $^2H(n,p)2n$ experiment

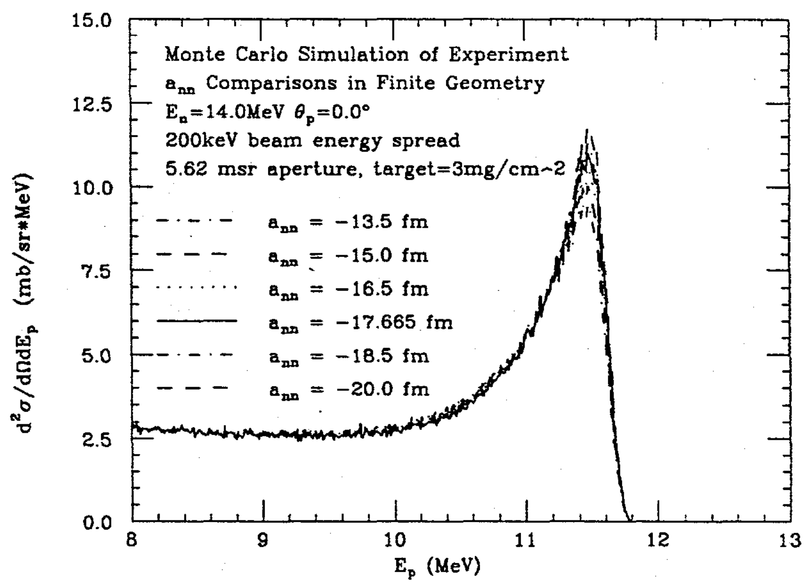

FIGURE 14: Comparison of a_{nn} values from Monte Carlo simulations of the $^2H(n,p)2n$ experiment.

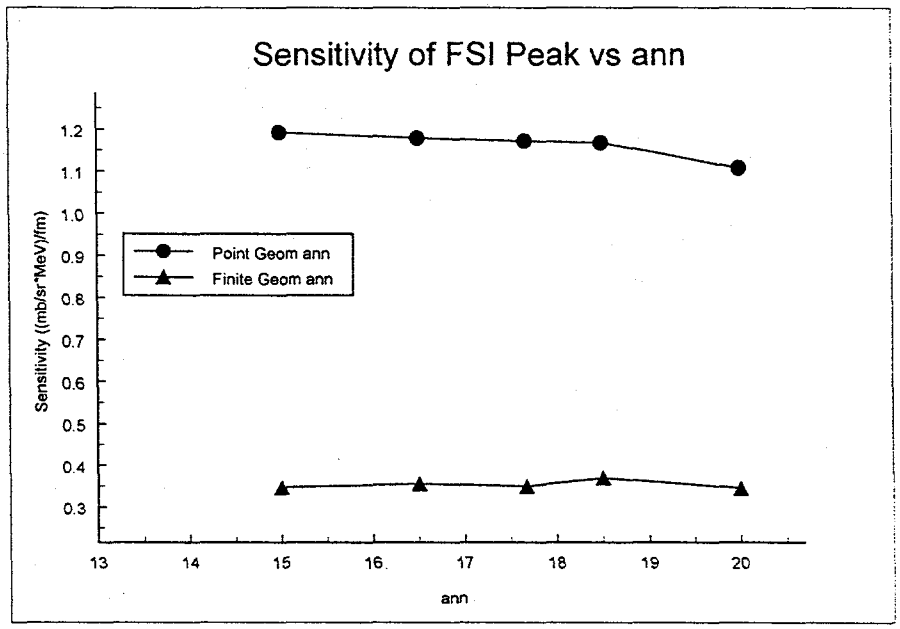

FIGURE 15: Comparison of FSI peak sensitivity versus a_{nn} for point geometry simulations and finite geometry simulations.

Preliminary a_{nn} Results

Figure 16 shows our measured cross section of the proton energy spectrum from the $^2H(n,p)2n$ experiment in comparison to theoretical finite geometry Monte Carlo simulations for the experiment. Our experimental data do not agree with the Monte Carlo calculations. To bring the data and the theoretical simulations roughly into agreement, a normalization factor of 0.72 was applied to the experimental data. The result of this action is shown in Figure 17. We note that data normalization was required also in the work of Tornow *et al.* [To93,To96b]. Also as we discovered earlier, the sensitivity of the FSI peak is four times smaller for the realistic finite geometry as compared to point geometry. The consequence of this can be seen in figure 17 by the poor separation between simulated cross sections of different a_{nn} values. Figure 18 is an expanded view of the normalized cross section data compared to simulated cross sections calculations falling within the error bars of the normalized data. This picture suggests the value of a_{nn} is between 16.5 and 18.5 fm. More work is required to resolve the disagreement between absolute cross section data and theoretical Monte Carlo calculations and to achieve a more precise measurement of the value of a_{nn}.

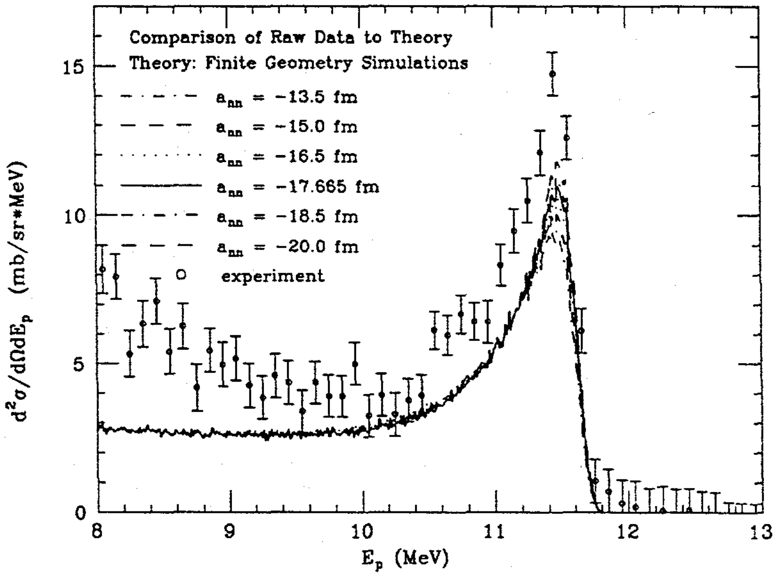

FIGURE 16: Comparison of measured data and theoretical finite geometry Monte Carlo simulations.

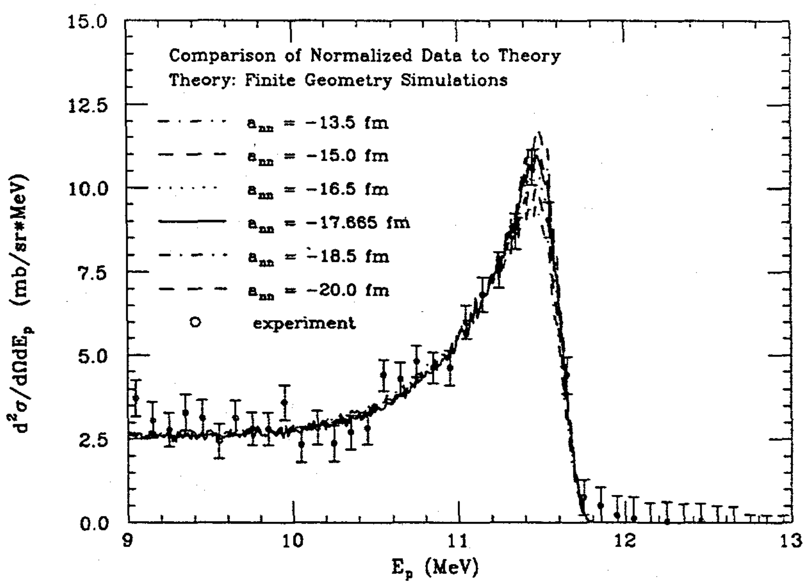

FIGURE 17: Comparison of theoretical finite geometry Monte Carlo simulations and measured data normalized by a factor of 0.72.

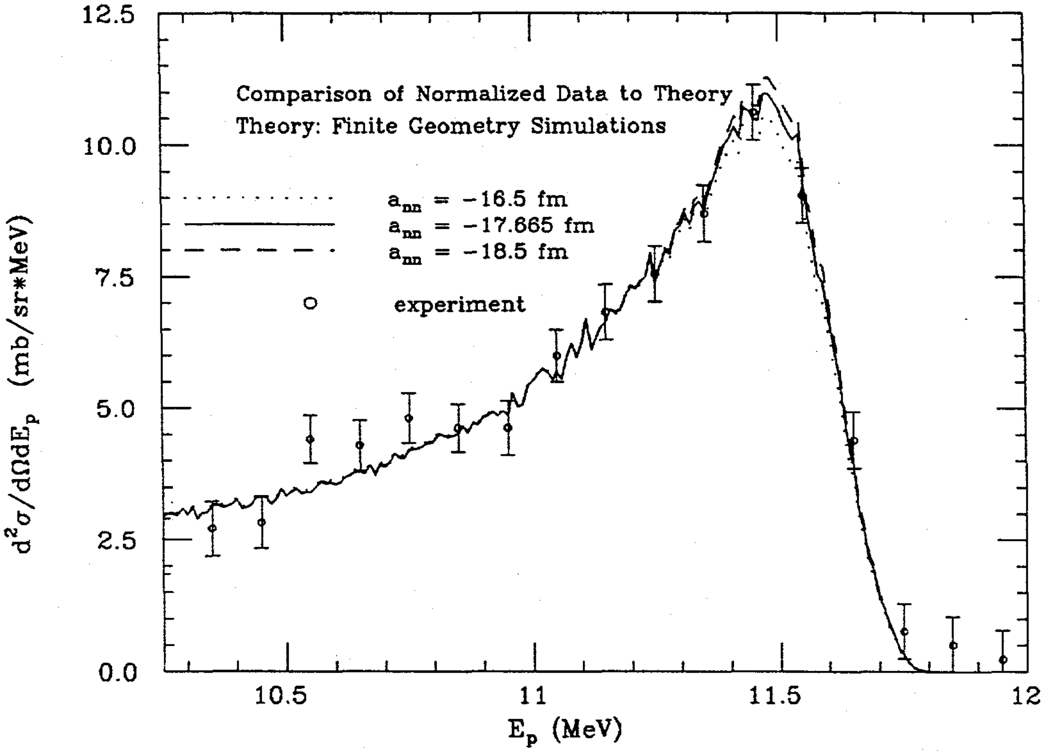

FIGURE 18: Expanded view near FSI peak of theoretical finite geometry Monte Carlo simulations and measured data normalized by a factor of 0.72.

Future Plans

The objectives of this research are to make a precise measurement of the proton energy spectrum from the $^{2}H(n,p)2n$ reaction and to extract very accurately the value of a_{nn} from these measurements. We induced the breakup reaction with 14-MeV neutrons, and measured the proton energy spectrum near 0° using an Enge split-pole magnetic spectrometer. To determine a_{nn} to within ±0.3 fm from the $^{2}H(n,p)2n$ reaction requires that the absolute cross section of the proton energy spectrum be measured to an accuracy of about ±1%. In our work to date, we have localized the a_{nn} value to be between 16.5 and 18.5 fm. We have encountered disagreement between our measured cross section data and our theoretical Monte Carlo simulations for the experiment. We also have identified a significantly low sensitivity level of the FSI peak versus a_{nn} for the realistic finite geometry of our experiment.

We plan to continue the work of measuring precisely the proton energy spectrum from the $^{2}H(n,p)2n$ reaction. We have acquired skill and expertise in the use of an Enge magnetic spectrometer in measurements of neutron induced reactions. We must explore different experimental arrangements to reduce the finite geometry effects that reduce sensitivity to measure a_{nn}. We also must resolve the issue of normalization between data and theoretical simulations.

Bibliography

Ba64 M. Bander, Phys. Rev. **134**, B1052(1964).

Ba73 M. bartle and H.O. Meyer, Nucl. Instr. and Meth. **112**, 615(1973).

Be77 W. Bertozzi et al., Nucl. Instr. and Meth. **141**, 457(1977).

Be81 R. Bellazzini et al., Nucl. Instr. and Meth. **190**, 627(1981).

BNL62 *Angular Distributions in Neutron-Induced Reactions*, M.D. Goldberg et al., BNL 400, 2nd ed. Vol. 1, 1962, p 1-2-4.

Bo82 R.A. Boie et al., Nucl. Instr. and Meth. **201**, 93(1982).

Ch94 A.E. Champange, TUNL Progress Report **XXXIII**, 132, (94)

De79 G.F. de Teramond, Phys. Rev. C **16**, 1976(1977).

En67 H.A. Enge, Nucl. Instr. and Meth. **49**, 181(1967).

En79 H.A. Enge, Nucl. Instr. and Meth. **162**, 161(1979).

Fo84 T.D. Ford et al., Nucl. Instr. and Meth. **228**, 81(1984).

Ga79 B. Gabioud et al., Phys. Rev. Lett. **42**, 1508(1979).

Gi75 W.R. Gibbs, B.F Gibson, and G.J. Stevenson, Phys. Rev. C **11**, 90(1975) and **12**, 2130(1975).

Gi77 W.R. Gibbs, B.F. Gibson, and G.J. Stevenson, Phys. Rev. C **16**, 327(1977).

Ha77 R.C. Haight, S.M. Grimes, and J.D. Anderson, Phys. Rev. **C16**, 97(1977).

Ha96 S.E. Hale, TUNL Progress Report **XXXV**, 126, (96)

Ha97 S.E. Hale, TUNL Progress Report **XXXVI**, 139, (97)

Hy84 M.V. Hynes et al., Nucl. Instr. and Meth. **224**, 89(1984).

Ho98 C.R. Howell et al., Phys. Lett. B **444**, 252 (1998).

Ko86 N. Koori et al., Conf. Few Body Systems in Particle and Nuclear Physics, eds. T. Sasakawa et al., Suppl. Res. Rep Tohoku Univ. **19**, 406, (1986).

Ma75 R.G. Markham and R.G.H. Robertson, Nucl. Instr. and Meth. **129**, 131(1975).

Ma79 R.G. Markham, Nucl. Instr. and Meth. **162**, 327(1979).

Ma89 R. Machleidt, Adv. Nucl. Phys. **19**, 189(1989).

Mi9O G.A. Miller, B.M.K. Nefkens, and I. Slaus, Physics Reports **194**, 1 (1990).

Mo82 C.L. Morris, Nucl. Instr. and Meth. **228**, 263(1982).

Sa75 R.M. Salter, Nucl. Phys. **A254**, 241(1975).

Sc86 J.M. Schippers, W.T. Borghols, and S.Y. Van der Werf, Nucl. Instr. and Meth. **A247**, 467(1986).

Sc87 O. Schori et al., Phys. Rev. C **35,** 2252 (1987).

Sh73 S. Shirato et al., Nucl. Phys. **A215**, 277(1973).

Sj84 T.P. Sjoreen et al., Nucl. Instr. and Meth. **224**, 421(1984).

St72 A. Stricker et al., Nucl. Phys. **A190**, 284(1972).

To93 W. Tornow, R.T. Braun, and H. Witala, Phys. Lett. **B318**, 281(1993).

To96a W. Tornow, R.T. Braun, H. Witala, and N. Koori, Phys. Rev. C **54**, 42(1996).

To96b W. Tornow, R.T. Braun, and H. Witala, Few-Body Systems **21**, 97(1996).

Tu92 <u>Trianigle Universities Nuclear Laboratories Annual Report TUNL XXXXI</u> (Duke University, Durham, 1992), p. 174.

Wi88 H. Witala, T. Cornelius, and W. Glockle, Few-Body Systems **3**, 1(1988).

Appendices

North Carolina A&T and the Department of Physics

North Carolina Agricultural and Technical State University is a unique, comprehensive University, which offers bachelor's, master's and Ph.D. degrees, with more than 79 undergraduate majors, more than 41 master's degree programs, and Ph.D. degrees in Mechanical and Electrical Engineering. The academic programs are offered through the schools of Agriculture, Business and Economics, Nursing, Technology, the Graduate School, and the Colleges of Engineering and Arts and Sciences.

North Carolina A&T State University is the nation's No. 1 producer of minorities with degrees in science, mathematics, engineering, and technology. A&T also is one of the largest producers of certified public accountants among historically black colleges and universities.

Strengths of the University begin with the enrollment of an outstanding student body, carefully selected from thousands of applicants annually. Once on campus, the nearly 7,500 students are taught and mentored by an excellent faculty, of whom 95 percent have earned doctoral or other terminal degrees from some of the nation's most prestigious graduate and professional schools.

The Department of Physics at North Carolina A&T State University provides graduate and undergraduate education which emphasizes fundamental physical principles and which permits development of scientifically trained individuals capable of meeting the scientific and technical challenges encountered in academic, governmental, or industrial settings. The undergraduate physics program has three degree tracks and the graduate physics program has two tracks:

Professional Physics -- BS
Engineering Physics -- BS
Secondary Education Physics -- BS

Professional Physics -- MS
Applied Physics -- MS

The environment in the Department of Physics is productive in academics and research, and provides students a secure platform from which to develop in physics. The Department of Physics at A&T has developed research programs which include nuclear physics and condensed matter physics. Scientific collaborations have been established by faculty members with national laboratories such as TJNAF (Thomas Jefferson National Accelerator Facility and its Continuous Electron Beam Accelerator), Lawrence Berkeley Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, and TUNL (Triangle Universities Nuclear Laboratory). Research collaborations exist also with several major universities in the state and in the nation. Faculty members have been engaged also in research with NASA (National Aeronautics and Space Administration) and established the department's Student Space Shuttle Program. An A&T student-developed scientific payload was launched on the NASA Space Shuttle Endeavor on October 2, 1994.

The Department of Physics has enjoyed much success in producing graduates who have gone on to earn the Ph.D. in physics. One famous graduate of A&T's physics program is Dr. Ronald McNair, astronaut of NASA. Dr. McNair is remembered as one of several astronauts who perished in the space shuttle Challenger disaster in 1986. Two brothers, Calvin Lowe and Walter Lowe, graduated from the physics program at A&T and went on to earn their doctorates from MIT and Stanford University, respectively. Dr. Calvin Lowe is Vice President for Research and the Dean of the Graduate College at Hampton University, and Dr. Walter Lowe is a highly respected Professor of Physics at Howard University. A number of other graduates from A&T's physics program have gone on to earn medical degrees. Dwight Davis, MD and an A&T physics graduate, played and important role in the development of the artificial heart at Penn State University. Graduates of the Department of Physics at A&T clearly have had a positive impact on science and technology in our nation.

Curriculum Vitae of P/I

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Education:
Doctor of Philosophy, Physics, North Carolina State University, Raleigh, NC, 1992
Master of Engineering, Electrical Engineering, University of Florida, Gainesville, FL, 1980
Bachelor of Engineering Technology, Electrical Engineering, Florida Agricultural and Mechanical University, Tallahassee, FL, 1977

Employment History

Academic:

Date	Rank/Title	Institution
1998-present	Associate Dean for Research and Graduate Programs, College of Arts and Sciences	NC A&T State University
1997 - 1998	Associate Professor and Chairperson	NC A&T State University
1995 - 1997	Assistant Professor and Chairperson	NC A&T State University
1994 - 1995	Assistant Professor and Interim Chairperson	NC A&T State University
1994 summer	Visiting Scientist	TUNL*
1993 summer	Visiting Scientist	CEBAF** and TUNL
1992 - 1994	Assistant Professor	NC A&T State University

* TUNL is Triangle Universities Nuclear Laboratory, Durham, NC
** CEBAF is Continuous Electron Beam Accelerator Facility, Newport News, VA

Industrial:

Date	Title	Company
1990 - 1992	Staff Engineer/Scientist	IBM** Corporation, RTP*, NC
1983 - 1990	Senior Associate Engineer	IBM Corporation, Boca Raton, FL and RTP, NC
1978 - 1983	Associate Engineer	IBM Corporation, Boca Raton, FL
1977 - 1978	Junior Engineer	IBM Corporation, Boca Raton, FL

** IBM is the International Business Machines Corporation
* RTP is the Research Triangle Park in North Carolina

Professional Societies: American Physical Society, National Council on Undergraduate Research, American Association of Physics Teachers

Research Fields: Experimental Nuclear Physics, Instrumentation, Experimental Plasma Physics

Research Activity: Measurement of the neutron-neutron scattering length parameter from neutron-deuteron breakup experiments at the Triangle Universities Nuclear Laboratory (TUNL). Wire chamber detector development for undergraduate research experiences. Hypernuclei studies at Thomas Jefferson National Accelerator Facility.

Selected Publications and Presentations:
1. "Quasifree (e,e'p) Reactions and Proton Propagation in Nuclei", with the E91-013 Collaboration of Thomas Jefferson National Accelerator Laboratory, accepted to *Physics Review Letters*.
2. "Quasi-free (e,e'p) reactions: the first look from CEBAF". E-91-013 Collaboration. Proceedings of the 14th International Conference on Particle and Nuclei, PANIC 96. World Scientific. New Jersey. pp.155-162.

3. "Momentum Transfer dependence of the H(e,e'K)Lambda cross sections". E-93-018 Collaboration. *Bul. Am. Phys. Soc.* **42(2)** (1997) 979.
4. "The Energy and A Dependence of Proton Propagation Through Nuclei as Measured in the (e,e'p) Reaction". E-91-013 Collaboration. *Bul. Am. Phys. Soc.* **42(2)** (1997) 1044.
5. "The TUNL Neutron-Proton Scattering Length Experiments", F. Salinas, C. R. Howell, W. Tornow, D. E. Gonzalez Trotter, T. S. Carman, Q. Chen, C. D. Roper, H. R. Setze, R. L. Walter, H. Witala, I. Slaus, H. Tang, Z. Zhou, and C. R. Jackson, *Bul. Am. Phys. Soc.* **40** (1995) 1045.
6. "Evaluation of a New ECR Ion Source for a Single Ended Van de Graaff Accelerator", C. R. Jackson, G. A. Vavrina, G. E. Mitchell, E. G. Bilpuch and C. R. Westerfeldt, *Bul. Am. Phys. Soc.* **36** (1991) 2731.
7. "A New ECR Ion Source for a Single Ended Van de Graaff Accelerator", C. R. Jackson, W. M. Hooke, G. E. Mitchell, E. G. Bilpuch and C. R. Westerfeldt, *Bul. Am. Phys. Soc.* **34** (1989) 2360.
8. "Effect of Vibrations on the Energy Unresolved Electron Scattering by H2 and D2", K. Szalewicz, W. Kolos, H. J. Monkhorst, and C. Jackson, *J. Chem. Phys.* **80** (1984) 1435.

Department and University Activities:

Chair of Committee on Graduate Programs for SACS 2000 Self-Study
Chair of the Search Committee for Associate Vice Chancellor for Academic Affairs and Dean of Graduate Studies
Chair of the Search Committee for Dean of Graduate Studies
Chair of the MS in Physics Planning Committee
Director of the A&T Physics Scholars Program
Member of the Committee on Patents and Copyrights
Member of the Teacher Education Council
Member of the Graduate Council
Member of the College of Arts and Sciences Curriculum Committee
Member of the College of Arts and Sciences Retention and Graduation Rates Committee
Chair of the Physics Department Curriculum Committee
Physics Department Curriculum Advisor