A proposal to measure the cross section of the space star in neutron-deuteron breakup in a recoil geometry setup

For the Period

1 July 2005 to 30 November 2008

U.S. Department of Energy

Final Report

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TABLE OF CONTENTS

1. <u>Project Description</u>

1.1 Team Members

The North Carolina Central University group is composed of Dr. Benjamin Crowe, Assistant Professor of Physics (PI), and Dr. Diane Markoff, Assistant Professor of Physics (Co-PI). Since the summer of 1998, the PI has collaborated with Professor Calvin Howell and the neutron-time of flight (NTOF) group at the Triangle Universities Nuclear Laboratory (TUNL). Dr. Markoff was a Research Assistant Professor at NC State University working at TUNL with the fundamental symmetries group and joined the NCCU faculty in September 2003.

The work of our group is partially supported by a grant from the Department of Energy. Because NCCU is primarily an undergraduate serving institution and our faculty have substantial teaching responsibilities relative to faculty at major research institutions, most of our group's research activity occurs during the summer months. The PI and Co-PI have spent two months each summer from 2005 through 2007 at TUNL. The close proximity of TUNL to NCCU, about 10 miles, enables us to maintain a modest level of research activity during the academic year. The PI and Co-PI spend about one to two days per week at TUNL doing data analysis and participating in experiments.

Students Supported By Grant

During the summer months from 2005 through 2007, five minority undergraduate students have contributed to the research efforts of this project. In addition, the indicated students (*) worked during the academic year.

Joseph Estevez* (Undergraduate Student- NCCU)

Clarisse Steans (Undergraduate Student –NCCU)

Louis Threatt* (Undergraduate Student –NCCU)

Larry Cumberbatch* (Undergraduate Student – NCCU)

Aaron Swindell (Undergraduate Student – Morehouse College)

Collaborators: Nd Star Collaboration

Calvin Howell (Professor and Director of TUNL, Duke University & TUNL)

Alex Crowell (Research Scientist, Duke University & TUNL)

Mathew Kaiser (Graduate Student, Duke University & TUNL)

Ronald Pedroni (Assistant Professor, North Carolina A&T State University & TUNL)

James Esterline (Graduate Student, Duke University & TUNL)

Brent Fallin (Associate in Research, Duke University & TUNL)

1.2 Introduction:

This work was motivated by a desire to gain insight into the space-star anomaly in nd breakup. The goal of our project was to measure the space-star cross-section at 19.0 MeV using an experimental technique that was significantly different from the one used in prior breakup experiments. The previous experiments were based on the coincidence detection of all three final state nucleons, *i.e.*, the two neutrons and the proton. In all previous cross-section measurements of the space-star configuration in nd breakup [1-7], essentially the same experimental setup was used. The common features of the setups were: (1) the deuteron scatterer was a deuterated scintillator (thereby enabling the detection of the emitted proton), (2) two neutrons were detected in coincidence using liquid organic scintillators, and (3) the target-beam integrated luminosity was determined by nd elastic scattering. The energy of the emitted proton and the momentum of each of the two neutrons were measured. The largest sources of systematic errors in these measurements are due to uncertainties in the beam-target luminosity determination, the neutron detection efficiency and the neutron attenuation correction. We proposed to use the technique that was developed by Huhn et al. [8] to measure the nn scattering length. In this setup, the deuterium scatterer is a thin foil and a neutron is detected in coincidence with the emitted proton. The target-beam luminosity is determined using two independent measurements that are made concurrently with the nd breakup measurements: nd elastic scattering and np elastic scattering. The nd elastic scattering measurements are made using the charged-particle arms of our experimental apparatus, and the np scattering measurements are made with a recoil-proton telescope that is positioned downstream of the CD_2 foil.

There are three possible scenarios for the outcome of this work: (1) the new data are consistent with previous measurements; (2) the new data are not in agreement with previous measurements, but are in agreement with theory; and (3) the new data are not in agreement with either theory or previous measurements. Any one of the three scenarios will provide valuable insight into the existing discrepancies in 3-body nuclear physics.

1.3 Accomplishments During the Proposal Period

Our main objective through the funding period was to measure the coplanar, space, and intermediate star configurations in nd breakup at 19.0 MeV using an experimental technique with systematic errors that were significantly different from those of the existing data. The proposed timeline for this research followed by the accomplishments made during each year of the grant period are given below.

1. Year 1: to evaluate the two options for detecting charge particles, to design a scattering chamber and initiate its fabrication, and to start developing a Monte-Carlo simulation program.

2. Year 2: to develop the experimental setup (constructing and testing the target chamber, the proton detector arm, the neutron detectors and the detector electronics setup and trigger circuits) and measurement techniques, which include carrying out test and development runs.

3. Year 3: to continue measurements of the star cross-sections and prepare the results for publication.

Year One Accomplishments: Determination of Methodology

We evaluated the two options proposed in the project to detect the recoil protons and deuterons in the charged-particle arm of the scattering chamber. The two options considered were: (1) employ the plastic scintillator for charged-particle detection as in the setup of Huhn et al. [8] and use particle identification and time-of-flight (TOF) to determine the particle energy, or (2) replace the plastic scintillator with a silicon surface barrier solid-state detector, which would give about a factor of seven improvement in the energy resolution of the charged-particle detection. Given that the energy spread of the emitted protons and deuterons due to their energy loss in the 30 mg/cm^2 thick CD_2 foil is comparable to the energy resolution of the TOF method, a reduction in the detector energy by an order of magnitude would give a substantial (more than 40%) improvement in the total resolution of the charged-particle energy measurement. The central issues in assessing the two options were: (1) whether the improvement in the energy resolution would be sufficient to resolve detected deuterons from nd elastic scattering from those from the ^{12}C(n,d) reaction so that nd elastic scattering can be used to determine the target-beam luminosity; (2) implementation cost; (3) durability in high neutron flux; and (4) engineering complexity.

In the first option the charged-particle arm of the scattering chamber would consist of a 5mg/cm^2 thick CH plastic scintillator followed by a five-inch diameter plastic scintillator placed 70 cm from the CD_2 foil. This setup enables particle identification by two means: time of flight measurements and ΔE-E techniques. The main limitation of this technique is the large intrinsic spread in the proton energy measurement, about 1.7 MeV (FWHM) for 5.6 MeV protons and fractionally increases with decreasing proton energy. Our ability to make measurements at lower energies is seriously limited with this setup for proton detection.

For the second option we considered using thin Si surface barrier ΔE detectors with thicknesses between 10-30 μm and 250-500 μm thick E detectors for stopping the protons. The resolution of the proton energy measurement will be about 243 keV (FWHM) for 5.6 MeV protons which is the energy of the protons at the star point at incident neutron energy of 19.0 MeV. This factor of seven improvement in the resolution of the proton energy measurement should enable us to maintain adequate charged-particle identification to make measurements at incident neutron energies below 19.0 MeV.

To evaluate the second option for the charged-particle arm, we had a test run in July 2005 using an existing scattering chamber at TUNL that was on loan from a group at the University of Bonn. We found in this run that the improvement in the charged-particle energy resolution was not adequate to cleanly separate the deuterons from nd elastic scattering from those from the $^{12}C(n,d)$ reaction. The factor of seven improvement in the detector energy resolution was not sufficient to overcome the energy spread due to the energy loss (around 4.1 MeV for deuterons and 2.3 MeV for protons) of the particles in the 30 mg/cm^2 target. If the 30 mg/cm^2 CD_2 foil is replaced with a 15mg/cm^2 foil, the energy loss reduces to 1.87 MeV for deuterons and 1.11 MeV for protons at incident neutron energy of 19.0 MeV. Our conclusion was that it would not be advantageous to use silicon detectors unless a thinner target is used but with that comes a linear decrease in the count rate. To compensate for the reduction in the count rate due to using a thinner target, the diameter of the silicon detectors must be increased to cover a larger solid angle than the plastic scintillator. The size requirement of the solid-state detector makes it much less cost effective than using plastic.

We decided to implement the charged-particle arm using option 1. The main consequence of this choice is that the poor charged-particle energy resolution of the system makes nd–elastic scattering less accurate for determining the beam-target luminosity for the break-up data, therefore requiring that we additionally use the np-elastic scattering data.

Year Two Accomplishments: Apparatus Design and Construction

During this year we completed the design and construction of the scattering chamber, and installed it on the shielded neutron beam line at TUNL. We also completed the experimental setup which includes the neutron detectors, the detector electronics and the event trigger circuits.

Based on the conclusions reached in the July 2005 test run, we designed the scattering chamber using plastic scintillation detectors for charged-particle detection. The new chamber was based on a modular design with five major components: (1) a central cylinder, (2) a top dome, (3) two charged-particle arms, (4) a target rod and (5) a bottom plate with ports for the ΔE detectors and attachments. In addition, we focused on developing the experimental setup (the neutron detector and the detector electronics setup and trigger circuits). A schematic diagram of four of the major chamber parts is shown in Figure 1. The modular design enables convenient and economical changes to the experimental setup. A main feature of our chamber design was to enable simultaneous measurements of multiple star configurations. Two proton detector arms are positioned symmetrically about the incident neutron beam axis to allow symmetric measurements about the incident beam axis.

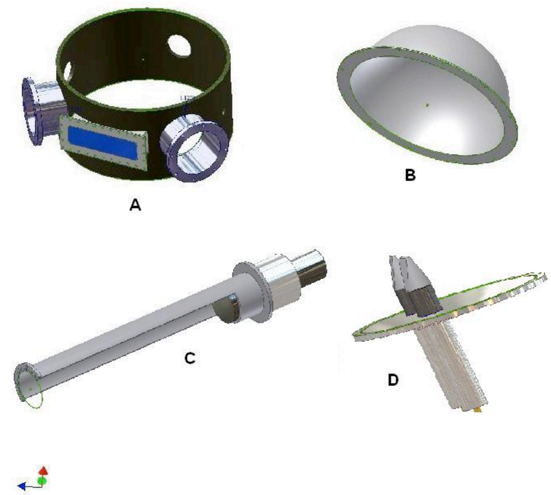

Figure 1: Four modules of the scattering chamber. (A) Central Chamber view with ports at 52.1^{o} with respect to the neutron beam axis and a 6.4 in. wide window port for outgoing neutrons, (B) Thin top dome (0.125 in thick aluminum) with flange (C) Sliced view of the proton arm showing the position of the E detector (D) Base plate showing positions of the ΔE detectors.

For educational reasons, the design phase of the chamber extended beyond the original projected allotted time period. We started the design project with two undergraduates and completed the project with two other undergraduate students. More time was needed to train the students to produce mechanical drawings appropriate for the machine shop and with a minimum of errors. The students produced all of the submitted drawings and provided the figures for conference presentations and these reports. Additional time was taken by the instrument shop for vacuum tests and repairs to make sure that the chamber with its many welded parts, did not leak substantially under vacuum.

Year Three Accomplishments: Initial Data Runs

During the third year of the project, we accomplished the tasks of building and testing the scattering chamber system and using it to collect 452 hours of data for the space and coplanar star configurations at TUNL. Because of space limitations and the potential problem of cross talk between the detectors, the nd-breakup cross section for the intermediate star configuration was not measured. Figure 2 shows a snapshot of the experimental setup used for the production runs. Neutron detectors (black cylinders) were set out of the plane of the beam for the space star configuration with azimuthal angles of 60° and 120° and at polar angles of $\pm$ 52.1^{o} with respect to the neutron beam axis while the neutron detectors for the coplanar star configuration were set in the plane of the beam at azimuthal angles of 0° and 180° and at polar angles of $\pm$16.9° with respect to the beam axis. The space and coplanar star detectors have flight paths from the CD_2 target foil of 50 cm and 70 cm, respectively.

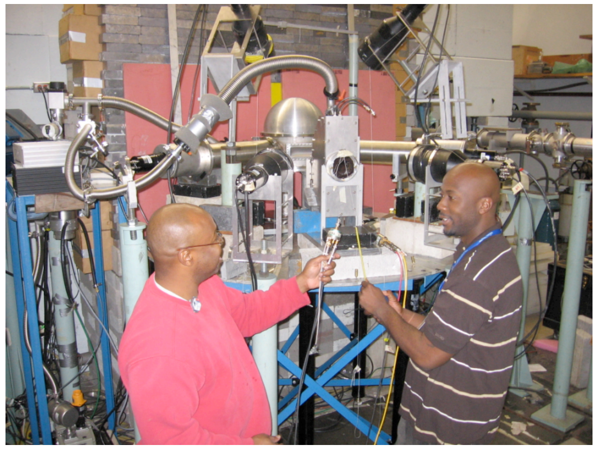

Figure 2: Experimental setup with new scattering chamber. Larry Cumberbatch (on the right) a junior in the department of Physics at North Carolina Central works with Dr. Crowe, PI (left) on connecting the preamps to the recoil proton telescope detectors. The recoil telescope is used to monitor the beam target luminosity and will be used to normalize the breakup data. The dome-topped target chamber and proton detector arms can be seen in the background.

We generated a Time of flight (TOF) spectra from the coincidence data between the E and ΔE charged particle proton arm detectors. Figure 3 shows a two dimensional (2D) particle ID spectrum generated from the charged particle detector TOF for nd breakup at 19.0 MeV. The separation between the proton, recoil electrons and deuteron bands is clear. With a gate set on the proton band in the 2D particle spectrum along with Pulse Shape Discrimination (PSD) to eliminate gamma rays, a time of flight spectrum for neutrons in coincidence with protons was generated as shown in Figure 4. The use of the proton-neutron coincidence and PSD technique significantly reduced the background in the time of flight spectrum giving a signal to noise ratio of about 7 to 1.

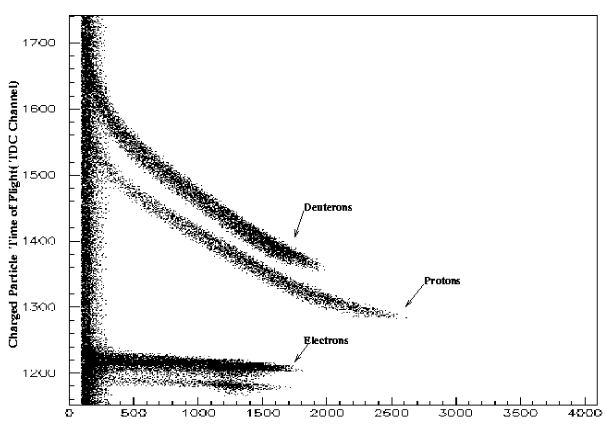

Figure 3: Demonstration of particle ID capabilities. The figure shows a plot of the TOF spectrum based on the coincidence of the E and ΔE proton detectors *vs*. the pulse height signal for one proton arm E detector. Clear separation can be seen for each particle band.

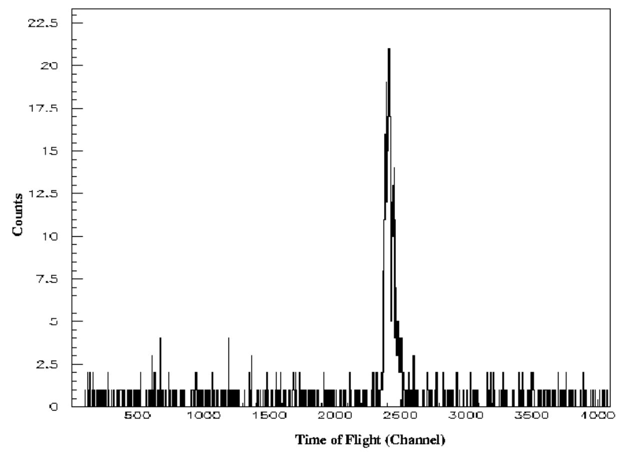

Figure 4: Time of flight spectrum of neutrons in coincidence with protons from the breakup reaction. The spectrum was generated with ⅓ of the total data using cuts placed on PSD (Pulse Shape Discrimination), PH (Pulse height) and PID (Particle ID). Time is represented on the x-axis and counts on the y-axis.

With analysis to calculate time of flights and particle energies, we generated kinematic loci for the space and coplanar star configurations (E_p and E_n). The kinematic locus from the space star data along with the point geometry curve is shown in Figure 5.

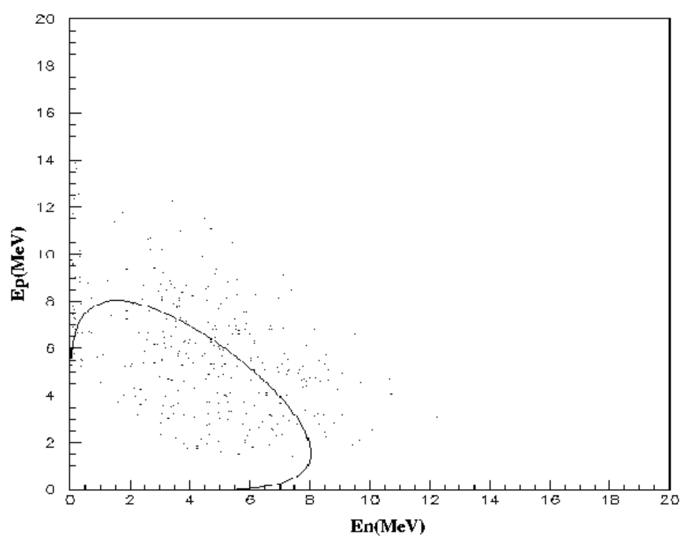

Figure 5: Kinematic locus for the Space Star Configuration in nd breakup at 19.0 MeV. The curve represents the point geometry calculation with the CD Bonn Potential for E_p *vs*. E_n for the space star configuration. The locus includes true plus accidental coincidence events.

We projected the data from the locus onto the neutron energy axis for the space-star configuration as shown in Figure 6. To obtain a preliminary cross section, we determined the yields around the star point. The data were summed in 1 MeV bins for both detector pairs to reduce the statistical uncertainty. The neutron software threshold levels were set to ½ Cs which gives a neutron efficiency of around 0.24 at the star point. After subtraction of the accidental coincidence events, the yields were extracted as a function of neutron energy and used to calculate a cross section. In order to normalize the breakup data we generated a spectrum for the np recoil telescope detectors and extracted the yields in the proton peak. With these measurements, we obtained a space-star cross section of $(0.44 \pm .03)$ mb/sr^2/MeV about the star point. Further analysis is needed before a comparison between theory and experiment is complete.

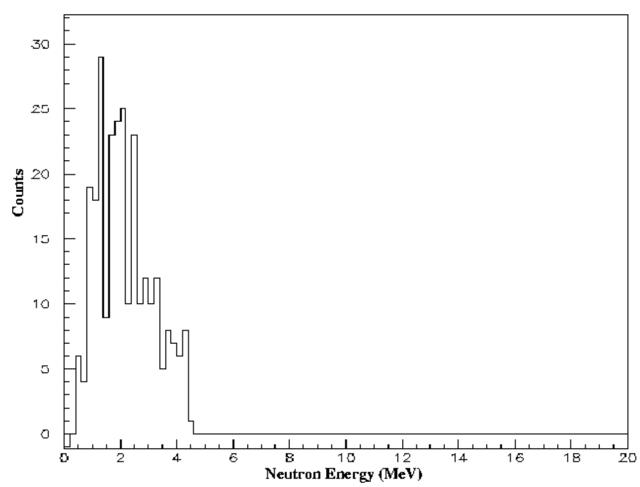

Figure 6: Projection of locus onto neutron energy axis for space star configuration at 19.0 MeV. The peak only contains true events; accidental coincidences have been subtracted.

We are continuing our analysis of the breakup data along with the development of the Monte Carlo simulation program. The current computational model of the apparatus is a modified version of a Monte Carlo code that was written for an earlier a_{nn} measurement carried out at TUNL. Since this was a learning process for our students, considerable time was needed for them to understand and modify the existing code. The students developed the cross-section libraries for the current code and programmed initial modifications for the star configuration. Analysis of recent data taken with the new apparatus is limited by the capability of the current Monte Carlo code that is in need of further development to correctly model the different star configurations. Therefore a complete analysis of the present data taken with the new apparatus cannot be directly compared to theory since we use the Monte-Carlo code results to take into account finite geometry, beam energy spread and detector time and energy resolution.

1.4 Future Work

The new work that we are proposing is a continuation and completion of the work on the 19 MeV data in particular the analysis of the coplanar and space star cross sections, measurements for the nd-breakup cross section for the intermediate star configuration, the continued writing of a workable Monte-Carlo simulation program and a new experiment to measure the nd-breakup cross section at 16 MeV at TUNL.

In the first three-year period of this research, we measured the space and coplanar star configurations in the ^{2}H(n,pn)n breakup reaction at 19.0 MeV at TUNL's shielded neutron source area. We present a preliminary cross section of (0.44 $\pm$ .03) mb/sr^2/MeV, where the quoted error is statistical only and which is lower than the point geometry predictions for the nd breakup cross section at the space-star point. With a working knowledge of the parameters in the experimental setup and the ability to measure cross sections, we are confident that we can measure the nd breakup cross sections at lower energies where the discrepancy between theory and data reaches a maximum.

The next energy we propose to measure is 16.0 MeV. The kinematics for the star configurations at 16 MeV is shown in Table 1. The kinematics are similar to that taken at 19 MeV. The angular difference between the two energies for the recoil proton at the star point is 0.6°, which is within the angular uncertainty (52.1 $\pm$ 1.5)$^\circ$ of the experimental setup for the proton arms. Therefore a new central chamber does not need to be fabricated to measure the star configurations at 16 MeV. The problem that we do face is that the energy of the charged particles is reduced so a thinner target is needed to prevent significant energy loss. A 15 mg/cm^2 target will be used to measure the breakup cross section at 16 MeV. The count rate is estimated for the intermediate star configuration because it has the smallest cross section of 0.82 mb/sr^2/MeV. For an incident deuteron beam current of 2.5 μA on a 6-cm long gas cell pressurized to 7.8 atm of deuterium, the neutron flux on the 30 mm diameter CD_2 foil is about 8.4×10^5 neutrons/s. The solid angles for the neutron and proton detectors are 25 msr and 45 msr, respectively. The neutron detector efficiency has been determined to be around 30% for 4.6 MeV neutrons at our threshold setting. The number of deuterons in the target foil is 1.125×10^{21} deuterons/cm^2. The estimated dead-time of the TUNL data acquisition is 15%. Using these parameters and taking into account that we use two detector setups that are symmetric about the neutron beam axis, we predict a count rate of 8 counts/bin/day for the intermediate star orientation. To achieve the desired statistical accuracy, about 57 days of production beam time are needed.

Star Configuration	Scattered Proton Angle (θ_p)	Proton Energy (E_p) at star point	Scattered Neutron Angle (θ_n)	Neutron Energy (E_n) at star point	Azimuthal angle (ϕ_{12})
Space Star	51.5°	4.6 MeV	51.5°	5.6 MeV	120°
Coplanar Star	51.5°	4.6 MeV	16.8°	8.5 MeV	180°
Intermediate Star	51.5°	4.6 MeV	23.2°	[illegible]	[illegible]

Table 1: Kinematics for star configurations at an incident neutron energy of 16.0 MeV. The azimuthal angle, ϕ_{12}, is the angle in the lab reference frame between the plane containing the neutron beam axis and the momentum vector of the proton and the plane that contains the neutron beam axis and the momentum vector of the detected neutron. The scattered neutron and proton angles are respect to the beam axis.

Our experimental results will be compared to Monte-Carlo simulations that are based on rigorous nd calculations [1]. Theoretical point-geometry cross section spectra for the space, coplanar and intermediate star configurations will be taken from cross-section libraries generated at the incident neutron energies and breakup proton and neutron angles of the experiment and used as input for our Monte-Carlo simulations.

1.5. Broader Impact: Student Participation

An important aspect of this project is the continued support of our undergraduates at North Carolina Central University to participate in research at a local, vibrant facility like TUNL. The work considered in this proposal fits well with TUNL's long-term commitment to the study of few-body nuclear systems and to the nuclear physics education and training of future scientists. The Department of Physics at NCCU has a well-developed teaching program, and an increased emphasis on research with a newly established Master's program and the goal of involving all graduate and undergraduate physics majors in active research projects.

The students that participated in this project were exposed to and actively participated in various aspects of successful research activities including design, construction and testing of apparatus, carrying out an experiment, dealing with problems and set-backs, and presenting the experiment and results to both scientists and students. All of the NCCU students learned to use AutoDesk Inventor, a computer-aided-design program and to work through mechanical design problems (from concept to machine drawing), providing them with invaluable practical skills. For example this learning experience helped Ms. C. Steans who will graduate in December 08 with a dual physics degree from NCCU and an engineering degree from Georgia Tech, and Mr. J. Estevez, who will complete an MS degree from NCCU in physics in May 2009, and Mr. L. Threatt who will combine this skill with his talent in graphic arts to pursue a technical position in industry. Several of the students participated in the established Research Experiences for Undergraduates (REU) program at TUNL during the summer. The NCCU students were exposed to fellow physics majors from across the country and took advantage of the professional, social and scientific opportunities that program offers, including visits to physics departments to learn about graduate programs, seminars on highlights in nuclear physics research, and social interactions with TUNL faculty and graduate students. The exposure of NCCU students and their acceptance into the research environment at TUNL greatly increased their confidence in themselves and their ability to successfully contribute to a scientific project.

The NCCU faculty on this project recognize the vital necessity that students understand their research projects well enough to present their work in a professional manner. The students therefore spent time learning how to discuss their work and to produce high-quality posters and presentations. Mr. J. Estevez won first prize for his presentation on the nd breakup cross section measurements given at the annual North Carolina Louis Stokes Alliance for Minority Participation (LSAMP) Conference, North Carolina A&T State University, March 25, 2006. Mr. L. Cumberbatch and Mr. L. Threatt both participated with a poster on the development of the scattering chamber and proton detector arms in the Conference Experiences for Undergraduates (CEU) program at the annual Division of Nuclear Physics of the APS fall meeting in Newport News, Virginia, October 2007 (BAPS, **52** 10, DA:00086). A paper was published by Mr. J. Estevez "Measurement of the Cross-Section of the Space-Star in Neutron-Deuteron Breakup in a Recoil Geometry Setup" in the NC Central University Undergraduate Research Journal (Volume **9**, p60, 2006).

In the next phase of the nd breakup project, the students will continue to play a major role in working with the PI and co-PI to develop the experiment. The students will participate fully in the set-up and running of the experiments. This includes Mr. L. Cumberbatch, a rising senior physics major, who is working with faculty and TUNL technicians to obtain certification to operate the accelerator, and will become one of the few undergraduate students at TUNL to do so. As mentioned above, there is considerable work needed in the development of the computer simulations (Monte Carlo) code, and to carry out data analysis. These research projects that will train students to understand and run large-scale codes and to tackle large programming tasks, are appropriately timed with the current development of a strong computational program at NCCU. Through continued support of this work we look forward to preparing NCCU students to present their accomplishments at conferences and meetings such as those sponsored by the American Physical Society (APS), including the Division of Nuclear Physics (DNP) and the Southeastern Section of American Physical Society (SESAPS), the North Carolina Louis Stokes Alliance for Minority Participation (NC-LS-AMP) and the National Society of Black Physicists (NSBP).

This collaborative effort between NCCU and TUNL provides opportunities for professional development of both the NCCU faculty and the NCCU students involved and enables NCCU researchers to carry out this work through direct access to TUNL personnel and infrastructure. Participation by NCCU faculty and students at TUNL greatly increases the level of diversity and minority participation (both of women and African-Americans) which is helpful for the overall environment and education at this DoE facility. This proposal directly supports the development of a quality research program at NCCU, the education and training of minority scientists, and the promotion of diversity in the nuclear physics community.

1.6 Student Conferences and Publications

Louis Threatt: Conference Poster Presentation
Threatt, L., B. J. Crowe, **L. Cumberbatch**, C. R. Howell, and D.M. Markoff, "A Scattering Chamber System to Measure Cross Sections of Multiple Star Configurations in Neutron-Deuteron Breakup at 19 MeV".
2007 Division of Nuclear Physics Annual Meeting, October 10–13, 2007; Newport News, Virginia; Bulletin of the American Physical Society, **52** 10, DA:00086.

L. (Larry) Cumberbatch: Conference Poster Presentation
Cumberbatch, L., "A Scattering Chamber Designed to Measure Multiple Star Configurations in Neutron-Deuteron Breakup at 19 MeV"
Annual Biomedical Research Conference for Minority Students (ABRCMS) held in Austin, TX November 7-10, 2007

J. Estevez: Undergraduate Research Journal
Estevez, J., "Measurement of the Cross-Section of the Space-Star in Neutron-Deuteron Breakup in a Recoil Geometry Setup" NC Central University Undergraduate Research Journal, **9**, 60 (2006).

J. Estevez: Conference Talks
"Measurement of the Cross-section of the Space Star in Neutron-Deuteron Breakup in a Recoil Geometry Setup", **Joseph Estevez**, LSAMP Conference, North Carolina A&T State University, March 25, 2006. (Note: Won 1st place for oral presentation.)

"Measurement of the Cross-section of the Space Star in Neutron-Deuteron Breakup in a Recoil Geometry Setup", **Joseph Estevez**, ABRCMS Biomedical Research Conference, Anaheim California, November 13-18 2006

Faculty Invited Talks:

"The Space-Star Anomaly in Neutron-Deuteron Breakup", Benjamin J. Crowe, North Carolina A&T University, October 3, 2005.

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