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Fabrication of a modular neutron array: A collaborative approach to undergraduate research

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The construction of the modular neutron array, a highly efficient time-of-flight detector, for use with the recently upgraded coupled cyclotron facility at the National Superconducting Cyclotron Laboratory has been accomplished by a collaboration of undergraduate physics departments. The collaboration presents an opportunity for involving faculty and students from undergraduate physics programs in state-of-the-art physics experiments at large user facilities. © 2005 American Association of Physics Teachers.

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I. INVOLVING UNDERGRADUATES IN RESEARCH

Active participation in creative and publishable research is key to preparing undergraduates for careers in physics and to attracting them to physics as a major.^{1,2} Recent studies underline the need for closer collaboration between graduate institutions and colleges and universities that have no graduate programs.^{3,4}

Research participation is important both for students who plan to enter the technical workforce immediately after graduation and students who plan to pursue graduate work in physics or another science. For example, a recent study of 21 thriving undergraduate physics programs determined that all of these work to involve students in research.⁵ The National Science Foundation has recognized the importance of involv-

ing undergraduates in research through popular and successful programs such as Research Experiences for Undergraduates (REU) and Research at Undergraduate Institutions (RUI).

However, in fields like nuclear and particle physics and increasingly condensed matter physics, cutting edge research is done at large user facilities. Most experimental groups travel to these facilities for runs, and graduate students and post doctoral fellows spend months away from their home campuses. Decisions about the direction of experiments and the design of facilities are made during group meetings. The research effort centers on the collaboration rather than on facilities at a home campus.

Participation in such large collaborations poses significant challenges for physics faculty and students in primarily un-

dergraduate departments. Undergraduate students have many demands on their time. Professors expect students to attend class, and the excellent students who excel in physics are generally conscientious about doing so. It is very difficult for these students to take even a couple of days off to participate in an experimental run. They can be most actively involved in research projects that allow them to participate in short blocks of time between classes during the academic year and in extended efforts during the summer.

Students also participate in intramural sports and undergraduate service and social organizations and conduct active social lives. Many need to hold jobs to help support their education. In many universities, increasing numbers of undergraduates are older with additional family obligations. Family responsibilities and the need to hold off-campus jobs often are important to these nontraditional students. For example, students from lower income families and single parents may need the income. Students from cultures that emphasize the importance of close family support may be unable to leave their local region for long periods of time.

Another set of problems with participation in large collaborations by physicists and students from smaller physics departments arises from the fact that the research often has a low profile on the home campus of the researchers. The physicists involved in the research may be actively engaged in planning experiments, participating in runs and analyzing data, but the equipment needed is frequently a computer work station. The undergraduates are seen by their peers to spend hours at a computer and to disappear for several days to participate in a run. There is little presence on campus of the equipment associated with modern physics experiments in sharp contrast with the laboratories available to chemists, biologists, and condensed matter physicists which are stocked with equipment with flashing displays and elaborate sample preparation areas.

The low on-campus profile can result in difficulty attracting students to the research groups. More importantly, many undergraduate institutions support faculty research through in-house grants for summer salaries and equipment. Such proposals are read by committees of faculty members from diverse departments. It can be difficult to convince such faculty that the proposed research is a local project done on the home campus. The quality of the research is not in question, and other physics faculty generally have little difficulty in determining an individual's contributions to the collaboration. However, cross-disciplinary promotion and tenure committees might question whether research that is part of large collaborations actually represents independent research based at the undergraduate institution.

Finally, it is important to involve undergraduates in research early in their college careers while they are still deciding their futures. First- and second-year students generally know too little physics to work independently on a research project. They need the support of an active research group with fellow students who are their seniors.

II. THE MODULAR NEUTRON ARRAY COLLABORATION

For all these reasons, undergraduate research participation in areas of physics characterized by large collaborations presents significant difficulties. There are at least two approaches to overcoming these difficulties. The first is that used by most programs sponsored by the national laborato-

Table I. Institutions in the MoNA Collaboration.

Central Michigan University	Mount Pleasant, Michigan
Concordia College	Moorhead, Minnesota
Florida State University	Tallahassee, Florida
Hope College	Holland, Michigan
Indiana University South Bend	South Bend, Indiana
Marquette University ^a	Milwaukee, Wisconsin
Michigan State University	East Lansing, Michigan
Wabash College ^b	Crawfordsville, Indiana
Western Michigan University	Kalamazoo, Michigan
Westmont College	Santa Barbara, California

^aOriginal work done at Ball State University, Muncie, Indiana.

^bOriginal work done at Millikin University, Decatur, Illinois.

ries and NASA as well as the Research Experiences for Undergraduates (REU) Program at the NSF. Undergraduates participate in research projects during the summer when they are free from classes and other on-campus responsibilities. They are paid a stipend so that they can afford to forgo a summer job, and they carry the excitement of a summer research experience back to their home departments. The model has been extremely successful. In Fiscal Year 2003, the NSF Division of Mathematics and Physical Sciences requested \$22.46 million to support REU sites and supplements to individual investigators for undergraduate students.⁶ The Physics Division supports about 50 REU sites (including those at Hope College and Michigan State University) which impact several hundred undergraduates annually.⁷

A second approach is exemplified in the modular neutron array (MoNA) project.⁸ This way of involving undergraduates in a large research collaboration has some advantages over the REU model in meeting the needs of nontraditional students and others whose backgrounds do not prepare them to benefit from REU opportunities or whose traditions and family responsibilities keep them close to a particular community. In this approach, eight undergraduate institutions working together with Michigan State University and Florida State University have formed a collaboration to construct a modular neutron array for use with the newly upgraded coupled cyclotron facility at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University.^{9,10} The institutions in the collaboration are listed in Table I. The intent of the cyclotron upgrade is to increase the energy and intensity of the radioactive beams available for experiments. The design and construction of a new sweeper magnet was done at Florida State University.^{11,12} To exploit the new magnet and higher energy beams, a neutron detector optimized for neutrons with energies between 50 and 250 MeV was needed. Current efforts to understand the details of the nuclear force can be tested by studying the properties of nuclei that are just barely stable so that one more nucleon cannot be bound; this limit defines the nuclear dripline.¹³ The new detector will permit studies of nuclei near the neutron dripline and allow experiments where more than one neutron must be detected.

The design of MoNA was carried out primarily at Michigan State University by the staff of the NSCL (Thomas Baumann and Michael Thoennessen). The detector will operate as a large-area neutron time-of-flight wall 2 m wide and 1.6 m high. It consists of 144 blocks of plastic scintillators each 2 m long with a cross section of $10 \times 10 \text{ cm}^2$. The detector blocks are currently stacked in 9 layers, each 16 blocks high. By using steel converters, the neutron-detection efficiency of

α Bar Attenuation Length

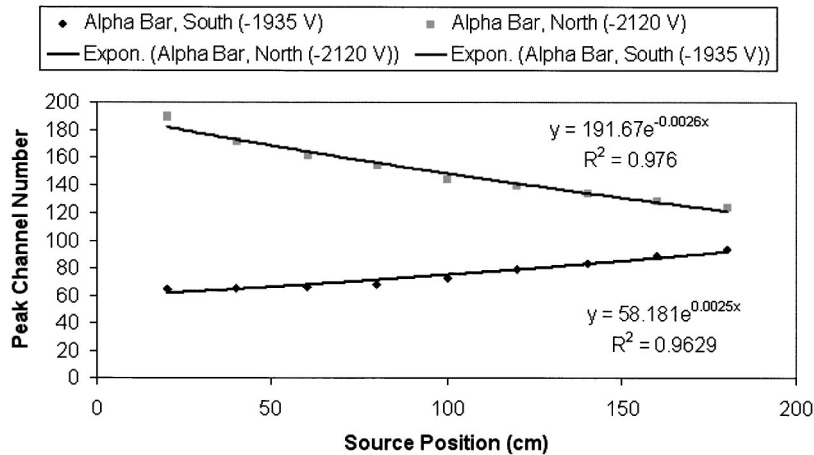


Fig. 1. A plot of channel number versus source position from each end of a scintillator bar showing the drift in energy caused by attenuation of the light signal traveling along the bar. This data was used to measure the characteristic attenuation length of the bar.

the detector at high energies will be greatly increased.¹⁴ The modular construction of the detector allows it to be reconfigured to optimize its efficiency in different experiments.¹⁵

Photomultiplier tubes (2 in diameter) are connected via light guides to each end of each scintillator block. The horizontal position of an arriving neutron can be determined from the time difference of light pulses registering at each end of the bar. The time-of-flight is measured using the average of the two times. At NSCL, the detector will have a flight path of approximately 15 m. The vertical position of a neutron is determined by the block in which it is detected.

Each undergraduate institution assumed responsibility for the construction of one layer of the detector. The project was funded by NSF grants to each of the undergraduate departments. The funding was primarily for detector materials including the scintillator blocks, the photomultiplier tubes with magnetic shields, associated electronics and the passive steel converters. The bidding process was done through NSCL in conjunction with the project design. However, orders were placed through the individual undergraduate departments.

The research groups consisted of one or two professors and one or more undergraduate students in each of the undergraduate physics departments along with their colleagues at Michigan State and Florida State. Undergraduate teams mounted the photomultiplier tubes on each scintillator block and carried out the calibration of each block. The research was conducted in laboratories on each of the individual campuses so that it was very visible in each of the physics departments involved. The undergraduate departments provided the modular electronics needed to conduct the basic calibration, and all had access to standard radioactive sources needed to conduct the calibration.

Each scintillator block was shipped by its manufacturer, Saint-Gobain Crystals and Detectors, and arrived with light guides and metal flanges attached to each end. The students unpacked the bars and carefully cleaned the end of the light guide before mounting a photomultiplier tube connected to a voltage divider and encased in a magnetic shield to each end of the detector block. The junctions between the tube and the light guide were taped to prevent light leaks. After testing to be sure that there were no light leaks, the gains of the photomultiplier tubes at each end of the detector were matched by adjusting the bias voltage applied to the tubes. Pulse-

height spectra were recorded for a variety of laboratory sources, generally ¹³⁷Cs, ⁶⁰Co, or ²¹⁰Bi, and the 20.7 MeV energy deposition peak from cosmic rays.

The amount of scintillation light collected decreases exponentially as the source is moved along the length of the detector bar. The attenuation length was determined for each end of each bar by moving a source along the top of the bar in 10 cm intervals. Figure 1 shows student data from the Ball State University group for the attenuation lengths from each end of a single bar. The difference in the time of arrival of the light at each end of the detector was measured and calibrated with the position of the source. Finally, the detector was allowed to accumulate cosmic rays and record the difference in the time of arrival at the ends of the tube. The graph of intensity versus time of arrival should be nearly flat because the cosmic rays impact the bar evenly along its length. Figure 2 shows a time difference spectrum taken with cosmic rays by the Concordia College group.

Individual departments were encouraged to do more than the required testing, thereby actively involving students and

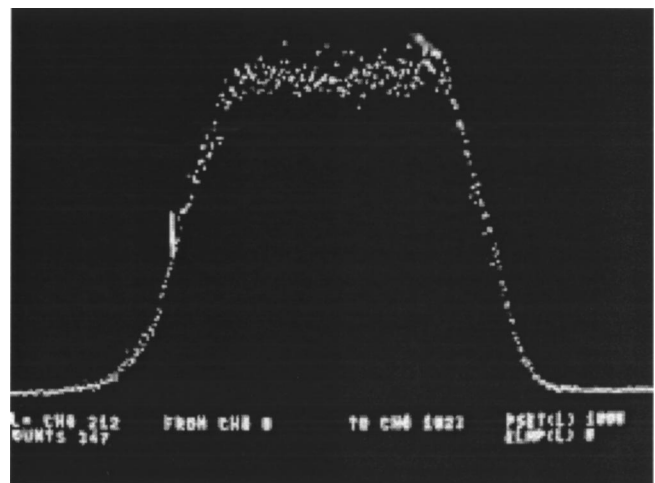


Fig. 2. The difference in the arrival time at each end of the bar for light signals measures the point in the scintillator bar where the event took place. As expected, this plot of the time differences shows the cosmic rays impacting uniformly along a scintillator bar.

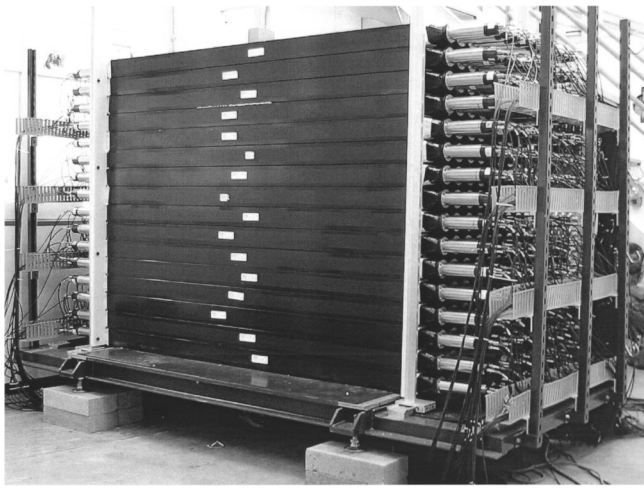


Fig. 3. The MoNA detector array in its current configuration.

faculty in testing ideas of their own. One of the groups performed a detailed analysis of the light propagation along the detector block, using a ray-tracing simulation program.¹⁶

Another group used the MoNA detectors for cosmic ray measurements, which also were used for calibration.¹⁷ The results were so promising that this group decided to construct a dedicated detector, modeled after MoNA, for cosmic-ray studies. These are just two examples that show how involvement in the MoNA project lead to other interesting research projects.

After the completion of testing and calibrations, the scintillator blocks with mounted photomultiplier tubes were transported to NSCL where they were stacked in a supporting frame and cabled together. Figure 3 shows the completed detector array. Undergraduates from the various collaborating institutions worked in teams to help with this assembly.

A major concern in organizing a project based on using undergraduate students was maintaining uniformity and quality across the eight sites involved in the construction. The NSCL partially supported one of the principal investigators from an undergraduate department (Bryan Luther) for a year-long sabbatical spent primarily on the MoNA project. He developed a manual detailing the procedures to be followed during the calibration including sample spectra and detailed specifications.¹⁸ In addition, he worked with his students to test the procedures and oversaw the initial orders for equipment. This procedure worked well because the deliveries of scintillator blocks were spread over about three months so that some sites started well ahead of others. Groups on different campuses exchanged hints, supplies, and sources for supplies. The group met as a whole at NSCL for a demonstration of the assembly and calibration procedures as well as talks on the physics that could be done with MoNA when it became operational.

To date, MoNA has directly involved 24 undergraduates and one high school student. Many of the original students graduated, and the next generation of undergraduates, approximately the same number, is currently beginning their work. Faculty and students from the MoNA collaboration have presented talks in a variety of forums. Several invited^{19,20} and contributed talks^{21,22} were presented at major conferences. In addition, undergraduates and the high school student (Yao Lu) were lead authors on eight posters presented at the last two APS Division of Nuclear Physics

Meetings.²²⁻²⁴ Undergraduates also presented their work with MoNA at sectional meetings of the AAPT.²⁵⁻²⁷

With the strong support of the NSCL, the group continues to meet once or twice a year. Undergraduates are an important part of each of the collaboration meetings. They have the opportunity to interact with faculty and students from NSCL as well as from the other participating undergraduate institutions. In addition to the satisfaction of constructing a working detector, they also have toured the cyclotron facility and observed experiments in progress. The collaboration meetings feature introductory material on experiments using MoNA that connect the undergraduate researchers to the larger enterprise of nuclear physics.

It is anticipated that these collaborations will continue in the future. Together with the sweeper magnet, MoNA will be commissioned during the summer, an ideal time for undergraduate students to participate. In addition, each member institution of the collaboration has the opportunity to participate in all experiments performed with MoNA. The program advisory committee of the NSCL has already approved two experiments that should be ready to run toward the end of the year.^{28,29}

III. CONCLUSIONS

With the successful completion of MoNA, the collaboration has demonstrated a way of involving undergraduates from relatively small physics departments in research in nuclear physics at a large user facility. Collaborations at remote facilities are ubiquitous in nuclear and particle physics, and are becoming more common in condensed matter physics, biophysics, and astronomy. Although not every detector construction project can be broken into identical modules, many of them offer the opportunity to divide a large project into smaller units that can be developed and tested by undergraduates in small physics departments. Security concerns for facilities at national laboratories may impact such a project. However, undergraduate institutions can host collaboration meetings if admission to a federal site is a problem.

The undergraduate collaboration demonstrated by MoNA has major advantages for the user facility. Undergraduates are inexpensive and intelligent labor for detector construction projects. By involving the undergraduate physics majors, the larger universities have the opportunity to recruit talented students as graduate students. For user facilities located at national laboratories, the recruiting benefit is to other large universities using the facility. The laboratory itself may recruit some of the undergraduates as engineers or junior scientists.

The advantages for the undergraduate institutions are equally obvious. Faculty and students are actively involved in research and in contact with the larger physics community. Students particularly enjoy interacting with students and faculty members from other undergraduate institutions. The work is visible on campus and helps attract other students to physics. The visibility makes obtaining local funding much easier. Physics faculty members have the opportunity to visit the user facility and to take sabbatical leaves there. The fact that the funding for the project resides at the undergraduate institutions is a significant assistance to faculty seeking promotion and tenure at the undergraduate institution.

A collaboration involving a group of undergraduate physics departments and a large user facility is clearly a beneficial

situation for all parties involved. The collaboration also is a winning proposition for physics as a profession because of the role it plays in attracting bright and energetic undergraduates to the profession.

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