Big Physics At Small Places: The Mongol Horde Model Of Undergraduate Research

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ABSTRACT

A model for engaging undergraduates in cutting-edge experimental nuclear physics research at a national user facility is discussed. Methods to involve students and examples of their success are presented.

INTRODUCTION

Faculty in all disciplines find themselves increasingly encouraged to involve undergraduates in research (Hilborn & Howes, 2003, Tobias, 1992, National ScienceBoard, 2003). They know of many bright, motivated students who expect more than lectures and laboratories from their college experience. Faculty recognize that they can attract majors when students participate in publishable research. They feel the pressure from department chairs and college deans to pursue this worthwhile academic endeavor. Faculty are enticed by rewards from the university and support from funding agencies. Generally, faculty embrace these opportunities and demands. However, not all research activities are easily adaptable to undergraduate students. This is particularly true for the most expensive and long-term research projects, called “big physics,” which are done by large multi-institution collaborations.

There are challenges associated with the involvement of undergraduate students in “big physics.” The time scale for large physics experiments, from proposal through publication, is often four years or more. Large facilities generally support ongoing experimental programs encompassing many individual experiments that explore a physical question over several years. In stark contrast, undergraduate physics students seldom begin participating in research before their sophomore year. Additionally, the analyses tasks are complex and must be carefully coordinated and the results have to be fully verifiable.

One approach to overcoming this challenge is the Research Experiences for Undergraduates (REU) funded by the National Science Foundation (NSF) and similar programs sponsored by other federal agencies. Undergraduates conduct 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 and has provided life-changing experiences for many physics students. For example, in FY 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 (NSF, 2003). The Physics Division alone supports about 50 REU sites that impact several hundred undergraduates annually (NSF, 2007). Yet the advantage of the summer programs can also be a drawback. The students get only a glimpse of real research and after the summer return to their home institutions with limited opportunities for further involvement. This model for undergraduate research also does little for the faculty at the student's home institution. Certainly, students and their home institutions would benefit more from an experience over an extended period of time.

In a recent article in *The Chronicle of Higher Education* (Zimmer, 2007) Marc Zimmer examines the traditional research groups at universities and compares them to complex military operations. The research done is expensive and involves large numbers of specialized troops (post docs and graduate students). There is pressure to publish to sustain the personnel in the group and to attract external support. In this environment it is difficult to give undergraduates meaningful research projects. Zimmer proposes another model which he calls Guerrilla Puzzling:

In contrast, undergraduate projects can be more like guerilla attacks. They can concentrate on one aspect of a puzzle and be done in one or two summers; the average grant for such a projects is less than $25,000. If they do not produce results, they do not make the professor less likely to get future grants, but they do not harm the undergraduates' chances of finding employment or getting into graduate or medical school. Therefore the professor can take more risks.

Guerrilla Puzzling is certainly a valid model for undergraduate research but we propose a second model which we call the Mongol Horde model. It has demonstrated success and advantages for students, faculty, and institutions. Mongol Hordes do science as a team. Faculty (Mongols) and undergraduate students (the horde) work together in relative isolation. They come together for short campaigns (called experiments) at a large national user facility. The spoils of this raid (event-mode data) are divvied up and carried off to the individual gers (home institutions) for enjoyment (data analysis and modeling) during the long winters (academic years). Of course, today the horde can make use of technology to stay connected, coordinate all the efforts, and provide assistance to one another when problems arise.

Science in the Mongol Horde model is located primarily in undergraduate departments working in close collaboration with a research university that houses a large experimental user facility. There are no lone researchers because all faculty and students are members of the horde. This is a significant advantage over Guerrilla Puzzling where each professor is working alone on an outpost of a scientific discipline. The Mongol Horde also offers students with jobs and/or family responsibilities that tie them to the location of their home institutions the opportunity to participate in undergraduate research. Each campus unit participates in a large and important mainstream project in science. Undergraduates have the opportunity to work with post docs and graduate students who teach them science while providing important role models.

Table 1: Members of 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

[a]Original work done at Ball State University, Muncie, Indiana
[b]Original work done at Millikin University, Decatur, Illinois

One such horde is the Modular Neutron Array (MoNA) collaboration. The MoNA collaboration is a group of faculty, staff scientists, post docs, graduate students and undergraduate students working together with Michigan

State University and Florida State University to conduct research at the newly upgraded Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (Marti et al., 2001 and Morrissey et al., 2003). Members of the collaboration are listed in Table 1. They are located across the country and stay connected through weekly video conferences that facilitate insightful discussions and useful instructions. During actual experiments at the NSCL, the horde converges to work in a coordinated and efficient manner, a direct benefit of these video conferences. While one may be skeptical about the role of undergraduates in such a group, our students have successfully constructed and calibrated portions of a one million dollar neutron detector (Howes et al., 2005), taken shifts during experiments, assumed primary responsibility for data analysis, performed simulations, and presented results. Clearly, our Mongol Horde model offers students an all-encompassing research experience and enables smaller undergraduate institutions to avoid isolation. It provides opportunities that transcend the traditional short REU experience while still embracing that level of involvement when appropriate. It also gives the NSCL the opportunity to train future nuclear physicists, recruit potential graduate students, and tap into a source of young, enthusiastic and intelligent labor.

SCIENTIFIC OVERVIEW

The collaboration studies unbound states in nuclei with half-lives of the order of zeptoseconds (10^{-21}s) which are produced with the Coupled Cyclotron Facility at the NSCL. The neutrons that MoNA detects come from the breakup of these nuclei which are produced when a rare isotope beam strikes a target placed upstream from the neutron detector. MoNA is designed for the detection of high-energy neutrons (100-200 MeV) and it measures both the velocity and direction of the neutrons leaving the target. Even though the neutrons are moving at about half of the speed of light, MoNA is designed so that it is able to detect 70% of all neutrons that reach it (Baumann et al., 2003). The Sweeper, a powerful superconducting dipole magnet constructed at Florida State University (Zeller et al., 2000 and Toth et al., 2002), is placed between the target and MoNA. It deflects all charged particles that would otherwise interfere with the measurement of the neutrons into an independent set of detectors which can identify them. A schematic layout of the Sweeper-MoNA setup is shown in Figure 1.

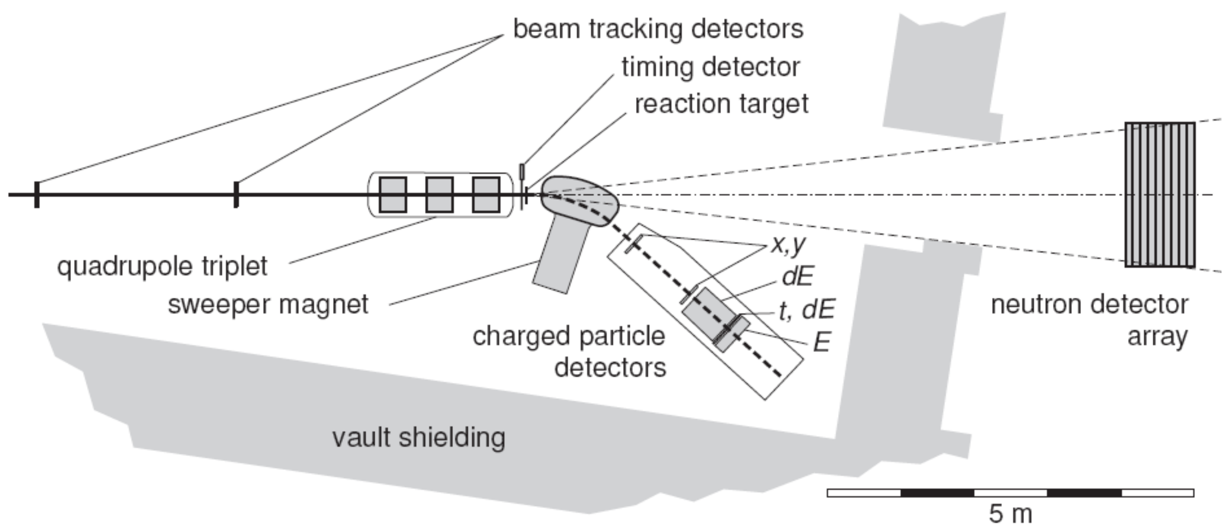

Figure 1: Schematic layout of the Sweeper-MoNA setup

Since neutrons are not charged, they cannot be directly detected. Instead, reliable neutron detection relies on observing the results when neutrons interact with a nucleus, such as scattering off it. The recoiling charged nucleus from the collision excites atoms as it moves through matter. The excited atoms give off light as they relax. This process is called scintillation, and it occurs in the active detector material that MoNA utilizes. Because of the relatively long distance the neutron will travel in matter before it scatters, an efficient neutron detector requires a large volume of detector material. Because their mass is close to the mass of the neutron, protons are especially effective at absorbing energy when they scatter neutrons. MoNA is therefore made from materials containing a high proportion of hydrogen.

The MoNA detector is shown in Figure 2. It consists of 144 individual bars of clear plastic scintillating material. The bars are stacked 16 high and 9 deep to form a large array. Each bar measures 10×10 cm^2 and is 2 m wide. The ends of each detector bar are equipped with photo-multipliers that are able to detect the faint scintillation light, convert the light to an electrical signal, and amplify its intensity by a factor of 30 million. The MoNA electronics enables us to determine within a few centimeters the position of the light emission along the bar. This is done by measuring the time difference of the signals arriving at the left and right photo-multipliers. This time difference has to be known to within 250 picoseconds. With this precise timing information, we also can calculate the velocity of the neutrons by their flight time from the target to the detector. Detailed descriptions of the construction and capabilities of the MoNA detector have been published (Luther et al., 2003 and Baumann et al., 2005).

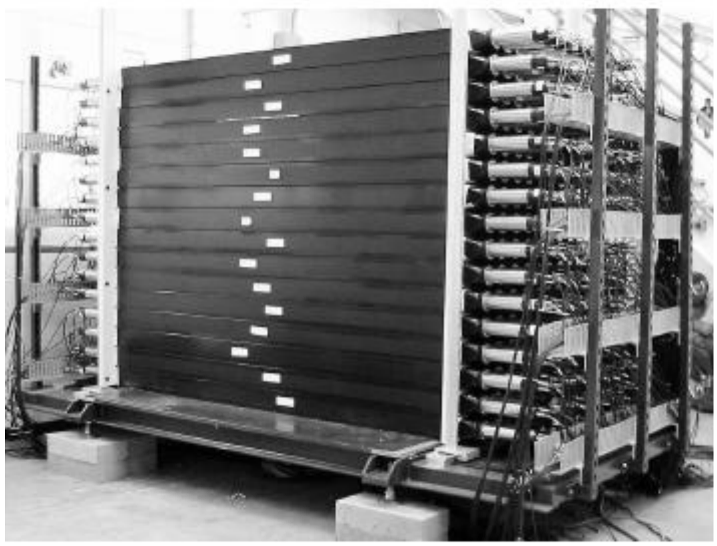

Figure 2: The MoNA detector array in its current configuration

The information we get from MoNA will enable us to build a picture of the interior of rare neutron-rich nuclei. Learning about these nuclei will give us a deeper understanding of their structure and the detailed operation of the nuclear force. It will also provide answers to astrophysical questions, since rare neutron-rich nuclei play a key role in the synthesis of the heavy elements and help drive tremendous stellar processes such as supernovae explosions and x-ray bursts. The exploration of the limits of stability and the observation of new phenomena in nuclei far from stability has been identified as one of the key science goals in nuclear physics (National Research Council, 2007).

INVOLVING UNDERGRADUATES FROM CONSTRUCTION TO PRODUCTION

Each of the collaboration's founding undergraduate institutions procured funding and then assembled, calibrated, and tested sixteen scintillation bars. The final construction and testing was completed at the NSCL in 2003. Since then, MoNA has been utilized extensively, including three thesis experiments for graduate students. Undergraduates have now participated not only in the construction and calibration of the detector, but also in preliminary runs and several experiments. Students involved in the construction and early experiments have now graduated. Thus, in order for the consortium of undergraduate universities to stay active in the MoNA collaboration, it has become necessary to train a second and third generation of undergraduate physics students to participate effectively in experiments and data analysis.

New generations of undergraduate researchers must be incorporated into the MoNA collaboration as early as possible in their academic careers. To do this efficiently, they must be rapidly acclimated to the equipment, procedures, and skills necessary for experimental involvement. Additionally, it is not sufficient to just teach the skills but the students deserve to understand the physics being studied as well. Facilitating such incorporation and acclimation poses major challenges. To address these challenges, the MoNA collaboration has created intensive summer training sessions designed for undergraduates, included the students in annual collaboration meetings, employed information technology to bring the distant undergraduate students together, and provided help and support to each others' students. Of course, given that the collaboration is a true horde, each mentor trains and prepares their students with variations on these common features.

Intensive Summer Sesssions

The first MoNA Summer Session in 2003 included formal presentations and mini-lectures on the experimental details and pertinent background material such as radioactive beam production, laboratory safety, and experimental electronics. The collaborator's undergraduate professors and NSCL staff shared these duties. Each morning a different topic would be discussed and then the students were put to work throughout the afternoon finishing preparations, calibrating detectors, and testing components. This intense and rigorous training period lasted for two weeks and culminated with MoNA's first complete test run during the third week. At the end of the Summer Session, the students returned to their summer obligations or began analyzing the data from the test run. In subsequent years this training has continued, but the time dedicated has not always been the full three weeks, depending on the amount of prior experience and the amount of individual training done at the home institutions.

The MoNA Summer Session differs dramatically from the traditional REU experience. The intense three week instructional period facilitates the rapid transition the students must make from the classroom to the large-scale experimental facility at Michigan State University. Students were introduced to both the broad topics necessary to give a proper physics context for the MoNA project (beam production and fragmentation) and the more focused topics required to function at a collaborative level during experiments (data acquisition and analysis software). And, though the length and nature of an REU experience would instill a greater depth of understanding in a specific area, the MoNA Summer Session provided the students with a broad introduction to "big physics," enabling them to return during the school year or following summer to continue participating in the collaboration.

The benefits of the MoNA Summer Session and subsequent long-term involvement in the collaboration may best be seen from a student's perspective. The following is a student's reflection on his experience with MoNA, which began with the first Summer Session in 2003 and continued through the rest of his undergraduate career at Central Michigan University:

The clear-cut advantage of the MoNA Summer Session was its rigor and brevity. I learned an incredible amount in a short time, without worrying about spending an entire summer involved with a branch of physics I may or may not find enjoyable. Yet despite its brevity, the Session proffered my first glimpse into the true profession of an experimentalist. I quickly realized that learning and discovery is not relegated to the repetitiveness of the lecture hall and the carefully crafted introductory laboratory experiments. Three weeks was ample time to affirm or redirect one's career interests, test the waters of research, and build beneficial relationships. And, in direct contrast to traditional REU programs, a student who decided his or her interests lie elsewhere would not leave with a sense of valuable time wasted, but of valuable experience gained.

In my case, the MoNA Summer Session piqued my interest in experimental nuclear physics. With the appropriate training under my belt, I was well prepared for continued involvement in the collaboration. I returned the following summer and again in the spring of my senior year to take shifts during experiments and participated in the collaboration's annual conference on Beaver Island. My involvement with MoNA helped develop me into a reliable undergraduate experimenter. And, with an appropriate outlet to put into practice what I learned in lecture, I became a more motivated student, eager to a gain deeper understanding of the discipline as a whole.

By far, the biggest impacts of my participation in the first MoNA Summer Session were the introduction to research at a world-class facility and the invaluable network of professors, faculty, and students from institutions across the nation that I acquired. Working with professors and faculty from other institutions, especially prospective graduate schools, allowed me to make connections and develop professional relationships, giving me an edge over other graduate school applicants of similar academic merit. One of the most valuable connections I made was with current graduate students at the NSCL, whose insights and advice helped me create a strong graduate school application and provided hints on how to survive the demands of graduate coursework and research. Indeed, the academic and personal discovery resulting from the MoNA Summer Session proved vital as I prepared to transition from my undergraduate career to graduate studies in nuclear physics.

Summer Meetings At Beaver Island

Near the end of each summer, the MoNA collaboration holds a retreat at the Central Michigan Biological Station on Beaver Island, located in the northern tip of Lake Michigan. Faculty and students participate in this annual gathering to write papers, discuss analysis, develop proposals for experiments and external support, and plan for the year ahead. With the facility located on fourteen hundred feet of Lake Michigan sand beach, this picturesque setting advances the team spirit of the collaboration and is an effective recruiting tool that helps tackle the collaboration's need to continually bring in new students. The remote locale is free of distraction and the yearly event has been very productive.

Student involvement in the meeting is exceptionally beneficial. They are given the chance to gain more insight into the physics that is being studied. There is discussion of data reduction, analyses, and results that may even be their work. There are presentations that are general in nature and future experiments are discussed. The students have the opportunity to learn the planning that goes into experiments and to see the big picture. They are also involved in writing and editing during this meeting. In addition, the faculty benefit from a dedicated time to write and a time to build good working relations with those that most of the year are only a voice and a small picture during video conferences.

Video Conferencing

At the 2005 Beaver Island retreat a proposal was developed and subsequently received funding of $50,000 from the Research Excellence Fund of Michigan to purchase digital video-conferencing equipment. In addition to the specific needs of the MoNA collaboration that this hardware has addressed, the video-conferencing infrastructure offers substantial benefits to individual student and faculty participants at the member undergraduate institutions, to these institutions themselves, to the collaboration, and to the broader profession.

The equipment allows undergraduate students to participate in the real-time acquisition and off-line analysis of data. This novel remote approach to doing physics gives students the opportunity to participate directly in MoNA experiments regardless of semester commitments and travel constraints. The digital video conferencing system also allows faculty and students to have regular group, sub-group, and point-to-point meetings where pre-experiment planning is discussed and post-experimental data analysis is coordinated. Furthermore, the system is used for training, educating and motivating new students, as well as fostering a continued sense of involvement and importance in more experienced students. Lastly, the video aspects, rather that just phone conference, facilitate what is at some level a social endeavor. Seeing colleagues fosters the connections, respect, and friendships that help keep everyone enthused, active, and accountable.

Faculty Involvement

The commitment of those at the NSCL and the particular undergraduate mentors is essential to the success of the research and the model. The video conferencing described above provides the means to an end but without committed people, there would be little success. In the Mongol Horde model, one can rely on someone to maintain the analysis computer server, while that person can rely on someone when there are questions about particular detector subsystems. A mentor trying to teach a student about the analysis system can count on help from others when things don't work as expected. The review of the student work by veteran researchers and the cross checking of results at different institutions insures reliable results.

DISTRIBUTED ANALYSIS AND FRAGMENTATION STUDIES

A key feature of our Mongol Horde is our emphasis and insistence on undergraduate participation in data analysis. This is the ultimate in going beyond the typical 10 week summer REU program. To facilitate this emphasis, the collaboration employs a large server at Indiana University South Bend to house analysis codes and the large data files. This frees every undergraduate institution from having to maintain the complicated codes and allows the undergraduate researcher to work in a variety of meaningful ways. For instance, with the help and guidance of their mentor and the collaboration, students may be given primary responsibility for particular pieces of the analysis. In another mode, students may work with more senior researchers where they provide hours on task and have a good overview of the experiment but do not have the ultimate responsibility for the results. Some collaboration members have undertaken the difficult work of improving the analysis algorithms. Still other undergraduate students with limited time can participate by working on very focused aspects such as the calibration of a single detector subsystem, code checking, or validation of the work of others. Students have also developed routines for use of MoNA during offline periods to monitor cosmic muon flux over time, and to image its flux distribution over a wide angular range in the sky.

We are able to involve undergraduate students in this variety of ways because we have the tradition of expecting such work from our students and because of the collaboration infrastructure. It would be difficult for single researchers from a primarily undergraduate institution to work successfully with their students on the analysis of such measurements in isolation. It is crucial that those involved can participate in regular video-conferences where recent results and problems are discussed with others also working on the same experiment or related analyses. The expertise that comes to the table in this fashion makes the group effort very strong. Giving the students responsibility for the analysis in these ways additionally results in increased effectiveness during the actual experiments.

EVIDENCE OF SUCCESS

In its six years of existence, 62 undergraduate students (11 of them women) from 11 different colleges and universities have been actively involved in building, testing, and operating the MoNA detector. Of the 44 MoNA students who have received undergraduate degrees, 16 are currently in graduate school in physics. Four of them are studying nuclear physics (three of them at the NSCL). Six of them have gone on to graduate school in engineering or chemistry, one of them in nuclear engineering, and three of them are pursuing careers as high school teachers. The other students for which we have records are pursuing a wide variety of careers including several with jobs in industry, one who is in the Peace Corps, and one who is seeking success as an opera singer.

These diverse undergraduate students have worked with one another in assembling and testing MoNA and in operating it during experimental runs. They have pulled shifts and put in the long hours that are characteristic of work in experimental nuclear physics. The graduate students and post docs at the NSCL provided approachable role models for them, and they felt free to ask questions of any of the faculty members in the group.

Throughout the project many of these students have taken the opportunity to present their work at national and regional conferences. This includes 19 undergraduate student-presented posters at national Division of Nuclear Physics meetings supported by the division's Conference Experience for Undergraduates Program and funded by the NSF and the Department of Energy. In addition, eight talks have been given by students at American Association of Physics Teachers meetings, Society of Physics Students meetings, and the National Conference on Undergraduate Research. Complete lists of these presentations are shown in Tables 2 and 3.

Twelve experiments with MoNA have been conducted to date. This activity of students and faculty has resulted in five publications in peer-reviewed journals and three conference proceedings. In addition to the talks given by students, there have been 26 presentations, including three invited talks, at national and international conferences. Faculty have also given 14 seminars and colloquia. The endeavor has been very successful in attracting external support. In addition to the nine NSF grants received to construct MoNA and the grant from the Research Excellence Fund of Michigan that supported the video conferencing project, seven collaborating faculty hold current NSF grants to support their MoNA related research activity. Details of all publication, presentation, and grant activities are available at the MoNA web page (MoNA, 2007).

Table 2: Undergraduate Posters at National Division of Nuclear Physics meetings

Meeting	Title of Poster
2002 Fall Meeting in East Lansing, Michigan	Veto Detectors for the Micro-Modular Neutron Array
	First Radioactive Beam Experiment with the Modular Neutron Array MoNA
	Neutron Testing of the Micro-Modular Neutron Array
	Cosmic Ray Testing of the Micro-Modular Neutron Array
	The MoNA Project
2003 Fall Meeting in Tucson, Arizona	Calibration of the Modular Neutron Array (MoNA)
	High Voltage Control of the Modular Neutron Array
	Cosmic Rays in MoNA
2004 Fall Meeting in Chicago, Illinois	Determination of Position Resolution for the Modular Neutron Array Using Cosmic Rays
	MoNA and Initial Measurements with ^{7}He Resonance
	Cosmic Muon Tracking with MoNA
	Calibration of the Modular Neutron Array
2005 Fall Meeting in Maui, Hawaii	Tracking Single and Multiple Events in MoNA
	MoNA Calibration and Neutron Tracking
2006 Fall Meeting in Nashville, Tennessee	An Automated Relative Time Calibration for MoNA
	Analysis of Kinematics and Decay Energy in the Breakup of ^{7}He
	Calibration of the Thick and Thin Scintillators for the NSCL/FSU Sweeper Magnet System
	Cosmic Muon Flux Variations Using the Modular Neutron Array
	Neutron Multiplicity Discrimination in MoNA

Table 3: Student talks on aspects of the MoNA detector

Meeting	Title of Talk
Illinois Section of the American Association of Physics Teachers, 2002 Fall Meeting in Decatur, Illinois	The MoNA Project
Minnesota Area Association of Physics Teachers, 2002 Fall Meeting in Morris Minnesota	The MoNA Project
Indiana Section of the American Association of Physics Teachers, 2003 Fall Meeting in Bloomington, Indiana	Calibration of Organic Scintillator Bars for the Modular Neutron Detector Array
	Neutron Detection by the Modular Neutron Array (MoNA)
	Experimental Developments along the Neutron Dripline
Society of Physics Students, Zone 9 2005 Fall Meeting in Milwaukee, Wisconsin	Tracking Single and Multiple Neutron Events in the Modular Neutron Array
2005 Joint Meeting of Argonne Symposium for Undergraduates in Science, Engineering and Mathematics & the Central States Universities, Argonne, Illinois	Tracking Single and Multiple Neutron Events in the Modular Neutron Array
20th National Conference on Undergraduate Research (2006), Asheville, North Carolina	Tracking Single and Multiple Neutron Events in the Modular Neutron Array

CONCLUSION

The diverse institutions of the MoNA collaboration have adopted a Mongol Horde model to involve undergraduate students in experimental nuclear physics and the results have been beneficial to all parties involved. The students are involved in cutting-edge science at the front line. The faculty and undergraduate researchers are never isolated as they work. There is a great deal of help dealing with problems, planning for the future, and understanding the results. The NSCL is a premier laboratory in nuclear physics and beam time is in high demand. There are tremendous opportunities for the undergraduates to work on problems that they would not normally see and to become integrated into the bigger research society early in their careers. The undergraduates participate in the weekly video conferences and the annual planning meeting where they see all the hard work that goes into planning and problem solving. The support structure to insure the work is carried to completion extends far beyond the single local faculty researcher.

The approach has major advantages for the user facility. By involving the undergraduate physics majors, the larger universities have the opportunity to recruit talented students as graduate students or technicians. The publicity generated by the project at the individual universities often makes local newspapers and presents the user facility as a partner with the local institutions. Finally, the user facility earns a great good will for the undergraduate institutions actually doing the work.

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 the other 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.

By far, the greatest benefit of our Mongol Horde approach is that it fosters in the students an enthusiasm and interest in continuing their education past their undergraduate studies. Furthermore, our students are extremely well prepared for the research expectations and experimental rigors required of graduate students. They have mastered many fundamental research skills and understand the problem solving process that is essential to carry research through to a conclusion.

This Mongol Horde model and the collaboration has been a success because of the commitment of all, including the university-based members, to see that the undergraduates are involved at a level that is appropriate and challenging. The university members are amenable to this because they have confidence in the faculty mentors to see that the students are kept on track but they also gain because more science gets done. Our Mongol Horde makes real contributions to physics by working in small groups on a major problem. We certainly need Guerrilla Puzzling in undergraduate research, but we also should sustain Mongol Hordes so that undergraduates have the opportunity to participate in cutting-edge, main stream research at large facilities.

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