An Undergraduate Ion Beam Analysis Laboratory

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Abstract: Hope College purchased a 1.7 MV tandem pelletron with nuclear microprobe capability with funding from the US National Science Foundation in 2004. The purpose of this facility is to perform publishable research in a variety of applied fields, and to provide educational opportunities and sophisticated technical training for undergraduates that will enter the workforce in science, technology, engineering and mathematics. Hope College has two senior investigators with experience in nuclear science and expertise with accelerators, and an institution with approximately 3200 undergraduates. The college also has a rich history of involving undergraduates in research and producing future Ph.D. scientists. The facility was installed and commissioned in October, 2004 and since that time hundreds of separate ion beam analysis experiments have been performed in fields as diverse as solid state physics, biochemistry, forensic science, electrochemistry, environmental science, mineralogy and palaeontology. Over 90% of the work has involved on-campus collaborations between different faculty members, and there are already over 50 different undergraduate research students that have been involved in ion beam analysis research. There are six manuscripts published or in press from this facility, with more than two dozen undergraduate co-authors. During the first four years, the facility has been operated entirely with undergraduates and a single technician who was trained to help maintain the facility. We have recently added a post-doctoral fellow to our research group to help with the large number of students that are interested in the research projects that have become possible with the new ion beam analysis facility. A brief tour of our facility and an overview of some of the successful research projects will be presented, plus some insights into best operating practices we have learned for maintaining a productive an ion beam analysis facility at an undergraduate institution.

1. Introduction

There is a need within the United States to address the way in which we teach undergraduates, especially those entering STEM (Science, Technology, Engineering and Mathematics) fields. All too often we have relied on the traditional approach of lectures and structured laboratories to train undergraduates in physics and the related disciplines, and trusted they might continue on in their studies to take an upper-level nuclear science course before they graduate and possibly become interested in pursing nuclear science. This traditional approach to nuclear science education is threatened by several factors: (1) changing student demographics, (2) changing student interests and (3) in the instance of nuclear science, a growing number of years since discovery. In the next two decades demographers predict there will be fewer students overall and they will have more diverse backgrounds[1]. Student interests in the life sciences have also increased dramatically over the past decade, together with funding, with the excitement of all the new discoveries in that area, while it has been 50 years since Sputnik spawned a real interest in physics and related disciplines *(see FIG 1).* From an international perspective, many of these same changes are occurring and in this presentation we present an alternative approach to educating undergraduates in nuclear science by engaging them early in a variety of research projects. This approach has been successful at our institution and is facilitated by advances in modern accelerator instrumentation and world-wide web connectivity, as well as the growth of many interdisciplinary fields in which accelerator science can participate.

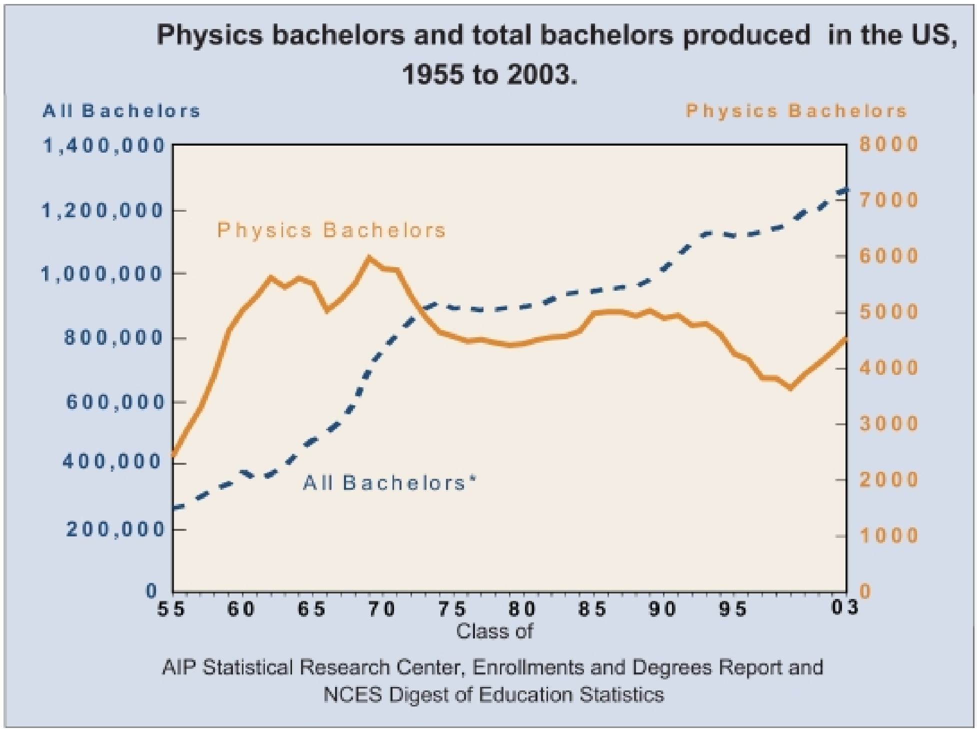

FIG 1. Physics bachelors degrees awarded in the US compared to all bachelors degrees between 1955 and 2003. The launch of Sputnik in 1957 is generally credited with the increased interest in physics that occurred in the late 1950's. Source: AIP Statistics [2].

As background, Hope College is a small liberal arts college in western Michigan, with about 3200 undergraduate students and a long history of integrating research and education in the sciences. We have two experimental nuclear scientists on staff (one in physics and one in chemistry) and one recently-hired postdoctoral fellow. The Hope College Nuclear Group has graduated over 70 students with extensive research experience in various aspects of nuclear science in the past 16 years. We have also published over 80 peer-reviewed scientific papers during this time, most with undergraduate co-authors. Our primary focus for most of these years has been heavy ion reactions, particular with radioactive nuclear beams at both the National Superconducting Cyclotron laboratory at Michigan State University, and the Nuclear Structure laboratory at Notre Dame University. An example of one successful research project includes the Modular Neutron Array (MoNA), which is a collaboration between 8 undergraduate institutions and two research universities to construct and operate a ~$1M state-of-the-art neutron detector. The device was built entirely with undergraduates, assembled at Michigan State and is operated routinely and the data analyzed by undergraduates. More than six publications have already resulted from this device and dozens of undergraduates have been actively engaged in modern nuclear science research. However, this model of research and training requires off-campus trips for the Nuclear Group, so we have actively pursued an on-campus applied nuclear science approach as well.

In 2004 we installed a new NEC 1.7 MV pelletron with nuclear microprobe beamline with funding from the National Science Foundation *(see FIG 2.)* This modern accelerator facility has been used to perform hundreds of experiments in a wide variety of disciplines in its first five years, and its impact on student research and training is remarkable. It is a standard "off-the-shelf" accelerator available from one of two commercial companies that

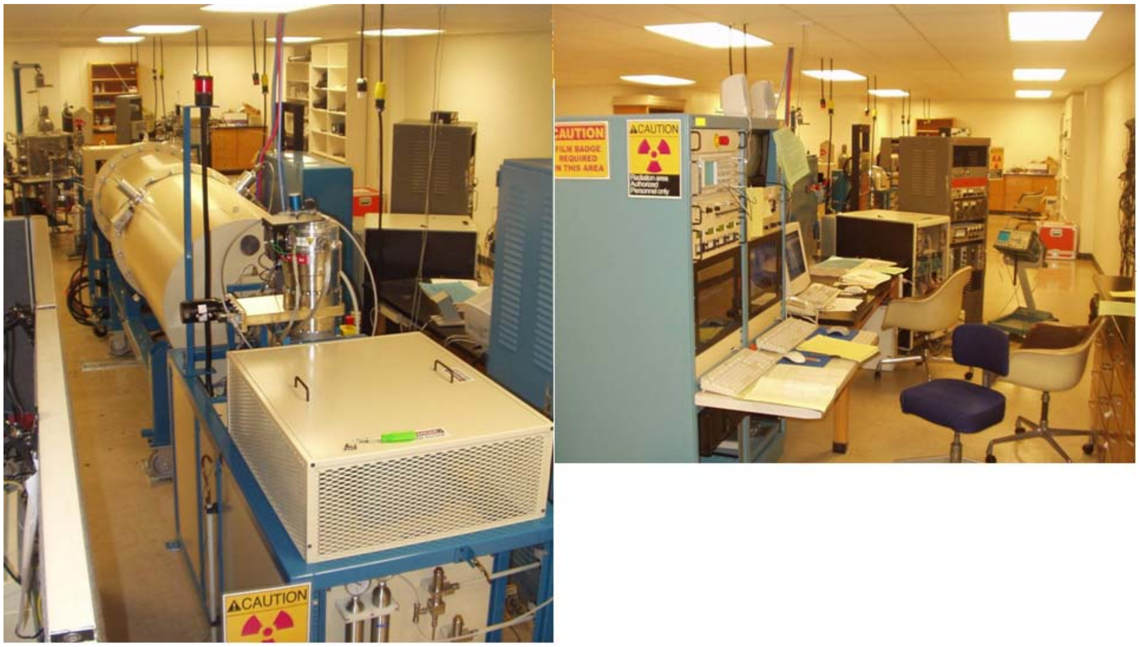

FIG 2. Photographs of the Hope College Ion Beam Analysis Laboratory. The 1.7MV tandem pelletron and alphatross ion source are visible on the left, while the control console and acquisition electronics are visible on the right. Note the absence of shielding walls due to the extra lead shielded installed during construction of the accelerator vessel.

provide such devices, and as can be seen in *FIG. 2* it fits into a single room, without external shielding, and is controlled (together with the target chamber mechanisms and data acquisition systems) from a single series of workstations. We have used the facility to develop several standard ion beam analysis techniques at Hope College: Particle Induced X-ray Emission (PIXE) spectrometry, Rutherford BackScattering (RBS) analysis, Proton Elastic Scattering Analysis (PESA), and Ion-Beam-Induced Luminescence (IBIL) spectrometry to date. Undergraduates are involved in all aspects of these ion beam analysis research projects, performing sample collection and preparation, accelerator operation, data acquisition and analysis, and even writing up the results for publication. A few recent examples are described here, simply to give an impression of the breadth and scope of the projects undertaken by undergraduates.

2. Results

One of our first successes has been investigating metal content in local lake sediments, compared with standard analytical chemical techniques. We have used ^{210}Pb dating of the sediments to establish a correlation between depth of sediment and year of deposition, and then used PIXE of the dried lake sediment to perform a multi-element analysis of metal deposition as a function of time. In addition to demonstrating the rise and decline of anthropogenic metals over the past 150 years - related to atmospheric pollution regulations in the US - we also stumbled into a new observation of diagenesis on the sediment surface that hadn’t been reported before in the Great Lakes. We have also developed a correlation between total metal content in the sediments and the eluted metal content that can be shown to vary from lake to lake that shows great promise for future analytical estimation of metal contamination potential in lake sediments. Our sample preparation and preliminary results for one lake have been published [3,4], and a typical result of the technique comparison is shown in *FIG. 3*.

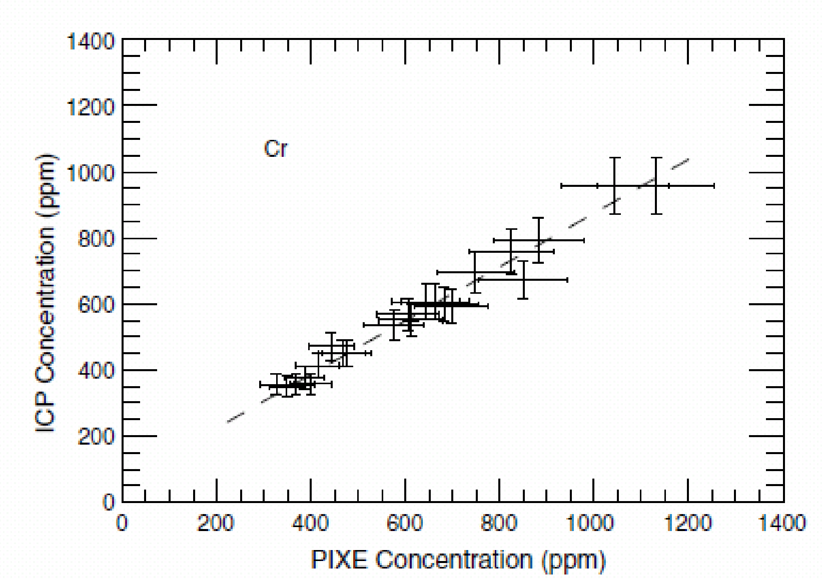

FIG 3. The PIXE and ICP-OES values for the concentration of chromium in White Lake sediment[from 3]. The replicate sample collection, preparation and analysis, including quality control was performed by undergraduates and the first draft of the manuscript prepared by one – the lead author.

Another recently-submitted publication[5] describes our approach to determining metal ion stoichiometry in metalloproteins, using a combination of PIXE and PESA. We have expanded the established technique of using sulfur-to-metal ratio with PIXE to establish the metal ion stoichiometry to include an absolute measurement of the number of protein molecules in aqueous metalloprotein. The hydrogen and heavy element scattering cross-sections are used to determine the absolute thickness of the protein sample, while PIXE gives an independent measurement of the number of metal atoms, providing a first absolute normalization of this ratio independent of protein loading factor, or even a priori knowledge of the protein structure. We have proven the technique with cytachrome-c, and are actively studying proteins of unknown stoichiometry.

Finally, a third successful example involves the forensic analysis of soils and sediments by a combination of PIXE and IBIL techniques. Similar to cathodoluminescence spectrometry used for years in geology, ion beams can be used to excite luminescence in many common minerals, which can be used for forensic analysis of provenance for the minerals within the sample. In addition to just using digital imagery and color analysis, a full spectroscopic capability has been developed by adding a commercial UV-Vis microspectrometer and fiber optic cable to our scattering chamber. Preliminary results indicate some interesting similarities and differences with cathodoluminescence spectra on the same mineral grains. An example is shown in *FIG. 4*, where the IBIL spectrum of a zircon is overlaid with a cathodoluminescence spectrum of the same mineral grain. Because of the rarity of particle induced luminescence results in the literature, there is a lot of basic research into the sources and details of this luminescence that is accessible to undergraduate researchers. This work will undoubtedly lead to publications in forensic science and quite possibly geological sciences as well and has lead to external grant support for two students to study the effect more fully this summer.

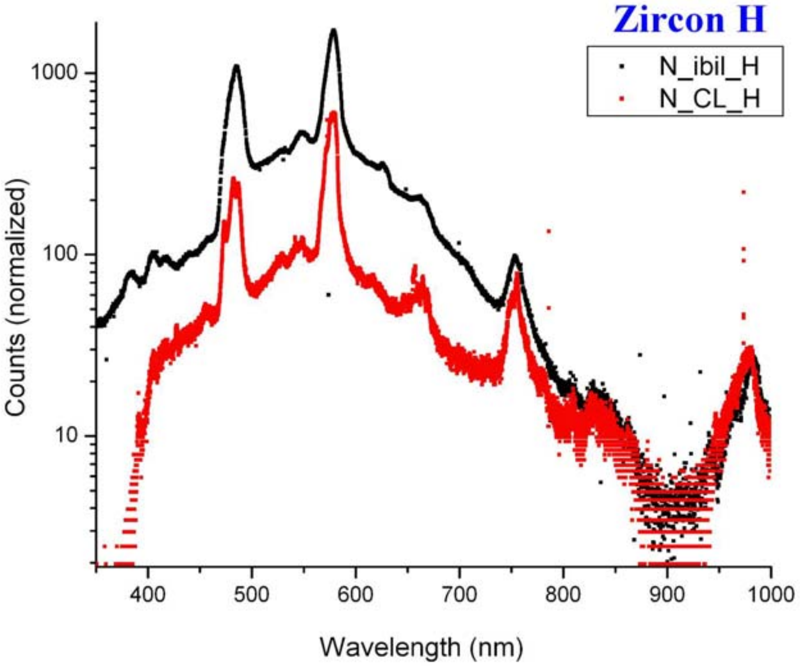

FIG 4. The IBIL and cathodoluminescence UV-VIS spectra compared for a single crystal of natural zircon. The broad luminescence background comes from the silicate matrix, while the sharper lines are distinctive of rare earth elements (Dy^{3+} *in this case) that are present in trace quantities in the mineral.*

3. Conclusions

In conclusion, we have demonstrated that undergraduates can be involved in all aspects of the scientific research process with a small accelerator, and that new instrumentation and networking capabilities allow much more 'hands-on" training than previously possible. Much of this work is very applied and interdisciplinary, which also appeals to student interest, and allows us to attract top students from a variety of undergraduate majors to our scientific research.

Although there has been a significant amount of change in our field recently, how we adapt to such change will be a direct measure of how well small accelerator-based science survives, or even succeeds in the future. These changes have taken place in our student demographics – they come from different backgrounds from us, they have different interests and abilities that we had as students, and they are motivated differently by younger scientific disciplines, compared to the well-established nuclear science disciplines from which accelerator-based science has grown. There has also been a remarkable change in technology over the past decade, especially with modern small accelerators that are much more robust and user-friendly than their counterparts from a few years earlier. In addition, there are tremendous advances in communication technology that allows much more regular exchange of information between remote locations via video conferencing and even remote operation/interaction of accelerator facilities. There has even been change, as there always has been, in the science we study. The disciplines today have their boundaries blurring rapidly with the increased importance of interdisciplinary work, and the increased emphasis of learning more broadly than just a single discipline, even as an undergraduate.

We suggest here, mostly by example, some ways in which we can respond to these challenges of the changing times. In terms of our changing student populations, we clearly need to change our educational approach. Teaching lectures and standard laboratories is not longer sufficient to attract a continual flow of students into our discipline. Engaging students in real research endeavors will do it, and they can be started very early in their scientific career with wonderful success, both in the science produced and in the educational outcomes for the students. Secondly, let us take advantage of the advances in technology to not only utilize modern small accelerator facilities with our students, but to increase the communication between this increasingly isolated community of experts. Not only can we attract outside users and students from other disciplines into our science by remote operation of accelerators and detector technology, but we can use cheap and effective videoconferencing technology over the web to connect labs from around the world that pursue similar types of ion beam analysis work. There is no need to re-invent the wheel at each of more than 50 accelerator facilities around the world, especially in terms of student recruitment and training, but development of a truly global shared database of expertise and methods would advance our field tremendously – and the technical tools to do this now exist. Not only methodology could be shared, but there are many examples of scientific research projects that could be expanded to become multi-institution projects. I cite, for example, our own work into forensic analysis of sand grains to determine provenance of the minerals within them. Clearly every small accelerator facility in the world has access to sand and soils, and this could easily become a joint project to develop a worldwide database of information that could be used in forensic geology readily. There are likely dozens of such projects that could be contemplated, and even funded eventually.

Lastly, we need to make our future educational efforts with small accelerators “science-driven”, rather than developing just pedagogical experiments for students. There is ample evidence from assessment in other fields that hands-on mentored research has a very positive and lasting impression on young students, and research with small accelerators is no different. Exposure to sophisticated instrumentation (with guidance) as well as the combination of exciting interdisciplinary projects for which ion beam analysis is well known, will undoubtedly attract students to our field – we just need to facilitate this with our existing instrumentation and with new instrumentation that is now becoming available.

4. References

1. MARY PAT SEURKAMP, Changing Student Demographics, University Business, 2007: http://www.universitybusiness.com/viewarticle.aspx?articleid=905&p=2#0
2. AMERICAN INSTITUTE OF PHYSICS, STATISTICAL RESEARCH CENTER: http://www.aip.org/statistics/
3. J.M. LUNDERBERG et al., “PIXE as a complement to trace metal analysis of sediments by ICP-OES”, Nucl. Instr. Meth. B266 (2008) 4782.
4. G. F. PEASLEE et al., “PIXE Analysis of Lake Sediment, as a Complementary Technique for ICP Analysis”, Geological Society of America Abstracts with Programs, 40 (2008) 131.
5. J. D. WARNER et al., “Quantitative Analysis of Metalloprotein Stoichiometry with PIXE and PESA”, Nucl. Instr. Meth. B (*submitted* 2009).