SPAGETTY AND THE GETTYSBURG COLLEGE 250-KEV PROTON ACCELERATOR PROGRAM IN RESEARCH AND TEACHING

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Abstract

Even though today's low-energy accelerators are primarily used in medical and industrial applications, our understanding of nuclear physics owes a debt to decades of research with low-energy accelerators. Here we present characteristics of the 250 keV Van de Graaff accelerator at Gettysburg College, Pennsylvania, USA. The research and education agenda involves physicists, chemists and undergraduate students in an interdisciplinary program including nuclear physics, surface physics, nuclear chemistry, polymer science, atomic physics, and materials physics.

Introduction

Low-voltage accelerators (300 keV or less) were once an integral part of most nuclear physics research programs, but the "edge" of nuclear physics currently depends on much higher energies. For this reason, many nuclear physicists depend on a few relatively large (and expensive) facilities. The need for higher and higher beam energies, however, does not mean that low-voltage accelerators are obsolete. In *applied* physics the research agenda is broad and the applications in industry are vibrant. For example, medical and digital electronics industries depend on accelerators, driving a need for an educated workforce. "The market for medical and industrial accelerators currently exceeds $3.5 billion dollars a year, and it is growing at more than ten percent annually [1]."

Low-voltage accelerators provide colleges and universities with an on-campus training tool, even though from a nuclear physics standpoint research programs that commit to low-voltage accelerators can seem limited. Some argue the low-voltage machines are "teaching tools" only, useful only to repeat hallmark experiments like Rutherford scattering. But by reaching beyond traditional *nuclear* physics boundaries, institutions can develop research programs that answer current *applied* physics questions with low-voltage accelerators such as SPAGetty (**S**tudent **P**roton **A**ccelerator at **Getty**sburg College).

Reaching beyond traditional nuclear physics boundaries means looking at open questions in other research areas, some outside of traditional science such as art history applications as in the Proton Induced X-Ray Emission (PIXE) analysis of the Gutenberg Bible by Guy Demortier [2]. Through the relationship between research-based courses and summer research opportunities, we plan to grow our research program to include PIXE

[3] and Proton Induced Gamma Emission (PIGE) [4]. In addition, we may be able to validate K x-ray production cross sections [5] and secondary electron studies via specular reflection.

In this paper we will describe one applied project currently underway at SPAGetty – a study of the effects of radiation damage by protons in the hundreds of keV range on silicone rubber, a material commonly used on satellites. The effect of radiation on spacecraft has led to work ranging from modeling the damage to measurements made in laboratories over a specific particle energy range for a specific type of satellite component.

Characteristics of SPAGetty

SPAGetty is a linear Van de Graaff accelerator, a PN-250 by High Voltage Engineering Corporation, with a proton beam ranging in energy from 250 keV down to 50 keV. At a typical proton beam energy of 130 keV, 10 μA of beam at zero degrees is typical. When running, the accelerator tank is filled with a buffer gas of 55% CO_2 and 45% N_2 at 100 psi to both provide a medium for the corona current as well as to prevent sparking.

The accelerator has two primary beamlines, both kept at 1 - 10 μtorr. An electromagnetic dipole magnet is used to separate the beam with the primary experimental beamline at 25°. This small accelerator has limited passive feedback via corona discharge. Nonetheless reasonable beam stability is achieved through active feedback from left/right slits placed after the 25° analyzer magnet. The difference in signal is used to control the belt charge of the Van de Graaff accelerator column.

SPAGetty does not have a generating voltmeter (GVM) typical of other similar machines so the column current is the main indicator of dome voltage. This is not optimal. We maintain beam stability with tight collimation before and after the bending magnet coupled with the slit feedback. Since typical applications, such as Rutherford Backscattering (RBS) require only nanoamperes of beam on target, we again rely on tight collimation and a known magnetic field for the analyzing magnet to contain the beam energy on target. When larger beam currents are needed we can focus the beam via quadrapoles, sacrificing energy resolution.

The present main measuring tool, an Ortec 3700 series scattering chamber, can be operated with two surface barrier PIPS (Passive Implanted Planar Silicon) detectors on independent rotating arms to determine angular information. The target pedestal can also rotate. During the silicone irradiation measurements the beam was monitored by a copper screen (1 mm square grid size) at the beam entrance to the target chamber. The screen current is calibrated before and after each target irradiation with an Al target and a 25 V electron suppressor ring. The detection energy of our charged particle detectors is calibrated with a ^{133}Ba source which emits conversion electrons ranging from 50 to 380 keV.

Research Agenda

Thirty to 200 keV protons in the Earth's exosphere damage all components of satellites [6]. At Gettysburg College's SPAGetty we want to replicate previous studies methyl silicone rubber and polydimethylsiloxane to confirm the findings of Ref. [7] and [8]. Both groups studied surface damage, mass loss, and in one case [8], chemical damage. We may not only replicate these measurements but may also be able to measure the increasing opacity in real time during irradiation using optical techniques.

Surface damage can be characterized using imaging microscopy and chemical damage with a ThermoElectron IR200 FT-IR Spectrophotometer, a Fourier-transform infared spectrometer in the Gettysburg College Chemistry department. Xiao *et al.* used a 3 mm thick sample of polymethylsiloxane (a type of organic silicone) at room temperature, imaging the light transmitted through the sample in a similar way as shown in Figure 1. In addition, they characterized the chemical changes with a Fourier transform infared spectrometer.

The work by Mingwei Di *et al.* [9] uses 150 keV protons to study radiation damage for three kinds of methyl silicone rubber. We are working to validate the work by Di *et al.* by bombarding methyl silicone with protons in the 50 keV to 250 keV energy range. Damage depends on fluence, but whether this damage increases linearly with fluence and if the damage is due solely to irradiation effects or if heating effects contribute remains to be seen.

At the time of this paper our silicone results are preliminary. We have irradiated methyl silicone over an energy range of 100 to 200 keV and over a fluence range of 5×10^{14} to 1×10^{16} cm^{-2}. Results confirm that optical damage increases with proton fluence. Preliminary results may also support the hypothesis of Zhang et al. [10], that the effects of irradiation on silicones changes from cross-linking below 150 keV to bond breaking above proton energies of 150 keV.

Figure 1 is a methyl silicone sample after irradiation by 150 keV protons at a fluence of 6×10^{15} cm^{-2}. The image was made with the Gettysburg College Biology Department's Nikon 90i Advanced Automated Research Microscope System, a digital microscope coupled with device-specific imaging software allowing magnification ranging from 10x to 1500x. As was seen in Ref. [7], [9], and [10] aging cracks are a characteristic feature. It also appears that a change in density and viscosity takes place as we consistenly see cracks emanate from boundary regions between high and low fluence regions on the target. The increased opacity in the irradiated silicone is most likely due to electrons in silicon and oxygen bond breaking. Irradiation also affects the silicone's viscosity and increases crosslinking, leading to the flow patterns and cracking [11].

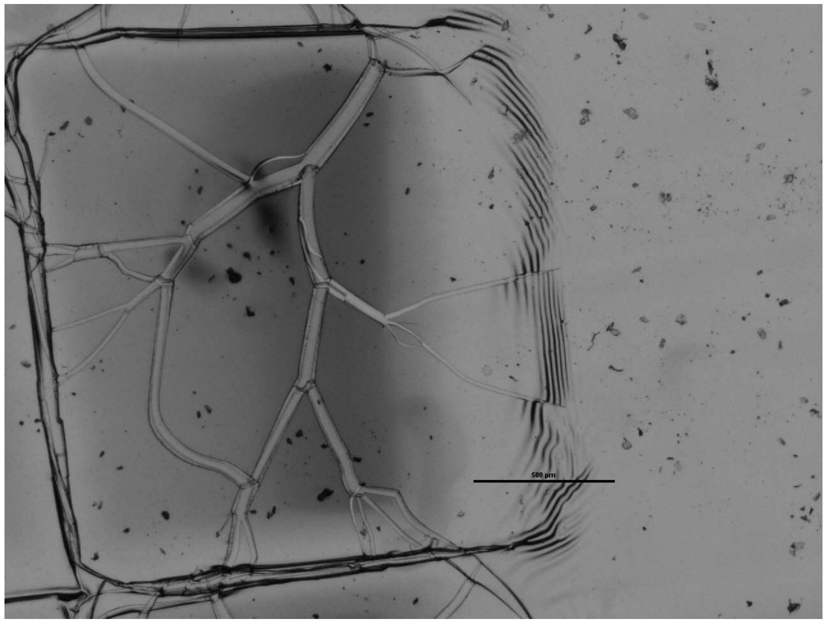

Figure 1: Methyl silicone after subjected to a fluence of 6×10^{15} cm^{-2} at proton energy of 150 keV. The black horizontal line is 500 μm in length. Cracks and rippling are at the boundary between regions of high and low fluence, where the beam is blocked by a Cu screen.

Another research area with many applications outside of physics is PIXE. Typical PIXE beam energies are higher than those from SPAGetty, but PIXE is possible at proton energies as low as 160 keV. Szegedi and Ibrahim [3] detect X-rays outside the vacuum system with a Si(Li) detector after first doing an energy calibration with the 163 keV resonance of ^{11}B using a Na(Tl) detector. Szegedi [12] also looked at K X-ray production cross sections for protons in an energy range well-suited to SPAGetty for all kinds of common elements (copper, aluminum, silicon, iron). We can validate this work with SPAGetty and the forthcoming work by Zhou *et al.*, where they also attempt to study the ratio of the emission cross section of K to L-shell X-rays for the copper, nickel, iron, and zinc [13].

Education Agenda

The Gettysburg College Physics department was one of the select programs studied by the American Institute of Physics because of our superlative track record for not only graduate school placement but also for placing bachelor degree recipients straight into science, technology, and engineering jobs. Part of our success lies in our physics curriculum. Every Gettysburg College physics major must, in their final year, complete either the Physics 420 course or the Physics 460 course, which focuses on more extended research projects.

If faculty choose to use SPAGetty as the primary research laboratory for Physics 420 and Physics 460, then the courses emphasize practical electromagnetics. Successful students come away understanding power supplies, the charging of the accelerator dome, the corona discharge in the buffer gas, radiofrequency discharge in the ion source, the electrostatics and magnetic focusing of the beam, magnetic beam steering, bremsstrahlung from backstreaming electrons, radiation measurement, vacuum systems (both the pumps and the measurement), charge particle detection and calibration, and slit feedback for controlling the beam. This list of skills and knowledge have a breadth and depth of physics knowledge that can be transferred to a wide array of physics work.

Physics 460 is an individualized research course where a single student works with a faculty member to experimentally or theoretically investigate a research-level physics problem. The course culminates with the student presenting their work in a departmental colloquium and by writing a thesis. Bret Crawford has supervised ten summer research projects with SPAGetty as the centerpiece of each project. Four of these summer research projects led to Physics 460 coursework during the academic year. These projects involved building apparatus for SPAGetty, calibrating the beam energy, vacuum system development, and in one case, verifying the $\sin^4$ dependence of $\theta/2$ in Rutherford scattering.

Physics 420, Advanced Research Methods in Physics, is a laboratory course usually taught to twelve or fewer students and led by a single faculty member, with emphasis on that faculty member's research area. Experimental techniques, error analysis, and written and oral communication are key components of Physics 420. This fall Bret Crawford taught Physics 420 as an independent study to Cole Rossiter, and the project centered on the silicone measurements described in the previous section.

Another course, Physics 325 (no longer offered at Gettysburg College) was taught by Bret Crawford, and in that course he used SPAGetty to do Rutherford Backscattering (RBS). Since RBS is a common technique for identifying elements based on their mass using their backscattered energies, and since the theoretical underpinnings of RBS are appropriate for the undergraduate curriculum, using RBS as an entry point into experimental work with SPAGetty makes sense for a small enrollment course like Physics 420. One could then introduce the theory of stopping ions in matter, leading to students working with ion transport simulations through James Ziegler's SRIM code [14]. Students also learn to appropriately include energy losses from both electrons and protons in the silicon of the charged particle detectors.

Conclusion

SPAGetty, a 250 keV linear Van de Graaff accelerator, is a teaching tool with research applications in various areas. Given here is one example of applied work that can be done with students characterizing the silicone damage on satellites caused by proton radiation. Other applied work using PIXE and PIGE is possible at this facility. In addition, studies of K x-ray production cross sections and secondary electron studies via specular reflection are part of our long-range plan. These kinds of projects not only train our future nuclear physicists, but also work at the intersections of nuclear physics, surface physics, and chemical physics.

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References

[1] W. Henning, C. Shank, Department of Energy Report from "Accelerators for America" Symposium (unpublished) (2010).
[2] G. Demortier, Nucl. Instr. and Meth. B, 30 434 (1988).
[3] S. Szegedi and S. M. Ibrahim, J. Radioan. Nucl. Ch. 209, 1, 201 (1996).
[4] Y. Wang and M. Nastasi (eds), Handbook of Modern Ion Beam Materials Analysis, sec. ed., Materials Research Society, Warrendale, PA (2009).
[5] E. A. Sanchez, M. L. Martiarena, O. Grizzi, V. H. Ponce, Phys. Rev. A 45 R1299 (1992).
[6] H. Garrett, D. Hastings, AIAA 94-0590 Conf. Proceedings 590 (1994).
[7] M. Di, S. He, R. Li, D. Lang, Nucl. Instr. and Meth. B 248, 31 (2006).
[8] H. Xiao, C. Li, D. Yang, S. He, J. Appl. Polym. Sci. 109, 4060 (2008).
[9] M. Di, S. He, R. Li, D. Lang, Nucl. Instr. and Meth. B 252, 212 (2006).
[10] L. Zhang, Z. Xu, Q. Wei, S. He, Radiat. Phys. and Chem. 75, 350 (2006).
[11] E. Grossman and I. Grouzman, Nucl. Instr. and Meth. B, 208 48 (2003).
[12] S. Szegedi, P. Rales, and M. Fayez-Hassan, Jour. Radio. Nucl. Chem., 206, 429 (2004).
[13] X. Zhou, Y. Zhao, R Cheng, Y. Wang, Y. lei, X. Wang, and Y. Sun, forthcoming in Nucl. Instr. and Meth. B (2013).
[14] http://www.srim.org/