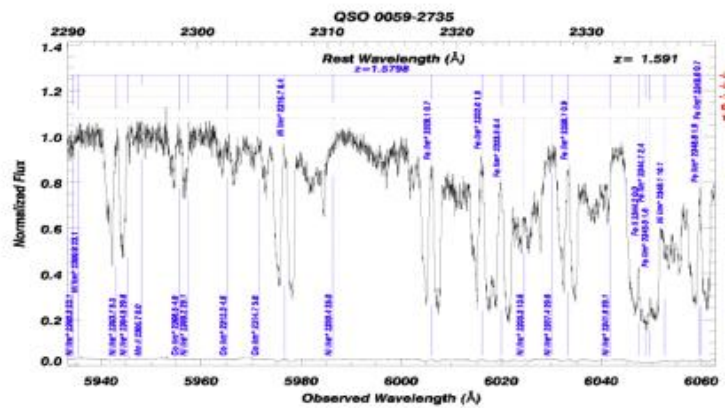
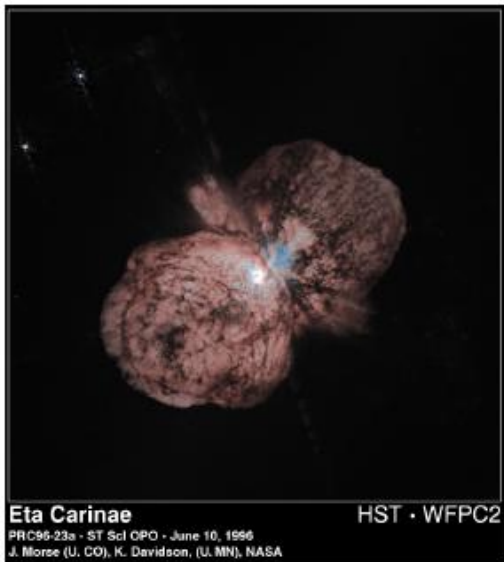
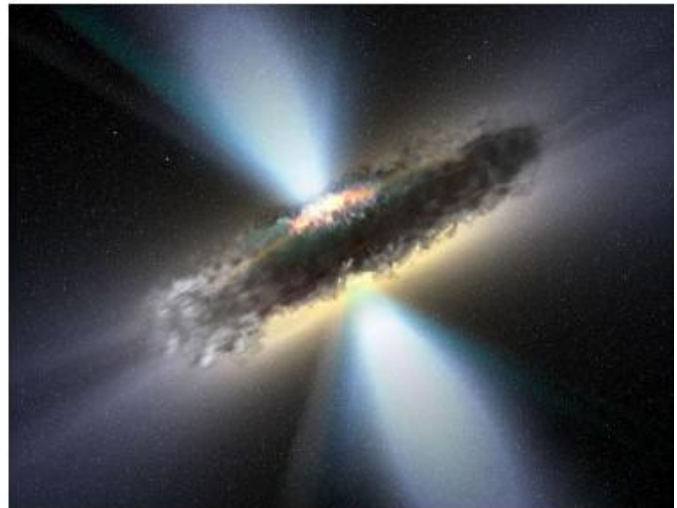
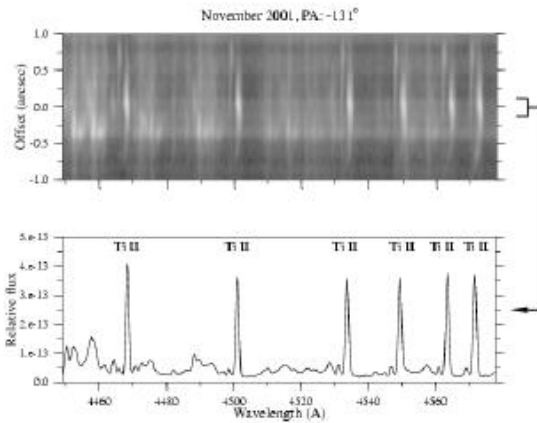


# W Research Report

WESTERN MICHIGAN UNIVERSITY  
College of Arts and Sciences  
Department of Physics

July 1, 2008 – December 31, 2009



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# 1 INTRODUCTION

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This is the thirty-eight in a series of annual reports that summarizes the research activities of the members of the Department of Physics at Western Michigan University.

The report includes summaries of research performed in the department as well as at national and international laboratory facilities. These include Michigan State University, Argonne National Laboratory, Lawrence Berkeley National Laboratory, and SLAC National Laboratory.

During the period July 1, 2008 through December 31, 2009, our department graduated seven M.A. students and four Ph.D. students. Faculty published over 80 articles and one book, presented over 60 talks at national and international conferences as well as seminars and colloquia, and received \$4,031,770 in research grants.

Special thanks to Ms. Kerry Cochran for her invaluable assistance in the preparation and presentation of this document.

*Nora Berrah*  
*Editor*

Cover design:

Astrophysical wonders as seen from space- and ground-based telescopes. On the left are the image of the star Eta Carinae taken with the Hubble Space Telescope (bottom) and a portion of the spectrum of a region of the nebula known as the Strontium Filament recorded with the STIS spectrograph on board of Hubble (top). On the right are an artistic illustration of an Active Galactic Nucleus (top) and a portion of a schell UV/optical spectrum of the quasar QSO 0059-2735 taken with the Very Large Telescope. Courtesy of Manuel Bautista.

## 2 FROM THE CHAIRPERSON

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Thank you for your interest in Physics research at Western Michigan University. If you are a regular reader, you may have noticed that we are shifting our annual research report to cover work done during a calendar year rather than the July through June period we used previously. We intend for future reports to cover one year of activity, January through December. We have made some other changes in format to streamline this publication, but it will still provide highlights from the great variety of research projects which our faculty and students are constantly engaged in.

As you can see, we remain active at the forefront of several subfields of physics, and continue to provide excellent opportunities in research for our students at all levels. We are particularly pleased to welcome a new member of our faculty, Dr. Manuel Bautista, whose work in measuring and modeling astrophysical plasmas bolsters our growing presence in the field of astrophysics. We look forward to more contributions from Dr. Bautista for years to come.

*Paul V. Pancelli*  
*Chair*

# 3 ASTRONOMY

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## 3.1 *Manuel Bautista*

### Astronomy and Atomic Physics

#### 1) **Research Abstract:**

I study astrophysical plasma and their spectra, including atomic and molecular processes, radiative transfer, and hydrodynamics. These plasmas, in the context of different kinds of astronomical objects, respond to the mechanical, thermal, and radiative energy, thus it is through understanding of these plasmas that we decipher how the universe operates. Objects like Eta Carinae, where dense shells of episodic ejections create an opaque nebula where mostly low ionization iron-peak species are seen and non-equilibrium photo-chemical reactions lead to the formation of molecules and grains. Galactic winds in Active Galactic Nuclei, that are thought to regulate the evolution of their super-massive Black Holes and the whole galaxy, and exhibit rich spectra that extends from the infrared to X-rays. Up to the photosphere of Sun-like stars where despite enormous gas pressures the intense radiation fields cause atoms to depart from local thermodynamic equilibrium and difficult our understanding of stellar structure and composition. Upon my arrival to WMU, on August 2009, I continued two main projects being funded by NASA (Astronomy and Physics Research and Analysis program) and the Space Telescope Science Institute. This work is in a systematic study of the spectra of low ionization iron-peak species and the construction of spectral models for these systems. These ions are crucial in the study of a great variety of galactic and extragalactic objects. The models will be benchmarked and applied in the analysis of spectra of Eta Carinae taken with the Hubble Space Telescope and high resolution ground based observations of Quasar outflows.

Another project, also continued at WMU, is on modelling the spectra through the inner K-shell of ions of Neon through Nickel. Thanks to continued support from NASA (Astronomy Theory program) we have computed the atomic parameters needed to interpret the atomic inner shell process involving the K-shell of ions of astronomical interest. The data has then been included into the atomic database and spectral modelling code XSTAR of T.R. Kallman and M.A. Bautista, which is widely used by the scientific community.

## **LIST OF PUBLICATIONS**

1. García, J., Kallman, T. R., Witthoeft, M., Behar, E., Mendoza, C., Palmeri, P., Quinet, P., Bautista, M. A., Klapisch, M., “Nitrogen K-Shell Photoabsorption” 2009, The Astrophysical Journal Supplement Series, vol. 185, pp. 477.
2. Bautista, M. A., Quinet, P., Palmeri, P., Badnell, N. R., Dunn, J., Arav, N., 2009, “Radiative transition rates and collision strengths for Si II,” Astronomy & Astrophysics, vol. 508, pp. 1527.

## **INVITED TALKS**

1. Bautista, Manuel A, “Spectral Models of Low Ionization Iron Peak Species,” in the first annual NASA UV-Vis SR&T workshop, 22 -23 September 2009, NASA Head Quarters, Washington D.C.

## **SCHOLARLY ACTIVITIES**

1. Referee of The Astrophysical Journal, Astronomy & Astrophysics, Journal of Physics B.

# 4 ATOMIC PHYSICS

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## 4.1 *Nora Berrah*

### **Probing Complexity using the ALS and the LCLS**

Ileana Dumitriu, Huaizhen Zhang, Rene Bilodeau, Matthias Hoener, Li Fang, Brendan Murphy, and Nora Berrah

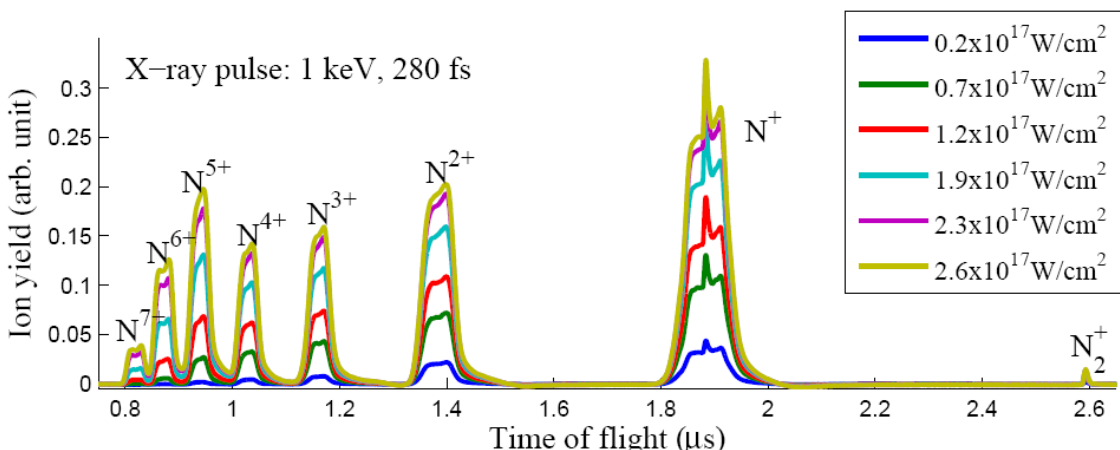
#### **1) Program Scope**

The objective of our WMU research program is to investigate complexity through *fundamental interactions between photons and gas-phase systems* to advance our understanding of correlated and many body phenomena. Our research investigations probe multi-electron interactions, the dynamics of interacting few body quantum systems and energy transfer processes from electromagnetic radiation. Most of our work is carried out in a strong partnership with theorists.

Our current interests include: 1) The study of non linear and strong field phenomena in the x-ray regime using the linac coherent light source (LCLS), the first x-ray ultra-fast free electron laser (FEL) facility at the SLAC National Laboratory. Our investigations will focus on atoms, molecules and clusters to understand ultrafast and ultra-intense phenomena. 2) The study of correlated processes in select molecules, clusters and their anions using advanced techniques with vuv-soft x-rays from the Advanced Light Source (ALS) at Lawrence Berkeley Laboratory. We present here results completed and in progress this past year.

#### **2) X-Ray Non-Linear Physics Studies of Molecules with Intense Ultrafast LCLS Pulses**

The LCLS *started lasing* in April 2009 and was scheduled to provide beamtime to users in September, 2009. My WMU team contributed to the commissioning of the LCLS AMO instrument during the 2009 summer. Furthermore, we were granted beamtime to carry out some of the first AMO experiments in October 2009. The instrument used to carry out the experiments consists of five electron time-of-flight (TOF) spectrometers and an ion detector to measure the electron angular distribution and the ion charged states resulting from the ionization of atoms, molecules and clusters with the X-ray FEL. Specifically, we carried out non-linear studies in  $N_2$  as a function of focused x-ray laser intensity and pulse duration. We studied multiple and multi-photon ionization focusing on the measurements of photoelectron and Auger electrons as well as ion subsequent to the ionization with 1 keV intense LCLS photons with 7fs, 80fs and 280fs pulse duration. In particular, the ionization of  $N_2$  with laser power of at least  $1.2 \times 10^{17} \text{ W/cm}^2$  results in fully stripping the fragment ion N as shown in Fig. 1. The figure also shows a very weak mother ionized molecules,  $N_2^+$  that after excitation fragments to give N atom. These in turn, due to the intensity of the laser, absorb sequentially up to five photons to produce fully stripped  $N^{7+}$ .



**Figure 1** Ion TOF spectrum for different x-ray beam intensities. The x-ray photon energy is 1 keV and the pulse width is 280 fs. The ion yields are normalized using the  $N_2^+$  signal.

### 3) Emergence of Valence Band Structure and Autoionization Resonances in Rare-Gas Clusters using the ALS

The formation of electronic band structure by the valence-shell of Ar, Kr, and Xe clusters was studied for various cluster sizes using angle-resolved photoelectron spectroscopy. Our experimental system allows us to probe selectively either the cluster surface or cluster bulk since the e-TOFs provide very good electron kinetic energy resolution. Different widths of the fine-structure components in the cluster spectra are attributed to a splitting of the outermost  $p_{3/2}$  levels due to valence-orbital overlap between neighboring atoms. Photoelectron angular distributions from the cluster differ from the atomic cases and vary substantially for different bands. Our measurements have shown unambiguously for the first time the evolution of the electronic structure with increasing cluster size. Our data demonstrate clearly the changes of the valence band structure in the transition from a condensed-phase monolayer to the bulk [1,2].

We have also measured the photoionization of argon clusters in the Ar  $3s \rightarrow np$  Rydberg resonance region. For the first time, partial photoelectron yields and photoelectron angular distributions for the two spin-orbit components in argon clusters are reported as a function of the photon energy. The angular distributions of cluster photoelectrons differ substantially from the atomic ones. It allows, moreover, the identification of bulk and surface resonances [3].

### 4) Molecular-Frame Angular Distributions of Resonant CO:C ( $1s$ ) Auger Electrons

Measurements of molecular-frame electron angular distributions (MFAD) allow access to an unprecedented level of detailed information, such as phases of photoelectron waves, localization of charge, core hole double-slit interference and photoelectron diffractions which are hidden in conventional gas-phase electron spectroscopy due to the random orientation of the molecules. Most of these studies to date have focused on photoelectrons. However, our team has used a novel methodology to determine for the first time the molecular-frame angular distributions of resonantly excited CO:C ( $1s$ ) Auger electrons. The molecular frame is the natural reference frame for the study of molecules and their interaction with electromagnetic radiation or charged particles. In order to experimentally determine MFAD the molecules have to be “fixed” in space, which can be realized by applying the angle-resolved photoelectron-

photoion coincidence technique [a]. Although most of these studies have focused on photoelectrons, Auger electrons provide complementary information on the electronic structure and the anisotropy of atoms, molecules, and solids after the initial excitation. Because of their element and sites specificity, Auger electrons are often used as a probe for the atomic environment in large molecules and solids. In the case of resonant excitation, the focus of our work, they represent the only way (apart from fluorescence) to obtain information since no other electron is emitted. From a theoretical point of view, understanding the MFADs is probably the most demanding open question in molecular Auger spectroscopy.

There is no report on MFADs of resonant Auger electrons probably because the high kinetic energy of Auger electrons combined with the necessary high kinetic energy resolution does not allow detection in the full  $4\pi$  solid angle. The determination of Auger electron MFAD is substantially more challenging and time consuming than the measurement of photoelectron MFADs [b,c]. Recently, in collaboration with the Sendai group, we used a newly developed analytical framework, allowing full three-dimensional MFADs from measurements of electrons at only two angles in combination with  $4\pi$  momentum-resolved ion detection [4]. This novel approach makes high-resolution measurements of Auger electron MFADs considerably more convenient and feasible as demonstrated in our subsequent work [5,6].

Our experiment [4] was performed at the ALS Beamline 4.0.1 in the two-bunch mode. Our apparatus consists of a coincidence system that employs a momentum imaging spectrometer with two electron time-of-flight (TOF) analyzers mounted in the plane perpendicular to the light propagation direction, at  $0^\circ$  and  $54.7^\circ$  with respect to the horizontal. The uniqueness of our coincidence system lies in the fact that we have very good electron kinetic energy resolution.

Specifically, our investigation was focused on elucidating the assignment of two main groups, “*h*” and “*i*” from the resonant Auger spectrum subsequent to the resonantly excited CO:C ( $1s$ )  $\rightarrow \pi^*$  Auger electrons [4]. For the selected geometry, the MFADs of the “*h*” and “*i*” groups show distinct differences. In particular, the MFAD of group “*h*” displays a strong asymmetry with a preferential emission of the electrons along the direction of the carbon atom, while the MFAD of group “*i*” is more isotropic and has a large fraction of its total intensity in the plane perpendicular to the molecular axis. The different shapes of the MFADs are well reproduced by ab initio calculations in the one-center approach. They provide an unambiguous assignment of group “*h*” to two states,  $3^2\Pi$  and  $4^2\Pi$ , which have almost identical MFADs. Group “*i*” appears in the energy region where the calculations predict transitions to the  $5^2\Pi$  and  $1^2\Phi$  states.

In conclusion, our findings point to very different angular distributions for two close lying electron spectator groups, both of which could be identified through the comparison with theoretical predictions [4]. Our calculations based on a one-center approach [d] are able to withstand the most stringent test of reproducing well the experimental angular distributions, and furthermore predict that the sum of all Auger transitions is strongly focused toward the carbon atom.

## 5) Multi-User Movable Ion Beamline

We have successfully built and completely commissioned a movable ion beamline (MIPB) that allows the photoionization study of positive and negative ions in the merged beam geometry. This instrument complements the existing excellent ion-photon beamline (IPB) facility fixed at the ALS beamline 10.0.1. The MIPB has been used using photons from beamline 8 that enable deep core-shell ionization in molecules and clusters. We have carried out experiments in  $C_2^-$  and  $C_4^-$  and plan to continue the investigation of the carbon chain. The instrument is available for any users to exploit the capabilities of any ALS beamlines, specifically below 9 eV and above 340 eV photon energies not available on BL10.0.1.

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- [a] E. Shigemasa et al., Phys. Rev. Lett. 74, 359 (1995), F. Heiser et al., Phys. Rev. Lett. 79, 2435 (1997); R. Dörner et al., Phys. Rev. Lett. 81, 5776 (1998); P. Downie et al., Phys. Rev. Lett. 82, 2864 (1999).
- [b] A. K. Edwards et al., Phys. Rev. A 55, 4269 (1997).
- [c] Th. Weber et al., Phys. Rev. Lett. 90, 153003 (2003).
- [d] R. F. Fink, S. L. Sorensen, and A. Naves de Brito, J. Chem. Phys. 112, 6666 (2000) .

## DISSERTATIONS

### **Ph. D.**

Huaizhen Zhang, *Photoionization of Rare Gas Clusters*, August 2009.

## PUBLICATIONS

1. D. Rolles, H. Zhang, Z. D. Pešić, J. D. Bozek, and N. Berrah, “Emergence of Band Structure in Valence Photoemission from Rare Gas Clusters,” Chem. Phys. Lett. 468, 148 (2009).
2. N. Berrah, D. Rolles, Z. D. Pešić, M. Hoener, H. Zhang, A. Aguilar, R. C. Bilodeau, E. Red, J. D. Bozek, E. Kukk, R. Dies Muino and G. Abajo, “Probing free Xe clusters from within,” Euro. Phys. J. Special Topics (EPJ) ST, **169**, 59 (2009).
3. H. Zhang, D. Rolles, J.D. Bozek, R. Bilodeau, and N. Berrah, “Photoionization of argon clusters in the Ar  $3s \rightarrow np$  Rydberg resonance region,” J. Phys. B: At. Mol. Opt. Phys., **42**, 105103, (2009).
4. D. Rolles, G. Prümper, H. Fukuzawa, X.-J. Liu, Z. D. Pešić, R. F. Fink, A. N. Grum-Grzhimailo, I. Dumitriu, N. Berrah, and K. Ueda, “Molecular-Frame Angular Distributions of Resonant CO:C(1s) Auger Electrons, Phys.,” Rev. Lett. **101**, 263002 (2008).
5. G. Prümper, H. Fukuzawa, D. Rolles, K. Sakai, K. Prince, J. Harries, Y. Tamenori, N. Berrah, and K. Ueda, “Is CO C 1s Auger Electron Emission Affected by the Photoelectron?,” Phys. Rev. Lett. **101**, 233202 (2008).
6. G. Prümper, D. Rolles, H. Fukuzawa, X. J. Liu, Z. Pešić, I. Dumitriu, R. R. Lucchese, K. Ueda, and N. Berrah, “Measurements of molecular-frame auger electron angular distributions at the CO C  $1s^{-1} 2\pi^*$  resonance with high energy resolution,” J. Phys. B: At. Mol. Opt. Phys. **41**, 215101 (2008).
7. Z. Pešić, D. Rolles, R. C. Bilodeau, I. Dumitriu, and N. Berrah, “Three-Body Fragmentation of CO<sub>2</sub><sup>2+</sup> upon K-shell Photoionization,” Phys. Rev. A **78**, 051401 (2008) (rapid C).
8. H. Zhang, D. Rolles, J. D. Bozek, B. Rude, R. C. Bilodeau, and N. Berrah, “Angular distributions of inner shell photoelectrons from rare-gas clusters,” Phys. Rev. A **78**, 063201 (2008).

9. M. Wiedenhoeft, A. A. Wills, X. Feng, S. Canton, J. Viefhaus, T. Gorczyca, U. Becker, and N. Berrah, "Exchange and PCI effects on Angular Distribution in Xe 4d<sub>5/2</sub>," J. Phys. B. **41** 095202, (2008).

## **GRANTS**

1. Principal Investigator: Department of Energy, Office of Science, BES, Division of Chemical Sciences, Geosciences and Biosciences grant. Project title: Probing Complexity using the ALS and the LCLS. Funded \$ 590,000 between March 2008-2011.
2. Principal Investigator: NSF international grant for US/CNRS research. Funded \$29,000 between May 2005-2011.
3. Principal Investigator: Department of Energy, Office of Science, BES, Division of Chemical Sciences, Geosciences and Biosciences grant. Project title: Probing Complexity using the ALS and the LCLS. Supplement \$80,000 (August, 2009)
4. Principal Investigator: Department of Energy, Office of Science, BES, Division of Chemical Sciences, Geosciences and Biosciences grant. Project title: Advanced Instrumentation for Ultrafast Science at the LCLS. Funded \$3,000,000 between September 2009-2011.
5. Beamtime granted at the x-ray free electron laser, LCLS at Stanford National Laboratory (SLAC).
6. Beamtime granted at ALS, Lawrence Berkeley National Laboratory.

## **INVITED TALKS**

1. "Imaging Clusters and Molecules," International Workshop in Photoionization, Uppsala, Sweden, July 15-20, 2008 (will be given by D. Rolles).
2. "Probing Matter from Within," Nordic Conference in Physics (NorWIP), Uppsala, Sweden, September 2008.
3. "Atomic, molecular, cluster and chemical science with the LCLS," Workshop at the LCLS users meeting, October 2008.
4. "First molecular experiment using the LCLS," Workshop at the LCLS users meeting, October 2009.
5. "Non-linear studies of molecules," Planning experiment workshop at the LCLS, March 2009.

6. "New generation light source," Workshop, BESAC, DoE, Washington, DC, February 25-27, 2009.
7. "First Experiments at the LCLS," BESAC meeting, DoE, Washington DC, November 2009.
8. "Molecular-frame angular distribution of normal and resonant Auger electrons," (e,2e) ICPEAC satellite, Lexington, July 28, 2009 (Given by D. Rolles).
9. "Three-Body Fragmentation of  $CO_2^{+2}$  upon K-shell Photoionization," International Conference on Photonic, Electronic and Atomic Collisions, ICPEAC 2009, MI, July 22, 2009. Given by Ileana Dumitriu (Special Report).

### **CONTRIBUTED TALKS**

1. R. C. Bilodeau, J. D. Bozek, I. Dumitriu, A. Aguilar, C. W. Walter, N. D. Gibson, D. Rolles, N. Berrah, "Inner-shell Ion-Photon Studies with the New Movable Ion Beamline," 2008 ALS users meeting, Oct 2008.
2. M. Hoener, D. Rolles, Z. D. Pešić, A. Aguilar, R. Bilodeau, E. Red, and N. Berrah, "Fragmentation Dynamics of Pure and Doped Rare Gas Clusters," 2008 ALS users meeting, Oct 2008.
3. I. Dumitriu, R. Bilodeau, T. W. Gorczyca, D. Gibson, W. Walter, A. Aguilar, Z. Pešić, D. Rolles, and N. Berrah, "Inner-Shell Photodetachment Threshold of Transition Metal Negative Ions," 40th Annual Meeting of the APS Division of Atomic, Molecular, and Optical Physics, May 19–23, 2009, p. 173, University of VA, Virginia.
4. N. Gibson, W. Walter, R. Field, D. Carman, J. Shapiro, R. Bilodeau, I. Dumitriu, N. Berrah, A. Aguilar, "Inner-Shell Photodetachment from  $Se^-$ ," 40th Annual Meeting of the APS Division of Atomic, Molecular, and Optical Physics, May 19–23, 2009, p. 172, University of VA, Virginia.
5. R. Bilodeau, I. Dumitriu, D. Gibson, W. Walter, and N. Berrah, "Promoting a core electron to fill a d-shell: A novel threshold law and shape and Feshback resonances," 40th Annual Meeting of the APS Division of Atomic, Molecular, and Optical Physics, p. 173, University of VA, Virginia.
6. N. Gibson, W. Walter, R. Field, D. Carman, J. Shapiro, R. Bilodeau, I. Dumitriu, N. Berrah, A. Aguilar, "Inner-Shell Photodetachment from  $Se^-$  at the ALS," XXVI International Conference on Photonic, Electronic and Atomic Collisions (ICPEAC) 2009, July 22-28, 2009.

7. Z. Pešić, D. Rolles, G. Prumper, H. Fukuzawa, X. J- Liu, R. Fink, A. Grum-Grzhimailo, I. Dumitriu, N. Berrah and K. Ueda, "Molecular frame angular distributions of resonant CO: C(1s) Auger electrons," XXVI International Conference on Photonic, Electronic and Atomic Collisions (ICPEAC) 2009, July 22-28, 2009.
8. I. Dumitriu, R. Bilodeau, T. W. Gorczyca, D. Gibson, W. Walter, A. Aguilar, Z. Pešić, D. Rolles, and N. Berrah "Shaoe resonances in inner-shell photodetachment of Transition Metal Negative Ions," XXVI International Conference on Photonic, Electronic and Atomic Collisions (ICPEAC) 2009, July 22-28, 2009.
9. Z. Pešić, D. Rolles, I. Dumitriu, and N. Berrah, "Photofragmentation of gas-phase furan following k-shell ionization," XXVI International Conference on Photonic, Electronic and Atomic Collisions (ICPEAC) 2009, July 22-28, 2009.
10. R. Bilodeau, I. Dumitriu, N. Gobson, W. Walter and N. Berrah, "Promoting a core electron to fill a d-shell: A novel threshold law and shape and Feshback resonances," XXVI International Conference on Photonic, Electronic and Atomic Collisions (ICPEAC) 2009, July 22-28, 2009.
11. H. Zhang, D. Rolles, J. Bozek, and N. Berrah, "Core-shell and valence shell photoionization of Ar clusters," XXVI International Conference on Photonic, Electronic and Atomic Collisions (ICPEAC) 2009, July 22-28, 2009.
12. A. Juarez, E. Red, M. Hoener, L. Hoyos-Campo, D. Rolles, N. Berrah, and A. Aguilar, "Ultra-low kinetic energy photoelectron angular distribution measurements in He and ne using a velocily map Imaging spectrometer," XXVI International Conference on Photonic, Electronic and Atomic Collisions (ICPEAC) 2009, July 22-28, 2009.

## **SCHOLARLY ACTIVITIES**

1. Member, APS, DAMOP, Nominating Committee, 2008-2010.
2. Member, ALS, LBNL, UC, Berkeley, Science Advisory Committee (SAC), 2007-2010.
3. Member, SSRL, SLAC, Stanford University, Science Advisory Committee (SAC), 2006-2009.
4. Co-team leader (with Lou DiMauro) for Atomic and Molecular Science at the Femtosecond Linac Coherent Light Source (LCLS) at SLAC, Stanford, CA (2004-present).
5. Co-Chair (with Artie Bienenstock), "Strengthening the Physics Enterprise in Universities and National Laboratories through Gender Equity," APS, CSWP, May 7-9, 2007.
6. Co-Chair (with John Tanis), International Conference on Photonic, Electronics and Atomic Collisions, ICPEAC09.

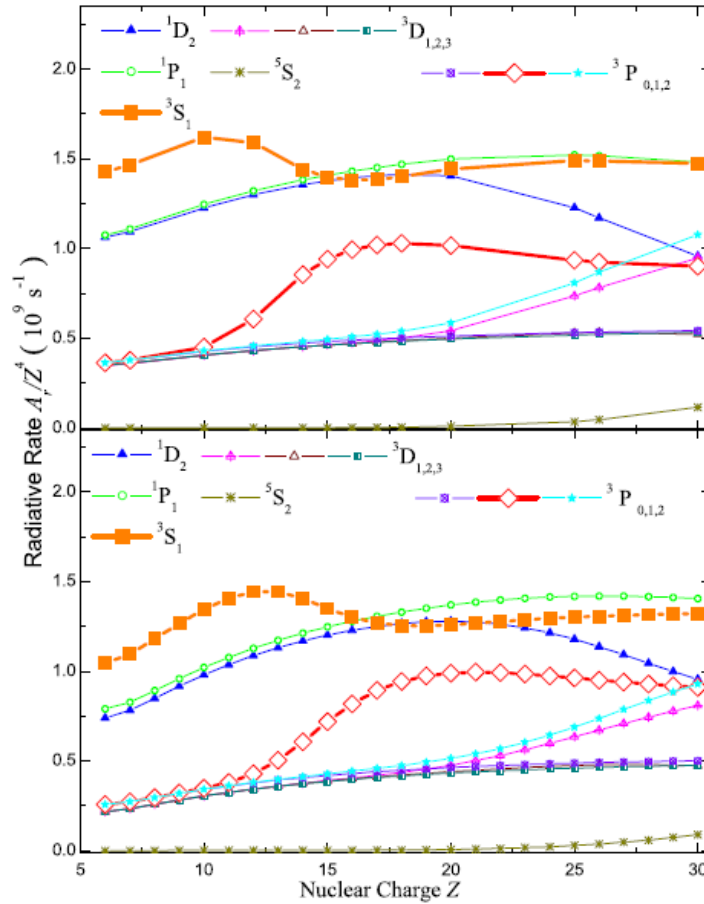
7. Member, Executive Committee, International Conference on the Photonic, Electronics and Atomic Collisions, 2005-2009.
8. Chair, APS, Committee of the Status of Women in Physics (CSWP), 2007-2008. Member, review committee of the FOCUS NSF Laser Center, U. of Michigan, 2007-2009.
9. Member, Graduate Committee Admissions, 1993-1996, '99-'present.
10. Member, Distinguished faculty Scholar Award.

## Theoretical Atomic physics

Thomas W. Gorczyca (Professor), Dragan Nikolić (Postdoctoral Research Associate), Fatih Hasoğlu (Graduate Student), and Shahin Abdel Naby (Graduate Student)

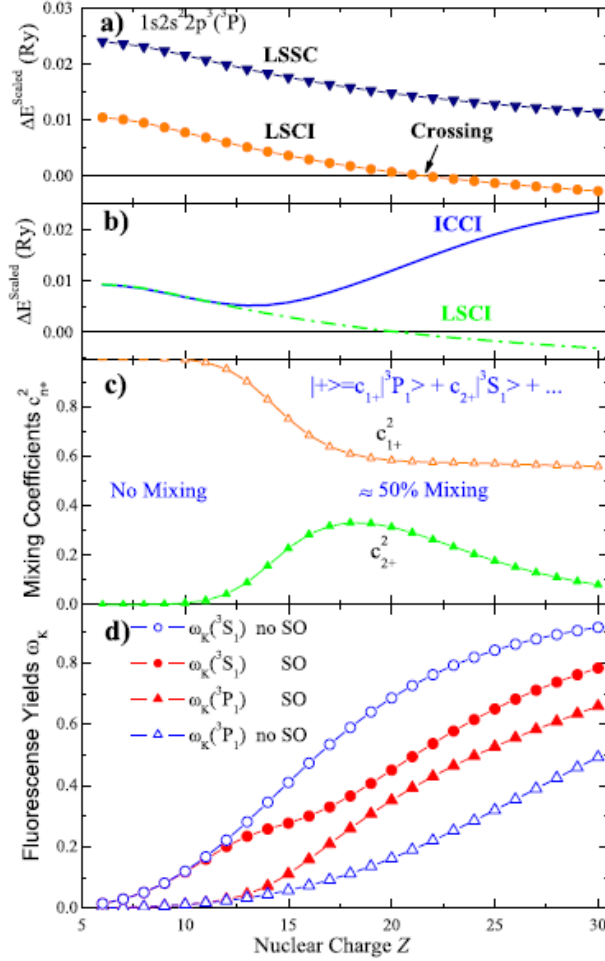
### Anomalous Behavior of Auger and Radiative Rates and Fluorescence Yields along the $1s2s^22p^3$ K-Shell Isoelectronic Sequence: Non-Monotonic Behavior as a Function of $Z$

Calculations using two different methodologies have revealed anomalous behavior of the radiative and Auger rates, and the associated fluorescence yields, of the six electron  $1s2s^22p^3$  K-shell vacancy isoelectronic sequence, exhibited as non-monotonic behavior as a function of nuclear charge  $Z$ . This behavior is explained in terms of an accidental degeneracy, an avoided-crossing of two nearly-degenerate spin-orbit coupled states. The results also demonstrate the importance of including both multielectron correlation and spin-orbit effects even at low- $Z$ .



**Figure 1** Calculated MCDF (top) and MCBP (bottom) radiative  $A_r$  rates for the 10 K-shell vacancy levels  $1s2s^22p^3$  ( $^{2S+1}L_J$ ) of the C-like isoelectronic sequence. Note that  $A_r$  is scaled by  $1/Z^4$  to factor out the strong  $Z^4$  dependence.

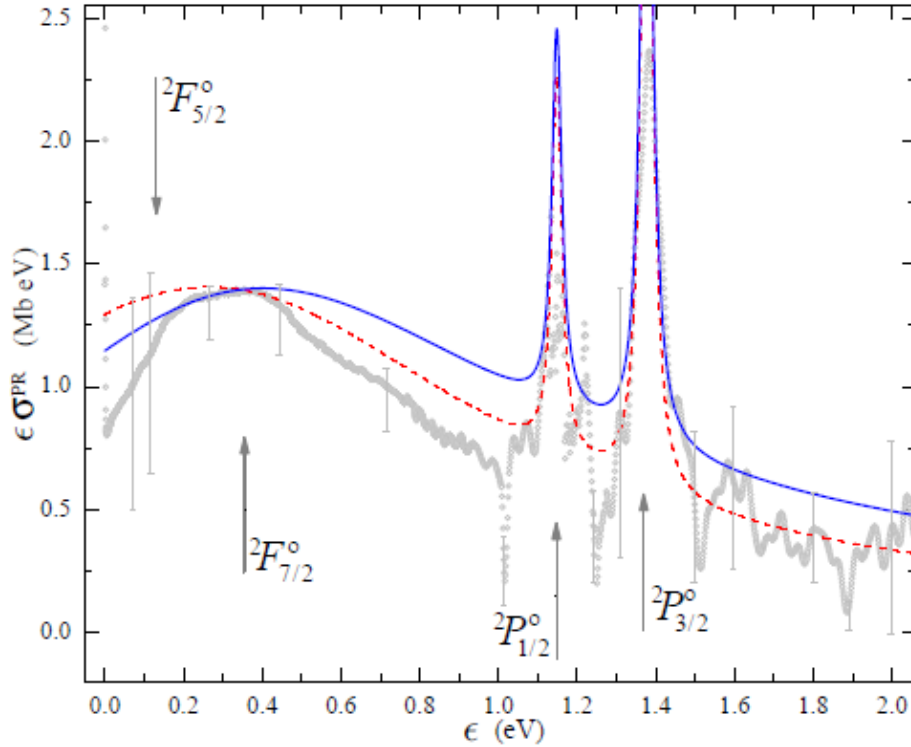
We demonstrated that higher-order configuration interaction (CI), spin-orbit, and energy level crossing effects, all considered together, result in anomalous behavior of the calculated radiative and Auger rates and fluorescence yields (see Fig. 1). The fact that we get precisely the same phenomenology using a MCPB methodology (based upon the Schrodinger equation) and MCDF (based on the Dirac equation) is convincing evidence that the anomalous behavior is not a calculational artifact. This behavior is understood within the framework of the Von Neumann-Wigner avoided crossings phenomena; an accidental degeneracy, or crossing, of the  $1s2s^22p^3\ ^3P_I$  and  $1s2s^22p^3\ ^3S_I$  non-relativistic energies at  $Z \approx 20$  results in significant spin-orbit mixing (nearly 50% of each) (see Fig. 2). This in turn leads to radiative and Auger rates from states of mixed character and anomalous behavior as a function of  $Z$ . Consequently, we have demonstrated that, in general, even interpolation of rates and yields along an isoelectronic sequence is unsafe and for one more reason, explicit calculations for each member of a sequence is necessary.



**Figure 2** a)  $\Delta E^{\text{scaled}} = (E(^3P) - E(^3S))/Z$  within the  $1s2s^22p^3$  configuration at the nonrelativistic single configuration and configuration interaction levels. b) Same as a) with nonrelativistic (dashed line) and full calculation including CI and relativistic effects in an intermediate coupling scheme (solid curve). c) Mixing coefficients for the relativistically (spin-orbit) mixed  $^3P_I$  and  $^3S_I$  states of the  $1s2s^22p^3$  configuration. d) Fluorescence yields excluding and including spin-orbit effects for the  $1s2s^22p^3(^3P_I)$  and  $1s2s^22p^3(^3S_I)$  states. The anomalous fluorescence yield behavior is seen to occur once there is appreciable spin-orbit mixing.

## Resonance Asymmetry and External Field Effects in the Photorecombination of $\text{Ti}^{4+}$

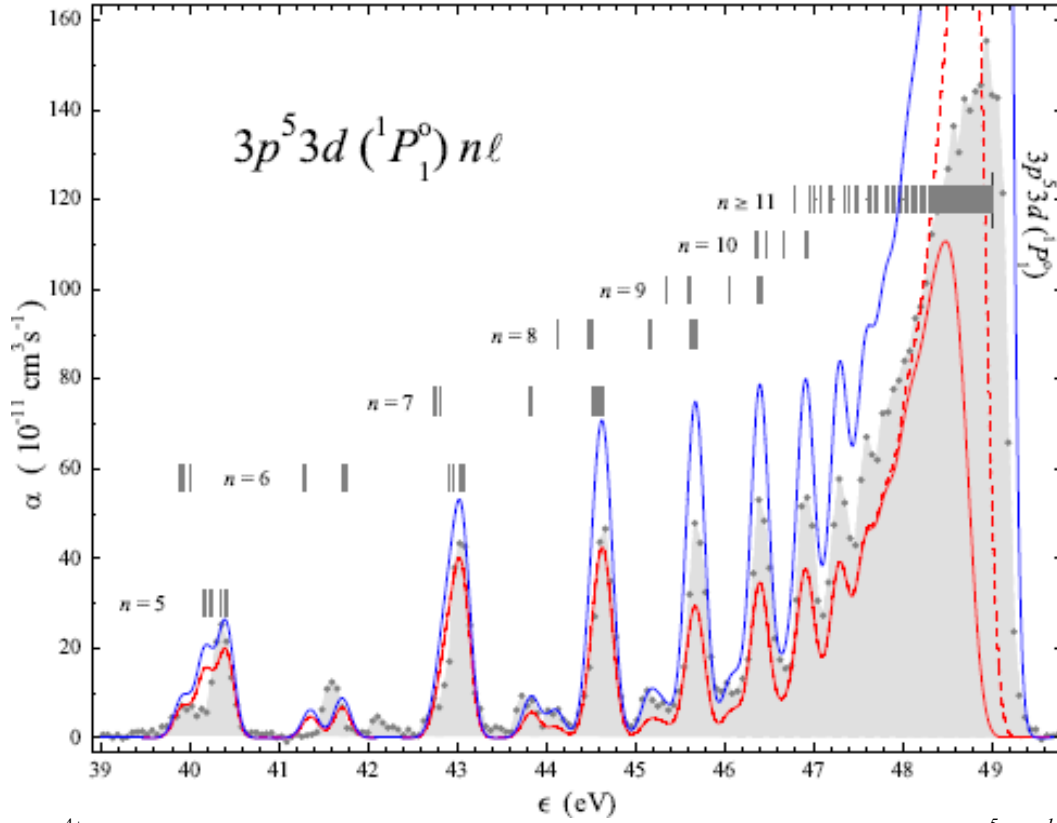
We have completed new multi-configuration Breit-Pauli calculations for the photorecombination of  $\text{Ti}^{4+}$  ions. Through a detailed comparison with Test Storage Ring measurements, we quantify the interference effects for the broad, asymmetric, near-threshold, highly-correlated  $3p^5 3d^2(^2F)$  resonances (see Fig. 1). We also addressed the enhanced field ionization effects on recombined  $3p^6 nl$  Rydberg states. This is due to the perturbation of the below-threshold tails of two of the broad  $3p^5 3d^2(^2F)$  resonances, giving rise to a “forced autoionization” phenomenon, increasing the field ionization effects. By accounting for interference for the lowest  $n=3, 4$  resonances, and field effects as  $n \rightarrow \infty$ , good agreement between our computed results and the experimental photorecombination spectrum is obtained (see Fig. 2).



**Figure 1** Demonstration of interference effects found in the near-threshold region of PR spectra of  $\text{Ti}^{4+}$ : gray points, deconvoluted Test Storage Ring experimental results, red dashed curve, lowest-order perturbation method result, and blue solid curve as its next-highest order modification containing interference effects.

In our study, we have found that the broad, highly-correlated, threshold-straddling, asymmetric  $3p^5 3d^2(^2F_{5/2,7/2}^o)$  resonances play a distinct role. At low incident-electron energies, the threshold PR behavior is dominated by those two resonances that only contribute partially to the total Maxwellian rate coefficient, due to their straddling of threshold. Further, there is noticeable asymmetry in the resulting resonance profile that can be observed experimentally at TSR via PR measurements and at ALS via PI measurements. Theoretical modeling of the resultant Fano profile was performed including higher-order resonant-direct (DR/RR) interference effects, and was found to quantify the asymmetry behavior, in good agreement with ALS PI results. At higher incident-electron energies, as the excited thresholds give rise to the dominant  $3p^5 3dnl$  Rydberg series of resonances, we find that the recombined series  $3p^6 nl$  are strongly perturbed by

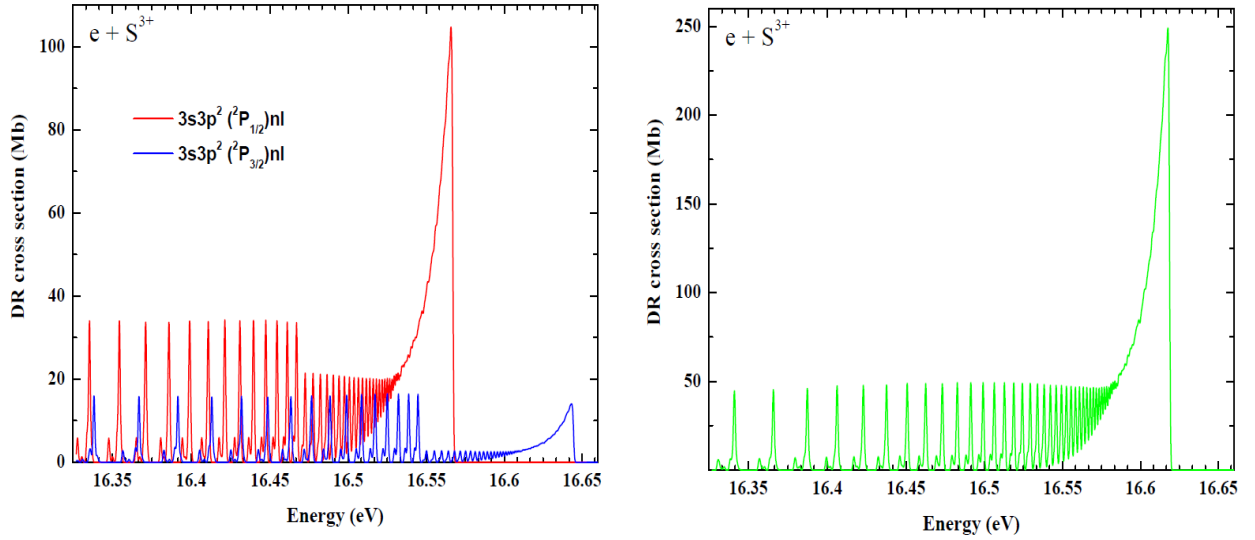
the below-threshold tail of those same  $3p^5 3d^2 (^2F^o)$  states. This leads to forced autoionization and a reduction in the experimentally observed DR strength. The reduction factor is the survival probability of recombined Rydberg states against reionization due to field effects and can be modeled qualitatively by a hydrogenic, perturbed Rydberg series approach.



**Figure 2**  $\text{Ti}^{4+}$  rate coefficient, consisting of the dominant Rydberg states converging to  $3p^5 3d (^1P^o_1)$  limit: gray area, experiment; blue curve, field-free MCBP results; dashed red curve, results incorporating motional field effects via a perturbed hydrogenic approximation, and only considering single radiative transitions; solid red curve, results also including full radiative cascade.

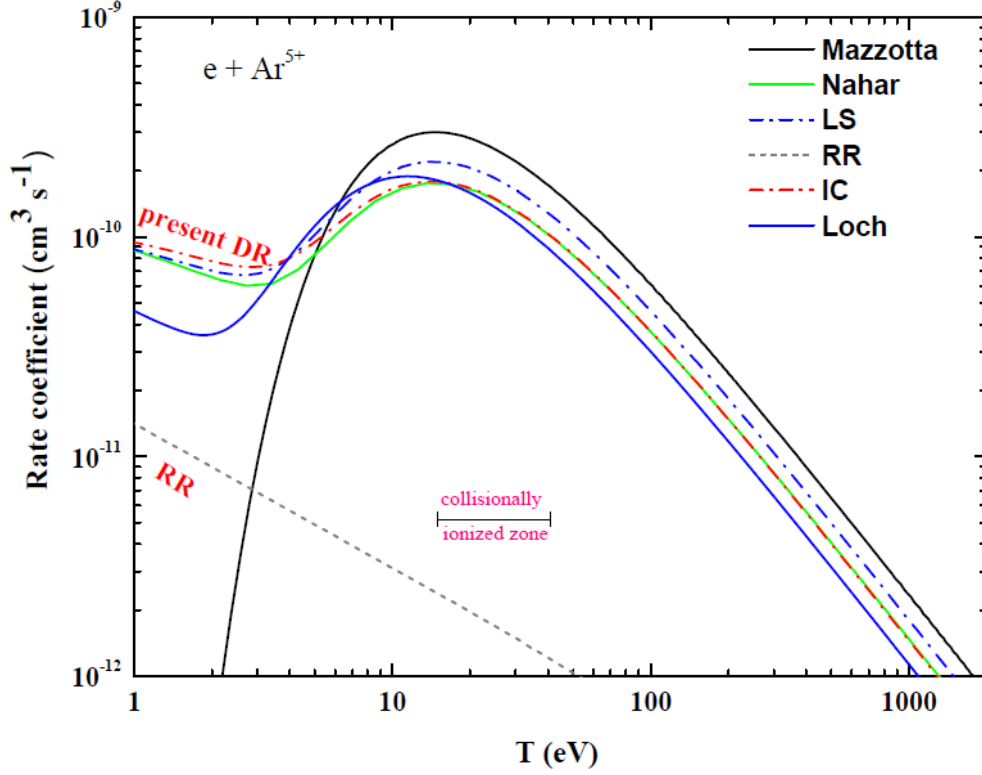
## Dielectronic Recombination for Al-like Argon

Dielectronic recombination (DR) is an important atomic process that is relevant to astrophysical plasma modeling. DR is responsible for the charge state balance as well as the cooling of plasmas, and it is the dominant electron-ion recombination process for most ions in both photoionized and collisionally-ionized plasmas. Accurate and reliable calculations for DR rate coefficients are needed to analyze the spectra obtained from astrophysical observations. We have been part of a huge effort for computing reliable DR and radiative recombination (RR) data for all isoelectronic sequences up through Mg-like ions using a state-of-the-art multi-configuration Breit-Pauli (MCBP) approach. Recently, we have focused our work on the complex third-row M-shell isoelectronic sequences, especially Al-like.



**Figure 1** DR cross section of  $S^{3+}$  for the atomic collision  $e^{-} + 3s^2 3p^2 P_{1/2} \rightarrow 3s 3p^2 ^2P_{1/2, 3/2} n\ell$  in both LS- and IC-coupling schemes. Left panel: DR cross sections in IC-coupling; Right panel: DR cross sections in LS-coupling. All series are convoluted by a FWHM Gaussian of 1.2 meV. The reduction in the cross sections occurs at  $n=36$ .

In our previous investigations for the DR rate coefficient of  $S^{3+}$ , we revealed the importance of the spin-orbit effect on the cross section and rate (see Fig. 1) [1]. Also, we recommend that calculations for DR rate coefficient for Al-like isoelectronic sequence should be performed beyond the LS-coupling approximation. We extend our calculations to other ions in the Al-like sequence. Here we also present the results for  $Ar^{5+}$  (see Fig. 2).



**Figure 2** Maxwellian-averaged DR rate coefficients for  $\text{Ar}^{5+}$ . We compare our calculated DR rate coefficients in both LS and IC-coupling schemes with the recommended data of Mazzotta *et al.* [2], total rate coefficient (DR + RR) of Nahar [3], and the configuration-average distorted-wave calculations of Loch *et al.* [4]. The collisionally ionized zone is as recommended by Bryans *et al.* [5].

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## **DISSERTATIONS**

### **P.h. D.**

**M. F. Hasoğlu**, *Calculations of K-Shell Fluorescence Yields and Photoabsorption Cross Sections for Carbon Ions at the K-Edge*, December 2008.

## **PUBLICATIONS**

1. **Sh. A. Abdel-Naby, D. Nikolić, T. W. Gorczyca**, N. R. Badnell, and D. W. Savin, *M-Shell Dielectronic Recombination: Theoretical Study*, American Institute of Physics Conference Series, 111 (2009).
2. **D. Nikolić, T. W. Gorczyca**, and N. R. Badnell, *Resonance Asymmetry and External Field Effects in the Photorecombination of  $Ti^{4+}$* , Phys. Rev. A **79**, 012703 (2009).
3. **M. F. Hasoğlu, D. Nikolić, T. W. Gorczyca**, S. T. Manson, M. H. Chen, and N. R. Badnell, *Nonmonotonic Behavior as a Function of Nuclear Charge of the K-Shell Auger and Radiative Rates and Fluorescence Yields along the  $1s2s^22p^3$  Isoelectronic Sequence*, Phys. Rev. A **78**, 032509 (2008).

## **GRANTS**

1. **T. W. Gorczyca** (PI), NASA Solar and Heliospheric Research and Technology Program, for project entitled *Calculations of High Temperature Dielectronic Recombination Rate Coefficients in Support of NASA's Sun-Earth Connection Program*, funded \$20,000 for period 2/1/2008-12/31/2008.
2. **T. W. Gorczyca** (PI) and K. T. Korista, NASA Astrophysics Research and Analysis Program, for project entitled *Improved Simulations of Astrophysical Plasmas: Computation of New Atomic Data*, funded \$335,000 for period 1/1/2007-12/31/2009.
3. **T. W. Gorczyca** (PI), NASA Chandra Project, *K-Shell Photoabsorption Studies for Modeling Interstellar Medium Spectra*, funded \$50,000 for period 1/1/2009-12/31/2009.

## **INVITED TALKS**

1. **Sh. A. Abdel-Naby**, *M-Shell Dielectronic Recombination: Theoretical Studies*, The 20<sup>th</sup> International Conference on the Application of Accelerators in Research and Industry, Fort Worth, Texas, August 10-15, 2008.

## **CONTRIBUTED TALKS**

1. **Sh. A. Abdel-Naby, D. Nikolić, T. W. Gorczyca**, N. R. Badnell, and D. W. Savin, *Dielectronic Recombination for Aluminum-Like Iron Peak Elements*, The 26<sup>th</sup> International Conference on Photonic, Electronic, and Atomic Collisions, Kalamazoo, Michigan, July 22-28, 2009; Journal of Physics Conference Series, 194, 062023 (2009).
2. **Sh. A. Abdel-Naby**, G. Omar, M. A. El-Fayoumi, H. Hamdy, F. Shahin, *Resonant Transfer Excitation Followed by X-Ray for Fluorine-Like Ions*, The 26<sup>th</sup> International Conference on Photonic, Electronic, and Atomic Collisions, Kalamazoo, Michigan, July 22-28, 2009; Journal of Physics Conference Series, 194, 082004 (2009).
3. **Sh. A. Abdel-Naby, M. F. Hasoğlu, T. W. Gorczyca**, *X-Ray Photoabsorption in Magnesium Ions Near the K-Edge*, The 26<sup>th</sup> International Conference on Photonic, Electronic, and Atomic Collisions, Kalamazoo, Michigan, July 22-28, 2009; Journal of Physics Conference Series, 194, 022001 (2009).
4. I. Dumitriu, R. C. Bilodeau, **T. W. Gorczyca**, C. W. Walter, N. D. Gibson, A. Aguilar, Z. Pešić, D. Rolles, N. Berrah, *Shape Resonances in Inner-Shell Photodetachment of Transition Metal Negative Ions*, The 26<sup>th</sup> International Conference on Photonic, Electronic, and Atomic Collisions, Kalamazoo, Michigan, July 22-28, 2009; Journal of Physics Conference Series, 194, 022086 (2009).
5. I. Dumitriu, R. C. Bilodeau, **T. W. Gorczyca**, C. W. Walter, N. D. Gibson, A. Aguilar, Z. Pešić, D. Rolles, N. Berrah, *Inner-Shell Photodetachment Thresholds of Transition Metal Negative Ions*, The 40<sup>th</sup> Annual Meeting of the Division of Atomic, Molecular, and Optical Physics, Charlottesville, Virginia, May19-23, 2009; APS Meeting Abstracts, 1047 (2009).
6. **Sh. A. Abdel-Naby, M. F. Hasoğlu, D. Nikolić, T. W. Gorczyca**, *X-Ray Photoabsorption in Magnesium Ions*, The 40<sup>th</sup> Annual Meeting of the Division of Atomic, Molecular, and Optical Physics, Charlottesville, Virginia, May19-23, 2009; APS Meeting Abstracts, 1024 (2009).
7. **T. W. Gorczyca, D. Nikolić**, N. R. Badnell, *Quantifying the Asymmetry of Giant Resonances in  $Sc^{3+}$  Photorecombination and  $Sc^{2+}$  Photoionization*, The 40<sup>th</sup> Annual Meeting of the Division of Atomic, Molecular, and Optical Physics, Charlottesville, Virginia, May19-23, 2009; APS Meeting Abstracts, 1030 (2009).
8. **Sh. A. Abdel-Naby, D. Nikolić, T. W. Gorczyca**, and D. W. Savin, *Theoretical Studies of Dielectronic Recombination for Al-Like Ions*, The 16<sup>th</sup> International Conference on Atomic Processes in Plasmas, Monterey, California, March 22-26, 2009.
9. **Sh. A. Abdel-Naby, D. Nikolić, T. W. Gorczyca**, N. R. Badnell, and D. W. Savin, *M-Shell Dielectronic Recombination: Theoretical Studies*, The 20<sup>th</sup> International Conference on the Application of Accelerators in Research and Industry (CAARI), Fort Worth, Texas, August 10-15, 2008.

### 4.3 Emanuel Kamber

#### Single- and Double-Electron capture by $\text{Ne}^{q+}$ ( $q = 2 - 5$ ) Ions from $\text{H}_2\text{O}$ and $\text{CO}_2$

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The study of single- and double-electron capture in slow collisions of multiply charged ions with molecules has grown tremendously in recent years, primarily because such processes are important in many ionized media including plasmas, ionospheres, and astrophysical environments. In addition,  $\text{H}_2\text{O}$  and  $\text{CO}_2$  are important components of many planetary atmospheres, and are also found in the earth's atmosphere [1].

Using translational energy-gain spectroscopy technique, we have measured the energy-gain spectra and absolute total cross sections for single- and double-electron capture in collisions of  $\text{Ne}^{q+}$  ( $q = 2 - 5$ ) recoil ions with  $\text{H}_2\text{O}$  and  $\text{CO}_2$  at laboratory impact energies between 250 and 3000 eV. The data were obtained on a differential energy-gain spectrometer, which has been described by Abu-Haija et al [2]. The final state populations were discussed on the basis of the reaction windows, which are calculated using the single-crossing Landau-Zener model [3] and the extended version of the classical over-the-barrier model [4].

Figure 1 shows the energy-gain spectra obtained for single-electron capture by 25q eV  $\text{Ne}^{q+}$  ( $q = 3 - 5$ ) ions from  $\text{CO}_2$  at  $0^\circ$  scattering angles. In all collision systems studied here, the dominant reaction channels are due to non-dissociative single-electron capture into excited states of the projectile product.

For  $\text{Ne}^{3+}$  -  $\text{CO}_2$  collisions, capture into 3p state is predominant, The structure in the spectrum at around 15 eV is due to capture into the 3s state with contributions due to capture from the metastable states of  $\text{Ne}^{3+}$  ions. For  $\text{Ne}^{4+}$  -  $\text{CO}_2$  collisions, the dominant reaction channel correlates with capture into the excited state 3d' of the  $\text{Ne}^{3+}$  ion from the ground state incident  $\text{Ne}^{4+}$  ( $2p^2\ ^3P$ ) ions with contributions due to capture into 3d state. In  $\text{Ne}^{5+}$  -  $\text{CO}_2$  collisions, the observed collision spectrum is dominated by non-dissociative single-electron capture from the ground state incident  $\text{Ne}^{5+}$  ( $2p\ ^2P$ ) ions into the excited state 4d of  $\text{Ne}^{4+}$ , with contributions due to capture into the 4s and 3d' states.

The reaction windows based on the ECOB model provide the best description of the position of the capture channels, while the reaction windows based on the LZ model favor channels with  $Q$ -values smaller than those of the dominant channels.

Figure 2 shows the energy dependence of total cross sections for single-electron capture by  $\text{Ne}^{q+}$  ( $q = 2 - 5$ ) from  $\text{CO}_2$  together with the predictions of the multichannel Landau-Zener (MCLZ) model and the classical over the barrier (COB) model. The total cross sections increase with

increasing impact energy, a pattern that is well documented for such collisions at low energies. This can be understood by the reaction window, which broadens with increasing energies and therefore increase the probability of capture channels with large Q-values. The present measurements are in good agreement with the COB model predictions and MCLZ calculations.

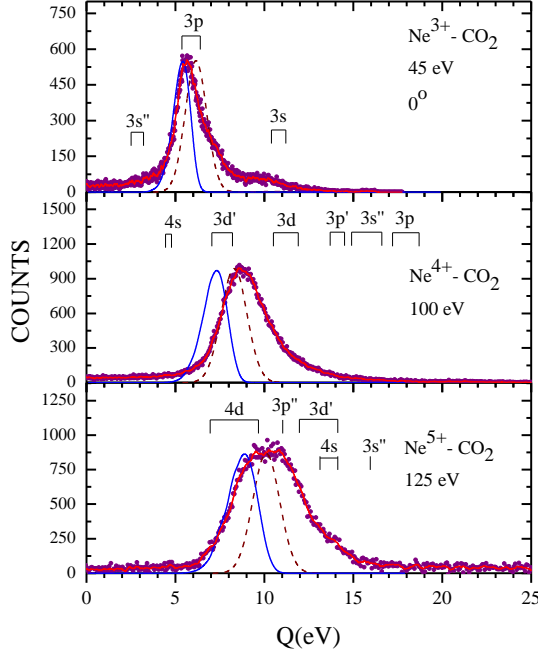


Figure 1 Translational energy-gain spectra for single electron capture by  $\text{Ne}^{q+}$  ( $q = 3 - 5$ ) from  $\text{CO}_2$  at zero degree scattering angles. Also shown are the reaction windows calculated on the basis of LZ model (full curves) and the ECOB model (dashed curves).

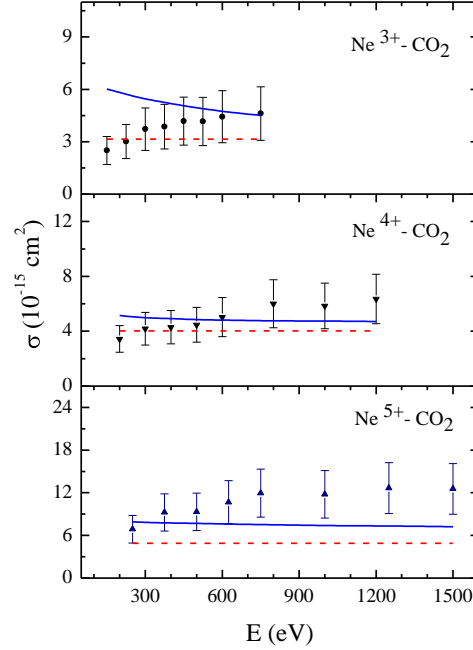


Fig. 2 Absolute total cross sections for single-electron capture by  $\text{Ne}^{q+}$  ( $q = 3 - 5$ ) from  $\text{CO}_2$  together with the predictions of the MCLZ model (full curves) and the COB model (dashed curves).

Doubly differential cross sections for single-electron capture in collisions of 25 qeV  $\text{Ne}^{q+}$  ( $q = 2 - 5$ ) recoil ions with  $\text{H}_2\text{O}$  have also been studied by means of translational energy-gain spectroscopy, see Figure 3. There is clear evidence of the present of the first and second metastable states in the incident  $\text{Ne}^{2+}$  and  $\text{Ne}^{3+}$  ion beams.

For the  $\text{Ne}^{2+} - \text{H}_2\text{O}$  collisions, the spectrum exhibits three peaks. Peak I $\beta$ X can be correlated with capture from ground state  $\text{Ne}^{2+}$  into the  $2s2p^6$  state of  $\text{Ne}^+$ . Peaks II $\beta$ X and III $\gamma$ A are due to capture from the metastable states  $2p^4\ ^1D$  and  $^1S$  of  $\text{Ne}^{2+}$  into excited states of  $\text{Ne}^+$  accompanied by target excitation to the  $A\ ^2A_1$  state of  $\text{H}_2\text{O}^+$ . For  $\text{Ne}^{3+} - \text{H}_2\text{O}$  collisions, the dominant peak is due to capture into the  $2p^3\ 3p$  states (I $\zeta$ X). The structure at about 5.5 eV (III $\mu$ X) is energetically identifiable with capture into the excited states from the metastable states in the incident  $\text{Ne}^{3+}$  ion beam. For  $\text{Ne}^{4+} - \text{H}_2\text{O}$  collisions, the dominant reaction channel correlates with capture into the excited state  $3d'$  of the  $\text{Ne}^{3+}$  ion from the ground state incident  $\text{Ne}^{4+}$  ( $2p^2\ 3p$ ) ions. The structure on the lower-energy side of the dominant peak corresponds to capture into  $4s$  and  $4p$  states. In  $\text{Ne}^{5+} - \text{H}_2\text{O}$  collisions, the observed collision spectrum is dominated by non-dissociative single-

electron capture from the ground state incident  $\text{Ne}^{5+}$  ( $2p^2P$ ) ions into the excited state  $4d$  of  $\text{Ne}^{4+}$  with production of  $\text{H}_2\text{O}^+$  in the ground state ( $X^2B_1$ ). The reaction windows based on the ECOB model provide the best description of the position of the capture channels, while the reaction windows based on the LZ model favor channels with  $Q$ -values smaller than those of the dominant channels.

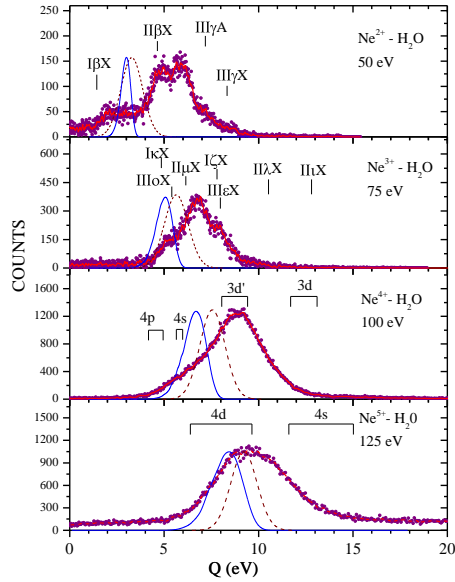


Figure 3 Translational energy-gain spectra for single electron capture by  $\text{Ne}^{q+}$  ( $q = 2 - 5$ ) from  $\text{H}_2\text{O}$  at zero degree scattering angles. Also shown are the reaction windows calculated on the basis of LZ model (full curves) and the ECOB model (dashed curves)

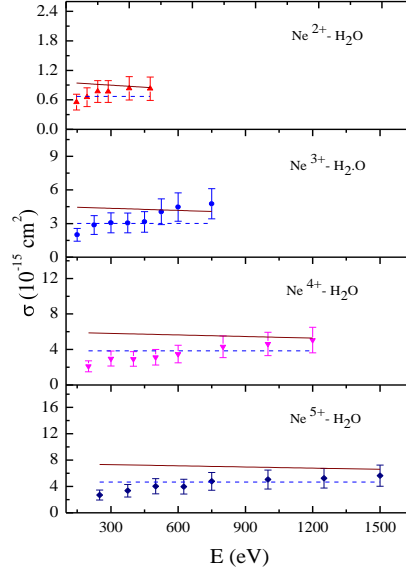


Figure. 2 Absolute total cross sections for single-electron capture by  $\text{Ne}^{q+}$  ( $q = 2 - 5$ ) from  $\text{H}_2\text{O}$  together with the predictions of the MCLZ model (full curves) and the COB model (dashed curves).

For  $\text{Ne}^{q+} + \text{H}_2\text{O}$  collisions, the total cross sections show no significant dependence on the collision energy. Our data are lower than those of the MCLZ model and in good agreement with the COB model predictions.

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- [2] O. Abu-Haija, E. Y. Kamber, S. M. Ferguson, and N. Stoltafoht, Phys. Rev. A **7**, 04271 (2005), and references there in.
- [3] R. E. Olson R E and A. Salop, Phys. Rev. A **14**, 579 (1976).
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## **PUBLICATIONS**

1. **D. P. Cassidy, E. Y. Kamber, A. Kayani, and J. A. Tanis**, “Dissociative and non-dissociative charge-changing processes in 1.0 – 2.0 MeV/u  $O^{5+}$  -  $O_2$  collisions,” *Journal of Physics: Conference Series* **163** (2009) 012054.
2. **E. Y. Kamber**, “Differential cross sections for single-electron Capture by low-energy  $O_2^{2+}$  ions from Ne and  $O_2$ ,” *Journal of Physics: Conference Series* **163** (2009) 012066.

## **CONTRIBUTED TALKS**

1. **D. P. Cassidy, E. Y. Kamber, A. Kayani, and J. A. Tanis**, “Dissociative and non-dissociative charge-changing processes in 1.0 – 2.0 MeV/u  $O^{5+}$  -  $O_2$  collisions,” 14<sup>th</sup> International Conference on the Physics of Highly Charged Ions, September 1 - 5, 2008, Chofu, Tokyo, Japan.
2. **Emanuel Y. Kamber**, “Differential cross sections for single-electron Capture by low-energy  $O_2^{2+}$  ions from Ne and  $O_2$ ,” 14<sup>th</sup> International Conference on the Physics of Highly Charged Ions, September 1 - 5, 2008, Chofu, Tokyo, Japan.
3. **A. Hasan, O. Abu-Haija, A. Kayani, and E.Y. Kamber**, “Total Cross Section for Electron Capture Processes in Slow Collisions of  $Ne^{6+}$  Ions with  $H_2O$  and  $CO_2$ ,” 26<sup>th</sup> International Conference on Photonic, Electronic and Atomic Collisions, Kalamazoo, Michigan, U.S.A., July 22 - 28, 2009, Conference Program. Edited by **Dragan Nikolic, Emanuel Kamber, Thomas Gorczyca, Nora Berrah, and John Tanis**, Fr 022.
4. **O. Abu-Haija, A. Hasan, and E.Y. Kamber**, “State-Selective Single- Electron Capture in Slow Collisions of  $Ne^{q+}$  ( $q = 2 - 5$ ) Ions with  $H_2O$ ,” 26<sup>th</sup> International Conference on Photonic, Electronic and Atomic Collisions, Kalamazoo, Michigan, U.S.A., July 22 - 28, 2009, Conference Program. Edited by **Dragan Nikolic, Emanuel Kamber, Thomas Gorczyca, Nora Berrah, and John Tanis**, Fr 023.
5. **D. P. Cassidy, E.Y. Kamber, A. Kayani, and J. A. Tanis** “Molecular and Dissociative Ionization in 1.0 - 2.0 MeV/u  $O^{5+} + CO_2$  Collisions,” 26<sup>th</sup> International Conference on Photonic, Electronic and Atomic Collisions, Kalamazoo, Michigan, U.S.A., July 22 - 28, 2009, Conference Program. Edited by **Dragan Nikolic, Emanuel Kamber, Thomas Gorczyca, Nora Berrah, and John Tanis**, We 006.

## **SCHOLARLY ACTIVITY**

1. Reviewed two papers for Journal of Physics: Conference Series.
2. Member of the Executive Committee for the International Conference on Photonic, Electronic, and Atomic Collisions (ICPEAC), July 2007-2011.
3. Co-Chair, International Conference on Photonic, Electronics and Atomic Collisions, ICPEAC09.

## 4.4 *John A. Tanis*

### **Atomic Physics Research**

Dr. Tanis is active in the field of atomic collision physics, investigating fundamental interactions that occur in collisions between atomic particles. Major emphases of this work at present are: (1) the transmission and guiding of fast electrons and ions through insulating nano- and micro-capillaries, a phenomenon that has several potential applications in the field of nanoscience, (2) (3) the study of interferences associated with electron ejection from diatomic molecules ( $H_2$ ,  $N_2$ , and  $O_2$ ) in collisions with fast ions, an effect that is analogous to Young's famous two-slit experiment for light, and (3) studies of detailed collision dynamics in processes of x-ray emission associated with charge-changing processes, including radiative double electron capture (RDEC) and x-ray emission associated with electron loss. In the first case, the work with capillaries lies at the intersection of atomic physics and materials science, and the latter two are projects involving pure atomic physics.

These various studies are carried out with collaborators at WMU and other laboratories, nationally and internationally. Dr. Tanis' research has been supported extensively by the U.S. Department of Energy, the National Science Foundation, and the Research Corporation. Several graduate, undergraduate, and high school students have been involved in this research and, to date, six students have received the Ph.D. degree under his supervision, with five more currently in progress.

Students who have been involved in the work covered by the period of this research report and their areas of specialty are as follows:

Asma Ayyad – Ph.D. (in progress), materials science/atomic physics

David Cassidy – M.A. (completed), atomic physics

Susanta Das – Ph.D. (completed), materials science/atomic physics

Buddhika Dassanayake – Ph.D. (in progress), materials science/atomic physics

Samanthi De Silva – Ph.D. (in progress), materials science/atomic physics

Tamer ElKafrawy – Ph.D. (in progress), atomic physics

Darshika Keerthisinghe – Ph.D. (in progress), materials science/atomic physics

Melike Winkworth – M.A. (completed), atomic physics

Réka Bereczky – Ph.D. (in progress, ATOMKI, Debrecen, Hungary), materials science/atomic physics

Anna Simon – Ph.D. (in progress, Jagiellonian University, Krakow, Poland), atomic physics

The various activities associated with Dr. Tanis' research including publications, presentations (invited talks and contributed), proposals and grants, scholarly activities, and Ph.D. and M.A. theses and committees for the period of this report are listed below:

## **DISSERTATIONS**

### **Ph.D.**

Susanta Das, *Transmission and Guiding of Fast Electrons through Insulating Anocapillaries and Comparison with Ion Guiding*, April 2009.

### **M.A.**

David Cassidy, *Dissociative and Non-Dissociative Charge-Changing Processes in 1.0-2.0 MeV/u  $O^{5+} + O_2$  Collisions*, June 2009.

Melike Winkworth, *Experimental Investigation of Interference Effects in Electron Emission from  $O_2$  by Impact with MeV/u  $H^+$  and  $O^{5,8+}$  Ions*, August 2009.

## **PUBLICATIONS**

1. **J. L. Baran, S. Das, F. J  rai-Szab  , K. P  ra, L. Nagy, and J. A. Tanis**, *Suppression of Primary Electron Interferences in the Ionization of  $N_2$  by 1-5 MeV/u Protons*, Phys. Rev. A **78**, 012710 (2008).
2. **J. A. Tanis**, *Interferences in Coherent Electron Emission from Diatomic Molecules*, Nucl. Instrum. Meth. Phys. Res. B **267**, 201 (2009).
3. **M. Winkworth, P. D. Fainstein, M. E. Galassi, J. Baran, B. S. Dissanayake, S. Das, A. Kayani and J. A. Tanis**, *Interferences in Electron Emission from  $O_2$  by 30 MeV  $O^{5,8+}$  Impact*, Nucl. Instrum. Meth. Phys. Res. B **267**, 373 (2009).
4. **B. S. Dissanayake, S. Das, A. Ayyad, A. Kayani, N. Stolterfoht, and J. A. Tanis**, *Guiding of Electrons and Fast Ions through Insulating Nanocapillaries*, AIP Conference Proceedings **1099**, (AIP, New York, 2009), pp. 125-128.
5. **G. T  th, P. A. Z  vodszy, and J. A. Tanis**, *Electron Capture and Loss Processes in Forward Electron Emission in Fast Ion-atom Collisions*, AIP Conference Proceedings **1099** (AIP, New York, 2009), pp. 129-132.
6. **M. Winkworth, P. D. Fainstein, M. E. Galassi, J. Baran, S. Das, B. S. Dissanayake, A. Kayani and J. A. Tanis**, *Interference Effects in Electron Emission Spectra for 3 MeV/u  $H^+ + O_2$  collisions*, J. Phys.: Conf. Ser. **163**, 012044 (2009).
7. **D. P. Cassidy, E. Y. Kamber, A. Kayani and J. A. Tanis**, *Dissociative and Non-dissociative Charge-changing Processes in 1.0-2.0 MeV/u  $O^{5+} + O_2$  Collisions*, J. Phys.: Conf. Ser. **163**, 012054 (2009).

## **GRANTS**

1. Research Corporation, Guiding of Fast Electrons and Positive Ions in Nanocapillaries, J. A. Tanis. Requested: \$50,000 (sponsor) + \$25,000 (required matching). Awarded: active, during the period 6/30/07 – 6/29/10.
2. Institute of Modern Physics, Applied Ion Beam Physics Laboratory, Fudan University, Shanghai (China), Visiting Lecturer/Researcher, J. A. Tanis. Requested: ~ \$7500 for two visits of one month each. Awarded: active, for the period 10/07 – 11/08.
3. International Union of Pure and Applied Physics (IUPAP), Support for ICPEAC, J. A. Tanis. Requested: \$25,000. Awarded: ~ \$20,000, 07/08 – 07/09.
4. National Science Foundation – Atomic and Molecular Dynamics Program, Collaborative Research: Inelastic Atomic Processes in Liquids, J. A. Tanis (PI) and R. D. DuBois (co-PI). Requested: \$455,844, 09/08; declined, 03/09.
5. National Science Foundation – Condensed Matter Physics, Interaction and Characteristics of Charged Particles Traversing Nano- and Micrometer-Sized Capillaries, J. A. Tanis. Requested: \$649,620, 11/08; returned without review due to a technical problem.
6. National Science Foundation – Major Research Instrumentation Program, MRI: Equipment acquisition for WMU accelerator lab upgrade, A. Kayani, PI, M. Famiano (co-PI), E. Y. Kamber (co-PI), J. A. Tanis (co-PI), and A. Wuosmaa (co-PI). Requested: \$294,044, 01/09. Awarded: \$294,044, 05/09.
7. National Science Foundation – Atomic and Molecular Dynamics Program, Electron and Ion Transmission in Nano- and Microcapillaries, J. A. Tanis (PI) and A. Kayani (co-PI). Requested: \$768,394, 09/09; declined, 03/10.

## **INVITED TALKS**

1. **J. A. Tanis**, *Electron Capture and Loss in Forward Electron Emission in Fast Ion-atom Collisions*, 20<sup>th</sup> International Conference on the Application of Accelerators in Research and Industry (CAARI), Fort Worth, TX, August 2008.
2. **B. S. Dassanayake**, *Transmission of Electrons and Ions through Insulating PET Nanocapillaries*, 20<sup>th</sup> International Conference on the Application of Accelerators in Research and Industry (CAARI), Fort Worth, TX, August 2008.
3. **J. A. Tanis**, *Fast Electron and Ion Transmission through PET Nanocapillaries*, Workshop on Ion Insulator Interactions 2008 (WIII08), Iiyama, Japan, September 2008.

4. **S. Das**, *Electron Guiding in PET Nanocapillaries: Inelastic Processes*, 17th International Workshop on Inelastic Ion-Surface Collisions (IISC-17), Porquerolles, France, September 2008.
5. **J. A. Tanis**, *Fast Electron and Ion Transmission and Interactions in Insulating Nano- and Macrocavillaries*, 2<sup>nd</sup> Symposium on Ion Insulator Interactions (SI3), Platja d'Aro, Girona, Spain, May 2009.
6. **B. S. Dassanayake**, *Electron Transmission through a Single Glass Capillary*, XXI International Seminar on Ion-Atom Collisions (ISIAC 2009), Norfolk, Virginia, July 2009.

### **CONTRIBUTED TALKS**

1. "Electron and Ion Guiding through Insulating Polymer Nanocapillaries," B. S. Dassanayake, S. Das, J. A. Tanis, N. Stolterfoht, *20<sup>th</sup> International Conference on the Application of Accelerators in Research and Industry (CAARI)*, Fort Worth, TX, August 2008, Book of Abstracts, MON-AP01-03.
2. "Quantum Electrodynamical Effects in He-like Uranium," Regina Reuschl, M. Trassinelli, A. Kumar, H. F. Beyer, C. Brandau, H. Braeuning, S. Geyer, A. Gumberidze, P. Indelicato, P. Jagodzinski, Ch. Kozhuharov, S. Hess, R. Maertin, J. Tanis, S. Trotsenko, G. Weber, Th. Stoeckler, *20<sup>th</sup> International Conference on the Application of Accelerators in Research and Industry (CAARI)*, Fort Worth, TX, August 2008, Book of Abstracts, TUE-AP03-03.
3. "Electron Capture and Loss Processes in Forward Electron Emission in Fast Ion-atom Collisions," J. A. Tanis, G. Tóth, P. A. Závodszky, *20<sup>th</sup> International Conference on the Application of Accelerators in Research and Industry (CAARI)*, Fort Worth, TX, August 2008, Book of Abstracts, FRI-AP08-02.
4. "Interference Effects in Electron Emission Spectra for 3 MeV  $H^+ + O_2$  Collisions," M. Winkworth, P. D. Fainstein, M.E. Galassi, J. L. Baran, S. Das, B. S. Dassanayake, T. Elkafrawy, D. Cassidy, A. Kayani and J. A. Tanis, *14<sup>th</sup> International Conference on the Physics of Highly Charged Ions (HCI 2008)*, Tokyo, Japan, September 2008, Book of Abstracts, A-b37.
5. "Dissociative and Non-dissociative Charge-changing Processes in 1.0-2.0 MeV/u  $O^{5+} + O_2$  Collisions," D. P. Cassidy, E. Y. Kamber, A. Kayani, and J. A. Tanis, *14<sup>th</sup> International Conference on the Physics of Highly Charged Ions (HCI 2008)*, Tokyo, Japan, September 2008, Book of Abstracts, A-b24.
6. "Electron Guiding in PET Nanocapillaries: Inelastic Processes," S. Das, B. S. Dassanayake, N. Stolterfoht, and J. A. Tanis, *17th International Workshop on Inelastic Ion-Surface Collisions (IISC-17)*, Porquerolles, France, September 2008, Book of Abstracts.

7. "K-x-ray emission in MeV/u  $O^{5+}$  on Ar collisions," T. ElKafrawy and J. A. Tanis, Division of Atomic, Molecular, and Optical Meeting of the American Physical Society, Charlottesville, Virginia, May, 2009, Abstract: T1.00033.
8. "Time evolution of electron transmission through a single glass capillary," B. S. Dassanayake, S. Das, R. J. Bereczky, K. Tőkési, and J. A. Tanis, Proceedings of the XXVI<sup>th</sup> International Conference on Photonic, Electronic, and Atomic Collisions, Kalamazoo, MI, July 2009, Book of Abstracts, eds. A. Starace, A. Orel, D. Nikolic, N. Berrah, T. Gorczyca, E. Kamber, and J. Tanis, abstract Th126; published in *Jour. of Phys.: Conf. Series* **194**, 132011 (2009).
9. "Guiding of electrons through a single glass macrocapillary," R. J. Bereczky, B. S. Dassanayake, S. Das, K. Tőkési, and J. A. Tanis, Proceedings of the XXVI<sup>th</sup> International Conference on Photonic, Electronic, and Atomic Collisions, Kalamazoo, MI, July 2009, Book of Abstracts, eds. A. Starace, A. Orel, D. Nikolic, N. Berrah, T. Gorczyca, E. Kamber, and J. Tanis, abstract Th122; published in *Jour. of Phys.: Conf. Series* **194**, 132014 (2009).
10. "Sample deterioration in electron guiding through PET nanocapillaries," S. Das, B. S. Dassanayake, N. Stolterfoht, and J. A. Tanis, Proceedings of the XXVI<sup>th</sup> International Conference on Photonic, Electronic, and Atomic Collisions, Kalamazoo, MI, July 2009, Book of Abstracts, eds. A. Starace, A. Orel, D. Nikolic, N. Berrah, T. Gorczyca, E. Kamber, and J. Tanis, abstract Th123; published in *Jour. of Phys.: Conf. Series* **194**, 132015 (2009).
11. "Energy dependence of electron transmission through a single glass capillary," B. S. Dassanayake, S. Das, R. J. Bereczky, K. Tőkési, J. A. Tanis, Proceedings of the XXVI<sup>th</sup> International Conference on Photonic, Electronic, and Atomic Collisions, Kalamazoo, MI, July 2009, Book of Abstracts, eds. A. Starace, A. Orel, D. Nikolic, N. Berrah, T. Gorczyca, E. Kamber, and J. Tanis, abstract Th125; published in *Jour. of Phys.: Conf. Series* **194**, 132016 (2009).
12. "Transmission of fast highly charged ions through  $Al_2O_3$  and PET nanocapillaries," A. M. Ayyad, B. S. Dassanayake, S. Das, A. Kayani, and J. A. Tanis, Proceedings of the XXVI<sup>th</sup> International Conference on Photonic, Electronic, and Atomic Collisions, Kalamazoo, MI, July 2009, Book of Abstracts, eds. A. Starace, A. Orel, D. Nikolic, N. Berrah, T. Gorczyca, E. Kamber, and J. Tanis, abstract Th196; published in *Jour. of Phys.: Conf. Series* **194**, 132033 (2009).
13. "Correlated radiative double electron capture (RDEC) in collisions of bare oxygen ions with carbon targets," A. Simon, J. A. Tanis, T. ElKafrawy, and A. Warczak, Proceedings of the XXVI<sup>th</sup> International Conference on Photonic, Electronic, and Atomic Collisions, Kalamazoo, MI, July 2009, Book of Abstracts, eds. A. Starace, A. Orel, D. Nikolic, N. Berrah, T. Gorczyca, E. Kamber, and J. Tanis, abstract Mo024; published in *Jour. of Phys.: Conf. Series* **194**, 082044 (2009).

14. "X-ray processes associated with projectile charge changing in  $\sim 1$  MeV/u collisions of  $O_5^+$  on Ar," T. ElKafrawy, and J. A. Tanis, Proceedings of the XXVI<sup>th</sup> International Conference on Photonic, Electronic, and Atomic Collisions, Kalamazoo, MI, July 2009, Book of Abstracts, eds. A. Starace, A. Orel, D. Nikolic, N. Berrah, T. Gorczyca, E. Kamber, and J. Tanis, abstract Th033; published in Jour. of Phys.: Conf. Series **194**, 082033 (2009).
15. "Molecular and dissociative ionization in 1.0-2.0 MeV/u  $O_5^+ + O_2$  collisions," D. P. Cassidy, E. Y. Kamber, A. Kayani and J. A. Tanis, Proceedings of the XXVI<sup>th</sup> International Conference on Photonic, Electronic, and Atomic Collisions, Kalamazoo, MI, July 2009, Book of Abstracts, eds. A. Starace, A. Orel, D. Nikolic, N. Berrah, T. Gorczyca, E. Kamber, and J. Tanis, abstract We006; published in Jour. of Phys.: Conf. Series **194**, 102021(2009).
16. "Interferences associated with electron emission from  $O_2$  by fast ions compared with  $H_2$  and  $N_2$ ," M. Winkworth, P. D. Fainstein, M. E. Galassi, J. Baran, S. Das, B. S. Dassanayake, A. Kayani, and J. A. Tanis, Proceedings of the XXVI<sup>th</sup> International Conference on Photonic, Electronic, and Atomic Collisions, Kalamazoo, MI, July 2009, Book of Abstracts, eds. A. Starace, A. Orel, D. Nikolic, N. Berrah, T. Gorczyca, E. Kamber, and J. Tanis, abstract We037; published in Jour. of Phys.: Conf. Series **194**, 102044 (2009).

## **SCHOLARLY ACTIVITY**

1. ICPEAC 2009 Conference Chair (with N. Berrah) for the *XXVI International Conference on Photonic, Electronic, and Atomic Collisions (ICPEAC)* held in Kalamazoo, July 22-28, 2009. This conference is the largest and most prestigious international conference on atomic collision physics attracting  $\sim 500$  participants and  $\sim 100$  accompanying persons. Activities included advancing and finalizing organizational details, seeking funding, examining and booking venues, website construction, securing a publisher and negotiating an agreement for the conference proceedings, and carrying out the conference.
2. Member of the Executive Committee, *International Conference on Photonic, Electronic, and Atomic Collisions (ICPEAC)*, 2003-11.
3. Member of the International Advisory Committee, *21<sup>st</sup> International Symposium on Ion-Atom Collisions (XXI ISIAC 2009)*, Norfolk, Virginia, 2008-09.
4. Member of the International Advisory Board, *15<sup>th</sup> International Conference on the Physics of Highly Charged Ions (HCI 2010)*, Shanghai, China, 2009-10
5. Refereed a total of 16 papers as follows:  
*Physical Review A* – 4  
*Journal of Physics B* – 1  
*Nuclear Instruments and Methods in Physics Research* – 2  
*Journal of Physics: Conference Series* – 4  
*American Institute of Physics: Conference Proceedings* – 1  
*Physica Scripta* – 1

*Journal of Atomic Molecular and Optical Physics* – 1

*Modern Physics Letters B* – 1

U.S. Department of Energy, research proposal - 1

6. Dr. Tanis has served or is serving on the Ph.D. thesis committees of the following individuals in a non-chairing role:

Mr. Shahin Abdel Naby – Ph.D. (in progress), atomic physics

Mr. Salem Al-Faify – Ph.D. (in progress), condensed matter

Ms. Ileana Dumitriu – Ph.D. (in progress), atomic physics

Ms. Anna Simon – Ph.D. (in progress, Jagiellonian University, Krakow, Poland), atomic physics

Ms. Huaizhen Zhang – Ph.D. (completed), atomic physics

# 5 CONDENSED MATTER PHYSICS

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## 5.1 *Clement Burns*

Graduate Students: Dan Adams, Mohammad Al-Amar, Xuan Gao, Khalil Hamam, Chengyang Li

### **Research**

This group has activities in two main areas, x-ray synchrotron studies of highly correlated systems and laboratory studies of energy related materials. From June 2008 – June 2009 Professor Burns was on sabbatical at the Pohang Light Source in Pohang, Korea.

### **Work in X-ray synchrotron studies**

Experiments were conducted at the Pohang Light Source in Korea, the SPring-8 synchrotron in Japan, and the Advanced Photon Source (APS) at Argonne National Laboratory in the United States.

#### Synchrotron Experiments - summary

- 1) Studies of high temperature superconductors and related compounds using inelastic x-ray scattering.
- 2) Development of polarization analysis for scattered x-rays for inelastic studies of highly correlated systems.
- 3) Low temperature (down to 0.05K) diffraction studies of the so-called supersolid state in solid helium.
- 4) Low energy resonant diffraction studies to understand the novel electronic properties at the  $\text{LaAlO}_3/\text{SrTiO}_3$  interface.
- 5) Studies of phonon shifts due to the superconducting transition in organic superconductors.
- 6) Studies of the changes in the properties of water in confined geometries.

### **Laboratory work at Western Michigan University**

- 1) Studies of fundamental properties of organic semiconductors relevant for low cost solar cells.
- 2) Creation of thin film organic solar cells.
- 3) Design and construction of a low temperature (0.05 K) refrigerator for studies of correlated systems.

## **DISSERTATIONS**

### **M.A.**

Daniel Adams, A Closed Cycle  $^3\text{He}/^4\text{He}$  Dilution Refrigerator for Use in Cryogenic Studies, August 2009.

## **PUBLICATIONS**

1. N. Mulders, J. West, M. H. W. Chan, C. N. Koddituwakku, C. A. Burns, and L. B. Lurio “Torsional oscillator and synchrotron x-ray experiments on solid helium in aerogel,” *Phys. Rev. Lett.*, 101, 165303 (2008).
2. C. A. Burns, N. Mulders, L. Lurio, M. H. W. Chan, A. Said, C. N. Koddituwakku, and P. M. Platzman, “X-ray Studies of Structure and Defects in Solid  $^4\text{He}$  from 50 mK to Melting,” *Phys. Rev. B*, 78, 224305 (2008).
3. X. Wang, C. A. Burns, A. H. Said, C. N. Koddituwakku, Y. V. Shvyd’ko, D. Casa, T. Gog, and P. M. Platzman, “Evolution of a Strongly Correlated Liquid with Electronic Density,” *Phys. Rev. B* (in press as of Dec. 2009).
4. T. Gog, G. T. Seidler, D. M. Casa, M. H. Upton, Jungho Kim, Yu. Shvyd’ko, S. Stoupin, K. P. Nagle, M. Balasubramanian, R. A. Gordon, T. T. Fister, S. M. Heald, T. Toellner, J. P. Hill, D. S. Coburn, Young-June Kim, A. H. Said, E. E. Alp, W. Sturhahn, H. Yavas, C. A. Burns, and H. Sinn “Momentum-Resolved Resonant and Nonresonant Inelastic X-ray Scattering at the Advanced Photon Source,” *Synchrotron Radiation News*, in press (Dec. 2009).

## **GRANTS**

1. U. S. Department of Energy, Basic Energy Sciences Program – Materials Science “Synchrotron Studies of Systems with Strong Correlations.” Received \$328,528 for a three year period November 1, 2005 –December 31, 2008.
2. National Science Foundation, Division of Materials Research, “Collaborative Proposal: Synchrotron x-ray scattering experiments on solid helium.” \$91,982 from 9/15/2008-8/31/2011 is the WMU portion of the grant.
3. U. S. Department of Energy, Basic Energy Sciences Program – Materials Science “X-ray Studies of Highly Correlated Systems.” Will receive \$300,000 for a three year period Jan. 4, 2009 – Jan 3, 2012.
4. WMU Faculty Research and Creative Activities Support Fund, for project entitled “Improving the Efficiency of Next Generation Solar Cells.” Received \$10,000 for July 1, 2009 – June 30, 2010.

## **INVITED TALKS**

1. “Inelastic X-ray Scattering Studies of a Highly Correlated Liquid Metal,” Physics Colloquium, POSTECH University, Pohang, South Korea, September 5, 2008.
2. “Inelastic X-ray Scattering: A Probe for Strongly Correlated Systems,” Physics Colloquium, KAIST University, Daejeon, South Korea, Nov. 6, 2008.
3. “X-ray Measurements on Supersolid Helium,” Advanced Photon Source Users Seminar, Argonne National Laboratory, Argonne, IL, February 6, 2009.
4. “X-ray scattering experiments on solid helium,” American Physical Society 2009 March Meeting, Pittsburgh, PA, March 19, 2009. Presented by Norbert Mulders (other authors C. A. Burns, M. H. W. Chan, C. N. Kodituwakku, L. B. Lurio, A. Said and J. T. West).
5. “Using Inelastic X-ray Scattering to Study Highly Correlated Systems,” Korean Physical Society, Daejeon Korea, April 24, 2009.

## **SCHOLARLY ACTIVITY**

### **Reviews**

1. Reviewed two proposals for the Department of Energy, Basic Energy Sciences.
2. Reviewed one paper for Physical Review B.
3. Reviewed one paper for American Journal of Physics.

### **External committees**

1. Member of the Beamline Advisory Group for Sectors 9 and 30 at the Advanced Photon Source at Argonne National Laboratory.
2. Chair of the Beamline Advisory Team for the High Resolution Inelastic X-ray Scattering Beamline at the National Synchrotron Light Source II facility. This beamline is one of two beamlines cited as the justification for the \$900 million dollar project.
3. Co-Chair of the Spectroscopy Group for the APS renewal; there are six working groups for the renewal project (estimated budget \$350 million).
4. External Examiner for Ph. D. in Physics from University of Toronto.

## 5.2 Sung Chung

### Entanglement perturbation theory for the elementary excitation in one dimension

**Sung Chung and Lihua Wang**

Western Michigan University, Kalamazoo, MI 49008

The importance of elementary excitations in condensed matter systems may be best understood in the superfluid  $^4\text{He}$ . The Tisza two-fluid model with the experimentally found phonon–roton spectrum explains fundamental properties of the superfluid  $^4\text{He}$  [1]. Feynman’s effort then to explain the roton spectrum is well known [2]. From the theorem of Bloch–Floquet, the elementary excitation with momentum  $k$  for a translationally invariant Hamiltonian  $H$  is written as

$$\Psi_k = \sum_{l=1}^N e^{ikl} O_l^+ |g\rangle \quad (1)$$

where  $|g\rangle$  is the ground state and the summation over  $l$  extends over the entire lattice sites. The  $O_l$  is a local cluster operator to be determined for a given Hamiltonian.

In spite of a simplicity and validity of the expression (1), not much progress has been made along this line since the days of Feynman. The Heisenberg antiferromagnet (HA) described by the Hamiltonian

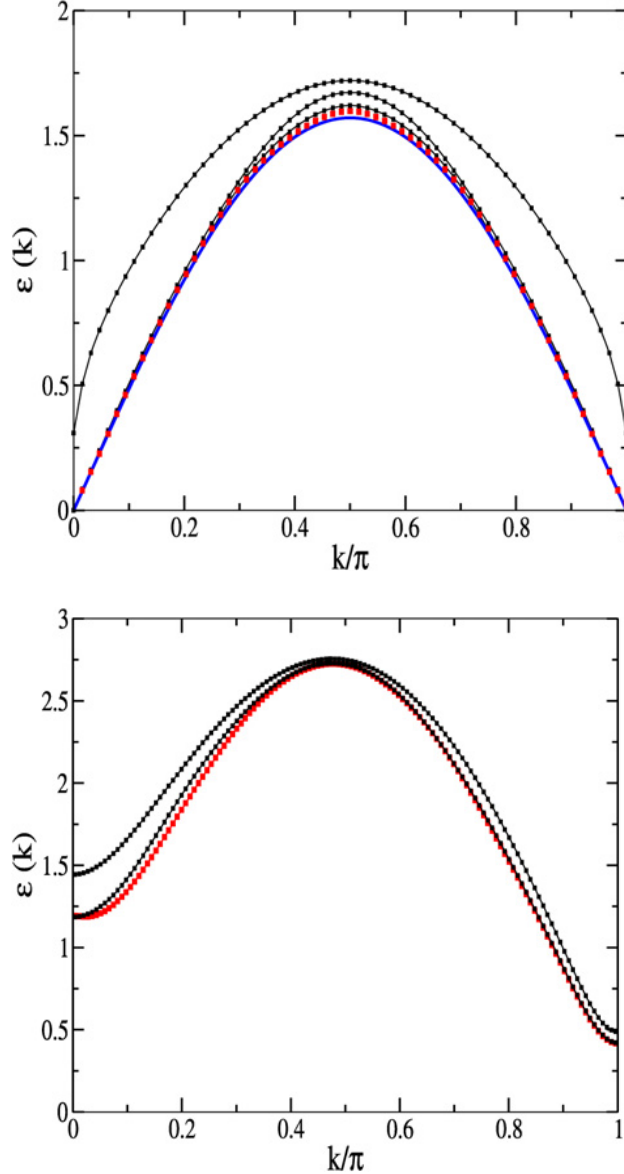
$$H = J \sum_i S_i \cdot S_{i+1} \quad (2)$$

is probably the best studied system concerning the excitation spectrum. In particular, Haldane conjectured in 1983 that the half-odd integer and integer spins might behave essentially differently [3], which together with a field theoretic prediction of Affleck [4] for a logarithmic correction to the power-law behavior in the spin–spin correlation function in the spin-1/2 case, triggered an intensive study of HA ranging from the exact diagonalization [5,6] and Monte Carlo [7,8] to DMRG (density matrix renormalization group) [9–11]. These studies along with the Bethe ansatz solution for the spin-1/2 case [12] lead to a confirmation of the both claims. Concerning the elementary excitation for the entire Brillouin zone, however, Takahashi’s two attempts following the Feynman variational method for  $^4\text{He}$  and a projector-Monte Carlo method were the only studies [13,14]. And none of the previous studies gave a serious consideration to the expression (1).

In this Letter, we analyze (1) exactly for the HA (2) with periodic boundary conditions by the recently developed entanglement perturbation theory (EPT). EPT is a novel many-body method which takes into account correlations systematically. Its mathematical implementation is singular value decomposition (SVD), intuitively *divide and conquer*. EPT has addressed so far classical statistical mechanics [15], 1D quantum ground states [16] and 2D quantum ground states [17]. We here address the elementary excitation in one dimension. By EPT, we are not only free from a negative sign problem which is inherent to MC for quantum spins and fermions, but can also handle an order of magnitude larger systems than MC and DMRG. The key of the

success lies in our ability of calculating the ground state  $|g\rangle$  precisely and most importantly in an *un-renormalized* form. We examine the cluster excitation operator  $O_l$  systematically.

The top figure shows the spin-triplet excitation spectrum for spin-1/2 with the chain size 512 and the cluster size  $n$  up to 4, from top to bottom. The EPT calculation almost converged at  $n = 4$ , and gives an agreement of 1% precision with BA [12], the solid blue line. The bottom figure shows the same for spin-1 up to the cluster size  $n = 3$ , from top to bottom where the calculation almost converged. The Haldane gap at  $k = \pi$  is found by EPT to be 0.414 agreeing with the previous results [7,10,14]. As for the region  $0 < k/\pi < 1/2$ , the spin-triplet spectrum is believed to be embedded in a continuum spectrum of a pair of magnons with the total spin-z component to be 0. The exact diagonalization for  $N = 14$  indeed tells us that the lowest excitation at  $k = 0$  is spin singlet, presumably a  $(-\pi, \pi)$  pair of spin-triplet magnons from  $k = \pm\pi$  [6,14]. We believe that the spin-triplet magnon spectrum for spin-1 for the entire Brillouin zone has been determined for the first time by EPT.



## References

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- [2] R.P. Feynman, *Phys. Rev.* 94 (1954) 262.
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- [13] M. Takahashi, *Phys. Rev. Lett.* 62 (1989) 2313.
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- [15] S.G. Chung, *Phys. Lett. A* 359 (2006) 707.
- [16] S.G. Chung, *Phys. Lett. A* 361 (2007) 396.
- [17] S.G. Chung, K. Ueda, *Phys. Lett. A* 372 (2008) 4845.

## DISSERTATIONS

### **PH. D.**

Lihua Wang, May 20, 2009.

## PUBLICATIONS

- 1. S. G. Chung and L. Wang, *Entanglement perturbation theory for the elementary excitation in one dimension*, *Physics Letters A* 373 (2009) 2277.
- 2. L. Wang, S. Yunoki and S. G. Chung, *Entanglement perturbation theory for antiferromagnetic spin chains*, submitted to *Physical Review B*.

## INVITED TALKS

- 1. *Entanglement perturbation theory for the quantum ground states in two dimensions*, International workshop on, “Nonequilibrium Nanostructures,” at Max Planck Institute for the Physics of Complex Systems, Dresden, Germany for December 1-6, 2008.
- 2. *Entanglement perturbation theory: A novel many-body method in statistical mechanics and strong correlation physics*, at Physics Department, Yonsei University, Seoul, Korea on May 27, 2009.

3. ***Entanglement perturbation theory: A novel many-body method in statistical mechanics and strong correlation physics***, at Physics Department, Pusan National University, Pusan, Korea on May 29, 2009.
4. ***Entanglement perturbation theory: A novel many-body method in statistical mechanics and strong correlation physics***, at Physics Department, Pohang University of Science and Technology, Pohang, Korea on June 3, 2009.
5. ***Entanglement perturbation theory: A novel many-body method in statistical mechanics and strong correlation physics***, at Physics Department, Seoul National University, Seoul, Korea on June 5, 2009.
6. ***Entanglement perturbation theory: A novel many-body method in statistical mechanics and strong correlation physics***, at Physics Department, RIKEN, Tokyo, Japan on June 10, 2009.
7. ***Entanglement perturbation theory: A novel many-body method in statistical mechanics and strong correlation physics***, at Physics Department, Aoyama Gakuin University, Tokyo, Japan on June 12, 2009.

### **CONTRIBUTED TALKS**

1. ***Entanglement perturbation theory for the excitation spectrum in one dimension***, American Physical Society March Meeting, Pittsburgh, March 17, 2009.
2. ***Entanglement perturbation theory for antiferromagnetic Heisenberg spins***, American Physical Society March Meeting, Pittsburgh, March 17, 2009 L. Wang and S. G. Chung, presented by L. Wang.
3. ***Entanglement perturbation: A new paradigm in many-body problem***, Poster presentation at Third Annual WMU Research and Creative Activities Poster Day, February 26, 2009, WMU.
4. ***Entanglement perturbation theory for antiferromagnetic Heisenberg spins***, Poster presentation at Third Annual WMU Research and Creative Activities Poster Day, February 26, 2009, WMU. L. Wang and S. G. Chung, presented by L. Wang.

### **GRANTS**

1. ***Novel many body method for strongly correlated condensed matter systems***, Faculty Research and Creative Activities Support Fund \$10,000 for 2008-2009.
2. ***ASTRA award***, \$450 on April 13, 2009.

## **SCHOLARLY ACTIVITIES**

1. I have refereed 3 papers for Journal of Physics Condensed Matter.
2. Reviewer for Faculty Research and Creative Activities Support Fund, WMU.

### 5.3 *Asghar Kayani*

#### **Students:**

Mr. Salem Al-Faify	– Ph.D. student
Mr. Amila Dissanayake	– Ph.D. student
Mr. Elias J. Garratt	– Ph.D. student
Mr. Nandasiri Manjula	– Ph.D. student
Mr. Rex Taibu	– M.A. student
Mr. George Tecos	– M.A. student
Mr. Adam Hammouda	– Undergraduate student
Mr. Andrew D. Bringley	– Undergraduate student

#### **RESEARCH ABSTRACTS:**

##### **1) Effect of bias and hydrogenation on the elemental concentration and the thermal stability of amorphous thin carbon films, deposited on Si substrate**

A. Kayani<sup>1</sup>, A. Moore<sup>1</sup>, M. I. Nandasiri<sup>1</sup>, S. AlFaify<sup>1</sup>, and E. Garratt<sup>1</sup>, D. Ingram<sup>2</sup>, M. Maqbool<sup>3</sup>

#### **Affiliations**

<sup>1</sup> Western Michigan University – Kalamazoo, MI 49008, United States

<sup>2</sup> Ohio University – Athens OH 45701, United States

<sup>3</sup> Ball State University, Muncie, IN 47306, United States

#### **Abstract**

Amorphous carbon films have been deposited with various levels of negative substrate bias and hydrogen flow rates using argon and argon+nitrogen as sputtering gas. The effect of hydrogenation and substrate bias on the final concentration of trapped elements is studied using ion beam analysis (IBA) techniques. The elemental concentrations were measured in the films deposited on silicon substrates with a 2.5 MeV H<sup>+</sup> beam and 16 MeV O<sup>5+</sup> beam. Argon was found trapped in the non-hydrogenated films to a level of up to ~ 4.6 %. The concentration of argon increased for the films deposited under higher negative bias. With the introduction of hydrogen, argon trapping was first minimized and later completely eliminated, even at higher bias conditions. This suggests the softness of the films brought on by hydrogenation. Moreover, the effect of bias on the thermal stability of trapped hydrogen in the films was also studied. As the films were heated in-situ in vacuum using a non-gassy button heater, hydrogen was found to be decreasing around 400 °C.

## 2) Growth rate induced surface characteristics of CeO<sub>2</sub> thin films on Al<sub>2</sub>O<sub>3</sub>(0001) grown by molecular beam epitaxy

M. I. Nandasiri<sup>1, 2</sup>, T. Varga<sup>2</sup>, R. Baxter<sup>2, 3</sup>, P. Nachimuthu<sup>2</sup>, V. Shutthanandan<sup>2</sup>, W. Jiang<sup>2</sup>, S. Kuchibhatla<sup>2</sup>, S. Thevuthasan<sup>2</sup>, S. Seal<sup>4</sup>, A. Kayani<sup>1</sup>

### Affiliations

<sup>1</sup> Physics Department, Western Michigan University, Kalamazoo, MI 49008, USA

<sup>2</sup> EMSL, Pacific Northwest National Laboratory, Richland, WA 99354, USA

<sup>3</sup> Department of Material Science and Engineering, University of Washington, Seattle, WA 98195, USA

<sup>4</sup> AMPAC, NSTC, University of Central Florida, Orlando, FL 32816, USA

### Abstract

CeO<sub>2</sub> thin films have been grown on Al<sub>2</sub>O<sub>3</sub>(0001) substrates by oxygen plasma assisted molecular beam epitaxy (OPA-MBE) at different growth rates. Then we have studied growth rate induced surface characteristics of CeO<sub>2</sub> thin films by various in-situ and ex-situ characterization methods. Change of the growth mode of CeO<sub>2</sub> thin films from three dimensional (3-D) islands to two dimensional (2-D) layers was identified with the increase of the growth rate, revealed by in-situ reflection high energy electron diffraction (RHEED). High resolution x-ray diffraction (HRXRD) confirmed (100) and (111) crystalline orientations of CeO<sub>2</sub> films at low (<7 Å/min) and high (>9 Å/min) growth rates, respectively. X-ray rocking curves indicate high crystalline quality of CeO<sub>2</sub>(100) compared to CeO<sub>2</sub>(111). At intermediate growth rates (4-7 Å/min) CeO<sub>2</sub> thin films exhibit (100) orientation with small (111) orientation, leads to two peaks in x-ray rocking curve. The narrow peak with a low full-width at half-maximum (FWHM) value attributed to the well aligned crystallites and the broad peak with a high FWHM value attributed to the poorly aligned crystallites in CeO<sub>2</sub>(100). X-ray pole figure for CeO<sub>2</sub>(100) shows multiple poles indicating the multiple in-plane domains. Despite the relatively poor crystalline quality, CeO<sub>2</sub>(111) exhibits single in-plane domain as expected. Significant lattice mismatch between the film and the substrate leads to highly strained film, reducing the crystalline quality of CeO<sub>2</sub>(111).

## 3) Compositional analysis of ultrananocrystalline diamond (UNCD) films using ion beam scattering

S AlFaify<sup>1</sup>, E Garratt<sup>1</sup>, M I Nandasiri<sup>1</sup>, A Kayani<sup>1</sup>, A V Sumant<sup>2</sup> and D C Mancini<sup>2</sup>

### Affiliations

<sup>1</sup> Department of Physics, Western Michigan University, Kalamazoo, MI 49008, USA

<sup>2</sup> Center for Nanoscale Materials, Argonne National Laboratory, Argonne, IL 60439-4812, USA

### Abstract

Determination of the elemental composition is important to correlate the electrical and the optical properties of ultrananocrystalline diamond (UNCD) films, doped with and without nitrogen. To obtain the complete picture of impurities in the UNCD thin films, Rutherford backscattering spectroscopy (RBS), Non-Rutherford backscattering spectroscopy (NRBS), Elastic recoil detection analysis (ERDA) and nuclear reaction analysis (NRA) were performed on UNCD films on Si substrate and on free standing films. Helium beam was used for RBS and ERDA and protons were used for NRBS measurements. Exploiting the nuclear reaction of

deuterons with C, O and N, 1.1 MeV  $D^+$  beam was used to quantitatively measure the concentration of these elements. Our results show that UNCD films contain less than 3% of Hydrogen while Nitrogen content incorporated in the film was estimated to be lower than 1%. The intermixing region between the substrate and the film was found to be negligible.

#### 4) The effects of thickness and dopant concentration on the electrical properties of samaria doped ceria thin films

M. Nandasiri<sup>1,2</sup>, D. Meka<sup>3</sup>, S. Gupta<sup>3</sup>, S. Kuchibhatla<sup>2</sup>, P. Nachimuthu<sup>2</sup>, M. H. Engelhard<sup>2</sup>, V. Shutthanandan<sup>2</sup>, W. Jiang<sup>2</sup>, S. Thevuthasan<sup>2</sup>, S. Prasad<sup>3,4</sup>, A. Kayani<sup>1</sup>

##### Affiliations

<sup>1</sup> Physics Department, Western Michigan University, Kalamazoo, MI 49008, USA

<sup>2</sup> EMSL, Pacific Northwest National Laboratory, Richland, WA 99354, USA

<sup>3</sup> Department of Electrical Engineering, Portland State University, Portland, OR 97201, USA

<sup>4</sup> Department of Electrical Engineering, Arizona State University, Tempe, AZ 85287, USA

##### Abstract

Resistive oxygen gas sensors stand out among various types of sensors due to their simplicity, low cost, portability, measurement circuit simplification, and low power consumption. Rare earth materials such as pure and doped ceria are potential candidates for resistive oxygen gas sensors due to their unique ability to lose or gain oxygen in response to ambient oxygen concentration. Anderson et al<sup>1</sup>. have recently proposed that Sm is the best dopant for optimizing oxygen ion conductivity in ceria. In order to develop resistive oxygen gas sensors based on doped ceria thin films, it is vital to gain a fundamental understanding of the influence of dopant concentration and film thickness on the electrical properties. In order to achieve this goal, we have grown samaria doped ceria (SDC) thin films on sapphire, Al<sub>2</sub>O<sub>3</sub> (0001) substrates by using oxygen plasma-assisted molecular beam epitaxy (OPA-MBE). 100nm thick films were grown with dopant concentration ranging from 0 – 14 Sm atom%. After realizing that the 6 atom% Sm doped ceria films have highest conductivity, Figure 1, films with thickness ranging from 50 – 300nm have been grown and their conductivity was studied. The resistance of these films, obtained by two probe measurement capability under various oxygen pressure (1mTorr- 100Torr) and temperatures (473K to 973K), will be discussed. The differences in the electrical properties, thereby the oxygen ion conductivity, will be explained based on the chemical and structural

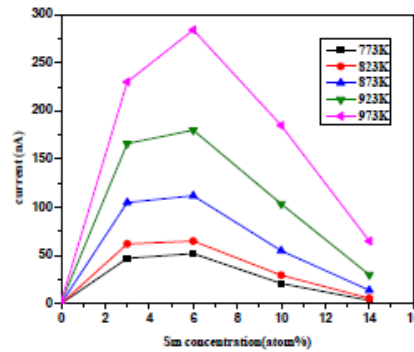


Figure 1 Current through the Sm doped ceria films as a function of Sm concentration for temperatures ranging from 773 to 973 K. The 6 atom% Sm doped sample shows the highest current over the temperature range.

characteristics of various films. Structural and chemical characteristics of the as grown films were analyzed by various *in situ* and *ex situ*, surface and bulk sensitive techniques<sup>2</sup>. Lowest resistance of the 6 atom % Sm doped ceria films is attributed to the maximum oxygen vacancy sites and best epitaxial quality leading to their alignment. The aligned oxygen vacancies result in low activation energy and there by better sensitivity to oxygen. With the increasing interest for miniaturized oxygen sensors for high temperature uses, the nano-scale thin film doped ceria sensors may have a significant role to play in various future functional applications.

#### References:

1. D.A. Andersson, et al., Optimization of ionic conductivity in doped ceria, Proceedings of the National Academy of Sciences of the United States of America, 103(10): p. 3518-3521 (2006)
2. S. Gupta, et al., Influence of Samaria doping on the resistance of ceria thin films and its implications to the planer oxygen sensing devices, Sensors & Actuators (2008)

### 5) Luminescence from Cr<sup>+3</sup>-doped AlN films deposited on optical fiber and silicon substrates for use as waveguides and laser cavities

Muhammad Maqbool<sup>1</sup>, Evan Wilson<sup>1</sup>, Joshua Clark<sup>1</sup>, Iftikhar Ahmad,<sup>2</sup> and Asghar Kayani<sup>3</sup>

#### Affiliations

<sup>1</sup>Department of Physics & Astronomy, Ball State University, Muncie, Indiana 47306, USA

<sup>2</sup>Department of Physics, Hazara University, Mansehra, NWFP, Pakistan

<sup>3</sup>Department of Physics, Western Michigan University, Kalamazoo, Michigan 49008

#### Abstract

Thin films of AlN doped with chromium were deposited on flat Si (100) substrates and optical fibers by rf magnetron sputtering, using 100–200 W rf power and 5–8 mTorr nitrogen. The thickness of the films on the flat silicon substrate was 400nm and on optical fibers with 80  $\mu$ m and smaller diameters was up to 10  $\mu$ m. Surface characterization and luminescence properties were investigated to fabricate resonant laser cavities. X-ray diffraction and scanning electron microscope studies showed that films deposited on flat silicon were amorphous, while those deposited on the fibers show columnar growth and some grain structure, most probably due to a temperature rise at the substrate during deposition. Cathodoluminescence and photoluminescence of the as-deposited and thermally activated AlN:Cr films showed an emission peak at 702nm as a result of the  $^4T_2 \rightarrow ^4A_2$  transition.

### 6) Enhanced cathodoluminescence from an amorphous AlN:holmium phosphor by co-doped Gd<sup>+3</sup> for optical devices applications

Muhammad Maqbool<sup>1</sup>, Martin E. Kordesch<sup>2</sup>, and A. Kayani<sup>3</sup>

#### Affiliations

<sup>1</sup>Department of Physics & Astronomy, Ball State University, Muncie, Indiana 47306,

<sup>2</sup>Department of Physics, Ohio University, Athens Ohio

<sup>3</sup>Department of Physics, Western Michigan University, Kalamazoo, Michigan 49008

## **Abstract**

Sputter-deposited thin films of amorphous AlN:Ho (1 at. %) emits in the green \_549 nm\_ region of the visible spectrum under electron excitation. The addition of Gd (1 at. %) in the film enhances the green emission linearly after thermal activation at 900 °C for 40 min in a nitrogen atmosphere. The luminescence enhancement saturates when the gadolinium concentration reaches four times the holmium concentration. The optical bandgap of amorphous AlN is about 210 nm, so that the film is transparent in the ultraviolet, allowing us to observe the ultraviolet emission at 313 nm from Gd. No significant quenching of the Gd emission is observed. Energy dispersive x-ray (EDX) spectra confirm the increasing concentration of Gd. X-ray diffraction (XRD) analysis shows no peaks other than those arising from the Si (111) substrate, confirming that the films are amorphous. The enhanced luminescence can be used to make high-efficiency optical devices.

## **DISSERTATIONS**

### **M.A.**

Andrew Moore, April 2009.

## **PUBLICATIONS**

1. **Effect of bias and hydrogenation on the elemental concentration and the thermal stability of amorphous thin carbon films, deposited on Si substrate**  
A. Kayani, A. Moore, M. I. Nandasiri, S. AlFaify, E. Garratt, D. Ingram and M. Maqbool, Diamond and related materials, 18, 1333 (2009).
2. **Enhanced cathodoluminescence from an amorphous AlN:holmium phosphor by co-doped Gd<sup>3+</sup> for optical devices applications**  
Muhammad Maqbool, Martin E. Kordesch, and A. Kayani, J. Opt. Soc. Am. 26, 998 (2009).
3. **Ion Beam Analysis of the Thermal Stability of Hydrogenated Diamond-Like Carbon Thin Films on Si Substrate**  
M. I. Nandasiri, A. Moore, E. Garratt, K. J. Wickey, S. AlFaify, X. Gao, A. Kayani, and D. Ingram AIP Conf. Proc. Vol 1099, pp. 318-322 (2009)
4. **High Temperature Thermal Stability and Oxidation Resistance of Magnetron-sputtered Homogeneous CrAlON Coatings on 430 Steel**  
A. Kayani, K. J. Wickey, M. I. Nandasiri, A. Moore, E. Garratt, S. AlFaify, X. Gao, R. J. Smith, T. L. Buchanan, W. Priyantha, M. Kopczyk, P. E. Gannon, and V. I. Gorokhovskiy, AIP Conf. Proc. Vol 1099, pp. 303-307 (2009)

5. **Guiding of Electrons and Fast Ions through Insulating Nanocapillaries**  
B. S. Dassanayake, S. Das, A. Ayyad, A. Kayani, N. Stolterfoht, and J. A. Tanis  
AIP Conf. Proc. Vol 1099, pp. 125-128 (2009).
6. **Measurement of the  $(p, \gamma)$  Cross Sections of  $^{46}\text{Ti}$ ,  $^{64}\text{Zn}$ ,  $^{114}\text{Sn}$  and  $^{116}\text{Sn}$  at Astrophysically Relevant Energies**  
Ravin S. Kodikara, Michael A. Famiano, Brenna M. Giacherio, V. G. Subramanian, and Asghar Kayani. AIP Conf. Proc. Vol 1099, pp. 719-723.
7. **Interferences in Electron Emission from  $\text{O}_2$  by 30 MeV  $\text{O}^{5,8+}$  Impact**  
M. Winkworth, P. D. Fainstein, M. E. Galassi, J. Baran, B. S. Dassanayake, S. Das, A. Kayani and J. A. Tanis, Nucl. Instrum. Meth. Phys. Res. B 267, 373(2009).
8. **Interference effects in electron emission spectra for 3 MeV/u  $\text{H}^+ + \text{O}_2$  collisions,**  
M Winkworth, P D Fainstein, M E Galassi, J Baran1, S Das, B S Dassanayake, A Kayani  
and J A Tanis, *J. Phys.: Conf. Ser.* **163**, 012044 (2009).
9. **Dissociative and non-dissociative charge-changing processes in 1.0-2.0 MeV/u  $\text{O}^{5+} + \text{O}_2$  collisions**  
D P Cassidy, E Y Kamber, A. Kayani and J A Tanis. *J. Phys.: Conf. Ser.* **163**, 012054 (2009).

## **GRANTS**

1. NSF Major research instrumentation grant \$ 294,044.00.
2. WMU International Education Faculty Development fund award \$ 1000.00.
3. Center of Nanoscale Materials proposal, Argonne National Laboratory: approved and allocated.

## **INVITED TALKS**

1. **Effect of Cr/Al Ratio on the Oxidation Resistance CrAlon Coatings on 430 Steel**  
A. Kayani, K. J. Wickey, M.I. Nandasiri, A. Moore, E. Garratt, ISAM 14-19 August (2009), Islamabad PAKISTAN. Scope of Audience “International.”

## **CONTRIBUTED TALKS**

1. **The Effects of Thickness and Dopant Concentration on the Electrical Properties of Samaria Doped Ceria Thin Films**  
M. I. Nandasiri, D. Meka, S. Gupta, S. V. Kuchibhatla, P. Nachimuthu, M. Engelhard, V. Shutthanandan, W. Jiang, S. Thevuthasan, S. Prasad and A. Kayani, 215th ECS Meeting - San Francisco, CA, May 24 - May 29, 2009.
2. ***Compositional analysis of ultrananocrystalline diamond (UNCD) films using ion beam scattering***  
S AlFaify, E Garratt, M I Nandasiri, A Kayani, A V Sumant and D C Mancini New Diamond and Nano Carbons Conference 2009, Traverse City, MI, 2009.

## 5.4 *Arthur McGurn*

### **PUBLICATIONS**

1. M. Abdel-Aty and **A. R. McGurn**, “Entanglement of three-level trapped ions with phonon trap modes,” *Physics Letters A*, Volume 373, issue 29, 29 June 2009, Pages 2420-2427.
2. **A. R. McGurn**, “Transmission through a Kerr Barrier in Photonic Crystal Waveguides: Dispersive Effects,” *J Phys: Condens. Matter* 21, 485302-1-485302-10 (2009).
3. **A. R. McGurn**, “Transmission through Kerr Media Barriers within Waveguides and Circuits” in *SPIE Proceedings*, Ed. By E. S. Kawata, V.M. Shalev, and D. P. Tsai, Vol. 7395, San Diego, USA, August 2009, 7395T-1-73951T-8.
4. A. K. Bandyopadhyay, P. C. Ray, Loc Vu-Quoc, and **Arthur R. McGurn**, “Multiple-time-scale analysis of nonlinear modes in ferroelectric LiNbO<sub>3</sub>,” *Phys.*

### **GRANTS**

1. FRACAS grant “Neutron Stars”--\$5000.00.

### **INVITED TALKS**

1. Arthur R McGurn, “The Wave Nature of Light: Applications to Scattering, Nano Photonics, and Quantum Computing,” public lecture at WMU for the Distinguished Faculty Scholar Award, March 11, 2009.
2. Arthur R. McGurn, “Transmission through Nonlinear Barriers and Junctions,” at Progress in Electromagnetic Research Symposium, July 2-6, 2008, Cambridge, Massachusetts, USA. -- Note I organized the sessions that this appeared in so I technically invited myself.
3. A. R. McGurn, “Transmission through Kerr Media Barriers within Waveguides and Circuits,” an invited talk at the SPIE (Society of Optical Engineers) meeting August 2009 in San Diego.

### **SCHOLARLY ACTIVITIES**

I organized and chaired three sessions at the meeting “Progress in Electromagnetic Research Symposium 2008,” July 2-6, 2008, Cambridge, Massachusetts, USA. The three sessions were entitled “Photonic Crystals and Metamaterials” I, II, and III.

#### Referee Reports Written:

1. *Physical Review Letters* – 10.
2. *Optics Letters* – 1
3. *Journal of Physics: Condensed Matter* – 2
4. *Waves in Random and Complex Media* – 1
5. *Physica A* – 1
6. *Progress in Electromagnetic Research Symposium and Journal of Electromagnetic Waves and Applications* – 3
7. *Journal of Physics D* – 1
8. *Optics Express* – 2
9. *Physical Review B* – 9
10. *Journal of Applied Physics* – 5
11. *Chaos* – 1
12. *Applied Optics* – 2
13. *Waves in Random Media* – 1
14. *Optics Communications* – 2
15. *Journal of Optics A* – 3
16. *Applied Physics Letters* – 6
17. *New Journal of Physics* – 3
18. *PIERS & JEMWA* – 4
19. *Physical Review A* – 1
20. *Journal of the Optical Society of America A* – 1
21. *Journal of Optics* – 1

1. I reviewed 2 different proposed books for Cambridge University Press, one for Graduate and one for Undergraduate courses in Mathematical Physics.
2. I served on a Site Visit Team to assess a proposed Science and Technology Center for the National Science Foundation.
3. I review two published paper entries in the BRHE 2010 Young Scientists Article Contest held by the Civilian Research and Development Foundation.
4. I served on 3 Fellowship Panels of the Institute of Physics.
5. I was invited to be a Managing Editor of the journal “Applied Mathematics and Information Sciences.”

#### Grant proposal reviewed:

1. Research Grants Council of Hong Kong – 3 proposals
2. Civilian Research and Development Foundation—2 proposals

# 6 NUCLEAR PHYSICS

## 6.1 Michael Famiano

Graduate Students: Ravin Kodikara, Brenna Giacherio, Subramanian Vilayurganapathy

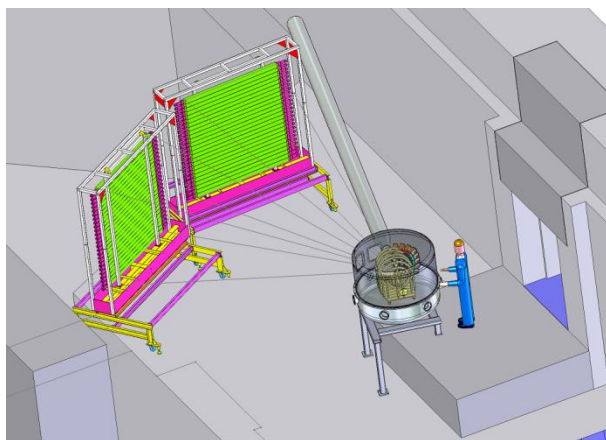
Undergraduate Students: John Novak, Paul Thompson, Stephen Dye, Justin Harris

### I. Research Activities

#### I.a Studies of In-Medium Nuclear Cross-Sections: Constraining the Nuclear Equation of State (EOS)

M.A. Famiano,<sup>1</sup> W.G. Lynch,<sup>2</sup> M.B. Tsang,<sup>2</sup> Wolfgang Mittig,<sup>2</sup> Daniel Bazin<sup>2</sup>

The previous year ended with the completion of the the NSCL S2 reactions area and the running of the first equation-of-state (EOS) experiment in this area. The reactions area provides a versatile area for the study of heavy ion collisions with a variety of particle detectors, including a permanent neutron time-of-flight installation, a movable, thin-walled scattering chamber useful for studying neutrons, but large enough to accommodate fairly large charged-particle arrays such as LASSA (1) or HiRA. (2) A diagram of the completed area layout is shown in Figure 1 showing the neutron walls, the scattering chamber, and the beamline. The neutron walls are able to be moved to backward angles in this area, and the scattering chamber can be removed to accommodate further setups such as the SEGA array. (3)



**Figure 1 - Technical drawing of the NSCL S2 reactions area showing the neutron TOF walls and scattering chamber.**

Since May 2009, at least three reactions experiments have been run in the S2 reactions area (in addition to the commissioning and several other experiments in this vault). One of these experiments is described in the following.

The first experiment run in the new S2 vault has been NSCL experiment #05049. This experiment was completed at the end of May in 2009. In this experiment, measurement of the relative neutron and proton flow observables were made to better understand and constrain the in-medium nucleon cross-sections, which are an unknown parameter in transport calculations. (4)

For an effective experiment, a fairly complicated setup was done which included neutron detectors with a large angular range, the Large Area Neutron Array (LANA) (5) and charged particle telescopes capable of a similar angular range, and a sufficient energy range to provide emission spectra extracted from the mid-rapidity region in the described reactions, and way of measuring the reaction impact parameter via charged particle multiplicity. These

<sup>1</sup> Western Michigan University

<sup>2</sup> National Superconducting Cyclotron Laboratory

devices already exist in the form of the large liquid scintillator neutron walls at the NSCL, (5) elements of the LASSA array and the MiniBall array. (6) Additionally, a simple position sensitive trigger detector array was constructed for timing and acquisition triggering.

The experimental setup is shown in Figure 1. Neutron walls were placed a distance of about 6-7 m from the target with an angular coverage in the lab of  $8^\circ$  to  $60^\circ$ , providing a center-of-mass coverage of  $70^\circ$  to  $110^\circ$  for the EOS experiment, as well as a large angular coverage at forward angles for the NN cross-section measurement. A similar coverage was provided by six charged-particle telescopes. The S2 vault is large enough to accommodate the neutron walls north of the target area.

Impact parameter was determined via charged-particle multiplicity in the MiniBall, (6) which was complimented by a granular plastic scintillator start detector. The Microball provides over 97% coverage over backward angles, as well as particle identification. The combined information from the charged-particle telescopes, the start detector information, and the MiniBall provided a good measure of the impact parameter and reaction plane needed for proper event characterization.

The start detector was a thin segmented plastic scintillator array placed at forward angles (see Figure 1). This array provides signals with a resolution of less than 300ps, and also served as the time reference for the experiment. In addition to providing the time reference, the multiplicity in this detector complemented the MiniBall multiplicity in the impact parameter selection. Past experiments have used a four-segment version of this device. (7) The proposed experiment utilized a replica with higher granularity of 16 segments in order to achieve better impact parameter identification. The thin-walled scattering chamber at the target location served to accommodate the charged-particle telescopes, the MiniBall, and the start detector.

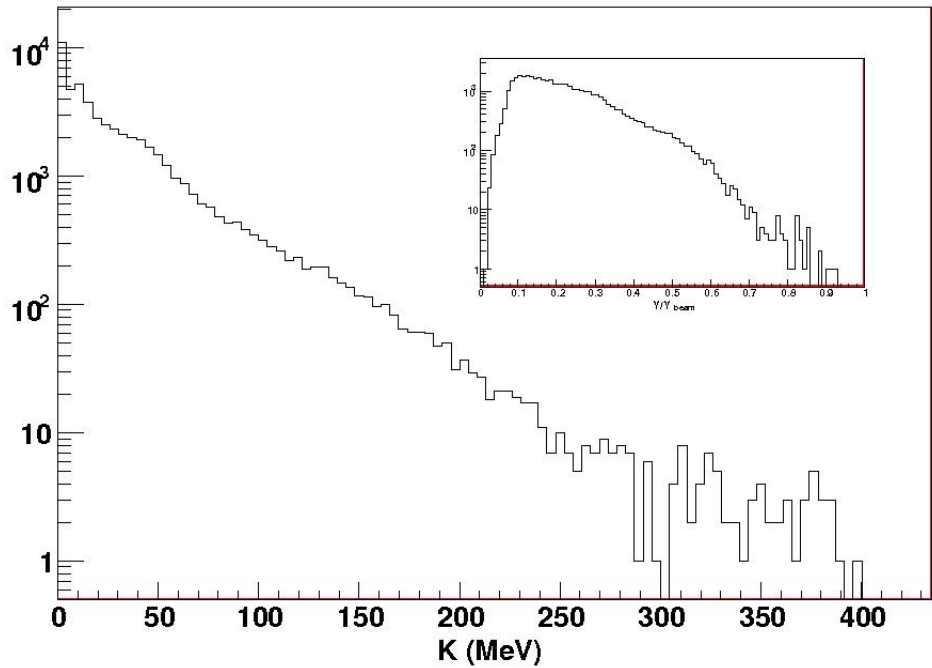


Figure 2 - Neutron energy spectra from the  $^{48}\text{Ca}+^{124}\text{Sn}$  reaction. Inset: relative rapidity distribution.

This experiment utilized  $^{(40,48)}\text{Ca}+^{(112,124)}\text{Sn}$  reactions at 140 MeV/u. Neutron and charged-particle kinematics were measured. Analysis is currently underway, and preliminary results are being produced.

As an example, neutron energy spectra are shown in Figure 2 for the  $^{48}\text{Ca}+^{124}\text{Sn}$  reaction, showing neutron energies well above 200 MeV. This is important as sensitivity to in-medium effective masses is greatest at highest particle rapidities. It is particularly interesting to note that the neutron wall also makes an excellent charged-particle detector. Charged particles are detected via their TOF-charge deposit relationship as shown in Figure 3. This may be extremely useful as we may very well be able to extract neutron-proton correlation functions, which may be a good indicator of the stiffness of the asymmetry term of the nuclear EOS. (8) Over the summer of 2010, the analysis should move very close to completion in this particle experiment. Preliminary physics data showing sensitivity to particle rapidity is expected.

The project continues to push towards exploration of the high-density EOS. In this regime, the most sensitive observable is thought to be pion production ratios. (9) Close work is being conducted with the SAMURAI and the AT-TPC collaboration to construct TPC detectors in Japan and the US for heavy ion research.

One of the first steps in establishing detectors for study of the high-density EOS has been to procure a

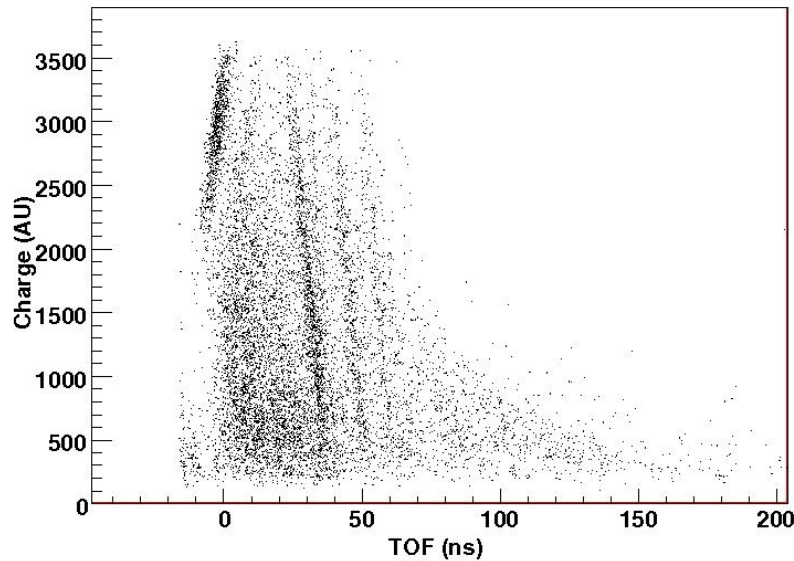


Figure 3 - Identification of charged particles in the neutron walls via TOF-charge comparison. Protons, deuterons, and tritons are shown. These may be used to study n-p correlations in LANA.

detector for device studies and preliminary testing. The final stages of procuring the BRAHMS TPC for such studies are underway. Over the next year, a working test setup of this device is expected to be completed with the associated electronics.

In Japan, colleagues in the SAMURAI collaboration are working closely with American counterparts to develop this device to accommodate a TPC detector system as well. Preliminary designs are underway, and we hope to have functional designs by the end of the year.

## Ib. Development of an Accelerator Facility for the Deep Underground Science and Engineering Laboratory

Michael Weischer,<sup>3</sup> Daniela Leitner,<sup>4</sup> Michael Famiano,<sup>5</sup> Alberto Lemut,<sup>4</sup> Art Champagne,<sup>6</sup> Uwe Greif<sup>7</sup>

The Deep Underground Science and Engineering Laboratory (DUSEL) at Homestake Mine in South

<sup>3</sup> University of Notre Dame

<sup>4</sup> Lawrence Berkeley National Laboratory

<sup>5</sup> Western Michigan University

<sup>6</sup> University of North Carolina

<sup>7</sup> Colorado School of Mines

Dakota will provide an opportunity for the development of a very low-background facility in the US to stay internationally competitive and become leaders in the field. Funding has been awarded for developing and providing a design for a two accelerator facility at DUSEL, Dakota Ion Accelerators for Nuclear Astrophysics (DIANA). The goal for this facility is to address three long-standing fundamental problems in nuclear astrophysics; *solar neutrino sources and the core metallicity of the sun, carbon-based nucleosynthesis, and neutron sources for the production of trans-Fe elements in stars.*

The next generation underground accelerator laboratory DIANA will build on the experience of the present LUNA facilities, but will provide much enhanced capabilities in terms of ion beam intensity (which will be more than one order of magnitude higher than in LUNA), ion species, and energy range. It will enable measurements of solar burning cross-sections at lower energies with higher precision and enhance our knowledge of more complex reaction mechanisms during late stellar burning, which is not possible at existing laboratories. The reactions associated with the nucleosynthesis of carbon and the neutron production for trans-iron nucleosynthesis are identified as the most critical for simulating the nucleosynthesis of late stellar evolution and for understanding ignition conditions of novae and type I supernovae.

Preliminary shielding calculations have been performed for the DIANA site with the primary goal of reducing radiation flux to DUSEL facilities external to the DIANA site. In particular, the most likely type of flux would be that from neutrons scattered into the hallways and other rooms of the DUSEL facility. While preliminary calculations have simulated the flux of 14 MeV monoenergetic neutrons in neighboring cavities, the current emphasis is on improving the realism of the simulation by incorporating the following simulated aspects into the calculation:

- Realistic rock composition using the mass fractions specified in the Yates and Poormann formation
- Finalizing entry and exit drift geometry and properties
- Realistic neutron energy spectra from the DIANA cavity

The stoichiometry of the intervening rock in the vicinity of the DIANA vault has been specified based on the site-specific Poormann rock formation, with the following stiochiometric ratios:

Al<sub>2</sub>O<sub>3</sub>: 10.255%  
CaO: 3.82%  
FeO: 11.74%  
MgO: 4.73%  
K<sub>2</sub>O: 3.21%  
Na<sub>2</sub>O: 0.53%  
S: 1.86%  
SiO<sub>2</sub>: 52.67%  
CO<sub>2</sub>: 4.22%

With this particular formation, the relative flux of 3 MeV monoenergetic neutrons as a function of door thickness in an entry drift with the neutron emission point and measurement point at opposite ends of the drift is shown in Figure 4. In this particular geometry, a 3m square cross section drift of length 20 m is simulated with a door composed of the intervening rock material placed at the halfway point in the drift.

For a door thickness of 0 m (no door) the reduction in neutron flux (relative to the flux measured at the front of the drift) corresponds to a reduction commensurate with the solid angle subtended by the end of the drift opposite that with the source. With a door of varying thickness, the neutron flux for a neutron emission rate roughly follows:

Where the flux  $\Phi$  is the flux measured at the end of the drift. The exponential reduction is due to the attenuation in rock of thickness  $d$  while the inverse square law applies to an empty drift of length  $r$ .

Ideally, a reduction in flux of  $\sim 10^{-6}$  is desired over the length of the drift to reduce the estimated neutron flux from DIANA in neighboring DUSEL cavities below that of the ambient neutron background. This comes from an estimated maximum neutron production rate of  $2.7 \times 10^9 \text{ s}^{-1}$ . Assuming a 40m square drift of width 9m with the production target placed roughly 10m from the drift and the entrance drift of a neighboring DUSEL cavity conservatively placed 20 m from that of the DIANA cavity, then the solid angle estimated neutron flux from neutrons scattered in the DUSEL hallways would be  $4.4 \text{ n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ . Given the DUSEL ambient neutron flux of  $3.29 \times 10^{-6} \text{ n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ , a reduction of at least  $10^{-6}$  of the initial flux would reduce the neutron flux to background levels. Of course, we note that the actual flux at neighboring cavities would be much lower, as the non-shielded flux is calculated assuming a straight-line hallway between the DIANA cavity and intervening cavities while the actual path between neighboring cavities is via at least three hallways with two  $90^\circ$  turns. Thus, we take a reduction of  $10^{-6}$  as a conservative safe rule of thumb for our simulations.

With the footprint of the DIANA cavity specified and the necessary reduction in flux, the remaining shielding aspect is thus the mapping of the DIANA entrance drift. The basic DUSEL drift configuration is shown in Figure 5. This configuration lays the basic

design for the simulations presented. Several scenarios of various configurations and dimensions have been considered. These vary in the approach path of the drift, the door composition, and the door thickness. For each of these configurations, the reduction in neutron flux has been simulated for 3.5 MeV neutrons emitted isotropically at the junction of the drift and the DIANA cavity.

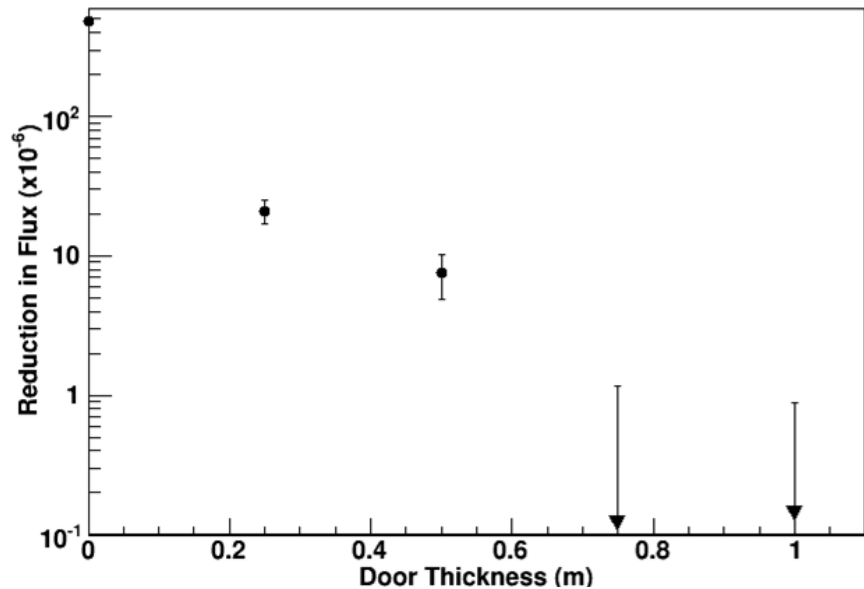
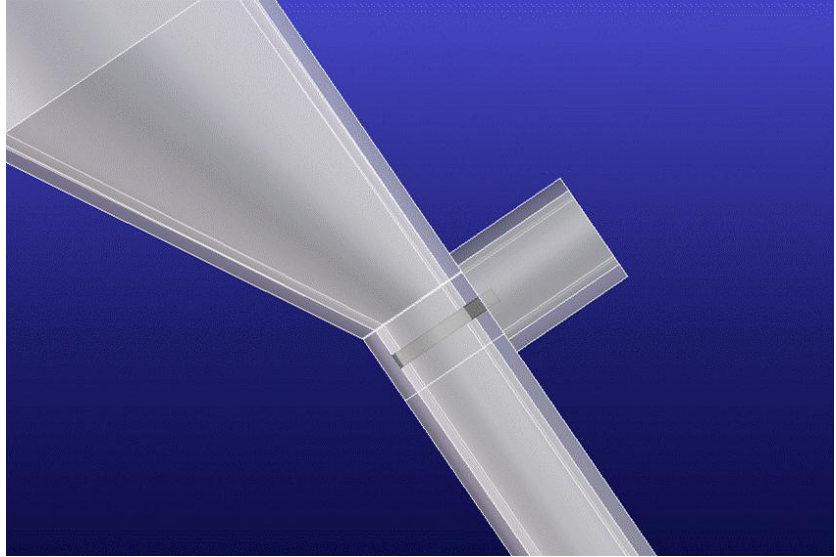


Figure 4 - Reduction in neutron flux in a 20 m drift hallway with a door midway in the hallway for various thicknesses of the door.

For each of the sample simulations, the reduction in flux is given in Table I. From this we can see that multiple desired scenarios. Most attractive is that with a removable water door spanning the equipment entry and somewhat narrower personnel entry similar to that shown in Figure 5. The main drift is 6m square, while a separate personnel egress is 3m in width around a central cube of native rock. This design can also accommodate a utility area. It can be seen from this table that a variety of configurations may be feasible, with the possible exception of scenario A. It should also be noted that this table represents conservative estimates in that the neutron spectra are monoenergetic at the maximum expected energy.



**Figure 5 - Basic DIANA cavity drift entrance configuration showing door and concave personnel entry.**

Table 1: Various reduction in incident neutrons for various configurations.				
Configuration	Door Material	Door Thickness	Reduction	Notes
A	Rock	1m	$2.45 \times 10^{-5}$	
B	Rock	1m	$9.8 \times 10^{-7}$	Two Doors
C	Rock	1m	$7.4 \times 10^{-7}$	Two Doors + Utility Area
D	Rock	1m	$6.1 \times 10^{-6}$	
E	Water	2m	$1.56 \times 10^{-6}$	

## Ic. New Isotope and Mass Measurements at the RIBF

Michael Famiano,<sup>8</sup> Toshiyuki Kubo,<sup>9</sup> Takashi Nakamura,<sup>10</sup> Daniel Bazin<sup>11</sup>

A tremendous amount of work is being put into establishing a program at the RIBF to measure nuclear masses of astrophysical relevance. The masses of many exotic nuclei are unknown, and theoretical predictions disagree considerably. As an example, mass predictions for several nuclei in the  $^{22}\text{Ne}$  region near the neutron drip line are shown in Figure 6 for several commonly used mass models. (10) (11) (12) This region is particularly interesting as it may represent a region with the heaviest known halo nuclei. (13) In addition, a particular result of this technique is the concurrent production of new isotopes.

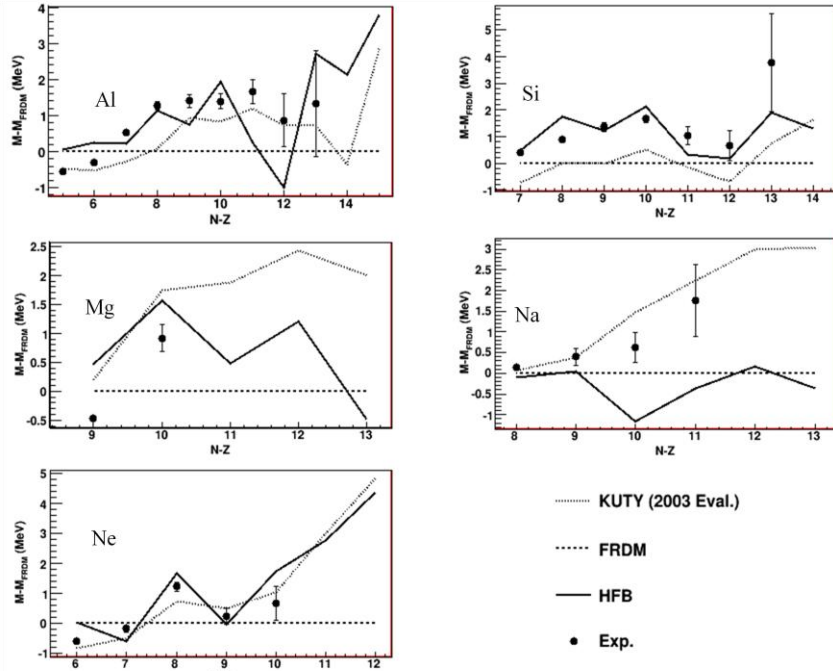
Using the RIBF as a detection device, the time-of-flight (TOF) of a nucleus between two points in the accelerator is related to its mass:

$$\gamma \frac{m}{Q} = \frac{B\rho}{L} t$$

where a nucleus of mass  $m$ , charge  $Q$ , Lorentz factor  $\gamma$ , and rigidity  $B\rho$  takes a time  $t$  to travel a distance  $L$  along the beamline. The travel time for two nuclei, one of well-known mass, can be compared using this technique. It is expected that masses of individual beam particles can be measured to an accuracy of  $\sim 10^{-4}$  with average mass measured to an accuracy of about  $2 \times 10^{-6}$ . The expected lifetime limit for nuclei studied in this experiment is about 445 ns.

The experimental configuration is diagrammed in Figure 7. A beam with a maximum energy of 345 MeV/A will be used on a Be target to produce the very exotic fragments of interest, which will be selected and separated in the BigRIPS fragment separator. Mass measurements will be

conducted by measuring magnetic rigidity and time-of-flight (TOF) of individual particles. The TOF will be measured between the beginning of the tagging section of BigRIPS at F2 and the focal plane of the Zero-Degree-Spectrometer(ZDS) at F11, operated in high-resolution dispersive mode. In this mode, the



**Figure 6 - Mass model calculations for several nuclei along the neutron drip line in the Ne region. Mass is given as a difference from the FRDM mass model. Experimental data is shown by the dots.**

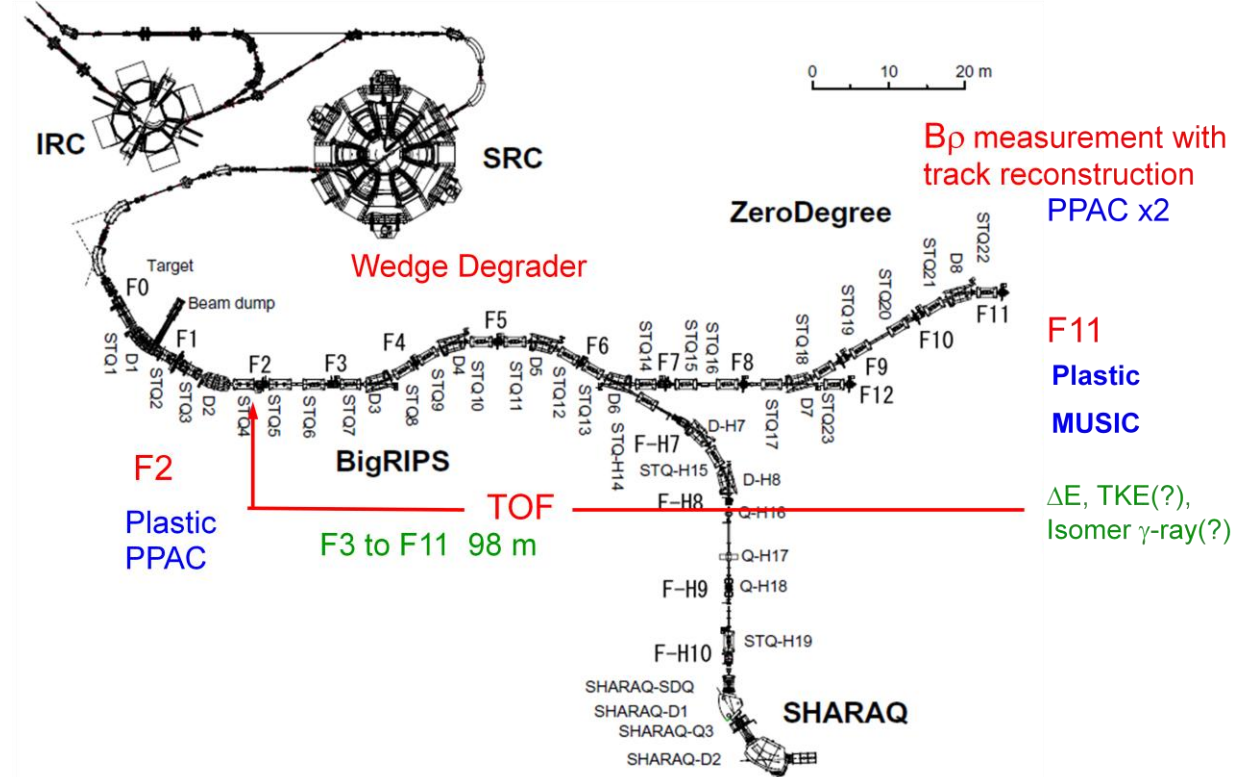
<sup>8</sup> Western Michigan University

<sup>9</sup> RIKEN Nishina Center

<sup>10</sup> Tokyo Institute of Technology

<sup>11</sup> National Superconducting Cyclotron Laboratory

dispersive focal planes of the ZDS located at F11 can provide a high resolution measurement of the magnetic rigidity with a PPAC located at the focal plane (F11). Trajectory measurements using the F2 and F11 focal planes will provide accurate track reconstruction. This mode has been successfully tested at the RIBF facility in May 2007.



**Figure 7 - Experimental layout showing the ZDS and associated beamline detectors.**

Particles can be identified in the ZDS by measuring their TOF and energy deposited in the focal plane using a MUSIC detector. For good energy resolution and particle separation – especially the separation of  $^4\text{He}$  from the beam, a thin achromatic wedge (250 mg/cm<sup>2</sup> of Al) is proposed at the F1 point of the BigRIPS. As the spectrometer focal plane may be rate-limited, narrow slits can be used at F2 prior to the TOF segment to reduce the rate of contaminant particles on the spectrometer focal plane as well as reduce the momentum width of measured particles to reduce aberrations.

The TOF will be measured by using thin plastic scintillators located at F2 in the BigRIPS and F11 in the ZDS. A TOF of about 445 ns is expected for exotic nuclei in the  $^{68}\text{Se}$  region, which was the first approved experimental region to be studied with this technique. The TOF of other studied nuclei is similar. An accurate measurement of the TOF would ideally use thin plastic scintillators (~100 micron) at both locations. A proper choice of equipment (plastic scintillator and fast PMT) can ensure an uncertainty contribution of about 40 ps from each scintillator.

The measured TOF can be corrected for the particle flight path and relative rigidity measurements and path reconstruction of individual particles. This can be done using the focal plane PPAC detectors at F2 in the BigRIPS and at F11 in the ZDS. The PPACs will provide an excellent position measurement of the position for the secondary beam energies provided over micro-channel plates, since the MCP resolution may decrease with energy. For the flight path indicated and the corresponding TOFs, the mass resolution is expected to be dominated by the uncertainty in the TOF  $\sigma T/T \sim 10^{-4}$ . This resolution has been shown in previous mass measurement tests in the ZDS. Also shown was the rigidity resolution of the ZDS, which

was measured to be 0.03%, or roughly equivalent to the TOF resolution. These two will result in a mass resolution of about  $4 \times 10^{-4}$ .

The proposed experiment is a good first experiment with the RIBF, as the setup is simple, requiring only a few beamline instruments and a few common auxiliary detectors. It will also provide an excellent opportunity to gauge the production rate and transmission capabilities of the BigRIPS and Zero-Degree Spectrometer. The risk of failure is low in this experiment, as even a reduction in intensity by nearly an order of magnitude under the predicted intensities of the nuclei of interest will permit mass measurements with an estimated accuracy  $\delta m/m$  of about  $2\text{--}5 \times 10^{-6}$ , which is comparable with previous measurements. The technique can be applied to a region of the table of isotopes and is generally immune to the limitations inherent in trap measurements while sacrificing accuracy.

The current development is in the setup and testing phase. While testing this technique and its feasibility, several new nuclei have also been discovered and the results are currently in press.

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2. *Short-lived Binary Splits of an Excited Projectile-Like Fragment Induced by Transient Deformation*, A. B. McIntosh, S. Hudan, J. Black, D. Mercier, C. J. Metelko, R. Yanez, R. T. de Souza, A. Chbihi, M. Famiano, M. O. Frégeau, J. Gauthier, J. Moisan, R. Roy, S. Bianchin, C. Schwarz, and W. Trautmann, Phys. Rev. C 81, 034603 (2010)
3. *Charge correlations and Isotopic Distributions of Projectile Fragmentation Events in  $^{124}\text{Xe} + ^{112}\text{Sn}$  at  $E/A=50$  MeV*, S. Hudan, A. B. McIntosh, J. Black, D. Mercier, C. J. Metelko, R. Yanez, R. T. de Souza, A. Chbihi, M. Famiano, M. O. Frégeau, J. Gauthier, J. Moisan, R. Roy, S. Bianchin, C. Schwarz, W. Trautmann, and A. S. Botvina. Phys. Rev. C 80, 064611 (2009).
4. *Projectile Fragmentation of Radioactive Beams of  $^{68}\text{Ni}$ ,  $^{69}\text{Cu}$ , and  $^{72}\text{Zn}$* , S. Lukyanov, M. Mocko, L. Andronenko, M. Andronenko, D. Bazin, M. A. Famiano, A. Gade, S. P. Lobastov, W. G. Lynch, A. M. Rogers, O. B. Tarasov, M. B. Tsang, G. Verde, M. S. Wallace, and R. G. T. Zegers, Phys. Rev. C 80, 014609 (2009).
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1. *Development of an Active Target Time Projection Chamber to Study Reactions Induced by Exotic Beams*, NSF Program: Major Research 1 Instrumentation. Amount: \$688,984. PI: Abigail Bickley. Co-PIs: Wolfgang Mittig, Michael Famiano, Umesh Garg. October 1, 2009 - September 30, 2013.
2. *DIANA, A Novel Nuclear Accelerator Lab Underground*, Submitted to NSF Program NSF 05-500, NSF S4 DUSEL Solicitation, Award #0918729. Amount: \$790,701. PI: Michael Wiescher. Co-PIs: Christian Iliadis, Daniela Leitner, Michael Famiano, Arthur Champagne. October 1, 2009 - September 30, 2012.

3. *MRI: Equipment acquisition for WMU accelerator lab upgrade*, Submitted to NSF Program: Major Research Instrumentation. Amount: \$294,044. PI: Asghar Kayani. Co-PIs: Alan Wuosmaa, Michael Famiano, Emanuel Kamber, John Tanis. September 1, 2009 - October 30, 2010.
4. *Expanding the Limits of Known Nuclear Masses Farther from Stability*, Submitted to NSF Program 06-632, NSF Physical Sciences, Award #PHY-0855013. Amount: \$213,062. PI: Michael Famiano. August 15, 2009 - August 12, 2012.
5. *Background Investigations for the DUSEL Project*, APS International Travel Grant Award Program. Amount: \$2,000. Support: International Travel. September 2008 - September 2013.
6. *Characterization of the Density Dependence of the Asymmetry Term of the Nuclear EOS*, Submitted to NSF Program 06-632, NSF Physical Sciences, Award #PHY-0757257. Amount: \$119,365. Support: Travel, Summer Support, and Students. May 2008 - April 2011.

### **INVITED TALKS**

1. *Neutron-Proton Emission Ratios as a Constraint on the Isospin Dependence of the Nuclear EOS*, NuSYM10 Conference, Wako, Japan, July 26 - 28, 2010.
2. *Effects of Excited-State Beta Decays on the Astrophysical  $r$ -Process*, Colloquium, Grand Valley State University, November 30, 2009.
3. *Recent Experimentation to Constrain Isotopic Observables of the Nuclear Equation of State*, International Workshop on Multifragmentation and Related Topics, Catania, Italy, November 4 - 7, 2009.
4. *Experimental Studies of the Nuclear EOS in the Era of FRIB*, Step Forward to FRIB, RIA/FRIB Workshop, Argonne National Laboratory, May 30 - 31, 2009.

### **CONTRIBUTED TALKS**

1. *Experimental Applications of the Nuclear Equation-of-State to Neutron Star Dynamics*, 11th Symposium on Nuclei in the Cosmos (NIC XI), July 19 - 23, 2010, Heidelberg, Germany.
2. *Experimental Investigations of the Asymmetry Term of the Nuclear Equation-of-State at Densities Exceeding Saturation Density*, ASY-EOS Workshop on Nuclear Symmetry Energy at Medium Energies, May 21 - 24, 2010, Noto, Italy.
3. *Large Area Neutron Array*, FRIB Equipment Workshop, East Lansing, MI, February 20 - 22, 2010.

4. *Laser Calibration System for the Active Target TPC*, NSCL User Workshop, East Lansing, MI, August 10 - 11, 2009.

### **SCHOLARLY ACTIVITIES**

1. [NSCL Users' Executive Committee](#). November 1, 2009 - October 31, 2012.
2. Departmental Colloquium Committee chair. September 2006 – May 2010.
3. [Michitoshi Soga Japan Center](#) Faculty Advisory Committee. May 2007 - Present.
4. Faculty Senator substitute for Charles Henderson September 2009 – May 2010.
5. Peer reviewer for the Department of Energy, reviewed five proposals between September 2008 and May 2010.
6. Peer reviewer for *Proceedings of Science*.

## 6.2 Dean Halderson

### **PUBLICATIONS**

1. **J. Grineviciute** and **D. Halderson**, *Dirac Oscillators and the Relativistic R-matrix*, Phys. Rev. C **80**, 044607 (2009).

### **INVITED TALKS**

1. **D. Halderson**, *Test of the Nijmegen Baryon Baryon Potential*, Nuclear Theory Seminar, Argonne National Laboratory, Sept. 24, 2009.

### **CONTRIBUTED TALKS**

1. **D. Halderson**, *The  $p$ -shell  $\Lambda$ -hypernuclear with the Nijmegen ESC04 baryon-baryon potential*, 2008. Midwest Nuclear Theory Get-together, Oct. 17-18.

### **GRANTS**

1. **D. Halderson**, National Science Foundation Grant, 2005-2009, \$26,820.
2. **D. Halderson**, National Science Foundation Grant, 2009-2012, \$24,420.

## 6.3 Alan Wuosmaa

### HELIOS: The HELIcal Orbit Spectrometer

A. H. Wuosmaa, J. C. Lighthall, B. B. Back, S. I. Baker, S. J. Freeman, H. Y. Lee, B. P. Kay, S. T. Marley, K. E. Rehm, J. E. Rohrer, J. P. Schiffer, D. V. Shetty, A. W. Vann, J. R. Winkelbauer

**A. H. Wuosmaa**<sup>1</sup>, B. B. Back<sup>2</sup>, **J. P. Lighthall**<sup>1</sup>, C. J. Lister<sup>2</sup>, **S. T. Marley**<sup>1</sup>, R. C. Pardo<sup>2</sup>, K. E. Rehm<sup>2</sup>, J. P. Schiffer<sup>2</sup>, **J. Winkelbauer**, S. J. Freeman<sup>3</sup>

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<sup>3</sup>Schuster Laboratory, University of Manchester.

The HELIOS device is a novel new spectrometer, based on a large-volume high-field magnetic solenoid, designed to study nucleon transfer and other reactions in inverse kinematics. A detailed technical description of the device and its expected capabilities are contained in Ref. [1]. HELIOS plays a prominent role in the future Strategic Plan for the ATLAS facility, as it is well matched to the ongoing CARIBU radioactive beam source development project.

Over the past 18 months, major progress has been made in the HELIOS project, and the spectrometer is complete in its prototype form. The magnetic solenoid, obtained from the Max Planck Institute in Tübingen, Germany, is installed at the ATLAS facility at Argonne National Laboratory. The field of the HELIOS magnet was mapped by WMU students Jack Winkelbauer and Jonathon Lighthall (see Fig. 1) who constructed a custom Hall-probe assembly and measured the field at 21,240 points inside, and outside the vessel. The mechanical elements that transform the bore of the magnet into an evacuated reaction chamber are complete and installed. Figure 2 shows a photograph of the completed spectrometer. Researchers from WMU have been involved at all stages of the development and construction of HELIOS, and one of the main contributions from WMU is the array of position-sensitive silicon detectors that is at the heart of the spectrometer. Figure 3 shows the assembled silicon-detector array installed in the HELIOS vessel.

The device has now been commissioned using stable, and unstable beams (see below). Since the initial commissioning of the device done in August 2008, experiments have been carried out studying ( $d,p$ ) reactions on a variety of nuclei, both stable and unstable, with masses ranging from 11 to 136. The results have demonstrated that the device functions as anticipated and provides the significant gains in excitation-energy resolution that were anticipated from simulations of the performance of the device.

[1] A. H. Wuosmaa *et al.*, Nucl. Instr. and Meth. in Phys. Res. A **580**, 1290 (2007).



Figure 1. Western Michigan University students Jonathon Lighthall (left) and Jack Winkelbauer (right) mapping the field of the HELIOS magnet.

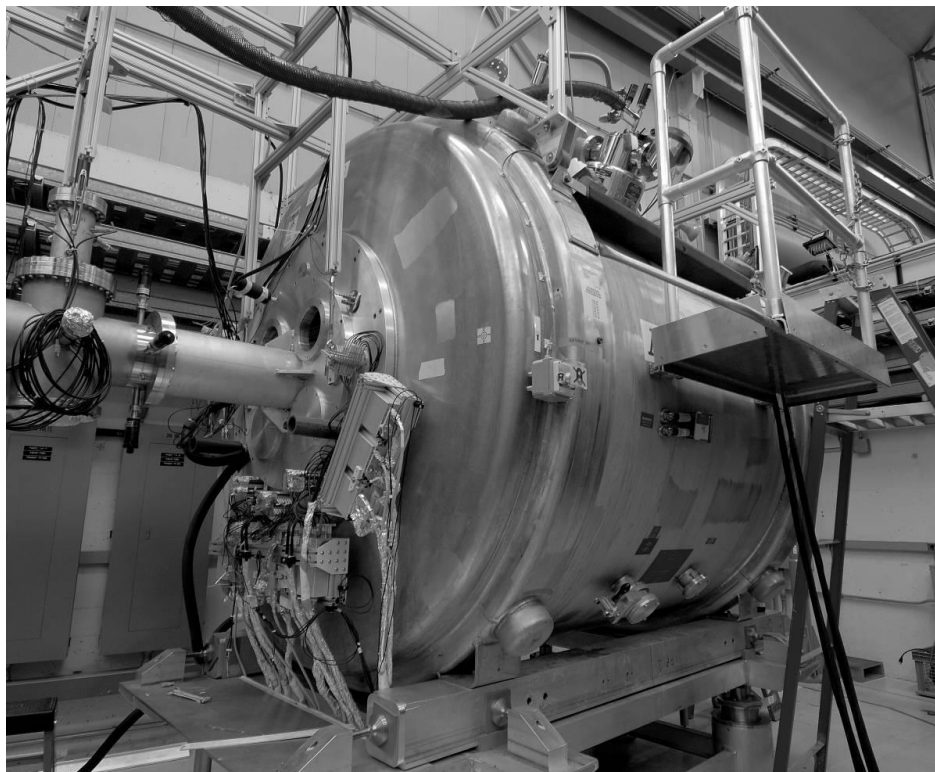


Figure 2. Completed HELIOS spectrometer at the ATLAS facility at Argonne National Laboratory

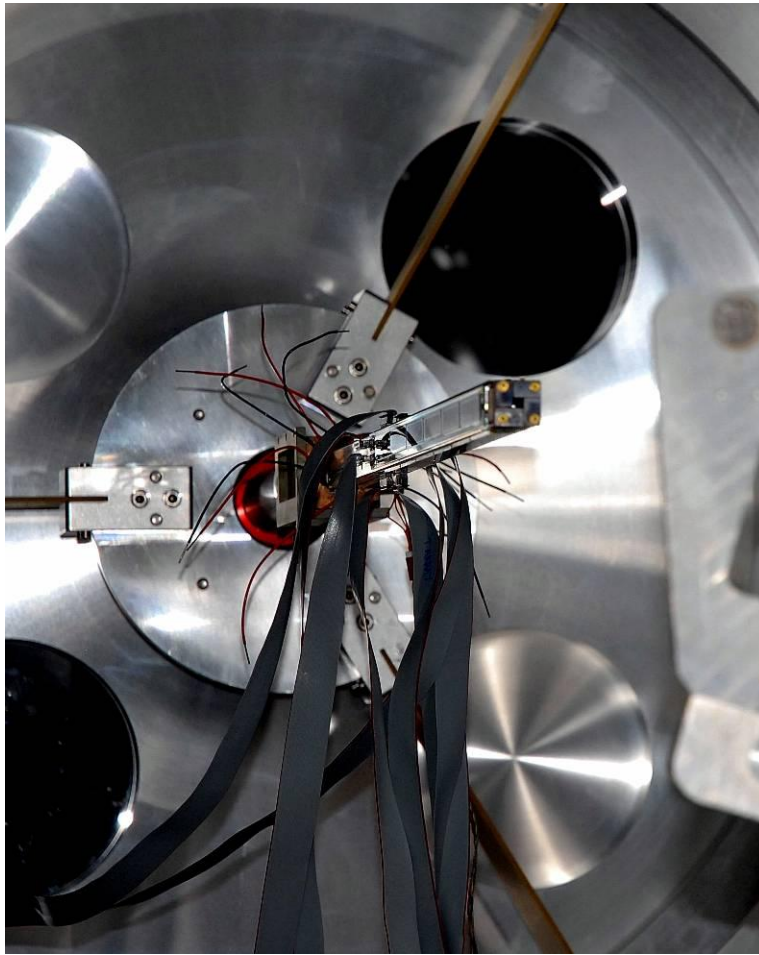


Figure 3. Silicon-detector array installed in HELIOS chamber.

## Commissioning of HELIOS with the $^{28}\text{Si}(d,p)^{29}\text{Si}$ reaction

**J. C. Lighthall**<sup>1,2</sup>, **A. H. Wuosmaa**<sup>1</sup>, B. B. Back<sup>2</sup>, S. I. Baker<sup>2</sup>, S. J. Freeman<sup>3</sup>, H. Y. Lee<sup>2</sup>, B. P. Kay<sup>2</sup>, **S. T. Marley**<sup>1,2</sup>, K. E. Rehm<sup>2</sup>, J. E. Rohrer<sup>2</sup>, J. P. Schiffer<sup>2</sup>, **D. V. Shetty**<sup>1</sup>, A. W. Vann<sup>2</sup>, **J. R. Winkelbauer**<sup>1</sup>

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<sup>3</sup>Schuster Laboratory, University of Manchester

The initial commissioning of the HELical Orbit Spectrometer (HELIOS) at the ATLAS facility at Argonne National Laboratory has been completed. The first commissioning experiment was the measurement of the  $^{28}\text{Si}(d,p)^{29}\text{Si}$  reaction in inverse kinematics. This reaction has been studied previously [1] and many states in  $^{29}\text{Si}$  are strongly populated. The measurement was carried out using a  $^{28}\text{Si}$  beam at a bombarding energy of 6 MeV/u, produced by the ATLAS accelerator at Argonne National Laboratory. The beam bombarded an 80  $\mu\text{g}/\text{cm}^2$  deuterated polyethylene ( $\text{CD}_2$ ) target. Protons from the  $^{28}\text{Si}(d,p)^{29}\text{Si}$  reaction were detected in the HELIOS silicon-detector array and identified by their flight time in the spectrometer, which is equal to their cyclotron period.

Figure 1 shows the dependence of the laboratory proton energy on distance from the target. Kinematic groups corresponding to different excited states in  $^{29}\text{Si}$  are observed as diagonal lines in Fig. 1 as expected from simulations of the HELIOS response. The top line is the group produced by the ground-state transition, and a total of 10 states in  $^{29}\text{Si}$  are observed. The continuous background arises from protons produced by fusion-evaporation reactions on  $^{12}\text{C}$  in the target, which have an identical flight time to those from the  $(d,p)$  reaction, as well as residual activity from a  $^{228}\text{Th}$  calibration source (horizontal lines in Figure 1). Figure 2 shows a spectrum of  $^{29}\text{Si}$  excitation energy derived from those data. The observed excitation energy, including all events from all silicon detectors is 120 keV FWHM, although the best resolution obtained from the best performing silicon detectors was 80 keV FWHM. This resolution is only slightly worse than that reported by Mermaz et al in a study of this reaction in “normal” kinematics, with a deuteron beam incident on a  $^{28}\text{Si}$  target [1]. This resolution demonstrates that the anticipated gains in excitation-energy resolution from HELIOS for reactions in inverse kinematics are achieved. Figure 3 illustrates angular distributions for the ground and first-excited states in  $^{29}\text{Si}$ . A manuscript describing this commissioning experiment has been submitted to Nuclear Instruments and Methods in Physics Research A.

[1] M. C. Mermaz, C. A. Whitten, J. W. Champlin, A. J. Howard, and D. A. Bromley, Phys. Rev. C **4**, 1778 (1971).

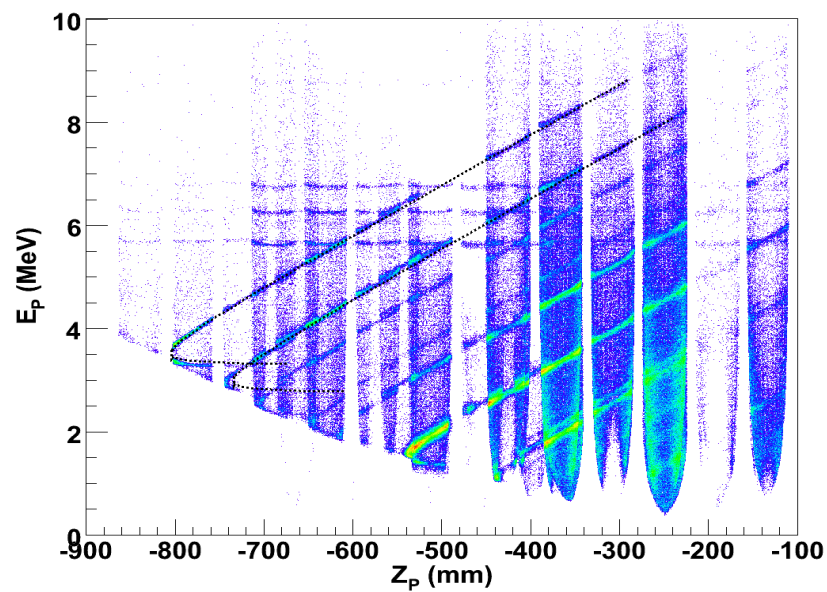


Figure 1. Energy-position correlation spectrum for protons from  $^{28}\text{Si}+\text{CD}_2$  events in HELIOS.

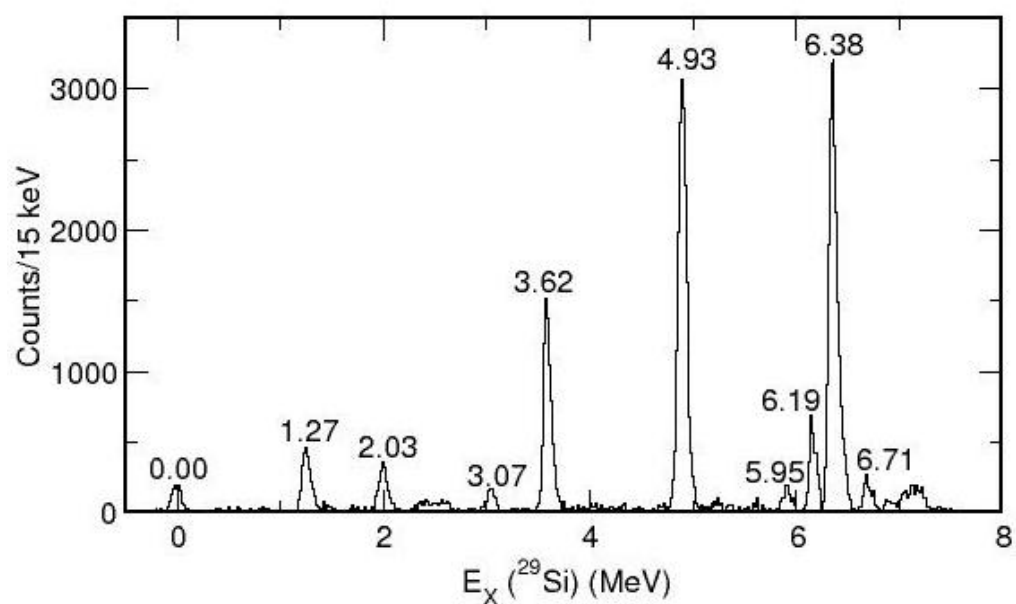


Figure 2.  $^{29}\text{Si}$  Excitation-energy spectrum from the  $^{28}\text{Si}(d,p)^{29}\text{Si}$  reaction in inverse kinematics measured with HELIOS.

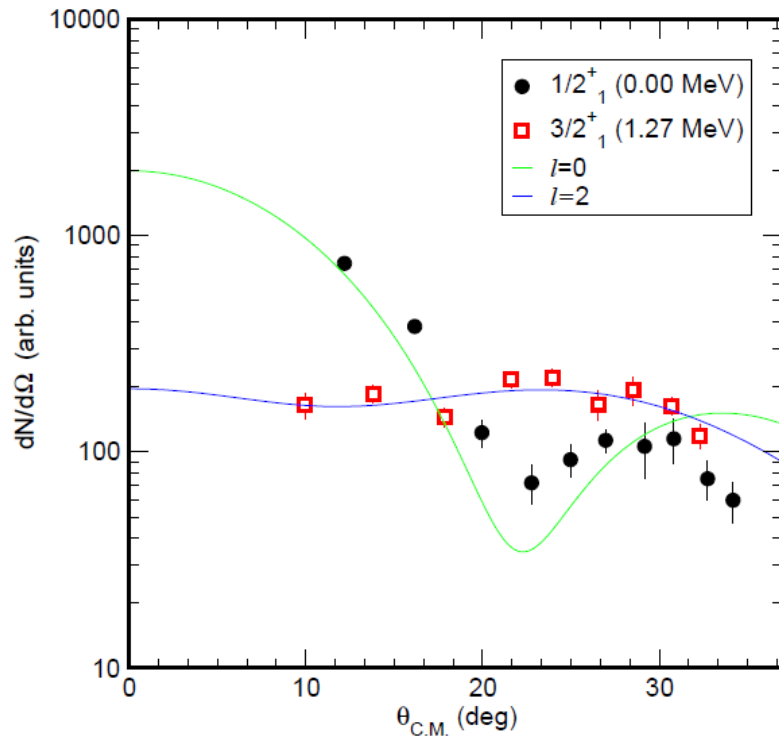


Figure 3. Angular distributions for the ground-state and first-excited-state transitions in the  $^{28}\text{Si}(d,p)^{29}\text{Si}$  reaction measured with HELIOS.

## Radioactive-beam commissioning of HELIOS with the $^{12}\text{B}(d,p)^{13}\text{B}$ reaction

A. H. Wuosmaa<sup>1</sup>, B. B. Back<sup>2</sup>, S. I. Baker<sup>2</sup>, C. M. Deibel<sup>2</sup>, S. J. Freeman<sup>3</sup>, B. J. DiGiovine<sup>2</sup>, C. R. Hoffman<sup>2</sup>, B. P. Kay<sup>2</sup>, H. Y. Lee<sup>2</sup>, J. C. Lighthall<sup>1,2</sup>, S. T. Marley<sup>1,2</sup>, R. C. Pardo<sup>2</sup>, K. E. Rehm<sup>2</sup>, J. P. Schiffer<sup>2</sup>, D. V. Shetty<sup>1</sup>, A. W. Vann<sup>2</sup>, J. R. Winkelbauer<sup>1</sup>

<sup>1</sup>Western Michigan University, Kalamazoo MI, 49008-5252

<sup>2</sup>Argonne National Laboratory, Argonne IL, 60439

<sup>3</sup>Schuster Laboratory, University of Manchester

The first commissioning of HELIOS with radioactive beams produced using the in-flight production method was carried out using the  $^{12}\text{B}(d,p)^{13}\text{B}$  reaction in inverse kinematics with a  $^{12}\text{B}$  beam ( $T_{1/2}=20.2$  ms). Due to the necessity of transporting the beam through the long silicon detector array, the concern existed that it might not be possible to obtain good transmission for unstable beams with emittance properties that were poorer than those of stable beams. The  $^{12}\text{B}$  was produced via the  $^{11}\text{B}(d,p)^{12}\text{B}$  reaction at an energy of 6.25 MeV/u. Previously, at other target stations intensities of  $10^5$  particles per second had been achieved, and in this experiment the observed intensity was  $6 \times 10^5$  particles per second on target, alleviating any concerns about transmission efficiency.

The  $^{12}\text{B}(d,p)^{13}\text{B}$  reaction was chosen due the interest in determining the spins and parities of two closely spaced positive-parity levels in  $^{13}\text{B}$  ( $E_X=3.48$  and 3.68 MeV). The  $N=8$   $^{13}\text{B}$  nucleus bridges a region of  $N=8$  isotopes between  $^{14}\text{C}$ , where the single-particle orbitals follow the following the familiar ordering of stable nuclei, and  $^{12}\text{Be}$ , where the  $s$ -wave rather than  $d$ -wave neutrons dominate the ground-state wave function. A previous measurement of this reaction at ATLAS using a conventional setup of segmented silicon detectors had resolution that was insufficient to separate the two states. It was hoped that HELIOS could provide the necessary resolution to make that separation.

Figure 1 shows the excitation-energy spectra from the  $^{12}\text{B}(d,p)^{13}\text{B}$  reaction measured with HELIOS for two different center-of-mass angle ranges:  $\theta_{c.m.}=6^\circ\text{-}29^\circ$  (a) and  $16^\circ\text{-}29^\circ$  (b). The two peaks are clearly separated and the strong enhancement of the yield for the 3.48 MeV state at smaller center-of-mass angles clearly favors an angular-momentum transfer of  $l=0$  for this transition, supporting a spin assignment of  $J^\pi=1/2^+$  for this state. These results confirm that HELIOS can deliver the performance necessary to study reactions in inverse kinematics with unstable, as well as stable, beams. A manuscript describing these results has been submitted to Physical Review Letters.

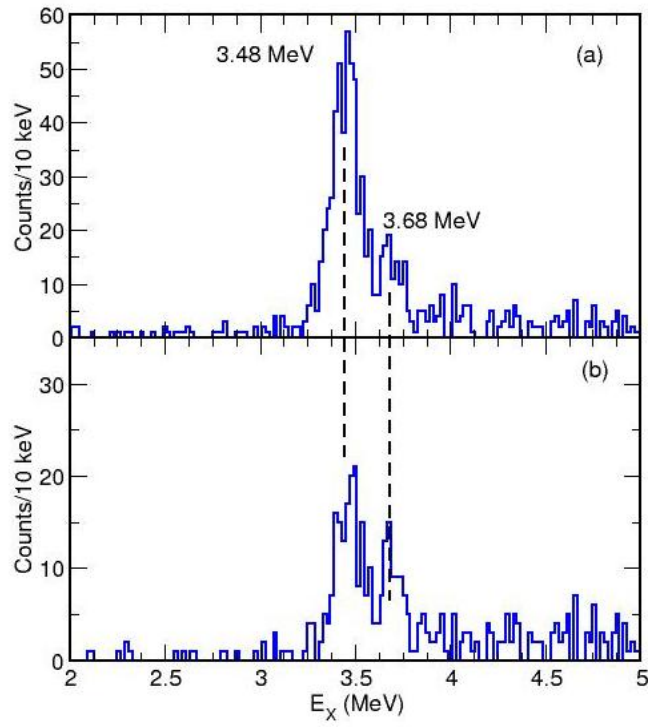


Figure 1. Excitation-energy spectra for the  $^{12}\text{B}(d,p)^{13}\text{B}$  reaction measured with HELIOS.

## Possible exotic behavior in $^{16}\text{C}$ and the $^{15}\text{C}(d,p)^{16}\text{C}$ reaction

A. H. Wuosmaa<sup>1</sup>, B. B. Back<sup>2</sup>, C. M. Deibel<sup>2,3</sup>, P. Fallon<sup>4</sup>, C. R. Hoffman<sup>2</sup>, B. P. Kay<sup>2</sup>, H. Y. Lee<sup>5</sup>, J. C. Lighthall<sup>1,2</sup>, A. O. Macchiavelli<sup>4</sup>, S. T. Marley<sup>1,2</sup>, R. C. Pardo<sup>2</sup>, K. E. Rehm<sup>2</sup>, J. P. Schiffer<sup>2</sup>, D. Shetty<sup>1</sup>, M. Wiedeking<sup>6</sup>

<sup>1</sup>Department of Physics, Western Michigan University, Kalamazoo MI, 49008 USA

<sup>2</sup>Physics Division, Argonne National Laboratory, Argonne IL 60439 USA

<sup>3</sup>Joint Institute for Nuclear Astrophysics, Notre Dame IN 46656 USA

<sup>4</sup>Lawrence Berkeley National Laboratory, Berkeley CA 94720 USA

<sup>5</sup>LANSCÉ-NS, Los Alamos National Laboratory, Los Alamos NM 87545 USA

<sup>6</sup>Lawrence Livermore National Laboratory, Livermore, CA 94550

Recent measurements [1,2] of the lifetime for the  $2^+_1$  to  $0^+_1$  gamma-ray transition in  $^{16}\text{C}$  have suggested exotic behavior in this nucleus. The  $B(E2)$  for this transition was observed to be considerably smaller than that in other neighboring comparable nuclei, suggesting an unusual decoupling of neutron and proton motion in this nucleus. Other measurements [3], however, report a value more in line with expectations derived from nuclei nearer stability. To provide more information for states in  $^{16}\text{C}$  and the interactions between the  $sd$ -shell neutrons, we have studied the neutron-stripping reaction  $^{15}\text{C}(d,p)^{16}\text{C}$  in inverse kinematics, using HELIOS. Angular distributions were measured for several final states in  $^{16}\text{C}$ , and the data compared to the results of Distorted Wave Born Approximation calculations in order to extract the relative neutron-transfer spectroscopic factors. Those spectroscopic factors can be compared with those obtained from previous studies of two-neutron interactions in the  $sd$  shell, as well as the predictions of shell-model calculations. These data can also provide information about the matrix elements for two  $sd$ -shell neutrons outside the closed  $N=8$  core. The analysis of the data is still in progress, however preliminary results indicate that the spectroscopic factors for neutron transfer are in good agreement with the predictions of shell-model calculations using a residual two neutron interaction derived from fits to many nuclei near stability. This agreement would call into question the interpretation of  $^{16}\text{C}$  as being a very exotic nucleus, and instead suggests that the observed behavior is in line with expectations based on well established physics.

[1] N. Imai et al., Phys. Rev. Lett. **92**, 062501 (2004).

[2] H. J. Ong et al., Phys. Rev. C **73**, 024610 (2006).

[3] M. Wiedeking et al., Phys. Rev. Lett. **100**, 152501 (2008).

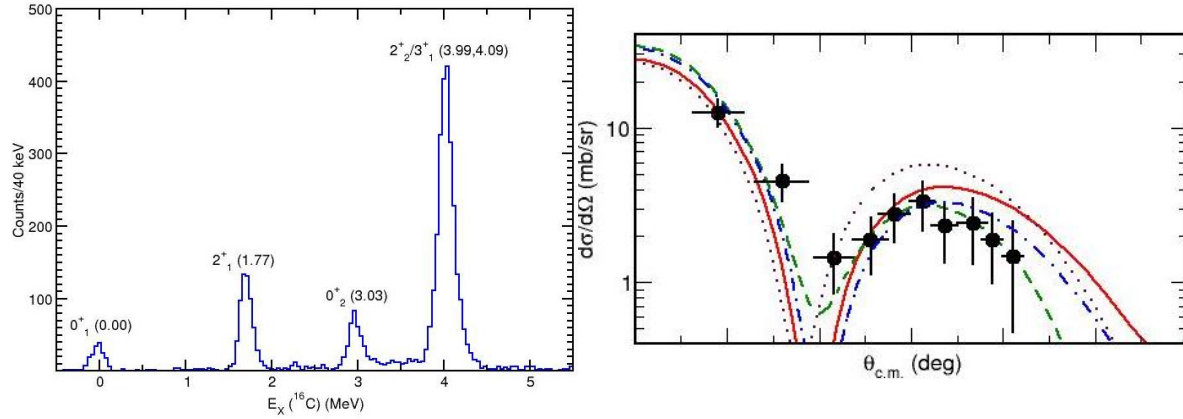


Figure 1: Excitation-energy spectrum (left) and ground-state angular distribution (right) for the  $^{15}\text{C}(d,p)^{16}\text{C}$  reaction.

## DISERTATIONS

### **M.A.**

Nicholas Goodman, August 2009.

## PUBLICATIONS

1. **Continuum spectroscopy with a  $^{10}\text{C}$  beam: Cluster structure and three-body decay**, R. J. Charity, T. D. Wiser, K. Mercurio, R. Shane, L. G. Sobotka, **A. H. Wuosmaa**, A. Banu, L. Trache, R. E. Tribble, Phys. Rev. C **80**, 024306 (2009).
2. **Complete correlation studies of two-proton decays:  $^6\text{Be}$  and  $^{45}\text{Fe}$** , L. V. Grigorenko, T. D. Wiser, K. Miernik, R. J. Charity, M. Pfutzner, A. Banu, C. R. Bingham, M. Wiok, I. G. Darby, W. Dominik, J. M. Elson, T. Ginter, R. Grzywacz, Z. Janas, M. Karny, A. Korgul, S. N. Liddick, K. Mercurio, M. Rajabali, K. Rykaczewski, R. Shane, L. G. Sobotka, A. Stolz, L. Trache, R. E. Tribble, **A. H. Wuosmaa**, M. V. Zhukov, Phys. Lett. **B677**, 30 (2009).
3. **Three-body decay of  $^6\text{Be}$** , L. V. Grigorenko, T. D. Wiser, K. Mercurio, R. J. Charity, R. Shane, L. G. Sobotka, J. M. Elson, **A. H. Wuosmaa**, A. Banu, M. McCleskey, L. Trache, R. E. Tribble, M. V. Zhukov, Phys. Rev. C **80**, 034602 (2009).
4. **Experimental study of the  $^{56}\text{Ni}(^3\text{He}, d)^{57}\text{Cu}$  reaction in inverse kinematics**, C. L. Jiang, K. E. Rehm, D. Ackermann, I. Ahmad, J. P. Greene, B. Harss, D. Henderson, W. F. Henning, R. V. F. Janssens, J. Nolen, R. C. Pardo, P. Reiter, J. P. Schiffer, D. Seweryniak, A. Sonzogni, J. Uusitalo, I. Wiedenhover, **A. H. Wuosmaa**, F. Brumwell, G. McMichael, M. Paul, R. E. Segel, Phys. Rev. C **80**, 044613 (2009).

5. **Investigation of particle-unbound excited states in light nuclei with resonance-decay spectroscopy using a  $^{12}\text{Be}$  beam**, R. J. Charity, S. A. Komarov, L. G. Sobotka, J. Clifford, D. Bazin, A. Gade, J. Lee, S. M. Lukyanov, W. G. Lynch, M. Mocko, S. P. Lobastov, A. M. Rogers, A. Sanetullaev, M. B. Tsang, M. S. Wallace, R. G. T. Zegers, S. Hudan, C. Metelko, **M. A. Famiano, A. H. Wuosmaa**, M. J. van Goethem, Phys. Rev. C **78**, 054307 (2008).
6. **Heavy ion radiative capture of  $^{12}\text{C} + ^{12}\text{C}$** , P. L. Marley, D. G. Jenkins, N. S. Pattabiraman, A. P. Robinson, R. Wadsworth, S. Courtin, F. Haas, D. Lebhertz, C. J. Lister, M. Carpenter, S. Zhu, D. Seweryniak, **A. Wuosmaa, J. Lighthall**, D. O'Donnell, Int.J.Mod.Phys. **E17**, 2040 (2008).
7. **Correlated two-proton decay from  $^{10}\text{C}$** , K. Mercurio, R. J. Charity, R. Shane, L. G. Sobotka, J. M. Elson, M. Famiano, **A. H. Wuosmaa**, A. Banu, C. Fu, L. Trache, R. E. Tribble, A. M. Mukhamedzhanov, Phys. Rev. C **78**, 031602 (2008).
8. **Structure of  $^7\text{He}$  by proton removal from  $^8\text{Li}$  with the (d,  $^3\text{He}$ ) reaction**, **A. H. Wuosmaa**, J. P. Schiffer, K. E. Rehm, J. P. Greene, D. J. Henderson, R. V. F. Janssens, C. L. Jiang, L. Jisonna, **J. C. Lighthall, S. T. Marley**, E. F. Moore, R. C. Pardo, N. Patel, M. Paul, D. Peterson, S. C. Pieper, G. Savard, R. E. Segel, R. H. Siemssen, X. D. Tang, R. B. Wiringa, Phys. Rev. C **78**, 041302 (2008).
9. **The Structure of  $^7\text{He}$**  **A. H. Wuosmaa**, K. E. Rehm, J. P. Greene, D. J. Henderson, R. V. F. Janssens, C. L. Jiang, L. Jisonna, **J. C. Lighthall, S. T. Marley**, E. F. Moore, R. C. Pardo, N. Patel, M. Paul, D. Peterson, S. C. Pieper, G. Savard, J. P. Schiffer, R. E. Segel, R. H. Siemssen, X. Tang, R. B. Wiringa, Proc. Frontiers in Nuclear Structure, and Reactions (FINUSTAR 2), Crete, Greece, 10-14 Sept. 2007, P. Demetriou, R. Julin, S. V. Harissopulos, Eds. p.225 (2008); AIP Conf. Proc 1012 (2008).
10. **A high efficiency, low background detector for measuring pair-decay branches in nuclear decay**, C. Tur, **A. H. Wuosmaa**, S. M. Austin, K. Starosta, J. Yurkon, A. Estrade, **N. Goodman, J. C. Lighthall**, G. Lorusso, **S. T. Marley, J. Snyder**, Nuclear Instruments and Methods in Physics Research Section **A594**, 66 (2008).

## GRANTS

1. **Study of exotic light nuclei with few nucleon transfer reactions**  
 Department of Energy Office of Nuclear Physics,  
 \$440,000 over three years  
 Amount awarded during the report period: \$145,000  
 A. H. Wuosmaa, Principal Investigator  
 Awarded; Active

2. **MRI: Equipment acquisition for WMU accelerator lab upgrade**  
National Science Foundation,  
\$294,044  
Asghar N. Kayani, Principal Investigator  
Alan H. Wuosmaa, Emanuel Y. Kamber, John A. Tanis, Michael A. Famiano, Co-Investigators.  
Awarded; Active

### **INVITED TALKS**

1. Department colloquium: “Transfer reactions with exotic beams” Department of Physics, Western Michigan University, January 2009.
2. Invited seminar: “HELIOS at ATLAS: A novel new spectrometer for inverse-kinematic reactions” Physics Division, Los Alamos National Laboratory, May 2009.
3. **Commissioning Experiments for the HELIOS Spectrometer, A. H. Wuosmaa** The 8<sup>th</sup> International Conference on Radioactive Nuclear Beams (RNB8). Grand Rapids MI, May 2009.
4. **Convener, Session on Reaction Physics with Radioactive Beams**, Facility for Rare Isotope Beams (FRIB) User Meeting, May, 2009.
5. **New Results From the HELIOS Spectrometer. A. H. Wuosmaa**, Gordon Research Conference, June 2009, Colby Sawyer College New London NH.

### **CONTRIBUTED TALKS**

1. **Commissioning of the HELIOS Spectrometer at ATLAS**  
**J. C. Lighthall** for the HELIOS collaboration. Division of Nuclear Physics meeting of the American Physical Society, Oakland, CA, October 2008.
2. **Status of the HELIOS Spectrometer at ATLAS**  
**A. H. Wuosmaa**, for the HELIOS collaboration. Division of Nuclear Physics meeting of the American Physical Society, Oakland, CA, October 2008.
3. **The HELIOS silicon detector array**  
**S.T. Marley** for the HELIOS collaboration. Division of Nuclear Physics meeting of the American Physical Society, Oakland, CA, October 2008.

4. **A Study of the  $^{30}\text{S}(\alpha, p)^{33}\text{Cl}$  Reaction Rate**  
C. M. Deibel, C. L. Jiang, B. P. Kay, H. Y. Lee, R.C. Pardo, K. E. Rehm, C. Ugalde, A. Woodward, J. M. Figueira, **S. T. Marley**, N. R. Patel, M. Paul, **A. H. Wuosmaa**. 3<sup>rd</sup> Joint meeting of the American Physical Society Division of Nuclear Physics and the Physical Society of Japan, Waikaloa, HA, October 2009.
5. **Study of the  $^{12}\text{B}(\text{d}, \text{p})^{13}\text{B}$  reaction with the HELIOS spectrometer**  
**A. H. Wuosmaa**, for the HELIOS collaboration. 3<sup>rd</sup> Joint meeting of the American Physical Society Division of Nuclear Physics and the Physical Society of Japan, Waikaloa, HA, October 2009.

# 7 PHYSICS EDUCATION

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## 7.1 Charles Henderson

### **PUBLICATIONS**

#### a. Published Journal Articles or Book Chapters

1. Henderson, C., & Beichner, R. (2009). Publishing PER Articles in AJP and PRST-PER. *American Journal of Physics*, 77 (7), 581-582.
2. Henderson, C., Beach, A., & Famiano, M. (2009). Promoting Instructional Change via Co-Teaching. *American Journal of Physics (Physics Education Research Section)*, 77 (3), 274-283.
3. Froyd, J., Beach, A., Henderson, C., & Finkelstein, N. (2008). Improving Educational Change Agents' Efficacy in Science, Engineering, and Mathematics Education. In H. Hartman (ed.), *Integrating the Sciences and Society: Challenges, Practices, and Potentials*, Bingley, UK: JAI Press, pp. 227-256.
4. Fynnewever, H., Henderson, C., Barry, S., Erwin, S., Hanson, S., Lindow, M., Huber, M., & Mirakovits, K. (2008) Honing Teachers' Behind The Scenes Work: Pragmatic Ideas From Best Practices, *MSTA Journal*, 53 (2), 2-7.
5. Henderson, C. & Dancy, M. (2009). The Impact of Physics Education Research on the Teaching of Introductory Quantitative Physics in the United States, *Physical Review Special Topics: Physics Education Research*, 5 (2), 020107.
6. Henderson, C. & Harper, K. A. (2009). Quiz corrections: Improving learning by encouraging students to reflect on their mistakes. *The Physics Teacher*, 47 (9), 581-586.

#### b. Other Published Articles

1. Henderson, C., & Dancy, M. (2009) Article Summary: Physics Faculty and Educational Researchers: Divergent Expectations as Barriers to the Diffusion of Innovations. *Annals of Research on Engineering Education*, 4 (2)
2. Henderson, C. & Dancy, M. (2009). Physics Faculty and Educational Researchers: Partners in Reform. *American Physical Society Forum on Education Newsletter*, Spring 2009, 13-14.

3. Dancy, M. & Henderson, C. (2008, October) Barriers and Promises in STEM Reform, *Commissioned Paper for National Academies of Science Workshop on Linking Evidence and Promising Practices in STEM Undergraduate Education*, Washington, DC, Oct 13-14, 2008.
  4. Henderson, C., Beach, A. Finkelstein, N., & Larson R. S. (2008) “Facilitating Change in Undergraduate STEM: Initial Results from an Interdisciplinary Literature Review”, *Proceedings of the 2008 Physics Education Research Conference*, AIP Conference Proceedings Volume 1064, p. 131-134.
  5. Beach, A. L., Henderson, C., Larson, R. S., & Finkelstein, N. (2008) Facilitating Change in Undergraduate Science Instruction: Synthesis of Change Strategies across Disciplines. *Research paper presented at the Association for the Study of Higher Education (ASHE) Annual Conference*, Jacksonville, FL, November 5-8, 2008.
  6. Henderson, C., & Dancy, M. (2009) The Impact of Physics Education Research on the Teaching of Introductory Quantitative Physics, *Proceedings of the 2009 Physics Education Research Conference* (Ann Arbor, MI).
  7. Dancy, M, & Henderson, C. (2009) Pedagogical Practices of Physics Faculty in the USA, *Proceedings of the 2009 Physics Education Research Conference* (Ann Arbor, MI).
- c. Published Book
1. Henderson, C. (2009) Faculty Conceptions of the Teaching and Learning of Problem Solving: An Examination of Six Research University Physics Faculty, LAP Lambert Academic Publishing: Köln, Germany.
- d. Accepted Journal Articles
1. Henderson, C., Finkelstein, N. & Beach A. (accepted). Beyond Dissemination in College science teaching: An Introduction to Four Core Change Strategies. Submitted May 2009 to *Journal of College Science Teaching*.
  2. Dancy, M. & Henderson, C. (accepted) Pedagogical Practices and Instructional Change of Physics Faculty, submitted October 2009 to *American Journal of Physics*, *Physics (Physics Education Research Section)*.

## **GRANTS**

1. PI (with H. Fynewever & H. Petcovic, co-PIs) “Identifying the Impacts of ATE Centers on Their Home Institutions: An Exploratory Study”, Subaward from University of Colorado-Boulder under NSF # 0832874, \$98,237 awarded for the period 10/1/08 to 8/31/10.

2. Co-PI (with H. Fynnewever, PI, and H. Petcovic, co-PI) “Alignment of Secondary Science Teacher Practice and Materials in the Battle Creek Region”, Michigan Department of Education, \$215,682 awarded for the period 11/1/07 to 7/31/09.
3. PI (with M. Dancy, co-PI), “Understanding Instructor Practices and Attitudes Towards the Use of Research-Based Instructional Strategies In Introductory College Physics”, NSF #0715698, \$331,143 awarded for the period 1/1/08 to 12/31/10.
4. PI (with A. Beach, N. Finkelstein, R. S. Larson, co-PIs), “Facilitating Change in Higher Education: A Multidisciplinary Effort to Bridge the Individual Actor and System Perspectives”, NSF #0623009, Awarded \$97,011 for the period 1/1/07 to 12/31/09.
5. Co-PI (with A. Beach, PI, and N. Finkelstein, co-PI), “STEM Educational Change Efforts in Higher Education: A Meta-Synthesis of Activities, Strategies, Concepts, and Theories across Disciplines”, NSF #0723699, \$198,379 awarded for the period 9/15/07 to 9/14/10.

### **INVITED TALKS**

1. Henderson, C. “The Study and Improvement of STEM Change Strategies,” invited presentation, Ohio Physical Science and Chemistry Modeling Instruction Workshops, Columbus, OH, June 25, 2009.
2. Finkelstein, N., Henderson, C., & Beach, A. “Examining Colorado's Approach to Sustaining and Scaling Educational Reform: Opportunities for Montana,” keynote address to the State-wide initiative, Montana Math and Science Teacher Initiative, Steering Committee Meeting, May 1, 2009, Helena Montana.
3. Henderson, C., Beach, A., & Finkelstein, N. “Facilitating Change in Undergraduate STEM: The Need to Problematize and Improve Our Approaches to Change,” invited workshop, PTEC Annual Meeting, Pittsburgh, PA, Mar 13, 2009.
4. Henderson, C. “The Study and Improvement of STEM Change Strategies,” invited presentation, Physics Education Research Colloquium, University of IL, Champaign-Urbana, IL, Mar 5, 2009.
5. Henderson, C., Beach, A., Finkelstein, N. & R. S. Larson “An Overview of the Four Core Categories of Change Strategies for Reforming STEM Instruction,” invited talk, AAPT/AAAS Winter Meeting, Chicago, IL, Feb 14, 2009.
6. Beach, A., Henderson, C., & Finkelstein, N. “Facilitating Change in Undergraduate STEM Instruction: Synthesis of Change Strategies across Disciplines,” poster presentation, NSF-REESE PI Meeting, Washington, DC, Feb 18-19, 2009.

7. Henderson, C. "The Study and Improvement of STEM Change Strategies," invited presentation, Center for Excellence in Science, Math, and Engineering Education Seminar Series, Iowa State University.
8. Dancy, M. & Henderson, C. "Barriers and Promises in STEM Reform Part 1: Examining the Development and Dissemination Change Model," invited talk, National Academies of Science Workshop on Linking Evidence and Promising Practices in STEM Undergraduate Education, Washington, DC, Oct 14, 2008.
9. Henderson, C. & Dancy, M. "Barriers and Promises in STEM Reform Part 2: The Study and Improvement of STEM Change Strategies," invited talk, National Academies of Science Workshop on Linking Evidence and Promising Practices in STEM Undergraduate Education, Washington, DC, Oct 14, 2008.
10. Henderson, C., Yerushalmi, E., Cohen, E., Kuo, V., Heller, K., & Heller, P. "Reflective Problem Solving Skills are Essential for Learning, But it is Not My Job to Teach Them," invited poster, Poster Session TP-C, 2008 Physics Education Research Conference, Edmonton, Canada, July 24, 2008.
11. Henderson, C. & Dancy, M. "Physics Instructors' Knowledge About and Use of Research-Based Instructional Strategies: Preliminary Results from a Web Survey," invited presentation, Physics Department Colloquium, Indiana University Purdue University Indianapolis, October 29, 2009.
12. Finkelstein, N., Mayhew, L., Henderson, C., & Beach, A. "Creating and Sustaining University-Community Partnerships in Science Education," invited talk, American Geophysical Union annual meeting, San Francisco, CA, December 14-18, 2009.
13. Henderson, C. "Promoting Instructional Change in New Faculty," invited talk, AAPT 2009 Summer Meeting, Ann Arbor, MI, July 28, 2009.
14. Henderson, C. & Harper, K. "Quiz Corrections: Improving Learning by Encouraging Students to Reflect on Their Mistakes," invited poster, 2009 Physics Education Research Conference, Ann Arbor, MI, July 30, 2009.

### **CONTRIBUTED TALKS**

1. Finkelstein, N., Henderson, C., & Beach, A. "R13.00007: What's all the fuss about Adoption and Diffusion? Study and Improvement of Change Strategies in Physics Education," contributed talk, American Physical Society April Meeting, Denver, CO, May 4, 2009
2. Dancy, M. H. & Henderson, C., "Preliminary Results From A Survey Of Physics Faculty On Use Of Research-Based Instructional Strategies," contributed poster, PTEC Annual Meeting, Pittsburgh, PA, Mar 13, 2009.

3. Henderson, C., Beach, A., Finkelstein, N., & Larson, R. S. "Facilitating Change in Undergraduate STEM: Preliminary Results from an Interdisciplinary Literature Review," contributed talk, Michigan Section of AAPT 2008 Fall Meeting, Port Huron, MI, Oct 11, 2008.
4. Henderson, C., Beach, A., Finkelstein, N., & Larson, R. S. "Facilitating Change in Undergraduate STEM: Preliminary Results from an Interdisciplinary Literature Review," contributed talk, AAPT 2008 Summer Meeting, Edmonton, Canada, July 21, 2008.
5. Cohen, E., Yerushalmi, E., Henderson, C., Heller, K., & Heller, P. "I Like These Problems But I Can't Use Them on My Test: How Instructors Lower the Bar for Student Performance," contributed poster, AAPT 2008 Summer Meeting, Edmonton, Canada, July 22, 2008.
6. Beach, A., Henderson, C., & Finkelstein, N. "Analysis of Published Strategies for Changing Undergraduate Science," contributed talk, American Educational Research Association National Meeting, San Diego, CA, April 15, 2009.
7. Henderson, C., Beach, A., & Dancy, M. "Facilitating Change in Undergraduate Science Instruction: Making Progress by Improving Communication between Administrators, Educational Researchers, and Faculty Developers," contributed session, Association of American Colleges and Universities Engaging Science, Advancing Learning Conference, Providence, RI, Nov 7, 2008.
8. Beach, A., & Henderson, C. "Identifying Connections within the Literature on STEM Instructional Change Using an Historiographic Approach," contributed poster, Association for the Study of Higher Education annual meeting, Jacksonville, FL, Nov 5-8, 2008.
9. Beach, A., Henderson, C., Finkelstein, N., & Larson, R. S. "Facilitating Change in Undergraduate Science Instruction: Synthesis of Change Strategies across Disciplines," contributed research paper, Association for the Study of Higher Education annual meeting, Jacksonville, FL, Nov 5-8, 2008.
10. Dancy, M., Henderson, C., & Turpen, C. "Faculty Experience with and Perceptions of Research-Based Instructional Strategies: Preliminary Interview Findings," contributed talk, 2010 APS/AAPT Joint Meeting, Washington, DC, February 17, 2010.
11. Henderson, C., Fynewever, H., & Petcovic, H. "Identifying the Impacts of ATE Centers on Their Home Institutions: An Exploratory Study," contributed presentation, ATE PI Meeting, October 22, 2009.
12. Henderson, C. & Dancy, M. "Physics Instructors' Knowledge About and Use of Research-Based Instructional Strategies: Preliminary Results from a Web Survey," contributed poster, AAPT 2009 Summer Meeting, Ann Arbor, MI, July 27, 2009.

13. Henderson, C. & Dancy, M. "The Impact of Physics Education Research on the Teaching of Introductory Quantitative Physics," contributed poster, 2009 Physics Education Research Conference, Ann Arbor, MI, July 29, 2009.
14. Dancy, M. & Henderson, C. "Pedagogical Practices of Physics Faculty in the USA," contributed poster, 2009 Physics Education Research Conference, Ann Arbor, MI, July 29, 2009.
15. Lin, Y., Henderson, C., Finkelstein, N., & Beach, A. "Examining Change Strategies in University STEM Education," contributed talk, AAPT 2009 Summer Meeting, Ann Arbor, MI, July 28, 2009.
16. Dobbin, D. & Henderson, C. "When and Why do Students Decide to Major in Physics," contributed talk, AAPT 2009 Summer Meeting, Ann Arbor, MI, July 28, 2009.
17. Lin, Y., Henderson, C., Finkelstein, N., & Beach, A. "Examining Change Strategies in University STEM Education" contributed poster, 2009 Physics Education Research Conference, Ann Arbor, MI, July 29, 2009.

### **SCHOLARLY ACTIVITIES**

1. Editor, Physics Education Research Section of American Journal of Physics, NoV. 2008 to present.
2. President, Michigan chapter of the American Association of Physics Teachers.
3. Chair, AAPT Committee on Research in Physics Education, Jan 2007 – Jan 2009.
4. Member, ex officio with voting rights, Physics Education Research Leadership and Organizing Council, Jan 2007 – Jan 2009.
5. Senator, Physics Representative to WMU Faculty Senate.
6. Member, AAPT Governance Review Committee, July 2007 to present.
7. Editor, Proceedings of the Physics Education Research Conference, April 2007 to April 2009.
8. Editor, "Getting Started in PER", an edited volume for the AAPT series Reviews in PER.
9. Member, Editorial Board, Annals of Research on Engineering Education.
10. Member, Editorial Board, Science & Engineering Education Sources, a book series published by Information Age Publishing Inc. and edited by Calvin Kalman, Spring 2007 to present.

11. External Evaluator, Physics and Astronomy New Faculty Workshop.
12. Outstanding Referee Award, American Physical Society.
13. 32 Scholarly reviews: Proceedings of the Physics Education Research Conference, The Physics Teacher, Journal of Research in Science Teaching, Physical Review - Special Topics: Physics Education Research, National Science Foundation Course Curriculum and Laboratory (CCLI) program, National Science Foundation Research and Evaluation on Education in Science and Engineering (REESE) program, Journal of Engineering Education, Journal of Computer Science Education, University Scholars Program at Jackson State University, Journal of Science Teacher Education, Higher Education Research and Development, John Wiley & Sons (textbook), Springer Publishers.

## 7.2 David Schuster

### Physics and Science Education Research

#### Overview

During this period I continued research on three active NSF-funded science education research projects, along with colleagues and graduate students, as well as pursuing ongoing work on cognition in physics problem solving. The research was accompanied by the continued development of a physics course, instructional materials and assessment, and a revised edition of my inquiry-based textbook. Dissemination was via journals, conference proceedings and presentations. The projects and progress are described below.

#### Research projects

1. *Development of a physics course for prospective teachers which interweaves learning and teaching issues with physics content and articulates with a teaching methods course*

This project, otherwise known as IATES: Integrated Apprenticeship in the Teaching of Elementary Science, is funded \$200,000 by the NSF's CCLI program and is in its third year. Products thus far include a purpose-developed textbook based on a scientific inquiry learning-cycle approach to topic development, a mechanics course pack, and compilations of structured 'teaching' problems. The effects of the new approach and materials on student learning and graduate instructor teaching have been substantial. A revised third edition of the textbook was produced in 2009. Following the development phase, implementation has been taking place each semester in the Physics 1800 courses at Western Michigan University, Lake Michigan College and Kalamazoo Valley Community College.

Dissemination during this report period has been via the third edition of the textbook, two refereed conference proceedings, and presentations at one national and one international conference, and via the textbook and course pack adoption at the other institutions.

2. *Experimental Comparison of Inquiry and Direct Instruction in Science*

This project is funded \$1.9 Million by the NSF's IERI program and is in its fifth year. The investigators and instructional developers are W.W. Cobern (PI), D.G. Schuster, B. Applegate, A. Undreiu and B. Adams.

The project compares the efficacy of 'inquiry-based' vs. 'direct' instructional approaches on 8th grade students' conceptual understanding of important science topics, specifically i. Force and Motion, and ii. Light, Climate and the Seasons. It is an experimental study 'in the field', involving the development of parallel teaching modules in the two instructional modes, assessment instruments, teacher preparation, and implementation in classrooms by experienced middle school teachers in a summer program. The third field trials were in 2009 with teachers switching instructional modes.

Dissemination during this report period has been via two refereed conference proceedings, and presentations at one national and one international conference.

### 3. *Assessing pedagogical content knowledge of inquiry science teaching*

This project is funded \$440,000 by the NSF in its ASA track, and is in its fourth year. David Schuster is PI, with co-PIs W. W. Cobern, R.S. Schwartz, and R.P. Vellom.

The project develops new types of assessment items and instruments for both formative and summative use, to assess pre-and in-service teachers' understanding of how to teach science by inquiry, and to identify their actual teaching orientations. The items involve creating case-based vignettes of actual classroom topic-teaching situations along with realistic response options corresponding to common teaching practices. An assessment item typology was devised and new items types and formats include 'Spectrum MCQ' and 'Likert testlet' formats. We first worked with teachers to devise realistic classroom vignettes and teaching options, and then with the typology in place created sets of items in various topic areas and grade levels. The next two stages will be detailed dissection and refinement of individual items by focus groups and large scale statistical field testing of the compiled instrument POSITT (Pedagogy of Science Inquiry Teaching Test).

Dissemination during this report period has been by two refereed conference proceedings, one invited conference presentation, and presentations at one national and one international conference. (Istanbul). There is also considerable interest in the project as indicated by significant email contact by faculty at other institutions.

### 4. *Cognition in physics problem solving*

This is ongoing unfunded research into the reasoning processes and knowledge schemata involved in physics problem solving, for both experts and novices. Part of it is being done in collaboration with my PhD student Adriana Undreiu. The cognitive process and compiled knowledge involved are much more complex and extensive than are represented by the model solutions that teachers and textbooks present to students as a final-product polished solutions. Thus principle-based reasoning, case-based reasoning, experiential-intuitive reasoning, analogy-based reasoning and everyday heuristic reasoning are all found to play roles for both learners and experts, especially when they encounter unfamiliar problems, and draw strongly on an individual's existing schemata in the domain. Ms. Undreiu and I studied this in depth for problem solving in reflection and refraction, and she is currently writing her dissertation. I have also done a similar study for problems involving acceleration in curved motions.

Dissemination during this report period has been by three refereed conference proceedings, and presentations at three conferences, one international (Istanbul).

## **PUBLICATIONS**

### ***Textbook***

David Schuster. *Light: Inquiry and Insights*. Third edition 2009. Kendall/Hunt Publishing Company, Dubuque, Iowa, ISBN 0-7575-2389-7.

### ***Refereed journal articles***

1. William W. Cobern, David Schuster, Betty Adams, Adriana Undreiu, Brooks Applegate, Brandy Skjold, Cathleen C. Loving and Janice D. Gobert. *Experimental Comparison of Inquiry and Direct Instruction in Science*. Experimental comparison of inquiry and direct instruction in science. Research in Science & Technological Education, 28(1), 2010, 81-96.
2. David Schuster, Betty Adams, David Brookes, Marina Miler-Bolotin, and Adriana Undreiu. *Motion-matching: A challenge game to generate motion concepts*. The Physics Teacher, 47, no 7, 2009, 434-438.

### ***Refereed conference proceedings***

1. David Schuster, Adriana Undreiu and Betty Adams. *Reasoning Modes, Knowledge Elements and Epistemic Frames in Problem-Solving in Optics*. Proceedings of the European Science Education Research Association, Istanbul, Turkey, Aug. 31-Sept 4, 2009.
2. David G. Schuster, Betty Adams, Adriana Undreiu, Brooks Applegate, Brandy Skjold, Janice D. Gobert, Cathleen C. Loving. Inquiry science instruction or direct? Experiment-based answers as to what practices best promote conceptual development of significant science content. Proceedings of the European Science Education Research Association, Istanbul, Turkey, Aug. 31-Sept 4, 2009.
3. Renee' S. Schwartz, David Schuster and Osman Titrek. *Assessing teachers' orientations toward inquiry science teaching: Instrument development and international collaboration*. Proceedings of the European Science Education Research Association, Istanbul, Turkey, August 31-Sept 4, 2009.
4. David Schuster and Adriana Undreiu, *Cognition of an expert tackling an unfamiliar conceptual physics problem*. Proceedings of the 2009 Physics Education Research Conference, Ann Arbor, MI, July 29-30, 2009, American Institute of Physics AIP Conference Proceedings.
5. William W. Cobern, David Schuster, Betty Adams, Adriana Undreiu, Brooks Applegate, Janice D. Gobert Cathleen C. Loving and Brandy Skjold. *Inquiry Science Instruction or Direct? Experiment-based Answers as to What Practices Best Promote Conceptual Development of Significant Science Content*. National Association for Research in Science Teaching International Meeting, Chicago, Feb 12-16, 2009.

### **GRANTS**

1. National Science Foundation NSF-CCLI-EMD. *Integrated Apprenticeship in the Teaching of Elementary Science. (IATES)* D Schuster (PI), C Henderson, P Vellom. \$200,000 for 4 years 2006-2010. Active.
2. National Science Foundation NSF- IERI Educational Research Initiative. *An experimental efficacy study of science achievement and attitude development amongst 8th grade students using an inquiry, integrated science-mathematics-engineering model of instruction*. W. W. Cobern (PI), D. G. Schuster, R. S. Schwartz, B. Applegate, \$1.9 million over 6 years 2004-2010. Active

3. National Science Foundation NSF-ASA track. *Assessing pedagogical content knowledge of inquiry science teaching*. D.G. Schuster (PI), W. W. Cobern, R.S. Schwartz, R.P. Vellom. \$440,000 including international supplement, over 4 years 2005-2010 Active.

### **INVITED TALKS**

1. David Schuster. *Assessing Pedagogical Content Knowledge of Inquiry-based Physics Teaching*. American Association of Physics Teachers Meeting, Chicago, Feb 12-16, 2009.

### **CONTRIBUTED TALKS**

#### *Proposals peer reviewed*

1. David Schuster, Adriana Undreiu and Betty Adams. *Reasoning Modes, Knowledge Elements and Epistemic Frames in Problem-Solving in Optics*. International conference of the European Science Education Research Association, Istanbul, Turkey, August 31-Sept 4, 2009.
2. David G. Schuster, Betty Adams, Adriana Undreiu, Brooks Applegate, Brandy Skjold, Janice D. Gobert, Cathleen C. Loving. Inquiry science instruction or direct? Experiment-based answers as to what practices best promote conceptual development of significant science content. International conference of the European Science Education Research Association, Istanbul, Turkey, August 31-Sept 4, 2009.
3. Renee' S. Schwartz, David Schuster and Osman Titrek. *Assessing teachers' orientations toward inquiry science teaching: Instrument development and international collaboration*. International conference of the European Science Education Research Association, Istanbul, Turkey, August 31-Sept 4, 2009.
4. David Schuster and Adriana Undreiu, *Cognition of an expert tackling an unfamiliar conceptual physics problem*. Physics Education Research Conference, Ann Arbor, MI, July 29-30, 2009
5. William W. Cobern, David Schuster, Betty Adams, Adriana Undreiu, Brooks Applegate, Janice D. Gobert Cathleen C. Loving and Brandy Skjold. *Inquiry Science Instruction or Direct? Experiment-based Answers as to What Practices Best Promote Conceptual Development of Significant Science Content*. National Association for Research in Science Teaching International Meeting, Chicago, Feb 12-16, 2009.

#### *Not peer reviewed*

1. David Schuster, Adriana Undreiu, Betty Adams, David Brookes and Marina Milner-Bolotin. *Motion Reproduction: a Challenge Activity to Generate Motion Descriptor Concepts*. Presentation at the American Association of Physics Teachers Conference, Edmonton, Alberta, July 19-23, 2008

2. Adriana Undreiu, David Schuster and Betty Adams, *Reasoning modes, knowledge elements and their interplay in optics problem-solving*. Presentation at the American Association of Physics Teachers Conference, Edmonton, Alberta, July 19-23, 2008.

## 8 Research and Public Lectures at WMU

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The Department of Physics sponsors lectures on physics research intended mainly for graduate students and faculty. These talks inform faculty and students at Western of research efforts here and at other institutions as well as acquaint visiting speakers with our research and academic programs at Western. The Department of Physics also sponsors public lectures on physics topics of general interest. These talks are intended for faculty, physics graduate students, physics undergraduate students, and non-physicists. The research and public lectures are listed below.

*Nuclear Reactions with Deuterons*, R. C. Johnson, University of Surrey, Guildford, Surrey, United Kingdom, September 3, 2008.

*Kerr Media Photonic Crystal Waveguide – A Functional Photonic Device*, **Buddhi M. Rai**, Doctoral Student, Department of Physics, Western Michigan University, September 10, 2008.

*Astrophysical Relevance of Heavy-Ion Photoionization*, Brendan M. McLaughlin, School of Mathematics and Physics, Queen's University of Belfast, September 17, 2008.

*Measurements of Electrostatic Interactions in Biological Membranes*, Horia Petrache, Indiana University – Purdue University, Indianapolis, September 24, 2008.

*From the Physics Lab to Capitol Hill: A Story of Tuna, Spies, and Dial-A-Porn*, Joseph Finck, Central Michigan University, October 8, 2008.

*The Nature of the Galactic Halo as Revealed by SDSS/SEGUE*, Timothy C. Beers, Michigan State University, October 15, 2008.

*One Atom too Many: An Atomic Physicist's Attempt to Learn About Simple Homonuclear Diatomic Molecules*, Timothy Gay, University of Nebraska, October 22, 2008.

*Depleted Uranium Weapons: What's the Big Deal, They are Depleted, Right?*, Russell Kincaid, Wilmington College, October 29, 2008.

*Engaging Students in Class and Beyond*, Andy Gavrin, Indiana University – Purdue University Indianapolis, November 5, 2008.

*Supernovae, Electron Capture and Gamow-Teller Strength*, Arthur Cole, Kalamazoo College, January 21, 2009.

*Transfer Reactions with Exotic Beams – Everything Old is New Again*, **Alan Wuosmaa**, Department of Physics, Western Michigan University, January 28, 2009.

*Recipe for a Universe: The Physics of the Large Hadron Collider*, Randal Ruchti, University of Notre Dame, February 11, 2009.

*Seeing the Mathematics Behind Supersymmetry Theories – Adinkras*, Sylvester James Gates, Jr., University of Maryland, February 16, 2009.

*Probing Surface Charge Fluctuations with Solid-State Nanopores*, David Hoogerheide, Doctoral Student, Harvard University, February 18, 2009.

*Probing Accretion, Feedback, and Tidal Interaction Mechanisms in Our Local Neighborhood*, Nicolas Lehner, University of Notre Dame, February 25, 2009.

*Cassiopeia A in 3D: A Spectacular View of the Explosion*, Tracy DeLaney, MIT Kavli Institute for Astrophysics and Space Research, March 18, 2009.

*Ultrafast Nonlinear Optical Properties of Semiconductor*, Qiguang Yang, Hampton University, March 23, 2009.

*Driving Multiple Core-holes with Strong Laser Fields*, Ryan N. Coffee, SLAC National Accelerator Laboratory, Menlo Park, CA, March 25, 2009.

*Differential Ionization Measurements using Positrons: How and Why*, Robert D. DuBois, Missouri University of Science and Technology, April 1, 2009.

*The Fe II Spectra of Quasars. Unfitting Pieces of a Complex and Exotic Puzzle or ‘Some Assembly Required’*, Manuel Bautista, Virginia Tech, April 8, 2009.

*Spatial Resolution Limits of Electron Beam Nanopatterning*, Leonidas E. Ocola, Argonne National Laboratory, April 15, 2009.

*Sleeping Phonons and Dancing Electrons: Computational Design of Novel Thermoelectric Materials*, Marco Fornari, Central Michigan University, September 21, 2009.

*Journey to the Core of a Neutron Star*, Edward Brown, Michigan State University, September 28, 2009.

*Non-sequential Double Ionization of Atoms by Intense Infrared and Visible-Wavelength Lasers: A Fully Classical Analysis*, S. L. Haan, Calvin College, October 5, 2009.

*Cognition of an Expert Tackling an Unfamiliar Conceptual Physics Problem*, **David Schuster**, Department of Physics, Western Michigan University, October 26, 2009.

*Electret Polymers: Principles, Characterization and Applications*, Axel Mellinger, Central Michigan University, November 2, 2009.

*Detecting Extrasolar Planets as Blemishes in Einstein's Lenses*, David Bennett, University of Notre Dame, November 9, 2009.

*Milton Meets Einstein: Inquiring Minds Want to Know*, Gordon Berry, and Mary Hynes-Berry, University of Notre Dame and Erikson Institute for Early Childhood Development, Chicago, November 23, 2009.

*Research with Polarized Noble Gases*, Tim Chupp, University of Michigan, December 7, 2009.

## 9 PERSONNEL

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### Faculty

Bautista, Manuel  
Berrah, Nora  
Burns, Clement  
Chung, Sung  
Famiano, Michael  
Gorczyca, Thomas  
Halderson, Dean  
Hasoglu, Muhammet Fatih  
(Part Time)  
Henderson, Charles  
Kaldon, Philip (Part Time)  
Kamber, Emanuel  
Kayani, Asghar  
Korista, Kirk  
McGurn, Arthur  
Miller, Mark (Part Time)  
Pancella, Paul (Chair)  
Paulius, Lisa (Co-chair)  
Rosenthal, Alvin  
Schuster, David  
Stahl, John (Part Time)  
Tanis, John  
Wuosmaa, Alan

### Faculty Emeriti

Bernstein, Eugene  
Hardie, Gerald  
Kaul, Dean  
Soga, Michitoshi  
Poel, Robert  
Shamu, Robert

### Staff

Cochran, Kerry  
Gaudio, Benjamin  
Kern, Allan  
Krum, Lori  
Scherzer, Bob  
Welch, Rick

### Post-Docs

Bilodeau, René  
Fang, Li  
Fivet, Vanessa  
Hoener, Matthias  
Murphy, Brendan  
Nikolić, Dragan  
Shetty, Dinesh

### Graduate Students

Abdel Naby, Shahin  
Abu-Hawwash, Riad  
Adams, Betty  
Adams, Dan  
Al-Amar, Mohammad  
Al Faify, Salem  
Ayyad, Asmá  
Baran, Jamie  
Bedoor, Shadi  
Chakraborti, Priyanka  
Cassidy, David  
Das, Susanta  
De Silva, Samantha  
Dissanayake, Amila  
Dumitriu, Ileana  
Durren, Michael  
El Kafrawy, Tamer  
Ganapathy, Subramanian  
Gao, Xuan  
Garratt, Elias  
Giacherio, Brenna  
Goodman, Nicholas  
Grineviciute, Janina  
Hamam, Khalil  
Hasoglu, Muhammet Fatih  
Ravandi, Saeedeh  
Keerthisinghe, Darshika  
Kodikara, Ravin  
Lagha, Rahmah  
Li, Chengyang

### Graduate Students (Cont.)

Lighthall, Jonathan  
Marley, Scott  
McCowen, Robert  
Moore, Andrew  
Nandasiri, Manjula  
Rai, Buddhi  
Senarath, Buddhika  
Stefanick, Trevor  
Strong, Benjamin  
Vyas, Anjali  
Wang, Lihua  
Winkworth, Melike  
Zhang, Huaizhen