

# Stewardship Science Academic Alliances Program

## Nuclear Stewardship Research.

**DOE Grant Number DE-FG52-05NA25929**

*P.I.: Cornelius W. Beausang  
Robert E. and Lena F. Loving Chair,  
Chairman, Physics Department,  
University of Richmond  
Phone: 804 289 8783  
E-mail: cbeausan@richmond.edu*

## Introduction

This report covers the period from June 2005 through May 2006. During this, the third year of our program, our research has focused mainly on applying the surrogate reaction technique and our newly developed surrogate ratio method to deduce neutron induced fission cross sections on uranium nuclei. The year has been marked by continued scientific progress, by the arrival of new personnel, by a growth in the numbers of students working in the group and by a continuation of our experimental program and close collaboration with staff and scientists from Lawrence Livermore National Laboratory and from Lawrence Berkeley National Laboratory.

This year saw some changes in the group personnel. Our new postdoctoral fellow, Dr. Shelly Leshner, arrived in Richmond in December 2005. Prior to joining the group Dr. Leshner was a postdoctoral fellow at KU Leuven, Belgium where she was involved in laser spectroscopy measurements of deformations in light Pb nuclei. Dr. Leshner obtained her Ph.D. in 2004 from the University of Kentucky, her thesis topic being the investigation of the nature and number of low-lying excited  $0^+$  states in deformed nuclei. Dr. Leshner is off to a flying start at Richmond. Indeed, only one week after relocating from Europe, she was off to Berkeley to collaborate with LLNL and LBL scientists in a triple-alpha branching experiment using STARS. Since then she, and the rest of the group, have collaborated on a variety of other surrogate measurements with STARS. She is currently analyzing a STARS / Liberate data set extracting the  $\sigma(n,f)^{234}\text{U} / \sigma(n,f)^{234}\text{U}$  cross section ratio using the surrogate ratio method.

Our graduate student at Yale, John Ai, is completing his Ph.D. work. Over the last several months he has extracted the first absolute measurement of the  $^{238}\text{U}(\alpha,\alpha'f)$  cross section, surrogate for the  $^{237}\text{U}(n,f)$  reaction. His analysis is nearing completion and I would expect

him to defend his thesis in the Fall or possibly Spring of 2007. He is currently seeking postdoctoral positions.

Five Richmond undergraduates also worked (at various intensity levels) in the group over the course of the year. Three of these actively participated in the stewardship measurements or data analysis.

- Ben Crider, a University of Richmond senior and physics major, has just graduated (May 2006) and is a big success of our program. Ben has been accepted to the Graduate School in the University of Kentucky where he intends to pursue his Ph.D. degree in experimental nuclear physics. He is working this summer with Professor Steve Yates at U.K. Ben participated in several surrogate experiments including one at LBL in December 2004.
- Two freshmen have recently joined the group. Mila Evtimova (she is the holder of a prestigious Ethyl Scholarship at the University of Richmond.) and Berta Darakchieva both traveled to Berkeley to participate in a STARS/Liberace experiment in early May 2006. Both Mila and Berta are spending the remainder of the summer doing research with me at Yale. Although it is early days yet, it appears that both of these young women intend to major in physics.
- Another Richmond undergraduate, Gabe Anderson, has just joined the group and is spending his summer doing research at Yale.
- The final member of the group, Jodi Cohen has been accepted to the Notre Dame REU program for the summer. She will be working in nuclear physics at ND and at ANL under the supervision of Philip Colon.

## Key Personnel

### University of Richmond

Cornelius W. Beusang,	Associate Professor, P.I., Chairman, Physics Department
Shelly Leshner,	Postdoctoral Fellow
Ho-Chaing Ai,	Graduate Student, Yale University
Ben Crider	Undergraduate Student (Class of 2006)
Jodi Cohen	Undergraduate Student (2007)
Gabe Anderson	Undergraduate Student (2008)
Mila Evtimova	Undergraduate Student (2009)
Berta Darakchieva	Undergraduate Student (2009)

### Lawrence Livermore National Laboratory

Lee Bernstein	Staff
Larry Ahle	Staff
Jason Burke	Staff
Jennifer Church	Staff

## Summary of Results

### The Surrogate Ratio Method and results for the actinides:

The surrogate ratio method [1,2,3], developed by us and our Livermore collaborators over the last two years is proving to be a very useful tool for deducing neutron induced cross sections in actinide nuclei.

Briefly, in traditional surrogate method measurements (pioneered in the 70's and recently revived) [4-10] the desired neutron induced reaction,  $A(n,x)$  ( $x$  represents a variety of exit channels and  $A$  is an unstable target), is mimicked by a surrogate reaction involving a stable beam on a stable target. The surrogate reaction is chosen to produce the same 'composite system' at similar excitation energies and with as similar an angular momentum distribution to the direct reaction as possible.

For example, in our work the  $^{237}\text{U}(n,f)$  reaction was mimicked by both the  $^{283}\text{U}(d,d'f)$  or  $^{238}\text{U}(\alpha, \alpha'f)$  reactions. To deduce the neutron induced cross section of interest requires both a calculation of the formation probability and a measurement of the decay probability for the excited nucleus. The experimental quantity extracted from such measurements is, for example, the ratio  $N(d,d'f)/N(d,d')$ . Often, due to target purity issues for example, the denominator,  $N(d,d')$ , in this expression is difficult or impossible to extract cleanly from the data.

In the ratio technique, the ratio of yields from two nuclei with similar structures is taken. In this ratio several difficult to determine factors, including effects of light ion target contamination, pre-equilibrium emission of nucleons, evaporation of nucleons, and some angular correlation effects cancel or are small. Thus the cross section of interest is given by

$$\frac{\sigma(n,f)^{236}\text{U}}{\sigma(n,f)^{238}\text{U}} = \frac{N(d,d'f)^{236}\text{U}}{N(d,d'f)^{238}\text{U}}$$

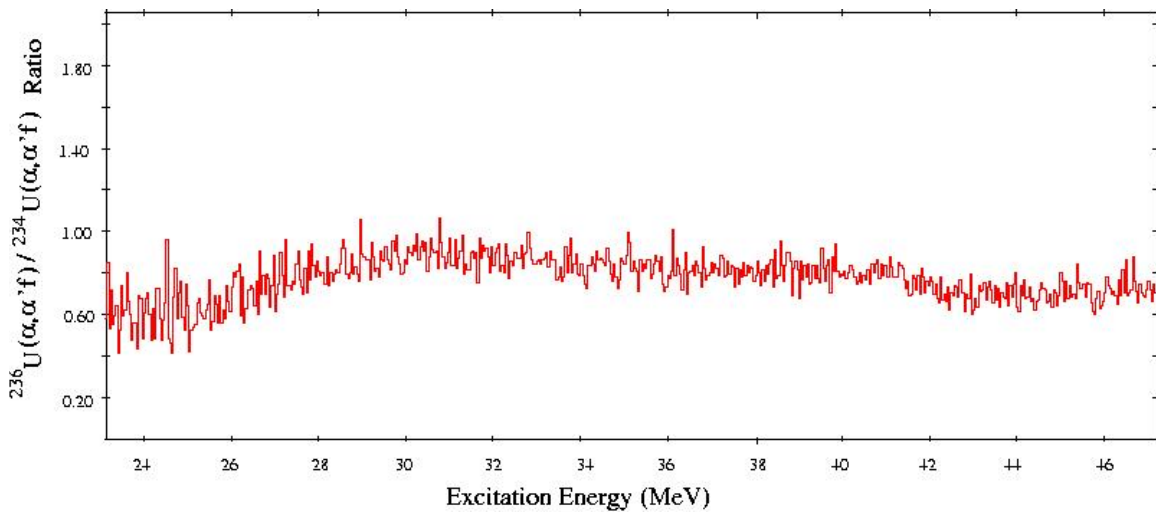
Benchmarking and testing the robustness of this technique are extremely important and we have carried out several experiments during the last two years aimed at doing exactly this, as well as extracting new information on unknown cross sections.

Early results from our group include the measurement of the previously known  $\sigma(n,f)^{236}\text{U}/\sigma(n,f)^{238}\text{U} = N(d,pf)^{236}\text{U}/N(d,pf)^{238}\text{U}$  cross section ratio [1,2]. This result is in excellent agreement with the results of direct measurement and hence serves to benchmark the technique.

From the same data sets the previously unknown ratio  $\sigma(n,f)^{235}\text{U}/\sigma(n,f)^{237}\text{U} = N(d,d'f)^{236}\text{U}/N(d,d'f)^{238}\text{U} = N(\alpha, \alpha'f)^{236}\text{U}/N(\alpha, \alpha'f)^{238}\text{U}$  could also be extracted giving valuable information on the  $\sigma(n,f)^{237}\text{U}$  over an unprecedented range of neutron energies [1,2,3].

These collaborative experiments have continued at LBNL over the last year. For example, figure 1 shows our preliminary results for the cross section ratio  $N(\alpha, \alpha' f)^{236}\text{U} / N(\alpha, \alpha' f)^{234}\text{U}$  (surrogate for  $\sigma(n, f)^{235}\text{U} / \sigma(n, f)^{233}\text{U}$ ) from a STARS/Liberace experiment carried out in December 2005 at LBNL. This data is currently being analyzed by Shelly Leshner at Richmond. Results are expected to be ready for publication by the end of the summer [11].

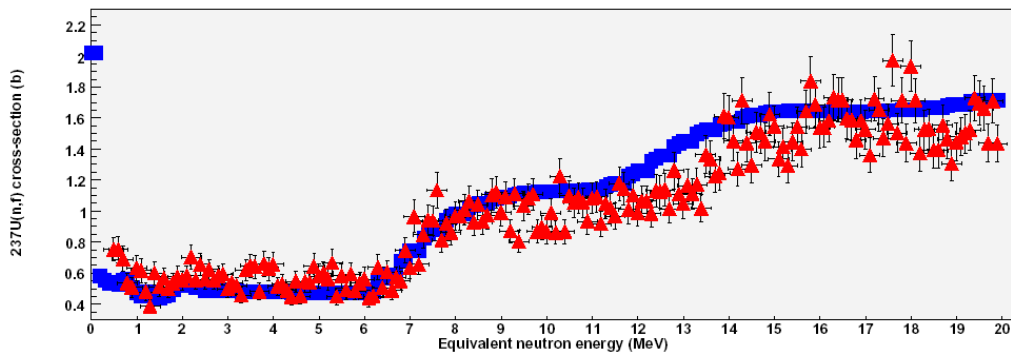
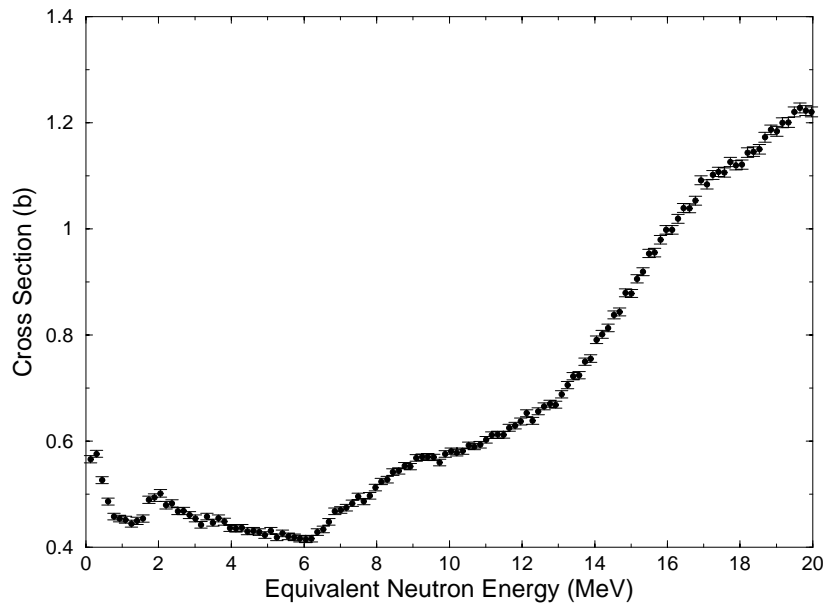
Another recently completed experiment at LBNL tests the validity of the technique when used with an odd-even and even-even target combination (spin effects). The reactions chosen in this case were  $^{235}\text{U}(\alpha, \alpha' f)$  compared to  $^{238}\text{U}(\alpha, \alpha' f)$ , each at a beam energy of 55 MeV [12].



### **Absolute Surrogate Measurement: Comparison with the Ratio Technique.**

While we and our LLNL collaborators are exploiting the surrogate ratio technique, at the same time, in an analysis lead by our graduate student John Ai, we are also extracting the first absolute surrogate cross section for  $\sigma(n, f)^{237}\text{U} \sim N(\alpha, \alpha' f) / N(\alpha, \alpha')$  which can be compared to the cross section deduced from the ratio technique [13]. Preliminary results from John are shown in figure 2 as a function of equivalent neutron energy and show many of the expected features for an (n, f) cross section (rapid increase at neutron binding energies) but also several (potentially very interesting) discrepancies with the result obtained indirectly from the ratio method (taken from reference [3] and shown in the lower portion of figure 2). Careful checks of a variety of effects including time and energy gates and thresholds are being made. While it is early days yet, the data in figure 2, in particular the difference between the shape of the cross section in figure 2 compared to that obtained from the ratio method may be indicative of the sensitivity of the absolute measurement to pre-equilibrium effects or particle evaporation from the compound system. As mentioned above the ratio method should be insensitive to such effects, which

entry into both the numerator and denominator as a product of (presumably) similar probabilities. A preliminary analysis of the data by John Ai does indeed show evidence for charged particle emission in coincidence with scattered beam particles (unfortunately our setup is insensitive to neutrons).



## Outlook for 2006-07

The outlook for the coming twelve month grant period looks extremely promising.

We plan to continue our investigations into the surrogate reaction mechanism, benchmarking the technique where possible and also extracting new cross section information. These experiments will take place at Berkeley using the STARS / Liberate array of charge particle and gamma-ray detectors.

Dr. Leshner will spend the majority of the summer at LBNL participating in several experiments and completing, in close collaboration with our Livermore colleagues the analysis of the  $^{234}\text{U}/^{236}\text{U}$  fission data. Dr. Beausang will also participate in these experiments and will continue to train and motivate the students.

In May we just completed the first test of the surrogate ratio method checking for spin effects using odd and even target combinations and have collaborated over the last few weeks in a triple-alpha decay experiment (led by Jason Burke of LLNL). The  $^{12}\text{C}$  triple- $\alpha$  reaction is one of the most critically important measurements for determining elemental abundances in the Universe and has applications to late stage stellar evolution, nucleosynthesis and core-collapse in supernovae. Using the STARS array at LBL, a test experiment was performed in December 2005. The  $^{12}\text{C}(\alpha, \alpha')$  reaction at around 55 MeV, did show the possibility of measuring all three alpha's of interest with a better precision than achieved in the past and allow the deduction of the branching ratios. In May 2006, the first full experiment was performed and the raw data appears looks promising.

As regards benchmarking the surrogate technique we have proposed an experiment to the collaboration to measure (simultaneously) a chain of isotopes using several different reactions (p, d, alpha,  $^3\text{He}$ , e.g.) The Gd isotopes seem ideal for this purpose. The chain of Gd isotopes,  $^{154}\text{Gd}$ ,  $^{155}\text{Gd}$ ,  $^{156}\text{Gd}$ ,  $^{157}\text{Gd}$ ,  $^{158}\text{Gd}$ , and  $^{160}\text{Gd}$  are all stable, while the half life of  $^{152}\text{Gd}$  is  $10^{14}$  years. Thus using a natural Gd target (or perhaps one slightly enriched in 2%  $^{154}\text{Gd}$ ) surrogate reaction cross sections for all of these nuclei can be simultaneously extracted. The clover detectors of the Liberace array will be used to measure the yields of the various isotopes, the energy resolution of the Ge detectors being sufficient to resolve the nearby low lying transitions in each. Thus this experiment could allow a comprehensive test of the surrogate reaction and ratio methods over a single isotopic chain. A test experiment may be carried out at Yale in the summer. We anticipate carrying out the full experiment in the early fall 2006.

## References

1. C. Plettner, H. Ai, C.W. Beausang, L.A. Bernstein, L. Ahle, H. Amro, M. Balibon, J.T. Burke, J.A. Caggiano, R.F. Casten, J.A. Church, J.R. Cooper, B. Crider, G. Gurdal, A. Heinz, E.A. McCutchan, K. Moody, J.A. Punyon, J. Qian, J.J. Ressler, A. Schiller, E. Williams, and W. Younes, Phys. Rev. **C71** 051602 (2005).
2. C. Plettner, H. Ai, C.W. Beausang, L.A. Bernstein, L. Ahle, H. Amro, M. Babilon, J.T. Burke, J.A. Caggiano, R.F. Casten, J.A. Church, J.R. Cooper, B. Crider, G. Gürdal, A. Heinz, E.A. McCutchan, K. Moody, J.A. Punyon, J. Qian, J.J. Ressler, A. Schiller, E. Williams and W. Younes, J. Phys. **G31** S1573 (2005).
3. J.T. Burke, L.A. Bernstein, J. Escher, L. Ahle, J.A. Church, F.S. Dietrich, K.J. Moody, E.B. Norman, L. Phair, P. Fallon, R.M. Clark, M.A. Deleplanque, M. Descovich, M. Cromaz, I.Y. Lee, A.O. Macchiavelli, M.A. McMahan, L.G. Moretto, E. Rodriguez-Viitez, F.S. Stephens, H. Ai, C.W. Beausang and B. Crider, submitted for publication to Phys. Rev. C.

4. Study of the Feasibility of simulating (n, $\alpha$ ) and (n,p) cross sections with charged particle direct reaction techniques. LANL Progress Report, Program Code – W223, H.C. Britt and J.B. Wilhelmy. November 15 1976.
5. W. Younes and H.C. Britt, Phys. Rev. **C68** 034610 (2003).
6. L.A. Bernstein, *et al.*, Phys. Rev. **C65** 021601 (2002).
7. C. Britt, et al., Phys. Rev. **175** 1525 (1968) and Phys. Rev. **C2** 1758 (1970).
8. J.D. Cramer and H.C. Britt, Phys. Rev. **C2** 2350 (1970) and Nucl. Sci. Eng. **41** 177 (1970).
9. J.D. Cramer and H.C. Britt, Nucl. Sci. and Eng. **41** 177 (1970)
10. W. Younes, H.C. Britt, J.A. Becker and J.B. Wilhelmy, Initial estimate for the  $^{237}\text{U}(n,f)$  cross section for  $0.1 \leq E_n$  (MeV)  $\leq 20$  UCRL-ID-154194 (2003).
11. S. Leshner et al. to be published.
12. B. Lyles et al. Thesis, to be published.
13. H. Ai et al., Thesis and to be published.

## Publications 2005-06

### ‘Stewardship’ Publications

#### 1. Determining neutron capture cross sections with the Surrogate Reaction

##### Technique: Measuring decay probabilities with STARS

J.A. Church, L. Ahle, L.A. Bernstein, J. Cooper, F.S. Dietrich, J. Escher, C. Forssen, H. Ai, H. Amro, M. Balibon, C.W. Beausang, J. Caggiano, A. Heinz, R. Hughes, E. McCutchan, D. Meyer, C. Plettner, J. Ressler, and V. Zamfir, Nucl. Phys. **A758** 126c (2005).

#### 2. Measuring reaction probability ratios to simulate neutron-induced cross-sections of short-lived nuclei

C. Plettner, H. Ai, C.W. Beausang, L.A. Bernstein, L. Ahle, H. Amro, M. Babilon, J.T. Burke, J.A. Caggiano, R.F. Casten, J.A. Church, J.R. Cooper, B. Crider, G. Gürdal, A. Heinz, E.A. McCutchan, K. Moody, J.A. Punyon, J. Qian, J.J. Ressler, A. Schiller, E. Williams and W. Younes, J. Phys. **G31** S1573 (2005)

#### 3. Deducing the $^{237}\text{U}(n,f)$ Cross Section using the surrogate ratio method

J.T. Burke, L.A. Bernstein, J. Escher, L. Ahle, J.A. Church, F.S. Dietrich, K.J. Moody, E.B. Norman, L. Phair, P. Fallon, R.M. Clark, M.A. Deleplanque, M. Descovich, M. Cromaz, I.Y. Lee, A.O. Macchiavelli, M.A. McMahan, L.G. Moretto, E. Rodriguez-Vietez, F.S. Stephens, H. Ai, C.W. Beausang and B. Crider, Phys. Rev. C **73**, 054604 (2006).

### Other Publications

#### 1. Isomers and seniority in the trans-Pb nuclei

J.J. Ressler, C.W. Beausang, R.F. Casten, N.V. Zamfir, H. Ai, H. Amro, M. Babilon, R.B. Cakirli, J.A. Caggiano, G. Gürdal, A. Heinz, R.O. Hughes, S.D. Langdown, E.A. McCutchan, D.A. Meyer, C. Plettner, J. Qian, P.H. Regan, M.J.S Sciacchitano, N.J. Thomas, E. Williams and A Yamamoto, J. Phys. **G31** S1605 (2005)

**2. Quadrupole moment measurements of TSD1 and TSD2 bands in  $^{167}\text{Lu}$**

G. Gürdal, H. Amro, C.W. Beausang, D.S. Brenner, M.P. Carpenter, R.F. Casten, C. Engelhardt, G.B. Hagemann, C.R. Hansen, D.J. Hartley, B. Herskind, H. Hübel, T.L. Khoo, T. Lauritsen, W.C. Ma, D.A. Meyer, E.F. Moore, A. Neusser, P. Bringel, D.G. Roux, G. Sletten, R.B. Yadav and Y. Zhang, J. Phys. **G31** S1873 (2005)

**3. RDDS Lifetime Measurement with JUROGAM + RITU**

T. Grahnla, A. Dewald, O. Moller, C.W. Beausang, S. Eeckhaudt, P.T. Greenlees, J.Jolie, P. Jones, R. Julin, S. Juutinen, H. Kettunen, T. Kroll, R. Krucken, M. Leino, A.-P. Leppanen, P. Maierbeck, D.A. Meyer, P. Nieminen, M. Nyman, J. Pakarinen, P. Petkov, P. Rahkila, B. Saha, C. Scholey, and J. Uusitalo, accepted for publication in Eur. Phys. Journal, February 2005.

**4. g factor of the  $2^+_1$  state of  $^{160}\text{Er}$**

A. Wolf, Z. Berant, N.V. Zamfir, D.S. Brenner, E.A. McCutchan, H. Ai, R.F. Casten, K. Dusling, A. Heinz, D.A. Meyer, E.A. Millman, N. Pietralla, C. Plettner, J. Qian, P.H. Regan, D. Swanson, J. Vinson, E. Williams, R. Winkler, **Phys. Rev. C 72, 027301 (2005)**.

**5. First Investigation of Excited States in the Odd-Proton Nucleus  $^{209}\text{Fr}$**

D. A. Meyer, C. W. Beausang, J. J. Ressler, H. Ai, H. Amro, M. Babilon, R. F. Casten, C. R. Fitzpatrick G. GÅurdal, A. Heinz, E. A. McCutchan, C. Plettner, J. Qian, N. J. Thomas, V. Werner, E. Williams, N. V. Zamfir, and Jing-ye Zhang, Phys. Rev. **C73**, 024307 (2006).

**6. The Breakdown of K-selection in  $^{178}\text{Hf}$**

B. Hayes, D. Cline, C. Y. Wu, J. Ai, H. Amro, C.W. Beausang, R. F. Casten, J. Gerl, A. A. Hecht, A. Heinz, R. Hughes, R. V. F. Janssens, C. J. Lister, A.O. Macchiavelli, D. A. Meyer, E. F. Moore, P. Napiorkowski, R. C. Pardo, Ch. Schlegel, D. Seweryniak, M. W. Simon, J. Srebrny, R. Teng, K. Vetter, H. J. Wollersheim, Phys. Rev. Lett. **96**, 042505 (2006).

**7. Lifetime measurements of yrast states in  $^{162}\text{Yb}$  and  $^{166}\text{Hf}$**

E.A. McCutchan, N.V. Zamfir, R.F. Casten, H. Ai, H. Amro, M. Babilon, D.S. Brenner, G. Gurdal, A. Heinz, R.O. Hughes, D.A. Meyer, C. Plettner, J. Qian, J.J. Ressler, N.J. Thomas, V. Werner, E. Williams, R. Winkler, **Phys. Rev. C 73, 034303 (2006)**.

**8. g factor of the  $2^+_1$  state of  $^{160}\text{Er}$ ,**

A. Wolf, Z. Berant, N.V. Zamfir, D.S. Brenner, E.A. McCutchan, H. Ai, R.F. Casten, K. Dusling, A. Heinz, D.A. Meyer, E.A. Millman, N. Pietralla, C. Plettner, J. Qian, P.H. Regan, D. Swanson, J. Vinson, E. Williams, R. Winkler, **Phys. Rev. C 72, 027301 (2005)**.



## **Talks and Presentations**

### **Invited Talks at International Meetings**

#### **1. Rn/Ra/Fr: Recent Results**

C.W. Beausang, Yale Workshop on Nuclear Structure Physics, Yale University, June 2005.

#### **2. Cross Section Measurements of $^{236,238}\text{U}(n, f)$ and the Surrogate Technique,**

H. Ai, Workshop on Nuclear Structure Physics Near the Coulomb Barrier, Yale University, June 2005.

#### **3. Stockpile Stewardship Program: Results to Date**

C.W. Beausang, Stockpile Stewardship Academic Alliances Symposium, University of Nevada, Las Vegas, August 2005.

#### **4. Recent Results on Actinide and trans-Pb Nuclei**

C.W. Beausang, Indo-U.S. workshop on Physics with Energetic Heavy Ions, Chandrigarh, India, October 2005.

#### **5. Recent measurements of the $^{237}\text{U}(n, f)$ & $^{235}\text{U}(n, f)$ cross sections using the surrogate reaction technique and new results for conversion coefficients in TSD $^{167}\text{Lu}$**

C.W. Beausang, Contemporary Frontiers in Nuclear Structure, 231<sup>st</sup> Meeting of the American Chemical Society, Atlanta, March 2006.

#### **6. Shape coexistence in Pb isotopes through in-source laser spectroscopy measurements**

S. Leshner, Contemporary Frontiers in Nuclear Structure, The ACS National Meeting, Atlanta, GA, 26-30 March 2006.

## **Other Talks and Seminars**

#### **1. Surrogate Reactions and Recent Results on Actinide Nuclei**

C.W. Beausang, Physics Department Colloquium, Virginia Commonwealth University, March 2006.

#### **2. Surrogate Measurement of the $^{237}\text{U}(n, f)$ Reaction Cross Section,**

H. Ai, April Meeting of the American Physical Society, Dallas, April 2006.