Electric Dipole Moment Measurements with Rare Isotopes - DOE-UM-ER41331

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1 Accomplishments

Our proposed reseach laid out the following goals

- Develop techniques for on-line EDM measurment with rare isotopes including collection and transfer and polarizaiton of radon isotopes by spin exchange and detection by gamma-ray anisotropy
- Develop advanced detection techniques (optical magnetometry) for two-photon excitation and readout of xenon and radon isotopes
- Develop and test magnetic shielding for EDM measurements including radon and the neutron
- Advance understanding and interpretation of EDM measurements
- Provide data on the unmeasured level structure of neutron-rich Rn isotopes.
- Develop new techniques for ^{238}U fragmentation studies at NSCL, which will also provide important technical developments for FRIB.
- Provide data that will be important to clarifying Schiff-moment enhancements in Rn isotopes.
- Provide direct measurements of ^{225}Ra octupole collectivity that will reduce uncertainty on its Schiff-moment enhancements.
- Measure octupole collectivity in odd-A and even-A isotopes to address outstanding questions regarding octupole deformation in the region A=86-88 and N=85-85.

We have succeeded at all of these goals with the following details:

- Developed and the collection and transfer apparatus at TRIUMF and tested with ^{120}Xe. Publications include the technical details of the apparatus, measurments of gas diffusion in metal foils and a new half-life measurement of ^{120}Xe.
- We have developed laser based magnetometry and successfully observed 2-photon transitions with 254 nm CW light in xenon. We have also developed noble-gas spin precession techniques to study the magnetic enviornments developed for our rare-isotope EDM measurments as well as neutron EDM measurements in the US. The work is being completed and publication will follow.
- We have help established the world's best magnetically shielded room and measured its performance and reported results in two papers.

- We have completed the first global analysis of all EDM measurments in the context of Effective Field Theory and published a paper on the results.

- We have taken part in measurements of gamma-ray spectra from coulomb-exchange-excited even-A isotopes of Rn and Ra at ISOLDE. Data on ^{220}Rn and ^{224}Ra were collected in summer 2011. The final analysis has been completed and a paper was published in Nature (May 9, 2013) that provides the first direct evidence of octupole collectivity with measurements of β_3 for both nuclei. Further conclusions include that ^{224}Ra is permanently deformed, though more weakly than ^{226}Ra, while ^{220}Rn has comparable octupole correlations but is most probably an octupole-vibrator. This, combined with evidence that ^{222}Rn is also a vibrator provide evidence that ^{221}Rn is not deformed. By similar reasoning, this suggests that ^{225}Ra **is** deformed with β_3 similar to ^{224}Ra. These results will surely lead to more detailed theoretical work; however the impact on octupole enhancement of the Schiff moment and atomic EDMs is most likely that the enhancement in ^{225}Ra is larger (e.g. up to an order of magnitude) than in ^{221}Rn, though enhancement in ^{223}Rn may be similarly to ^{225}Ra. On the other hand, the Schiff moment of ^{221}Rn, proportional to β_3^2, is likely to be significantly enhanced for ^{221}Rn relative to ^{199}Hg. At any rate, these results strengthen the motivation to pursue the Radon-EDM program.

- We attempted to extend the coulomb-exchange studies to odd-A ^{221}Rn in order to directly study the octupole collectivity (as opposed to the somewhat indirect reasoning regarding ^{221}Rn discussed in the preceding paragraph). There was significantly less beam than anticipated; however we did identify three new lines in the 200-300 keV range, which are shown in Fig. 1. ISOLDE is in shut-down mode for several upgrades, and when the beam returns in late 2015, we anticipate scheduling of continued experiments on more neutron-rich isotopes.

- In February, 2013, we ran NSCL experiment 12006, in-beam gamma-spectroscopy and fragmentation of ^{238}U. In this experiment, the GRETINA array viewed an active diamond/carbon target that induced fragmentation and fission of the incident 80 MeV/nucleon ^{238}U. The products (energy-degraded primary beam, heavy fragments and fission products) were momentum analyzed in the S-800 spectrometer with ΔE, energy and position resolution along with timing provided by the active target. A tune-up run preceded the three-day S-12006 production run. . Preliminary analysis (see Fig. 2 suggests that fission and heavy fragments up to Z 60 are clearly identified and separated though the particle-ID resolution appears to be limited for higher Z. A large amount of data were collected and further analysis for all detected fragments is underway.

- The use of actinide targets at TRIUMF-ISOLDE has allowed development work that will lead to At beams that populate excited states of Rn for identification of spin and parities. A new efficient 3-step laser ionization process was developed by the TRILIS group by starting with ^{199}At and moving up to neutron-rich ^{219}At. The 8-π spectrometer was used to identify the isotopes. One problem is contamination from easily ionized Fr isotopes;

however for short lived alpha emitters this is manageable, in contrast longer-lived Fr and Ac isotopes with lifetimes¿ 1 min. led to a large surface ionized contamination of the beam that completely dominated the much less intense laser-ionized At isobars. TRIUMF has assigned Beam Development Priority 1 to the ^{221}At beam for S929, and a major effort has led to development of the IG-LIS (Ion-Guide-Laser-Ion-Source). With the IG-LIS, surface-ionized beam contamination is suppressed by combining the laser ion source with an RFQ. IG-LIS has been successfully commissioned at ISAC using a SiC target, and a 6 order of magnitude reduction in surface ions and a factor of 50 reduction in the unwanted laser-ionized species were observed. The suppression may be somewhat different for heavier masses, but are very encouraging at this time. For ^{221}At we can anticipate around 20 s^{-1} ^{221}At delivered to the 8π compared to expected contamination of 40 s^{-1} ^{221}Fr and 400 s^{-1} of ^{221}Ra. These levels of contamination should allow for low-background measurements with the 8-π spectrometer. A December, 2013, run is planned with a UCx target to provide the At beam to the 8π spectrometer for the ^{221}Rn structure studies (the last experiment planned with the 8π spectrometer.

- We have developed a new method of detecting the NMR-precession of noble gases, specifically ^{129}Xe using a 2-photon transition. This will be directly applicable to a Radon-EDM experiment and will provide the most sensitive possible measurement more sensitive than the previously proposed methods observing nuclear decays. This has been motivated most directly by the ideas for a ^{129}Xe co-magnetometer for neutron-EDM measurements (the ^{129}Xe would take the place of ^{199}Hg used in the ILL experiment). Conventional 1-photon magnetometers are not practical for the 147 nm transition; however two-256 nm photons will populate the triplet-D state from the ground state. In our scheme, the two photons are circularly polarized, and will thus effect only Δm=2 transitions serving to probe the ground state polarization. Precession of the nuclear spin will lead to modulation of the fluorescence, absorption or optical rotation at the Larmor frequency. We have been working on a model-experiment in Yb, which is a 2-electron atom with atomic structure similar to xenon, and will test the scheme with xenon in collaboration with E. Babcock and P. Fierlinger groups at Garching, who have appropriate lasers for both ^{129}Xe polarization and 2-photon magnetometry. Two-photon noble-gas magnetometry also has broader applications to magnetic field measurements in environments where freely diffusing gasses are useful.

- It's important to include the work underway on a global analysis for interpretation of EDM experimental results in collaboration with M. Ramsey-Musolf that is part of our invited Reviews of Modern Physics article on EDMs. The crux of our analysis has isolated six EDM observables that constrain combinations of the larger set of (13) effective-field theory parameters (see [1]), and this points to the importance of several on going EDM endeavors including octupole deformed ^{225}Ra and Radon-EDM experiments and improvement of ^{129}Xe sensitivity as well as a potential proton-EDM measurement.

- Papers:

"Nuclear and Atomic Electric Dipole Moments," Tim Chupp, Nucl. Phys. A. 827, 428-435 (2009).

"Electric Dipole Moments of Atoms and Molecules," T. Chupp Advances in AMO Physics vol. 59, 129-174 (2010).

"A next generation measurement of the electric dipole moment of the neutron at the FRMII," I. Altarev, D.H. Beck, S. Chesnevskaya, T. Chupp, W. Feldmeir, P. Fierlinger, A. Frei, E. Gutsmiedl, F. Kuchler, P Link, T. Lins, M. Marino, J. McAndrew, S. Paul, G. Petzoldt, A. Phichmaier, R. Stoepler, S. Stuiber, B Taubenheim, Nuovo Cim. C035N04 122 (2012).

"Time reversal and the neutron," T.E. Chupp , Hyperfine Interactions 214, 97 (2013).

"Tests of fundamental physics with optical magnetometers," D. F. Jackson Kimball, S. K. Lamoreaux and T. E. Chupp in Optical Magnetometry, D.F. Jackson and D. Budker (ed) ISBN:9781107010352, .), Cambridge U.P., March 2013

"Studies of nuclear pear-shapes using accelerated radioactive beams" L. P. Gaffney, et al. Nature 497, 199 (2013) - doi:10.1038/nature12073.

Improved Measurement of the Half-Life of ^{121}Xe, E. R. Tardiff, G. C. Ball, T. E. Chupp, D. S. Cross, C. Cunningham, G. Demand, A. Diaz-Varela, M. Djongolov, R. Dunlop, P. Finlay, A. B. Garnsworthy, P. Garrett, K. L. Green, G. Hackman, M. E. Hayden, D. Jamieson, C. A. Kierans, W. Lorenzon, M. R. Pearson, E. T. Rand, C. Sumithrarachchi, C. E. Svensson, S. Triambak, S. J. Williams, J. Wong, and J. Zirnstein, in preparatin for submission to Phys. Rev. C.

The Radon EDM Apparatus E.R. Tardiff E.T. Rand G.C. Ball T.E. Chupp A.B. Garnsworthy P. Garrett M.E. Hayden C.A. Kierans W. Lorenzon M.R. Pearson C. Schaub C.E. Svensson, Hyperfine Interactions

A magnetically shielded room with ultra low residual field and gradient, I. Altarev, E. Babcock, D. Beck, M. Burghoff, S. Chesnevskaya, T. Chupp, S. Degenkolb, I. Fan, P. Fierlinger, A. Frei, E. Gutsmiedl, S. Knappe-Grneberg, F. Kuchler, T. Lauer, P. Link, T. Lins, M. Marino, J. McAndrew, B. Niessen, S. Paul, G. Petzoldt, U. Schlaepfer, A. Schnabel, S. Sharma, J. Singh, R. Stoepler, S. Stuiber, M. Sturm, B. Taubenheim, L. Trahms, J. Voigt, and T. Zechlau, Rev. Sci. Instruments 85, 075106 (2014).

Fundamental Symmetries at the Intensity Frontier, J.L. Hewett *et al.* arXiv:1205.2671.

Determination of the B(E3, 0(+) -¿ 3(-))-excitation strength in octupole-correlated nuclei near A approximate to 224 by the means of Coulomb excitation at REX-ISOLDE, M. Scheck et al., Journal of Physics Conference Series, 533, 012007 (2014).

A large-scale magnetic shield with 106 damping at mHz frequencies , I. Altarev, M. Bales, K. Fierlinger, P. Fierlinger, F. Kuchler, M. G. Marino, B. Niessen, G. Petzoldt, J. T. Singh, R. Stoepler, S. Stuiber, M. Sturm, and B. Taubenheim , D. H. Beck, T. Chupp, T.

Lins, U. Schlaepfer, A. Schnabel and J. Voigt, JOURNAL OF APPLIED PHYSICS 117, 183903 (2015).

Electic dipole moments: a global analysis, T.E. Chupp, M.J. Ramsey-Musolf, Phys. Rev.C 91 035502 (2015).

- Professor Chupp has given over 20 invited talks on EDMs and related topics as follows:

  Electric Dipole Moment Measurements with Radon Isotopes, Helion 2002, Mainz, Germany (September 2002).

  Electric Dipole Moment Measurements with Radon Isotopes, Institute for Nuclear Theory Seminar, University of Washington (October 2002).

  Electric Dipole Moment Measurements with Radon Isotopes, RIA Detector Workshop (March 2003).

  Laser Polarized Noble Gases, Colloquium, Oakland University (April 2003).

  Fundamental Interaction Studies, RIA Summer School (August 2003). Introductory Talk on Fundamental Interactions, RIA Workshop (2004).

  Electric Dipole Moment Experiments with Rare Isotopes, Invited talk for Canadian Association of Physics Annual Meeting (June 2005)

  Electric Dipole Moment Measurements with Rare Isotopes, ISOLDE Seminar (CERN), Geneva, Switzerland (March 2006)

  Summary, RIA Theory Workshop, Argonne, Ill. (April 2006)

  Fundamental Symmetries in Nuclear Physics, RIA-JLab Workshop, Washington, DC (October 2006)

  The Radon-EDM Experiment, Institute for Nuclear Theory CP violation workshop, Seattle (March 2007).

  The Radon-EDM Experiment, RIA Theory Workshop, Seattle (September 2007).

  Electric Dipole Moments, Panic, Eilat Israel (2008)

  EDM Measurements with Octupole Deformed Nuclei Tel Aviv University (November 2008).

  The Radon EDM Experiment, Michigan State University, February 2009.

  Electric Dipole Moments: neutron atoms molecules, Summer School Lecture, National Nuclear Physics Summer School, East Lansing, July 3, 2009.

  Fundamental Symmetry Studies with Rare Atoms Colloquium: Old Dominion University, Norfolk, VA March 16, 2010.

  Atomic Electric Dipole Moments, Invited Talk at Canadian Association of Physics Annual Meeting, Toronto, June 7-11, 2010.

Electric Dipole Moment Measurements with Rare Atoms, Invited Talk International Workshop on EDMs and Related Topics, Shanghai Jiao Tong University, June 14-16, 2010.

Electric Dipole Moment Measurements with Rare Atoms invited talk at Modern Trends in Production and Applications of Polarized 3He, Munich July 2010

Noble Gas EDM Measurements and Noble Gas Magnetometry PSI2010 Invited Talk, October 11-14, 2010, Villigen, Switzerland.

EDMs of Rn and Xe, ECT, Trento Italy, Invited Talk, November 17, 2010.

EDM Measurement with 129Xe, Excellence-Cluster Universe, Technical University of Munich, August 30, 2011.

Atomic EDMs at the Intensity Frontier Invited Talk, Fundamental Physics at the Energy Frontier Workshop, November 30, 2011.

Probing Time-reversal invariance with atoms and neutrons, University of Wisconsin Seminar, May 17, 2012.

Low energy precision tests to limit the Standard Model, Invited Plenary Talk at Confinement X (Confinement and Hadronic Spectrum), October 11, 2012.

"Electric Dipole Moments Lunchtime Talk, Physics Department UC Berkeley, March 21, 2013.

Electric Dipole Moments AMO Seminar, University of Maryland., April 17, 2013.

International Conference on Nuclear Physics Invited Talk, The RadonEDM Experiment Florence June 2013

Ariel Science Workshop - TRIUMF, The RadonEDM Experiment, July 2013

PSI2013, The RadonEDM Program, Sept 2013

Argonne Colloquium, Pear Shaped Nuclei Nov 2013

University of Kentucky Nuclear Physics Seminar, Nov 2013

Univeristy of Kentucky Colloquium, Nov 2013

PAVI invited plenary talk: EDMs and MORE Syracuse July 2014

PTB-Berlin Colloquium, Noble-ga EDM Experiments August 2014

LesHouches, Fundamental Symmetry Experiments with Polarized Noble Gases October 2014

Amherst Center for Fundamental Interactions FRIB Workshop, EDMs Oct 2014.

APS Spring Meeting, Baltimore, Invited Talk on Fundamental Symmetries: EDM Searches with Rare Gas Atoms, April 2015

Baryon and Lepton Number Violation (BLV) workshop, Invited Talk: EDM Experimenta Overview Amherst April 2015

University of Deleware Colloquium, Electric Dipole Moments: Searching for New Physics on the Tabletop October 2015

Deutsche Forschungs Gesellshaft Priority Program meeting, WildbadKreuth, Global Analysis of EDM Experiments November 2015

Atomic EDMs, Munich Institute for Astro-Particle Physics Workshop Baryogenesis- Status of Experiment and Theory June 7, 2016.

"Atomic and Molecular EDMs, APS Division of Nuclear Physics Meeting, Vancouver, Canada, October 14, 2016

2 Impact

The Radon-EDM Experiment is part of a nested set of programs in CP-violation, fundamental symmetries and rare-atom physics that will make up a significant part of the rare-isotope and intensity frontier programs. We have the primary goal of advancing the study of CP violation and EDM techniques with rare atoms and the neutron at the most powerful facilities in the world. While the ^{199}Hg measurement is a stunning achievement that sets the bar high for all future endeavors, it cannot, alone, teach us all we need to know about CP violating EDMs. Thus we need to push techniques in several directions. The Radon-EDM Experiment has several features that make it an attractive EDM measurement, the most important of which are 1) established techniques with noble gas atoms is cells[2]; 2) co-magnetometers; and 3) octupole enhancements. We emphasize that the enhancements could span a range from tens (if there is no permanent deformation) to hundreds. If we scale the ^{199}Hg result by a factor of 10 (*i.e.* no permanent deformation - but allowing for enhancement due to collective octupole strength[3, 4]), we see that the ultimate goal of the Radon-EDM measurement is $few \times 10^{-28}$ e-cm.

3 Participants

Professors Chupp and Lorenzon at the University of Michigan. At the beginning of the project, two graduate students worked on developing the test apparatus at TRIUMF: Sarah Nuss-Warren and Eric Tardiff. Nuss-Warren left the Univeristy in 2005 and Tardiff recieved his PhD in 2008, and is currently a Research Fellow at Harvard. In 2010 graduate student Skyler Degenkolb joined the group and received his PhD in 2016. In 2013 graduate student Natasha Sachdeva joined the group. Dr. Fei Gong was supported as a post-doctoral research fellow by the Univeristy of Michigan and this grant from

The TRIUMF polarization effort was supported by John Behr in it's early stages and Matt Pearson, and the gamma-ray group includes Adam Garnsworthy and Greg Hackman. Professor Mike Hayden of Simon Fraser is an active collaborator with expertise in cryogenics, NMR, optical pumping and EDM measurements. The Guelph group, led by S-929 co-spokesman Carl Svensson along with Paul Garrett, is leading the nuclear structure studies and the gamma-ray detection development. With the notable experience and leadership provided by this collaboration, we

are poised to make full use of the ISAC beams and to continue the development of this program that will continue into the FRIB era. The ISOLDE program is led by Professor Peter Butler and a large group. At MSU the local spokesperson of 120006 is Jill Berryman and key collaborators are Alexandra Gade and Brad Sherrill.

4 Student Tracking

Student	Entry Date	Joined Group	Degree	Awarded/Expected	Advisor
Sarah Nuss Warren	09/03	07/10	MSc	2015	Chupp
Eric Tardiff	09/02	09/03	PhD.	2008	Chupp
Skyler Degenkob	09/10	07/10	PhD.	2016	Chupp
Natasha Sachdeva	09/13	09/13	PhD.	2018	Chupp

Table 1: Graduate Students.

References

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[2] M.A. Rosenberry and T. E. Chupp, *Phys. Rev. Lett.* 86, 22 (2001).

[3] V.V. Flambaum, V.G. Zelevinsky, Phys. Rev. **C68**, 035502 (2003).

[4] J. Engel, M. Bender, J. Dobaczewski, J.H. de Jesus, P. Olbratowski, *Phys. Rev.* C68, 025501 (2003).