Project Title	**Investigation of Neutrino Properties with Bolometric Detectors**
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Abstract

Neutrino mass and mixing are amongst the major discoveries of the past decade. The particle nature of neutrinos and the hierarchy of mass eigenstates, however, are unknown. Neutrinoless double beta-decay ($0\nu\beta\beta$) is the only known mechanism to test whether neutrinos are their own antiparticles. The observation of $0\nu\beta\beta$ would imply lepton number violation and show that neutrinos have Majorana mass. This report describes research activities performed at the University of Wisconsin in 2011-2014 aimed at the search for $0\nu\beta\beta$ with CUORE-0 and CUORE with the goal of exploring the inverted mass hierarchy region and probing an effective neutrino mass of ~40-120 meV.

Introduction

The experimental neutrino group at the University of Wisconsin-Madison (UW) led by Professor Karsten Heeger and Assistant Professor Reina Maruyama has led the development of instrumentation and hardware for the CUORE neutrinoless double beta decay experiment and the study of the sensitivity and discovery potential of CUORE-0 and CUORE as well as future bolometric double beta decay experiments. Specific responsibilities of the group for CUORE include the development of a detector calibration system (DCS), the doping and analysis of the thermistors for CUORE, the physics study of the CUORE discovery potential, and an analysis effort to understand and optimize the calibration of the CUORE experiment. In addition, with Assistant Professor Maruyama the Wisconsin group has taken on new physics leadership in the collaboration. This report details the activities of the Wisconsin group in 2011-2014 before the move of group of Professors Heeger and Maruyama to the Wright Laboratory at Yale University.

CUORE is a one-ton, cryogenic experiment aimed at the search for ($0\nu\beta\beta$ in ^{130}Te using 988 TeO_2 crystals at a working temperature of 10 mK. With about 200 kg of ^{130}Te CUORE is one of the largest and most sensitive upcoming experiments and will be sensitive to an effective neutrino mass down to the inverted hierarchy. Over the last decade much progress has been made in the use of bolometric detectors, and large bolometers are known to be excellent detectors for the search of neutrinoless double beta-decay. Bolometric detectors have been used for years in Cuoricino and are the detectors of choice for the CUORE experiment, the Cryogenic Underground Observatory for Rare Events under construction at Gran Sasso National Laboratory in Italy. CUORE uses crystals of TeO_2 as source and absorbers. They register the heat rise in the crystals from the energy deposited in nuclear decays with high resolution and can be made with high natural abundance of isotopes of interest for double beta-decay searches. Candidate events for neutrinoless double beta-decay are selected based on their energy near the Q-value of the transition. Calibration of the energy scale of each individual crystal is necessary for the search of neutrinoless double beta-decay and for the discrimination of backgrounds. The energy calibration of CUORE is a challenging technical and cryogenic problem that requires the insertion of movable radioactive calibration sources into the cryostat and their positioning in the detector region.

Wisconsin Group

The bolometer group at the University of Wisconsin (UW) has been led by Professor Karsten Heeger and Assistant Professor Reina Maruyama. Postdoctoral researchers involved in the work of the group over the period of this grant included Daniel Lenz and Kyungeun Lim Postdoc Lenz joined the group from the GERDA experiment in Germany. Following his work on CUORE Lenz accepted a position in industry in Germany. Lim joined the UW group in March

2013 from Columbia University where she performed here thesis work on the Xenon-100 experiment. Lim added technical expertise, on-site knowledge, and analysis leadership to the Wisconsin group. Three graduate students were supported throughout the course of this grant: Larissa Ejzak, Adam Dally and Lauren Wielgus. Graduate student Larissa Ejzak graduated in May 2013 and is now pursuing a career in science publishing. Student Adam Dally defended his thesis in December 2014. The steady-state size of the group includes 2 faculty (Heeger, Maruyama), 1 postdoctoral researcher, and 2 graduate students.

In addition, several undergraduate researchers have been involved in the work of the group over the past years. Ian Guinn worked with the UW group for over 2 years and is now a graduate student at the University of Washington in Seattle on the SNO+ experiment. Pingchuan Zhao joined the group in summer 2012 and is currently doing a senior thesis on the performance characterization of the CUORE detector calibration system with Professor Heeger.

Technical support for the group's work has been provided by senior researcher Tom Wise from the Wisconsin Physics Department as well as UW machine shops. Occasional specialized support is obtained from the UW Physical Sciences Laboratory. The UW technical efforts are supported by CUORE project funds and university support.

University Wisconsin Support and Other Contributions

Between 2011-2014 the CUORE activities of Heeger's group were supported by this DOE grant, Heeger's start-up funds, funds from Heeger's Alfred P Sloan and UW Romnes Faculty Fellowship as well as CUORE project funds through a subcontract from Lawrence Berkeley National Laboratory. Heeger and Maruyama have leveraged substantial matching funds and external support for their work on CUORE. The group has also benefited from the extensive computing support and infrastructure available at the University of Wisconsin.

Responsibilities and Activities of the Wisconsin Group

The Wisconsin group has had responsibility for key hardware and physics tasks for the CUORE-0 and CUORE experiments, and both Heeger and Maruyama hold management and leadership positions in the collaboration. The responsibilities and leadership positions of the Wisconsin group are listed below.

<u>Management and leadership activities</u> include the following:

- Maruyama was appointed as the US Physics Coordinator
- Heeger is the technical lead for the detector calibration system and a member of the cryostat technical coordinator board
- Heeger is the first elected Chair of the CUORE Council
- Both Heeger and Maruyama are active members of the editorial group for publications
- Maruyama completed her term on the Publication Board
- Heeger completed his term as Chair of the Data Vetting Board

<u>Instrumentation, hardware, and project activities</u> of the Wisconsin group include

- Development, installation, and commissioning of a detector calibration system with radioactive sources
- Techniques for the characterization of neutron transmutation doped thermistors
- Integration and commissioning activities between the calibration system and the cryostat

Physics analyses led by Wisconsin students and postdocs include

- Sensitivity and discovery potential of the CUORE experiments (Ejzak)
- Energy calibration for a sensitive search for neutrinoless double beta decay: Using the Cuoricino experience to prepare for CUORE (Ejzak)
- Low-energy analysis of CUORE-0 data (Wielgus)

CUORE support activities

- Heeger and the Wisconsin group provide web-based communication systems including a wiki, several mailing lists, and electronic logbooks to the collaboration
- Shifts for data taking and commissioning activities of CUORE-0 are provided by all members of the group

As leader of the CUORE detector calibration system Professor Heeger has had overall responsibility for the design, construction, installation, and commissioning of the detector calibration system for CUORE. This represents one of the key deliverables of the US CUORE project to the experiment. Heeger brings extensive experience in the design and construction of low-background instrumentation and large detector systems to the project, and he represents this subsystem on the CUORE cryogenic technical coordinator board. Heeger also guided Wisconsin students in the studies of the CUORE sensitivity and discovery potential and in developing an optimized calibration strategy for CUORE. This is the main focus of Ejzaks's PhD thesis. In addition, Heeger has taken on a leadership role in the organization of the CUORE Council and related collaboration matters.

Assistant Professor Maruyama was one of the original members of the US Cuoricino collaboration and she is now a faculty member and co-investigator on CUORE. Maruyama led the characterization of the Neutron Transmutation Doped (NTD) thermistors for the CUORE bolometer array and was recently appointed as the US Physics Coordinator. With the start of data taking for CUORE-0 and the anticipated release of first results at TAUP2013 Maruyama now fulfills a central role as US physics coordinator in the collaboration.

Postdoctoral researcher Daniel Lenz and Kyungeun Lim organized the system testing of the detector calibration system in Wisconsin, played a lead role in the DCS hardware installation at LNGS, and are providing critical on-site presence for both the Wisconsin group and US CUORE at LNGS. Lim has also been involved in the analysis of CUORE-0 data.

Accomplishments and Highlights

Development of the Detector Calibration System for CUORE

The CUORE detector calibration system (DCS) consists of 12 radioactive source strings that are able to move, under their own weight, through a set of guide tubes that route them from outside the cryostat at 300K to their locations between the bolometers in the detector region inside the cryostat. The DCS consists of a vacuum motion system above the 300K flange, a thermalization mechanism at the 4K stage of the cryostat, and a set of guide tubes in the lower region of the cryostat. Weak ^{232}Th radioactive sources are integrated into a Kevlar-based string with copper crimps and teflon coating to minimize friction. For the energy calibration of the CUORE detector array with radioactive sources the source strings are moved into the detector region of the cryostat, and removed during regular data taking. The calibration of the entire array

of 988 crystals is expected to take about 1 day, plus about 1-2 days of insertion and retraction time. The source insertion and energy calibration with radioactive sources are expected to be performed about once a month during the regular operation of CUORE.

The Wisconsin group developed the original design concept for the system and has made significant technical progress towards the final installation and commissioning of the detector calibration system:

- We completed the fabrication and off-site testing of the hardware at Wisconsin. The hardware is now at LNGS for the 4K cold test in the CUORE cryostat.
- The cooldown concept of the system was demonstrated down to 9K in a cold test at Wisconsin.
- Following cold testing at Wisconsin several cryogenic motion parts were simplified and re-designed to ensure reliable, long-term functionality of the system.
- DCS installation work on-site started in summer 2012 and major elements of the DCS have now been installed
- First cooldown of the DCS down to 4K inside the CUORE cryostat was performed in summer 2013 with subsequent cooldowns and cold tests at LNGS in 2014.
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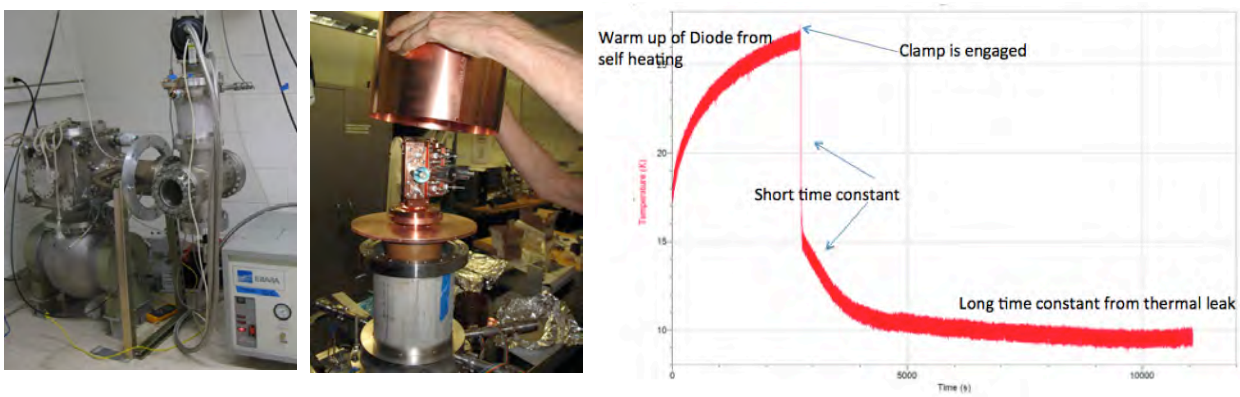

Figure 1: Cold test of the DCS thermalizer system down to 9K. Left: Experimental setup at UW. Middle: Cold-head and thermalizer. Right: Data showing the cooldown to 9K during the engagement of the thermalizer mechanism.

Figure 2: Calibration system tests in Wisconsin. Left: Full-scale motion setup. 2nd from left: Detail of thermalizer system. 2nd from right: Motion system for source strings. Right: Details of string motion system and pulley design.

Figure 3: Installation of calibration components on-site by the Wisconsin group. Left: Researcher Wise installing guide tube assemblies. Middle: Students Wielgus and Dally installating the first DCS motion box. Right: Student Dally and postdoc Lim working on the 4K cryostat plate.

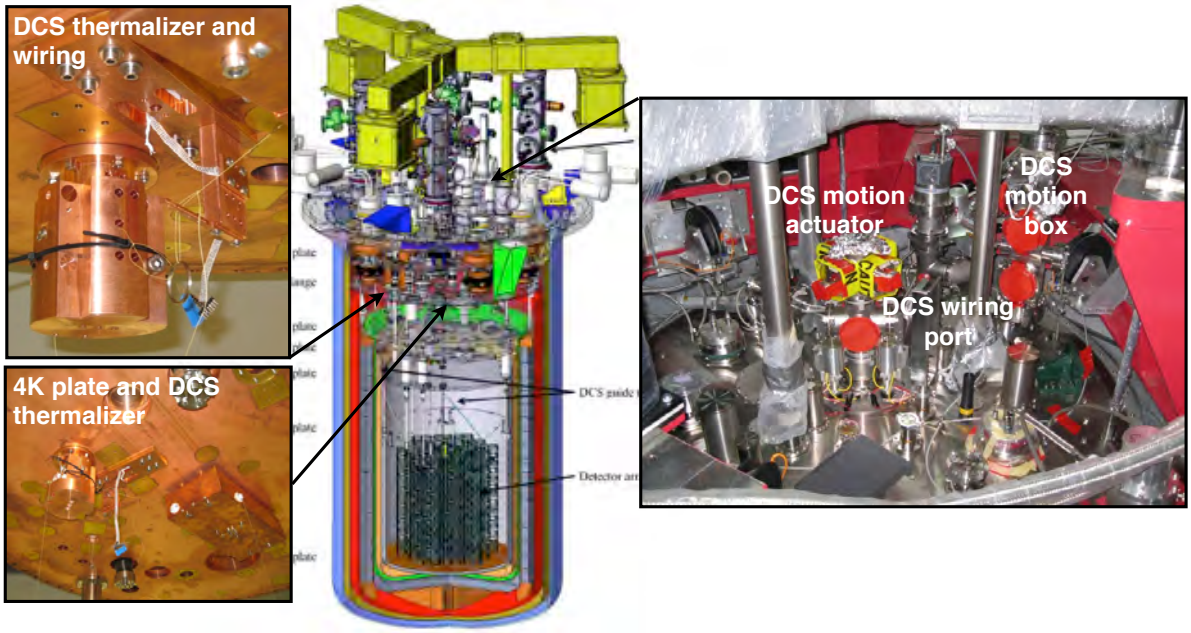

Figure 4: Status of the DCS hardware installation in the cryostat. Some of the major components including the motion components on top of the 300K plate (right) and below the 4K plate (left) have been installed.

Installation and Commissioning of Detector Calibration System

In 2013-2014 the Wisconsin group completed most of the CUORE detector calibration system. This includes the fabrication of the motion boxes and drive spools, the design and integration of the guide tubes in the detector region, and the delivery of all remaining DCS hardware to LNGS. Installation of the DCS systems into the cryostat has continued through 2014 and follows closely the on-site assembly and commissioning of the CUORE cryostat. The Wisconsin group has closely coordinated on-site installation activities with the cryostat group. Frequent and extended on-site presence by Wisconsin personnel has been essential to perform these tasks. Postdoctoral researcher Lim has provided scientific oversight for the on-site work, while senior researcher Wise has been responsible for the technical aspects of the DCS work.

Cryostat Commissioning and Integration

The commissioning of the CUORE cryostat is a critical element in the start-up of CUORE. The detector calibration system shares many interfaces with the CUORE cryostat and close coordination between the various technical groups has been critical. As a technical expert senior researcher Tom Wise has been key to the successful integration of the DCS into the CUORE cryostat and the integration of these subsystems. His effort is supported by CUORE project and UW funds but his role is key to the successful completion of the calibration task mentioned above. Faculty Heeger has coordinated the role of Tom Wise in the CUORE work.

CUORE Assembly and Commissioning

Assembly and commissioning of the CUORE detector has been one of the primary focus of the collaboration in 2013-2014. This has required a focused effort of experienced on-site personnel – both technical and scientific. From the Wisconsin group, faculty Heeger, Researcher Wise, postdoc Lim and graduate student Dally have been actively involved in the on-site

hardware activities. Lim has split her time between the onsite work for the DCS and the CUORE detector, and CUORE-0 data analysis activities.

Optimization of the CUORE Energy Calibration

As part of the thesis work on the energy calibration for CUORE, graduate student Larissa Ejzak optimized the peak identification of gamma lines from the ^{232}Th sources and optimized the calibration time for a source calibration inside the cryostat. The results of this work are documented in her thesis and shown below. The thesis was submitted in May 2013 as partial fulfillment of her dissertation. Figure 5 shows the energy calibration spectrum from ^{232}Th sources, the simulated hit rate in a layer of the CUORE detector array, as well as the calibration time requirements for all 988 CUORE channels. The results of this work show that a calibration of the entire CUORE detector array can be performed in 1-2 days.

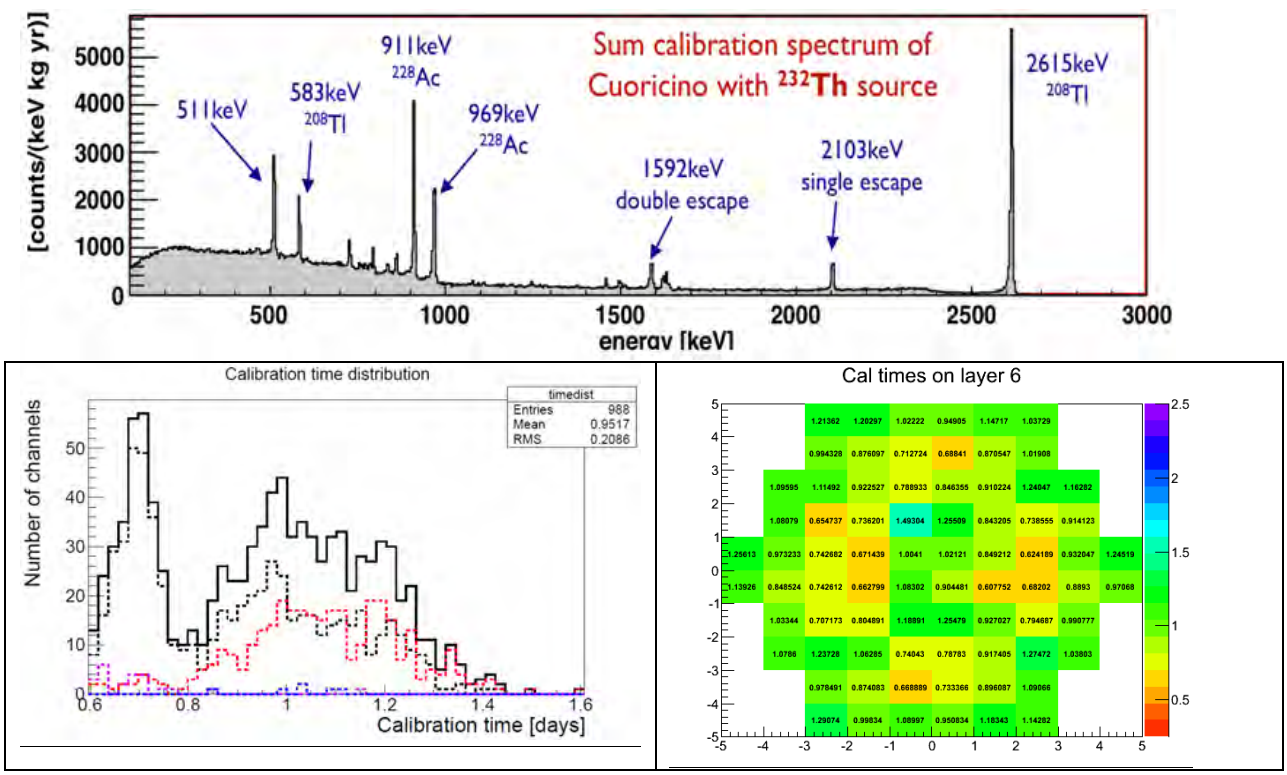

Figure 5: Calibration spectrum from radioactive Th sources (top), hit pattern in a middle layer of the CUORE detector array (right), and time required to calibrate the CUORE channels. Within 1.5 days all bolometers can be calibrated with 5 gamma lines.

Study of the Sensitivity and Discovery Potential of CUORE

Graduate student Larissa Ejzak also completed a study of the sensitivity and discovery potential of the CUORE-0 and CUORE experiments. The results of this work have been adapted as the official CUORE sensitivity study and have been submitted for journal publication. Figures 6-7 below show the main results from the work. CUORE remains one of the leading next-generation double beta decay experiments with the ability to probe the inverted hierarchy. Its sensitivity is comparable to other ongoing experiments within the uncertainties of the nuclear matrix elements. While SNO+' decision to load the scintillator with ^{130}Te may yield comparable sensitivity limits in case of a null result, an unambiguous discovery of $0\nu\beta\beta$ will require the

identification of a peak near the Q-value. With its excellent energy resolution of about 5keV and the expected low background of about 0.01 counts/kev-kg-yr CUORE will be in an excellent position to make this potential discovery.

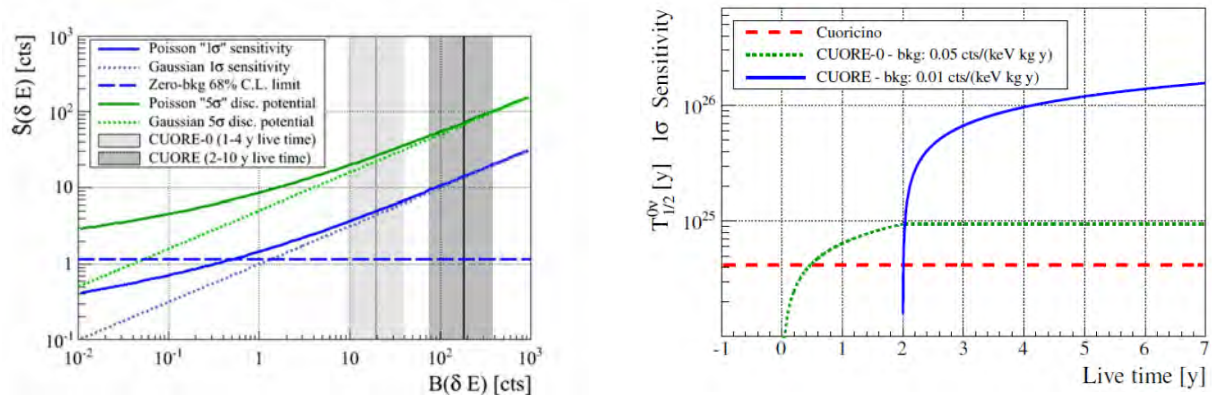

Figure 6: Discovery potential and sensitivity limits for the CUORE-0 and CUORE experiments as a function of background counts and livetime. All figures courtesy of L.Ejzak, Wisconsin.

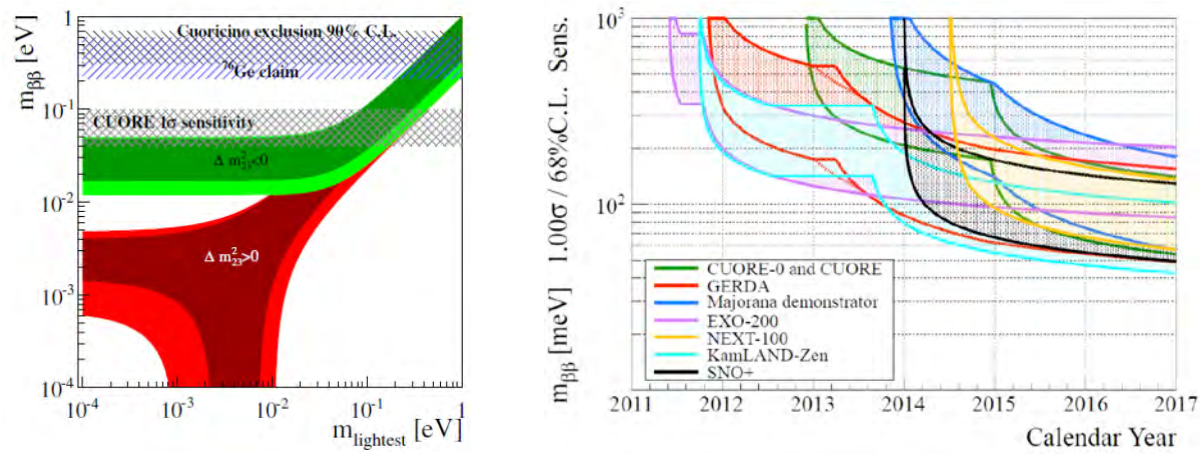

Figure 7: Discovery potential and sensitivity limits for the CUORE-0 and CUORE experiments as a function of background counts and livetime. All figures courtesy of L.Ejzak, Wisconsin.

<u>Analysis of CUORE-0 Data</u>

With the start of CUROE-0 data taking in 2012 the Wisconsin group as well as the CUORE collaboration as a whole has started to prepare the analysis of CUORE-0 data. As US Physics Coordinator, Maruyama has organized the US analysis effort, and the interface with the Italian part of the CUORE collaboration. Postdoc Lim and graduate student Wielgus have focused at leats half time on the data analysis. They will take responsibility for the calibration and calibration processing of CUORE-0 and in the overall analysis for neutrinoless and two-neutrino double beta decay. Assistant Professor Maruyama has guided this work in the Wisconsin group.

Synergistic and Professional Activities

Professor Heeger and Maruyama are regular reviewers for DOE, NSF, and NSERC as well as several scientific journals including PRC. In 2012 Heeger was appointed associate editor

for the European Physics Journal C. Heeger was the 2012-2013 chair of the APS Committee on International Scientific Affairs (CISA) and led the development of the APS program with China. Both Heeger and Maruyama regularly organize conferences and workshops.

Transition of the Heeger-Maruyama Group to Yale University

In May 2013 Heeger and Maruyama accepted offers to join the Physics Department at Yale University starting in summer 2013. While the official appointment of Heeger and Maruyama has started in summer 2013 it took through 2014 to transition the Wisconsin group to the Yale Wright Laboratory. This is the final report for the group's activities at the University of Wisconsin. Heeger and Maruyama now continue their research activities under a new grant at the Wright Laboratory at Yale University.

Graduate Students

During the course of this grant the Wisconsin group mentored three graduate students. Larissa Ejzak defend her thesis in May 2013 and Adam Dally in December 2014. Over the grant period the steady-state size of the group included 2 students. The student data and thesis titles are shown below.

Student's Name	*Entered Graduate School*	*Joined Group*	*Mentor*	*(Expected) Date of Graduation*
Larissa Ejzak	August 2006	January 2007	K. Heeger	May 2013
Adam Dally	August 2007	September 2010	K. Heeger	December 2014
Lauren Wielgus	August 2011	July 2012	R. Maruyama	July 2016

The thesis titles of the Wisconsin graduate students are listed below:

" Energy Calibration for a Sensitive Search for Neutrinoless Double-Beta Decay: Using the Cuoricino Experience to Prepare for CUORE"
L. Ejzak, graduated in May 2013

"Development and Characterization of an Energy Calibration for the CUORE Bolometric Detector Array"
A. Dally, graduated in December 2014

"Study of the Low-Energy Spectrum of CUORE-0 for Rare Event Searches"
L. Wielgus, expected graduation in July 2016

Journal Publications and Products Related to this Award

This section lists journal publications as well as other significant products related to the work performed under this award in 2011-2014.

Journal Publications

10. *CUORE and beyond: bolometric techniques to explore inverted neutrino mass hierarchy*
D.R. Artusa et al., arXiv:1407.1094

9. *Exploring the Neutrinoless Double Beta Decay in the Inverted Neutrino Hierarchy with Bolometric Detectors*
D.R. Artusa et al. (CUORE Collaboration),
Eur.Phys.J. C74 (2014) 10, 3096

8. *Searching for neutrinoless double-beta decay of ^{130}Te with CUORE*
D.R Artusa et al (CUORE Collaboration),
arXiv:1402.6072

7. *Initial Performance of the CUORE-0 Experiment*
C.P. Aguirre *et al.* (CUORE Collaboration),
Eur.Phys.J. C74 (2014) 8, 2956

6. *Sensitivity of Discovery Potential of CUORE to Neutrinoless Double Beta Decay*
F. Alessandria et al. (CUORE Collaboration),
arXiv:1109.0494, Submitted to Astroparticle Physics (2012)

5. *Validation of techniques to mitigate copper surface contamination in CUORE*
F. Alessandria et al. (CUORE Collaboration),
arXiv: 1210.1107, Submitted to JCAP (2012)

4. *Search for 14.4 keV solar axions from M1 transition of Fe-57 with CUORE crystals*
F. Alessandria et al. (CUORE Collaboration),
arXiv:1209.2800, Submitted to JCAP (2012)

3. *The low energy spectrum of TeO_2 bolometers: results and dark matter perspectives for the CUORE-0 and CUORE experiments*
F. Alessandria et al. (CUORE Collaboration),
JCAP 1301 (2013) 038

2. *Target Mass Monitoring and Instrumentation in the Daya Bay Antineutrino Detectors*
H.Band et al.,
arXiv: 1206.7082, Submitted to JINST (2012)

1. *CUORE Crystal Validation Runs: Results on Radioactive Contamination and Extrapolation to CUORE Backgrounds*

F. Alessandria et al. (CUORE Collaboration),
Astropart.Phys. 35, 839-849 (2012)

Conference Proceedings

1. *Status of the Cryogen-free Cryogenic System for the CUORE Experiment*
A. Nucciotti et al.
14th International Workshop on Low-Temperature Detectors (LTD-14), (2012)

Whitepapers and Reports Related to this Award

Discovering the New Standard Model: Fundamental Symmetries and Neutrinos
V. Cianciolo et al.,
arXiv:1212.5190 20120

Invited Lectures at Schools

V. International Pontecorvo Neutrino Physics School,
Alushta, Crimea, Ukraine, September 6-16, 2012
http://pontecorvosch.jinr.ru/General.html

4th International Summer School on Neutrino Physics (INSS) 2012
Virginia Polytechnic Institute and State University, VA, USA, July 10-21, 2012
http://cnp.phys.vt.edu/inss2012.html

EDIT2012 – Excellence in Detectors and Instrumentation Technologies
Fermilab, Batavia, Il, USA, February 13-24, 2012
http://detectors.fnal.gov/EDIT2012/