FINAL REPORT

Federal Agency and Organization: DOE, Office of Science, High Energy Physics Program
Grant number: DE-FG02-03ER41255
Project title: New Technique for Barium Daughter Ion Identification in a Liquid Xe-136 Double Beta Decay Experiment
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Recipient Organization: Colorado State University, Sponsored Programs, 2002 Campus Delivery, Fort Collins, CO 80523-2002
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ACCOMPLISHMENTS:

Major goals and objectives of the project:

(1) EXO-200 operation

The CSU group of up to 3-4 graduate students and one faculty member comprises a significant portion of the EXO Collaboration. Objective (1) is to fill a proportionate share of the shifts on EXO-200 at the detector site, the Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico and at a remote operations center at CSU.

(2) EXO-200 analysis

Since the first EXO-200 physics data in spring 2011, the CSU group has been active in analysis of EXO-200 data. A specific objective in EXO-200 analysis for the CSU group is analysis of alpha and beta decay events in the liquid xenon (LXe) detector in the radon chains.

(3) Ba^+ tagging research

This DOE grant supported a portion of the CSU research in Ba^+ tagging for background elimination in the next generation EXO experiment, nEXO. Specific goals this period related to this original concept included: (a) completing studies of observed fluorescence, Ba^+ or some other ion species, in LXe (K. Hall thesis), (b) monitoring the species entering the LXe from gaseous Xe (GXe) using a tunable dye laser (C. Benitez thesis), (c) initial work on detecting small numbers of Ba atoms in solid xenon (SXe), (d) studies of freezing solid xenon (SXe) on the end of a cold probe dipped in LXe for a second and more successful method of Ba tagging of capturing ^{136}Ba daughters in solid xenon on the end of a probe inserted into LXe to the decay site and (e) support of other Ba^+ tagging research within the EXO Collaboration.

Accomplishments under these goals:

(1) EXO-200 operation (goal 1)

A major portion of the DOE funding supports CSU's role in the operation of the EXO-200 experiment and in data analysis for the EXO-200 experiment. The PI and his graduate students have taken shifts running the EXO-200 experiment at the Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM and have achieved "expert shifter" status. Since January, 2014, we have also had a remote EXO-200 operation station at Colorado State University. We fulfilled our budgeted commitment to EXO-200 operations through the funding DOE has provided.

The EXO-200 experiment has been very successful. Four landmark papers with new ^{136}Xe double beta decay results were published. (1) From the first months of data taken in 2011,

two-neutrino double beta decay of ^{136}Xe was discovered. The lifetime was 2.11 +- 0.04 (stat) +- 0.21 (sys) x 10^{21} yr.[1] (2) A world's best half-life limit on neutrinoless double beta decay of $1.6x10^{25}$ yr (90% C.L.) and effective Majorana mass limit of less than 140–380 meV was published in 2012.[2] This publication was the first to put significant constraints on the claim of a positive result in ^{76}Ge.[3] (3) A The new 2νββ half-life result, 2.165 +- 0.016 (stat) +- 0.059 (sys) x 10^{21} yr was published in 2013.[4] This is the most precisely measured half-life of any 2νββ decay. (4) New 0νββ decay limits based on 2 years of data taking were published in Nature in June, 2014.[5] The 90% CL half-life sensitivity of $1.9x10^{25}$ yr is the best published value to date for ^{136}Xe. For most nuclear matrix elements, the EXO-200 sensitivity compares favorably with the other leading experiments.

Many additional EXO-200 papers have been published with CSU co-authors and are listed in the publications section. These include detailed detector papers, limits on neutrinoless double beta decay with Majoron emission, limits on double beta decays to excited states, etc.

(2) EXO-200 analysis (goal 2)

The PI, W. Fairbank, and two past students have studied alpha decay events in the detector, beginning with the first data taking. Our group did the analysis that determined the ^{222}Rn content in the detector, 3.6±0.7 μBq/kg. This experimental value fixed internal ^{238}U chain backgrounds in the 0νββ window in energy. 3-D plots of ^{222}Rn peak scintillation signals also provide corrections on the "light map" determined by calibration data that spatially corrects the scintillation energy of beta, gamma and 2-beta events in the detector.

A more comprehensive analysis of the ^{222}Rn chain, led former CSU student, Brian Mong, a postdoc on EXO at Laurentian University in Canada, and the PI, W. Fairbank, resulted the first measurement of the fraction of ionized daughter atoms from alpha and beta decay in a liquid noble gas detector: 50.3±3.0% for ^{218}Po daughter atoms from ^{222}Rn alpha decay and 76.4±5.7% for ^{214}Bi daughters of ^{214}Pb beta decay.[6]. An unexpected result of this work was the observation of a change in the average drift velocity of the ^{218}Po daughter ions along their path, from 1.48±0.01 mm/s at small Δt to 0.83±0.01 mm/s at large Δt. This is indicative of a chemical reaction or a charge transfer reaction that is correlated with the measured electron lifetime in the detector, but is not understood yet.

The daughter ion fraction is also important for nucleon decay studies in which the CSU group now has a lead role. The lifetime for various modes of nucleon decay can be determined by setting limits for beta decays of daughter atoms in the detector, e.g., of ^{133}Sb from ppp decay. However, for charged daughters with half-lives greater than a typical ion transit time in the detector, a significant fraction of the daughters decay on the cathode. Thus an estimate of the neutral daughter fraction is needed to quantify the relative bulk and cathode components. As a part of the work for this project, the CSU group developed a preliminary model of daughter ion fractions for extending the ^{218}Po and ^{214}Bi daughter ion fraction measurements in this work to other cases, such as ppp decay and ^{136}Ba daughters from 0νββ double beta decay.

(3) Barium tagging progress under DOE support (goal 3)

Kendy Hall completed his Ph.D. thesis on studies of fluorescence of ions in LXe from laser ablation of Ba metal targets above LXe (goal 3a). A novel result from his work was the discovery of 2- and 3-photon ionization of LXe by pulsed ultraviolet lasers. Ionization cross sections were measured for two wavelengths.

Cesar Benitez completed his Ph. D. thesis on detailed measurements of Ba^+ ions from laser ablation in gaseous xenon (goal 3b). Important results contained in this thesis include: (1) measurements of the pressure broadening of Ba^+ ions in gaseous xenon (GXe) at different

pressures, (2) determination of the fluorescence efficiency of Ba^+ in GXe, (3) measurements of the mobility of Ba^+ in GXe, and (4) determination of the relative rates of 3-body association and 2-body dissociation reactions that lead to a varying percentage of Ba^+ atomic ions and $BaXe^+$ molecular ions in gaseous xenon at different pressures.

This project also supported the final work of Shon Cook's Ph.D. thesis on detecting small numbers of Ba atoms in SXe (goal 3c). Spectra of small numbers of Ba atoms were recorded. This was the seminal work forming a basis for a 2015 paper on spectroscopy of Ba atoms in SXe.[7]

With the success of Cook's research, the single Ba detection work in SXe has been supported by a separate NSF grant, while this DOE grant has supported separate studies on freezing SXe on a cold probe in LXe (goal 3d). A modified medical cryoprobe, cooled by Joule-Thomsen expansion of high pressure argon inside the end of the probe, has been used to freeze cylinders and balls of SXe on the probe tip while immersed in LXe. The solid xenon is completely transparent. Measurements of the radius of the xenon "ice" cylinder as a function of time with various argon gas pressures have been taken and fit with a thermodynamic model. With a probe extraction apparatus built on top of the LXe cell, probes with SXe frozen have been extracted from LXe and successfully raised to an observation region. After closure of a valve, the temperature of the probe and Xe gas pressure can be lowered to optimum conditions for detection of single Ba atoms in the SXe on the probe. These are significant milestones in our plans for barium tagging in solid xenon on a probe.

CSU currently contributes through consultation and visits to Stanford to the research on the grabber/trap and gas TPC Ba^+ tagging options (goal 3e), and has had a role in two recent papers from this work.[8,9]

Opportunities for training and professional development project provided:

This project has provided primary funding for three successive graduate students to complete or work on Ph.D. degrees: Kendy Hall (Ph.D. 2012), Cesar Benitez (Ph.D. 2013) and Adam Craycraft (current Ph.D. student). In addition, 4 other students in the CSU group, have had part support to cover Ba tagging research and operation EXO-200. These students received extensive training in a wide spectrum of state-of-the-art technologies, including, lasers, spectroscopy, cryogenics, and electronics in the CSU labs and in advanced cryogenic detectors at WIPP. These students had opportunities to take shifts on EXO-200 with experts from around the world, and to interact with all Collaboration members at twice yearly EXO Collaboration meetings and numerous phone meetings. These students have given talks at prominent APS meetings, such as April, Division of Particles and Fields, Division of Nuclear Physics and Four Corners Section.

Dissemination of results to communities of interest:

Results of this project have been published in leading physics journals. Invited and contributed talks have been given by the PI and graduate students at major national meetings and neutrino physics meetings.

PRODUCTS:

Journal Publications

F. LePort et al., "A magnetically-driven piston pump for ultra-clean applications", Rev. Sci. Instrum. 82, 105114 (2011). {arXiv:1104.5041]

N. Ackerman et al., "Observation of two-neutrino double-beta decay in Xe-136 with EXO-200, Phys. Rev. Letters 107, 212501 (2011) [arXiv:1108. 4193]

A. Dobi et al., "Xenon purity analysis for EXO-200 via mass spectrometry",Nucl. Instrum. and Methods A 675, 40 (2012). [arXiv 1109. 1046]

M. Auger et al., "The EXO-200 detector, part I: Detector design and construction", J. Inst. 7, P05010 (2012). [arXiv:1202.2192]
M. Auger et al., "Search for Neutrinoless Double-Beta Decay in ^{136}Xe with EXO-200", Phys. Rev. Letters 109, 032505 (2012). [arXiv:1205:5608]
J. B. Albert et al., "An improved measurement of the 2nbb half-life of ^{136}Xe with EXO-200", Phys. Rev. C 89, 015502 (2014). [arXiv;1306.6106]
J. B. Albert et al., "Search for Majorana neutrinos with the first two years of EXO-200 data", Nature 510, 229 (2014). [arXiv:1402:6956]
K. Twelker et al., "An apparatus to manipulate and identify individual Ba ions from bulk liquid Xe", Rev. Sci. Instrum. 85, 095114 (2014). [arXiv:1407.0618v1].
J. B. Albert et al., "Search for Majoron-emitting modes of double-beta decay of ^{136}Xe with EXO-200", Phys. Rev. D 90, 092004 (2014). [arXiv:1409.6829]
B. Mong et al., "Spectroscopy of Ba and Ba^+ deposits in solid xenon for barium tagging in nEXO", Phys. Rev. A 91, 022505 (2015). [arXiv:1410.2624]
T. Brunner et al., "An RF-only ion-funnel for extraction from high-pressure gases", Int. J. Mass Spec. 379, 110 (2015). [arXiv:1412.1144]
J. B. Albert et al., "Investigation of radioactivity-induced backgrounds in EXO-200", Phys. Rev. C 92, 015503 (2015).
J. B. Albert et al., "Measurements of the ion fraction and mobility of alpha and beta decay products in liquid xenon using EXO-200", Phys. Rev. C 92, 045504 (2015). [arXiv:1506.00317]
J. B. Albert et al., "Search for 2νββ decay of 136Xe to the 0_1^+ excited state of ^{136}Ba with the EXO-200 liquid xenon detector", Phys. Rev. C 93, 035501 (2016). [arXiv:1511.04770].
J. B. Albert et al., "Cosmogenic Backgrounds to 0νββ in EXO-200", J. Cosmol. Astropart. Phys. 04, 029 (2016). [arXiv:1512.06835]
J. B. Albert et al., "First Search for Lorentz and CPT Violation in Double Beta Decay with EXO-200", Phys. Rev. D 93, 072001 (2016). [arXiv:1601.07266]

Ph.D. Theses

Kendy Hall, "In-situ Laser Tagging of Barium Ions in Liquid Xenon for the EXO Experiment", Ph.D. thesis, Spring, 2012 (funded by this DOE grant).
Shon Cook, "Detection of Small Numbers of Barium Ions Implanted in Solid Xenon for the EXO Experiment", Ph.D. thesis, Summer, 2012 (part funded by this DOE grant).
Cesar Benitez, "Mobility and Fluorescence of Barium Ions in Xenon Gas for the EXO Experiment", Ph. D. thesis, Spring, 2014 (funded by this DOE grant).
Tim Walton, "Imaging Single Barium Atoms in Solid Xenon for Barium Tagging in the nEXO Neutrinoless Double Beta Decay Experiment", Ph.D. thesis, Spring, 2016 (funded in part by this DOE grant).

Participants (role, person months worked, other support, residence)

William Fairbank, Professor, PI, 18 mo., NSF, CSU academic year, Colorado
Shon Cook, Grad. student, Ba spectroscopy in SXe, EXO-200 operations, 10 mo., NSF, Colorado
Kendy Hall, Grad. student, Ba^+ in LXe studies, EXO-200 operations, 6 mo., Colorado
Cesar Benitez, Grad. student, Ba^+ in GXe studies, EXO-200 operations, 16 mo., Colorado
Tim Walton, Grad. Student, Ba spectroscopy in SXe, EXO-200 operations, 8 mo., NSF, Colorado
Adam Craycraft, Grad. Student, Cold probe studies, EXO-200 analysis and operations, 22 mo., Colorado
Chris Chambers, Grad. Student, EXO-200 operations, 4 mo., Colorado
Scott Alton, Grad. Student, EXO-200 analysis, 2 mo., Colorado

Organizations involved as partners EXO and nEXO Collaborations institutions

Carleton, Laurentian and McGill Universities and TRIUMF, Canada
University of Bern, Switzerland
Technische Univ. Munchen and University of Erlangen-Nuremberg, Germany
IHEP, Beijing, China

ITEP, Moscow, Russia
IBS Center for Underground Physics, South Korea
Caltech, Drexel, Duke, Stanford SUNY Stony Brook, Alabama, Illinois, Indiana, Maryland, Massachusetts, and South Dakota Universities USA
Brookhaven, Lawrence Livermore, Oak Ridge, Pacific Northwest and SLAC National Labs USA

IMPACT:

Impact on the principal discipline of the project:

EXO-200 has produced world-leading results in double beta decay during this period. These include the first discovery of two-neutrino double beta decay, the first neutrinoless double beta decay results that challenged a famous claim of a positive result in ^{76}Ge, the most precise measurement of two-neutrino double beta decay, and a current sensitivity for neutrinoless double beta decay among the world's best. These four landmark papers have been cited 424 times already.

Major steps have been taken towards barium tagging for nEXO during this project, as described above. If such a technique could be implemented, it is expected that nEXO would be able to cover the full inverted mass hierarchy region of neutrino mass and begin to probe the normal mass region. This would be a major breakthrough in the field.

Impact on other disciplines:

The novel techniques pioneered for detection of single atoms in noble gas solids may be applied in the near future to situations that require extreme sensitivity, down to the single atom level, in a noble gas environment. There is much related work in chemistry with macroscopic numbers of atoms and molecules at the present time. Applications especially in ultrasensitive chemistry should be expected.

Impact on the development of human resources:

This project has contributed primarily or partially to the training of 4 Ph.D. physicists, who are now employed in top positions, three in industry (Raytheon, Intel, Prism Computational Sciences) and one in academia (SLAC). Two others are well on their way to Ph.D. degrees, with primarily (one) and partial (one) work on this project.

Impact on teaching and educational experiences:

Examples from this work have been used in classes taught, although no specific materials have been developed.

Impact on infrastructure:

Through this project a major infrastructure for novel experiments in single Ba atom detection in liquid and solid xenon has been developed.

Impact on technology transfer:

EXO-200 has pioneered technology for LXe double beta decay detection that will be used in the 25x larger nEXO experiment. The discovery of multiphoton ionization of liquid xenon may have application for calibration of other liquid xenon detectors.

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[1] N. Ackerman, et al. (EXO collaboration), "Observation of Two-Neutrino Double-Beta Decay in ^{136}Xe with the EXO-200 Detector, Phys. Rev. Letters 107, 212501 (2011).

[2] M. Auger, et al. (EXO collaboration), "Search for Neutrinoless Double-Beta Decay in Xe-136 with EXO-200", Phys. Rev. Letters 109, 032505 (2012). [arXiv:1205:5608]

[3] Klapdor

[4] J. B. Albert, et al. (EXO collaboration), "An improved measurement of the 2νββ half-life of Xe-136 with EXO-200", Phys. Rev. C 89, 015502 (2014).

[5] J. B. Albert et al., "Search for Majorana neutrinos with the first two years of EXO-200 data", Nature 510, 229 (2014). [arXiv:1402:6956]

[6] J. B. Albert et al., "Measurements of the ion fraction and mobility of alpha and beta decay products in liquid xenon using EXO-200", Phys. Rev. C 92, 045504 (2015). [arXiv:1506.00317]

[7] B. Mong et al., "Spectroscopy of Ba and Ba^+ deposits in solid xenon for barium tagging in nEXO", Phys. Rev. A 91, 022505 (2015). [arXiv:1410.2624]

[8] K. Twelker et al., "An apparatus to manipulate and identify individual Ba ions from bulk liquid Xe", Rev. Sci. Instrum. 85, 095114 (2014). [arXiv:1407.0618v1]

[9] T. Brunner et al., "An RF-only ion-funnel for extraction from high-pressure gases", Int. J. Mass Spec. 379, 110 (2015). [arXiv:1412.1144]