CRF 8G (Revised Sep 15)

RGC Reference CUHK3/CRF/10
please insert ref. above

The Research Grants Council of Hong Kong
Collaborative Research Fund Group Research Projects
Completion Report

(*for completed projects only*)

Part A: The Project and Investigator(s)

1. Project Title

High Precision Measurement of Neutrino Oscillation at Daya Bay

2. Investigator(s) and Academic Department/Units Involved *(please highlight approved changes in the composition of the project team and quote the date when RGC granted approval of such changes)*

Research Team	Name/Post	Unit/Department/Institution	Average number of hours per week spent on this project in the current reporting period
Project Coordinator	Chu, Ming-chung/ Professor	Physics/CUHK	
Co-Principal investigator(s)	Cheng, Kwong-sang/ Professor Leung, John Kon-chong/ Honorary Associate Professor Luk, Kam-Biu/ Professor Pun, Jason Chun-shing/ Principal Lecturer Wang, Yifang/Director	Physics/HKU Physics/HKU Physics/U. C. Berkeley Physics/HKU Institute of High Energy Physics, CAS	
Collaborators/ Others			

3. Project Duration

	Original	Revised	Date of RGC Approval (*must be quoted*)
Project Start Date	June 30, 2011		
Project Completion Date	June 29, 2014	October 29, 2014	January 13, 2014
Duration (*in month*)	36	40	January 13, 2014
Deadline for Submission of Completion Report	June 29, 2015	October 29, 2015	

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Part B: The Final Report

5. Project Objectives

5.1 Objectives as per original application

- 1. To contribute to the commissioning and monitoring of the Daya Bay antineutrino detectors;
- 2. To contribute to the analysis of the Daya Bay experimental data;
- 3. To design and construct a continuous radon monitoring system;
- 4. To design and construct a cover gas system for the Daya Bay antineutrino detectors;
- 5. To study cosmic-ray muons and their reactions in the Aberdeen Tunnel Laboratory.

5.2 Revised objectives

Date of approval from the RGC: 17 February 2011

Reasons for the change: Because our proposed budget has been reduced by almost HK$2.5M, we have to scale down on our proposed objectives in order to reduce cost and required manpower. We have not made any revision to the first three items, those being most important scientifically. The revisions are:

- We have added "contribute to" in item 4 (design and construction of a cover gas system for the Daya Bay antineutrino detectors) because we are now collaborating with the University of Wisconsin team in this task. As a result, we will only contribute to a fraction of the cost for this item.

- We have deleted item 5 in order to save money and manpower.

1. To contribute to the commissioning and monitoring of the Daya Bay antineutrino detectors;
2. To contribute to the analysis of the Daya Bay experimental data;
3. To develop a continuous radon monitor of fast response with precision of 5% for monitoring the radon levels in the experimental halls;
4. To contribute to design and construct a cover gas system for the Daya Bay antineutrino detectors;

6. Research Outcome

6.1 Major findings and research outcome
(maximum 1 page; please make reference to Part C where necessary)

1. We have discovered a new mode of neutrino oscillation, in which electron anti-neutrinos oscillate into other types, parameterized by a mixing angle θ_{13}. The relative antineutrino rates and energy spectra between detectors gave $\sin^2 2\theta_{13} = 0.084 \pm 0.005$ and $|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3}$ eV^2 in the three-neutrino framework [1, 4, 7, 9, 11].
2. We have searched for light sterile neutrino mixing with the first 217 days of data from the Daya Bay Reactor Antineutrino Experiment, which is uniquely sensitive to neutrino oscillations to a fourth (sterile) neutrino in the 10^{-3} eV^2 < $|\Delta m^2_{41}|$ < 0.3 eV^2 range. The relative spectral distortion due to the disappearance of electron antineutrinos was found to be consistent with that of the three-flavor oscillation model. The derived limits on $\sin^2 2\theta_{14}$ cover the largely unexplored region of 10^{-3} eV^2 $\lesssim |\Delta m^2_{41}| \lesssim$ 0.1 eV^2 [8].
3. We have measured the flux and energy spectrum of electron antineutrinos from six 2.9 GW_{th} nuclear reactors with six detectors deployed in two near (effective baselines 512 m and 561 m) and one far (1,579 m) underground experimental halls in the Daya Bay experiment. The measured inverse-beta decay yield is $(5.92 \pm 0.14) \times 10^{-43}$ cm^2/fission, which is consistent with previous short-baseline reactor antineutrino experiments and is 0.946±0.022 (0.991±0.023) relative to the flux predicted with the Huber+Mueller (ILL+Vogel) fissile antineutrino model. The measured IBD positron energy spectrum deviates from both spectral predictions by more than 2σ over the full energy range with a local significance of up to 4σ between 4-6 MeV, a new feature that most calculations missed. A reactor antineutrino spectrum of IBD reactions is extracted from the measured positron energy spectrum for model-independent predictions [12].
4. We have measured the muon-induced neutron yield at a depth of 611 meters water equivalent to be $Y_n = (1.19 \pm 0.08(\text{stat.}) \pm 0.21(\text{syst.})) \times 10^{-4}$ neutrons/(μ g cm^{-2}). This value agreed with the FLUKA simulation results [15].
5. We derive the neutrino favor transition probabilities with the neutrino treated as a wave packet. The decoherence and dispersion effects from the wave-packet treatment show up as damping and phase-shifting of the plane-wave neutrino oscillation patterns. If the energy uncertainty in the initial neutrino wave packet is larger than around 0.01 of the neutrino energy, the decoherence and dispersion effects would degrade the sensitivity of reactor neutrino experiments to mass hierarchy measurement to lower than 3σ confidence level [14].
6. We have carried out hardware research and development, fabrication, and installation work:
   i. a set of eight, functionally identical antineutrino detectors to measure the reactor neutrino flux and spectrum at baselines of 300–2000m from the Daya Bay and Ling Ao Nuclear Power Plants [2, 6];
   ii. a cover gas system for the antineutrino detectors, one for each underground hall [3];
   iii. a muon system for vetoing cosmic muons [10];

iv. a highly sensitive and reliable automatic radon monitoring system for each of the 3 Daya Bay experimental halls [13];
v. a mineral oil clarity monitoring system for each of the 8 anti-neutrino detectors [16];
vi. a neutron and muon detector system in the Aberdeen Tunnel Laboratory to study muon-induced neutrons in an underground lab [5, 15].

6.2 Potential for further development of the research and the proposed course of action *(maximum half a page)*

1. The Daya Bay Reactor Neutrino Experiment will continue to take data until 2017, resulting in the world's largest set of high-precision reactor neutrino data.
2. We will continue to improve the measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$, by improving the statistics as well as the understanding of the systematic errors. This will help the next generation of neutrino experiments to determine the neutrino mass hierarchy and the CP phase.
3. We will continue to participate in searches for new physics, such as non-standard neutrino interactions, unusual time dependence of neutrino flux, etc.
4. The Daya Bay detectors have already joined in the Supernova Early Warning network, to monitor supernovae.

6.3 Research collaboration achieved *(please give details on the achievement and its relevant impact)*

1. Collaborating with 40 institutes in China, Chile, Czech Republic, Russia, Taiwan, and USA in the Daya Bay Reactor Neutrino Experiment. This collaboration has attracted world-wide attention since our discovery of a non-zero value for the θ_{13} in 2012.
2. Collaborating with 7 institutes in China, Taiwan, USA in the Aberdeen Tunnel Experiment, a satellite experiment of the Daya Bay experiment. We have trained many undergraduate and graduate students through this local underground laboratory.
3. We have hosted 3 Daya Bay Collaboration Meetings in Hong Kong.

7. The Layman's Summary

(describe in layman's language the nature, significance and value of the research project, in no more than 200 words)

The discovery of neutrino oscillation – a neutrino travelling in space transforms from one type to another – has profound impacts on nuclear/particle physics, astrophysics and cosmology. The Daya Bay Reactor Neutrino Oscillation Experiment has discovered a new mode of neutrino oscillation and measured a fundamental neutrino mixing parameter, θ_{13}, to an unprecedented precision of better than 0.3 degrees, which is critical to the design of future experimental tests of a possible explanation of why matter dominates anti-matter in the universe, a key condition for our existence. We have searched for a new kind of neutrinos and derived severe constraints on its properties. We have also measured the flux and energy spectrum of electron antineutrinos produced in nuclear reactors and found current fissile antineutrino models deficient.
The Hong Kong team has been an active member of the Daya Bay Collaboration, collaborating with 40 institutions world-wide. We participated in the commissioning and monitoring of the experiment and analysis of data, with the help of a subsystem of the antineutrino detector built by our team. We have designed and constructed a continuous radon monitoring system and a cover gas system to minimize contamination of the detectors. We also studied cosmic muons and their interactions with matter in a small local underground laboratory, the Aberdeen Tunnel Lab.

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Part C: Research Output

8. Peer-reviewed journal publication(s) arising directly from this research project

(Please attach a copy of the publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.)

The Latest Status of Publications				Author(s) *(denote the corresponding author with an asterisk*)*	Title and Journal/Book *(with the volume, pages and other necessary publishing details specified)*	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of RGC *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Year of publication	Year of Acceptance (For paper accepted but not yet published)	Under Review	Under Preparation (optional)						
2012				F. P. An *et al.*, the Daya Bay Collaboration	Observation of Electron-Antineutrino Disappearance at Daya Bay, Physical Review Letters **108**, 171803 (2012).	Yes (2012)	Yes [1]	Yes	Yes
2012				F. P. An *et al.*, the Daya Bay Collaboration	A side-by-side comparison of Daya Bay antineutrino detectors, Nucl. Instrum. Meth. **A685**, 78 (2012).	No	Yes [2]	Yes	Yes
2012				H. Band *et al.*	Daya Bay Antineutrino Detector Gas System, Journal of Instrumentation **7**, P11029 (2012).	Yes (2012)	Yes [3]	Yes	Yes
2013				F. P. An *et al.*, the Daya Bay Collaboration	Improved Measurement of Electron Antineutrino Disappearance at Daya Bay, Chinese Physics C**37,** 011001 (2013).	Yes (2012)	Yes [4]	Yes	Yes

2013				S. C. Blyth *et al.* (the Aberdeen Tunnel Collaboration)	An Apparatus for Studying Spallation Neutrons in the Aberdeen Tunnel Laboratory, Nucl. Instrum. Meth. **A723**, 67-82 (2013).	Yes (2012)	Yes [5]	Yes	Yes
2013				H. Band *et al.*	Assembly and Installation of the Daya Bay Antineutrino Detectors, Journal of Instrumentation **8**, T11006 (2013).	No	Yes [6]	Yes	Yes
2014				F. P. An *et al.*, the Daya Bay Collaboration	Spectral Measurement of Electron Antineutrino Oscillation Amplitude and Frequency at Daya Bay, Physical Review Letters **112**, 061801 (2014).	No	Yes [7]	Yes	Yes
2014				F. P. An *et al.*, the Daya Bay Collaboration	Search for a Light Sterile Neutrino at Daya Bay, Physical Review Letters **113**, 141802 (2014).	No	Yes [8]	Yes	Yes
2014				F. P. An *et al.*, the Daya Bay Collaboration	Independent measurement of the neutrino mixing angle θ_{13} via neutron capture on hydrogen at Daya Bay, Physical Review D**90**, 071101 (2014).	No	Yes [9]	Yes	Yes
2015				F. P. An *et al.*, the Daya Bay Collaboration	The muon system of the Daya Bay Reactor antineutrino experiment,	No	Yes [10]	Yes	Yes

					Nucl. Instrum. Meth. A**773**, 8 (2015).				
2015				F. P. An *et al.*, the Daya Bay Collaboration	New measurement of antineutrino oscillation with the full detector configuration at Daya Bay, Physical Review Letters **115**, 111802 (2015).	No	Yes [11]	Yes	Yes
2015		Y		F. P. An *et al.*, the Daya Bay Collaboration	Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay, submitted to Physical Review Letters (2015)	No	Yes [12]	Yes	Yes
2015		Y		M. –C. Chu *et al.*	The Radon Monitoring System in Daya Bay Reactor Neutrino Experiment, submitted to Nucl. Instrum. Meth. A, 2015.	Yes (2012)	Yes [13]	Yes	Yes
2015		Y		Yat-Long Chan *et al.*	Wave-packet treatment of neutrino oscillations and its implications on determining the neutrino mass hierarchy, submitted to Journal of High Energy Physics, 2015	No	Yes [14]	Yes	Yes
2015			Y	S. C. Blyth *et al.* (the Aberdeen Tunnel Collaboration)	Measurement of Cosmic-ray Muons and Muon-induced Neutrons in the Aberdeen	No	Yes [15]	Yes	Yes

					Tunnel Underground Laboratory, submitted to Physical Review D, 2015				
2015			Y	Y. L. Chan *et al.*	A Mineral Oil Monitoring System for the Daya Bay Neutrino Experiment	No	Yes [16]	Yes	Yes

9. Recognized international conference(s) in which paper(s) related to this research project was/were delivered *(Please attach a copy of each conference abstract)*

Month/Year/ Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of RGC *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
08/2011 Kaohsiung, Taiwan	High precision measurement of θ_{13} at Daya Bay	OCPA 7	Y (2012)	Yes [17]	Yes	No
08/2011 Kaohsiung, Taiwan	Cosmic ray muons and spallation neutrons in the Aberdeen Tunnel Laboratory, Hong Kong	OCPA 7	Y (2012)	Yes [18]	Yes	No
06/2014 Boston, U.S.A.	Production of muon-induced radioactive isotopes at Daya Bay	XXVI International Conference on Neutrino Physics and Astrophysics	N	Yes [19]	Yes	No
07/2014 Valencia, Spain	Measurement of Cosmic-ray Muon-induced Spallation Neutrons in the Aberdeen Tunnel Underground Laboratory	ICHEP 2014 37th International Conference on High Energy Physics (ICHEP)	N	Yes [20]	Yes	Yes
03/2015 Venice, Italy	Spallation Neutron Kinematics in Antineutrino Detectors	XVI International Workshop on Neutrino Telescopes	N	Yes [21]	No	No
06/ 2015, HKUST, Hong Kong.	Recent Results from Daya Bay	Gordon Research Conference on Particle Physics	N	Yes [22]	Yes	No

06/2015 HKUST, Hong Kong	Reconstruction of Spallation Neutron Kinematics in Antineutrino Detectors	Gordon Research Conference on Particle Physics	N	Yes [23]	Yes	No
06/2015 HKUST, Hong Kong	Measurement of Cosmic-ray Muons and Spallation Neutrons in the Aberdeen Tunnel Underground Laboratory	Gordon Research Conference on Particle Physics	N	Yes [24]	Yes	No
08/2015 Kolymbari, Crete, Greece	Recent Results from Daya Bay	4th International Conference on New Frontiers in Physics (ICFNP2015)	N	Yes [25]	Yes	Yes

10. *Student(s) trained* (please attach a copy of the title page of the thesis)

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Chan Yat Long	MPhil	2010-08-01	2012-07-01
Chen Xiaocong	PhD	2009-08-01	2013-06-31
Cui Kexi	MPhil	2011-09-01	2014-03-12
Fung Ka Yu	MPhil	2012-01-01	2014-09-01
Leung Kar Yee Amy	MPhil	2010-09-01	2012-10-01
Li Shengchao	MPhil	2013-09-01	2015-08-31 (submitted)
Liu Sishuo	MPhil	2012-09-01	2014-12-05
Ngai Ho Yin	PhD	2008-09-01	2012-02-01
Tam Yiu Ho	PhD	2010-08-01	2013-08-31
Xu Jianyi	PhD	2011-08-01	2015-08-22

11. Other impact *(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, etc.)*

1. Research result selected as one of top ten breakthroughs by Science Magazine, 2012.
2. Research result widely reported in the media both internationally and in Hong Kong.
3. Through the Daya Bay experiment, we have carried out fruitful collaboration with 40 institutions in China, Chile, Czech Republic, Russia, Taiwan and U.S.A. This helps us to build long-term ties with these institutions.
4. We have given quite a few popular science talks in Hong Kong. A short video has also been produced to introduce the Daya Bay experiment for Hong Kong audience: http://youtu.be/-NNDXB7ttHk.
5. Our work has led to further development of high energy physics in HK, including the formation of a Hong Kong team ATLAS team to join one of the two general-purpose LHC experiments at CERN and recruitment of more scientists working in fundamental physics in CUHK, HKU and HKUST. A Joint Consortium for Fundamental Physics has been formed among the three universities to foster collaboration and interaction among colleagues working in the broad area of fundamental physics.

Project Coordinator

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