RGC Ref.: A-CUHK403/13
(please insert ref. above)

The Research Grants Council of Hong Kong
ANR/RGC Joint Research Scheme
Completion Report

(Please attach a copy of the completion report submitted to the ANR by the French researcher)

Part A: The Project and Investigator(s)

1. Project Title (ANR Acronym)

Quantum Control of an Ultracold Gas of Polar Molecules (COPOMOL)

2. Investigator(s) and Academic Department/Units Involved

	Hong Kong Team	French Team
Name of Principal Investigator *(with title)*	Prof. Dajun Wang	Dr. Olivier Dulieu
Post	Associate Professor	Directeur de Recherche
Unit / Department / Institution	Department of Physics/CUHK	Laboratoire Aimé Cotton, Orsay
Contact Information	djwang@cuhk.edu.hk/+852-39436395	Olivier.dulieu@u-psud.fr/+33(0)169352013
Co-investigator(s) *(with title and institution)*		Dr. Goulven Quéméner, Laboratoire Aimé Cotton, Orsay

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	01-01-2014	01-01-2014	22-8-2017
Project Completion date	31-12-2017	31-12-2018	
Duration *(in month)*	48	60	
Deadline for Submission of Completion Report			

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. The formation of a gas of ultracold, chemically stable $^{23}Na^{87}Rb$ molecules in their absolute ground state with a large permanent electric dipole moment;

2. The control of polar $^{23}Na^{87}Rb$ molecules with external electric fields to reach a regime of strong dipolar interactions;
3. The creation of a quantum degenerate gas of polar bosonic $^{23}Na^{87}Rb$ molecules;
4. The observation of signatures of many-body effects with $^{23}Na^{87}Rb$ molecules loaded in an optical lattice.

5.2 Revised Objectives

Date of approval from the RGC: ____________________

Reasons for the change: ____
____

1.
2.
3. ....

6. Research Outcome

Major findings and research outcome

(maximum 1 page; please make reference to Part C where necessary)

1) Formation of ultracold NaRb Feshbach molecules via magneto-association. As stated in the proposal, at the beginning of this grant, we already had a mixture of Na and Rb and investigated the Feshbach resonances between them. As the first critical task for the current fund, the Hong Kong team investigated the formation of Feshbach molecules with the resonance at 347.7 G. Initially, only a small sample with 1000 Feshbach molecules could be obtained. Later on, in an upgraded setup, we increased the sample size to 10^4 molecules. (**New Journal of Physics, 17, 035003 (2015)**)
2) Molecular spectroscopy for the intermediate level. The French group carried out a series of calculations on the several triplet/singlet mixed states, especially the $2^1\Sigma^+/1^3\Pi$ manifold. Based on these calculations, the Hong Kong team carried out the molecular spectroscopic work starting from a sample of pure Feshbach molecules. Due to the low duty cycle of this process, it took us nearly a year to finally get the right intermediate level. The final level of choice has an anomalously large $0+/0^-$ coupling, which enables a large hyperfine splitting. This coupling mechanism is fully modelled by the French group. The level we selected also has enough transition dipole moment to both the Feshbach and the absolute ground state. (**Physical Review A, 93,012508 (2016), Physical Review A 96, 052505(2017**)
3) Setting up the ultra-stable Raman lasers. Two semiconductor lasers are then locked to the cavity. We achieved narrow linewidths of <5 kHz for both lasers, enough for the high efficiency Raman transfer.
4) The formation of a gas of ultracold $^{23}Na^{87}Rb$ molecules in their absolute ground state. The Hong Kong team realized populating the ground state $X^1\Sigma^+\left|v''=0, J''=0\right\rangle$ by the applying a Stimulated Raman Adiabatic Passage to the Feshbach molecules with carefully designed Raman pulse sequences. The French team calculated the hyperfine structures of the $X^1\Sigma^+\left|v''=0, J''=0\right\rangle$. The Hong Kong team successfully resolved these structures. With this, we achieved one of the major objectives of this project, the production of the absolute ground state NaRb molecules, i.e. NaRb in the lowest electronic, vibration, rotation and hyperfine state. **(Physical Review Letters 116, 205303(2016))**
5) Complete internal state control of the molecules. With the Raman process and with the addition of microwave photons, we realized the capability of creating NaRb molecule in fully controlled vibration, rotation and hyperfine level. **(Physical Review A 97,020501(R)(2018))**
6) Investigation of collisions between absolute ground state NaRb. The two-body chemical reaction $2NaRb \rightarrow Na_2 + Rb_2$ is energetically forbidden. Unfortunately,

we still observed a large decay of the NaRb sample. By controlling the chemical reactivity with vibrational excitation, we compared the loss with and without the chemical reaction, just to find they are very similar. The French group developed the complex formation model to explain the loss without chemical reaction. (**Science Advances 4, eaaq0083(2018)**)

7) The control of polar $^{23}Na^{87}Rb$ molecules with external electric fields. We studied the loss of molecules with large induced dipole moments up to 0.7 D. A step wise increase of the loss due to the opening of higher partial waves is observed. The results fit the model by the French group very well. (**Physical Review X 8,041044(2018)**)
8) Due to the unexpected loss, we have not been able to perform evaporative cooling to create a degenerate gas of NaRb molecules. This is currently the main problem faced by all cold molecule groups. We have successfully created ground-state molecules in a 3-D optical lattice and achieved about 10 s lifetime. We are now trying to confirm the many-body effect from dipolar interactions.

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

The main problem facing ultracold molecule research is the loss which, from our investigation, seems to be universal. It doesn't depend on the chemical reactivity and molecular species. Although our data agrees with the complex formation model reasonably well, the fact that we can only detect the loss of molecules prevents us from reaching a very clear picture. Especially, what will happen to the complex after its formation? Why cannot we see any of its impact on the molecules via complex-molecule collisions? These are the things we need to understand in future investigations. We believe finding on this issue will give us valuable insights on how to obtain a long-lived bulk sample suitable for evaporative cooling.

Given the success of our project, and the high level of investment from the two teams largely supported by their home institutions, we jointly applied for a new proposal at the end of 2018, in the same framework of the joint call between RGC and ANR. Unfortunately, the proposal has not been preselected by CUHK as a priority for 2019. We will make a new attempt for the next call next Fall.

This proposal entitled PASSUM, for "Probing and Associating Ultracold Molecules into Clusters", aims at extending the expertise acquired during the COPOMOL project, to study to more complicated constituents, such as small clusters, by associated ultracold atoms and molecules using laser light.

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 Bose-Einstein condensation of a dilute, ultracold atomic gas was first realized in 1995. It has opened up the way to an unprecedented revolution in modern physics. Interactions between atoms are nonetheless dictated by intrinsically weak van der Waals interactions. In contrast, polar molecules, which possess a permanent electric dipole moment in their own frame, interact through strong long-range dipole-dipole forces, when an electric field is applied in the lab frame. At ultracold temperatures, this strong, long-range, anisotropic dipole-dipole interaction plays a dominant role and thus leads to a completely new set of highly controllable physics which is not accessible with atoms.

In this project, we realized a quantum gas of ultracold NaRb polar molecules with high density and ultracold temperature. We also carried out a series of well-controlled collisional studies and obtained some valuable insight into the molecule-molecule interaction at ultracold temperatures. These molecules are now loaded into optical lattices which will soon enable us to study strongly correlated many body physics with long-range interactions. Our findings shed new light on the field of dipolar quantum gases and provided valuable information on molecule interaction at ultracold regime.

Part C: Research Output

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

(Please attach a copy of each 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) (***bold** the authors belonging to the project teams and 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 this Joint Research Scheme *(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)*						
2019				**Bo Lu and Dajun Wang***	Ultracold dipolar molecules 超冷極性分子（invited review paper）, Acta Physica Sinica 物理學報 68,043301(2019)	N	Y	N	

2018				**Mingyang Guo, Xin Ye, Junyu He, Goulven Quéméner and Dajun Wang***	High resolution internal state control of ultracold ground-state NaRb molecules, Physical Review A 97,020501(R)(2018)	N	Y	Y	
2018				**Mingyang Guo, Xin Ye, Junyu He, Maykel L. Gonzalez-Martınez, Romain Vexiau, Goulven Quemener, and Dajun Wang***	Dipolar Collisions of Ultracold Ground-state Bosonic Molecules, Physical Review X 8,041044(2018)	N	Y	Y	
2018				**Xin Ye, Mingyang Guo, Maykel L. Gonzalez-Martınez, Goulven Quemener, and Dajun Wang***	Collisions of ultracold NaRb molecules with controlled chemical reactivity, Science Advances 4, eaaq0083(2018).	2017	Y	Y	
2017				**Mingyang Guo, Bing Zhu, Bo Lu, Xin Ye, Fudong Wang, Romain Vexiau, Nadia Bouloufa-Maafa, Goulven Quemener, Olivier Dulieu, and Dajun Wang***	High-resolution molecular spectroscopy for producing ultracold absolute-ground-state 23Na87Rb molecules, Physical Review A 96, 052505(2017).	2017	Y	Y	

2016				**Bing Zhu, Xiaoke Li, Xiaodong He, Mingyang Guo, Fudong Wang, Romain Vexiau, Nadia Bouloufa-Maafa, Olivier Dulieu, and Dajun Wang***	Long-range states of the NaRb molecule near the Na(32S1/2)+Rb(52P3/2) asymptote/ Physical Review A, 93,012508 (2016)	2015	Y	Y	
2016				**Mingyang Guo, Bing Zhu, Bo Lu, Xin Ye, Fudong Wang, Romain Vexiau, Nadia Bouloufa-Maafa, Goulven Quemener, Olivier Dulieu, and Dajun Wang***	Creation of an ultracold gas of ground-stateNaRb molecules, Physical Review Letters 116, 205303(2016)	2017	Y	Y	
2015				**Fudong Wang, Xiaodong He, Xiaoke Li, Bing Zhu, Jun Chen and Dajun Wang***	Formation of Ultracold NaRb Feshbach molecules/ New Journal of Physics, 17, 035003 (2015)	2015	Y	Y	

9. Recognized international conference(s) in which paper(s) related to this research project was/were delivered *(Please attach a copy of each delivered paper. All listed papers must acknowledge RGC's funding support by quoting the specific grant reference.)*

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 this Joint Research Scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
June/2018/ Wuhan, China	Dipolar Collisions Between Ultracold NaRb molecules	The 8th international symposium on cold atom physics		Y	Y	
June/2018/Hannover, Germany	Dipolar Collisions of ultracold NaRb molecules	The 5th international Work shop on "Long-range interactions in quantum systems"		Y	Y	
March/2018/ New Orleans, LA, USA	Collisions of ultracold NaRb molecules	255th ACS national meeting		Y	Y	
June/2018/Ft. Lauderdale, Florida	Collisions of ultracold ground-state NaRb molecules	49th Annual Meeting of the APS DAMOP		Y	Y	
June/2018/Ft. Lauderdale, Florida, USA	Collisional studies of ultracold 23Na87Rb molecules	49th Annual Meeting of the APS DAMOP		Y	Y	
June/2017/Sacramento, CA, USA	Collisions of ultracold NaRb molecules with controlled chemical reactivity	48th Annual Meeting of the APS DAMOP	2017	Y	Y	
June/2017/Sacramento, CA, USA	Dipolar collisions of ultracold NaRb molecules.	48th Annual Meeting of the APS DAMOP	2017	Y	Y	
June/2017/Sacramento, CA, USA	Internal state control of a dense sample of ultracold NaRb molecules	48th Annual Meeting of the APS DAMOP	2017	Y	Y	
May/2016/Providence, RI, USA	Creation of a strongly dipolar gas of ultracold ground-state NaRb molecules	47th Annual Meeting of the APS DAMOP	2016	Y	Y	
May/2016/Providence, RI, USA	Molecular spectroscopy for producing ultracold ground-state NaRb molecules	47th Annual Meeting of the APS DAMOP	2016	Y	Y	
June/2015/Columbus, OH, USA	Towards ultracold ground-state NaRb molecule	46th Annual Meeting of the APS DAMOP	2015	Y	Y	

June/2015/Columbus, OH, USA	Prospect for the formation of a gas of ultracold polar NaRb molecules	46th Annual Meeting of the APS DAMOP	2015	Y	Y	
June/2015/Columbus, OH, USA	Excited-state spectroscopy for producing ultracold ground-state NaRb molecule	46th Annual Meeting of the APS DAMOP	2015	Y	Y	

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
Xiaoke Li	PhD	August 2011	August 2015
Bing Zhu	PhD	August 2012	August 2016
Fudong Wang	PhD	August 2011	August 2016
Mingyang Guo	PhD	August 2013	February 2018
Xin Ye	PhD	August 2014	August 2018

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

Nil