Annual Progress Summary, July 2012

To: technicalreports@afosr.af.mil

Subject: Annual Progress Statement to Dr. Tatjana Curcic

Contract/Grant Title: (MURI 09) Production, Manipulation, and Applications of Ultracold Polar Molecules

Contract/Grant #: FA9550-09-1-0588

Reporting Period: 08/01/2011 to 07/31/2012

Annual accomplishments:

Production, Cooling, and Detection.

We have realized a MOT and cooling of YO, and we have calculated and observed evaporative cooling of OH, longitudinal slowing of an SrF beam slow enough for trap loading, and determined that TlF can be laser-cooled. Photoassociation into X(v=0,J=0) RbCs now promises accumulation in an optical trap. We constructed/tested a 4T-deep superconducting trap, with lasers for CaF/CaH. Photoassociation also has allowed formation of $^{85}Rb_2$ a(v=0) and, using resonant coupling, KRb X(v=0). We have produced 5×10^4 NaLi (i.e., the lightest bi-alkali and one of only two ultracold fermonic) Feshbach molecules using sweeps across a narrow Feshbach resonance. We studied superradiance between vibrational states, which is likely to play a role in most polar molecules. Present studies test this avenue for laser cooling.

Structure and Chemistry.

We have measured the anisotropic ac polarizability of KRb in an optical lattice. Homonuclear molecules and tetramers were investigated, and the effect of higher moments on long-range interaction: quadrupole repulsion could stabilize a pair of otherwise attractive KRb (or other) molecules. We studied dynamics, rotational purity, state selectivity of decelerated molecular beams for collisions and calculated g.s. potential energies/permanent dipole moments for LiBe, LiMg, LiCa, LiSr, LiYb and collisions of g.s. alkali-metal dimers in electric fields/optical lattices. Resonances were identified for Rb/Cs. We found universal features among all dimers that can react at zero temperature and compiled a major review article on ultracold chemistry.

Quantum Information/Simulation.

We explored cluster states in optical lattices, and a hybrid atom-molecule platform for quantum computing, analyzed impurities to find attractive polarons and manifestations of Anderson's orthogonality catastrophe. Non-equilibrium studies of two-component Fermi-gases illuminate the interplay between Pauli-blocking and confinement in the formation of molecules, while the quantum mechanics of clustering leads to interesting phase diagrams.

Molecular Ions.

A new cryostat allows to increase microwave power to the superconducting trap chip, and a new chip design holds the ion 190 μm above the surface and thus increases the effective field strength. $BaCl^+$ serves as example on how we calculated electronic properties of dipolar ionic molecules, with focus on sympathetic cooling.

Archival publications (published) during reporting period (references with "*" are published papers mentioned as "submitted" last year):

[1] J.F. Barry, E.S. Shuman, and D. DeMille. A bright, slow cryogenic molecular beam source for free radicals. *Phys. Chem. Chem. Phys.*, 12:18936, 2011 *.

[2] J.F. Barry, E.S. Shuman, E.B. Norrgard, and D. DeMille. Laser radiation pressure slowing of a molecular beam. *Phys. Rev. Lett.*, 100:103002, 2012.

[3] M.A. Bellos, D. Rahmlow, R. Carollo, J. Banerjee, O. Dulieu, A. Gerdes, E.E. Eyler, P.L. Gould, and W.C. Stwalley. Formation of ultracold Rb_2 molecules in the v"=0 level of the a triplet Σ_u^+ state via blue-detuned photoassociation to the $1^3\Pi_g$ state. *Phys. Chem. Chem. Phys. (Special Issue on Ultracold Molecules)*, 13:18880, 2011 *.

[4] Jason N. Byrd, Robin Côté, and Jr John A. Montgomery. Long-range interactions between like homonuclear alkali metal diatoms. *J. Chem. Phys.*, 135:244307, 2011.

[5] Jason N. Byrd, Jr. H. John A. Montgomery, and Robin Côté. Controllable binding of polar molecules and meta-stability of 1-d gases with attractive dipole forces. Accepted for publication in Phys. Rev. Lett. (arXiv:1207.2797), 2012.

[6] Jason N. Byrd, Jr. H. John A. Montgomery, and Robin Côté. Long range forces between polar alkali diatoms aligned by external electric fields. Submitted to Phys. Rev. A (arXiv:1207.3546), 2012.

[7] Jason N. Byrd, H. Harvey Michels, Jr. John A. Montgomery, Robin Côté, and William C. Stwalley. Structure, energetics, and reactions of alkali tetramers. *J. Chem. Phys.*, 136:014306, 2012.

[8] K. Chen, S. J. Schowalter, S. Kotochigova, A. Petrov, W. G. Rellergert, S. T. Sullivan, and E. R. Hudson. Molecular-ion trap-depletion spectroscopy of $BaCl^+$. *Phys. Rev. A*, 83:030501(R), 2011 *.

[9] A. Choatia, B. Neyenhuis, S. Moses, B. Yan, J. P. Covey, M. Foss-Feig, A. M. Rey, D. S. Jin, and J. Ye. Long-lived dipolar molecules and feshbach molecules in a 3d optical lattice. *Phys. Rev. Lett.*, 108:080405, 2012.

[10] N. J. Fitch, D. A. Esteves, M. I. Fabrikant, T. C. Briles, Y. Shyur, L. P. Parazzoli, and H. J. Lewandowski. State purity of decelerated molecular beams. Journal of Molecular Spectroscopy, in press, 2011.

[11] A. V. Gorshkov, S. R. Manmana, G. Chen, J. Ye, E. Demler, M. D. Lukin, and A. M. Rey. Tunable superfluidity and quantum magnetism with ultracold polar molecules. *Phys. Rev. Lett.*, 107:115301, 2011 *.

[12] M.-S. Heo, T.T. Wang, C.A. Christensen, T.M. Rvachov, D.A. Cotta, J.H. Choi, Y.R. Lee, and W. Ketterle. Formation of ultracold fermionic nali feshbach molecules. Phys. Rev. A, in print; arXiv: 1205.5304, 2012.

[13] L.R. Hunter, S.K. Peck, A.S. Greenspon, S.S. Alam, and D. DeMille. Prospects for laser cooling tlf. *Phys. Rev. A*, 85:012511, 2012.

[14] N.R. Hutzler, Hsin-I Lu, and J.M. Doyle. Buffer gas cooling and intense, cold, slow molecular beams. Chem. Rev. (Special Issue on Ultracold Molecules), accepted, 2012.

[15] J.T. Kim, Y. Lee, B. Kim, D. Wang, W.C. Stwalley, P.L. Gould, and E.E. Eyler. Spectroscopic analysis of the coupled $1^1\Pi$, $2^3\Sigma^+(\Omega = 0^-, 1)$, and $b^3\Pi(\Omega = 0^{+/-}, 1, 2)$ states of the KRb molecule using both ultracold molecule and molecular beam experiments. *Phys. Chem. Chem. Phys. (Special Issue on Ultracold Molecules)*, 13:18755, 2011 *.

[16] J.T. Kim, Y. Lee, B. Kim, D. Wang, W.C. Stwalley, P.L. Gould, and E.E. Eyler. Spectroscopic prescription for optimal stimulated raman transfer of ultracold heteronuclear molecules to the lowest rovibronic level. *Phys. Rev. A*, 84:062511, 2011.

[17] M. Knap, E. Berg, M. Ganahl, and E. Demler. Clustered wigner crystal phases of cold polar molecules in arrays of one-dimensional tubes. Phys. Rev. B in print (arXiv:1112.5662), 2012.

[18] M. Knap, A. Shashi, Y. Nishida, A. Imambekov, D. Abanin, and E. Demler. Time dependent impurity in ultracold fermions: orthogonality catastrophe and beyond. arXiv:1206.4962, 2012.

[19] S. Kotochigova, A. Petrov, M. Linnik, J. Klos, and P. S. Julienne. Ab initio properties of Li-group-II molecules for ultracold matter studies. *J. Chem. Phys.*, 135:164108, 2011.

[20] Elena Kuznetsova, T. Bragdon, Robin Côté, and S. F. Yelin. Cluster-state generation using van der Waals and dipole-dipole interactions in optical lattices. *Phys. Rev. A*, 85:012328, 2012.

[21] Elena Kuznetsova, Robin Côté, and Susanne Yelin. *Coherent laser manipulation of ultracold molecules*, page 53. in "Femtosecond Optics," Intech, 2011 *.

[22] Elena Kuznetsova, Seth T. Rittenhouse, Hossein R. Sadeghpour, and S. F. Yelin. Rydberg atom mediated polar molecule interactions: a tool for molecular-state conditional quantum gates and individual addressability. *Phys. Chem. Chem. Phys.*, 13:17115, 2011 *.

[23] Elena Kuznetsova, S. F. Yelin, and Robin Côté. An atom-molecule platform for quantum computing. *Quantum Inf. Proc.*, 10:821838, 2011.

[24] G.-D. Lin and S. F. Yelin. Superradiance: An integrated approach to cooperative effects in various systems. to be published as Chapter 6 of Advances in Atomic, Molecular, and Optical Physics, v.61, 2012.

[25] G.-D. Lin and S. F. Yelin. Superradiance in spin-j particles: Effects of multiple levels. *Phys. Rev. A*, 85:033831, Mar 2012.

[26] Hsin-I Lu, J. Rasmussen, M.J. Wright, D. Patterson, and J.M. Doyle. A cold and slow molecular beam. *Phys. Chem. Chem. Phys.*, 12:18986, 2011 *.

[27] V. Pietilä, D. Pekker, Y. Nishida, and E. Demler. Pairing instabilities in quasi-two-dimensional fermi gases. *Phys. Rev. A*, 85:023621, 2012.

[28] G. Quéméner, J. L. Bohn, A. Petrov, and S. Kotochigova. Universalities in ultracold reactions of alkali polar molecules. *Phys. Rev. A*, 84:062703, 2011.

[29] G. Quéméner and P. S. Julienne. Ultracold moulecules under control! Chem. Rev. (Special Issue on Ultracold Molecules), accepted, 2012.

[30] B. C. Sawyer, B. K. Stuhl, M. Yeo, T. V. Tscherbul, M. T. Hummon, Y. Xia, J. Klos, D. Patterson, J. M. Doyle, and J. Ye. Cold heteromolecular dipolar collisions. *Phys. Chem. Chem. Phys. (Special Issue on Ultracold Molecules)*, 13:19059, 2011 *.

[31] R. Schmidt, T. Enss, V. Pietilä, and E. Demler. Fermi polarons in two dimensions. *Phys. Rev. A*, 85:021602, 2012.

[32] B. K. Stuhl, M. Yeo, B. C. Sawyer, M. T. Hummon, and J. Ye. Microwave state transfer and adiabatic dynamics of magnetically trapped polar molecules. *Phys. Rev. A*, 85:033427, 2012.

[33] W.C. Stwalley, M. Bellos, R. Carollo, J. Banerjee, and M. Bermudez. Shortcuts for understanding rovibronic spectroscopy of ultracold alkali metal diatomic molecules. molecular physics. (Special Issue-Festschrift for Dudley Herschbach), in press, 2012.

[34] Tetsu Takekoshi, Markus Debatin, Raffael Rameshan, Francesca Ferlaino, Rudolf Grimm, Hanns-Christoph Nägerl, C. Ruth Le Sueur, Jeremy M. Hutson, Paul S. Julienne, Svetlana Kotochigova, and Eberhard Tiemann. Towards the production of ultracold ground-state RbCs molecules: Feshbach resonances, weakly bound states, and the coupled-channel model. *Phys. Rev. A*, 85:032506, Mar 2012.

Changes in research objectives, if any: None

Change in AFOSR program manager, if any: None

Extensions granted or milestones slipped, if any: None

Include any new discoveries, inventions, or patent disclosures during this reporting period (if none, report none): None