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14. ABSTRACT

We are studying fundamental interactions between ultracold atoms and near-resonant laser light. In particular, we have been investigating ultracold collisions between one alkali atom (rubidium) and one metastable noble gas atom (argon). The research is geared to the ultimate goal of producing ultracold molecules for use in a new generation of matter wave interferometers with enhanced sensitivity. Such devices will improve the performance of gyroscopes used in naval navigational systems.

The project addressed above is a long term (multi-year) endeavor. During the performance period of the ONR grant, we have observed a surprisingly weak interaction between ultracold rubidium and ultracold, metastable argon. We have measured a total trap loss rate coefficient for rubidium due to the presence of argon. Experiments to assign the exact mechanism of trap loss (radiative escape, Penning ionization, associative ionization...) are ongoing. We successfully implemented a quadrupole mass spectrometer system which is capable of differentiating between ionization products. As a result, a new measure of the ratio of Penning to associative ionization in metastable argon traps has been made.

15. SUBJECT TERMS

inertial sensing, matter-wave interferometer, ultracold molecules, Penning ionization, associative ionization, dual-species magneto-optical trap, heteronuclear interactions

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Application of Ultracold Molecules to Inertial Sensing for Navigation

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FINAL REPORT

Introduction

We recently achieved the simultaneous confinement of ultracold rubidium and ultracold, metastable argon in a dual species magneto-optical trap.[1] Such a mixture yields a unique system for studying heteronuclear interactions, including ionization processes, at low temperature and for investigating the production of weakly bound, ultracold molecules.

The proposal funded by the Office of Naval Research provided for one-time support for the grant period July 1, 2003 to December 31, 2003 to allow us to continue our investigations of Rb-Ar* interactions at ultracold temperatures with the explicit goal of working toward the extension of ultracold *atomic* interferometry to ultracold *molecular* interferometry to enable the realization of a new generation of matter wave interferometers with enhanced sensitivity. Such devices will improve the performance of gyroscopes used in naval navigational systems.

Discussion of the Underlying Physics of the Project

A principal area in which the research will have a direct impact on the objectives of the ONR is in the development of matter wave interferometers for inertial sensing.[2] Consider rotation sensing, for example, with a Sagnac interferometer. The accumulated matter wave phase shift is given by:

$$\Delta\phi = \frac{4\pi mA}{h}\Omega$$

where m is the mass, A is the enclosed area, h is Planck's constant, and Ω is the angular rotation rate. The ratio of sensitivities of matter wave interferometers compared to their photon based counterparts is $mc^2/\eta\omega$ -which is roughly 10^{10}. Although a good portion of this enhancement is lost because achievable photon flux's surpass that of atomic beams, recent performance of matter wave interferometers was shown to be comparable to the best active ring laser gyroscopes.[3,4] Clearly, the "figure of merit" for the sensitivity of a Sagnac interferometer is the product mA. For a fixed area device, the sensitivity therefore scales directly with mass, making the transition from atoms to molecules an attractive prospect for increasing sensitivity. It should be mentioned that the area A may depend on the mass; for example if diffractive optics are used to spatially separate the arms of the interferometer. In that case, higher sensitivity is principally obtained by going to *slower* atoms or molecules. Ideally, one wishes to increase both the mass and area independently in order to maximize the device sensitivity. Since there is an upper limit on atomic mass, the use of molecules is the solution for increasing the mass component. Recent results in guided atom optics holds the promise for simultaneously increasing the area of the interferometer by application of a multi-pass "storage ring".[5]

The RbAr molecule we are studying has molecular mass of 125 amu- nearly identical to the atomic Cs mass of 133 amu, thereby allowing for initial ultracold molecule experiments to be compared directly with current ultracold Cs atomic interferometers.

Summary of the Long Term Research Program

Study I: Ionization of Colliding Atoms

Ionization in collisions can occur by several distinguishable channels. The primary channel for ionization in collisions of metastable noble gases is the *Penning ionization* reaction:

$$Ar^* + Ar^* \rightarrow Ar + Ar^+ + e^-$$

Another process which plays a role in collisions is the *associative ionization* reaction:

$$Ar^* + Ar^* \rightarrow Ar_2^+ + e^-$$

in which colliding atoms are photoassociated to neutral dimer states which are coupled to the ion state, and as a result, can subsequently autoionize.

Experimental Measurements

Central to our study of ionization processes in traps is measurement of the two-body collisional loss rate coefficients β. For collisions of unlike atoms this is defined by the familiar relation:

$$R = \alpha N_{Ar} + \frac{\beta_{Ar\text{-}Ar}}{2}\int d^3r\, n_{Ar}^2(\vec{r}) + \frac{\beta_{Ar\text{-}Rb}}{2}\int d^3r\, n_{Ar}(\vec{r})\, n_{Rb}(\vec{r})$$

in which R is the rate at which ions are produced, the coefficient α characterizes collisions with background gas, N is the number of trapped atoms, and $n(\vec{r})$ is the atomic density distribution. The coefficient β itself is comprised of two terms, one from Penning ionization (PI) and the other from associative ionization (AI). Our study will be able to differentiate these mechanisms by measuring the rate at which individual reaction products ($ArRb^+$, Ar^+, Rb^+, Ar_2^+) are produced.

Study II: Photoassociative spectroscopy of RbAr*

Photoassociative spectroscopy, the probing of free-bound transitions with high resolution, has proven to be a powerful tool for determining the energy levels and dissociation energies of excited and ground states of molecules, for investigating states which are not accessible by conventional spectroscopy, and for isolating effects due to hyperfine structure.

Experimental Measurements

A Coherent 899 Ti:Sapphire laser or a diode laser will be used as the probe laser to take photoassociative spectra near the dissociation limit of the first excited attractive states directly above the Rb $S_{1/2}$ + (noble gas)* $ns[3/2]_2$ "ground" state. The information derived from this study will be used to select appropriate channels for producing ultracold RbAr.

Study III: Production of Ultracold RbAr for Use in Molecular Interferometry

Previous work on ultracold molecule production has demonstrated the scheme of photoassociating colliding atoms into an excited state molecule- which then decays to a ground state molecule- is general and that multiple channels for molecule production exist. Using the results of Studies I and II above, along with guidance from theoretical calculations, we will use additional lasers ("catalysis" lasers) to initiate photoassociative collisions through channels which produce bound, ground state RbAr molecules for use in molecular interferometry studies.

Results to Date

The project is a multi-year effort and the grant period is just 6 months; nonetheless, significant results have already been obtained in this short period of time.

Rubidium-Metastable Argon Interaction Observed

We have observed a surprisingly small interaction between ultracold rubidium and ultracold, metastable argon atoms. Our initial measurements indicate a total trap loss rate coefficient of rubidium due to the presence of argon of $\gamma_{Rb\text{-}Ar} = 4.8\times10^{-11}$ cm^3/s. No loss of argon due to

rubidium has yet been observed, but the signal to noise ratio precludes a conclusion about the reciprocity of trap loss at this time.

Ion Selective Detection Scheme Implemented

We have successfully implemented our ion selective detector system. This was accomplished through modification of a commercially available residual gas analyzer to incorporate the use of the quadrupole mass filter and ion detector *without* the use of the electron bombardment ionizer. As a result, we were able to make new measurements of the relative strength of Penning versus associative ionization in collisions between metastable argon atoms. We find the ratio to be approximately a factor of six. Our results are in good agreement with previous measurements of this process.

Preliminary searches for the production of rubidium ions in the dual species trap yielded a null result, but further enhancements to the signal processing capability, along with longer observation times, are expected to yield positive detection results shortly.

Argon Trap Loss Measured

Although not central to our molecule studies, we have also made new measurements of the trap loss coefficient for metastable argon in a single species trap. These represent the best measurements to date of this process. We find a loss rate coefficient of 2.7×10^{-10} cm^3/s in the presence of the trap light.

Molecule Detection Laser Ready

We have constructed the YAG pumped pulsed dye laser system which will be used to ionize molecules produced in the dual MOT. These ions will be detected with high sensitivity by combining time-of-flight detection with quadrupole mass filter selectivity. The search for molecule production will be commencing in the Spring of 2004.

Conclusion

In a short period of time, we have made substantial progress on the stated objectives of the project. We expect to continue to obtain high-quality results as we move forward with our experimental effort to produce cold molecules for interferometry which will allow the realization of high sensitivity inertial sensors for navigation.

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