Production of Quantum Degenerate Mixtures of Alkali and Alkaline-Earth-Like Atoms

Hideaki Hara

Ultracold atomic gas mixtures consisting of different elements have new interesting possibilities such as dipolar physics with polar molecules, study of heteronuclear Efimov resonances, and exploration of novel quantum phases. I focus on a pair of alkali Li and alkaline-earth-like Yb atoms, which has unique features different from other mixed gases. One of the distinct features of this mixture is the very large mass ratio of 29. Because of this large mass ratio, the tunneling rate of Yb atoms is more than three orders of magnitude smaller than that of Li in an optical lattice with a wavelength of 1064 nm, for example. Therefore light fermionic atoms of ^{6}Li behave as itinerant electrons and heavy atoms of Yb behave as localized impurities, which are thought to play a key role in Anderson localization, and some novel quantum phases such as Bose glass etc. For the studies of disorder and impurities, the ultracold atoms in an optical lattice have the advantage, over solid state systems, that Hubbard parameters are highly controllable and that even disorder and impurity are treated as controllable parameters. This mixture, thus, provides the various possibilities for quantum simulation of disorder and impurity problems. Another feature of this mixture is that a molecule produced from alkali and alkaline-earth-like atoms like this mixture has not only an electric dipole moment but also electron spin degrees of freedom in the ground $^2\Sigma_{1/2}$ state. Spin doublet molecules enable us to implement quantum simulation of lattice-spin models. In addition, the ultra-narrow optical transition $^1S_0$-$^3P_2$ for Yb in the presence of Feshbach resonances between the $^3P_2$ state Yb and the $^2S_{1/2}$ state ^{6}Li enables the exploration of the dynamics of Anderson's orthogonality catastrophe not only in a frequency domain but also in a time domain, while it is difficult to observe the dynamics in a solid state system due to the fast time scale.

To reach these goals, it is desirable to achieve quantum degenerate regime simultaneously in a mixed gas. In the first half of this thesis I report the first production of a quantum degenerate Bose-Fermi mixture of ^{174}Yb and ^{6}Li and a Fermi-Fermi mixture of ^{173}Yb and ^{6}Li. The experiment begins with a simultaneous magneto-optical trapping (MOT) of Yb and Li. Then we transfer both atoms from the MOT into a crossed optical far-off-resonant trap (FORT) with wavelengths of 1070 nm and 1083 nm, and perform sympathetic cooling of ^{6}Li with evaporatively cooled Yb. After evaporative cooling we obtain quantum degenerate mixtures of Yb and Li. In the case of Bose-Fermi mixture, the temperature of ^{174}Yb is $T_{\mathrm{Yb}} = 280 \pm 20$ nK, below the Bose-Einstein condensate (BEC) transition temperature $T_c = 510$ nK. The number of ^{174}Yb atoms in the condensate is

$N_{\mathrm{BEC,Yb}} = 1.5 \times 10^4$, which exist with the relatively large thermal atoms. For ^{6}Li, the number is $N_{\mathrm{Li}} = 2.5 \times 10^4$ and the temperature is $T_{\mathrm{Li}} = 290 \pm 30$ nK, corresponding to $0.08 \pm 0.01\ T_F$. In the case of Fermi-Fermi mixture, $N_{\mathrm{Yb}} = 2.0 \times 10^4$ and $T_{\mathrm{Yb}} = 170 \pm 10$ nK, corresponding to $0.52 \pm 0.12\ T_F$, and $N_{\mathrm{Li}} = 1.8 \times 10^4$ and $T_{\mathrm{Li}} = 220 \pm 40$ nK, corresponding to $0.07 \pm 0.02\ T_F$. The equality of the temperatures between Yb and Li atoms within the experimental error indicates that Yb cloud provides good thermometry for the very cold Fermi gas of ^{6}Li. Using cross-thermalization measurements in a FORT, the absolute values of s-wave scattering lengths are obtained as $|a_{^{174}\mathrm{Yb}\text{-}^6\mathrm{Li}}| = 1.0 \pm 0.2$ nm and $|a_{^{173}\mathrm{Yb}\text{-}^6\mathrm{Li}}| = 0.9 \pm 0.2$ nm. We also reveal that the equality of these lengths is consistent with mass-scaling analysis.

In the second half of this thesis, I report the development of an optical lattice system with a wavelength of 1064 nm for the ultracold atom mixture of Yb and Li with interest in disorder and impurity problems. We successfully load a BEC of ^{174}Yb into a three-dimensional optical lattice, confirmed by observing the matter-wave interference patterns of ^{174}Yb atoms in a time-of-flight image at a relatively shallow optical lattice. We also measure the coherence property of ^{174}Yb in an optical lattice in both cases with and without ^{6}Li at various lattice potential depths. Furthermore, we perform a high resolution laser spectroscopy of ^{174}Yb in an optical lattice using the ultra-narrow optical transition ^{1}S$_0$-^{3}P$_2$ in both cases with and without ^{6}Li. Due to the weak interaction between ^{174}Yb and ^{6}Li, the clear differences between the mixture and the pure ^{174}Yb in both the obtained interference patterns and the excitation spectra are not observed. In addition, we also measure the polarizabilities of the ^{3}P$_2$ state of ^{174}Yb atoms in a FORT with a wavelength of 1070 nm and determine the scalar and the tensor polarizabilities, which indicate that the polarizability of the ^{3}P$_2$ state of ^{174}Yb can be tuned to positive, zero, or the same as the ground state. This information is important for the spectroscopy which we perform and for the various future experiments.

The quantum degenerate mixtures of Yb and Li and the successful loading of this mixture into the optical lattice, realized in this thesis, are the essential first step toward the quantum simulation of impurity or disordered systems, dipolar physics with ultracold polar molecules, and exploration of novel quantum phases.