II-B Laser Cooling and Trapping of Neutral Atoms

When atoms absorb or emit photons, the atoms are accelerated or decelerated because photons have momenta. On the other hand, a strong radiation field modifies the internal energy of an atom, so that an atom in an inhomogeneous radiation field receives a force from the field. The former mechanism allows us to decrease the translational temperature of neutral atoms down to an extremely low temperature by means of laser radiation, and the latter enables the spatial control of neutral atoms with lasers. As the translational temperature goes down to the nano kelvin region, the atomic de Broglie wavelength becomes a macroscopic size and some macroscopic quantum-mechanical collective motion of atoms can then be expected to occur. Such a long de Broglie wavelength also enables us to realize the atomic interferometry. On the other hand, easy control of the atomic spatial position and velocity with lasers is expected to open the possibility of various applications. For these reasons, we have been studying the laser cooling and trapping of neutral atoms.

II-B-1 Quantum Statistical Effects in Ultracold Ionizing Collisions between Spin-Unpolarized Metastable He($2s^3S_1$) Atoms

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We have carried out a precise theoretical investigation on the cause of the isotopic difference in collisional ionization rate coefficients between cold ^{4}He($2s^3S_1$) + ^{4}He($2s^3S_1$) and ^{3}He($2s^3S_1$) + ^{3}He($2s^3S_1$) collisions at 0.5 mK, which is observed in our previous magneto-optical trap experiments on He atoms. The rate coefficients experimentally obtained for ^{4}He-^{4}He and ^{3}He-^{3}He collisions are $(3.8 \pm 1.1) \times 10^{-10}$ cm^3/s and $(1.1 \pm 0.4) \times 10^{-9}$ cm^3/s, respectively, and there is a large isotopic difference of a factor of 3 between them. Through our theoretical calculation, we have found that this difference is an explicit manifestation of the differing quantum statistics of those isotopes: at such a low temperature, the ionization process is mainly caused by only a single scattering partial wave (*s*-wave). Therefore, the electronic states that can contribute to the ionization explicitly differ between ^{4}He-^{4}He and ^{3}He-^{3}He collisions because of the differing quantum statistical symmetries of the isotopes. This is the main reason why there is a large isotopic difference in the ionization rate coefficients. Our calculation, which is based on this consideration and takes into account not only the spin conservation rule in the ionization process but also a small contribution of the *p*-wave tunneling through its centrifugal barrier, has given the rate coefficients of 2.2×10^{-10} cm^3/s and 1.0×10^{-9} cm^3/s for ^{4}He-^{4}He and ^{3}He-^{3}He collisions, respectively. These values agree well with the experimental results. It is interesting that the rate coefficient for the fermionic isotope (^{3}He) is larger than for the bosonic one (^{4}He), which is just contrary to the results of similar experiments on cold ionizing collisions of spin-polarized Kr[1] and Xe[2] atoms. From our calculation, we have found that this is because the spin conservation rule holds good in He atoms while in heavier rare gas atoms it breaks down. An optical enhancement of the collisional ionization is also observed in our previous experiment on the cold atomic collision irradiated with trap laser beams. Our theoretical values are in good agreement with the experimental results, and this enhancement has been attributed to the fact that in the presence of the laser irradiation many partial waves up to the 6-th order can contribute to the ionization. We have also found that this fact results in the smaller isotopic difference in the enhanced ionization rates.

References

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II-C Spectroscopy of Atoms and Ions in Liquid Helium

Ions and atoms in liquid helium are known to reside in bubble-like cavities due to the Pauli repulsive force between electrons. Physical properties in these exotic surroundings are determined by the potential energy of the impurity-He$_n$ system, the surface tension energy of the liquid helium, and the pressure-volume energy. Spectroscopic studies of ions in liquid helium are expected not only to give information on the structure and dynamics of the bubbles, but also to contribute to the study on the property of superfluid liquid helium. Moreover, if we can study ions distributed just below the liquid helium, it will be a new method for the experimental research on the low dimension plasma physics.

II-C-1 Spectroscopic Study of Alkali-Earth Atoms in Liquid ^{3}He

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The comparison between spectra of atoms in liquid ^{3}He and ^{4}He can allow us to find interesting phenomena arising from differing quantum features of each liquid helium, such as the quantum statistics and fluidity (normal and super). From this viewpoint, we have measured some spectra of Mg and Ca in liquid ^{3}He. As a result, it has been found that (a) excitation spectra of both atoms in liquid ^{3}He are much narrower and their blue shifts are significantly smaller than the ones in

liquid ^{4}He, and that (b) there is a large isotope shift in the emission spectrum of Mg while such a shift is not observed for Ca. The smaller width and shift in each excitation spectrum can be explained by the difference in the number density and surface tension between liquid ^{3}He and ^{4}He: because of the smaller mass of ^{3}He, its wavefunction has a size larger than ^{4}He, so that the number density of ^{3}He should be smaller. Moreover, because of the difference in the quantum statistical symmetry, the surface tension of liquid ^{3}He is about one third of that of liquid ^{4}He at 1.4 K. These facts make the size of an atomic bubble much larger in liquid ^{3}He than in liquid ^{4}He (soft cage effect), so that perturbations by surrounding ^{3}He atoms is much weaker. This effect results in the smaller peak shift and spectral width in the excitation spectra for liquid ^{3}He. In the case of Mg, while its excitation spectrum for liquid ^{3}He is narrower than for liquid ^{4}He, the width of its emission spectrum is almost the same as the one in liquid ^{4}He. These facts result in that the emission and excitation spectra for liquid ^{3}He have almost the same widths, although such a situation is quite unusual and hardly seen in ordinary bubble spectra. This fact can be understood with a model of exciplex formation in the excited state, which is similar to the one previously introduced to explain the emission spectrum of Mg in liquid ^{4}He. This model also consistently explains the red shift of the peak position in the emission spectrum, since it just agrees with an isotope shift estimated from the molecular vibrations.