RESEARCH ACTIVITIES II
Department of Molecular Structure

II-A Laser Cooling and Trapping of Metastable Helium Atoms

In the past two decades, extensive developments have occurred in the laser cooling and trapping of neutral atoms, with many workers reporting the application of these techniques to such diverse atomic species as alkali atoms, alkali earth atoms, and rare gas atoms. Among these, the helium atom is unique on account of its small mass, simple energy level structure, and easy availability in two isotopic forms (^{3}He and ^{4}He) of differing quantum statistics. For this reason, we have been studying the laser cooling and trapping of helium atoms.

II-A-1 Magneto-Optical Trap of Metastable Helium-3 Atoms

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A magneto-optical trap (MOT) of metastable ^{3}He atoms has been demonstrated for the first time. Some 10^5 atoms have successfully been confined in a region with a diameter of ~0.4 mm at a temperature of ~0.5 mK; the atomic number density is estimated to be ~10^9 /cm^3 at the trap center. These characteristics of the ^{3}He MOT are almost comparable to those of the ^{4}He MOT so far demonstrated by many workers. Monitoring the fluorescence from the MOT, the trap loss rate has also been measured and discussed. Since ^{3}He is a unique fermionic atom on account of its small mass and simple energy level structure, we can expect that such a ^{3}He MOT will be useful as a fundamental tool for future studies on the physics of fermions at ultralow temperatures.

II-B Spectroscopic Studies on Atoms and Ions in Liquid Helium

Atoms and ions in liquid helium are known to reside in bubble-like cavities due to the Pauli repulsive force between electrons. Physical properties of 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 work. Spectroscopic studies of such impurity atoms and 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.

II-B-1 Theoretical Studies on the Spectra of Yb$^+$ Ions in Liquid Helium

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In our previous experimental studies on Yb$^+$ in liquid helium, we found that its spectra have two characteristic properties: (1) The $4f^{14}6s^2S_{1/2}$–$6p^2P_{1/2}$ (D1) excitation spectrum is much broadened and blue-shifted compared with the spectrum of free Yb$^+$ ions, while the emission spectrum of the same transition has relatively small spectral width and shift compared with the excitation spectrum. (2) The excitation spectrum of the $4f^{14}6s^2S_{1/2}$–$6p^2P_{3/2}$ (D2) transition is doubly peaked. To explain these properties, we have carried out theoretical calculations on the basis of a vibrating bubble model, in which the bubble surface is assumed to vibrate in the spherical (breathing), dipolar and quadrupolar modes. These calculations are essentially based on adiabatic potential curves of an Yb$^+$–He pair, which have been obtained from our complete-active-space self-consistent field (CASSCF) and multi-reference configuration-interaction (MRCI) calculations. Consequently, it has been found that the blue shifts are well understood with this bubble model, and also that the dynamic Jahn-Teller effect due to the quadrupole vibration of the bubble plays an important role for the double-peaked profile of the D2 excitation spectrum.

II-B-2 Measurements of Fine Structure Changing Cross Sections of Ca$^+$ and Sr$^+$ in Collisions with He Atoms

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In our previous spectroscopic study of Yb$^+$ in liquid helium, we observed an emission from its $4f^{14}6p$ $^2P_{1/2}$ fine structure level not only when this level was directly excited but also when another fine structure level ($4f^{14}6p$ $^2P_{3/2}$) was excited. This suggested the presence of a fast inter-multiplet transition from $^2P_{3/2}$ to $^2P_{1/2}$ due to the interaction between Yb$^+$ and He atoms. From our estimation, which was based on the comparison between the emission intensities measured when the $^2P_{1/2}$ and $^2P_{3/2}$ levels were excited, we found that the $^2P_{3/2} \rightarrow$ $^2P_{1/2}$ transition should be extremely faster than expected for two-body collisions of other atoms and ions with He. This enhancement of the transition may have arisen from some many-body effect, such as the quadrupole vibration of the helium bubble surface. However we could not discuss it any more, because there were no data on the fine structure changing rate in two-body collisions, which was necessary to exactly estimate the many-body effect. This fact motivated us to study fine structure changing rates of alkali-earth ions in two-body collisions with He.

We have started with measurements on Ca^+ and Sr^+ to test our experimental apparatus. These ions have been produced by laser ablation of pure metal samples. Detecting laser induced fluorescence, we have measured cross sections of collision induced transitions between fine structure levels in the $4p^2P_J$ state of Ca^+ and the $5p^2P_J$ state of Sr^+ due to collisions with He atoms at room temperature (298 K). The cross sections obtained are $\sigma(Ca^+: 4p^2P_{3/2} \to 4p^2P_{1/2}) = 1.17 \pm 0.05$ Å^2, $\sigma(Ca^+: 4p^2P_{1/2} \to 4p^2P_{3/2}) = (7.92 \pm 0.44) \times 10^{-1}$ Å^2, and $\sigma(Sr^+: 5p^2P_{3/2} \to 5p^2P_{1/2}) = (1.44 \pm 0.10) \times 10^{-2}$ Å^2. These cross sections are much smaller than those of neutral K and Rb atoms, which have the same electron configurations as Ca^+ and Sr^+, respectively. This may probably be because stronger spin-orbit couplings in the $2P_J$ states of Ca^+ and Sr^+ prevent their electron spins from flip-flopping all the more. On the other hand, it is known that the cross sections of alkali atoms are roughly proportional to $e^{-C\Delta E}$ (where ΔE is the fine structure splitting and C is a constant). This is seen from the fact that the cross sections for alkali atoms are almost on a straight line in Figure 1. However, the present cross sections for Ca^+ and Sr^+ significantly deviate upward from this line, as seen in Figure 1; that is, these cross sections are much larger than expected from only the sizes of the fine structure splittings. This may probably be due to a difference between the interactions in ion-He and atom-He pairs.

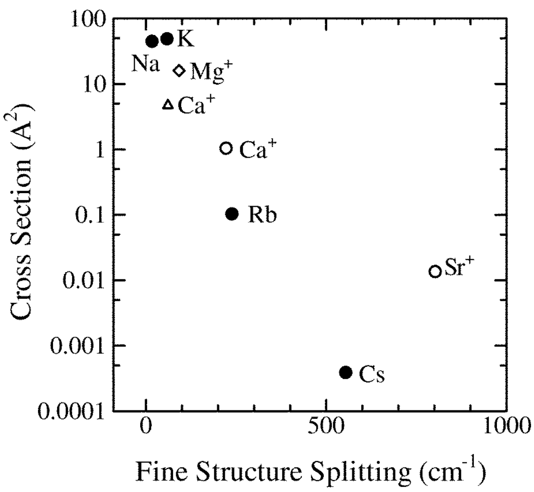

Figure 1. Fine structure changing cross sections so far measured for various alkali atoms and alkali earth ions in collisions with He atoms, as a function of their fine structure splittings; ● shows the one for the $np^2P_{3/2} \to np^2P_{1/2}$ transition of each alkali atom (for Na, K, Rb and Cs, n = 3, 4, 5 and 6, respectively, and the collision temperature T = 397, 368, 340 and 311 K, respectively) (by Krause), ◇ Mg^+ $3p^2P_{3/2} \to 3p^2P_{1/2}$ at 1600 K (by Brust), △ Ca^+ $3d^2D_{5/2} \to 3d^2D_{3/2}$ at 10000 K (by Knoop *et al.*), and ○ the present data.