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Summary of thesis:
Variation of the electronic states of Ca$_2$RuO$_4$ and Sr$_2$RuO$_4$
under uniaxial pressures

Haruka Taniguchi

Competition and cooperation among spin, orbital, and lattice degrees of
freedom are key concepts to understand intriguing phenomena in condensed
matter systems. As one of such fascinating systems, the layered perovskite
ruthenates Ca$_{2-x}$Sr$_x$RuO$_4$ have been attracting wide interest for their variety
of electronic states originating from multiple degrees of freedom: for example,
Ca$_2$RuO$_4$ is an antiferromagnetic (AFM) Mott insulator$^1$, whereas Sr$_2$RuO$_4$
is a leading candidate for a spin-triplet superconductor$^2$.

For studying a system like Ca$_{2-x}$Sr$_x$RuO$_4$ with orbital degree of freedom,
uniaxial pressure (UAP) is expected to be effective because it will couple well
with the orbital which spatially spreads along a certain direction. UAP can
realize different crystal structures depending on pressure direction and
selectively control the symmetry of the crystal differently from hydrostatic
pressure.

Therefore, we have studied the electronic states of Ca$_2$RuO$_4$ and Sr$_2$RuO$_4$
under UAPs with three different pressure directions: two in-plane directions,
[100]$_T$ and [110]$_T$, and the out-of-plane direction, [001]$_T$, using the tetragonal
notation. [100]$_T$ and [110]$_T$ direction are parallel and diagonal to the in-plane
Ru-O bond of the RuO$_6$ octahedra, respectively. Single crystals of Ca$_2$RuO$_4$
were provided by Prof. F. Nakamura in Kurume Inst. of Tech., and Sr$_2$RuO$_4$
were synthesized in our Lab lead by Prof. Y. Maeno.

For revealing the in-plane UAP effect on Ca$_2$RuO$_4$, we performed
magnetization and resistivity measurements$^3$. We succeeded in inducing
the ferromagnetic metallic (FM-M) phase. The mechanism of this Mott
transition is considered to be the same as that under hydrostatic pressure:
the out-of-plane flattening distortion of RuO$_6$ octahedra is released, and the
$xy$ and $\{yz,zx\}$ bands of Ru 4$d$ electrons approach energetically and overlap.
The critical pressures of the FM-M phase for the UAPs (0.4 GPa for $P/\lbrack100\rbrack_T$
and 0.2 GPa for $P/\lbrack110\rbrack_T$) are substantially lower than that for the
hydrostatic pressure (0.5 GPa$^4$). Interestingly, the critical pressure of the
FM-M phase and the pressure dependence of FM component of
magnetization were found to be highly anisotropic. These peculiar
anisotropic results can be naturally understood as a consequence of the orthorhombic crystal distortions in Ca$_2$RuO$_4$ and existence of orthorhombic crystalline twin domains in the sample.

Surprisingly, the out-of-plane UAP effect on Ca$_2$RuO$_4$ was opposite to a simple prediction$^5$; from resistivity measurements, we have clarified that the insulating gap is suppressed from 3000 K to 700 K. This result suggests that Ca$_2$RuO$_4$ approaches a metallic state under the out-of-plane UAP with a mechanism, which is different from that of the Mott transition under in-plane UAP. Since the crystalline field splitting between the $xy$ and $\{yz,zx\}$ bands should become larger, this gap suppression is attributed to the enhancement of the band width as a result of the release of rotation or/and tilting distortion of RuO$_6$ octahedra.

In the study of the out-of-plane UAP effect on the superconductivity (SC) of Sr$_2$RuO$_4$, we used Sr$_2$RuO$_4$-Ru eutectic crystals in order to compare the UAP-originated 3-K SC with the interfacial 3-K SC in the same sample$^6$. We previously revealed that the onset of superconducting transition temperature $T_c$ of Sr$_2$RuO$_4$ without Ru inclusions is enhanced from 1.5 K to 3.2 K, which is the same as the onset $T_c$ of the SC realized near interfaces between Sr$_2$RuO$_4$ and Ru in the eutectic crystal$^7$. In this thesis, we newly proposed the out-of-plane UAP dependence of the spatial distribution of 3-K SC in Sr$_2$RuO$_4$-Ru from AC susceptibility and resistivity measurements.

The in-plane UAP effect on Sr$_2$RuO$_4$ was also revealed to be significantly anisotropic from AC susceptibility measurements; we clarified that $P//[100]_T$ rather than $P//[110]_T$ is favorable for inducing 3-K SC. This result can be understood consistently with previous studies$^8$.

Our results strongly demonstrate the effectiveness of UAP to control the electronic state of systems which have multiple degrees of freedom.