Appearance of Beating in the Shubnikov-de Haas Oscillations of the Organic Conductor $\kappa$(BEDT-TTF)$_2$Cu(NCS)$_2$ Under Pressure

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Introduction
Coherence peaks and beats in the Shubnikov-de Haas or de Haas-van Alphen oscillations are regarded as firm evidence for the coherent third-dimensional electron motion in layered materials. Sometimes, a coherence peak is observed in the absence of beating behavior in some Q2D compounds. The absence of beating in $\kappa$(BEDT-TTF)$_2$Cu(NCS)$_2$ could be either because the interlayer transport is incoherent ($\hbar/\tau > t_{\perp}$, $\tau^{-1}$ is a quasiparticle scattering rate) or because the interlayer hopping $t_{\perp}$ is so small that the beat frequency cannot be resolved experimentally. From the coherence peak, $t_{\perp}$ and $E_F$ were estimated as 0.04 meV and 19.1 meV at ambient pressure. This makes $t_{\perp}/E_F$ approximately 1/500.$[1,2]$ For isotructural compound of $\kappa$-(BEDT-TTF)$_2$I$_3$, the coherence peak gave an approximate value of $t_{\perp}/E_F$ upper limit of 1/3000.$[3]$ For both the compounds, the absence of beating in spite of the presence of a coherence peak can be explained by the smallness of $t_{\perp}$ compared to $E_F$.

Experimental
Interlayer resistance, $R_{zz}$, along the crystallographic $a^\star$-axis was measured using the standard four-wire ac technique in magnetic fields up to 18T at 0.41 K. Pressure was applied to samples in a clamped BeCu cell at room temperature using Daphne 7373 oil as the pressure transmitting medium.$^7$ The pressure at low temperature was 7 kbar.

Results and Discussion
Figure shows (a) the oscillating resistance normalized with the non-oscillating background and (b) $dR_{zz}/dH$ as a function of the inverse magnetic field between 4 and 18 T at $\theta = 21.3^\circ$. The oscillatory behavior including beating is amplified in $dR_{zz}/dH$. The node in the beating that appeared around $1/H \sim 0.11 T^{-1}$ is indicated with a downward arrow. Beating behavior in SdH oscillations of $\kappa$-(BEDT-TTF)$_2$Cu(NCS)$_2$ at 7 kbar can be caused by nonuniform pressure distribution. However, the possibility of nonuniform pressure is excluded for the following reasons. First, if the inhomogeneous pressure generates dispersions of the SdH frequencies, they must be omnipresent regardless of field orientations. The beats at only certain field orientations are not explainable by the spurious effect of nonuniform pressure. Second, well established Lebed resonances and Yamaji resonances in angular magnetoresistance measurements in the same run confirmed the uniformity of pressure.$[4]$ In addition, the possibility of sample twinning is also excludes for the same reason.

Conclusions
We observed beating of the SdH oscillations in the pressurized sample at certain field orientations, confirming the pressure effect on the charge transfer. Compared with the results at ambient pressure, the interlayer transfer integral $t_{\perp}$ at 7 kbar quadruples while $E_F$ doubles. As a result, the value of $t_{\perp}/E_F$ is significantly enhanced making it possible to observe beating behavior in the SdH oscillations.

References