Introduction
Atomically-thin crystals of the transition-metal disulphides (MoS2 and WS2) and diselenides (MoSe2 and WSe2) constitute a novel class of monolayer semiconductors that possess direct optical bandgaps located at the degenerate K and K' valleys of their hexagonal Brillouin zones. The considerable recent interest in these 2D transition-metal dichalcogenides (TMDs) derives from their strong spin-orbit coupling and lack of structural inversion symmetry which, together with time-reversal symmetry, couples spin and valley degrees of freedom and leads to valley-specific optical selection rules: light of σ+ circular polarization couples to inter-band exciton transitions in the K valley, while the opposite σ- circular polarization couples to transitions in the K’ valley. The ability to populate and/or probe electrons and holes in specific valleys using polarized light has renewed long-standing interests in understanding and exploiting such ‘valley pseudospin’ degrees of freedom for both fundamental physics and far-reaching applications in, e.g., quantum information processing.

Experiment & Results
We report circularly-polarized optical reflection spectroscopy of monolayer WS2 and MoS2 at low temperatures (4K) and in high magnetic fields to 65 T. Both the A and the B exciton transitions exhibit a clear and very similar Zeeman splitting of approximately $\pm 230 \mu$eV/T ($g = -4$), providing the first measurements of the valley Zeeman effect and associated $g$-factors in monolayer transition-metal disulphides. These results complement and are compared with recent low-field photoluminescence measurements of valley degeneracy breaking in the monolayer diselenides MoSe2 and WSe2. Further, the very large magnetic fields used in our studies allow us to observe the small quadratic diamagnetic shifts of the A and B excitons in monolayer WS2 (0.32 and 0.11 $\mu$eV/T2, respectively), from which we calculate exciton radii of $~1.53$ nm and $~1.16$ nm. Moreover, when analyzed within a model of non-local dielectric screening in monolayer semiconductors, these diamagnetic shifts also constrain and provide estimates of the exciton binding energy. For example, using a reduced A exciton mass of $0.16m_0$, the A and B exciton binding energies are constrained to be 410 meV and 470 meV, respectively. These results further highlight the utility of high magnetic fields for understanding new 2D materials.

The Figure shows a) reflection spectrum of monolayer WS2, b-e) the shifts of the A and B excitons to 65T, f) the valley Zeeman splitting, and g) the measured diamagnetic shift.

References