Orbital selectivity causing anisotropy and particle-hole asymmetry in the charge density wave gap of $2\text{H}^{-}\text{TaS}_2$


DOI
10.1103/PhysRevB.96.125103

Publication date
2017

Document Version
Final published version

Published in
Physical Review B
Orbital selectivity causing anisotropy and particle-hole asymmetry in the charge density wave gap of $2H$-TaS$_2$

J. Zhao, K. Wijayaratne, A. Butler, J. Yang, C. D. Malliakas, D. Y. Chung, D. Louca, M. G. Kanatzidis, J. van Wezel, and U. Chatterjee

1Department of Physics, University of Virginia, Charlottesville, Virginia 22904, USA
2Department of Chemistry, Northwestern University, Evanston, Illinois 60208, USA
3Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA
4Institute for Theoretical Physics, Institute of Physics, University of Amsterdam, 1090 GL Amsterdam, The Netherlands

(Received 12 May 2017; published 5 September 2017)

We report an in-depth angle-resolved photoemission spectroscopy study on $2H$-TaS$_2$, a canonical incommensurate charge density wave (CDW) system. This study demonstrates that just as in related incommensurate CDW systems, $2H$-TaSe$_2$ and $2H$-NbSe$_2$, the energy gap ($\Delta_{\text{CDW}}$) of $2H$-TaS$_2$ is localized along the $K$-centered Fermi surface barrels and is particle-hole asymmetric. The persistence of $\Delta_{\text{CDW}}$ even at temperatures higher than the CDW transition temperature $T_{\text{CDW}}$ in $2H$-TaS$_2$, reflects the similar pseudogap behavior observed previously in $2H$-TaSe$_2$ and $2H$-NbSe$_2$. However, in sharp contrast to $2H$-NbSe$_2$, where $\Delta_{\text{CDW}}$ is nonzero only in the vicinity of a few “hot spots” on the inner $K$-centered Fermi surface barrels, $\Delta_{\text{CDW}}$ in $2H$-TaS$_2$ is nonzero along the entirety of both $K$-centered Fermi surface barrels. Based on a tight-binding model, we attribute this dichotomy in the momentum dependence and the Fermi surface specificity of $\Delta_{\text{CDW}}$ between otherwise similar CDW compounds to the different orbital orientations of their electronic states that participate in the CDW pairing. Our results suggest that the orbital selectivity plays a critical role in the description of incommensurate CDW materials.

DOI: 10.1103/PhysRevB.96.125103

I. INTRODUCTION

Layered transition-metal dichalcogenides (TMDs) are highly sought after materials for their extremely rich phase diagrams, which encompass diverse quantum states including metals, semiconductors, Mott insulators, superconductors, and charge density waves (CDWs) [1–5]. $2H$-TaS$_2$, a prominent member of the TMD family, is an extremely versatile material by itself. In its pristine and bulk form, $2H$-TaS$_2$ hosts an incommensurate CDW order with the wave vector $q_{\text{CDW}} \sim (2/3 \pm 0.02)\Gamma M$ [6] and the $T_{\text{CDW}} \sim 75$ K [7,8]. The CDW order coexists with the superconductivity [9–11] at temperatures lower than 0.8 K. Similar to various other TMDs [12–18], the CDW and superconducting properties of $2H$-TaS$_2$ are also intertwined and can be tuned via various materials processing techniques such as chemical intercalation [19–26], strain engineering [27], and exfoliation [28]. Furthermore, $2H$-TaS$_2$-based alloys, intercalated with 3$d$ elements [29], are shown to have great relevance in applications in magnetic devices. For example, a very pronounced out-of-plane magnetocrystalline anisotropy emerges upon Fe intercalation [30].

Studies of incommensurate CDW order in TMDs such as $2H$-NbSe$_2$ and $2H$-TaS$_2$ have attracted a lot of attention lately. For example, a series of spectroscopic measurements [31–41] has revealed that $\Delta_{\text{CDW}}$ of these compounds opens up only around specific regions of their underlying Fermi surfaces (FSs) [31,32]. Contrary to the common view [42] FS nesting alone was shown not to be responsible for the CDW instability in $2H$-NbSe$_2$ [31,43]. However, there are reports both for and against FS nesting alone as the driver of the CDW order in $2H$-TaSe$_2$ [44,45]. Moreover, $\Delta_{\text{CDW}}$ in $2H$-NbSe$_2$ has been found to be particle-hole asymmetric [12,33,46,47], and nonzero even at temperatures ($T^*$) greater than $T_{\text{CDW}}$ [12,31], which resembles the enigmatic pseudogap (PG) behavior in underdoped cuprate high-temperature superconductors (HTSCs) [48–50]. The PG behavior has also been observed in $2H$-TaSe$_2$ [44]. Recently, a theoretical analysis of the CDW order in $2H$-NbSe$_2$ showed that these intriguing observations can be modeled within a single theory based on strong electron-phonon (el-ph) coupling [46,47]. Quite strikingly, the orbital character of the electronic states involved in the CDW formation as well as the momentum dependence of the el-ph coupling play equally significant roles in this model.

In light of the above-described developments in our understanding of incommensurate systems such as $2H$-NbSe$_2$ and $2H$-TaSe$_2$, and the close parallel between these systems and the cuprate HTSCs, an important question emerges: Which of the above-described experimental observations are universal attributes of incommensurate CDW systems? In order to address this, we present here a comprehensive study of the electronic structure of $2H$-TaS$_2$ as a function of $T$ and momentum ($k$). Unlike the cases of $2H$-NbSe$_2$ and $2H$-TaSe$_2$, spectroscopic investigations on $2H$-TaS$_2$ are rather limited. Angle-resolved photoemission spectroscopy (ARPES) studies on $2H$-TaS$_2$ [40] and a related material Na$_x$TaS$_2$ [37,38] have found nonzero $\Delta_{\text{CDW}}$ only along selected regions of the underlying FS in each case. These were corroborated by the optics data [39].

The objectives of this paper are (i) to determine whether $\Delta_{\text{CDW}}$ is particle-hole symmetric or asymmetric, (ii) to examine the possible existence of PG behavior for $T > T_{\text{CDW}}$, and (iii) to investigate whether the experimental data bear any manifestation of orbital-selective CDW pairing. Establishing the $k$ and $T$ dependence of $\Delta_{\text{CDW}}$ and its FS specificity are vital to unveiling the mechanism of CDW order in $2H$-TaS$_2$. Moreover, a direct comparison of this information with that
from $2H$-NbSe$_2$ and $2H$-TaSe$_2$ will be helpful to identify the universal traits of incommensurate CDW systems.

Our ARPES data, combined with arguments based on a tight-binding model, establish the following: (i) As in $2H$-NbSe$_2$, $\Delta_{CDW}$ in $2H$-TaS$_2$ is particle-hole asymmetric and persists for $T > T_{CDW}$; (ii) in contrast to $2H$-NbSe$_2$, $\Delta_{CDW}$ in $2H$-TaS$_2$ is clearly visible at each measured momentum location along both $K$-centered FS barrels; and (iii) the difference between the momentum anisotropy and the FS specificity of $\Delta_{CDW}$ in $2H$-TaS$_2$ and that in $2H$-NbSe$_2$ can be understood by comparing the orbital natures of the electronic states involved in CDW pairing.

II. EXPERIMENTAL DETAILS

We have conducted ARPES measurements using the 21.2 eV He i line of a discharge lamp combined with a Sciencia R3000 analyzer at the University of Virginia, as well as 75 and 22 eV synchrotron light equipped with a Sciencia R4000 analyzer at the Plane Grating Monochromator (PGM) beamline of the Synchrotron Radiation Center, Wisconsin, respectively. The angular resolution is $\sim 0.3^\circ$, and the total energy resolution is $\sim 8$–15 meV. For $T$-dependent studies, data were collected in a cyclic way to ensure that there were no aging effects in the spectra. All experiments were performed in an ultrahigh vacuum (better than $5 \times 10^{-11}$ Torr, both in the helium lamp system and in the beamline). Single crystals of $2H$-NbSe$_2$ and $2H$-TaS$_2$ were grown using the standard iodine vapor transport method. A conventional four-terminal configuration was employed for measuring the resistivity of a $2H$-TaS$_2$ single-crystal sample in a Quantum Design physical properties measurement system (PPMS). Electrical resistivity measurements indicate $T_{CDW} \sim 75$ K [Fig. 1(g)], for $2H$-TaS$_2$, in agreement with previous studies [9].

III. RESULTS

A. FS topology and nesting vectors

The first-principles calculations for both $2H$-TaS$_2$ and $2H$-NbSe$_2$ predict two closely spaced pairs of quasi-two-dimensional FS cylinders around the $\Gamma$ point as well as around the $K$ point [6,51–53]. These cylinders are double walled due to the presence of two formula units per unit cell. Figures 1(a) and 1(d) show the FS intensity maps of $2H$-TaS$_2$ and $2H$-NbSe$_2$, respectively, in their normal states. These FS intensity maps present the ARPES data at $\bar{\omega} = 0$ as a function of the in-plane momentum components $k_x$ and $k_y$, where $\bar{\omega}$ is the electronic energy measured with respect to the chemical potential $\mu$. Notice that no symmetrization of ARPES data has been incorporated for constructing either of the FS intensity maps in Figs. 1(a) and 1(d). As expected [6,51–53], double-walled FS barrels around the $\Gamma$ and $K$ points can be observed in both compounds. The regions with high intensity along $\Gamma-K$, which are due to saddle bands, can also be noticed in both materials. However, the pancakelike intensity profile around the $\Gamma$ point, which is observed in $2H$-NbSe$_2$, is not detected in $2H$-TaS$_2$. All these observations are consistent with previous experiments on related compounds [12,31,32,38,40].

In the case of a Peierls-like CDW instability [42], one expects the CDW wave vector to span nearly parallel regions of the FS. Figure 1(a) shows that although the FS of $2H$-TaS$_2$ has a number of nearly parallel regions, their separations do not agree with the magnitude of $\mathbf{q}_{CDW}$. For instance, both FS barrels around the $\Gamma$ point are too large in size for being self-nested by any of the three primary CDW wave vectors $\mathbf{q}_1$, $\mathbf{q}_2$, and $\mathbf{q}_3$ [shown by red arrows in Fig. 1(a)]. As in the case of $2H$-NbSe$_2$ [31], a simple FS nesting is therefore expected not to play a key role in the CDW formation in $2H$-TaS$_2$.

B. CDW energy gap

In order to interrogate the momentum structure of $\Delta_{CDW}$ along the $K$-centric FS barrels of $2H$-TaS$_2$, we focus on ARPES data as a function of $\bar{\omega}$ at specific momentum values, known as energy distribution curves (EDCs), at $T = 45$ K $< T_{CDW}$ [Figs. 2(a)–2(c)]. The momentum locations of the EDCs in Figs. 2(a) and 2(b) are marked in the FS intensity map around the $K$ point in Fig. 2(d). To determine the presence of a CDW energy gap, the effects of the Fermi function (FF) and energy resolution are to be eliminated from the EDCs. This can be accomplished to a good approximation after the EDCs are divided by the resolution broadened Fermi function [54,55]. We refer the method that takes into account the Fermi cutoff and energy resolution via the division of EDCs by resolution broadened FF as method 1.

The $\bar{\omega}$ location of the quasiparticle peak in the FF divided EDC can be seen to be below zero at each measured momentum point along the $K$-centric FS barrels [Figs. 2(e) and 2(f)]. This means that both $K$-centered FS barrels are gapped. To visualize this better, we stacked EDCs before and after division by a resolution broadened FF at equal momentum spacing in

FIG. 1. (a) FS intensity map of a $2H$-TaS$_2$ sample obtained using ARPES with photon energy $h\nu = 75$ eV at $T = 90$ K. The red arrows correspond to the three primary CDW vectors $\mathbf{q}_1$, $\mathbf{q}_2$, and $\mathbf{q}_3$, (b) and (c) schematically indicate the dominant orbital contribution to the electronic states around the $K$ point of $2H$-TaS$_2$, while (d) and (e) indicate that of $2H$-NbSe$_2$. (d) The FS intensity map of a $2H$-NbSe$_2$ sample at $T = 50$ K using $h\nu = 22$ eV. The pancakelike FS around the $\Gamma$ point is pointed out using the red arrow. Note that the data have been integrated over an energy window of 10 meV to enhance the spectral features in both (a) and (d). (g) Resistivity ($\rho$) plotted against $T$ for the $2H$-TaS$_2$ sample. The CDW-induced anomaly, signaling $T_{CDW} \sim 75$ K, is identified by the discontinuous change in the slope of the $\rho(T)$ curve, indicated by the black dashed arrow.
We describe in Sec. III D how this can be understood in terms of comparison, we plot the EDCs obtained after adopting the Lucy-Richardson iterative technique, which is different from the methods 1 and 2 in Fig. 2(h). The momentum location of the coherence peak from the spectra for $T > T_{\text{CDW}}$ do not have well-defined peaks, they do have a clearly discernible “kink” feature, defined as a discontinuous change in slope. From Fig. 3(b), it is apparent that the $\bar{\omega}$ location of this kink in the spectra at $T > T_{\text{CDW}}$ is approximately constant, and it is the same as that of the coherence peaks for $T < T_{\text{CDW}}$. The decrease in intensity of the coherence peak with increasing temperatures can be visualized from Fig. 3(a) as well.

We cannot determine the exact magnitude of the CDW energy gap from our ARPES measurements because of the particle-hole asymmetry of $\Delta_{\text{CDW}}$. Nevertheless, the fact that the peak/kink structures in the FF divided ARPES spectra are positioned at energy values $\bar{\omega} < 0$, evidences that a nonzero $\Delta_{\text{CDW}}$ persists even for temperatures $T > T_{\text{CDW}}$. The energy gap remains particle-hole asymmetric for all measured temperatures. Moreover, there is a loss of single-particle coherence at $T_{\text{CDW}}$, indicated by the disappearance of a peak from the spectra for $T > T_{\text{CDW}}$. Similar behavior was observed in 2H-NbSe$_2$ [12] and underdoped Bi2212 HTSC [59] as $T$ is increased through $T_{\text{CDW}}$ and $T_c$, respectively. These observations suggest that the disappearance of the CDW order at $T_{\text{CDW}}$ in 2H-TaS$_2$ occurs due to loss of long-range phase coherence, as suggested for 2H-NbSe$_2$ also [12].
fit to the electronic band structure is required \cite{62}, which
barrel. In order to estimate the size of this effect, a tight-binding
nearest neighbor overlaps only) has the value 1
overlap matrix
schematically in the top row. They result in different entries of the
gapped electronic state to an incoherent and gapped one.
HTSCs can thus be viewed as a transition from a coherent and
both incommensurate CDW systems and underdoped cuprate
materials, where the experimental signatures of the CDW order are
consistent with a small ratio of gap sizes. On the contrary,
the larger ratio for 2H-NbSe$_2$ results in ARPES data\cite{31,32}
finding $\Delta_{\text{CDW}}$ to be restricted to the inner K-centered FS
barrels only.

In addition to explaining the apparent difference between
the momentum profiles of the CDW gap in 2H-NbSe$_2$ and
2H-TaS$_2$, this model is based on the presence of strong
electron-phonon coupling, which also provides a natural expla-
nation for the existence of a pseudogap phase at temperatures
above $T_{\text{CDW}}$. Analogous to the difference between weak-
coupling (BCS) and strong-coupling (Eliashberg) theories for
superconductivity, a strong-coupling CDW phase generally
melts its charge order through increased phase fluctuations,
rather than a suppressed CDW amplitude\cite{12,46}. Since the
CDW gap is directly proportional to the local amplitude of the
order parameter, it is present both in the short-range fluctuating
phase at $T > T_{\text{CDW}}$ and in the phase with long-range CDW
order at $T < T_{\text{CDW}}$.

IV. CONCLUSIONS

Among the family of the TMDs, 2H-TaS$_2$ and 2H-NbSe$_2$
are both considered prototypical incommensurate CDW mate-
rials, where the experimental signatures of the CDW order are
similar in various ways. Both have particle-hole asymmetric
gaps on only some of their FS sheets, and in both cases
the $\Delta_{\text{CDW}}$ persists into a pseudogap phase above $T_{\text{CDW}}$.
Furthermore, FS nesting alone does not seem to be the driver
of the CDW instability in both compounds. On the other hand,
we also have established some pronounced differences. $\Delta_{\text{CDW}}$
in 2H-NbSe$_2$ is nonzero only near a few hot spots within
a single K-centric FS barrel, while it is nonzero along both
barrels of 2H-TaS$_2$. This dichotomy between 2H-NbSe$_2$ and
2H-TaS$_2$ can be realized in terms of the difference in the
orbital structures of their electronic states in the vicinity of their
Fermi levels. The different orientation of the 2H-TaS$_2$ states
as compared to those of 2H-NbSe$_2$ directly affects the relative
size of the el-ph coupling on the concentric FS barrels. Within
a strong-coupling description of the CDW formation, the result
is a strongly barrel-dependent gap size in 2H-NbSe$_2$, and an
approximately uniform gap in 2H-TaS$_2$, in agreement with
our current ARPES observations and previously published
data. Additionally, the description in terms of a strong-
rather than weak-coupling scenario implies that the location
of the CDW gap depends on the momentum variations of the
electron-phonon coupling rather than just the electronic
structure, and hence will generically be centered slightly away
from the FS, making it particle-hole asymmetric. Moreover,
the order in strong-coupling theories is destroyed at $T_{\text{CDW}}$
by phase fluctuations, leaving the local gap size nonzero, and
hence giving rise to a pseudogap phase above $T_{\text{CDW}}$. Given
the striking agreements between the results of the strong-
coupling approach and the experimental observations from
the two distinct incommensurate CDW systems, we conjecture
that strong el-ph coupling, including a strong dependence on
the electronic momentum as well as the orbital character of

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
$S_1$ & $\frac{1}{2}(dd\sigma)_{1} + \frac{3}{4}(dd\delta)_{1}$
\hline
$S_2$ & $\frac{1}{2}(dd\sigma)_{1} + \frac{3}{4}(dd\delta)_{1}$
\hline
$S_3$ & $\frac{1}{4}(dd\sigma)_{1} + \frac{1}{4}(dd\delta)_{1}$
\hline
\end{tabular}
\caption{Overlap integrals relevant to a tight-binding description
\of the electronic band structure. The different orbital orientations
in the K-centered FS barrels of 2H-NbSe$_2$ and 2H-TaS$_2$ are shown
schematically in the top row. They result in different entries of the
overlap matrix $S(k)$, which (at the K point, taking into account
the nearest neighbor overlaps only) has the value $1 + 2S_3 - S_1$
for its diagonal elements, and $S_1$ for its off-diagonal elements. The squared
ratio of these elements determines the ratio of CDW gap sizes in the
concentric barrels.

Such an interpretation agrees with the fact that transmission
electron microscopy measurements on 2H-TaS$_2$ show the
presence of short-range CDW order at temperatures above
$T_{\text{CDW}}$\cite{19}. In this scenario, the transition to the PG state in
both incommensurate CDW systems and underdoped cuprate
HTSCs can thus be viewed as a transition from a coherent and
gapped electronic state to an incoherent and gapped one.

D. Dichotomy between 2H-NbSe$_2$ and 2H-TaS$_2$

Whereas the K-centered FS barrels of 2H-NbSe$_2$ consist
primarily of $d_z^2$ orbitals aligned along the crystallographic c
axis, as shown schematically in Figs. 1(e) and 1(f), the smaller
size of the pockets in 2H-TaS$_2$, and the corresponding
proximity to a high-symmetry point, cause their electronic states
to approach $d_z^2$ orbitals rotated onto the crystallographic ab
plane\cite{6,46,60,61}. The in-plane orbital configuration [shown
schematically in Figs. 1(b) and 1(c)] has been used before to
argue that 2H-TaS$_2$ contains a hidden one-dimensional order
\cite{60}, as well as a specific type of orbital order\cite{61}.

The orbital character of the electronic states will influence the
strengths of the el-ph coupling in each K-centered FS
barrel. In order to estimate the size of this effect, a tight-binding
fit to the electronic band structure is required\cite{62}, which
involves the same set of overlap integrals between neighboring
$d$ orbitals in the case of 2H-TaS$_2$ as it does for 2H-NbSe$_2$. The
relation between the two cases is shown in Fig. 4. The ratio
diagonal (in-plane) and off-diagonal (out-of-plane) elements in
the overlap matrix $S(k)$ determines the relative
strength of the el-ph coupling matrix elements in the two K-
centered FS barrels, and hence the ratio of CDW gap sizes\cite{46,47}.

Taking all overlap integrals to be zero, except $(dd\sigma)_1 =
(dd\sigma)_2 \approx 0.5$, our model yields a gap ratio between inner and
outer barrels in 2H-NbSe$_2$ of 6.8, while in 2H-TaS$_2$ it is much
smaller, $\sim 2.7$. The contrast in gap ratios that emerges already at
this simplest possible level of approximation, is in accord with
the observed dichotomy in the CDW gap structure between
2H-TaS$_2$ and 2H-NbSe$_2$. The ARPES data in 2H-TaS$_2$ clearly
exhibit a CDW gap along both FS barrels around the K point,
consistent with a small ratio of gap sizes. On the contrary,
the larger ratio for 2H-NbSe$_2$ results in ARPES data\cite{31,32}
finding $\Delta_{\text{CDW}}$ to be restricted to the inner K-centered FS
barrels only.

FIG. 4. Overlap integrals relevant to a tight-binding description
of the electronic band structure.
the participating electronic states are the defining attributes of the incommensurate CDW orders in TMDs.

**ACKNOWLEDGMENTS**

U.C. acknowledges support from the National Science Foundation under Grant No. DMR-1454304 and from the Jefferson Trust at the University of Virginia. Work at Argonne National Laboratory (C.D.M., D.Y.C., M.G.K.) was supported by the US Department of Energy, Office of Basic Energy Sciences. Division of Materials Science and Engineering. D.L. is supported by the Department of Energy, Grant No. DE-FG02-01ER45927. J.v.W. acknowledges support from a VIDI grant financed by the Netherlands Organisation for Scientific Research (NWO).