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April 19, 2022

Physical Review B

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## **Structure and pressure dependence of the Fermi Surface of lithium**

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**Abstract:**

We report studies of the Fermi Surface (FS) of isotopically pure polycrystalline  $^7\text{Li}$  from ambient pressure to 4.7 GPa. Shubnikov-de-Haas (SdH) oscillations at 300 mK in external magnetic fields up to 35 T are measured to map the spherical parts of the FS of lithium. Our ambient pressure data show that the principal SdH frequencies consist of three distinct peaks at  $41.25 \pm 0.05$ ,  $41.65 \pm 0.05$  and  $42.05 \pm 0.05$  kT, which are theoretically consistent with the presence of two crystal structure domains exhibiting nearly spherical FS. The size of the spherical parts of the FS is compatible with bcc and fcc crystal structures. The measured frequencies at 41.25 and 42.65 kT present the direct quantitative evidence for the spherical deformation of the FS in fcc Li. Our high-pressure data show that while the FS of Li deforms under compression, it remains mostly spherical up to 4.7 GPa and the pressure-dependence of the SdH frequency is consistent with the theoretically calculated pressure-dependence in the fcc structure. Finally, we find that the electron effective mass does not deviate under pressure significantly from its ambient pressure value.

While having only three atomic electrons, the electronic and structural properties of solid lithium are quite complex. Lithium is the only monovalent superconducting metal at ambient pressure ( $P$ ) which breaks Matthias's empirical rule<sup>1,2</sup>. Its phase diagram becomes progressively more complex under  $P$  and exhibits a number of symmetry-breaking structural phase transitions e.g. 3–6 leading to an elemental topological semimetal<sup>7,8</sup>, electride phase<sup>9</sup> and anomalous isotope effects within the superconducting state<sup>10</sup>. Unlike most other simple metals, the superconductivity in lithium is enhanced by five orders of magnitude under  $P$ , reaching the highest  $T_c$  of any element below 100 GPa<sup>11–17</sup>. Many of the non-trivial electronic properties of Li are related to the morphology of its FS and its changes under compression<sup>17,18, 19,20,21,22</sup>. Therefore, mapping the FS of Li is central to understanding its complex phase diagram.

A direct way to construct a FS is from measurements of quantum oscillations (QO) under the application of high magnetic fields. Fermiology experiments at ambient and high  $P$  have been carried out on the majority of metallic elements and many other compounds e.g. 23–29. Notably, recent fermiology studies on tellurium and black phosphorous have been used to detect their topological electronic states<sup>30,31</sup>. However, despite being the first alkali metal the only successful studies on Li at low temperature, even at ambient  $P$ , were done using an unconventional sample preparation, where small size particles were confined within paraffin wax<sup>32–34</sup>. This unique approach was envisioned in order to suppress the shear-driven partial martensitic transition in Li, since it was thought that the presence of a mixed phase with random crystalline orientations would cause severe phase smearing, which would diminish any observable oscillations at low  $T$ . In these early studies, the anisotropy of the bcc structure was calculated by comparing the width of the measured de-Haas van-Alphen frequency to the calculated free electron frequency in Li. Other methods, such as positron annihilation, were also used but only to determine the FS of Li above its martensitic transition<sup>35</sup>.

Measurements of the FS of Li under  $P$  are even more challenging due to anisotropic deformations from non-uniform stress. These deformations and the associated phase smearing cause a spread of the QO frequencies and reduce their amplitude<sup>36</sup>. As such, fermiology studies of Li under  $P$  have not been hitherto successful. Moreover, measurements on other alkali metals have only been carried out at  $P$  below 0.5 GPa<sup>37</sup>.

Here we use advanced fermiology methods in higher and more uniform magnetic fields than previously accessible, accompanied by theoretical calculations, to revisit the experiments in polycrystalline, single-grain, and isotopically pure Li samples. We could observe strong QO and resolve the structural details of the spherical part of the FS of isotopically pure polycrystalline  $^7\text{Li}$  samples at ambient  $P$ . Furthermore, we are able to detect strong QO under pressures exceeding 4.7 GPa.

The presence of impurities, defects, and non-uniform stress can influence the results of fermiology studies, both by suppressing the QO and by affecting the martensitic transitions, which in turn would lead to changes in the FS. To prevent such undesirable effects, isotopically pure polycrystalline samples of  $^7\text{Li}$

(99.9% isotopically enriched, 99.99% metallic purity from Alfa Aesar) covered with mineral oil were cut and immediately used in our experiments.

To avoid deformations introduced by electrodes, we used a non-contact method with a contactless LC resonant tank circuit driven by tunnel diode oscillators (TDO)<sup>38,39</sup>. Ambient  $P$  data were collected in a  $^3\text{He}$  superconducting magnet at a base temperature of 360mK up to 18 T. Additional data were also collected in a dilution refrigerator at a base temperature of 20 mK at magnetic fields up to 16 T.

At ambient  $P$ , we can distinguish three distinct SdH peaks near  $\sim 42\text{kT}$ . To eliminate the possibility of experimental errors such as a field anisotropy leading to slight shifts in the peak positions under various angles, we performed simultaneous calibration experiments on sodium samples which were prepared using identical methods<sup>40</sup>(Fig. 1). Na has the most spherical FS and is an ideal system for calibration<sup>40,41</sup>. Therefore, if the peak splitting were an experimental artifact, we expect to observe them in Na as well. The SdH oscillation frequency spectrum of Na only exhibits one principal peak at 28.1 kT. The shift in frequency of SdH oscillations originating from different orientations is minimal (Fig 1d) and the full width half maxima for Na is 0.3 kT. This comparison confirms that the observed splitting in Li is an intrinsic property of the sample FS.

Both Li and Na undergo partial martensitic transitions upon cooling. However, while the transition from bcc Li at ambient  $P$  is nearly complete by 10 K (75%-90%) and it becomes entirely martensite at 4.2 K<sup>33,42,43</sup>, the maximum martensite portion in Na does not exceed 43%<sup>43–45</sup>. The structure of martensite Li based on available diffraction pattern data is closely related to a stacking fault mixture of fcc and hcp known as 9R. However, the X-ray and neutron diffraction measurements are not fully compatible with this structure and recent theoretical analysis of the FS of lithium suggests that 9R is not likely the structure of the martensite phase<sup>46</sup>. Moreover, molecular dynamic simulations generate a structure composed of fcc and hcp domains which fit the crystallography data better than 9R<sup>47</sup>. The Brillouin zones (BZ) of  $^7\text{Li}$  differ significantly in different crystalline structures and 9R does not exhibit a significant number of peaks close to  $\sim 42\text{kT}$ . However, small gaps in the 9R FS may break down under high fields, leading to the appearance of an unreconstructed FS in this frequency range. Meanwhile, both fcc and bcc have their principal peaks between 40 and 45 kT<sup>46</sup>.

A comparison with theoretical calculations of the Li FS for different structures<sup>46</sup> shows that the frequency region where the triple peak is observed (near 42 kT) coincides with the location of the calculated single bcc peak and the double peak coming from the spherical part of the fcc FS (Fig 1 e-g). Note that the SdH frequencies are sensitive to the structural parameters (see Fig. S11) and the theoretical calculations rely on 0K optimized lattice constants. The spread of frequencies over the measured triple peak is within the corresponding accuracy of the computed lattice parameters. Furthermore, due to the incomplete nature of the martensitic transition and the potential presence of other domains such as hcp, deviations of the location of the observed peaks from those calculated for perfect fcc or bcc are expected. Thus, the comparison suggests that the measured SdH spectrum can be assigned to a combination of bcc and fcc, but the data does not provide conclusive, quantitative proof. A comparison of the amplitude of the peaks suggests that the majority of the sample is in the fcc phase. It should be noted that the FS of fcc lithium

has a neck, which theoretically also produces SdH frequencies around 17 kT<sup>46</sup>, however, here experimental evidence for this was only found in two orientations. This is not unexpected, since the necks of the fcc Fermi surfaces are directional and the signal that they produce is low in weight in an orientationally averaged spectra (see Fig S13).

Previous fermiology studies on Li have also noted the presence of a potential anisotropy in the radial distortion of its bcc FS, which was not observed in calculations<sup>48</sup>. Due to lack of sufficient resolution, the prior experimental data remained inconclusive as they could not identify the main peaks or resolve the structure of the principal spectra of the FS<sup>34</sup>.

We have also studied the  $P$ -dependence of the spherical part of the FS of lithium. Under compression, as the FS becomes larger, a shift to higher frequencies is expected. High  $P$  experiments were done in a non-magnetic miniature turnbuckle DAC<sup>49</sup>, small enough to fully rotate in the constrained dimensions of a high field magnet bore. The composite gaskets used were MP35N formers with an insert of diamond powder and epoxy. Inside the  $P$  chamber, the sample was placed in a 3-turn TDO coil of 150  $\mu\text{m}$  ID, made of 12  $\mu\text{m}$  diameter insulated copper wire. Mineral oil was used as a  $P$ -transmitting medium.

High  $P$  data were collected in 3He magnets at a base temperature of 360 mK. Data from the 18 T superconducting magnet were analyzed in 16-18 T range and from the 35 T resistive magnet in the 28-30 T range. The  $P$  was measured using ruby fluorescence both at room and base temperatures with a fiber optic collecting system. We observe a  $P$ -induced shift of the frequency spectrum to higher values between 0-2.8 GPa (Fig. 2a). In contrast to ambient  $P$  data, the peaks at higher pressures are concentrated in a small frequency range. However, it is possible that due to the lower signal to noise ratio in high  $P$  experiments, we were unable to detect the weaker peaks. The  $P$ -dependence and value of the highest amplitude peaks are consistent with theoretically calculated values for fcc (Fig. 2b,c). The comparison indicates that the fraction of fcc increases with  $P$ . We also succeeded to measure the FS of 7Li at higher pressures (Fig. S12). The  $P$  was determined to be 4.7 GPa at room temperature, however, we were unable to measure  $P$  at low temperature due to technical difficulties. Since we expect a  $P$  increase during cooling, the low temperature  $P$  was estimated by extrapolation of the fcc data.<sup>46</sup> The peak position in this experiment is 51.4 kT, for which we estimate the low temperature  $P$  to be  $\sim 9$  GPa. At the highest  $P$ , non-hydrostatic conditions led to phase smearing which significantly reduced the amplitude of QO. Observation of QO at higher  $P$  requires modifications to the design of the current DAC to allow loading of helium or other quasi-hydrostatic  $P$  medium.

We measured its electron effective mass ( $m^*$ ) at 1.7 GPa from the temperature dependences of the QO amplitudes (Fig. 3). The temperature reduction factor of the amplitude ( $R_T$ ) is given by  $R_T = (\frac{2\pi^2 p k T}{\beta^* H}) / \sinh(\frac{2\pi^2 p k T}{\beta^* H})$ , where,  $p = 1$  for the first harmonic term,  $\beta^* = \frac{e h}{2\pi m^* c}$ ,  $e$  is the electron charge,  $h$  is the Planck constant,  $c$  is speed of light and  $H$  is magnetic field,  $k$  is the Boltzmann constant and  $T$  is temperature. Fitting this equation with our temperature dependent data at 1.7 GPa results  $m^* = 2.30 \pm$

$0.15 m_0$ . Where  $m_0$  is the free electron mass. The previously reported  $m^*$  at ambient  $P$  is  $(2.10 \pm 0.06) m_0$ <sup>27</sup>.

We have calculated the band mass  $m_b$  associated with each extreme orbit on the FS of lithium (Fig 3c and Table S1) and the principal SdH peaks for Na (Table S2). Assuming the difference between the measured  $m^*$  and calculated  $m_b$  is entirely due to electron-phonon effects, the two are related via  $m^* = m_b(1+\lambda)$ , where  $\lambda$  is the electron-phonon coupling constant, which was previously estimated<sup>20</sup> to be 0.51 in bcc Li and 0.41 in 9R. The spherical parts of the FS represent nearly-free electron states and the corresponding  $m_b$  are closer to unity. Accordingly,  $m_b$  is smaller in Na than in Li in both bcc and fcc, and slightly smaller for bcc-Na than fcc-Na. Overall, there is a weak  $P$ -dependence for  $m_b$  in Na. This is consistent with previous calculations<sup>50</sup> which reported a slight increase in  $m^*$  from 1.031 to 1.036  $m_0$  when Na is compressed from 0 to 0.4 GPa; our values for bcc Na at 0 GPa are 1.0367  $m_0$  (average) and 1.0355  $m_0$  (principal peak). Notice that Elliott and Datars<sup>37</sup> reported slightly decreasing  $m^*$  in Na from 0 to 0.35 GPa<sup>32</sup>. However, the slope of their measured  $m^*$  versus  $P$  is small compared to the experimental uncertainties.

The FS of Li has more spherical deformation than that of Na in all structures. Therefore, even in bcc-Li  $m_b$  (and  $m^*$ ) is higher than in bcc-Na and exhibits stronger  $P$ -dependence. Furthermore, the FS in fcc-Li has necks and the SdH orbits passing through them have significantly higher  $m^*$  than those from the spherical region of the FS. The  $P$ -dependence of  $m_b$  of these orbits is also stronger, but opposite;  $m_b$  decreases with  $P$ . Since in the high- $P$  experiment, we are only focusing on the spherical part of the FS, the actual value of  $m_b$  for the electrons in neck orbits is not relevant for the purpose of direct comparison. However, the presence of neck orbits is at least partially reflected by the measurements. The interaction of the FS with the BZ boundaries causes deformation of the belly region of the FS as well. The effect is twofold. On one hand, the volume of the spherical region decreases, thus making the electron states within this region more free electron-like. This is the reason why the principal orbits of fcc-Li have smaller  $m_b$  than that of bcc-Li (see Fig 3c). On the other hand, the fraction of belly orbits which pass near the neck regions and acquire higher effective mass increases. Theoretically, in bulk of Li there is a partial cancellation of the  $P$ -dependence of  $m_b$  from the spherical and neck regions of the FS. As a result, the weighted average  $m_b$  (Table S1) initially increases with  $P$  until about 1 GPa, after which it begins to decrease slowly, but remains higher than that of bcc-Li and Na (bcc and fcc).

Comparison of the calculated  $m_b$  with the experimental  $m^*$  for orbits near 42 kT for different candidate structures of Li, supports the model that, Li consists of more than one structure and that a mixture for two or more phases (bcc, fcc and possibly 9R) is present in the sample; for fcc alone we have  $m_b(1+\lambda) < 2.11 m_0$  at 1.7 GPa, which is lower than the experimental  $m^* = 2.30 \pm 0.15 m_0$ . The observed changes in the effective mass with  $P$  are the combined effect of: (1) the  $P$ -dependence of  $m^*$  of different structures with orbits near 42kT; and (2) the relative stability of these phases as a function of  $P$  (and temperature). Notably, the martensitic transition is monotonically suppressed in Na, while enhanced by external  $P$  up



to 3 GPa in Li. Therefore, Li has larger  $m^*$ , increasing under compression, with a stronger  $P$ -dependence compared to Na.

In summary, we present a high-resolution study of the spherical part of the FS of isotopically pure  $^7\text{Li}$ . By using large single grain polycrystalline samples in high magnetic fields, we establish that the principal peak of the FS of lithium at ambient  $P$  is made up of three distinct peaks. Based on comparative calibrations against sodium and comparison with theoretical calculations<sup>46</sup>, we propose that these peaks originate from distinct crystal structures. The locations of the peaks are consistent with contributions from bcc and fcc domains, with a larger contribution from the fcc structure. This is compatible with previous results from molecular dynamics simulations on the proposed structures of lithium martensite. These data can be used in calculations of the ambient  $P$  superconductivity of lithium. We also present the measurements of the FS of lithium for pressures above 4.7 GPa in the fcc region and directly measure the changes in the size of the spherical part of its FS under compression. The electron effective mass measurements at 1.7 GPa show that lithium remains a nearly free electron system under compression. Although the present measurements were limited below the onset of high- $P$  superconductivity and predicted topological states of lithium, they demonstrate the essential steps towards the extension of these studies to higher pressures.

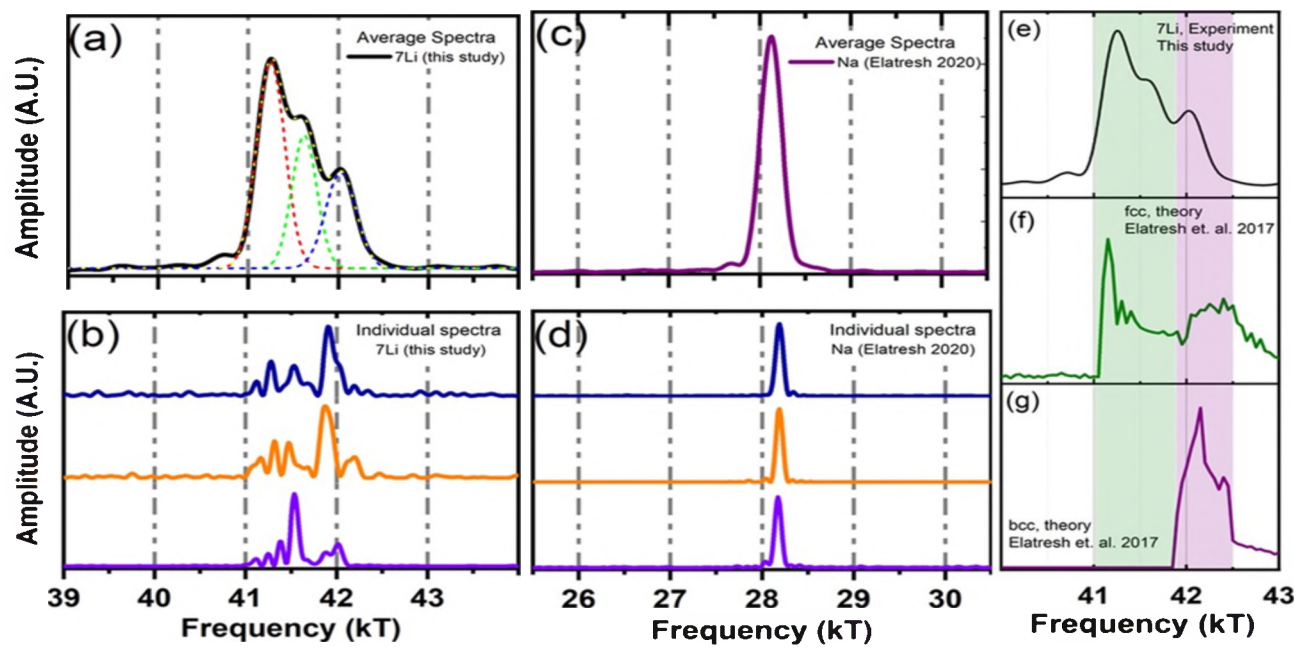
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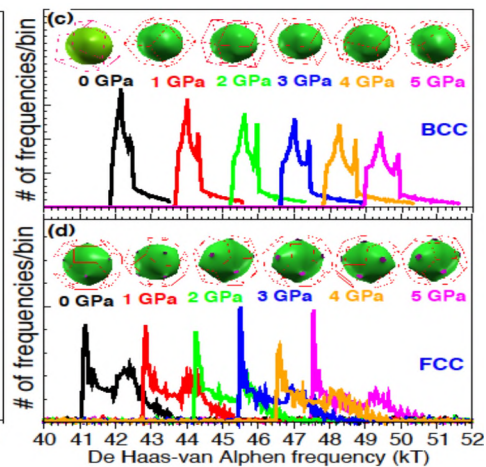
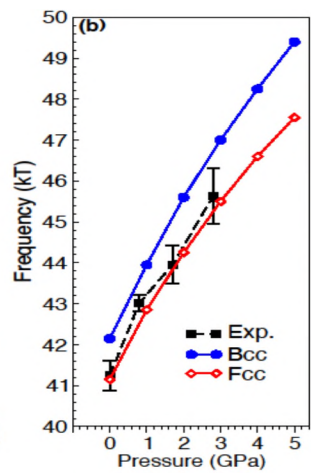
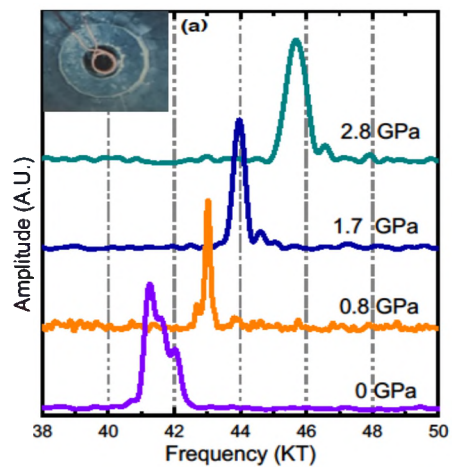
**Fig1:** (a) Average SdH frequency spectrum (solid line) of  $^7\text{Li}$  data in a 1 T range from measurements at 52 sample orientations. The dotted lines are theoretical fits to the experimental data. (b)  $^7\text{Li}$  SdH measurements in a 2 T range at a rate 0.30 T/min in three selected orientations. (c) Average of Na SdH data in a 1 T range from measurement at 24 sample orientations. (d) Na SdH measurement in a 2 T range at a rate of 0.30 T/min in three selected orientations. (e-g) Comparison of the experimental QO average spectrum of  $^7\text{Li}$  to the calculated values for bcc and fcc structures<sup>46</sup>. The shaded green and purple regions indicate where the area of the spherical parts of the FS are consistent with theoretically calculated principal frequencies of lithium in the fcc and bcc structures, respectively.

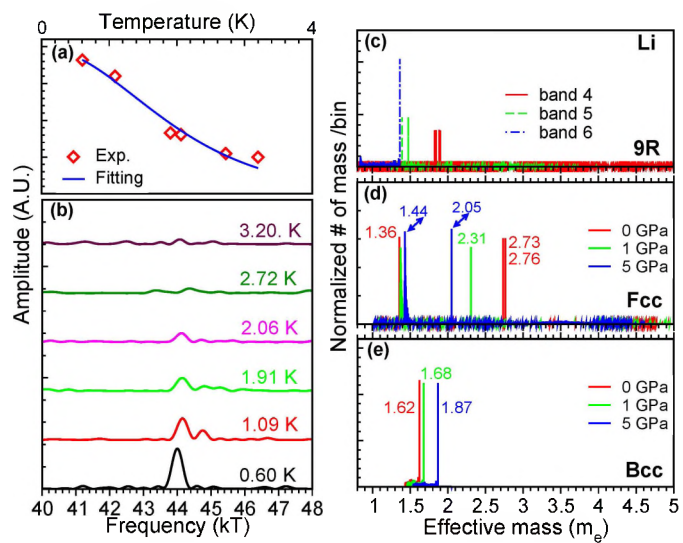
**Fig 2:** (a) Average of SdH frequency measurements at different pressures. Here 0 GPa data are the average at a 1T range and all the others are in the 2 T range. The inset is an image of the coil inside of the DAC for high  $P$  measurements. (b) Comparison of the theoretical  $P$ -dependence of bcc and fcc peaks with the experimental data. (c) Theoretical bcc and fcc QO frequencies for all orientations.

**Fig.3:** (a) Amplitude of the SdH peaks vs.  $T$  at 1.7 GPa. A fit using the expression for  $R_T$  gives electron effective mass of  $2.30 \pm 0.15 m_0$ . (b) SdH frequency spectrum of  $^7\text{Li}$  at 1.7 GPa at different temperatures. At 1.09 K the main peak is split into two and the intensity of the peaks are added. (c)-(e) Theoretical calculations of band mass ( $m_b$ ) of Li in the (c) 9R, (d) fcc and (e) bcc structures at selected pressures for

fcc and bcc, and at 0 GPa for 9R. The plots show histograms of  $m_b$  calculated for all angular orientations (corresponding to all extreme orbits) and grouped in bins with size equal to  $10^{-4}m_e$ . All orientations are sampled by varying the angles  $\phi$  and  $\theta$  from  $0^\circ$  to  $90^\circ$  and 0 to  $360^\circ$ , respectively, in increments of  $1^\circ$  deg. The definitions of  $\phi$  and  $\theta$  are as in Fig.6 (D) of ref.<sup>46</sup>. The band masses of the electrons in the principal orbits of bcc and fcc at the selected  $P$  are given in the plot with different colors. For 9R the colors distinguish  $m_b$  originating from different bands; the 9R band structure is shown in SI Appendix, Fig. S5 in ref. <sup>46</sup>. For all structures, the lower  $m_b$  values are for orbits along the spherical part of the FS, while the neck orbits have higher  $m_b$ . The former increase with  $P$ , while the latter decrease.







## Acknowledgement:

The authors acknowledge the major contributions, theoretical support, supervision and discussions during this project by N. W. Ashcroft who unfortunately passed away prior to writing the manuscript. The authors acknowledge guidance and support from R. Hoffman throughout this project. We thank L. Adams for help with data analysis. The experimental research at University of Utah was supported by National Science Foundation Division of Materials Research Award No. 13519862 and 2132692 and the US Department of Energy, Office of Science, Fusion Energy Sciences under Award No. DE-SC0020340. The work at Guelph was funded by Natural Sciences and Engineering Research Council of Canada (RGPIN-2017-03931) (EJN). The theoretical research was enabled in part by support provided by Graham & Cedar and Compute Canada ([www.computecanada.ca](http://www.computecanada.ca)). The work at LLNL was performed under the auspices of the U.S. Department of Energy under Contract No. DE-AC52-07NA27344. The National High Magnetic Field Laboratory is supported by the National Science Foundation through NSF/DMR-1157490/1644779 and the State of Florida. The work at NHMFL was also partially funded by the US DOE under NNSA SSAA DENA0001979.

S.F.E. performed the theoretical calculations. S.A.B and E.J.N supervised the theoretical research. A.D.G., W.A.C., and S.W.T. provided user support for the magnet time. Experimental data collection, analysis, and sample preparation were performed by T.B., A.D.G., W.C., M.T.H and S.D. S.D. designed and supervised the experiments. All authors contributed to the writing of the paper.

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