theory by placing two moments in the effective medium and using perturbation theory to calculate their indirect interaction. The result is the well-known Ruderman-Kittel-Kasuya-Yosida formula,[21] but now with modified propagators that include the effects of spin-fluctuation scattering. We obtain for the interaction between moments at nearest-neighbor sites i and j, $\Delta E_{ij} \sim -\frac{1}{2} J \vec{\xi}_i \cdot \vec{\xi}_j$. The resulting value of J turns out to be negative corresponding to antiferromagnetic coupling between moments. Taking the estimate $kT_N \sim z|J|$, where z is the number of nearest neighbors, we arrive at an ordering temperature $T_N \sim 3.8$ °K.

In summary, we have shown that the magnetic properties at the (100) surface of vanadium are drastically different from those in the bulk, the main difference being the appearance of large localized magnetic moments. The surface contribution is found to obey a nearly perfect Curie law and the surface moments have antiferromagnetic interactions. These results are in qualitative agreement with the experimental findings of Ref. 4. Moreover, the theoretical values for the magnetic moment and Néel temperature are close to the experimental values. Detailed quantitative comparison, however, has to await the type of experiments[22] performed on single-crystalline surfaces.

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[a]Present address: Department of Physics, University of Pennsylvania, Philadelphia, Penn. 19104.

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Open Orbits in Potassium

P. G. Coulter and W. R. Datars

Department of Physics, McMaster University, Hamilton, Ontario L8S 4M1, Canada

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Structure in the induced torque rotation pattern of potassium, observed for magnetic fields above 5 T and at a sample temperature of 1.4 K, gives evidence of open orbits in potassium. The presence of open orbits is expected from the charge-density–wave model of potassium but the directions of induced-torque peaks are not explained satisfactorily by the model.

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Research on potassium has been of interest because of the conflicting evidence that the electronic ground state of potassium is a charge-density-wave (CDW) state as proposed by Overhauser.[1] In this state, the electronic charge is modulated with a wave vector $\vec{Q}$ whose magnitude is deter-

mined by the dimension of the Fermi surface. Evidence for the state has not been found in neutron diffraction or de Haas–van Alphen (dHvA) experiments at zero pressure. However, results from experiments such as optical absorption, the dHvA effect at high pressure, and induced torque appear anomalous when compared with free-electron theory and suggest the possibility of charge-density waves in potassium.

The induced torque for a spherical sample of a material with a spherical Fermi surface is expected to be isotropic for rotation in any crystallographic plane, because the resistivity components are isotropic, and to have a magnitude which varies quadratically with magnetic field at low fields and becomes independent of field at high fields.[2] These predictions were not followed in experiments[3,4] with magnetic fields up to 2.3 T for potassium which has a Fermi surface spherical to within 0.2%.[5] There was a fourfold induced-torque pattern with an anisotropy ratio at 2 T of 5:1 for samples prepared in oil and up to 45:1 for samples prepared in a mold. We have extended induced-torque measurements to higher magnetic fields and have found evidence of open orbits which strengthens the possibility of charge-density waves in potassium.

The experiments were performed at 1.4 K with a torque magnetometer[6] in which the sample was rotated slowly while in a constant magnetic field produced by a superconducting solenoid. Measurements were made of either the total torque required for sample rotation or the induced torque obtained directly by superimposing oscillations on the rotating motion and detecting the induced torque at the frequency of oscillation. Five crystals approximately 4 mm in diameter either were replaced by forcing molten potassium out of a syringe into mineral oil and held in place during the experiment by frozen oil or were grown in plastic molds in which they were held during the experiment. Crystals were oriented by x rays with an accuracy of 2°, mounted in a random, known orientation and could be turned about an axis during an experiment to study different crystal planes.

Examples of induced torque for samples prepared by both ways are shown in Fig. 1. The induced torque below 3.5 T has two maxima in a 180° rotation corresponding to the fourfold pattern observed previously at fields below 2.3 T. Structure becomes apparent on the fourfold pattern of the torque taken at 5.0 T in Fig. 1(a) and at 5.5 T in Fig. 1(b). At fields of 8.5 T in Fig. 1(a) and 6.8 T in Fig. 1(b), the structure consists of a set of narrow peaks. The general features of the high-field, induced torque of all five samples are similar: Structure appears at fields of ~5 T and there are up to twenty narrow peaks in 180° rotation at high fields. The peaks are narrower and a little larger for the samples prepared in molds. Most of the structure occurs on fourfold peaks but a few features, such as peak *A* in Fig. 1(b), exist near low-field minima.

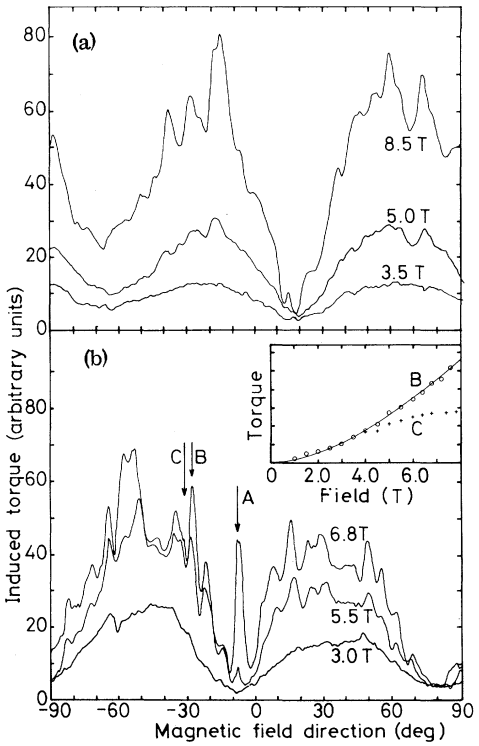

FIG. 1. Induced torque of potassium as a function of magnetic-field direction: (a) a sample grown in oil at magnetic fields of 3.5, 5.0, and 8.5 T; (b) a sample grown in a mold at magnetic fields of 3.0, 5.5, and 6.8 T. The inset shows the magnetic-field dependence of the induced torque at directions *B* and *C* with the amplitude at *B* fit to the power law $B^{1.7}$, where *B* is the magnetic induction.

The growth axis in the mold was within 3° of a [210] direction. The magnetic field was in a plane containing this axis and within 2° of a (321) plane for the data in Fig. 1(b). One minimum in the fourfold pattern occurred with the magnetic field parallel to the growth axis as was the case previously[4] for a mold-grown sample. The growth axis of the sample grown in oil could not be determined. The plane of rotation for Fig. 1(a) was within 3° of a (211) plane.

There were no visible surface irregularities or sample cracks to which the high-field structure might be attributed. Very minute cracks or surface roughness are also unlikely causes of the structure because it is improbable that they would give the same type of high-field structure starting at the same magnetic field in samples prepared by quite different methods.

The total torque shown in Fig. 2 consists of several components that include induced torque and an angle-dependent background torque due to electrical connections to coils that were used to rotate the sample electrically. The difference between the curves gives the induced torque since induced torque changes sign when the direction of rotation is reversed, while other torques are independent of rotation direction. Thus, the sharp peaks shown by arrows in Fig. 2 are induced torque peaks and establish that the high-field structure in the torque is due to induced currents.

A quadratic field dependence of induced torque at high fields is expected only when there are open orbits[2] and, in for example[7] ReO_3, the magnetic-field power dependence is between 1.45 and 1.97 depending on the angle between the open orbit and torque directions. The induced torque at high-field peaks follows a similar magnetic-field dependence as shown for peak B in the inset of Fig. 1(b) with a field dependence of $B^{1.7}$ from zero up to 8.5 T while the induced torque at the high-field minimum C saturates above 5 T. The very narrow width of the peaks is also characteristic of induced torque from open orbits in metals.[7] We are therefore led to conclude that the high-field, induced-torque structure indicates the existence of open orbits in potassium. However, the situation is more complicated than for other metals because the induced-torque peaks in potassium occur only at fields above 5 T.

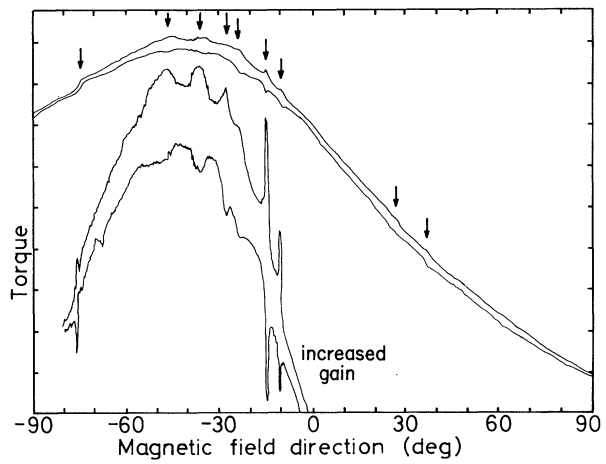

FIG. 2. Total torque measured as a function of magnetic-field direction for the mold-grown sample. The plane of rotation is different than for Fig. 1(b). Curves are shown for clockwise and counterclockwise sample rotation for two different gain settings.

Effects of strain and the suggestion[8] that strain causes a partial martensitic transformation have been invoked to explain anomalies in potassium. Thus, it is important to ensure that the samples used were strain-free single crystals. The samples were x rayed before and after the experiment by the transmission Laue technique. Only those samples which gave precise spots showing no evidence of crystalline irregularities or gross defects in the bulk material were used in this experiment. Samples from the same source material and prepared in oil by the techniques used in this experiment were also used in a dHvA experiment.[9] That they were high-purity strain-free samples is indicated by Dingle temperatures of 0.2 to 0.3 K at zero pressure. Similar experiments[10] show that for sodium, which undergoes a martensitic transformation,[11] temperature cyclings induce the transformation as indicated by an increased Dingle temperature and finally a disappearance of dHvA oscillations. Such effects are not found in potassium after repeated temperature cyclings. The low-field, four-fold induced-torque pattern occurs from samples covered with oil or in a sample mold which might induce strain and is not observed with clean samples.[4] However, we observed high-field, induced-torque structure with approximately fifteen peaks above 5 T in a sample which did not show the low-field, four-fold pattern. This variety of evidence shows that it is highly unlikely that there is sufficient strain to induce a martensitic transformation or any other lattice distortion that would cause the high-field structure.

In the CDW state the two periodicities that arise from the crystal lattice with reciprocal-lattice vector $\vec{G}$ and the CDW with wave vector $\vec{Q}$ give heterodyne energy gaps in the band structure in a plane normal to $\vec{q}' = \vec{G} \pm n\vec{Q}$. Open orbits can exist between the gaps along $\vec{q}'$. For the direction of $\vec{Q}$ which minimizes the distortion energy in potassium,[12] there are twenty-four symmetry-related directions of $\vec{q}'$, which could exist in CDW domains in a macroscopic sample. The large number (24) of open orbits predicted by this model is supported by the multitude (up to 20) of clearly-resolved, high-field induced-torque peaks. How-

ever, the agreement between the observed directions of the peaks measured in a set of crystallographic planes of a sample and calculated directions for $\vec{q}' = \vec{G}_{110} - \vec{Q}$ and for other translations $2\vec{Q} - \vec{G}_{110}$ and $3\vec{Q} - 2\vec{G}_{110}$, where $\vec{G}_{110}$ is the [110] reciprocal-lattice vector, is not good. The agreement is not improved with any other set of twenty-four symmetry-related directions of $\vec{q}'$. This disagreement must be resolved before the CDW state in potassium is established. It could be that CDW domains are controlled by the crystal growth direction or a large magnetic field. We are presently investigating what effects these factors have on the high-field induced torque of potassium.

Peak *A* in Fig. 1(b) is different than other peaks, appearing at a magnetic field of 4.5 T and then increasing quickly in amplitude up to 8.5 T. This large change with magnetic field indicates the possibility of magnetic breakdown occurring at this direction. Such breakdown may occur at the conical tips of the Fermi surface in the CDW model.

In conclusion, the high-field induced-torque rotation pattern exhibits structure which suggests the presence of open orbits in potassium. The existence of open orbits is expected in the charge-density–wave model of potassium. However, the directions of the induced-torque peaks are not explained satisfactorily by the charge-density–wave model.

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