

Quantum magnetic properties of the interface between solid and liquid ^3He

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The atomically rough quantum interface between solid and liquid ^3He is shown to be ferromagnetic. Isolated kinks on an atomically smooth surface create one-dimensional polarized regions. The growth of ^3He crystals is determined by the magnetic structure of the surface.

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1. Andreev and Parshin¹ have demonstrated theoretically that essentially all the phenomena which occur at interfaces between solid and liquid phases of the isotopes ^3He and ^4He are of a quantum nature. The interface between a crystal and a quantum liquid exhibits translational invariance. The amplitude of the zero-point vibrations in helium is on the order of the interatomic distance a , and the energy spectrum of any point defect on the interface forms a band. Depending on the width of this band, Δ , and the formation energy of the point defect, ϵ , there may be either atomically smooth quantum surfaces ($\Delta < \epsilon$) or atomically rough quantum surfaces ($\Delta > \epsilon$, with the atomic concentration of defects). The crystallization and melting are determined by the kinetics of the surface defects. Crystallization waves have been observed² in ^4He , confirming the theory of Andreev and Parshin¹ and suggesting that an interface may be either atomically smooth or atomically rough, depending on its orientation. In the present letter we will show that the properties of an interface in ^3He are qualitatively different from those in ^4He , because ^3He has a spin. We will show that a defect on an atomically smooth surface is surrounded by a one-dimensional, spin-polarized region, while an atomically rough quantum liquid-crystal interface necessarily has a ferromagnetic order, which alters the entire crystallization picture. The specifically quantum characteristics of a liquid-crystal interface are observed on that part of the equilibrium curve¹ where the transition entropy is small, i.e., near the flat parts of the P, T phase diagram. For ^3He , this region is either the region near the minimum on the melting curve at $T \sim 0.3$ K or the low-temperature region, $T \lesssim 1$ mK, where liquid ^3He is a superfluid, while solid ^3He is antiferromagnetic.

2. A kink on a crystal-liquid interface is a point defect on an atomically smooth interface^{1,3} (Fig. 1). The high amplitude of the zero-point vibrations in ^3He should (by analogy with ^4He) have resulted in a delocalization of the kink in the direction along the step and to the formation of a band. The motion of a kink into ^3He is accompanied by the attachment of spins of arbitrary orientation to the crystal, with the result that the spin state of the step is altered, and the various positions of the kink are made translationally nonequivalent. These effects disrupt the coherence of the motion of the kink and prevent the formation of a band. The possible tunneling of a kink to adjacent lattice sites, however, leads to a strong exchange interaction of the crystal atoms on the

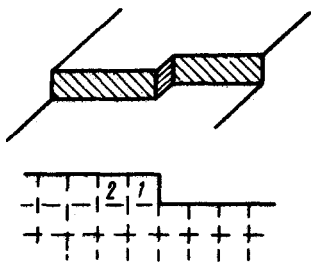


FIG. 1.

step near the kink. As an example, we consider the exchange corrections to the state of atoms 1 and 2 in Fig. 1 which result from the virtual displacement of a kink and a subsequent return to its original position. As the kink moves two lattice sites to the left, atoms 1 and 2 go from the crystal into the liquid, and two new quasiparticles with spins equal to the spins of atoms 1 and 2 appear in the liquid. Upon the inverse displacement of the kink, the resultant spin of the particles which have arrived at lattice sites 1 and 2 is equal to the spin in the original state, since otherwise additional quasiparticles would remain in the liquid. The spins at sites 1 and 2, however, may either remain the same or exchange positions. In this manner, the degeneracy in terms of the spin direction for the atoms on the step is lifted. The corresponding exchange integral is determined by the probability for the tunneling of the kink and must be a quantity on the order of 1 K. This exchange interaction leads to a polarization of the spins on the step. The energy of the system decreases with increasing size of the polarized region, R_0 , in proportion to $\Delta (a/R_0)^2$, where Δ is a quantity on the order of the exchange integral. At $T > I_{\text{sol}}$ (where $I_{\text{sol}} \sim 1$ mK is the exchange energy in solid ^3He), the polarization of the step is prevented by an entropy factor, while at $T < I_{\text{sol}}$ the increase in the energy upon the polarization is related to a rupture of antiferromagnetic bonds in the crystal. The question of the size of the polarized region is a one-dimensional analog of the problem of a vacancy in a ^3He crystal.^{4,5} The free energy reaches a minimum upon the formation of a ferromagnetic region near a kink of size

$$R_0 = a \left(\frac{2}{\ln 2} \frac{\Delta}{T} \right)^{1/3}, \quad R_0 = a \left(\frac{2\Delta}{I_{\text{sol}}} \right)^{1/3}. \quad (1)$$

The first expression in (1) refers to the case $T \sim 0.3 \text{ K} \gg I_{\text{sol}}$, in which the spins in the crystal are disordered. The second expression corresponds to the case $T \sim I_{\text{sol}}$, in which the crystal is antiferromagnetic. In principle, the exchange interaction at the crystal surface, which results from the movement of atoms into the liquid and their subsequent return to the crystal, should also occur in the absence of kinks. In this case, however, the exchange integrals are small because of the high energy of the intermediate states, which is caused in turn by the need to form a surface defect upon the transition of an atom into the liquid. In a magnetic field, the size of the polarized region near the kink, (1), increases. At $T \sim 0.3 \text{ K}$ we have $R(H) = R_0 \{ \ln(1 + \exp[-2\beta H/T]) \}^{1/3}$. At $T \lesssim I_{\text{sol}}$ the increase in T depends on the particular structure of the antiferromagnetic ^3He . If exchange effects of this type are to be observed at a crystal-liquid interface, it is necessary to ensure that there is no scattering in the liquid: $T \ll \epsilon_F$ is the Fermi energy of liquid ^3He . The properties of the

polarized regions are analogous to those of vacancies,^{6,8} with the important distinction that the motion of these regions results from a rapid transfer of the spin through the liquid phase with a strong exchange interaction.

3. The situation discussed above corresponds to an atomically smooth surface with few defects. An atomically rough surface (with a defect concentration at the atomic level) has already been observed in ⁴He, and we can expect to find the same phenomenon in ³He. The formation of a kink is accompanied by a polarization of part of the surface, so that an atomically rough surface is necessarily ferromagnetic. Two-dimensional fluctuations disrupt the long-range order. The scale dimension of such fluctuations at $T \ll \Delta$ is $L \sim a \exp(\Delta / T) \gg a$, and this dimension is substantial at $T \sim 0.3$ K. At $T \lesssim I_{\text{sol}}$, L is usually larger than the dimension of the sample. The ferromagnetic order of the ³He surface has been discussed elsewhere (see Ref. 9, for example) on the basis of a zero-point vacancy model. On the basis of data on the ⁴He surface and on vacancies in solid helium, the exchange mechanism discussed in the present letter seems more realistic for the ³He crystal-liquid interface. The transition from an atomically smooth surface to an atomically rough (quantum) polarized surface should depend on the magnetic field, in a manner similar to the behavior of a transition to a ferromagnetic vacancy phase in the interior of solid ³He (Refs. 10 and 11). Such a magnetic transition at a surface may prove to be one of the reasons for the thermodynamic anomalies which have been observed¹² in the crystallization of ³He in a magnetic field at low temperatures.

4. There is particular interest in the crystallization and melting of ³He in cases in which an atomically rough surface moves, remaining polarized. The spin-relaxation time associated with the dipole-dipole interaction, τ_d , is long (τ_d may reach several tens of minutes at low temperatures), and the total spin is usually conserved during the motion of the interface. During the motion of the interface, the spins which are directed parallel to the polarization of the interface become attached to the interface (or become detached from it); this behavior corresponds to a band motion of the defects. Oppositely directed spins can only "leak" across the interface. This leakage occurs because of an exchange interaction in the direction perpendicular to the interface. The mechanism for this exchange is illustrated for the case of two kinks in Fig. 2: When kinks move to the left and subsequently return to their original positions the spins of atoms 1 and 2 may exchange states, while the states of the other particles remain the same. The magnitude of the corresponding exchange integral is also on the order of Δ . The rate at which the flipped spins leak across the ferromagnetic interface layer are estimated to be

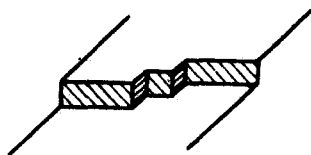
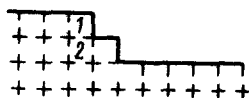


FIG. 2.



$$v \lesssim (\Delta a / \hbar) \exp(-z/a), \quad (\Delta a / \hbar) (a/z)^2 \exp(-\Delta/T). \quad (2)$$

The thickness of the boundary layer, z , is a few atomic dimensions, and the rate in (2) turns out to be far lower than the rate of attachment of spins directed parallel to the polarization of the interface, $\Delta a / \hbar$. The first of the rates in (2) refers to the low-temperature region and is determined by the tunneling of the spin across the layer; the second rate is determined by classical above-barrier diffusion.

The motion of the interface due to the attachment of spins is accompanied by the appearance of opposite polarizations in the liquid and solid phases. At $T \sim 0.3$ K this effect is not very important: The polarized domains of dimension L are rapidly dissipated by spin diffusion, and the total spin flux across the interface is zero. At $T \lesssim I_{\text{sol}}$ the motion is accompanied by a flux of the total spin across the interface and by opposite polarizations of the liquid and the crystal. The velocity of the interface is proportional to the difference between the chemical potentials of the spins directed parallel to the polarization of the interface in the liquid and solid phases. The polarization of the liquid leads to a sharp decrease in this difference and to a decrease in the velocity (for a given external pressure). The subsequent motion of the interface is governed by either spin relaxation in the liquid phase or the mechanism of a leakage of slipped spins across the interface, discussed above. Polarization of the solid phase has only a slight effect on the velocity of the interface, and at $T \lesssim I_{\text{sol}}$ an overpressure of less than 10^{-2} – 10^{-3} atm would be required.

The growth of atomically smooth ^3He surfaces is determined by the appearance of a magnetic structure, (1), which leads to the appearance of an additional small factor, $\exp\{- (3/4)(4\ln 2)^{2/3}(\Delta/T)^{1/3}\} = \exp\{- (3/2)(R/a)\ln 2\} \ll 1$.

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