Quantum Diffusion of ^{3}He in Solid ^{4}He

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Introduction

One of the most outstanding problems of contemporary low temperature physics is the development of an understanding of the physical state of solid ^{4}He in the temperature and density range for which experiments have demonstrated an appreciable non-conserved rotational inertial fraction (NCRIF) in oscillating disc experiments [1]. It is not clear whether this observation is evidence for a Bose-Einstein condensation to form a "supersolid" or whether the results can be explained in terms of the motion of ^{4}He near grain boundaries or reflects the quantum properties of dislocations in the solid. In order to answer these questions we have designed experiments to study the dynamics at the atomic scale by observing the motion of dilute ^{3}He in solid ^{4}He.

Theoretical

Since the ^{3}He impurity concentration must be kept very low to observe the NCRIFs, a critical design feature of the experiment is to ensure that the nuclear spin-lattice relaxation time is reasonably short < 1000 sec., so that NMR experiments can be carried out without difficulty. A critical analysis was therefore carried out of the quantum diffusion of isotopic impurities in solid ^{4}He. We have analyzed previous experiments in terms of the relaxation induced by the diffusive motion of impurities, thermally activated vacancies (for T> 1K), or the quantum tunneling of ^{3}He impurities at low temperatures. The results were compared with experiments that have been carried out by other groups [2,3] down to 0.4 K. Typical results for the diffusion constant are shown in Fig. 1. The symbols represent direct experimental observations [2] and the solid line represents the calculations reported here.

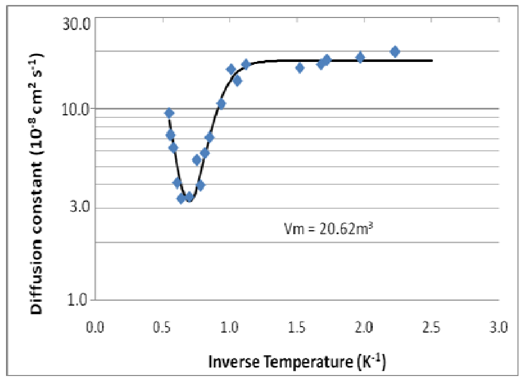

Fig. 1. Comparison of the calculated values (solid line) with experimental values (symbols) of the spin diffusion constant of ^{3}He impurities (100 ppm) in solid ^{4}He.

Results and Discussion

The critical parameters are (i) the effective ^{3}He-^{4}He exchange frequency, $J_{34} \sim 2x10^5$ s^{-1} , and (b) the impurity-impurity scattering time $\tau_c \sim \hbar\pi/(48x_3\sigma_{II}J_{34})$ where σ_{II} is the impurity-impurity scattering cross-section.

σ_{II} = 12.7 for the fit shown in Fig. 1. This result leads to scattering rates $\tau_c^{-1} \sim 2.2x10^4$ s^{-1} for x_3 =100 ppm. The spin-spin relaxation time $T_2 \sim 2s(\tau^{-1}_c/M_{20}x_3)$ where M_{20} =5x10^8 s^{-2} is the rigid lattice second moment for x_3 =1. We find $T_2 \sim 0.9$ s in reasonable agreement with the observed values [2].

Conclusions

The results of the calculations of the quantum diffusion of ^{3}He impurities in solid ^{4}He provides a good fit to available data for solid densities in the range where "supersolid" features are observed. This fit allows us to determine the optimum magnetic field for new experiments at very low temperatures. Since $T_1 \sim T_2\,(\omega\tau_c)^2$ where ω is the Larmor frequency, and requiring $T_1 < 10^3$ s, the desired Larmor frequency for new experiments in $\omega \sim 10^7$ s^{-1}. Lower values of ω reduce the signal/noise and higher values yield unacceptable relaxation times.

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References

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