A_1 and A_2 Transitions in Superfluid ^{3}He in 98% Porosity Aerogel

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(Received 25 May 2004; published 1 October 2004)

Superfluid ^{3}He in high porosity aerogel is the system in which the effects of static impurities on a *p-wave* superfluid can be investigated in a systematic manner. We performed shear acoustic impedance measurements on this system (98% porosity aerogel) in the presence of magnetic fields up to 15 T at the sample pressures of 28.4 and 33.5 bars. We observed the splitting of the superfluid transition into two transitions in high fields in both bulk and liquid in aerogel. The field dependence of the splitting in aerogel resembles that of the bulk superfluid ^{3}He caused by the presence and growth of the A_1 phase. Our results provide the first evidence of the A_1 phase in superfluid ^{3}He/aerogel.

DOI: 10.1103/PhysRevLett.93.145302 PACS numbers: 67.57.Pq, 67.80.Mg

The response of Cooper pairs to various types of impurities depends on the symmetry of the order parameter [1–3]. The strong influence of a small concentration of paramagnetic impurities on a low temperature superconductor is in contrast to its insensitivity to nonmagnetic impurities [1,2]. Unconventional superconductors with non-*s*-wave pairing are vulnerable to any types of impurity [3], and this fact has been used to test the unconventional nature of the order parameter in heavy fermion and cuprate superconductors.

It has been almost a decade since the high porosity silica aerogel was introduced as a potential candidate for static impurities in *p-wave* superfluid ^{3}He [4,5]. Given a great deal of quantitative understanding of the intrinsic properties of superfluid ^{3}He [6], the aerogel/^{3}He system provides a unique opportunity to conduct a systematic investigation on the effects of static disorder in unconventional superfluids. In this system, a wide range of impurity pair breaking can be attained by continuously varying the sample pressure. Furthermore, the nature of the impurity scattering can be readily altered by modifying the composition of the surface layers. A number of experimental and theoretical studies have been performed mainly with 98% porosity aerogel. The fragile nature of the *p*-wave Cooper pairs against impurities was clearly demonstrated by the significant depression of the transition [4,5,7–9]. To date, two superfluid phases have been observed in aerogel in the presence of magnetic fields, and they are believed to have the same symmetries as the *A* phase and the *B* phase of the pure superfluid [9–11], although the microscopic identification of the *A* phase in aerogel is still in question [12]. In this Letter we report our finding of the third superfluid phase in 98% aerogel in the presence of magnetic fields up to 15 T. Based on our observation, we claim that this new phase is the A_1-like phase as observed in pure liquid.

In pure superfluid ^{3}He, minute particle-hole asymmetry causes the splitting of the superfluid transition through the Zeeman coupling in magnetic fields. As a result, the third phase, the A_1 phase, appears between the normal and the A_2 phase (the *A* phase in magnetic fields) [13,14]. In this unique phase, the condensate is fully spin polarized and coexists with the normal component in the opposite spin projection. The A_1 phase has been studied by several groups and the width of the phase was found to increase almost linearly in field by ≈ 0.065 mK/T at the melting pressure [14–17]. Recently, Gervais *et al.* [10] performed acoustic measurements in 98% aerogel up to 0.5 T and found no evidence of splitting in the transition.

Baramidze and Kharadze [18] made a theoretical suggestion that the spin-exchange scattering between the ^{3}He spins in liquid and solid layers on the aerogel surface could give rise to an independent mechanism for the splitting of the transition. Detailed calculations [19,20] show that antiferromagnetic (ferromagnetic) exchange reduces (enhances) the total splitting in low fields, but one recovers the rate of the particle-hole asymmetry contribution in high fields as the polarization of the localized spins saturates. These calculations were performed with the assumption that the *A* phase in aerogel is the Anderson-Brinkman-Morel phase.

However, Fomin [12] recently formulated an argument that the order parameter of the *A*-like phase in aerogel should be inert to the arbitrary spatial rotation in the presence of the random orbital field presented by the aerogel structure. This condition enforces a constraint on the order parameter, and a class of order parameters for equal spin pairing (different from the axial state) was found. This theory predicts that an A_1-like phase would be induced by a magnetic field for a certain condition (e.g., in the weak coupling limit). This is a new type of ferromagnetic phase with nonzero populations for both spin projections. However, the splitting of the A_1 and A_2 transitions in this case seem to evolve in a different manner compared to bulk ^{3}He. If the *A* phase in aerogel is correctly identified as an axial state, then a similar field

dependent splitting of the superfluid transition must exist at least in the high field region since the level of particle-hole asymmetry is affected only marginally by the presence of high porosity aerogel.

We performed continuous wave shear acoustic impedance measurements on both bulk liquid (pure) and liquid in aerogel (dirty) in the presence of magnetic fields ranging from 0 to 15 T at 28.4 and 33.5 bars. The acoustic technique is described in detail elsewhere [10,21], and we used the same acoustic cavity that was utilized in the work of Gervais *et al.* [10]. In brief, we detect the change in electrical impedance of an ac-cut quartz transducer in contact with both pure and dirty liquid. The acoustic measurement is performed at 8.7 MHz for all the data presented. The main body of the cell is made out of titanium and silver. The volume of the cell is designed to be less than 1 cm^3 to ensure a short thermal relaxation time. The sample liquid in the cell is cooled by the $PrNi_5$ demagnetization stage (DS) through a 0.9 m long annealed silver heat link extending below DS. The transitions in the pure liquid were confirmed independently by a vibrating wire (VW) [22] placed near the ultrasound transducer. The acoustic spectrometer output was recorded continuously while the temperature of the sample varied slowly. No significant hysteresis was observed for data taken in both directions. The data presented were taken on warming and the typical warming rate in our study is 0.1–0.2 mK/h. Temperature is determined by the ^{3}He melting pressure thermometer (MPT) attached to the silver heat link right below the cell in the experimental field region. The calibration procedure will be elaborated upon later.

The acoustic traces for three different fields at 33.5 bars are shown in Fig. 1. For 15 T (bottom graph), the acoustic trace is plotted along with that of the VW to compare the transition signatures of the bulk liquid. The vibrating wire measurement was done in a similar fashion as described in Ref. [17] and the amplitude of the resonance is shown in the figure. Two sharp cusps in the VW trace correspond to the A_1 and A_2 transitions in pure liquid as reported in a previous work [17]. These features are concurrent with the jumps in the acoustic trace. The transitions in aerogel are not as sharp as in the bulk. However, the smooth slope changes are quite clear and similar signatures of the superfluid transition in aerogel have been observed by Gervais *et al.* [10]. At zero field, the superfluid transitions in the bulk and aerogel look almost identical to the ones labeled as T_{A1} and T_{aA1} in the 15 T trace, respectively. Only one sharp jump and a quite distinct slope change were seen. The field dependent evolution of the transition features is demonstrated in Fig. 1. Below 3 T, we were not able to resolve the double transition features in aerogel while the features from the bulk can be traced down to zero field, merging into one. As the field increases, the gap between the two transition features in each liquid widens. It is important to emphasize that the

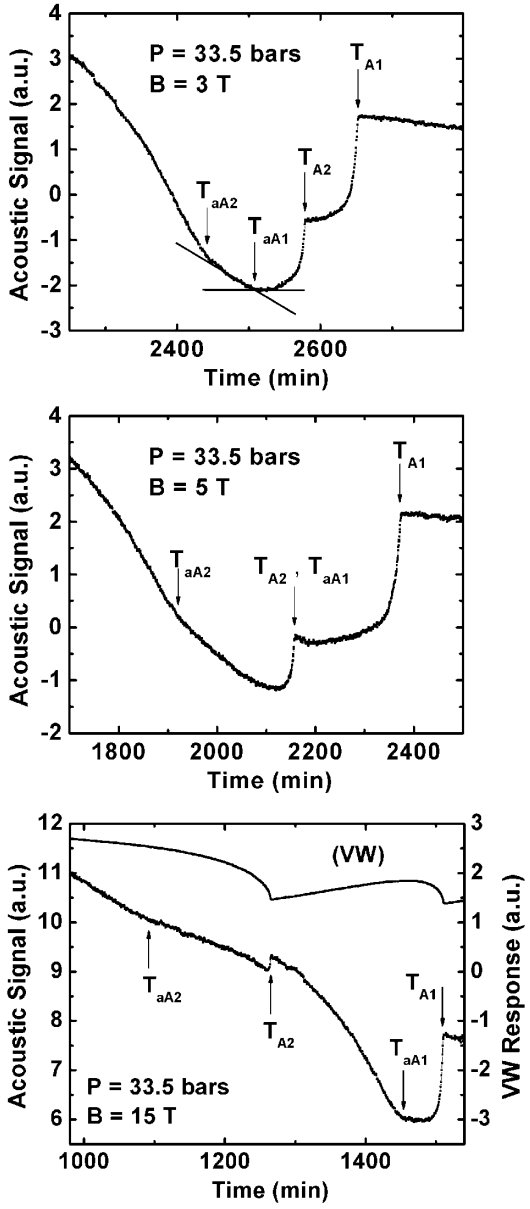

FIG. 1. Acoustic traces for 3, 5, and 15 T at 33.5 bars on warming. The bottom graph shows the acoustic trace at 15 T along with that of the vibrating wire. The sharp jumps in the VW trace are identified as A_1 and A_2 transitions in the bulk liquid. The acoustic trace also shows two sharp features at the exactly same time positions. $T_{aA1(2)}$ indicates the position of $A_{1(2)}$ transition in aerogel. The same scale is used in all three graphs for the acoustic signal. The straight lines in the top panel are shown to illustrate the change in slopes at the transition.

bulk A_2 and aerogel A_1 cross each other around 5 T and continue to move apart in higher fields. A similar behavior was observed at 28.4 bars, but the crossing occurred around 7 T.

At zero field, the Greywall scale [23] was adopted to convert the measured melting pressure to temperature using the solid ordering transition as a fixed point to

establish the pressure offset. In the presence of magnetic fields, the recent calibration by a University of Tsukuba group [24,25] was employed. In the work, the calibration was given in two separate regions—the paramagnetic phase and the high field phase of solid ^{3}He—up to 14.5 T. Unfortunately, below 3.5 mK where we are interested, only the calibration in the high field phase is available. Consequently, the range of our temperature determination is limited to fields between 7 and 13 T for the pressures of our work. The dash-dotted lines in Fig. 2 represent the high field phase transition of the solid ^{3}He in MPT and below the boundary is the region where the calibration is done. The melting pressure in the high field phase was given by $P(T;H) = P_o(H) + c_4(H)T^4 + c_6(H)T^6$ [24] where the fourth-order temperature dependence is expected by spin-wave theory and the sixth-order correction originates from the dispersion correction. We used the width of the bulk A_1 phase identified in the acoustic trace to fix the pressure offset. At each field, the calibration curve $P(T;H)$ is vertically adjusted so that the measured melting pressure interval of the bulk A_1 phase maps out the correct temperature width at the same experimental condition (two point calibration method). The pressure offsets for all fields (including zero field) are around 6 kPa within 10%. The temperature width of the A_1 phase was obtained using the results from Sagan *et al.* [15] and Remeijer *et al.* [17]. By using the A_1 width rather than the actual transition temperature as a fixed point, we can circumvent the possible inconsistency in the absolute temperature scale used in the previous work. The data points represented by the solid and open circles in Fig. 2 were obtained in this way. The sensitivity of the melting pressure thermometry rapidly declines in higher fields and lower temperatures due to a decrease in solid entropy. For example, $|dP/dT|$ drops from $\approx$3.3 kPa/mK at 2 mK and zero field to $\approx$ 0.1 kPa/mK at 15 T for the same temperature. This intrinsic property of the melting curve, in combination with the enhanced noise in high fields, renders it practically impossible to make an accurate determination of the aerogel A_2 transition temperatures well below the dotted line where $|dP/dT| \ll 0.1$ kPa/mK. Typical noise in our high field pressure measurement is about $\pm$4 Pa.

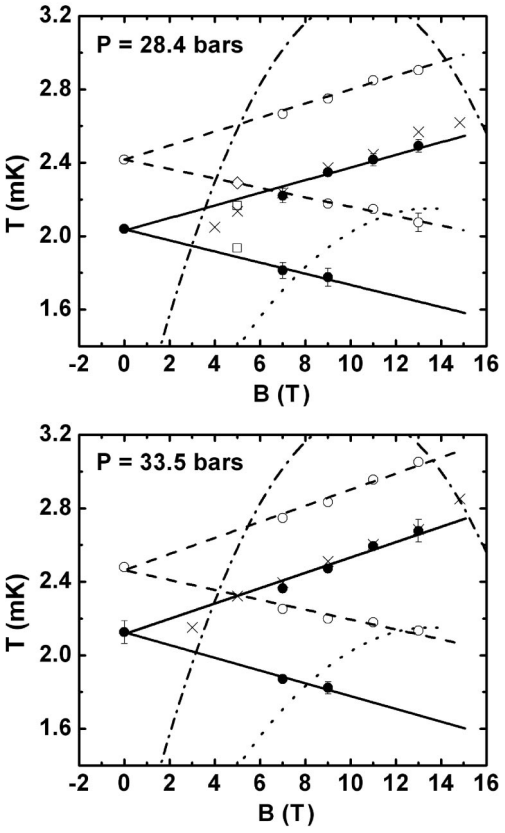

FIG. 2. Transition temperatures vs magnetic field for 28.4 and 33.5 bars. Open (solid) circles are for the bulk (aerogel) transitions determined by the two point calibration scheme. Open squares for 28.4 bars are obtained by the single point calibration method. Crosses are based on the constant warming rate. See the text for the temperature calibration procedures. The solid (dashed) lines are the results of linear fit for aerogel (bulk) (see the text). The dash-dotted lines represent the paramagnetic to high field phase transition line and on the dotted line, $|dP/dT| = 0.1$ kPa/mK.

The straight lines in Fig. 2 are the results of linear fits to the data points represented by the open (bulk) and solid (aerogel) circles including zero field results. The slope of each linear fit is listed in Table I. For 5 T at 28.4 bars, the aerogel transition temperatures (squares) were determined by forcing the bulk A_2 transition (diamond) on the linear fit for T_{A2} (single point calibration method). The asymmetry in the splitting is of special importance in two ways. First, the asymmetry ratio is a direct measure of strong coupling effects. Second, it provides a valid self-consistency check for our temperature calibration since only the total width of the splitting has been utilized. The asymmetry ratios are also listed in Table I where $r_{(a)} = -(T_{(a)A1} - T_{(a)c})/(T_{(a)A2} - T_{(a)c})$ and $T_{(a)c}$ is zero field bulk (aerogel) transition temperature. The bulk slopes and r are in good agreement with previous measurements within 8% [15,17]. It is notable that there is no appreciable difference in the A_1 slopes for the bulk and aerogel, which is consistent with the theory of Sauls and Sharma. However, the asymmetry in the aerogel is con-

TABLE I. Slopes (mK/T) of the splitting for the A_1 and A_2 transitions in bulk and aerogel at 28.4 and 33.5 bars. The asymmetry ratios, r for bulk and r_a for aerogel, are also listed (see the text for a definition).

	T_{A1}	T_{A2}	r	T_{aA1}	T_{aA2}	r_a
28.4 (bars)	0.038	−0.026	1.46	0.034	−0.030	1.13
33.5 (bars)	0.043	−0.028	1.54	0.042	−0.035	1.20

sistently smaller by 22% than the bulk value for both pressures.

The asymmetry ratio is related to the fourth-order coefficients, β_i, in the Ginzburg-Landau free energy expansion as defined in Ref. [6] by $r = -\beta_5/(\beta_2 + \beta_4 + \beta_5)$. In the weak coupling limit at low pressure, $r \to 1$ and the strong coupling effect tends to increase this ratio as pressure rises. Within the spin-fluctuation model, the strong coupling correction factor, δ, can be estimated from $r = (1 + \delta)/(1 - \delta)$ [6]. For 33.5 bars in aerogel, $\delta \approx 0.09$. The level of the strong coupling contribution at this pressure corresponds to that of the bulk at around 15 bars [15,17], which indicates substantial reduction of the strong coupling effect. The weakening of strong coupling effects by the presence of impurity scattering has been discussed theoretically [26] and confirmed experimentally through an independent estimation from the field dependent suppression of the A-B transition by Gervais *et al.* [10]. Their value of $g(\beta)$ (the coefficient of quadratic field dependence of the A-phase width) at 34 bars in aerogel also matches that of 15 bars in bulk. It is worth mentioning that T_{ac} at 33.5 bars also falls on T_c around 15 bars. However, the A_1-like phase suggested by Fomin [12] requires a quite different asymmetry ratio. In this case, the asymmetry ratio $r_F = -\{1 + B/(\beta_1 + \beta_5)\}^{-1}$, where $B = 9\beta_2 + \beta_3 + 5\beta_4 + 4\beta_5$ and reaches ≈ 0.15 in the weak coupling limit. This asymmetry ratio is inconsistent with our observation allowing for reasonable variations in the β parameters.

Sauls and Sharma [19] suggest that the antiferromagnetic coupling of 0.1–0.2 mK between spins in solid and liquid might be responsible for the suppressed splitting below 0.5 T observed by Gervais *et al.* The calculations show that the slope of the splitting starts to increase smoothly around 0.5 T ($\sim$exchange field strength between spins in solid) and reaches the slope close to that of bulk superfluid in high fields. Our data cannot confirm this behavior owing to the lack of low field temperature calibration. However, we made an estimation of the aerogel A_1 transition temperatures by assuming a constant warming rate set by the bulk transition temperatures and time interval. The crosses are obtained in this manner. The agreement between the filled circles and crosses in the overlapping region is excellent and encouraging (see Fig. 2). We point out that the data points acquired in this way characteristically fall below the linear fit in the low field region. This fact along with the observations made in low fields by us and Gervais *et al.* might suggest antiferromagnetic exchange coupling between the localized and mobile ^{3}He spins.

In summary, we observed the superfluid transition in 98% aerogel split into two transitions in the presence of magnetic fields above 3 T at 28.4 and 33.5 bars. The field dependence of each transition is consistent with that of the A_1 phase observed in pure liquid with a significantly reduced strong coupling effect.

This work is partially supported by the NSF through DMR-0239483 and a NHMFL IHRP grant. The experiment was performed at the High B/T Facility of NHMFL at the University of Florida. We acknowledge useful discussions with P. Kumar, M. Meisel, J. Sauls, Y. Takano, G. Kharadze, and I. Fomin. Y. L. thanks the Alfred P. Sloan Foundation for financial support.

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