Magnetic properties of ^{3}He nanoclusters embedded in hcp ^{4}He

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Abstract

The magnetic properties of ^{3}He nanoclusters in phase-separated solid ^{3}He-^{4}He mixture were investigated for samples with pressures between 2.64 and 3.71 MPa and temperatures between 0.6 and 10 mK. From pulse NMR from 62 to 250 kHz, it was found that there are two components with different spin-spin relaxation times. For the samples of intermediate pressure, the component with longer T_2^* showed large downward deviation from Curie law or decrease of magnetization at about 1.1 mK which was larger for lower field. The component with shorter T_2^* showed ferromagnetic tendency. The solid-like fraction was obtained from the relative magnitudes of magnetization and it shows a sharp increase with pressure around 2.95 MPa.

Key words: ^{3}He; nanocluster; NMR; antiferromagnetism

Magnetic ordering in solid ^{3}He has been studied for several decades and the multiple-exchange theory has had reasonable success in explaining the observed behavior. Various recent studies of solid and liquid ^{3}He clusters and films have shown that their properties are quite different from those of bulk. In the phase-separated ^{3}He nanoclusters in hcp ^{4}He solid matrix, Schrenk *et al.* [1] reported a history-dependent maximum in the heat capacity at $T \approx 1$ mK for pressures as low as 2.80 MPa. Although they suggested that this is a smooth continuation of the bulk T_N, they did not see the latent heat and much of the spin entropy remained at their lowest temperature. Matsunaga *et al.* [2] reported decrease of the magnetization around 1.05 mK for similar samples from 2.96 MPa to 3.06 MPa.

The experimental setup was described elsewhere in detail [2]. The NMR cell is packed with 70 nm Ag powders to the filling factor of about 45%. A PLM-4 pulsed NMR spectrometer was used at 62.5, 125 and 250 kHz and the wideband output from PLM-4 was recorded. The background from the electronics was subtracted using measurement without field. A miniature coin silver pressure transducer was glued to the NMR cell.

The sample was made from a mixture of 0.6% ^{3}He in ^{4}He using the blocked capillary technique . It was annealed for at least several hours at the temperature just below the departure from the melting curve. Around 150 mK the mixture solid was phase-separated into hcp ^{4}He matrix and ^{3}He nanoclusters. The size of ^{3}He clusters was estimated to be ~20 nm by assuming that all ^{3}He atoms in a typical pore of 100 nm size were aggregated to make one cluster. For samples at $P \lesssim 3.5$ MPa, partial melting of ^{3}He nanoclusters was observed by pressure measurement during further cooling. Cooling down to 0.5 mK was achieved using $PrNi_5$ nuclear demagnetization stage. Temperature was measured by MCT calibrated against the PLTS-2000 scale [3].

Figure 1(a) shows typical FIDs at 124 kHz for the sample of 2.95 MPa. The FIDs at only three temperatures are shown for clarity. The phase-corrected envelop of the FID was calculated by the inverse fourier transform from the FFT spectrum. Below $\approx$ 1.1 mK, it is clear that there are two components with long (3.6±0.3 ms) and short (0.8±0.2 ms) T_2^*. The T_2^*'s have small temperature and field dependence but are con-

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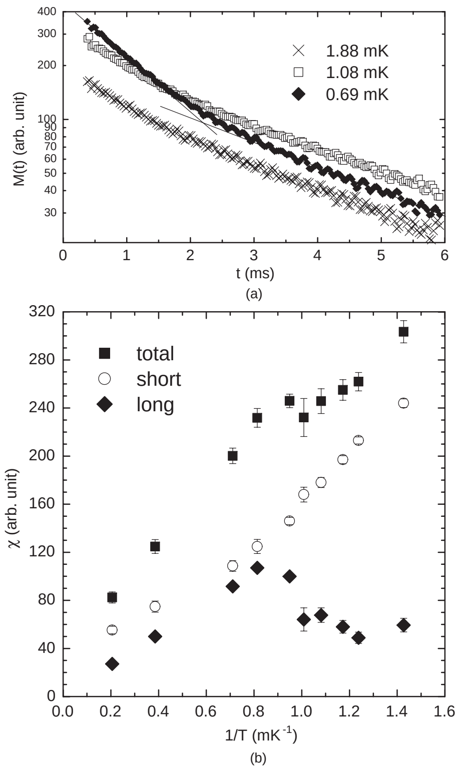

Fig. 1. (a) Typical FIDs for 2.95 MPa sample at 124 kHz and 1.88, 1.08, and 0.69 mK. The lines are for aid to eyes to clarify the two components. (b) The amplitudes of the FIDs at 62kHz of 2.95 MPa sample fitted into the two-exponential decay. The 'short' and 'total' curves are shifted by 40 to be separated from the 'long' curve.

stant within error bars.

Figure 1(b) shows the amplitudes of the FID fitted to two-exponential decay for the same sample at 62 kHz. The short component has a ferromagnetic tendency with the Weiss constant of $\sim$400 μK with small field dependence. The long component has antiferromagnetic tendency with the Weiss constant of ~ -300 μK at 249 kHz decreasing to nearly 0 at 62 kHz. Because of the mutual dependence of fitting parameters between the longer and shorter T_2^* components, it was difficult to quantify these parameters more accurately. The decrease of the magnetization of the long component below 1.1 mK is sharper and larger at smaller field (not shown). This behavior is observed reproducibly for samples around 3.0 MPa. In view of the antiferromagnetic tendency of the long component, this decrease may be considered as antiferromagnetic ordering, although there is not an abrupt drop of the magnetization as seen in bulk ^{3}He. The sharper decrease at smaller field implies that a clear abrupt drop of the magnetization might be seen at even lower field.

This behavior of the long component is very similar to that of the total magnetization of similar samples observed by Matsunaga *et al.* [2] They didn't see the ferromagnetic short component and this may be the result of inadequate truncation of the data. In the range of the magnetization decrease, the long component shows hysteresis. This might have some relation with the hysteresis seen in the heat capacity measurement of Schrenk *et al.* [1]

This pressure range of magnetization decrease is related to the change of the Curie and Weiss constant in the higher temperature part. We saw that there is a fast decrease of the Curie constant around 2.95 MPa. The detailed result will be published elsewhere. One point which should be noted is that the external pressure is not a perfect parameter to label the internal state of ^{3}He nanoclusters inside the ^{4}He matrix. There is some dependence of the characteristics of the samples on the exact preparation procedure. But the above mentioned behavior of the long component occurs only for the samples near the drop of the Curie constant.

As for the Weiss constant, there is a ferromagnetic tendency at the highest pressures and gradual change to slight antiferromagnetic tendency occurs as the pressure is lowered. Around 2.95 MPa there is an abrupt change to strong ferromagnetic tendency and this maintains to 2.64 MPa, the lowest pressure measured. At these lower pressures, the main contribution to the magnetization is thought to come from the outer solid-like layer near the interface with ^{4}He. This kind of ferromagnetic behavior of the layers near the interface was observed on various substrates (for example, see ref. [4]). These results suggest that the short component comes from the outer layer surrounding the inner long component. This is partly supported by the fact that the amount of the short component calculated from the magnetization is similar to that of the solid-like fraction below the drop of the Curie constant.

Acknowledgements

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