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IN-SITU TEMPERATURE CALIBRATION BELOW 1 K USING THE μ^+ KNIGHT SHIFT IN CMN

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We present μ^+ paramagnetic shift measurements between 12 K and about 65 mK in cerium magnesium nitrate (CMN) to investigate its utility as an in-situ temperature calibration source for low temperature μ SR experiments. CMN is a salt which exhibits Curie-law susceptibility to temperatures as low as 5 mK. The μ^+ Knight shift is measured to be $-(1.46 \pm 0.03) \times 10^{-3} / T + (0.004 \pm 0.02) \times 10^{-3}$, corresponding to a transferred hyperfine field of -28.5 kOe/ μ_B .

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The power of the muon spin rotation technique to investigate magnetic and superconducting phenomena at temperatures below 1 K is well documented [1]. As capabilities to carry out experiments at lower and lower temperatures become available, it is important to be able to accurately calibrate the sample temperature, particularly below 50 mK. Even with commercially calibrated temperature sensors, problems can arise from such sources as poor thermal contact between the sample and cold finger and rf heating induced by ground loops in the temperature-sensing circuitry. It is therefore useful to investigate ways in which the true temperature at the cold finger of a dilution refrigerator can be measured *in situ*; i.e., under the actual conditions of a μ SR experiment. Here we present the results of μ SR Knight shift measurements on cerium magnesium nitrate (CMN), a paramagnetic salt with a Curie-law susceptibility down to temperatures of 5 mK [2]. Our results show that the μ SR Knight shift in this material is easily measurable, and thus can be used as an *in-situ* means of temperature calibration at very low temperatures.

The experiments were carried out at the Paul Scherrer Institute in Villigen, Switzerland, using both the General Purpose Spectrometer (GPS) and the Low Temperature Facility (LTF). A sample was prepared by mixing powdered CMN with high-purity silver powder (about 30% by volume) to achieve good thermal conductivity. This mixture was pressed into a pellet approximately 1 cm. in diameter and 0.5 cm. thick. Transverse field data were taken between 3.5 K and 12 K in the GPS, where the sample temperature was well determined using resistive thermometry and the applied field was calibrated with a Hall probe, and to below 100 mK in the LTF. The applied field H ranged from 0.6T in the GPS to between 0.01T and 1.2T in the LTF, depending on the nominal temperature, as discussed below.

Figure 1 shows a fast Fourier transform of the time-differential spectrum obtained in the LTF at $T \cong 0.5$ K and $H \cong 0.6$ T. Two frequency components are observed, a narrow line from the Ag and a broad line at a slightly lower frequency from the CMN. The time differential relaxation function $G(t)$ is thus well described as a sum of two components, each exponentially relaxed:

$$G(t) = A_1 \exp(-\lambda_1) \cos(2\pi\nu_1 + \phi_1) + A_2 \exp(-\lambda_2) \cos(2\pi\nu_2 + \phi_2). \quad (1)$$

The analysis demonstrates that in the LTF ($T < 1$ K) the ratio of the asymmetries A_1/A_2 was about 2.8 to 1.0 (CMN to Ag) and that the Ag line was broadened, but unshifted, by the fields originating in the nearby CMN grains. Thus the μ SR line from the Ag serves as a calibration from which to derive the μ^+ Knight shift in CMN. We found that the CMR and Ag linewidths λ_1 and λ_2 scaled with H/T , as expected for powder broadening with susceptibility following an inverse temperature law (see below and Figure 4). Likewise, the frequency shift between the Ag and CMN lines also scale with H/T . This means that in order to obtain good separation between the two spectral lines at any given temperature the field has to be adjusted to an optimal H/T value. This was not always possible; for example, in the GPS ($3 \text{ K} < T < 12 \text{ K}$), where the applied field was limited to ≤ 5 T, a clean separation of the spectral lines could not be achieved because of the elevated temperatures. However, the data could be analyzed with two components even in the GPS, by fixing ν_2 at the value given by the applied field and λ_2 at a small value ($\approx 0.02 \mu\text{s}^{-1}$), independent of temperature.

Figure 2 gives the μ^+ Knight shift K as a function of inverse temperature for the data taken in both the GPS and LTF facilities. The solid line is a least-squares fit, showing that there is reasonable agreement with the expected Curie-law behavior. Excluding the lowest temperature point at $T < 100$ mK (see below), we find $K(\%) = - (0.146 \pm 0.003)/T + (0.0004 \pm 0.002)$. The Knight shift is given by $K = \{\sum_i (H_{\text{hf}})_i \chi_i\} / N_A \mu_B$, where $(H_{\text{hf}})_i$ is the hyperfine field from the i^{th} component of the dimensionless susceptibility χ_i and N_A is Avagadro's number. The powder averaged susceptibility of CMN is $0.21/T$ emu/mol-Ce at least down to 0.005 K [2], yielding a dimensionless $\chi = 0.29 \times 10^{-3} / T$, and a hyperfine field $H_{\text{hf}} = -28.5$ kOe/ μ_B . This is an order of magnitude larger than the expected dipolar field and must therefore originate from a transferred hyperfine mechanism. The site of the muon in this material is unknown.

To illustrate the utility in using the CMN Knight shift as a temperature calibration tool, we show Knight shift data in Figure 3 which was taken with the LTF alone. The data points are plotted at their nominal set-point temperatures. One sees that the lowest temperature point, taken at a set point of 50 mK, is actually more consistent with a sample temperature 66 ± 6 mK.

Figure 4 illustrates the scaling of the CMR linewidth λ_1 with H/T . The values of H range from 0.03 T to 1.2 T for temperatures ≤ 0.7 K. All points are plotted at their nominal set-point temperatures. The solid line is a guide to the eye and is given approximately by $\lambda_1 (\mu\text{s}^{-1}) \cong 1.7 H(\text{Tesla})/T(\text{Kelvin})$. One sees that three points do not fall near the straight line. The two lowest nominal temperature points (at 50 mK) are more consistent with higher actual temperatures. The arrows show where they would be plotted if their actual temperatures were near 66 ± 6 mK, as determined by the Knight shift values discussed above. The point at the largest value of H/T was taken at $H = 1.2$ T and $T = 0.5$ K, indicating that the value of λ_1 may be saturating at these higher fields.

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Figure Captions

Fig. 1 Fourier power spectrum of CMN (broad, low frequency line) mixed with silver powder (narrow, higher frequency line) at $T = 0.5$ K and $H = 0.6$ T.

Figure 2. Muon Knight shift in CMN vs. inverse temperature. The solid line is a least squares fit to the data (see text).

Figure 3. Muon Knight shift in CMN vs. inverse temperature. The solid line is a least squares fit to the data, excluding the point with the largest negative shift (about -2.25 %), which is plotted at the set point temperature of 50 mK. The actual temperature was closer to 66 mK.

Figure 4. Inhomogeneous linewidth λ_1 from CMN vs. H/T . The solid line is a guide to the eye. The data are plotted at their set-point temperatures. The arrows indicate where the data points would lie if corrected to their actual temperatures determined from the Knight shift data. The point with λ_1 equal to about $3.1 \mu\text{s}^{-1}$ shows the apparent saturation of the linewidth at 1.2 T field.