Observation of Quantized Muon Spin Precession Frequencies in Paramagnetic PrPb$_3$

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We report $\mu$SR measurements in PrPb$_3$, where an antiferro-quadrupole ordering with long periodic structures has been found [1]. The muon localization site in PrPb$_3$ was identified to be $3d$ site, at the midpoint of two Pr ions, from the local symmetry probed by muon Knight shift [2]. Surprisingly, we observed spontaneous muon spin precession with five quantized frequencies in the paramagnetic state (Fig. 1), which suggests a strong coupling between the muon spin and the nearest neighbor $^{141}$Pr nuclear spins, i.e., formation of spin entangled state $^{141}$Pr-$\mu^+ - ^{141}$Pr. The frequencies gradually increase with decreasing temperature and the lowest frequency reaches $\sim$3 MHz at 1.7 K. This behavior indicates that the $\mu^+$ and $^{141}$Pr nuclear spins are coupled not only through bare nuclear dipole interactions, but with the assistance of the 4$f$ dipole moment induced by a strong intra-atomic hyperfine coupling. We will discuss the interplay of the 4$f$ electrons and the positive charge of the implanted muon for the formation of a spin entangled state.


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