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High-field ESR and thermodynamic studies of uniform and bond-alternating S=1 spin chains

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Recently, field-induced phenomena in quantum spin systems have attracted considerable interest. Gapped one-dimensional (1D) spin systems with a spin value$S$=1 subject to an external magnetic field strong enough to close the gap (H_c) are driven into a new phase. Spin excitations in this field-induced phase have been studied by experiments on a uniform S=1 antiferromagnetic spin chain $Ni(C_5H_{14}N_2)_2N_3(PF_6)$, alias NDMAP and a bond-alternating one $Ni(C_9H_{24}N_4)NO_2(ClO_4)$, alias NTENP. We performed high-field and multi-frequency ESR experiments at 1.5 K on these compounds and observed gapped excitations above H_c. Two or three excitation modes were observed depending on the field direction in NDMAP and only one excitation in NTENP. These results are consistent with those obtained by inelastic neutron scattering experiments in a magnetic field. Both compounds exhibit the long-range order (LRO) at a magnetic field above H_c and a low temperature. Observed gapped excitations are very different from those expected from a conventional spin-wave theory in the LRO state. For NDMAP, observed branches satisfactorily agree with those analyzed by a phenomenological field theory. The difference of observed gapped excitations between NDMAP and NTENP can be explained by an interaction with a low-lying two magnon continuum at q=π that is present in a bond-alternating chain but absent in a uniform one. When an antiferromagnetic spin chain with$S$=1 has an XY or Heisenberg symmetry, the phase above H_c is critical and its low-energy physics is described by a Tomonaga-Luttinger liquid (TLL), which is characterized by a gapless k-linear energy dispersion with an incommensurate k_0 and a spin correlation having an algebraic decay. NTENP has nearly an XY symmetry and a linear temperature(T) dependence of the specific heat (C_{mag}) was observed for the magnetic field parallel to the chain above H_c in a temperature region above that of the LRO state. The ratio C_{mag}/T increases as the magnetic field approaches H_c from above and is in good agreement with the prediction of the c=1 conformal field theory, providing a conclusive evidence for a TLL in a gapped quasi-1D antiferromagnet.