Berry phase investigation of spin-S ladders

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We investigate the properties of antiferromagnetic spin-S ladders with the help of local Berry phases defined by imposing a twist on one or a few local bonds. In gapped systems with time reversal symmetry, these Berry phases are quantized, hence able in principle to characterize different phases. In the case of a fully frustrated ladder where the total spin on a rung is a conserved quantity that changes abruptly upon increasing the rung coupling, we show that two Berry phases are relevant to detect such phase transitions: the rung Berry phase defined by imposing a twist on one rung coupling, and the twist Berry phase defined by twisting the boundary conditions along the legs. In the case of non-frustrated ladders, we have followed the fate of both Berry phases when interpolating between standard ladders and dimerized spin chains, with the surprising conclusion that, at least far enough from dimerized chains, they define different domains in parameter space. A careful investigation of the spin gap and of edge states shows that a change of twist Berry phase is associated to a quantum phase transition at which the bulk gap closes, and at which, with appropriate boundary conditions, edge states appear or disappear, while a change of rung Berry phase is not necessarily associated to a quantum phase transition. The difference is particularly acute for regular ladders, in which the twist Berry phase does not change at all upon increasing the rung coupling from zero to infinity while the rung Berry phase changes $2S$ times. By analogy with the fully frustrated ladder, these changes are interpreted as cross-overs between domains in which the rungs are in different states of total spin from 0 in the strong rung limit to $2S$ in the weak rung limit. This interpretation is further supported by the observation that these cross-overs turn into real phase transitions as a function of rung coupling if one rung is strongly ferromagnetic, or equivalently if one rung is replaced by a spin $2S$ impurity.