Influence of Sample Shape on the Production of Intrinsic Localized Modes in an Antiferromagnetic Lattice

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Influence of sample shape on the production of intrinsic localized modes in an antiferromagnetic lattice

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The formation of intrinsic localized modes (ILMs) via the uniform mode instability is considered for different crystal geometries for a layered quasi-1D antiferromagnet (C$_2$H$_5$NH$_3$)$_2$CuCl$_4$. By varying the sample shape and hence the demagnetization factor, it is possible to tune the frequency of the uniform mode with respect to the long-wavelength spin wave frequencies. Molecular dynamics simulations predict that the smaller the difference between the two frequencies, the easier to create ILMs from the large amplitude uniform mode. High power nonlinear experiments on samples of different shapes confirm this prediction. © 2002 American Institute of Physics.

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I. INTRODUCTION

The idea that lattice discreteness can stabilize highly localized excitations in perfect nonlinear lattices1–3 is now under experimental investigation both at the macroscopic4,5 and microscopic level.6 Theoretical studies of discrete magnetic systems7–9 have provided a foundation for recent experimental investigations. It has been predicted through simulation studies that intrinsic localized modes could be created via a modulational instability when the lowest frequency uniform spin wave mode for a spherical sample of the layered quasi-1D antiferromagnet (C$_2$H$_5$NH$_3$)$_2$CuCl$_4$ is driven to a large amplitude.10,11 The first experimental study, while demonstrating the instability of the antiferromagnetic resonance (AFMR), was unable to characterize the ILM spectrum completely because of the long pulse lengths used and the low time resolution of the detection scheme.12 Our previous study employing high power, short and chirped pulses characterized the break-up of the uniform AFMR mode into ILMs circumventing some of the previous difficulties.13 The resulting incoherent absorption spectrum, which provides a time dependent signature of ILM production and decay, has been mapped out experimentally for a plate-shaped sample by using a second weak CW microwave probe beam in conjunction with the excitation pulse. As the production of such nanoscale ILMs and the associated energy localization represent a newly predicted behavior for the dynamics of nonlinear atomic lattices, the exact details are of fundamental interest.

Since the AFMR frequencies of the layered quasi-1D antiferromagnet (C$_2$H$_5$NH$_3$)$_2$CuCl$_4$ depend on sample shape through the demagnetization factors ($N_a + N_b + N_c = 4\pi$) (Ref. 14) while the spin-wave mode frequencies do not, the opportunity exists to exploit how the large-amplitude uniform-mode break up is initiated by energy transfer to nearby spin-wave modes. The shape-controlled frequency gap between these two dynamical components is expected to play an important role in the outcome. Here we explore both with molecular dynamics (MD) simulations and with high power experiments how the demagnetization factor influences the modulational instability of the uniform mode and the resulting evolution of ILMs.

II. MOLECULAR DYNAMICS SIMULATIONS

Figure 1 shows the calculated zero-field dispersion curve of spin-wave modes, where $k_{BZ}$ is the Brillouin zone boundary, as well as the AFMR for the lower branch of the biaxial antiferromagnet (C$_2$H$_5$NH$_3$)$_2$CuCl$_4$. The AFMR frequency is a function of the demagnetization factor, $N_c$, along the antiferromagnetic stacking axis (the one-dimensional $c$ axis), which is the polarization direction of this branch.14 The solid circles in the figure show a few cases for different sample shapes illustrating that the AFMR frequency falls between the long-wavelength limits of the $c$-magnon frequency and the $ab$-magnon frequencies (magnons with $k$ perpendicular to the $c$-axis). As the frequency of the magnons do not depend on the demagnetization factor, the AFMR frequency can be tuned with respect to the $c$-magnons by preparing different shape crystals. Only in a very small region of $k$-space ($k/k_{BZ} \sim 2 \times 10^{-2}$) do $ab$-plane magnons drop below the $c$-magnon in frequency. Since the extent of this region in $k$ space is smaller than the minimum $k$ value ($k/k_{BZ} \sim 4 \times 10^{-3}$) for a 500-spin lattice, a one-dimensional approxima-

![Image]

FIG. 1. AFMR frequencies for several demagnetization factors and the dispersion curves for the lower branch spin-wave mode, near the zone center for propagation along $a$, $b$, and $c$ axis directions. The $k/c$ identifies the 1D spin wave branch of interest. The solid circles identify the AFMR for different sample demagnetization factors. (a) Plate: $N_c = 4\pi$, (b) sphere: $N_c = 4\pi/3$, and (c) rod: $N_c = 0$.
tion is used in the simulations. It is assumed that magnons propagating in the \(ab\)-plane do not participate in ILM formation.

MD-simulations have been performed on a 1D chain of 500 classical spins with realistic parameters including the effects of exchange, anisotropy and dipole–dipole interactions as described in Ref. 11, but now the demagnetization term is included to account for nonspherical sample shapes. To determine the instability threshold for a specific sample shape the simulation is started with the spin deviation (transverse excitation) energy in the uniform mode. If after 2000 cycles, which is ten times the number required to develop an ILM,\(^\text{11}\) the uniform mode remains intact then the excitation is identified as stable. Simulations were carried out as a function of spin deviation (maximum value=1) for different demagnetization factors to identify the instability threshold levels for ILM creation for different sample shapes and the results are shown in Fig. 2. The larger the demagnetization factor, the smaller is the spin deviation threshold, and hence the smaller is the power required to produce ILMs. Another statement is that as the uniform mode frequency approaches the bottom of the \(c\)-magnon band it becomes easier to create the instability to form ILMs.

Additional simulations reveal that the nucleation of ILMs is related to two effects: (1) a nonlinear frequency shift of the spin-wave band participating in the instability and (2) an energy transfer process from the uniform mode to the energetically shifted spin-wave modes. Figure 3 quantifies this statement with an illustration for a particular sample shape. A rod-shaped sample, \(N_c=0\), corresponds to the largest frequency difference shown in Fig. 1 between \(k||c\) and point (c). The simulated difference between these two frequencies is found as a function of spin deviation. Dispersion curves are obtained by a Fourier transformation both in space and time. A small amount of noise is used to excite and to observe all spin wave-modes. As the instability threshold is approached (vertical line at 0.34), the frequency difference goes to zero. Thus, to overcome the large initial energy difference between the linear AFMR and the spin wave mode, a large nonlinear frequency shift is required. In the experiment this requirement translates into excitation pulses of significantly increased energies.

III. EXPERIMENTAL SETUP AND RESULTS

The main components of the pump–probe experiments consist of a voltage-controlled oscillator followed by a diode switch, which produces chirped microwave pulses of 1–10 \(\mu\)s duration. These are then amplified by a 50 W amplifier to create the pump pulses. A weak, tunable continuous wave source acts as the probe to obtain the absorption spectra. (See Ref. 13 for more details.) Both the pump and probe beam produce an ac-magnetic field at the sample via a surrounding coil. For the thicker crystals, a pair of coils is used in order to keep the ac-field uniform over the entire sample.

Samples were cut from a thick single crystal using a wire saw and shaped into a rectangular bar long in the \(c\)-direction. After each successive measurement, a sheet perpendicular to the long axis was peeled off to increase the demagnetization factor along the \(c\)-axis. This procedure was repeated until the sample was thin enough to span the entire range of demagnetization factors.

Figure 4 shows high power results for two limiting demagnetization factors. The excitation level, pulse width, and chirping depth are the same for both cases. [A weak magnetic field is applied in case (a) to adjust the AFMR frequency relative to the starting frequency of the chirped pulse.] The gray-scale density plots show the incoherent absorption as a function of frequency and time. Before the pulse is turned on, the linear AFMR frequency is seen as the initial black line at \(t=0\). During the 10 \(\mu\)s pulse which follows, only the position of the driver frequency is seen in these data due to a blocking switch. The data in Fig. 4(a) are for \(N_c\sim4\ \pi\). The broadband absorption feature, which is the signature of ILMs, is easily seen. On the other hand, for the case where \(N_c\sim0\) shown in Fig. 4(b) no ILMs are observed on this time scale. In light of Fig. 3, it seems likely that we could reproduce a long-lived broad absorption spectrum for the cases of \(N\sim4\ \pi\) by appropriately increasing the pump-pulse power. This would mean that in Fig. 4(b) the breakup into ILMs was not complete by the end of the pump-pulse due to insufficient power.
IV. CONCLUSIONS

The formation of ILMs in an antiferromagnetic lattice has been investigated as a function of the frequency difference between its uniform mode and the near-by spin-wave modes by varying the demagnetization factor via the sample geometry. MD simulations predict that the smaller this difference, the easier it is to create ILMs. This is confirmed by the experiments on several samples with different demagnetization factors.

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