Collision of clusters of vertical Bloch lines in a domain wall of a ferromagnet

M. V. Chetkin, I. V. Parygina, V. B. Smirnov, S. N. Gadetskiĭ, A. K. Zvezdin, and A. F. Popkov
M. V. Lomonosov State University, Moscow

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Experiments have shown that in a collision of two clusters of vertical Bloch lines the laws of conservation of the topological charge and momentum are conserved, despite the considerable damping in the system. A head-on collision of two identical clusters gives rise to the formation of a breezer, whose lifetime is approximately equal to the relaxation time of the domain wall flexure.

Chetkin *et al.*[1,2] measured the motion of clusters of vertical Bloch lines (VBL). They showed that in the case of strong damping clusters of vertical Bloch lines in a magnetic system are accompanied by solitary waves of an asymmetrically shaped domain wall flexure which are produced as a result of the action of the gyroscopic force, consistent with the theoretical predictions (see Ref. 2). The leading edge of the solitary wave is very steep and the trailing edge is extended. At a constant velocity of the domain wall the clusters containing many vertical Bloch lines move slower than the clusters consisting of fewer VBL. This situation makes it possible to study experimentally the consequences of a collsion of two clusters: a small cluster moving at a faster velocity and a large cluster moving in the same direction and in the opposite direction.

Two positions of a dynamic domain wall, moving at a velocity of 15 m/s, along which clusters of vertical Bloch lines propagate, were recorded in Refs. 1 and 2. Each cluster is formed by means of a single current loop which crosses the domain wall. It receives two current pulses of different amplitudes after a certain time interval. Two positions of two clusters of VBL on a dynamic domain wall are shown in Fig. 1. The positions were recorded by double high-speed photograph. In the first position, a small cluster containing 2–4 pairs of Bloch lines, which trails a large cluster containing 6–8 pairs of Bloch lines, overtakes it; both clusters are moving from right to left. In the second position the small cluster is leading. Its amplitude and velocity are equal to the amplitude and velocity it had before the collision. This situation also applies to the large cluster. From these double high-speed photographs we determined the velocities of the two clusters before and after their collisions as a function of their relative distance. These results are shown in Fig. 2. We see that in the case of large, positive values of x the cluster velocities differ by a factor of ~ 2. With a decrease in the value of x, the velocity of the small cluster increases by 10–20%. This increase occurs because at the leading edge of the solitary wave of the DW flexure, which accompanies the small cluster $(\partial q/\partial x)$ decreases when the small cluster overtakes the large cluster. Its velocity increases, in accordance with the result obtained theoretically in Ref. 2. The azimuthal angle has a small twist at the trailing edge of a solitary wave of the DW flexure. All of its changes occur in a narrow region near the maximum flexure of the

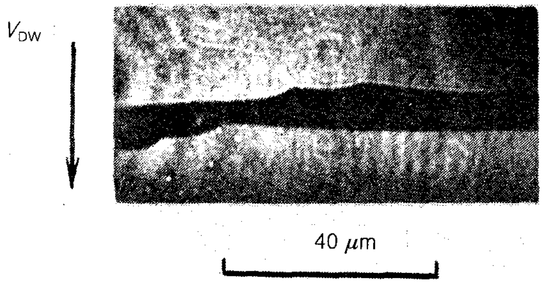

FIG. 1. Double high-speed photograph of the positions of two VBL clusters on a dynamic domain wall moving at different velocities before the collision (top) and moving in in the same direction 700 ns after the collision (bottom).

domain wall. If the values of x are negative, we again have two clusters which move in the same direction at the velocities before the collision. It is difficult to set up an experiment of this sort for fluxons in an extended Josephson junction.

In a system with a strong dissipation (the dimensionless damping parameter in the Landau-Lifshitz equation is $\alpha = 0.4$) the momentum and topological charge conservation laws thus hold in the case of a collision of two clusters moving in the same direction. Here we have in fact an elastic central collision in a one-dimensional system. Ignoring the DW flexure, this is in fact such a system. In $1D$ magnetic materials the solitons can be seen from the scattering of neutrons. It is, however, very difficult to interpret such a scattering.[3]

If two VBL clusters are bucking each other, the azimuthal angle twist in the DW in them must be in the opposite direction. A head-on collision of two clusters, which contain 2–4 pairs of Bloch lines, with opposite topological charges, and which have the same amplitudes, produces a breezer (Fig. 3). As a result of convergence, the clusters interpenetrate each other (Fig. 3b). The topological charges of these clusters, which have the same sign, annihilate each other, and the DW flexure relaxes in a time on the order of 1 μs, which corresponds to the relaxation time of the DW flexure in a gradient magnetic field. This time is given by the relation $\tau^{-1} = \mu(dH/dx)$. For $\mu = 1.2\times 10^2$ cm/sOe and $dH/dx = 4000$ Oe/cm, we find $\tau = 2\times 10^{-6}$ s. The photograph in Fig. 3 showing the formation of a breezer is identical to the photograph obtained in the

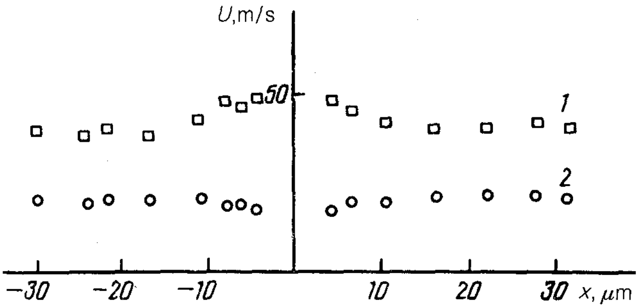

FIG. 2. The velocities of the small cluster (1) and the large cluster (2) in the VBL versus the distance between them before the collision and after it.

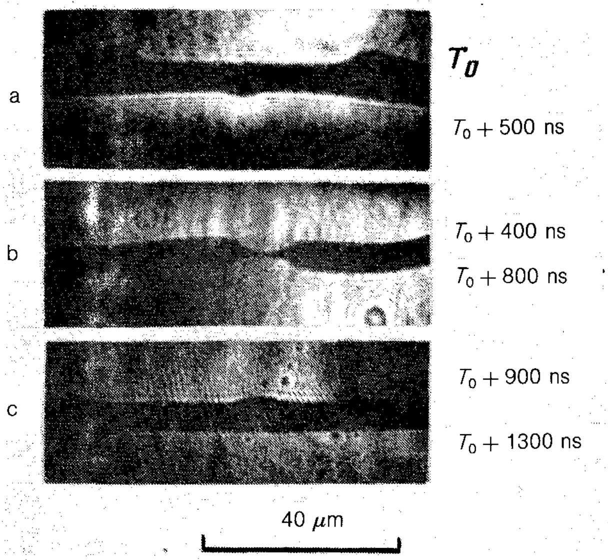

FIG. 3. Double high-speed photographs of the head-on collision of two identical VBL clusters and the appearance of a breezer.

collision of a fluxon and an antifluxon in an extended Josephson junction.[4] Such studies of garnet ferrite films with smaller clusters containing fewer vertical Bloch lines and with a record-low damping would be of interest.

As a result of a head-on collision of two VBL clusters of different amplitudes, only one cluster continues to move. The direction of motion of this cluster is the same as that of the large cluster and its amplitude is equal to the difference in their amplitudes. The results obtained by us show that the laws of conservation of the momentum and topological charge hold in the collision of two VBL clusters moving in the same direction at different velocities. These laws also hold in the case of a head-on collision of two clusters with an equal number of VBL and with opposite topological charges in a system with a large damping.

The Slonczewski equations are usually used to describe the dynamics of VBL

$$2A\,\nabla^2\psi - 2\pi M_S^2 \sin 2\psi - \alpha M_S \gamma^{-1}\dot{\psi} + \gamma^{-1}\Delta^{-1} M_S \dot{q} = 0, \tag{1a}$$

$$(2M_S/\mu)\,\dot{q} - \sigma\nabla^2 + q + kq = 2M_S(H_z - \gamma^{-1}\dot{\psi}), \tag{1b}$$

where M_S is the saturation magnetization, A is the nonuniform exchange constant, Δ, μ, and σ are the thickness, the mobility, and the energy of the DW, kq is the restoring force acting on the DW as it is driven from the equilibrium state, and α is the Landau-Lifshitz dimensionless damping constant. The plane of the DW is parallel to the xz plane and the z axis is parallel to the normal (n) to the plane of the film. The asymptotic behavior of Eqs. (1) is intriguing. If the restoring force is large $|kq| \gg |\sigma\nabla^2 q|$, $|2M_S/\mu\dot{q}|$, we find the following expression from Eq. (1b):

$$q = K^{-1}\,2M_S(H_z) - \gamma^{-1}\dot{\psi}). \tag{2}$$

Substituting (2) in (1a), we find

$$\ddot{\psi} - c^2 \nabla_\perp^2 \psi + \frac{1}{2} \omega_p^2 \sin 2\psi = \nu \dot{\psi} - \gamma \dot{H}_z, \tag{3}$$

where $c = \gamma(A\Delta k M_S^{-2})^{1/2}$, $\omega_p = \gamma(2\pi k\Delta)^{1/2}$, and $\nu = \alpha 2\pi M_S$ are the velocity, the gap in the spectrum, and the damping frequency of the Winter magnons. This equation is the same in form as the equation for the order-parameter phase of the extended Josephson junction. In this asymptotic expression a solitary VBL is described by a single-soliton solution (a kink) and a VBL cluster is described by a multisoliton solution. The isomorphism of the equation detected above leads us to conclude that the collision and annihilation of VBL clusters observed experimentally manifest the theoretically predicted[5] properties of multisoliton (and breezer) solutions of the sine-Gordon equation with a characteristic particle-like behavior.

The asymptotic behavior of the Slonczewski equations, which is fundamentally important, is inadequate for a more detailed description of the behavior of the VBL clusters which were studied experimentally. Under our experimental conditions we must take into account the DW flexure caused by the motion of the VBL (it must also be taken into account in order to vizualize the moving VBL), i.e., the second term in (1b). The relationship between the displacement q of the DW and the angle ψ will then be nonlocal and the equation for ψ will not reduce to a sine-Gordon equation. The particle-like behavior of the VBL clusters does not change in this more general case. To describe approximately such a behavior of VBL clusters, we can use the reduced equations which operate with the average characteristics of the clusters x_i, P_i, and N_i: the "center-of-mass" coordinate, the momentum, and the number of VBL (the topological charge). The equation for the free motion of the first cluster is

$$\frac{dP_i}{dt} + \frac{N_i m_L \dot{x}_L}{\tau_L}\left(1 + \frac{\pi^2}{8b} N_i \frac{\dot{x}_L^2}{S^2}\right) - \frac{2M_S\pi}{\gamma} N_i V_z = 0, \tag{4}$$

where $P_i = N_i m_L \dot{x}_L (1 + \dot{x}_L^2/S^2)$, $S = (8\pi\gamma^2 A)^{1/2}$, $m_L = \pi(4b\gamma^2 Q^{1/2})^{-1}$, $\tau_L = \pi(16\alpha b\gamma M_S)^{-1}$, $b = (k\Delta/2\pi M_S^2)^{1/2}$, $Q = K_u/2\pi M_S^2$, V is the DW velocity, and K_u is a uniaxial anisotropy constant. Equation (4) is a generalization of the equations for a solitary VBL, which were obtained in Ref. 6. The presence of nonlinear viscous friction in the cluster [the second term in (4)] accounts for the fact that a single moving domain wall has two (or more) different clusters ($N_1 \neq N_2$), which move steadily at different velocities.

The time constant τ_L characterizes the rate at which a cluster loses its momentum due to friction. This constant appears in experiments on the annihilation of clusters with opposite topological charges in the case of a head-on collision. Under our experimental conditions $M_S = 10^2$ G, $\alpha = 0.4$, $\Delta = 10^{-6}$ cm, $K_u = 2 \times 10^5$ erg/cm^3, and $b \approx 5 \times 10^{-3}$. According to (4), we then find $\tau_L \approx 0.5 \times 10^{-6}$ s, which is approximately equal to the measured value, $\tau_{\text{exp}} \approx (0.6 \pm 0.2) \times 10^{-6}$ s.

The laws of conservation of the topological charge and momentum hold, in our view, in the case of an "elastic" collision of clusters. In this case the following condition must be satisfied: $t_{\text{col}} \ll \tau_L$, where t_{col} is the collision time. Under our experimental conditions $t_{col} \approx l_{cl}/\Delta U \ll \tau_L$, where l_{cl} is the length of the smaller cluster, and ΔU is the difference in the cluster velocities, i.e., the condition that the collision be elastic is in fact satisfied.

It follows from Eq. (4) that if the topological charges N_1 and N_2 are conserved during the collision, the velocities $\dot{x}_1$ and $\dot{x}_2$ before and after collision are conserved. To describe the particular features of the collision of the clusters, the Slonczewski equations would have to be analyzed numerically and then generalized to the case of a pronounced domain-wall flexure.

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