Do Magnetic Forces in Matter Act Solely on the Boundary Surfaces? Evaluating the Formulations of Minkowski, Helmholtz and Lorentz

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Electromagnetic forces inside matter are fundamental in condensed matter physics but there are multiple theories that describe them and it is yet to be determined which theory is correct. There are three prominent formulations of electromagnetic stress tensors, those of Minkowski, Helmholtz and Lorentz (or Ampère-Lorentz). While most of the past studies have been focusing on electric forces, the present research investigates magnetic forces. This work presents experimental and numerical evidence that Minkowski stress tensor most consistently describes magnetic forces. First, the deformation of a liquid surface under a static magnetic field, which is known as the Moses effect, was measured. Careful comparison between the simulation and measurements showed that the results were inconsistent with the Lorentz formulation. Second, we numerically analyzed the breakup of liquid oxygen in pulsed high magnetic fields and compare the results with existing observations in which the top of the liquid was torn apart and thrown off. In the simulation, the velocity field calculated with the Minkowski stress tensor had a concentrated peak on the boundary, while the counterpart calculated with Helmholtz stress tensor had a more distributed field. Force distributions and forces on the top of the liquid were also calculated, the latter of which could be measured with piezoelectric. This is the first study to test competing formulations of the electromagnetic stress tensor under magnetic fields, providing evidence potentially in favor of the Minkowski stress tensor over those of Helmholtz and Lorentz.

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