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Magneto-electric momentum transfer to atoms and molecules

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We report the first observation of mechanical momentum transferred to atoms and molecules upon application of crossed electric and magnetic fields. We identify this momentum as the microscopic analogue of the classical Abraham force. Several predictions of additional magneto-electrically induced mechanical momentum are addressed. One of them, proposed to result from the interaction with the quantum vacuum, is experimentally refuted, others are found to be currently below experimental detection.

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It has been shown that in crossed electric and magnetic field \mathbf{E} and \mathbf{B} , the optical and electrical properties of matter become anisotropic along the axis $\mathbf{E} \times \mathbf{B}$ [1] [2] [3]. As this anisotropy manifests itself in the dispersion law and thus in the momentum of the photons and the charge carriers respectively, one may wonder whether a similar anisotropy can exist in the mechanical momentum of particles in crossed fields.

Invariance under time, charge and parity reversal straightforwardly shows it to be symmetry allowed for a particle to acquire a mechanical momentum \mathbf{p} upon applying a crossed electric and magnetic field \mathbf{E} and \mathbf{B}

$$\mathbf{p} = a\mathbf{E} \times \mathbf{B} \quad (1)$$

If we assume the particles to be in a gaseous phase in a container, and the collisions between the particles to be elastic, the momentum imparted to each of the particles by the application of the fields will be conserved within the gas as a whole, and ultimately transferred to the wall perpendicular to $\mathbf{E} \times \mathbf{B}$. If we apply a harmonically oscillating electric field $\mathbf{E}(t) = \mathbf{E} \sin \omega t$ and a static magnetic field \mathbf{B} , each particle will contribute a force on this wall given by

$$\mathbf{F}_p = \frac{d\mathbf{p}}{dt} = a\omega\mathbf{E} \times \mathbf{B} \quad (2)$$

Such a force exerted on individual atoms would be the microscopic equivalent of the so-called Abraham force density which was first formulated for macroscopic media, and has been the subject of a long-standing controversy [4–7]. In the so-called Abraham version one finds a macroscopic force density (in SI units) $\mathbf{f}_A = \varepsilon_0 (\varepsilon_r - 1/\mu_r) \mathbf{E} \times \mathbf{B}$ [8], whereas in the Minkowski version $\mathbf{f}_M = \varepsilon_0 (\varepsilon_r - 1) \mathbf{E} \times \mathbf{B}$ (ε_r and μ_r are the relative dielectric permittivity and magnetic permeability respectively). This can be compared to the quantum-mechanical conserved pseudo-momentum of a neutral atom in a homogeneous magnetic field, $\mathbf{K} = \sum_i m_i \dot{\mathbf{r}}_i +$

$\sum_i q_i \mathbf{B} \times \mathbf{r}_i$ [9]. An additional electric field creates a finite polarization $\langle \mathbf{P} \rangle = \langle \sum_i q_i \mathbf{r}_i \rangle = \alpha \mathbf{E}$ (α is the static electric polarizability of the particle with SI unit Cm^2/V) in the ground state so that $0 = \dot{\mathbf{K}} = \sum_i m_i \ddot{\mathbf{r}}_i - \alpha \partial_t \mathbf{E} \times \mathbf{B}$. This would lead to a force density $\mathbf{f} = N\alpha \partial_t \mathbf{E} \times \mathbf{B}$ (where N is the particle density) and which is consistent with the Minkowski version, since $\varepsilon_0(\varepsilon_r - 1) = N\alpha$, and we deduce $a = \alpha$ in Eq.(1). Note that the pseudo-momentum in this model equals neither the *conjugated* momentum $\mathbf{P} = \sum_i m_i \dot{\mathbf{r}}_i + \frac{1}{2} \sum_i q_i \mathbf{B} \times \mathbf{r}_i$, nor the kinetic momentum $\mathbf{P}_{\text{kin}} = \sum_i m_i \dot{\mathbf{r}}_i$. Both were proposed by Barnett [7] to solve the Abraham-Minkowski controversy.

The observation of the Abraham force due to a crossed oscillating electric field and a static magnetic field was reported by James [10] and by Walker et al [11] [12] in solid dielectrics. It should be noted that the Abraham force due to a static electric field and an oscillating magnetic field was reported *not* to be observed, against all expectation [13–15]. For a discussion of these and related experiments, see [4] and [6].

Feigl was the first to consider the interaction of a macroscopic magneto-electric material with the quantum vacuum [16]. The so-called Feigl effect implies that momentum from the vacuum fluctuations can be transferred to matter by the intermediary of the optical magneto-electric anisotropy and that therefore an QED contribution exists to the classical Abraham force, corresponding to a 'Feigl' momentum p_F :

$$p_F = \frac{1}{32N\pi^2} \Delta n_{MEA} \hbar \left(\frac{\omega_c}{c} \right)^4 \quad (3)$$

where $\Delta n_{MEA} \equiv \chi_{MEAE} B$ is the magneto-electric optical anisotropy [1] [2]. In order to avoid the notorious UV catastrophe, Feigl was obliged to introduce an empirical cut-off frequency ω_c for the material's response. Particularly this cut-off procedure was contested by several groups, since it is widely believed that the UV catastrophe should somehow be absorbed in the parameter values

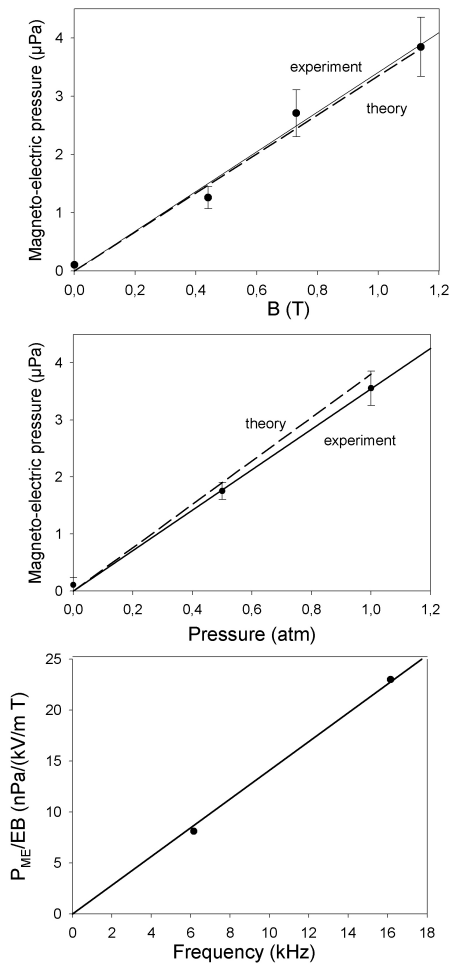


FIG. 2: Magneto-electric acoustic pressure observed in nitrogen gas. Top panel; 6,15 kHz, 1 atm, $E = 370$ kV/m, Middle panel; 6,15 kHz, 1 atm, $B = 1,14$ T. Bottom panel; 1 atm. Solid lines are linear fits to the data, dashed lines theoretical predictions.

calculated by the same authors. For the two molecules in the table with the highest magneto-electric anisotropy, the predicted contributions for the Feigel effect are much larger than the experimental uncertainties on α_{MEMT} , up to 7,5 times for furan. As α_{MEMT} and α_{LIT} agree within the experimental uncertainties, we conclude from these results that the prediction for the Feigel effect as expressed by Eq. 3 is not observed. Note that the Feigel prediction contains one adjustable parameter, the response cutoff wavelength λ_c , and that increasing its value to 0,17 nm decreases the prediction of the Feigel momentum contribution to below our experimental uncertainty. However, strong magneto-electric anisotropy was still reported at 0,16 nm wavelength [30], the shortest wavelength at which its observation was ever attempted. Our experimental results therefore unambiguously contradict Feigel's prediction. Recent theoretical work on simple models suggests that χ_{MEA} decays algebraically

as ω^{-2} at high frequencies, in much the same way as the dynamic electrical polarizability [31]. This makes the UV catastrophe in the macroscopic description as proposed by Feigel, unavoidable and unreparable.

In a QED version of the Feigel effect by Kawka and Van Tiggelen [9], this UV catastrophe was removed by mass regularization. Our current experimental accuracy does not allow to make quantitative statements concerning this prediction, but our setup could be improved to attain the 1% accuracy estimated to be necessary for the observation of this regularization. We hope that this perspective will stimulate realistic calculations of this regularization, beyond the harmonic oscillator approximation and in a relativistic context.

In order to make a contribution to the Abraham-Minkowski debate, our experiment would have detect the difference between 1 and $1/\mu_r$. The gas with the largest μ_r to our knowledge is oxygen, with $\mu_r - 1 = 3,4 \cdot 10^{-3}$ at room temperature and 1 atm. [24]. Attaining such a precision is a considerable experimental challenge, but going to lower temperatures or higher pressures could increase $\mu_r - 1$ to accessible values.

In summary, we have reported the first observation of mechanical momentum transferred to atoms and molecules by applying crossed time-varying electric fields and static magnetic fields. We quantitatively identify this momentum as the microscopic analogue of the classical Abraham force. We exclude the existence of additional magneto-electrically transferred momentum, as proposed by Feigel to result from the optical magneto-electric anisotropy interacting with the quantum vacuum fluctuations. Other predictions for additional contributions to the Abraham force are currently beyond our experimental resolution, but the new method described in this Letter has potential to successfully address these issues.

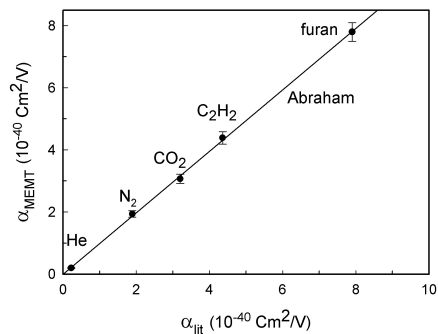


FIG. 3: Polarizability for different atoms and molecules as deduced from magneto-electrically generated pressure, as a function of the literature values. Solid line corresponds to the classical Abraham force prediction.

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gas	α_{MEMT} ($10^{-40} \frac{Cm^2}{V}$)	α_{LIT} ($10^{-40} \frac{Cm^2}{V}$)	χ_{MEA} ($10^{-22} \frac{m}{VT}$)	p_F/p_A
He	$0, 20 \pm 10\%$	0, 22 [24]	0, 017 [26]	1, 5%
N ₂	$1, 9 \pm 5\%$	1, 89 [24]	0, 47 [25]	4, 8%
C ₂ H ₂	$4, 4 \pm 5\%$	4, 4 [24]	3, 7 [26]	16%
furan	$7, 8 \pm 4\%$	7, 9 [29]	12 [28]	29%

TABLE I: Polarizabilities deduced from magneto-electric momentum transfer, the corresponding literature values, the experimental or calculated magneto-electric anisotropy, and the calculated ratio of Feigel and Abraham momenta for the gases studied.

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