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Absence of toroidal moments in 'aromagnetic' anthracene

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Abstract. Colloidal suspensions of anthracene and other aromatic compounds have been shown to respond to a magnetic field as if they possessed a permanent magnetic moment. This phenomenon was named 'aromagnetism' by Spartakov and Tolstoi, and it was subsequently attributed to the interaction of an electric toroidal moment with a time-varying magnetic field. However, there has been no independent confirmation of the original work. Here, we have selected purified anthracene crystallites which respond to a low magnetic field and investigate how this response depends on the gradient and the time derivative of the field. We conclude that the anomaly cannot be attributed to a toroidal interaction but is due to a constant magnetic moment of the particles. Close examinations using magnetometry and scanning electron microscopy reveal metallic clusters of Fe and Ni up to a few hundred nanometres in size embedded in the anomalous crystallites. These inclusions represent 1.8 ppm by weight of the sample. The observed presence of ferromagnetic inclusions in the ppm range is sufficient to explain the anomalous magnetic properties of micron-sized anthracene crystals, including the reported optical properties of the colloidal suspensions.

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1. Introduction

In 1981, Spartakov and Tolstoi [1] reported an unexpected magnetic phenomenon exhibited by microscopic crystals of several aromatic compounds (anthracene, phenantrene, etc), suspended either in water or other liquids. Performing a magneto-optical experiment, they observed that a small percentage of the suspended particles, although very pure, appeared to possess a permanent magnetic moment. The authors claimed it was a fundamentally new kind of permanent magnetism, which they named ‘aromagnetism’, and formulated several hypotheses regarding the origin of the behaviour.

This magneto-optical experiment on colloidal suspensions was essentially based on the fact that an external magnetic field orientates the particles of the suspension. If they are aspherical, this induces in the solution a certain anisotropy leading to optical dichroism. Starting from a suspension of particles at a very low concentration, when these are all aligned along the same direction, the extent to which a polarized light beam is attenuated when it passes through the suspension depends on whether the polarization is directed along the orientation axis or perpendicular to it. Naturally, magnetic orientation requires some magnetic anisotropy of the particles, such as an anisotropic susceptibility or a permanent magnetization. When the polarization is fixed, a periodic change in the orientation axis of the particles causes a periodic modulation of the transmitted light.

The same authors [2] observed that when a magnetic square wave was imposed on a suspension of aromatic microcrystals, light modulation was excited. The excitation began as the field changed sign, and decayed towards the end of each pulse. The observed modulation came from the switching of the orientation axis and it could result from only a constant magnetic moment of the particles. Indeed, the orientation associated with the diamagnetic anisotropy is an effect which is quadratic in H (one power of H induces a moment in the anisotropic susceptibility, and the second power of H rotates this moment along with the particle). The square wave field has $H^2 = \text{constant}$ and it could not cause a reorientation of the particle. The fact that there was a modulation proved that there existed a fraction of the crystals that possessed a magnetic moment [1]–[3].

In the original experiment two circular magnets were cut along their diameter and joined, as shown in figure 1, to generate the magnetic square wave. A cuvette with the dispersion was placed in the gap between the two discs, in the radial direction and close to the periphery of the object. The discs rotated simultaneously at around 1 Hz so that a low-frequency sign-varying field was applied, with the switching occurring in less than 10^{-3} s. A polarized light beam was detected after traversing the cuvette. Since the duration of the observed modulation corresponded to the rotation time of the crystallites, it enabled an estimate of the magnitude

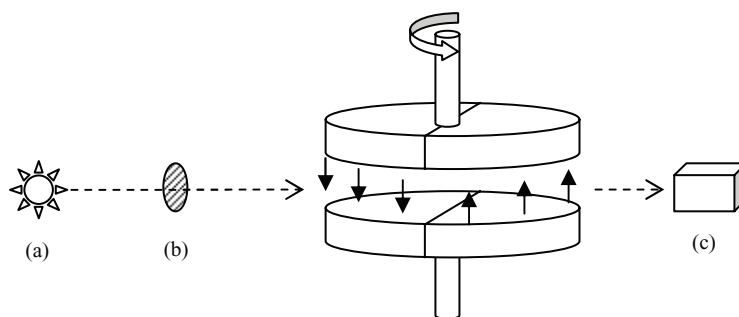


Figure 1. Schematic diagram of the original magneto-optical experiment. (a) Light source. (b) Polarizer. (c) Photodiode. A polarized light beam is sent through a cuvette (not shown) placed between two rotating discs which produce a sign-varying magnetic field. The light is detected by a photodiode.

of the magnetic moment of approximately $10^{-4} \mu_B$ per anthracene molecule, similar for all the substances investigated. Observing the way the particles orientated themselves along the field, it was also possible to deduce that the magnetic moment lay in the plane of the molecules, along the same crystal axis for all the particles.

Spartakov and Tolstoi opined that aromatic molecules possessed an intrinsic magnetic dipole and that an ordered arrangement of these moments arises in microscopic crystals.

They claimed that their ‘weakly ferromagnetic’ samples were free from any ferromagnetic impurities, and that the observed stable magnetism could not be explained by the standard theory of magnetic ordering.

As it is well known that organic molecules do not possess permanent magnetic moments of either orbital or spin origin at room temperature, aromagnetism was later suggested to be non-magnetic in nature [4]. Martsenyuk believed the phenomenon was the first experimental observation of toroidal interactions. An example of a system which has an axial toroidal moment \mathbf{T} is a closed ring of electric or magnetic dipoles (figure 2). The electromagnetic properties of toroids were determined theoretically in 1986 by Dubovik *et al* [5], but toroidal moments were still awaiting direct experimental observation. It was shown that interactions between toroidal structures and electromagnetic fields could display a number of intriguing properties. For instance, the strength of such interactions should depend not on the value of the field, but on its time derivatives. This is unrelated to any induced emf due to Faraday’s law.

Martsenyuk’s hypothesis was that in aromatic compounds the toroidal structure was given by the benzene ring, under the assumption that electric dipoles p were located at the vertexes of the C_6 fragment (figure 2, right).

The energy of the interaction of a toroidal moment \mathbf{T} with a time-varying field $\dot{\mathbf{H}}$ is:

$$U = \lambda \mathbf{T} \cdot \dot{\mathbf{H}}/c = -\lambda \mathbf{T} \cdot \nabla \times \mathbf{E}. \quad (1)$$

Under the assumption that the moment is tied rigidly to the axis of the particle, we can calculate the torque Γ which acts on the particle in the field $\dot{\mathbf{H}}$

$$\Gamma = -\nabla U = -\lambda [\mathbf{T} \times \dot{\mathbf{H}}/c]. \quad (2)$$

It follows that in a viscous liquid, the particle, subjected to a torque, should rotate on its axis.

Martsenyuk considered that the interactions of toroidal moments with each other would lead them to align at room temperature, so that an ordered arrangement exists in a microcrystal.

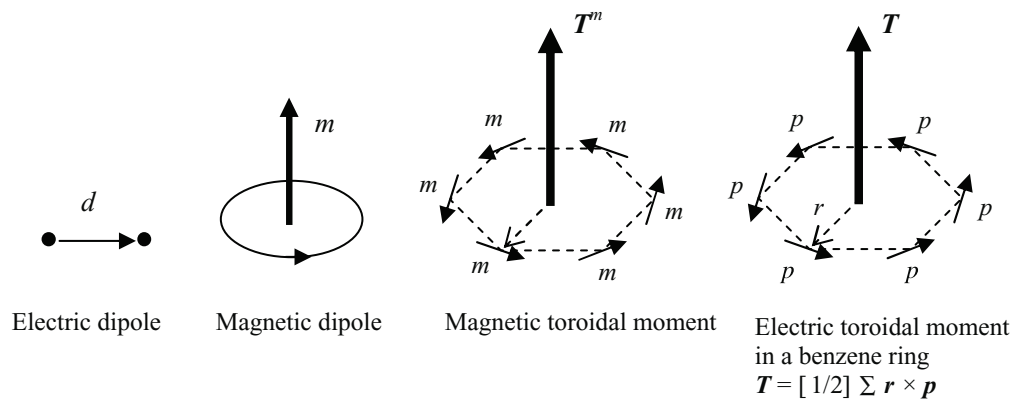


Figure 2. (From the left) An electric dipole originated from two electric charges of opposite sign, a current spiral giving rise to a magnetic dipole, and two kinds of toroids: a closed chain of electric or magnetic dipoles, the curl of the dipoles gives the toroidal moment, perpendicular to the plane of the ring. In the case of a benzene ring, assuming that electric dipoles are placed on the ring of carbon atoms, it is expected that a toroidal moment arises.

The reorientation of the particles in the sign-varying field, observed by Spartakov and Tolstoi, was therefore determined not by the magnetic field \mathbf{H} itself but by its time derivative $\dot{\mathbf{H}}$, which, interacting with the electric toroidal moment of the particles, rotated them at each field inversion. Qualitatively, this interpretation was able to explain the observed ‘aromagnetism’.

Despite the importance of toroidal moments in the context of classical electrodynamics, aromagnetism was not investigated further. Nevertheless, the work of Spartakov and Tolstoi has been considered the first experimental observation of toroidal moment interactions [6, 7], even though there has been no subsequent experimental confirmation.

A first attempt to confirm aromagnetism was recently undertaken by Fedotov *et al* [8], who could not reproduce the unusual magnetic response. They showed that toroidal interactions are expected to be much too weak to be detected in the original experiment of Spartakov and Tolstoi.

Here, we challenge the interpretation given by Martsenyuk on toroidal interaction in aromatic substances. We succeeded in reproducing, with a different approach, the results obtained by Spartakov and Tolstoi. ‘Aromagnetic’ particles were selected and investigated either using different frequencies of modulation of the magnetic field or an intense field gradient. We show that the observations actually contradict the existence of toroidal moments in the anomalous particles and that, depending on the fabrication process, ferromagnetic nanoparticles which are embedded in a small fraction of crystals of material that on average is very pure, are responsible for the observed magnetic behaviour.

2. Experiment

Commercial anthracene was purified by repeated sublimation, and plasma mass spectroscopy (ICP) showed that iron, cobalt and nickel were below the sensitivity limit of 10 ppm. The microcrystals appeared as thin foils (1–2 μm thick), with an average diameter of 10 μm (figure 3(a)). By observing the morphology, it has been possible to deduce the crystal orientation as described in [9] (figure 3(b)). Anthracene is a hydrocarbon made up of three benzene rings

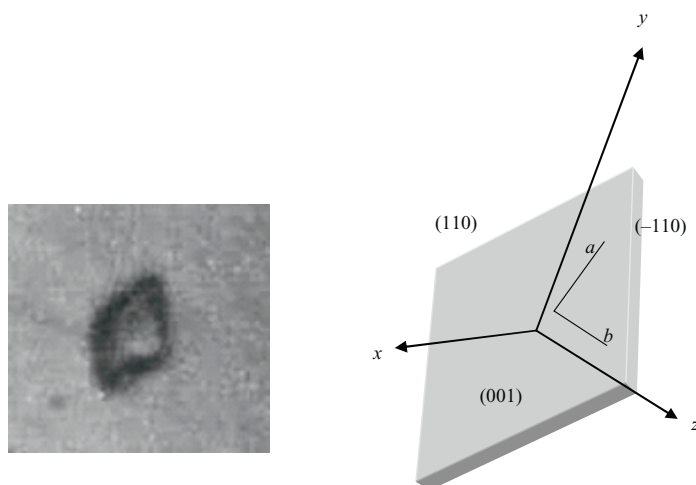


Figure 3. Left: Picture of an anthracene microcrystal. Right: Reconstruction of the crystal showing the lattice planes, the unit cell axis and the orientation of the susceptibility axis.

combined together in a single planar structure. The molecules are magnetically anisotropic, with a large overall diamagnetism. A SQUID measurement on a monocrystalline powder gave us an average value of $\chi_{\text{mol}} = -1.62 \times 10^{-9} \text{ m}^3 \text{ mol}^{-1}$ (or $\chi_{\text{p}} = -9 \times 10^{-9} \text{ m}^3 \text{ kg}^{-1}$ and $\chi = 1.12 \times 10^{-5}$).

Our experimental method differed from the original magneto-optical experiment. In order to avoid any dependence on mathematical modelling to understand the results [1], we observed the mechanical effects produced by a variable magnetic field on the small crystals directly under a microscope.

A magnetic field of about a few mT was applied to a vessel containing an aqueous dispersion of anthracene crystallites. The field direction was transverse to the direction of observation, and a standard optical microscope with a magnification of 200–400 \times was employed to observe the orientation of the crystallites. The vessel was filled with 0.2 ml of water and a few tens of crystallites from the anthracene powder were added, which settled on the bottom. The reorientation of the particles upon switching the field direction was then studied (figure 4).

This simple method required some modifications to reduce the friction between the crystals, the bottom of the vessel and the surrounding material. Indeed, the torque which the magnetic field exerts on particles which have any type of magnetic anisotropy is extremely weak ($\sim 10^{-17} \text{ N m}$ for a typical particle), and friction with the external environment can impede their motion.

A small amount of surfactant, sodium dodecyl sulfate, (less than 0.1% by weight) was added to the water, in order to obtain complete wetting of the crystallites. The bottom of the container was polished with a coarse grit. In this way the anthracene, which is insoluble in water and has a density of 1.25 g cm^{-3} , lay on the bottom of the vessel without sticking to it; the crystallites maintained good lateral mobility and, thanks to the reduced friction, were free to move under the effect of any externally applied forces.

First, we observed the well-known diamagnetic orientation of the crystals, using two permanent magnets to produce a magnetic field of about 300 mT. The relevant point is that

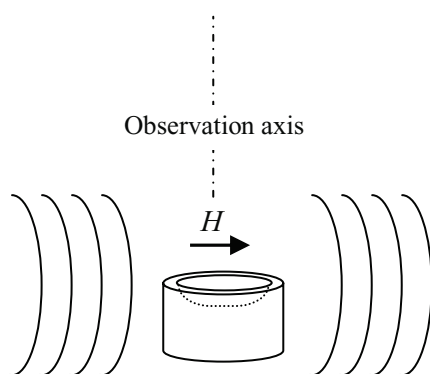


Figure 4. Schematic representation of the setup we used; the anthracene grains were settled on the bottom of the vessel and the coils applied a uniform magnetic field.

after switching the field direction (without rotating the field, which was achieved by changing the separation of the magnets), the crystallites remained in the same equilibrium position. The magnets were mounted on a rail, facing each other, with the vessel placed in the gap between them. In this way, the magnets could be separated until the field across the vessel was negligible. They were then removed from the rail, reversed and reinstated to produce a field in the opposite direction.

The diamagnetic susceptibility of anthracene is anisotropic. The response of the particles to the field is determined by the minimization of the free energy, which, in turn, depends upon the direction of the induced magnetic moment relative to the field. There are three principal axes with different susceptibilities, and the equilibrium position occurs when the particle has rotated so that the minor diamagnetic susceptibility axis lies along the field axis, regardless of the field direction. The induced torque is quadratic in field and does not depend on the sign of H . Our investigation confirmed this behaviour in a relatively intense applied field.

However, we observed anomalous behaviour when the applied magnetic field was just a few mT. Here, we used a function generator, a current supply and two small Helmholtz coils (1 cm in diameter) to apply a low-frequency (0.1–1 Hz) square wave of intensity about 5 mT. We placed the vessel in the 5 mm gap, and the applied field, transverse to the observation axis, was uniform in the volume occupied by the particles (figure 4).

A few of the crystals were clearly seen to rotate through nearly 180° with each reversal of the applied field. In such a weak field, the diamagnetic polarization is quite negligible and the remaining crystals did not manifest any orientation. The sign-varying field itself does not induce any diamagnetic torque, as explained above. These observations ruled out the possibility of explaining this behaviour of the anomalous crystallites in terms of diamagnetism; they suggested that these particular crystals might possess a permanent magnetic moment.

The fraction of anomalous crystals was of the order of 1%. This fraction was not modified by exposure to a 5 T field. The rotation took usually less than 1 s and, from this, we can roughly estimate the magnetic moment. Balancing the torque due to the friction in a viscous liquid with the torque due to the external magnetic field

$$8\pi\omega\eta r^3 = \mu_0 m H, \quad (3)$$

where ω is the observed angular velocity, η the water viscosity and r the radius of the particle, we deduce that the value of the magnetic moment m is about 6×10^{-15} A m² per crystallite. This

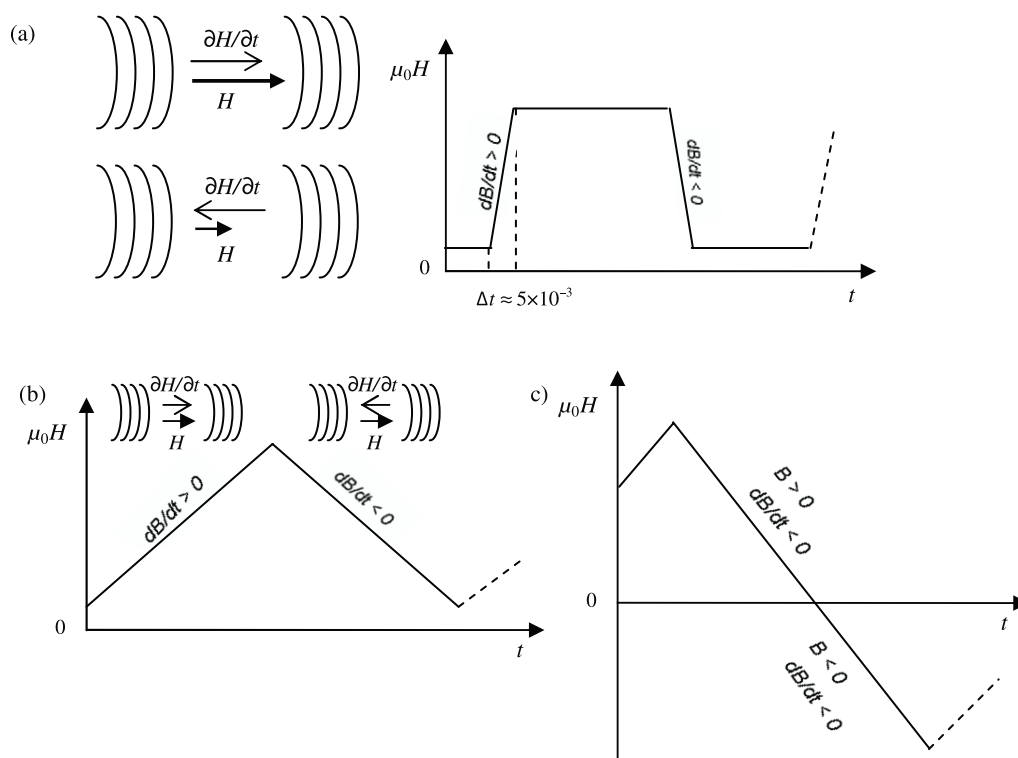


Figure 5. (a) The vector H differs from dH/dt ; two coils can be used to switch the relative direction from parallel to antiparallel so that the induced effects can be distinguished. In the graph, the magnetic field profile is shown; to keep H pointing along the same direction its value was kept strictly positive, the time derivative switches upon an ascending and descending ramp. (b) The duration of the ramp is decreased to around 5 s; a train of positive triangles was applied, and the particles did not react. (c) The magnetic field was allowed to switch; whenever it crosses the zero, the particular microcrystals start to rotate through 180° .

is equivalent to $6 \times 10^{-5} \mu_B$ per molecule, which is close to the value reported in the original work ($10^{-4} \mu_B$). It is useful to note that the induced diamagnetic moment in the same field is of the order of $10^{-7} \mu_B$ per molecule, two orders of magnitude smaller.

As shown in figure 3(a), the crystals have a well-defined shape; thus, it became possible for us to correlate the orientation of the particles in the magnetic field with the crystal structure. It turned out that the anomalous particles tended to align as if the magnetic moment lay close to the plane of the benzene ring. These experimental observations are analogous to those that led Spartakov and Tolstoi to opine that a new form of magnetism existed in aromatic substances.

In this first experiment, it was hard to discern whether the observed reorientation was an effect due to toroidal interactions or to magnetic torques. The particles rotated when the field reversed, as expected in either case.

To find out whether the observed behaviour was really due to the existence of a toroidal moment [4], we investigated those particles identified as anomalous by imposing a magnetic field with a selectable time derivative. According to equation (2), the torque should be

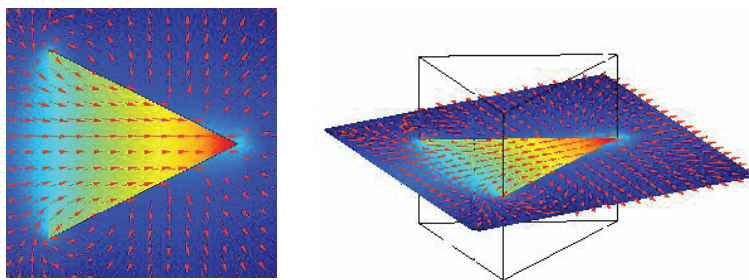


Figure 6. An NdFeBo magnet has been shaped to give a high field gradient (36 T m^{-1}), approximately uniform across the sample. The vessel was placed immediately beside one face of the magnet.

proportional to the rate of change of the field, but does not depend on the magnitude of a steady field.

We applied a periodic field with the particular feature that the vector \mathbf{H} and its time derivative $\dot{\mathbf{H}}$ are arranged to be either parallel or antiparallel, so that the reorientation due to either a permanent moment or a toroidal moment could be distinguished. In figure 5(a), the magnetic field profile kept \mathbf{H} pointing along the same direction; as shown, its value was kept positive, but oscillated between a minimum and a maximum value (0.1–3.0 mT). It cannot exert any torque on an oriented permanent magnetic moment. However, the time derivative switches direction upon an ascending and descending ramp; thus, it would be expected to rotate a crystallite with toroidal moment.

Initially (figure 5(a)), we ramped the field in about 5×10^{-3} s to reproduce the experimental conditions of the original experiment. As we observed no reactions, either of the anomalous particles or the normal microcrystals, we extended the duration of the ramp up to about 5 s by applying a positive triangular wave (figure 5(b)). However the crystallites still showed no response. We note that $\partial H / \partial t$ depends only on the duration of the ramp, as the field range was approximately the same. Our aim was to investigate over a large range of field derivatives, to see if there was any response of the ‘aromagnetic’ crystals at all, but there was none.

Next, we allowed the applied magnetic field to switch its direction (figure 5(c)). The anomalous crystallites began to rotate, while all the other crystals remained unaffected. The key point is that as soon as the magnetic field crossed zero and reversed its sign, the anomalous crystallites immediately began to flip through 180° , regardless of the switching duration.

We conclude that the field derivative $\dot{\mathbf{H}}$ is irrelevant in determining the reorientation in our experiment. On the contrary, the torque Γ which acted on the particles was evidently dependent on the field \mathbf{H} itself, as expected for a constant magnetic moment m .

To obtain conclusive proof, we carried out a further investigation with an intense field gradient. A magnetic field gradient establishes a force which tends to repel or attract material according to whether it is diamagnetic or ferro/paramagnetic. As anthracene is diamagnetic, the microcrystals were expected to be repelled in an imposed gradient.

We shaped an Nd–Fe–Bo permanent magnet as shown in figure 6. The dimensions were $2 \times 2 \times 2$ cm and, when placed near the vessel, the magnet produced an approximately uniform gradient of $\sim 36 \text{ T m}^{-1}$. The majority of the crystals were slightly repelled; the induced magnetic moment was small due to the weak field intensity (from 300 to 30 mT across the vessel), but

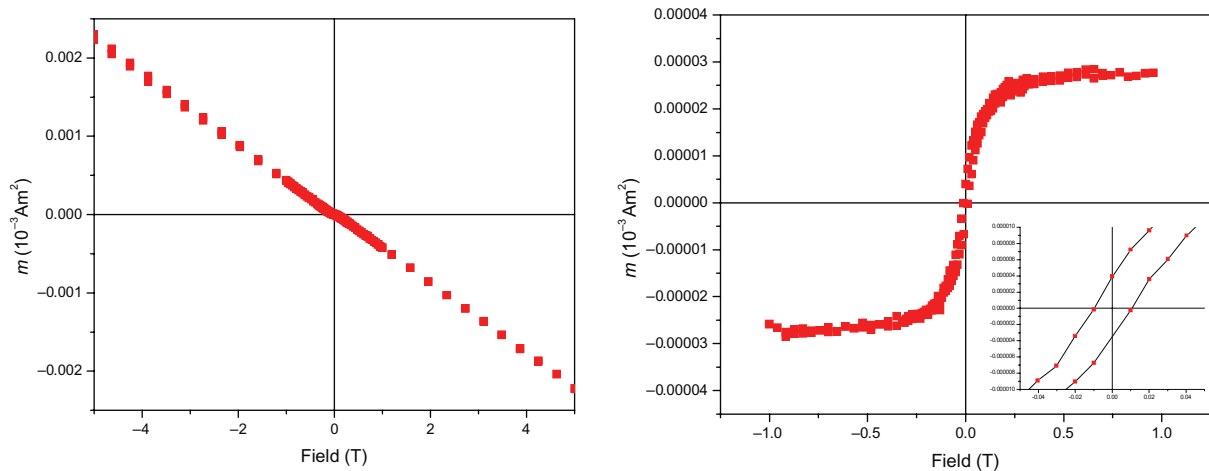


Figure 7. Left: Susceptibility measure on sublimated anthracene; the large diamagnetic susceptibility is $\chi_p = -9 \times 10^{-9} \text{ m}^3 \text{ kg}^{-1}$. Right: Ferromagnetic signal attributable to Fe/Ni/Co contamination, obtained after subtracting the diamagnetic component; in the window, the coercive field is highlighted.

the induced force led us to observe and to recognize the diamagnetic response. On the other hand, the anomalous crystallites (those which responded in the previous experiments) were clearly seen to move down the gradient, in the opposite direction to the diamagnetic crystals. The applied gradient dragged these crystallites, which moved closer to the shaped magnet.

This is clear evidence that ‘aromagnetic’ particles actually possess a constant magnetic moment.

The moment comes from magnetic contamination included in a small fraction of, on average, very pure microcrystals. The contamination should appear in the form of a ferromagnetic or ferrimagnetic inclusion, as diluted paramagnetic ions do not result in a net magnetic moment (there is no exchange interaction, as the average nearest-neighbour distance is too great). Further, the ferromagnetic clusters must have a size of at least some tens of nm; below this threshold, the particles are super-paramagnetic. We had estimated a magnetic moment of about $6 \times 10^{-5} \mu_B$ per molecule; this is roughly equivalent to one atom of iron for every 10 000 anthracene molecules, or 100 ppm of iron, in an ‘aromagnetic’ crystallite. As the fraction of anomalous crystals was 1%, we expect an average contamination of about 1 ppm.

A susceptibility measurement of the purified substance performed on 63.2 mg with a superconducting SQUID magnetometer (MPMS XL, Quantum Design) has shown that the sample exhibits a small hysteresis loop (figure 7). After subtracting the diamagnetic component, it is possible to determine the saturation magnetization S and extrapolate the amount of iron in ppm embedded in the crystallites, assuming it is in the metallic form

$$S = \frac{\text{Saturated moment}}{\text{Mass}} = \frac{2.6 \times 10^{-8} \text{ Am}^2}{63.2 \times 10^{-6} \text{ kg}} = 4.1 \times 10^{-4} \text{ Am}^2 \text{ kg}^{-1}, \quad (4)$$

$$\text{Fe content} = \frac{S}{S_{\text{Fe}}} = \frac{4.1 \times 10^{-4} \text{ Am}^2 \text{ kg}^{-1}}{220 \text{ Am}^2 \text{ kg}^{-1}} = 1.8 \text{ ppm}. \quad (5)$$

The amount will be approximately double if iron is present in its oxide form, as Fe_3O_4 . This result is in agreement with the estimate that comes from the dynamics of the anomalous crystallites. The presence of a coercive field around 10 mT, highlighted in the window in the right-hand side figure, indicates that the impurities do not simply give a paramagnetic contribution but that they possess a ferromagnetic moment. In other words, they must appear as clusters rather than as diluted ions.

To further explore the validity of this hypothesis, we fabricated anthracene microcrystals by different techniques, the idea being that different fabrication processes may facilitate the inclusion of different forms of magnetic contamination, diluted or aggregated. We wanted to verify whether the observed anomalous behaviour depended on the growth method.

We grew the crystals first by slow evaporation: zone refined and analytical anthracenes were dissolved in acetone or CCl_4 [10]; the saturated solution was then covered and left to slowly evaporate. After 1 day, a few particles crystallized on a suspended plate, and they were harvested and used for seed crystallization in further solutions. The crystals ranged from tens of μm to a few mm. We ground them to obtain the same average size as in the previous experiment (10 μm).

Thin films were grown with the method described by Zhou *et al* [11]; a crystalline film of anthracene grew at the meniscus of an organic solution and a glass slide. We obtained single-domain microcrystals from the film itself.

On repeating our experiments, we barely detected any anomalous behaviour of these materials. This fact led us to the conclusion that the anomaly was strictly dependent on the fabrication process. Other methods, such as PVD and zone refining, were tested, leading to the same conclusion that different techniques gave different probabilities of finding the ‘aromagnetism’. To interpret this dependence, we recall that the crystals typically obtained by the slow evaporation technique are well known to include a significant amount of the solvent in which they dissolved. However, even though this method may have given impure crystallites, it appears to diminish the number of ferromagnetic micro-clusters embedded in the crystals, thus reducing the probability of detecting the magnetic anomaly. Fedotov *et al* [8] recently reported their failure to reproduce the ‘aromagnetic’ response; it is our opinion that they eliminated any potential anomalies by means of a correct choice of the fabrication method (i.e. solvent displacement method) [12].

The authors of the original work (1981) obtained their crystals, a powder of micro-grains, by grinding purified anthracene. It seems most likely that a small fraction of the particles contained ferromagnetic inclusions. As a chemical analysis gives an average value, the substances appeared very pure.

No noticeable difference between the normal and anomalous crystallites can be observed with optical imaging, so we used an SEM equipped with an x-ray microprobe. The instrument was employed in backscattering mode in order to observe the presence of higher Z elements in the organic matrix. Before examining the sample, we ran the experiment to identify the anomalous crystallites, as described before. After that, we let the water in the vessel evaporate; in this way the anomalous anthracene crystals stuck to the bottom of the cavity could be investigated with the SEM. In figure 8(a), an anomalous crystallite is shown. Three dark spots are clearly visible; figure 8(b) shows the x-ray emission spectra taken from a region centred on these dark spots, having a radius of approximately 2 μm . The main peak is due to carbon. Along with carbon, traces of other elements are observed, and their presence is due to the surfactant material. The most interesting feature, however, is the presence of Fe and Ni in the dark spots.

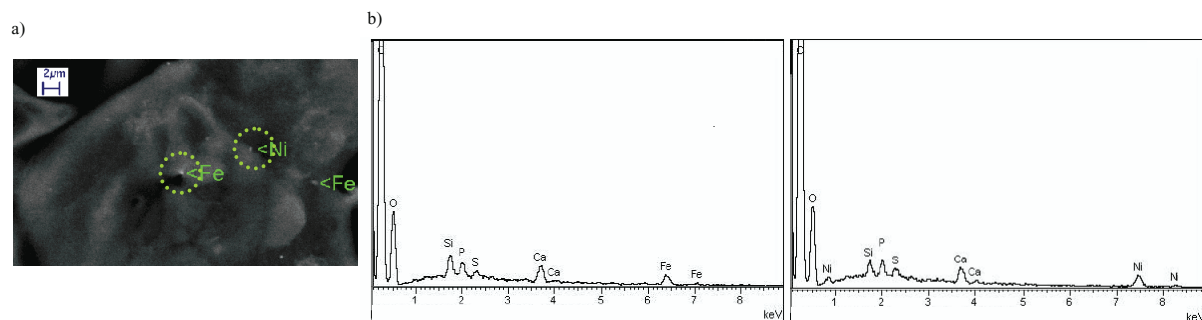


Figure 8. (a) SEM image of the surface of an anomalous crystallite, taken in backscattering mode. The dark spots indicate the presence of higher Z inclusions. (b) X-ray emission from the circular area centred on the spots. Ni and Fe peaks are distinguishable.

The spectra taken from other regions of the grain do not reveal their presence. In summary, the dark spots are bulk inclusions of ferromagnetic elements. The same analysis performed on a crystal which did not rotate on switching the field did not reveal the presence of any iron or nickel inclusions. This is strong evidence that the ‘aromagnetic’ effect is related to inclusions of ferromagnetic metals.

3. Discussion

We found no features imputable to the presence of a toroidal moment in anthracene. The value of the toroidal moment T per anthracene molecule was given in [4], $T = eaR$, where a is the size of a carbon atom and R the radius of a benzene ring. Following Fedotov *et al* [8] we can compare the magnitude of T with the diamagnetic torque due to anisotropic susceptibility. The maximum torque exerted by the time-varying field on the toroid of a crystallite is given by:

$$K = eaR(dB/dt) \approx eaR(B_0\Delta t) \approx 4.8 \times 10^{-39} \text{ N m}; \quad (6)$$

in our experimental conditions, $B_0 = 5 \text{ mT}$ and $\Delta t = 5 \text{ ms}$. The maximum torque on the induced diamagnetic moment (with $\Delta\chi$ being the molar diamagnetic anisotropy $\approx \chi_{\text{mol}}$) is:

$$K \approx B^2 \Delta\chi / 2N_a \mu_0 \approx 1.1 \times 10^{-31} \text{ N m}. \quad (7)$$

Thus, the expected strength of toroidal interaction is eight orders of magnitude weaker than necessary to compete with diamagnetism, which in turn is negligible in the case at hand (no diamagnetic reorientation was observable in a weak field). In fact, even the expression given by Martsenyuk, $T = eaR$, is a questionable estimate, as there is no reliable evidence of substantial static electric dipoles located at the vertexes of the benzene ring.

Tolstoi and Spartakov emphasized that the apparent magnetic moment lay in the plane of the molecule, along the minor susceptibility direction, and we confirmed this interesting feature. They considered this as a strong indication that the magnetic response was not due to contamination but was an intrinsic property of carbon-based aromatic molecules.

Finally, we consider how this anisotropy might arise in the present case. One idea is that the dipole field produced by the inclusion interacts with the anisotropic susceptibility of anthracene, thus leading to anisotropy of the energy for different orientations of the magnetization.

Considering only the parallel component of the dipole field, the anisotropic energy is obtained by integrating over the volume surrounding the inclusion the scalar product of the dipole field and the induced diamagnetic moment:

$$\Delta U = \int \Delta\chi \frac{m}{4\pi r^3} \frac{\mu_0 m}{4\pi r^3} 4\pi r^2 dr = \frac{\Delta\chi \mu_0 m^2}{4\pi} \int \frac{1}{r^4} dr = \frac{\Delta\chi \mu_0 m^2}{4\pi} \left[\frac{1}{3r^3} \right]_{R_1}^{R_2} \approx 10^{-20} \text{ J}, \quad (8)$$

where $m \approx 10^{-14} \text{ A m}^2$ is the magnetic moment of the inclusion, R_i is the radius of the inclusion and of the crystallite, up to 500 nm and $10 \mu\text{m}$, $\Delta\chi \approx 1.125 \times 10^{-5}$ is the volume anisotropic diamagnetic susceptibility and μ_0 is the permeability.

However, the calculated anisotropic energy associated with the magnetization in the anisotropic medium is just less than 1 J m^{-3} . This value is actually very small compared to the shape anisotropy and thus suggests that the most likely reason for the orientation is the shape of the inclusions embedded during the growth process. This shape anisotropy might be related to the distribution of magnetic nanoparticles within the anthracene crystallites.

4. Conclusion

Our investigations have established that the ‘aromagnetism’ of anthracene has nothing to do with toroidal interactions. Our observations contradict the predictions of Martsenyuk and strongly support the hypothesis that ‘aromagnetism’ is an artefact due to ferromagnetic contamination. If toroidal moments exist in aromatic substances, they are much too small to be detected by the method used by Spartakov and Tolstoi. Our estimation shows that, most likely, they were due to a weak contamination of their samples. No anomalies are observed in carefully prepared crystals. The anomalies are attributed to inclusions of ferromagnetic material which are of the order of 100 nm in size in a small fraction of the crystallites in a contaminated batch, where the overall impurity level is of the order of 1 ppm.

Acknowledgments

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