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ON THE MAGNETIC ASYMMETRY OF MUSCLE FIBERS*

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Communicated by Albert Szent-Györgyi

On November 4, 1845, Faraday discovered diamagnetism. On December 18 he read a paper[1] before the Royal Society on this "New Magnetic Action." At that time he had already shown that his magnet repelled a number of biological specimens, such as wood, ivory, dried mutton, fresh and dried beef, fresh and dried blood, leather, and apple. Since Faraday's original research, there have been surprisingly few studies on the magnetic properties of biological objects. On the subject of magnetic anisotropy we have found only four papers; three are by Nilakantan[2] on mother of pearl, molluscan shells, and teakwood, respectively; the fourth is by Loeb and Welo[3] on cellulosic materials.

Our interest in this subject grew out of an observation made in Dr. Szent-Györgyi's laboratory in the summer of 1956. A piece of muscle fiber, several times longer than it was wide, was suspended in an inhomogeneous magnetic field; it tended to set its long axis at right angles to the direction of the field, as was to be expected of a diamagnetic object. A shorter piece of muscle fiber, whose length was one and one-half times its width, was found to set its long axis parallel to the field. This curious behavior could be understood if the muscle fiber were anisotropic in its magnetic properties. It is our purpose in this paper to show that this is so.

An object with no permanent magnetic moment, when suspended in a horizontal magnetic field, is acted on by four different torques around the vertical axis.

1. Assume the sample to be anisotropic, with K_1 as the volume susceptibility in one horizontal direction and K_2 in the other; K_1 is taken in the direction in which the algebraic value of the susceptibility is greatest. Then, if V is the volume of the sample, H the strength of the field, and θ the angle between K_1 and the direction of the field, there is a torque given by

$$V(K_1 - K_2)H^2 \cos \theta \sin \theta$$

tending to turn the object so as to make K_1 parallel to the field.

2. Unless the object is a sphere, it will have different demagnetizing factors in the different directions. This effect gives a torque tending to set the long axis of the sample parallel to the field. However, since the magnitude of this torque

depends upon the square of the susceptibility, it will be negligible. In fact, this torque has never been detected for any diamagnetic object.

3. The poles of the sample will form magnetic images in the iron of the pole pieces, but again the torque depends upon the square of the susceptibility and thus can be neglected except for ferromagnetic samples.

4. Unless the magnetic field is homogeneous, the forces that tend to move diamagnetic material from regions of strong field to regions of weak field can produce a torque on any nonspherical sample. This is the torque observed by Faraday and the one commonly seen when a diamagnetic sample is suspended between the poles of a magnet.

From the above we see that the only sensible torque acting on a diamagnetic sample suspended in a uniform magnetic field is the one due to magnetic anisotropy. This is essentially the method developed and used by Krishnon.[4]

Mr. Harlow, of the Marine Biological Laboratory, constructed for us a large magnet that has a very uniform field. The pole pieces are soft steel 3 × 3 inches; when they are separated by 5/8 inch, the field is about 3,000 gauss. The magnetomotive force is furnished by two large Alnico magnets.

In order to show that the magnetic field was sufficiently homogeneous, we suspended in it two 1/8-inch diameter glass balls, cemented together so as to form a figure 8-shaped object when looked at from above. The suspension was a fine nylon filament some 63 cm. long. The upper end of the suspension was fastened to a torsion head that could be rotated about the vertical axis. The angle of rotation we shall call ψ. Curve A gives the angular position of the two balls as the torsion head was rotated; as can be seen, the curve is fairly straight. It must be remembered that, since glass is more diamagnetic than muscle and the two balls are larger than the muscle samples that we used, the torque due to any inhomogeneity of the magnetic field is several times larger in the case of the glass balls than for the muscle sample (see Fig. 1).

A sample of fresh rabbit psoas muscle, 6 × 3 × 3 mm., was used to give curve B. The curve is discontinuous because of the anisotropy of the muscle. As the torsion head is rotated, the sample rotates in the same sense but through a smaller angle until θ reaches a critical value somewhere between 45° and 90°, whereupon the sample suddenly spins to a new position of equilibrium. If we let A be the torsion constant of the suspension, the total torque (T) on the sample can be written as

$$T = A(\psi - \theta) - V(K_1 - K_2)H^2 \cos \theta \sin \theta = 0,$$

where the first term is due to the suspending filament and the second term is due to the magnetic anisotropy. Both ψ, the angle of the torsion head, and θ, the angle of the sample, are measured from the stable equilibrium position in which K_1 is parallel to the field. Experimentally, K_1 is found to be in the direction of the muscle fiber. For the sample to be stable at any angle θ we must have $dT/d\theta$ negative:

$$\frac{dT}{d\theta} = -A - V(K_1 - K_2)H^2 (\cos^2 \theta - \sin^2 \theta)$$

Thus, whenever

$$A < V(K_1 - K_2)H^2,$$

we shall have a critical angle at which the sample becomes unstable and spins. This spinning is the most dramatic evidence of magnetic anisotropy. If the sample is large and the torsion constant sufficiently small, the spin may amount to four or five complete revolutions of the sample.

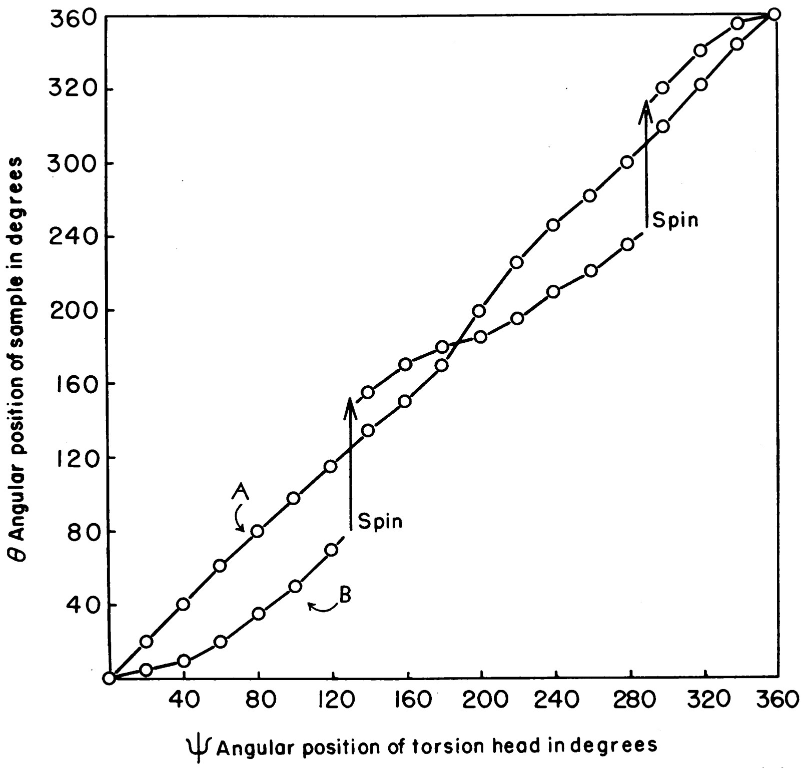

FIG. 1.—Angular position of sample as a function of the angular position of the torsion head. Curve A is for the two glass balls. Curve B is for a sample of psoas muscle.

The apparatus available does not allow us to make precise quantitative measurements; however, a rough estimate of the torsion constant and critical angle shows that $(K_1 - K_2)$ is approximately 2×10^{-8} c.g.s. units/cc. We do not know the magnetic susceptibility of muscle fiber, but the observation that, when suspended in air, muscle fiber is repelled by an inhomogeneous magnetic field shows that it is diamagnetic, just as Faraday reported. The observation that, when suspended in water, the fiber is attracted by a magnet shows that it is less diamagnetic than water. The magnetic susceptibility of water is -0.7×10^{-6}. The asymmetry found for muscle is as large as that observed for many crystals.

Although determination of magnetic properties of muscle before and after contraction would certainly be of great interest, our apparatus again does not permit precise quantitative measurements. Experiments show that in fresh muscle, contracted by freezing and thawing, the asymmetry has the same sign in both states. However, in the case of freeze-dried muscle, the asymmetry changes sign upon contraction brought about by dipping the preparation in water.

A sample of muscle fiber, suspended in air as we have described, can be observed for many hours. If the sample is allowed to dry slowly, it becomes less and less diamagnetic as the drying proceeds. Eventually, many of our samples became paramagnetic. During the drying, the magnetic anisotropy remains; this means that at a certain stage in the process the muscle fiber is paramagnetic in the direction of the fiber axis and diamagnetic normal to that axis.

Glycerated[5] muscle preparations, as well as air-dried and freeze-dried muscle fibers, showed strong magnetic anisotropy.

Both nerve and tendon taken from the rabbit showed asymmetric magnetic properties. In a sample of fresh beef liver no magnetic anisotropy could be detected with certainty.

SUMMARY

1. The magnetic susceptibility of muscle fiber is asymmetric.

2. The muscle fiber is more diamagnetic normal to its long axis than parallel to it.

3. We feel that magnetic measurements can be made to give useful information about the structure of biological tissues.

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[1] M. Faraday, *Experimental Researches in Electricity* (London, 1855), **3**, 27.

[2] P. Nilakantan, *Proc. Indian Acad. Sci.*, A, **2**, 621, 1935; **4**, 542, 1936; **7**, 38, 1938.

[3] L. Loeb and L. A. Welo, *J. Textile Research*, **23**, 251, 1953.

[4] K. S. Krishnon, B. C. Guha, and S. Banerjee, *Phil. Trans. Roy. Soc. London*, A, **231**, 235, 1933.

[5] A. Szent-Györgyi, *Biol. Bull.*, **96**, No. 2, 144, 1949.

Since writing the above we have found a fine paper by E. Cotton-Feytis and Emmanuel Fauré-Frémiet, *Compt. rend.* **214**, 996–998, 1942 in which they made magnetic measurements on silk, hair, horn and tendon.

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*MOLECULAR GROWTH REQUIREMENTS OF SINGLE MAMMALIAN CELLS: THE ACTION OF FETUIN IN PROMOTING CELL ATTACHMENT TO GLASS**

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In an earlier paper[1] it was shown that the growth requirements for small molecules exhibited by single S3 HeLa cells varied with the degree of dialysis of the