vary in position, so it cannot be easily obtained from the above intuitive picture. It is surprising also because of its dependence on the electric field: as the current loop representing the dipole may have no charge, it might be expected not to couple to an electric field. Also, this force is doubly nonlinear; it does not reverse in direction if either the electromagnetic field strength or the magnetic moment is reversed. I know no other force that is nonlinear in the field strength (as opposed to the potential). But after four separate derivations[1,2], in quantum and classical physics, I was convinced that it does exist.

A key to understanding the new force is that for this dipole the kinetic momentum (classically $m\mathbf{v}$) differs from the canonical momentum $\mathbf{p}$. The canonical momentum is associated with the wave nature of the particle and is conserved if there is translational symmetry in space, as when the dipole interacts with a uniform electromagnetic field. In fact, $m\mathbf{v} = \mathbf{p} - \mu \times \mathbf{E}$. The rate of change of $m\mathbf{v}$ is the total force, by Newton's second law. The time derivative of $\mathbf{p}$ is $\mathbf{F}$, and the time derivative of the second term, called the *hidden* momentum, which is due to relativistic effects, is $\mathbf{f}$ (assuming that $\mathbf{E}$ is time independent).

For the neutron, it turns out that when $B = 1$ tesla and $E = 10^7$ V m^{-1}, which can be realistically achieved in the laboratory, the acceleration caused by the new force is of the order of 12 cm s^{-2}. On the face of it, this acceleration is large enough to be seen easily. But the neutron's spin (and therefore its magnetic moment, which is antiparallel to the spin) precesses rapidly about $\mathbf{B}'$ due to the torque it experiences. With a precession frequency here of 1.8×10^8 radians s^{-1}, $\mathbf{f}$ averages to zero very quickly. That is why it has not already been observed in the large number of experiments in which a dipole interacts with an electromagnetic field. I suggested that to make the effect of the force accumulate, instead of cancel out, $\mathbf{B}$ could be kept constant while $\mathbf{E}$ alternates in space[1,2].

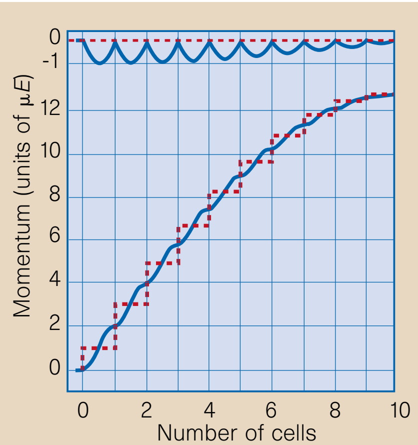

Figure 2 **The *x* and *y* components of the mean kinetic momentum of the neutrons in Fig. 1, without (dotted lines) and with (solid lines) the additional force f. (Adapted from ref. 3.)**

Now Wagh and Rakhecha[3] have studied this proposal in detail. A neutron is assumed to pass through a sequence of cells each having length l and containing transverse uniform electric fields $-\mathbf{E}$, $\mathbf{E}$, $-\mathbf{E}$, $\mathbf{E}$ ... such that $\mathbf{E}$ is parallel to a uniform magnetic field $\mathbf{B}$ (Fig. 1). The length l is chosen so that the time taken for the neutron to travel each cell is half the Larmor period — that is, the time for its spin to rotate once around the magnetic field $\mathbf{B}'$.

Given the geometry of Fig. 1, if the spin $\mathbf{S}$ starts by pointing in the y direction then it will precess around $\mathbf{B}'$ — approximately rotating in the x–y plane, as $\mathbf{B}'$ is close to $\mathbf{B}$. As the neutron traverses the first cell, its spin and magnetic moment rotate by 180°, so S_x is always negative, whereas S_y is positive and negative for equal durations inside this cell. In the next cell, S_x is positive, but owing to the reversal of the electric field, f_x is positive again. Hence, the velocity steadily increases in the x direction, whereas in the y direction it fluctuates as shown in Fig. 2.

The cumulative effect could be detected by allowing the accelerated beam of neutrons to interfere with an unaccelerated beam. In neutron interferometry, the fringe contrast is greatest when both beams are in the same spin state, so Wagh and Rakhecha suggest letting the neutron go through another series of cells, to restore its original spin state.

But an unambiguous way of observing $\mathbf{f}$ is from the deviation of the neutron beam in the y direction[4]. As shown in Fig. 2, this component would be zero in the absence of the new force $\mathbf{f}$ because of the translational symmetry in this direction. In the presence of it, v_y is negative in each of the cells, and therefore the beam deviates increasingly towards the negative y direction as it passes through the cells. The detection of this deviation would be definitive evidence of $\mathbf{f}$.

The observation of $\mathbf{f}$ would provide direct evidence of the hidden momentum. If that is the only objective, it can be achieved more simply by passing the neutron into a region of uniform $\mathbf{E}$-field, with no $\mathbf{B}$, such as the space between two capacitor plates, and measuring its velocity change due to the change in the hidden momentum $\mu \times \mathbf{E}$. But the earlier proposal has the advantage that it would detect $\mathbf{f}$, which would be interesting also because $\mathbf{f}$ is the analogue of the nonlinear terms in the gauge-field forces that govern weak and strong interactions, which cannot be seen in the same manner because they are short range. □

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1. Anandan, J. *Phys. Lett. A* **138,** 347–352 (1989).
2. Anandan, J. in *Proc. Int. Symp. Foundations of Quantum Mechanics*, Tokyo, August 1989 (eds Kobayashi, S. *et al.*) 98–106 (Phys. Soc. Japan, 1990).
3. Wagh, A. & Rakhecha, V. C. *Phys. Rev. Lett.* **78,** 1399–1403 (1997).
4. Anandan, J. & Hagen, C. R. *Phys. Rev. A* **50,** 2860–2864 (1994).

Daedalus

Flower power

Plants have a rich, even a rococo, chemistry. They elaborate many strange and complex substances — terpenes, alkaloids, phenols, and so on, widely exploited in herbal medicine. Yet this medicine rests on uneasy foundations. For all these plant metabolites have but one purpose — to discourage or kill anything that tries to eat the plant.

Fortunately, most plant metabolites are targeted, not at us, but at insects. They can even be released to counter a local insect threat. Cotton plants, for example, release a terpene vapour when attacked by armyworms. Some substance in the saliva of the insects, or generated by its attack, triggers the release of the vapour.

Daedalus sees this as a splendid new source of herbal fuel. Such fuels are being rapidly developed — witness 'biodiesel' oilseed fuel, and the recent Indian herbal fuel fraud. Plant terpenes, the constituents of turpentine, are an excellent hydrocarbon fuel. They are metabolically 'cheap', too — some tropical shrubs and trees release such copious terpene vapours that the scent carries for kilometres. There's a claim that it can be a chemical signal to other plants. So DREADCO biochemists are placing various insects on the leaves of terpene-releasing plants, to study the detailed chemistry of their mastication. They hope to identify the trigger compound that tells a plant that it is under insect attack, and must switch all its resources to terpene synthesis.

Once identified and synthesized, the terpene trigger will open the way to a new fuel technology. A plantation of shrubs or trees — pine, perhaps, or eucalyptus — will be enclosed in a huge plastic-film greenhouse. The terpene trigger will be pumped in, and every plant will start pouring out terpene vapour as if its life depended on it. The greenhouse air will be continuously extracted, and cooled or passed over absorbents to collect the terpenes, which will be re-formed into motor fuel. The level of terpene trigger will need to be carefully regulated. Just enough must be supplied to divert most of the plants' metabolic effort into terpene production, without sapping their vitality.

This elegant technology has all the ecological virtues. Unlike other biofuel schemes, it needs no labour-intensive planting and harvesting. The fuel ultimately comes from the carbon dioxide of the atmosphere; when burnt, it returns without augmenting it. And the plantations will not need expensive insecticidal spraying.

David Jones