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ABSTRACT

It is shown that proof of the trapping of magnetic monopoles by ferromagnetic substances relies on the existence of the well known attractive force when monopoles are outside the substances, and on basic principles of physics. To deny trapping would require the existence of a new energy source. If monopoles exist, but no new source of energy is available, trapping in material containing ferromagnetic components is ensured and can be relied upon as it was relied upon in previous experiments.

1. INTRODUCTION

Goto[1] pointed out that monopoles would be trapped in a ferromagnetic material, because they are subject to a force proportional to the gradient $\vec{H}$ of the magnetic potential and energy would be needed to extract them from the material. In spite of these arguments, the trapping hypothesis has been questioned[2] since the reported discovery of a monopole in flight by Price et al[3]. If monopoles were not trapped, one could understand how they could be as abundant as implied by that discovery and still not be detected by any of the more sensitive experiments that relied on trapping[4,5]. The purpose of this paper is to show how reliable the trapping hypothesis is by spelling out the arguments in favor of trapping by ferromagnetic material. This is done assuming nothing about the behavior of monopoles inside ferromagnetic material except energy conservation. The subject may look less interesting since the cosmic ray event that was considered as evidence for a monopole in ref. [3] now has an alternate explanation[6]. However, since doubts have been expressed[2] about ferromagnetic trapping, it is worth analyzing the arguments in detail in case someone else discovers a magnetic monopole some other time under similar circumstances.

In the experiments that rely on trapping, monopoles are supposed to slow down, get thermalized, and be trapped in material containing ferromagnetic substances. Of course, it would be sufficient that they be trapped by <u>any</u> material. Indeed there are reasons to believe that monopoles should be bound to nuclei with a magnetic moment[7]. However, the fate of the monopole-nucleus compound depends on the chemistry of magnetically charged atoms, a chemistry that is, of course, unknown. One can argue that the compound may be chemically bound to the rest of the material.

If not, it would probably still remain in the crystal lattice, judging from analogies which can be drawn between such a compound and an atom of the noble gases produced by nuclear decay or spallation in the substances used for geological dating. There is experimental proof that noble gases trapped for millions of years are released only when the substances are heated to very high temperatures. These arguments in favor of trapping of monopoles are plausible but do not seem inescapable. We are looking for a more unchallengeable argument. We think such an argument can be made about trapping of monopoles or monopole–nucleus compounds by the ferromagnetic substances contained in the material. The argument is useful only to take care of the case where monopoles are not already trapped in matter by other means.

From now on, we abbreviate the words ferromagnetic material by FM.

2. ESSENCE OF THE ARGUMENT

A monopole is considered to be trapped by FM (ferromagnetic material) if it cannot migrate from the FM or from its vicinity to infinity. The argument in favor of trapping relies on the following considerations:

a) in the presence of a piece of FM, there is a region where a monopole has at least 70 eV less energy than at infinity *(see section 4)*. At least part of this region is outside of the FM and will be referred to here as the "low energy region outside the ferromagnetic material" (LEROFM). Of course a monopole may be attracted from LEROFM into the FM if its potential energy is lower there, but, since we don't discuss the fate of a monopole inside FM but only its ability to go back to infinity, this possibility is irrelevant to the argument.

b) If a monopole migrates from LEROFM to infinity, it has to gain energy of at least 70 eV. Something else must have lost the energy that the monopole has gained.

c) When the monopole was in LEROFM the material was in its ferromagnetic state, the solid state of lowest energy[8]. Therefore, if the monopole goes to infinity, the energy must come from somewhere else. This argument stands whether the monopole has taken a detour inside the FM or not. We just compare energies before and after and, in both cases, the monopole is outside of the FM.

d) After reviewing physical processes that would give that monopole enough energy to break loose from LEROFM and go to infinity, we conclude that they all imply new mechanisms that are much more "far out" than the monopole hypothesis itself *(see section 5)*. If any such mechanisms existed, it would have enormous implications for physics.

e) Unless one is willing to accept the existence of such mechanisms, we must conclude that monopoles cannot migrate from LEROFM to infinity. Therefore either the FM or the LEROFM will represent a trap for monopoles.

3. MONOPOLE PROPERTIES SUFFICIENT TO ENSURE TRAPPING

The properties assumed for the monopoles are the following:

$$\mathrm{div}\, \vec{B} = 4\pi\, \rho_m\,, \tag{1}$$

where $\vec{B}$ is the magnetic induction and ρ_m is the magnetic charge density. This can be considered as the definition of magnetic charge.

Magnetic charge is conserved as is required to adapt the Maxwell equations to its existence *(see appendix A)*. Therefore, if a monopole can decay, at least one of its decay products must be magnetically charged. At the end of the chain of decay, there is a monopole that cannot decay anymore. That stable particle is the monopole of concern in this study. We will also assume that its magnetic charge is as large as or larger than the minimum value predicted by the Dirac theory[9], $\sim 3 \times 10^{-8}$ emu.

There is a force $\vec{F}$ on a magnetic monopole in the presence of a magnetic field

$$\vec{F} = g\,\vec{H}\,, \tag{2}$$

where g is the magnetic charge and, in principle, $\vec{H}$ is the magnetic field, not the magnetic field induction $\vec{B}$ *(see appendix A)*. Arguments against trapping have been made by raising doubts about the use of $\vec{H}$ in eq. (2) when the monopole is inside the FM[10]. To avoid any such debate, we will use eq. (2) only when the monopole is outside of the FM, actually only in places where $\vec{B} = \vec{H}$. However, we will still assume that energy is conserved one way or another when the monopole is inside the FM as well as when it is outside. If the monopole has not only a magnetic but also an electric charge, there will be an electric field that can be screened by the electrons of the environment. At large distances there will be only the effect of the magnetic charge that cannot be screened by the electrons.

We will use eq. (2) and neglect relativistic effects and wave mechanics to describe the motion of a monopole. It is possible to consider that a monopole is at rest at a point only if its wavelength is small with respect to the distances r involved and if that short wavelength does not imply a kinetic energy larger than the potential energy W. Therefore, we deduce the following restriction on the mass M of the monopole for which this study applies:

$$M >> \frac{(\hbar/r)^2}{2 \times W} . \qquad (3)$$

To prevent large relativistic effects, we need in addition

$$M >> W \simeq 70 \text{ eV} , \qquad (4)$$

since 70 eV is a minimum binding energy *(see section 4)*. Zero mass monopoles[11] and tachyon monopoles[12] are not considered in this study.

Eq. (2) also applies to a monopole if it is bound to a nucleus, as it may likely be[7]. If there is a process by which a monopole–nucleus compound can associate more nucleons taken from other nuclei around, we want to consider here the monopole–nucleus compound with the maximum binding energy that can be reached by this process. Therefore, additional freeing of energy by attachment of more nucleons is impossible. In this case, inequalities (3) and (4) will apply to the mass of the compound system.

Summary. A monopole is the source of magnetic induction $\vec{B}$ (eq. (1)). In the presence of a magnetic field it is subjected to a force $\vec{F}$, expressed by eq. (2), outside of the FM. The magnetic charge g is at least 3×10^{-8} emu. The monopole considered here is stable against further decay and as tightly bound to nuclear matter as possible. Its' mass M satisfies inequalities (3) and (4). Energy is conserved.

4. THE LOW ENERGY REGION OUTSIDE A FERROMAGNETIC MATERIAL (LEROFM)

When the geometrical dimensions of the FM are several thousands of Å or more, we will approximate the properties of the FM by a relation between $\vec{B}$ and $\vec{H}$ inside the substance

$$\vec{B} = \mu\vec{H} \,, \tag{5}$$

where the magnetic permeability μ is a large number (>10 say). Then the field lines between the substance and a monopole sitting outside are the lines sketched on fig. 1. The field outside of the FM is nearly as if there was just a monopole of opposite charge sitting at the same distance from and on the other side of the surface with the FM removed. That magnetic image of the monopole is the analog of the electric image in a conductor of an electron outside the conductor. The force on the monopole is

$$F = \frac{g^2}{(2r)^2} \,, \tag{6}$$

where r is the distance from the monopole to the surface of the FM. To push a monopole from a distance r to infinity, work has to be performed, therefore energy has to be supplied, namely

$$W = \frac{g^2}{4r} \,. \tag{7}$$

Since W depends on the position of the monopole outside the FM and not on the trajectory, we will call W the "potential energy" of the monopole.

This picture would still be true if r is smaller than the domain size, because the field of the monopole would distort the spin alignments of the electrons in the domain.

For a monopole of the minimum charge predicted by the Dirac theory sitting at 200 Å from the surface, the maximum value of the $\vec{B}$ field in the FM is 15 kG and the energy required to push the monopole back to infinity is 70 eV. We will use that distance of 200 Å for the energy calculation because it makes the field in the FM close to 15 kG, and that is near saturation for the most abundant FM's. In this case we say the LEROFM extends up to 200 Å from the surface of the FM.

For a monopole with a larger charge or for the minimum charge sitting closer to the surface, the field is larger than 15 kG and corrections to eq. (7) from saturation effects should soon be introduced. However, the binding energy would be larger and not smaller than 70 eV whenever $r < 200$ Å or g is larger than the minimum predicted by Dirac. The magnetic force is the same if the monopole is bound to a nucleus, therefore the binding energy is also the same. In any case, LEROFM extends to 200 Å or beyond, from the surface.

If the piece of FM is smaller than a few hundred Å, the validity of eq. (5) is in doubt, because the FM is made out of one domain generating a magnetic field of about 20 kG in the neighborhood of the piece of material (fig. 2). There is a region around the domain where the monopole is pulled toward the domain. The magnetic field is of the order of 20 kG in a range of the order of R, the dimension of the piece of FM. The energy necessary to push the monopole back to infinite distances is

$$W \approx g \times R \times 20 \text{ kG} . \qquad (8)$$

Whenever the dimension R is larger than 100 Å and g is larger than or equal to the minimum charge allowed by the Dirac theory, the energy W is greater than ~ 350 eV. We conclude again there is a LEROFM corresponding to 70 eV and extending beyond 100 Å.

For distances equal to or larger than 100 Å, inequality (4) is more binding than inequality (3). Therefore, to legitimize our computation with respect to wave mechanics and relativity, we need only the condition of inequality (4).

<u>Summary</u>. There is a LEROFM where the potential energy of monopoles with mass greater than, say, 1 keV is at least 70 eV less than at infinity. It extends 100 Å or more from the FM.

5. REVIEW OF SOME POSSIBLE ENERGY SOURCES

In order to legitimize the experiments that relied on trapping, we consider the worst case, i.e. when monopoles have not been trapped by non-ferromagnetic processes. One would picture them bouncing from atom to atom or nucleus to nucleus with thermal kinetic energies as thermalized neutrons do. This picture is still valid if the monopoles are in LEROFM if there is some non-ferromagnetic material in that region. Once a thermalized monopole is in the LEROFM at a temperature less than 1000°C its kinetic energy is less than 0.15 eV and insufficient to overcome the potential energy. We must find another source of energy to let the monopoles escape. The following processes are obvious ones.

a) <u>Thermal diffusion</u>. According to this process, the thermal agitation would make the monopole drift to large distances. However, below 1000°C the average thermal energy is less than $\frac{1}{2}kT = 0.05$ eV per degree of freedom. From the rule of equipartition of energy one can estimate the probability for a monopole originally bound in the LEROFM or in the FM by more than 70 eV to be found at such a large distance from the FM that its binding energy is near, let's say, 30 eV. The computation is dominated by the factor $\exp(-40\mathrm{eV}/kT) < 10^{-170}$. Because of the small probability implied, this can never happen in the lifetime of the universe.

b) A new solid state with lower energy than the initial ferromagnetic state. According to this scheme, a monopole could induce a transition of the whole piece of FM into a new non-ferromagnetic state. The monopole could then leave because there is no ferromagnetism any longer, but the state of the material after the monopole has left must have a lower energy. No such solid state has been discovered yet.

c) Change of permanent magnetization. It is possible that the FM's permanent magnetization will be changed in the presence of a monopole. As the domains get reoriented, is it possible that the monopole picks up enough energy to leave the material? As far as is known, changes in permanent magnetization are always associated with a consumption of free energy. It takes energy to magnetize and it takes energy to demagnetize, because of some friction between the domains. Therefore energy could not be collected by a monopole by changing permanent magnetization.

d) Chemical energy. The process is similar to the process considered under b). Here, the monopole induces chemical combination of the FM with atoms of the environment. Oxidation of iron is one of the possible processes. This is a source of energy in a process during which the ferromagnetic property of the material is being destroyed. As the chemical combination proceeds, the FM shrinks and so does the LEROFM around it. During that time the monopole will move in toward the remaining

FM. When no FM is left, the monopole loses its ferromagnetic bond and may escape trapping.

In this process the monopole (or the monopole-nucleus compound) acts like a chemical catalyzer. However, it is a catalyzer composed of a single particle. In order to induce combination of the whole piece of FM, catalysis has to apply to atoms of the environment situated far away from the monopole. For a solid environment, as was the case for the moon sample of ref. [5], the catalysis has to be effective at distances as large as the size of the piece of FM, i.e. larger than, let's say, 1000 Å. At this distance, the magnetic field of the monopole is below 3 kG, even for a magnetic charge equal to 10 times the minimum of the Dirac theory. It is known that magnetic fields of this magnitude are unable to disturb the chemical properties enough to cause the catalysis required in this scenario. Therefore a new long-range force completely unrelated to the monopole's magnetic properties is required to accomplish that catalysis.

In atmospheric environment, note that if monopoles were able to grab every atom of oxygen that comes within 200 Å and every oxygen atom was effective for immediate oxidation it would take a year to oxidize a cubic millimeter[13].

e) Nuclear disintegration. A monopole would fall into the FM and be captured by a nucleus and induce a disintegration similar to the way a neutron induces fission in uranium. Either the energy gained would largely be conferred to the monopole that could then leave the FM or the total FM may end up transmuted, destroying the trap. However, the nuclei of the FM have binding energy of 8.8 MeV/nucleon at the peak of the binding energy curve. After the monopole would have escaped, there is no known nuclear configuration that would have less energy. Therefore, this is not a possible source of energy if the number of nucleons is conserved. For this mechanism to work, one would probably have to postulate that nucleon number is not conserved in the presence of monopoles.

Conclusion. Of course this list of processes by which monopoles may escape ferromagnetic trapping is not claimed to be exhaustive, but these processes are typical of what has to be imagined. If any one of them is possible, there is a need for a revision of some concept of physics aside from the existence of monopoles.

6. A PERPETUAL MOTION DEVICE

If no energy source were required to prevent trapping, we can show one way energy conservation could be violated. Fig. 3 shows a machine that could be built[14]. The magnet is a piece of ferromagnetic material so small that it can be composed by only one domain. It is already in its lowest state of energy. We immerse the magnet in a viscous environment where the velocity $\vec{v}$ of the monopole and the force $\vec{F}$ acting on it are related by

$$\vec{v} = k\,\vec{F}\,. \tag{9}$$

The monopole placed in A follows the field line to B then to C outside the magnet. It has no way to get out on the C side, since the force would pull it in again. The only way for the monopole to get out is on the A side. Then, if it is not trapped inside or in the LEROFM around point C, it will get to the A side and go around and around, heating the environment. If the domain gets demagnitized in that exercise, the machine will stop for awhile with the monopole outside, since it is not trapped. The domain will cool off and return to its state of lowest energy, which is magnetized. Therefore the process can continue forever, generating energy from nothing.

Of course we believe that this machine cannot work, because we believe that monopoles would be trapped.

7. CONCLUSIONS

A monopole of high energy produced in or entering a material will lose energy because of its interactions with the environment. The energy loss process will cease once the kinetic energy of the monopole is thermal. It will either be trapped in ordinary matter or wander around. In the latter case, it will reach one LEROFM with a finite probability, whether it stayed alone or got attached to a nucleus. Its kinetic energy will be of the order of thermal energy, therefore it will be trapped in the LEROFM or in the FM. If it is not trapped, it doesn't have the basic properties described in section 3, or a new kind of interaction or energy source exists.

Accumulation of monopoles by trapping has been used as a property of monopoles in searches for them in materials exposed over long periods of time[4,5]. Of course, any trapping in the material will be adequate for the accumulation, either trapping in FM or non ferromagnetic material, but the existence of FM trapping as described above will ensure the accumulation in any material containing FM[4,5,15,16].

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APPENDIX A

THE MAXWELL EQUATIONS

To adapt Maxwell equations in the presence of matter to the existence of magnetic charges, one writes:

$$\begin{aligned} \text{curl}\,\vec{H} - \frac{1}{c}\frac{\partial\vec{D}}{\partial t} &= 4\pi\,\frac{\vec{J}_e}{c} \\ \text{div}\,\vec{D} &= 4\pi\,\rho_e \\ \text{curl}\,\vec{E} + \frac{1}{c}\frac{\partial\vec{B}}{\partial t} &= -4\pi\,\frac{\vec{J}_m}{c} \\ \text{div}\,\vec{B} &= 4\pi\,\rho_m\,, \end{aligned} \tag{A1}$$

where $\vec{H}$ ($\vec{E}$) is the magnetic (electric) field, $\vec{B}$ ($\vec{D}$) is the magnetic (electric) induction, ρ_m (ρ_e) is the magnetic (electric) charge density, and $\vec{J}_m$ ($\vec{J}_e$) is the current density of magnetic (electric) charge. The procedure by which one arrives at these equations involves averaging the Maxwell equations for the microscopic fields over space[17]. The densities ρ_m (ρ_e) and $\vec{J}_m$ ($\vec{J}_e$) are usually referred to as the "free" densities.

From equations A1, it is easy to derive

$$\frac{\partial\rho_m}{\partial t} + \text{div}\,\vec{J}_m = 0\,; \tag{A2}$$

thus, magnetic charge is conserved.

The symmetry of Maxwell equations with respect to exchange of magnetism and electricity is:

$$
\begin{array}{lll}
\vec{D} \to \vec{B} & \vec{E} \to \vec{H} & \\
\vec{H} \to -\vec{E} & \vec{B} \to -\vec{D} & \\
\rho_e \to \rho_m & \rho_m \to -\rho_e & \\
\vec{J}_e \to \vec{J}_m & \vec{J}_m \to -\vec{J}_e &
\end{array} \tag{A3}
$$

$\vec{H}$ and $\vec{D}$ are exchanged for $\vec{E}$ and $\vec{B}$. The force $\vec{F}$ on an electric charge q moving with velocity $\vec{v}$ is:

$$\vec{F} = q\,(\vec{E} + \frac{\vec{v}}{c} \times \vec{B})\,. \tag{A4}$$

By analogy we derive the force on a magnetic charge g moving with velocity $\vec{v}$ by making the substitutions (A3) in eq. (A4):

$$\vec{F} = g\,(\vec{H} - \frac{\vec{v}}{c} \times \vec{D})\,. \tag{A5}$$

Since only electric charges but no magnetic charges have been observed, $\vec{E}$ and $\vec{B}$ are in general considered as more fundamental than $\vec{D}$ and $\vec{H}$. The definition of $\vec{E}$ and $\vec{B}$ then reduces itself to a simple average of the microscopic fields. However, if we assume that monopoles exist, $\vec{H}$ and $\vec{D}$ are to the magnetic charges what $\vec{E}$ and $\vec{B}$ are to the electric charges. $\vec{H}$ and not $\vec{B}$ has to be used in eq. A5. This point, however, is irrelevant to the argument developed in the core of this paper, since eq. (2) is used only in places where $\vec{B} = \vec{H}$.

Footnotes and References

*Work performed under the auspices of the U.S. Energy Research and Development Administration.

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Figure Captions

Fig. 1. Magnetic field lines ~~outside~~ of the ferromagnetic material (FM) when a monopole (g) sits at a distance r from the surface. The point indicated as g' is the magnetic image of g.

Fig. 2. Field lines around a very small piece of FM. The region called LEROFM in the text is at the bottom of the figure for a north magnetic monopole.

Fig. 3. Perpetual motion device that could work if monopoles were not trapped in FM. The rectangle is one domain immersed in a viscous medium. The field line ABC is one of the possible trajectories that the monopole would follow outside the domain.

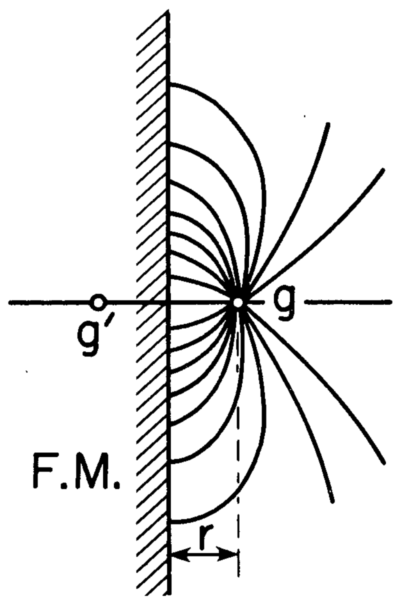

Fig. 1

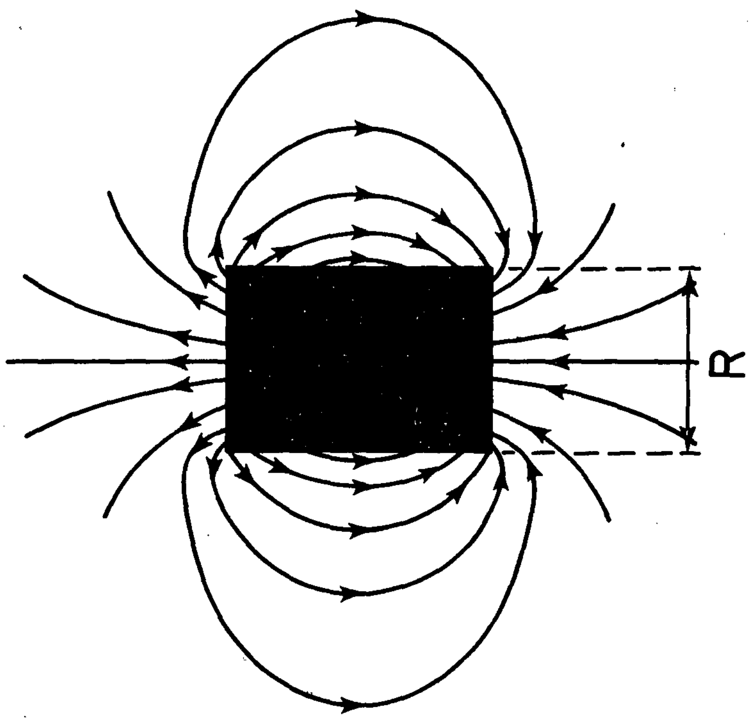

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Fig. 2

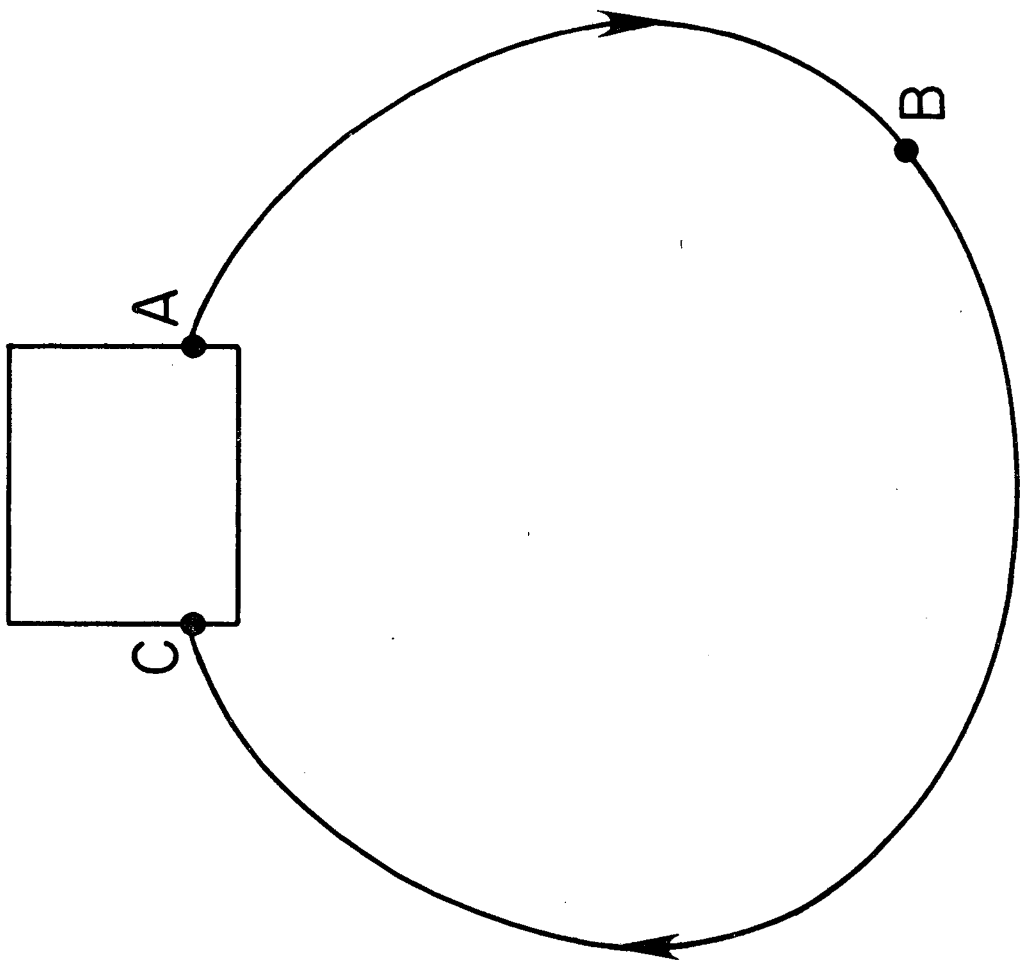

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Fig. 3

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