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Permanent poleless magnet

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Abstract

This paper describes a permanent magnet with an external circular magnetic field (poleless permanent magnet) and its properties, as well as a method for its creation. The magnet generates a strong external azimuthal magnetic field around a cylinder of a magnetically hard high-coercivity material, such as NdFeB, SmCo, AlNiCo or hard ferromagnetic ceramics. The field has a circular (azimuthal) geometry, not a dipole. There are no pronounced north and south poles. Maxwell's law $\nabla.\vec{\mathrm{B}} = 0$ is not violated. The field strength is proportional to the remanence $\overrightarrow{\mathrm{B_r}}$ of the material, the geometric dimensions of the cylinder (diameter, length) and its reversed magnetic permeability μ_{rec}.

1. Introduction

Magnetism is a fundamental physical phenomenon in which certain materials or moving electric charges create a magnetic field around themselves. This field is an invisible force that can attract or repel other materials, as well as exert a force on other moving electric charges. Magnetism and electricity are the two sides of electromagnetism. The relationship between them is mathematically described by Maxwell's equations[1,2]. The force that a magnetic field $\vec{B}$ exerts on a charge q moving with a velocity $\vec{v}$ is $\vec{F}=q(\vec{v} \times \vec{B})$-the Lorentz force[2]. Each electron rotates around the nucleus and has its own "spin". The spin and orbital motion create the microscopic magnetic field. The magnetic field of permanent magnets arises mainly from the collective arrangement of the spin magnetic moments of electrons[3,4]. The electron spin[3] is a fundamental internal angular momentum of a purely quantum mechanical nature, with no classical analogue. It is an intrinsic property of the particle, similar to mass and electric charge, and gives rise to a spin magnetic moment. In atoms and solids, electronic states obey the Pauli exclusion principle, according to which two fermionic particles cannot occupy the same quantum state. Since spin is part of the set of quantum numbers, the antisymmetry of the complete electronic wave function leads to the emergence of an exchange interaction[4,5]. It is this interaction that is responsible for the energetically preferred parallel arrangement of spins in ferromagnetic materials and for the appearance of spontaneous magnetization below the Curie temperature.

In contrast, the magnetic field around a current-carrying conductor arises from the macroscopic motion of electric charges and is classically described by Maxwell's equations (Ampere–Maxwell's law). In this case, the dominant contribution is from the convection current of the conduction electrons, while the spin contribution is negligible for ordinary conductors in thermodynamic equilibrium. The spin magnetic moment becomes a leading factor in materials in which exchange interactions allow collective alignment of the spins (ferromagnets, ferrimagnets), as well as in special quantum regimes — for example, at low temperatures or in systems studied in spintronics and quantum condensed matter[6,7]. The general rule is that the magnetic field always tends to form closed loops with minimal energy[8.9].

The magnets we know, whether permanent or electromagnets, have clearly defined north and south poles, where the magnetic field intensity is greatest[1,2]. Magnetic lines of force are closed loops, emerging from the north pole and entering the south pole. Moreover, with respect to the pole axis, in any pole plane (the plane in which the pole axis lies), the magnetic induction vectors $\vec{B}_R$ and $\vec{B}_L$ are oppositely directed, forming with respect to the pole plane completely separate R and L half-spaces, in which the magnetic field acts as two independent $\vec{B}_R$ and $\vec{B}_L$ magnetic fields (called poleless magnetic fields), which repel each other. They have the same magnitude but opposite direction of force properties and induce opposite EMFs in conductors and conductor loops[13,14].

As a natural continuation of my previous works[13,14] on this subject, in this article we will consider permanent magnets and a methodology with such an arrangement of the spin orbital moments, in which the classical dipole magnets with the characteristic north and south poles are not obtained. We will consider this as a new breakthrough in the field of magnetism.

2. Creation of internal magnetization

A high-amperage current pulse (about 10,000 A) is passed through a straight conductor located along the axis of a cylinder of magnetically hard material or parallel to the axis in close proximity as shown in Fig. 1.

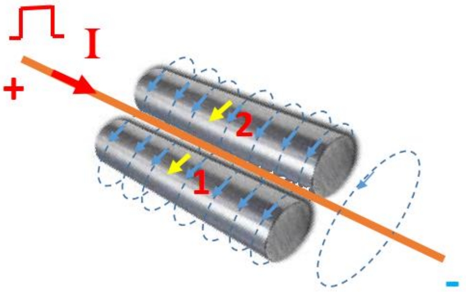


Fig. 1 - *Magnetization of magnetically hard materials 1 and 2 by passing a high-amperage current pulse*

This pulse generates a powerful circular magnetic field $\vec{H}$ in the material of the cylinder[2]. In the magnetically hard material, the domains are oriented in the direction of this field. After the end of the pulse, the material retains a residual magnetization $\vec{M}$ directed along the circumference (azimuthally)[4,12]. In this closed cylinder, the lines of force of the magnetic induction $\vec{B}$ are almost entirely concentrated inside the material with high magnetic permeability. This state is magnetically equivalent to a toroid[3,11].

Unlike the solenoid, here there are no free currents J_{free} in the volume, therefore for the magnetic field $\vec{H}$ in the material it is valid:

$$\nabla \times \vec{H} = J_{free} = 0 \tag{1}$$

and therefore for each closed curve Ampere's law in integral form is valid:

$$\oint \vec{H}.d\vec{l} = 0 \qquad (2)$$

for each closed loop[1,2].

The source of the field[1,3] is the magnetization $\vec{M}$, as:

$$\vec{B} = \mu_0(\vec{H} + \vec{M}) \qquad (3)$$

In the closed loop the field $\vec{H}$ is practically zero, since it is compensated by $\vec{M}$, where m0 is the magnetic permeability in vacuum[3].

In an azimuthally magnetized cylinder:

$\vec{M}$ is along circles around the axis.

At each point the vector is tangential.

For each direction there is an opposite point with an opposite vector.

Corollary:

$$\int \vec{M} dV=0 \qquad (4)$$

That is, there is no resultant dipole moment[4,5].

Such configurations are described as dipoleless or toroidal magnetic structures, in which the magnetic lines are completely enclosed inside the material[10,11]. Due to the lack of magnetic poles and the high magnetic permeability, the external field is negligible[2,3]:

$$\vec{B}_{ext} \approx 0 \qquad (5)$$

3. Creation of an external field

After the azimuthally magnetized cylinder is fabricated, a longitudinal slit is made along its entire length with a milling cutter. This mechanical air gap fundamentally changes the boundary conditions of the magnetic field and breaks the toroidal symmetry of the system.

In the uncut cylinder, the magnetization $\vec{M}$ gives rise to equivalent coupled surface currents[1]:

$$\vec{K}_b=\vec{M}\times\vec{n} \qquad (6)$$

which form a closed solenoidal structure.

In this case, the following[3] holds:

$$\nabla \cdot \vec{M}=0 \tag{7}$$

in the volume, which corresponds to the absence of magnetic “charges”.

The chain of equivalent surface currents representing the magnetization $\vec{M}$ is interrupted.

The solenoidal character of $\vec{M}$ is broken along the edges of the slit. A magnetization divergence ($\nabla . M \neq 0$) appears in the slot area, which manifests itself as an effective surface magnetic charge density $\boldsymbol{\sigma_m}$[1,3]:

$$\boldsymbol{\sigma_m} = \vec{M}.\vec{n} \tag{8}$$

where $\vec{n}$ is the unit vector normal to the cut surface. The edges of the slot act as substitute magnetic poles through which part of the internal magnetic flux escapes. This leads to the appearance of a noticeable external magnetic field.

The width of the slot must be small enough not to excessively increase the reluctance of the magnetic circuit, since the air interlayer has a magnetic permeability $\mu \approx \mu_0$, which is much smaller than that of the ferromagnetic material[2,6].

At the same time, the slot must be wide enough to prevent magnetic bridging by residual contact or local domain reorganization[4,12].

For a cylinder with a diameter of approximately 20 mm, the practical optimum width is of the order of tenths to units of millimeters, which provides a balance between a sufficiently strong external field and a minimal reduction of the total magnetic flux. The experimentally established depth of the slot is between 10% and 30% of the cylinder radius. A shallower slot leads to a complete interruption of the equivalent surface currents. For reasons of mechanical strength, the slot can be filled with a non-magnetic material, for example polystyrene (PS), whose magnetic permeability is close to that of air ($\mu r \approx 1$) and which does not restore the magnetic connection between the two sides of the cut[18]. This guarantees the preservation of the modified boundary conditions and stability of the external magnetic field. Its direction is indicated by a permanently applied yellow arrow, according to Fig. 1, where two magnets are depicted.

4. Properties of the external magnetic field

The external field has a circular (azimuthal) geometry, not a dipole one. The reason is that the primary magnetization in the material is azimuthal, and the slot simply brings out part of the existing internal flux. The field lines of force go around the cylinder, leaving one edge of the slot and entering the other, thus remaining closed[1,2]. This does not violate Maxwell's law $\nabla.\vec{B} = 0$.

The field strength is proportional to the remanent magnetization $\vec{B}_r$ of the material, the geometric dimensions of the cylinder (diameter, length) and its recoil magnetic permeability $\boldsymbol{\mu}_{\mathbf{rec}}$[6,12].

$\boldsymbol{\mu}_{\mathbf{rec}}$ is the slope of the local $\vec{\mathrm{B}} - \vec{\mathrm{H}}$ characteristic for small reversible changes around the operating point. For high-quality materials[6] (e.g. neodymium) the external field can reach from tens to hundreds of mT.

After making the slit, a strong demagnetizing field $\vec{\mathrm{H}}_{\mathrm{d}}$ may appear, leading to partial local demagnetization near the edges of the slit[4,12]. For this, to reach maximum power of the external field, a second high-current pulse can be applied through the axial conductor, already after the slit is made. This pulse "Supersaturates" the material in the new, open geometry and compensates for local demagnetizations[4,6].

The slit changes the distribution of the magnetostatic energy of the system[1]:

$$\mathbf{U} = \frac{1}{2} \int (\vec{\mathrm{B}}.\,\vec{\mathrm{H}})\, \mathrm{dV} \tag{9}$$

By opening the magnetic circuit, the fraction of the energy stored in the external space (air or polymer) increases. Therefore, the total magnetostatic energy of the system increases. The magnet is no longer in a minimum energy state, but in a metastable one, which is supported by the high coercivity of the materia[4,12].

5. Direction of the external circular field

From the experiments carried out, it is established that the direction of the circular field of the magnetized cylinder is determined by the direction of the pulse current that created it, and obeys the right-hand rule for a straight conductor[2]. In the magnetically hard cylinder, the domains are arranged in the direction of this field. After the current is stopped, the residual magnetization $\vec{B}_r$ retains the same circular orientation due to the hysteresis nature of the material[4,12]. The cylinder becomes a permanent magnet, whose internal circular field (and, accordingly, the external field after the cut) has a direction given by the right-hand rule relative to the original magnetizing current.

6. Experimental setup for studying the interaction between two poleless magnets or a poleless magnet with a dipole magnet

Two poleless permanent magnets or a poleless magnet and a dipole magnet are placed on a flat, mirror-smooth surface. The surface is so smooth that the friction between it and the magnets can be neglected. The interaction between two poleless magnets 1 and 2 with a circular field depends on their relative orientation and position. They do not behave like magnets that have a "north" and "south" pole at both ends. In the interaction between the poleless magnet and the dipole magnet, the poleless magnet is stuck motionless and only the dipole magnet can move freely.

Results and discussion

Three main scenarios are observed from the qualitative experiments conducted:

6.1 Interaction between two poleless magnets

Scenario A: Parallel longitudinal axes, same direction of magnetization. This is shown in Fig.2. - the magnets attract.

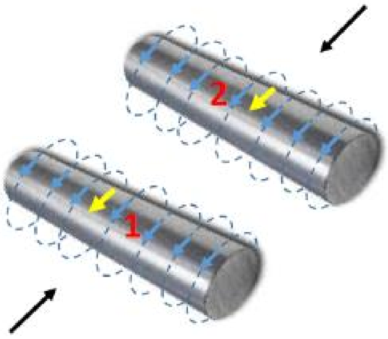


Fig.2 - *Two permanent poleless magnets with the same orientation attract*

Scenario B: Parallel axes, opposite directions of magnetization - the magnets repel. This is shown in Fig.3.

At a close distance of the order of the diameter of the cylinders, the magnets repel, as shown in Fig. 3. But, when they are moved apart by distances greater than the length of the cylinders, the magnets rotate so that they attract each other, as shown in Fig. 2.

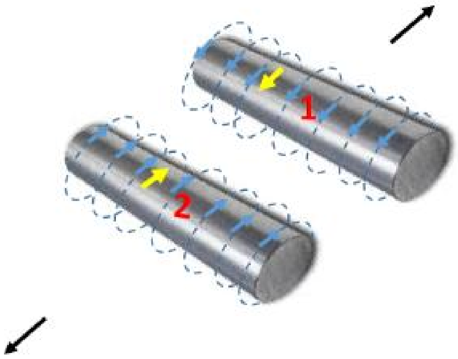


Fig. 3 - *Two permanent poleless magnets with opposite orientations repel each other*

Scenario B: When the longitudinal axes of the poleless magnets coincide, regardless of the distance between them - there is no pronounced attraction or repulsion. This is shown in Fig.4.

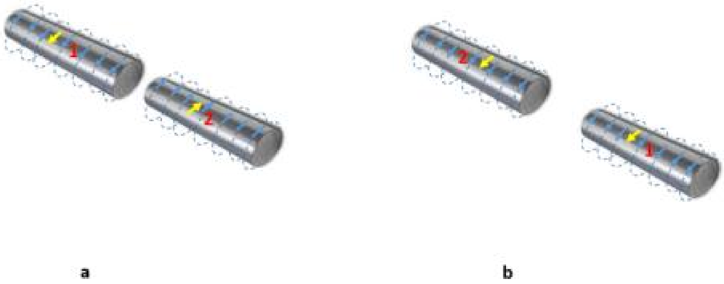


Fig. 4a and 4b - *With coincident axes in a straight line, there is no attraction or repulsion between the permanent poleless magnets*

6.2 Interaction between a poleless magnet and a dipole magnet

From the qualitative experiments carried out, in each case the two magnets tend to form a common magnetic field with closed loops with minimal energy, as shown in two of the cases in Fig.5a and Fig.5b.

In Fig.5a, the fixed stationary permanent poleless magnet has a $\vec{B}_L$ magnetic field (magnetic induction is counterclockwise) relative to the dipole magnet. Its longitudinal axis is parallel to the pole axis of the dipole magnet, with its north pole to the left in the plane of the sheet. In this position, the dipole magnet rotates about its center so that its magnetic field in the direction of the poleless magnet is counterclockwise, after which the two magnets are attracted.

In Fig.5b, the fixed stationary permanent poleless magnet has a $\vec{B}_R$ magnetic field (magnetic induction is clockwise) relative to the dipole magnet. Its longitudinal axis is parallel to the pole axis of the dipole magnet, with its north pole to the left in the plane of the sheet. In this position, the dipole magnet rotates about its center so that its magnetic field in the direction of the poleless magnet is clockwise, after which the two magnets attract each other.

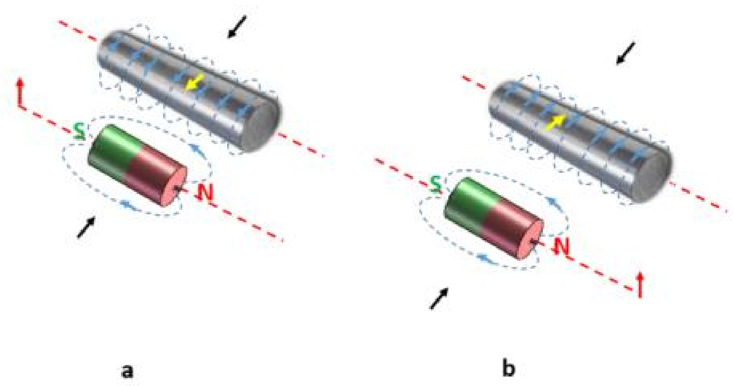


Fig.5- *Interaction between a stationary poleless magnet and a dipole magnet*

In both cases a. and b. the dipole magnet rotates in the direction of the red arrow so that its magnetic lines of force coincide with the direction of the magnetic lines of force of the poleless magnet, after which they attract each other

7. Experimental setup for generating EMF when changing the magnetic field created by a permanent poleless magnet

Theoretically, if a conductor moves radially through the circular field of the cylinder, or if the cylinder itself rotates around its axis while the conductor remains stationary, an induced electromotive force (EMF) arises in the conductor[1,2]. This EMF is due to the Lorentz force acting on the free charges in the moving conductor, and is described by the general integral law:

$$\mathbf{E}= \oint_{\text{path in the conductor}} (\vec{v}\times\vec{B}).d\vec{l} \qquad (10)$$

where: $\vec{v}$ is the velocity of a conductor element relative to an inertial system related to the magnetic field, $\vec{B}$ is the local magnetic induction, $d\vec{l}$ is an element along the closed integral path in the conductor.

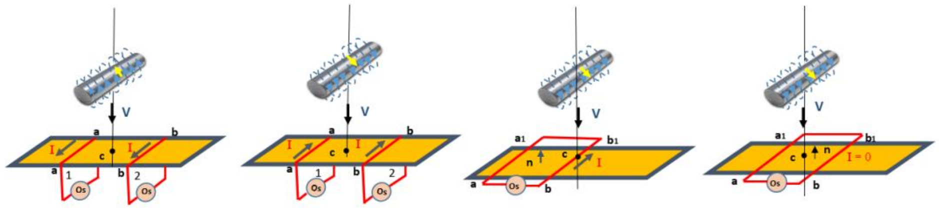
Experimentally, a permanent poleless magnet is dropped from a height h with a velocity V at the moment of fall in a plastic box in the shape of a parallelepiped, as shown in Fig. 10. The permanent poleless magnet falls onto movable conductor loops a, a or b, b or a,b,a1,b1, lying on a wooden board covered with shock-absorbing rubber. A USB oscilloscope is connected to each conductor loop. Measures have been taken to ensure that the magnetic field of the permanent poleless magnet does not affect the oscilloscope.

Typical cases:

1. In the case shown in Fig.10A1, the poleless magnet falls at point C, which is in the middle, at equal distances from two conductor loops. The magnetic induction vector $\vec{\boldsymbol{B}}_{\boldsymbol{L}}$ is oriented counterclockwise. The created increase in magnetic induction when the magnet falls generates EMF in the section a,a of loop 1 and the section b,b of loop 2.

2. In the case shown in Fig.10A2, the poleless magnet falls at point C, which is in the middle, at equal distances from two conductor loops. The magnetic induction vector $\vec{\boldsymbol{B}}_{\boldsymbol{R}}$ is oriented clockwise. The created increase in magnetic induction generates EMF in the section a,a of loop 1 and the section b,b of loop 2.

3. In the case shown in Fig.10A3, the poleless magnet falls at point C, which is in the middle of the section b,b_1 of the contour a,a1,b,b_1. The magnetic induction vector $\vec{\boldsymbol{B}}_{\boldsymbol{R}}$ is oriented clockwise. The increase in magnetic induction created when the magnet falls generates an EMF only in the section b,b_1. If the magnet falls near the section a,a_1, the increase in magnetic induction created when the magnet falls generates an EMF only in the section a,a_1.



A1 A2 A3 A4

Fig.10

A1-Increase in magnetic induction $\vec{B}_L$ *when the poleless magnet falls generates EMF in the section a,a of loop 1 and section b,b of loop 2. The current I is directed from the sheet to us.*

A2- Increase in magnetic induction $\vec{B}_R$ *when the poleless magnet falls generates EMF in the section a,a of loop 1 and section b,b of loop 2. The current I is directed from us to the sheet.*

A3- Increase in magnetic induction $\vec{B}_R$ *when the poleless magnet falls generates EMF in the section b,*b_1 *of loop a. The current I is counterclockwise.*

A4- Increase in magnetic induction $\vec{B}_R$ *when the poleless magnet falls does not generate EMF in the loop a,*a_1*,b,*b_1*. The circular current I = 0.*

4. In the case shown in Fig.10A4, the poleless magnet falls at point C, which is in the middle, on the contour a,a_1,b,b_1. The magnetic induction vector $\vec{B}_R$ is oriented clockwise. The increase in magnetic induction created when the magnet falls does not generate EMF in the contour.

Results and discussion

In <u>case 1</u>, the increase in magnetic induction $\vec{B}_L$ generates EMF only in the section a,a of loop 1 and the section b,b of loop 2. The same circular currents are created in the conductor loops, directed counterclockwise. It can be seen that the current follows the direction of the magnetic induction of a poleless magnet.

In <u>case 2</u>, the increase in magnetic induction $\vec{B}_R$ generates EMF only in the section a,a of loop 1 and the section b,b of loop 2. The same circular currents are created in the conductor loops, directed clockwise. It can be seen that the current follows the direction of the magnetic induction of a poleless magnet.

In case 3, the increase in magnetic induction $\vec{\boldsymbol{B}}_{\boldsymbol{R}}$ generates EMF only in the section b,b_1 of the conductor loop. The loop is sized so that the poleless magnet practically creates a change in magnetic induction only in the section bb_1. In one way, the section a, a_1 is far enough away. The created circular current is directed counterclockwise.

However, if the magnet falls to the section a, a_1, the created circular current is directed explainably opposite - clockwise.

In case 4, the increase in magnetic induction $\vec{\boldsymbol{B}}_{\boldsymbol{R}}$ does not create a circular current in the conductor loop. No EMF arises. Here, point C is in the middle of the loop and the magnetic field affects both sections of the current loop equally. In other words, the sections a, a_1 and bb_1 are close enough to each other. The created equal currents in the sections a, a_1 and bb_1 are in opposite directions and mutually compensate each other. This case is opposite to Faraday's experiment with dipole magnets, in which an EMF is generated in the conductor loop.

Hence the inefficiency of a poleless magnet as a "piston" magnet: If we try to repeat Faraday's experiment by simply pushing the cylinder in and out of the solenoid (as is done with a bar magnet), we will get almost no emf. This is the cardinal difference between a poleless magnet and a dipole magnet.

9. Practical significance and analogies

Generator: The cylinder rotating in a solenoid is a basic model of an AC generator.

Rotation sensor: This effect can be used to create contactless tachometers or encoders. The rotating cylinder induces a voltage in a stationary coil whose frequency is proportional to the revolutions.

10. Do we have a reason to call this magnet a poleless permanent magnet?

Yes, we have an extremely solid reason. This magnet with a circular field is precisely a poleless permanent magnet because in the ideal, closed cylinder the lines of magnetization $\vec{\mathrm{J}}$ and the magnetic induction $\vec{\mathrm{B}}$ are enclosed in the material itself, forming vortex lines. There are no free magnetic charges (surface poles), since the magnetization $\vec{M}$ is purely solenoidal $\nabla \cdot \vec{M}=0$ throughout the volume and on the surface). The external field is practically zero. The magnet does not exhibit the classical properties of a dipole. It does not attract ferromagnetic particles, it has no identifiable north and south poles.

The slit "opens" the magnet, but this does not change its nature.

Locally around the slit, effective poles appear. Globally, the field structure remains fundamentally different from the dipole one. Instead of lines of force coming out of one end and going in at the other, here they go around the magnet. The term "poleless" still applies in the sense that there are no two discrete, opposite poles defining the magnet's axial symmetry. It has a linear pole density along the slot, which is quite different. Ordinary "bar" magnets are dipoles. Their energy is minimal when two poles are in contact with opposite poles of another magnet. This magnet has no such poles to "grab". This is "poleless" by design.

It is permanent because it stores remanent magnetization and

poleless because its fundamental field structure is circular/vortex, not dipole. It lacks a total magnetic moment.

11. **Conclusion**

A high-amp short current pulse in a straight conductor, generating a circular azimuthal magnetic field around itself, orients the spin-orbital moments of the magnetically hard material azimuthally, creating a circular residual magnetic field. After breaking the internal symmetry of the field with a longitudinal slot, the resulting azimuthal circular external permanent magnetic field turns the magnetically hard material into a poleless permanent magnet. This does not violate Maxwell's law $\nabla . \vec{B} = 0$. The field strength is proportional to the residual magnetization $\vec{B_r}$r of the material, the geometric dimensions of the cylinder (diameter, length) and its reversed magnetic permeability μ_{rec}. The resulting permanent magnet has no poles, but its magnetic field represents closed concentric circles perpendicular to the axis of the cylinder with decreasing intensity as their radius increases. The magnetic field has a direction: clockwise - $\vec{B}_R$ magnetic field or counterclockwise -$\vec{B}_L$

magnetic field. Through its external circular magnetic field, a magnet attracts magnetic materials. Two poleless permanent magnets attract each other when the direction of their magnetic fields is the same and repel each other when they are not. The poleless magnetic field around a poleless permanent magnet is actually the most elementary magnetic field that exists in nature. It obeys Maxwell's laws.

Unlike a poleless magnetic field, each dipole magnet has a composite magnetic field. It consists of two parts (two opposite poleless magnetic fields). [13, 14]

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