Intrinsic Fluid Magnetism and Magnetic Monopole Clues in Liquid Metal Droplet Machines

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Abstract

Magnetism and magnetic monopoles are classical problems in physics. Conventional magnets are typically composed of rigid materials, which may face challenges when addressing extreme questions. Here, for the first time, departing from conductive fluid materials that differ from rigid magnets, we propose the generation of fluidic endogenous magnetism and thereby the construction of magnetic monopoles through the regulation of liquid metal machines. Based on theoretical explanations and proof-of-concept experimental evidence, we elucidate that when gallium-based liquid metal in solution rotates under electrical driving, an endogenous magnetic field forms within it, which provides a sound explanation for the experimental phenomenon that two such separated metal droplets can readily merge together, as a result of mutual attraction between their corresponding N and S poles. Furthermore, we further demonstrate that self-propelled liquid metal machines manifest as an endogenous fluidic magnet with electromagnetic homology; when liquid gallium in solution ingests aluminum, it forms a rotating motor and an in-body dynamically varying charge distribution, thereby generating endogenous magnetism internally; this explains the frequent phenomena of reflective collisions and attractive fusion between moving liquid metal motors, phenomena attributable respectively to the dynamic adjustment of N and S poles between the motors. Finally, we propose that magnetic monopoles can be realized through such fluidic endogenous magnets, and put forward four technical approaches to achieve this goal: 1. Engineering the internal flow field of liquid metal machines; 2. Leveraging the superposition effect of external electric field effects and magnetic fields; 3. Employing composite structures between magnetic particles and liquid metal motors; 4. Chemical approaches, such as through galvanic cell reactions. Overall, the theory and experimental evidence provided in this paper reveal the mechanism of liquid metal machines as fluid-type endogenous magnets, and identify several promising routes toward realizing magnetic monopoles. This foundation may enable the development of unconventional magnetoelectric devices and applications in the near future.

Full Text

Preamble

Fluidic Endogenous Magnetism and Magnetic Monopole Clues from Liquid Metal Droplet Machine

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Abstract

Magnetism and magnetic monopoles are classical issues in physics. Conventional magnets are generally composed of rigid materials that may face challenges in extreme situations. Here, from an alternative perspective beyond rigid magnets, we propose for the first time to generate fluidic endogenous magnetism and construct magnetic monopoles through tuning liquid metal machines. Based on theoretical interpretation and conceptual experimental evidence, we illustrate that when gallium-based liquid metal in solution rotates under electrical actuation, it forms an endogenous magnetic field inside, which well explains the phenomenon that two such discrete metal droplets could easily fuse together, indicating their reciprocal attraction via N and S poles. Further, we clarify that the self-fueled liquid metal motor also operates as an endogenous fluidic magnet owning electromagnetic homology. When liquid gallium in solution swallows aluminum inside, it forms a spin motor with dynamically variable charge distribution that produces endogenous magnetism inside. This explains the phenomena that reflection collisions and attraction fusion often occur between running liquid metal motors, which are just caused by the dynamic adjustment of their N and S polarities, respectively. Finally, we conceive that such an endogenous magnet could lead to magnetic monopoles, and four technical routes to realize this objective are thus suggested: (1) Matching interior flow of liquid metal machines; (2) Superposition between external electric effect and magnetic field; (3) Composite construction between magnetic particles and liquid metal motor; (4) Chemical ways such as via galvanic cell reaction. Overall, the present theory and revealed experimental evidence disclose the role of liquid metal machines as fluidic endogenous magnets and point out promising ways to realize magnetic monopoles. A group of unconventional magnetoelectric devices and applications may become possible in the near future.

Keywords: Fluidic magnet; Magnetic monopole; Liquid metal; Endogenous magnetism; Droplet machine; Tiny motor

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1. Introduction

Although magnetic fields are invisible and intangible, they constitute a special substance that exists objectively, ranging from cells to the periphery of stars. So far, researchers have conducted in-depth studies on various known magnetic fields [1,2], such as those in coils, Earth, and galaxies, as shown in [Figure 1: see original paper]A-C. Magnets exert forces and moments on each other through their respective magnetic fields. With the magnetic field as a medium, objects can transmit magnetic force without contact. The study of magnetic fields is of great significance to scientific and technological progress, with applications in electronic cooling [3], microfluidic chips [4], graphene orientation control [5], medical imaging and tumor treatment [6-8], visual probes of amino acids [9], life science magnetic proteins [10], magnetotactic bacteria [11,12], and many others.

According to modern physics, the magnetic field produced by moving electric charges (Figure 1A) is fundamentally determined by moving electrons or protons. The atom is the smallest basic unit that constitutes a substance, and the magnetism of a substance is the collection of the magnetism of all the atoms it contains. Inside the atom, the nucleus has spin motion, and the electrons outside the nucleus rotate while revolving around the nucleus. These motions generate tiny circular currents. According to Maxwell' s electromagnetic theory, electricity and magnetism are induced by each other. These tiny circular currents will induce a corresponding magnetic field. Therefore, the magnetic field generated by current or point charge is the macroscopic manifestation of the magnetic field generated by a large number of moving electrons or protons.

Traditionally, from microscopic magnetic nanoparticles to macroscopic natural magnets, as well as artificially manufactured excitation coils (Figure 1B) and permanent magnets, all are composed of rigid materials, with their N and S poles located at fixed ends of the magnet. Generally, their shape and structure cannot be changed on the eigen-scale, which makes their applications somewhat limited. To improve magnet adaptability to different situations, researchers have invented magnetic fluid functional materials, which are colloidal solutions formed by surface-active-agent-encapsulated nanomagnetic particles dispersed in a base fluid [13], exhibiting special magnetic and optical properties. Although fluidity has been enhanced, the part that exhibits magnetism has not deviated from the essence of rigid magnets. Recently, as a base fluid material for loading magnetic nanoparticles, liquid metal has been gradually developed as multifunctional materials due to its outstanding electrical and thermal conductivity and ductility. Its excellent deformability allows droplets to adapt to paths of different sizes. In particular, the chemical properties of room-temperature liquid eutectic alloys such as GaIn and GaInSn are relatively stable under normal conditions. Their low toxicity and good operability allow researchers to adjust the alloy ratio to achieve various melting points and characteristics, enabling them to perform tasks that rigid materials cannot.

Previous studies on the magnetic properties of liquid metal have mostly involved adding iron particles [14] or chemically coating a layer of nickel on the droplet surface [15], then using magnets to manipulate the composite material. The orientation of the magnet causes changes in the droplet' s motion state. Even when the droplet' s position is unknown, the magnet can attract the liquid metal to achieve rapid control. However, the story does not end there. Here, we conceive that on a microscopic level, the spherical liquid metal droplet in fact forms a weak endogenous magnetic field when excited by its own circular current or an external current during rotation. This rapidly rotating liquid metal droplet not only possesses the magnetic properties of rigid materials but also flows like water, belonging to a new kind of magnetic matter, termed a fluidic magnet.

Furthermore, we conceive that the disclosure of the fluidic magnet offers another important clue to answer the classical issue of magnetic monopoles, one of the most intriguing scientific mysteries in nature. When people try to tackle the fundamental problem of whether magnetic monopoles exist, they tend to explore clues in rigid materials or magnets, which may not always be rational in reality. The magnetic poles of such materials are usually in fixed positions. The magnetic field lines are emitted from the N pole outside the magnet and return to the S pole, while inside the magnet, the S pole points to the N pole, forming countless closed circuits. This fixed pattern of magnetic field distribution limits the routes to verify the actual existence of magnetic monopoles.

So far, magnetic monopoles have only appeared as quasi-particles in condensed matter, such as the flipping excitation of spin ice [16-18] and similar structures produced by vortices of super-cold rubidium atoms in Bose-Einstein condensates (BEC) [19]. However, we realized that as a variable fluidic conductor, the liquid metal machine generates a constantly changing endogenous magnetic field during random spin motion. When an external electric or magnetic field is superimposed, or when compounding with magnetic particles, or through artificially modifying the magnetic field via internal chemical reactions, even more diverse magnetic field configurations or behaviors will be generated. This is fundamentally different from conventional rigid magnetic materials with fixed poles. This article is dedicated to presenting a new conceptual fluidic magnet and providing several possible technical routes toward finding magnetic monopoles.

2. Experimental Evidences of Fluidic Endogenous Magnetism from Liquid Metal Machine

2.1 Basic Properties of Conductive Fluidic Metal

At the macro level, the flexibility or rigidity of a material has an important impact on its application. In recent years, with the development of materials science, various unique effects of soft matter have been gradually discovered and utilized. Particularly, room-temperature liquid metal possesses many favorable properties, including large surface tension, ideal flexibility, high conductivity, and low toxicity. From [20], it can be seen that typical liquid metals generally have very similar fluidity to water while their thermal conductivities are dozens of times higher. Especially, the excellent electric conductivity of such matters molds them into intrinsically conductive fluid. Basically, electrically conductive solutions such as aqueous NaOH, NaCl, etc., may also display similar behavior with liquid metal. But considering the huge conductivity of liquid metal, such fluid will particularly play a dominant role in developing liquid magnets and is therefore the core of current analysis.

As gradually realized by recent studies, the excellent characteristics of liquid metal make it available in the fields of fluidics ([Figure 2: see original paper]A), printed circuits ([Figure 2: see original paper]B), flexible sensors, transformable machines ([Figure 2: see original paper]C), self-driving motors ([Figure 2: see original paper]D), and the base carrier fluid for magnetic particles ([Figure 2: see original paper]E), etc. The present research focuses on the electromagnetic effects of such fluidic conductive material. Particularly, the shape and motion of liquid metal have great variability and controllability, and the magnetic field generated by it will have rather rich possibilities, which appears more competent on some occasions. In this sense, we can come up with a generalized matter state, which can be termed as electromagnefluid, indicating material that simultaneously consists of electronics, magnetism, and fluid inside together.

2.2 Magnetism Induced from Liquid Metal Energized Coil

Liquid metal has good flexibility and conductivity and can replace traditional rigid coils, making the moving parts of electromagnetic actuators more flexible, thereby improving the ability to deal with complex situations. Currently, there are two main methods to make liquid metal electromagnetic coils. One is to use optical mask technology to lithograph microchannels on PDMS substrates and then inject liquid metal into them [25]. In this way, the liquid metal remains in fluidic form ([Figure 3: see original paper]A).

Another method is to use a mask with a specific shape to cover the PDMS substrate and uniformly print the liquid metal on the PDMS film through a liquid metal spray gun ([Figure 3: see original paper]B) [26]. Compared to the first method, this direct printing method has a shorter production cycle and simpler operation. In this case, the liquid metal exists on the PDMS in a semi-solid form; that is, the part in contact with air is oxidized to solid, but the liquid metal inside still retains the possibility of flowing behaviors.

In the magnetic driving device, the magnet was placed above or below the liquid metal electromagnetic coil ([Figure 3: see original paper]C), and the magnetic field lines passed through the electromagnetic coil. When alternating current was applied, the Lorentz force **F** was generated in the coil:

$$\mathbf{F} = I\mathbf{dl} \times \mathbf{B}$$

where **dU** as indicated in [Figure 3: see original paper]D is the potential difference between the two ends of the microsegment **dl**. Macroscopically, the Lorentz force generated by the magnetic field component parallel to the coil drove the coil to move closer to or away from the magnet.

Regarding the first injection method, since the flow channel is sealed and the operating temperature is higher than the freezing point of the liquid metal, the alloy in the flow channel is always liquid. Under the action of an external electric field, in addition to inducing a magnetic field, the microsegment would also generate an endogenous magnetic field under alternating current. This segment had weak attractive or repulsive interaction with the placed magnet and other microsegments. However, this force was too weak; only the device action dominated by the Lorentz force of the coil could be observed.

2.3 Endogenous Magnetism Generated by Electrically Tunable Liquid Metal Machine

Applying an electric field to liquid metal can induce its transformation, movement, or rotation, and its motion state depends on the direction and strength of the applied electric field, contact with the electrode, and the surrounding solution environment, respectively [22]. To illustrate the basic principle of generating an endogenous magnet by electrically controlled liquid metal machine, we designed a cylindrical channel with a smooth surface and placed a spherical liquid metal droplet in the electrolyte-filled solution ([Figure 4: see original paper]). After applying an external field, the liquid metal immediately responded, rotating and moving toward the positive electrode. The original spherical droplet was stretched; taking the advancing direction of the droplet as the head, we observed that the tail had slight deformation. When the applied electric field was large enough, the droplets were dragged instantaneously ([Figure 4: see original paper]A-D) and even separated into two small droplets, as shown in [Figure 4: see original paper]D.

Due to the difference between the physical properties of the liquid metal and the electrolyte solution, the electric field would be stepped at the two-phase contact interface, thereby generating electrical stress. At the same time, GaIn liquid metal could react with NaOH solution to generate $[\mathrm{Ga(OH)_4}]^-$, which would be specifically adsorbed onto the Ga surface—that is, in the Helmholtz layer. The surface of Ga was negatively charged due to the abundance of reactive electrons, and the diffusion layer was positively charged, forming an electric double layer (EDL). According to Lippmann’ s equation, there was a connection between surface tension and potential difference [23]:

$$\gamma = \gamma_0 - \frac{1}{2}cV^2$$

where γ is the surface tension, c is the capacitance per unit area of EDL, V is the potential difference of EDL, and γ_0 is the maximum surface tension when V = 0.

The EDL makes the charge distribution of two droplets similar. Using an electrode to drag a droplet and approach another in the solution, when the distance between the two was small enough, they would quickly merge. This internal rotation caused by an external electric field was similar to the spontaneous rotation of the droplet after swallowing aluminum, which we will explain in detail in a later section.

In the system composed of liquid metal and water, we found that the influence of liquid metal on the surrounding water was rather evident under the action of an external electric field. The system layout is shown in [Figure 5: see original paper]A, where a spherical liquid metal droplet was placed in water and a pair of electrodes extended into the surrounding solution. When current was applied, the liquid metal sphere started to rotate, and two eddies appeared in the surrounding solution, spinning continuously with the rotation of the liquid metal sphere. Therefore, the external electric field could induce the liquid metal to rotate, causing real-time change of the electronic charge distribution on the droplet surface. This moving charge would cause the droplet to generate an endogenous magnetic field, as shown in [Figure 5: see original paper]B.

Because the flow direction of the droplet surface was along the electric field gradient, when applying alternating current, the direction of the electric field changed periodically, and the flow state of the liquid metal would also change accordingly, as shown in [Figure 5: see original paper]C. Before and after the external electric field was applied, the electric field on the liquid metal-electrolyte interface would change ([Figure 5: see original paper]D). As the alternating frequency increased, the vortex current formed inside could become stronger, and the magnetic field generated inside would be strengthened accordingly. It should be noted that such an endogenous magnetic field was a manifestation of electricity and magnetism on a microscopic level, and its intensity was much smaller than the magnetic field induced by the change of the external electric field.

2.4 Endogenous Magnetic Field Generated from Self-Driving Liquid Metal Motor

According to our former discovery, small liquid metal droplets possess intriguing self-driving capability after being fueled with aluminum [28] and can automatically converge or diverge [29], which is a very unconventional feature that traditional rigid machines do not possess. We placed a spherical liquid metal droplet in NaOH solution and added some aluminum foil, as shown in [Figure 6: see original paper]A. According to Rebinder' s effect, after a period of time, the aluminum foil was completely infiltrated and corroded by the liquid metal; the oxide layer on the aluminum surface was destroyed, causing Al to activate and triggering a redox reaction. The electrons from the aluminum interior preferentially deoxidized the oxidized gallium near the Al. The charge distribution of the EDL changed, resulting in a potential gradient and asymmetric surface tension on the droplet surface [30]. According to the Young-Laplace equation, the pressure difference p between the solution and the liquid metal droplet can be expressed as:

$$p = \gamma \left(\frac{1}{r_1} + \frac{1}{r_2} \right)$$

where 1/r is the curvature of the droplet surface [31].

The liquid metal sphere moved randomly in the solution and was accompanied by its own rapid rotation, as shown in [Figure 6: see original paper]B. Their lifetime lasted for more than one hour without any other external energy [23]. According to our former measurement, this self-fueled liquid metal motor generated electrical voltage and current between its surface and the surrounding electrolyte ([Figure 6: see original paper]C). It is this dynamically variable electrical field that leads to the generation of endogenous magnetism inside the liquid metal motor.

In addition, there was a galvanic reaction composed of liquid metal, aluminum foil, and electrolyte solution, which accelerated the speed of the electrochemical reaction. After being corroded by GaIn alloy, aluminum aggregated or dispersed on the surface, then was uniformly distributed in the liquid metal in the form of small particles, and hydrogen was generated by the electrochemical reaction (Equation 4):

$$2\mathrm{Al} + 2\mathrm{NaOH} + 2\mathrm{H_2O} = 2\mathrm{NaAlO_2} + 3\mathrm{H_2} \uparrow$$

The average voltage and current between the liquid metal and the electrolyte could be measured by Avometer [23], as shown in [Figure 6: see original paper]C. The gas released from the interface also pushed the liquid metal forward, forming a self-driving motor. When the droplet size was larger, the specific surface area would reduce and the electrochemical reaction sites were limited, resulting in less gas generation, and the driving force of the gas did not have an obvious effect on the large droplet. Therefore, the self-driving of liquid metal in a large volume mainly depended on the tension gradient, and the effect of the latter was negligible.

Next, we explored the mergences of rotating droplets ([Figure 7: see original paper]). In the solution, two liquid metal droplets rotated inside after swallowing aluminum, changing the flow line of the surrounding fluid [32]. When the distance between the two was small enough, they would quickly merge into one. It could be seen from the former section that the surface charge distribution of the droplets changed in the electrolyte and formed an electric double layer. This structural similarity promoted the mergences of the droplets.

Here, we proposed that the rotation inside the droplet not only enabled itself and the surrounding flow field to maintain a state of motion but also had the ability to excite an endogenous magnetic field. During the rotation process, through adaptive adjustment, it induced a magnetic field that attracted each other. The two droplets were brought closer and merged into one, as shown in [Figure 7: see original paper]A-D. Over the process, various endogenous magnetic fields were induced inside the liquid metal ([Figure 7: see original paper]E-H). This mechanism allows discrete droplet machines to be quickly assembled, which has profound significance for self-assembly machines with internal trigger motion.

2.5 Liquid Metal Spin Superimposed on an External Magnetic Field

Adding aluminum to liquid metal can form tiny motors in NaOH solution, but the movement is random and lacks specific direction and speed [32]. If this random movement can be controlled, the liquid metal self-driving motor can be used in more applications, such as transformable intelligent robots, precise drug delivery, and detectors/sensors. We placed a permanent magnet under the petri dish to introduce a magnetic field to adjust the random movement of the motor. The $GaIn_{10}$ liquid metal motor exhibited a significant group effect at the boundary of the permanent magnet. Over time, the motor group gathered near the boundary of the magnet and then rebounded after a short stay. Tan et al. [33] suggested that this peculiar phenomenon was related to the magnetic flux density of the bottom magnet, with magnetic intensity being zero at the boundary of the magnet. At first, these droplet motors were attracted by the magnet, leading to aggregation. The higher magnetic intensity on the side of the magnet prevented the motor from passing, while the peak of the magnetic field on the side away from the magnet was lower. The droplet motor selectively tended to the low-peak position, thus limiting the motor’ s range of motion.

Based on our former experimental video [33], we tracked the motion path of a single droplet motor and carried out a more in-depth interpretation of the interaction mechanism between the liquid metal and the permanent magnet. Here, we proposed a conjecture that the spin of liquid metal generated a weak magnetic field on a microscopic level. Since the motor was small enough and in a solution environment, the spin drive of the motor could more clearly show characteristics related to the magnet. The magnetic field generated by the spin is non-directional, and the droplet exhibited the same or opposite magnetic poles as the magnet at the boundary of the magnetic field, resulting in repulsion or attraction.

We studied the effect of the external magnetic field on the moving liquid metal droplet in the above phenomenon. From the present analysis, it is known that the rotating liquid metal droplet will generate a magnetic field, and there will be negatively charged free electrons flowing through it. The magnetic field intensity of a permanent magnet around it is **H**, and the magnetic induction intensity is **B**. Then the liquid metal sphere will be subjected to the Lorentz force of permanent magnet induction intensity on the charged sphere, and simultaneously the force of magnetic field intensity on the sphere’ s own magnetic field. First, we analyze the Lorentz force on the sphere. Assuming that the moving speed of the liquid metal sphere is **v** and the overall charge is **Q** at a certain time, the liquid metal sphere can be regarded as a large charged particle. Then the force $\mathbf{F}_1$ at this time can be obtained from the Lorentz force formula in classical electromagnetics:

$$\mathbf{F}_1 = Q\mathbf{v} \times \mathbf{B}$$

The stress of the liquid metal sphere in the magnetic field intensity is analyzed using the equivalent magnetic charge theory available in classical textbooks. Assuming that the magnetization of the liquid metal sphere is **M** and the magnetization in the solution is **M** , then the equivalent surface magnetic charge density on the surface of the liquid metal sphere is:

$$\kappa = \mu_0(\mathbf{M}_p - \mathbf{M}_s) \cdot \mathbf{n}$$

where $_0$ is the vacuum permeability and **n** is the normal vector of the liquid metal sphere surface.

By integrating the surface S of the sphere, the magnet product force of the sphere under the magnetic field intensity can be obtained:

$$\mathbf{F}_2 = \int_S \kappa \mathbf{H} \, dS$$

Therefore, the total force of the applied magnetic field on the liquid metal sphere in this system is:

$$\mathbf{F} = \mathbf{F}_1 + \mathbf{F}_2$$

For a small-volume liquid metal motor, as shown in [Figure 8: see original paper]A-D, the magnetic field strength was smallest near the magnetic field boundary, and the magnetic force on the droplet motor was weak. Therefore, the motor oscillated in a small range nearby. The force was converted into the momentum of the drop, making the momentum continuously accumulate. When the motor moved away from the magnetic field, the magnetic pole facing the magnet was the same as the magnet, producing a repulsive force. When it reached a certain value, it could break away from the restraint of the magnetic field boundary, appearing to be bounced off by the magnet on the macroscopic view.

Due to the increase of the magnetic field along the diameter of the magnet, the droplet far away from the magnet would be in a larger magnetic flux density space, the magnetic force would become more obvious, and the momentum would further increase. Although the magnetic poles generated by the endogenous magnetic field might be attracted by the permanent magnet at the next moment, the attractive force could not pull back the large-momentum droplet moving away from the magnet at that time, so the droplet eventually moved away from the magnet.

However, large-volume motors were not as sensitive to weak magnetic fields at the boundary of magnets as small-volume motors, as shown in [Figure 8: see original paper]E-H. When the large-volume motor happened to approach the permanent magnet with the same pole, it would be hindered by the external magnetic field. In the process of approaching the center of the magnetic field, the motor' s potential energy continued to accumulate and the momentum gradually decreased. Under continuous accumulation of reverse acceleration, the liquid metal motor began to move away from the magnet ([Figure 8: see original paper]I), and the accumulated potential energy turned back into its own momentum. When the speed reached a certain level, it could break away from the restraint of the magnetic field boundary.

Based on the above discussion, we suggested that when the motor had the same or opposite magnetism as the bottom permanent magnet, it was bounced or attracted ([Figure 8: see original paper]J), resulting in the macroscopic effect of the motor group rotating, oscillating, gathering, and bouncing off the boundary of the magnet. This effect was affected by the volume of the motor.

2.6 Magnetic Field Generated from Liquid Metal under Chemical Environment

Liquid metal reacts with other metals to form a galvanic cell, which is also a form of causing self-rotation. Since liquid metal is easily oxidized in air and forms an oxide layer on the surface, which is not conducive to observation and analysis of surface and internal movement, we usually place the liquid metal in an acid or alkaline solution for operation to remove the surface oxide film, and on this basis, build a galvanic battery with other metals.

Previous studies have revealed the Marangoni effect caused by gallium-copper galvanic corrosion couples [34], which is the phenomenon where the tension gradient between the liquid interface moves the mass. Here, liquid metal was used as the anode, Ga was oxidized to Ga^{3+}, and copper was adopted as the cathode. The cathode had a corrosion potential between (Ga/Ga^{3+}) and (H/H^{+}), so H^{+} was reduced to H_2 on the cathode (Equations 9, 10). Therefore, the essence of the liquid metal Marangoni phenomenon was galvanic corrosion:

$$\mathrm{Ga} \rightarrow \mathrm{Ga}^{3+} + 3e^{-}$$

$$2\mathrm{H}^{+} + 2e^{-} \rightarrow \mathrm{H}_2$$

Ga reacted with HCl solution to produce gas at the liquid interface. By tracking the movement trajectory of the bubble, the flow state of the liquid metal could be obtained. As shown in [Figure 9: see original paper]A, the liquid metal on the left was in contact with the copper sheet, and the streamlines of liquid gallium were marked in yellow. Here, the liquid metal participated in the reaction as part of the galvanic battery, and the internal rotation could make the charge continue to flow through it ([Figure 9: see original paper]B and C), which also provided conditions to excite the endogenous magnetic field.

In addition to the above-mentioned characteristics, liquid metal also has unique reversibility, that is, via synthetically chemical-electrical mechanism (SCHEME) to control its structure [35]. As shown in [Figure 10: see original paper]A, two platinum electrodes were inserted into the liquid metal and electrolyte. According to our former research, when direct current was applied, an oxide layer was formed on the gallium surface at the anode, and the surface tension decreased. The originally spherical droplet appeared to spread out ([Figure 10: see original paper]B), and the surface area increased, even reaching five times the original size. When the applied electric field was removed, the gallium oxide on the surface chemically reacted with NaOH solution, and the surface tension of the droplet increased and returned to the spherical state, as shown in [Figure 10: see original paper]C and D. This reversible SCHEME was affected by many factors, such as current intensity, electrode spacing, liquid metal volume, electrolyte concentration, and so on.

In this system that combines chemical dissolution and electrochemical oxidation, liquid metal was both a conductor and a reactant. In the process of continuous expansion and contraction, the change of surface tension and the redistribution of charge could be achieved by controlling the external electric field. In this process, the internal oscillations were synergistic with the movement of electric charges, and the electric charges of these motions were also related to the dynamic magnetic field. Therefore, the internal chemical mechanism of liquid metal also had the possibility of generating an endogenous magnetic field.

3.1 Generation of Endogenous Magnetic Field from Liquid Metal Machines

When an external electric field is applied or the liquid metal reacts with other metals to form a galvanic cell, the liquid metal acts as a conductor with current passing through its surface while the inside of the droplet rotates simultaneously. From the above experiments, we have observed that liquid metal can generate endogenous magnetic fields through rotation. Next, based on some basic principles available in classical electromagnetics textbooks, we will conduct theoretical analysis and formula derivation of this peculiar phenomenon and attempt to provide a more in-depth explanation.

For the physical properties of the liquid metal spherical droplet, its density , electrical conductivity σ, and magnetic permeability $_0$ are all constants. According to Maxwell' s electromagnetic equations, the electromagnetic equations describing the space around the spherical droplet of liquid metal can be obtained as:

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{D} = \rho_e$$

And its physical property equations are:

$$\mathbf{B} = \mu_0 \mathbf{H}$$

$$\mathbf{J} = \sigma \mathbf{E}$$

$$\mathbf{D} = \varepsilon \mathbf{E}$$

where $\mathbf{H}$ is the magnetic field strength (unit: $\mathrm{A \cdot m^{-1}}$), $\mathbf{E}$ is the electric field strength (unit: $\mathrm{V \cdot m^{-1}}$), $\mathbf{B}$ is the magnetic induction (unit: T), $\mathbf{J}$ is the current density (unit: $\mathrm{A \cdot m^{-2}}$), $\mathbf{D}$ is the electric displacement (unit: $\mathrm{C \cdot m^{-1}}$), and is the dielectric constant.

First, we analyze the liquid metal droplet in rotating state after swallowing aluminum foil, as shown in [Figure 11: see original paper]A and B. The liquid metal droplet, aluminum foil, and electrolyte solution together constitute a short-circuit galvanic cell system, with aluminum foil as the cathode and liquid metal as the anode. For the rotating liquid metal droplet, its internal current will be composed of two parts: the first part is the galvanic current I_1 produced by the electrochemical reaction of the galvanic cell, and the second part is the rotating current I_2 produced by charge moving in the rotating process. The current density of the liquid metal droplet is also composed of these two parts, named J$_1$ and J$_2$ respectively, and the synthetic magnetic field of the liquid metal droplet is generated under these two different currents.

We define the angular velocity of the liquid metal droplet as ω and suppose that when current flows inside, the direction of the current is parallel to the rotation axis of the liquid metal droplet in dynamic equilibrium. The radius of the sphere of the liquid metal droplet is ‘a’ , the center of the sphere is the origin, and the axis of rotation is the polar axis to establish a spherical coordinate system; r is the distance from any point to the center of the sphere. Assuming that Q$_1$ is the total charge passing through the maximum cross-section (radius = a) of the liquid metal droplet within time t, the current passing through the maximum cross-section can be equivalent to:

$$I_1 = \frac{Q_1}{t}$$

During time t, the current density flows on any circular cross-section perpendicular to the current direction on the sphere as follows:

$$\mathbf{J}_1 = \frac{I_1}{s_1}\mathbf{n}_1$$

where s$_1$ is the area of the circular cross-section (with $0 < \mathrm{r} \leq \mathrm{a}$), and $\mathbf{n}_1$ is the normal vector of surface s$_1$.

For the second part, the liquid metal droplet will also produce current I$_2$ in the process of rotating. Assuming that in the process of constant rotation, the charge amount of the liquid metal droplet is Q$_2$, then the volume charge density is:

$$\rho = \frac{3Q_2}{4\pi a^3}$$

The corresponding current density is:

$$\mathbf{J}_2 = \rho\mathbf{v} = \rho\omega \times \mathbf{r}$$

Under steady conditions, using the formula of the vector potential generated by current in the classical theory of electromagnetics, the vector potential of any point A (r$_1$, , ϕ) outside the liquid metal droplet can be obtained as:

$$\mathbf{A}(\mathbf{r}_1) = \frac{\mu_0}{4\pi}\int \frac{\mathbf{J}_1 + \mathbf{J}_2}{|\mathbf{r}_1 - \mathbf{r}|}\,dV$$

where $|\mathbf{r}_1$ - $\mathbf{r}|$ is the distance between point $\mathbf{r}_1$ (r$_1$, $_1$, ϕ_1) and point $\mathbf{r}$ (r, , ϕ).

According to the basic equation under steady electric fields, the galvanic current and the rotating current flowing through the liquid metal droplets can be obtained together at any point A outside the body. The resulting expression of the total magnetic induction is:

$$\mathbf{B}(\mathbf{r}_1) = \nabla \times \mathbf{A}(\mathbf{r}_1)$$

Next, we analyze the liquid metal sphere rotating under a constant external electric field, as shown in [Figure 11: see original paper]C and D. This is similar to the previous analysis. The only difference is that the liquid metal sphere droplet does not have the current generated by the galvanic reaction but has an external conduction current under the external electric field. When an electric field is applied, the liquid metal droplet in the electrolyte solution will not only conduct current but also form a rotating current. In this case, it is also assumed that I_3 is the conduction current flowing through the largest cross-section (r = a) of the sphere; then the area current density flows on the circular cross-section perpendicular to the current direction is:

$$\mathbf{J}_3 = \frac{I_3}{s_2}\mathbf{n}_2$$

where $\mathbf{n}_2$ is the normal vector of surface s_2.

Similarly, it is assumed that liquid metal droplets will also generate a rotating current I_4. During constant rotation, it always has a charge of Q_4, so the charge density is:

$$\rho = \frac{3Q_4}{4\pi a^3}$$

Its current density is:

$$\mathbf{J}_4 = \rho\mathbf{v} = \rho\omega \times \mathbf{r}$$

Similar to the above analysis, the vector potential of any point B (r_2, , ϕ) outside the body of the liquid metal droplet can be obtained using the same current-to-vector-potential formula:

$$\mathbf{A}(\mathbf{r}_2) = \frac{\mu_0}{4\pi}\int \frac{\mathbf{J}_3 + \mathbf{J}_4}{|\mathbf{r}_2 - \mathbf{r}|}\,dV$$

where $|\mathbf{r}_2$ - $\mathbf{r}|$ is the distance between point $\mathbf{r}_2$ (r_2, $_2$, ϕ_2) and point $\mathbf{r}$ (r, , ϕ).

Then the liquid metal droplet under external electric field is integrated by the conduction current and the rotating current, and the total magnetic induction intensity generated at any point B outside the body is expressed as:

$$\mathbf{B}(\mathbf{r}_2) = \nabla \times \mathbf{A}(\mathbf{r}_2)$$

Through the analysis and calculation of the above two motion phenomena of the liquid metal sphere droplet, it can be seen that when the liquid metal droplet is rotating in the solution and there is current passing through it, the sphere itself will also generate a rotating circular current due to the rotating motion. The superposition of these two currents will generate a magnetic field together. At the same time, due to the instability of the rotation of the liquid metal spherical droplet on the plane, its rotational direction will suddenly change within a period of time, resulting in a change in the direction of the magnetic field.

What needs to be pointed out here is that the spherical liquid metal droplets that rotate by swallowing aluminum foil generate a specific magnetic field, which is essentially different from the magnetic fluid widely reported in the past. This kind of liquid metal is still in full fluid form. It can adjust the rotation speed, volume, and current in the rotation process and can possibly be applied to various research applications that require flexible magnetic fluid by virtue of the characteristics of full fluid.

3.2 Technical Routes to Realize Magnetic Monopole from Liquid Metal Machines

Most of the liquid metal magnetoelectric devices and magnetic drive structures reported in the past used an external electric field to change the overall magnetic field of the structure, thereby causing the device to act. For example, a layer of spiral GaIn alloy was printed on PDMS to obtain a flexible electromagnetic driver [26]. When alternating current was applied to both ends of the coil, the coil would generate a magnetic field, which was attracted and repelled by the magnets on both sides according to the alternating frequency of the current, simulating jellyfish swimming, fish tail swinging, and other actions as made in the present authors' lab. There were also studies using the electromagnetic interaction between a magnet and a Galinstan liquid metal coil to generate sound waves and made a retractable dynamic acoustic device [36].

However, the spin motion of liquid metal can excite the endogenous magnetic field in essence. Because the two magnetic poles of traditional rigid materials are relatively fixed, it is difficult to find a matching substance when searching for magnetic monopoles, and it is even more difficult to find a case through experimental observation. Considering the aforementioned four basic ways of exciting the magnetic field with liquid metal, we proposed several possible methods of artificially synthesizing a liquid metal sphere similar to a magnetic monopolar state.

Route 1: Matching the interior flow field of liquid metal droplet machines. As shown in [Figure 12: see original paper]A, while the liquid metal sphere rotates itself after swallowing the aluminum foil, there may be vortex-shaped small spheres inside which move opposite to the outer fluid. This unique nested structure makes it possible to artificially synthesize magnetic monopoles. When the outer sphere rotates around the axis, the inner four small spheres perform their respective circular motions in opposite directions. Then, through micro-scale manipulation, such as regulating the position and speed of the rotation, the magnetic effect of the N pole or S pole generated in the outer area and the magnetic poles generated by the four small spheres in the interior are mutually offset, so that the entire liquid metal sphere exhibits only a single magnetic pole.

Route 2: Superposition between external electric effect and magnetic field. Secondly, an external field superposition method can be adopted. As shown in [Figure 12: see original paper]B, a tiny permanent magnet is inserted into the bottom end of the liquid metal sphere. When the liquid metal sphere is spinning, the permanent magnet is fixed, so that the magnetic field of the permanent magnet and the magnetic field generated by the spin of the liquid metal sphere are superimposed. Since the permanent magnet is at one end of the liquid metal sphere, the endogenous magnetic field excited by the spin interacts with the magnetic field of the permanent magnet. When the two cancel out at a certain moment, the remaining magnetic field is located at the end far away from the permanent magnet. At this time, the liquid metal sphere will exhibit such un-cancelled magnetism.

Route 3: Composite construction between magnetic particles and liquid metal motor. In addition, adding appropriate magnetic nanoparticles into the liquid metal sphere is also a possible method, as shown in [Figure 12: see original paper]C. Since the ferromagnetic particles are very tiny, when they are uniformly mixed with the liquid metal spheres, the spinning liquid metal spheres will also generate many tiny magnetic fields. The endogenous magnetic field can also interact with the ferromagnetic particles added. Proper control of the number, shape, and position of magnetic nanoparticles can also make the synthetic magnetic field of the liquid metal sphere exhibit a certain unipolar characteristic.

Route 4: Chemical ways such as via galvanic cell reaction between liquid metal motor and substrate or foreign substances. Finally, chemical reaction can generally be a possible option, as shown in [Figure 12: see original paper]D. As mentioned above, when copper contacts the surface of the liquid metal to form an electrode pair, a galvanic battery system that can undergo electrochemical reactions is formed in an alkaline solution. When current flows through the liquid metal, the droplet spins under the influence of the surface tension gradient. In such an environment where two different metals are in contact with each other, it is possible to simultaneously manipulate another metal substrate (like copper) and a spinning liquid metal sphere, so that the sphere produces a synthetic magnetic field with apparent single-pole characteristics.

Overall, in the above four different methods of constructing the single magnetic pole, the control of the spin vortex inside the liquid metal is a certain challenge due to the changeable rotation state of the droplet, while the other three methods have certain feasibility. Therefore, it is possible to synthesize a magnetic substance that acts as a source or sink of magnetic field lines by using the spin characteristics of the liquid metal sphere and through artificial control, which is expected to provide supporting evidence for the actual existence of magnetic monopoles in the coming time.

4.1 Revisit of Classical Magnetic Monopole Theory

Under active vacuum conditions, Maxwell' s equations do not satisfy the invariance of electromagnetic duality; that is, electrons are regarded as the source and sink of electric field lines, implying that particles with basic magnetic charges are related to the emission of magnetic field lines. Therefore, Dirac proposed the magnetic monopole theory in 1931 to resolve this problem [37]. A magnetic monopole is a magnetic substance with only a single magnetic pole of N or S pole in theoretical physics, and its magnetic line of induction is similar to the electric field lines of a point charge, as shown in [Figure 13: see original paper]A. Dirac used a mathematical formula to guess its existence by analyzing the phase uncertainty of the wave function of a quantum system. It should be pointed out that if the magnetic monopole really exists, the electric charge and magnetic charge must be quantized in quantum mechanics. In modern physics, charge quantization has become an important theory, and this theory has also promoted the process of researchers looking for magnetic monopoles.

To find magnetic monopoles, researchers have conducted many explorations for decades. A well-known theory related to magnetic monopoles is the Grand Unified Theory (GUTs), in which strong interaction forces, weak interaction forces, and electromagnetic forces can be unified into a normative interaction. Unlike elementary particles, a magnetic monopole is a regional energy called a solitary wave. The size and mass of a magnetic monopole can be estimated through unified field theory, and the mass of a magnetic monopole is approximately about 10^{16} GeV [38,39]. At the same time, the internal space freedom of the gauge theory makes the magnetic monopole have a certain topological structure and provides a guarantee for stability. Although GUTs is dedicated to unifying the interaction forces between microscopic particles, it has not been finally verified, nor can it solve problems such as the “excess” of magnetic monopoles [40]. In addition, String theory, M-theory, etc., have also conjectured the existence of magnetic monopoles.

4.2 Extension of Magnetic Monopole Concepts

Except for the classical approach, some physicists turned to strictly mathematical approaches to find possible clues toward magnetic monopoles. For example, Yang et al. [41] introduced the overlapping area of the sphere to construct a dual coordinate system to eliminate singular chords and proved that any curl of the two vector potentials could reasonably give the magnetic field of a monopole, providing a magnetic monopole solution in the overall description of the gauge field—that is, the Wu-Yang magnetic monopole. Abrikosov [42] proposed that the quantum state on the sphere of graphene was related to monopole harmonics. Under certain operators, keeping the magnetic monopole at the center of the sphere unchanged, rotating the sphere would produce a part related to spin, and this part was caused by a magnetic monopole.

On the basis of rich theories, some researchers have tried to explore the existence of magnetic monopoles through experimental means. For example, by mixing tiny magnetic spins [43], as shown in [Figure 13: see original paper]B, or artificially constructing a magnetic monopole at the end of a nano-magnetic needle [44]. Fang et al. [45] found that there was an anomalous Hall effect in ferromagnetic crystals, and only the hypothesis of the existence of magnetic monopoles could explain this phenomenon. This result might serve as indirect evidence for the existence of magnetic monopoles in the momentum space of the crystal.

Because spin ice exhibits unique magnetic field characteristics, some studies have found analogues of magnetic monopoles in strange spin ice [16-18]. This is due to the dipolar magnetic excitation caused by spin flipping that produces free defects distributed in the crystal lattice ([Figure 13: see original paper]C), thus exhibiting the properties of a magnetic monopole [46], which has magnetic charges and electric dipoles [47] but cannot be separated from the material [18]. Dusad et al. [48] used a superconducting quantum interference device (SQUID) to detect the quantization jump of the magnetic flux of the $Dy_2Ti_2O_7$ crystal and found that the magnetic noise generated by the magnetic monopole could be heard by humans after amplification. This is the more intuitive observation of magnetic monopoles in spin ice so far.

In the field of condensed matter physics, theoretically, the spin structure of BEC could be manipulated with point-like topological defects through an external magnetic field [49]. On this basis, Ray et al. [50] used cold atoms to generate Raman transitions from lasers of different frequencies under a magnetic field gradient to simulate the effect of the magnetic field. Since the magnetic spin arrangement of rubidium atoms was controllable, the magnetic spins were arranged in the form of large vortices, and the middle part would produce the effect of synthesizing magnetic monopoles. At this time, the spin direction of the atom could point to a certain point in space simultaneously, which also proved the basic quantum characteristics of the magnetic monopole, as shown in [Figure 13: see original paper]D.

4.3 Experimental Challenges and New Fluidic Way to Realize Magnetic Monopole

Although abundant evidence for the existence of analogues of magnetic monopoles has been found, direct observation of Dirac monopoles in the medium of a quantum field has not yet achieved a breakthrough. For decades, with the support of GUTs, String theory, M-theory, and other theories, researchers have even searched for relevant magnetic monopole trajectories in particle accelerators and lunar geotechnical sampling. But researchers have not yet observed its actual existence by experimental means. However, liquid metal combines the properties of electrical conductors, magnets, and fluids, which endows it with rather profound possibilities. When an electric or magnetic field is applied, or a galvanic cell is formed with other metals, the interior flow field will keep moving, which is closely related to the movement of electric charge and the excitation of the endogenous magnetic field. In this sense, the rich operability of liquid metal machines offers quite a few experimental approaches for the discovery of magnetic monopoles.

The magnetic field described by Maxwell's electromagnetic equations is a passive field; that is, each closed magnetic line of induction does not have a starting point and an end point. If the magnetic monopole exists, the magnetic field will become an active field. Maxwell' s equations need to undergo appropriate coordinate transformation and conditional restrictions, which does not violate their correctness. The revised equations are as follows:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} - \mathbf{J}_m$$

$$\nabla \cdot \mathbf{B} = \rho_m$$

Compared with Maxwell' s equations, which originally did not consider the existence of magnetic monopoles, the two differential equations related to the magnetic field have changed. Since the movement of the magnetic monopole may also excite the electric field, the magnetic current density vector **J** is introduced into Equation (12) to obtain Equation (30). At the same time, the magnetic monopole can excite the magnetic field by itself, and the divergence of the magnetic field is no longer zero (Equation 31). The equations will show a more symmetrical electromagnetic field excitation form. Under the new category of liquid metal magnetic monopole which is fluidically tunable via diverse options, many theoretical and experimental works are worthy of pursuing in the coming time.

4.4 Endogenous Magnet from Rigid, Soft to Fluidic Matters

From the initial discovery of natural magnetic fields, the manufacture of artificial magnets, to the conclusion of electromagnetic-related theories, people have experienced a long exploration in this process. Based on the above systematic interpretation, we outlined [Figure 14: see original paper] as follows, which comparatively illustrates the evolution diagram of various forms of magnets that people have manufactured—that is, from rigid matter to soft material until now fluidic magnetism.

[Figure 14: see original paper]A depicts magnets of various shapes that are widely known and commonly used in daily life. Many important electromagnetic field theories are based on those. [Figure 14: see original paper]B refers to a soft magnetic substance, which can be attached to a specific substrate. This magnetic material has been applied to various electronic devices, such as sensors and flexible circuits. [Figure 14: see original paper]C is a composite of magnetic nanoparticles and fluid proposed in recent years. This fluid has no magnetic attraction in static state and only exhibits magnetism when an external magnetic field is applied. It has a wide range of applications in medical equipment and magnetic fluid beneficiation but is still not an ideal all-magnetic fluid. Stepping further, the rotating liquid metal machine or motor proposed in this work belongs to a new kind of magnetic fluid, or electromagnefluid, as shown in [Figure 14: see original paper]D. In this category, there is no need to add additional magnetic particles, which is a complete magnetic fluid in the true sense. The discovery of room-temperature liquid metal full magnetic fluid will bring new visions and directions for research in diverse fields, which has profound significance for the academic society to further understand magnets and fully utilize them.

In nature, the north and south poles always exist simultaneously. Cut a magnet into two pieces, and each piece will form its own north and south poles, which makes it difficult to achieve the existence of one pole alone. Compared with traditional rigid magnets, the advantage of liquid metal lies in its fluidity, which makes it easier to adjust to different shapes and reduces restrictions on particle movement. While surface charges move fast, the inside of the fluid is constantly rotating, making the surrounding magnetic field in a state of constant change. If the single charge on the surface of the liquid metal can be manipulated—even controlling the positive and negative features of the charge in a certain position —then the direction of a single magnetic particle can be reversed, making it possible to construct a liquid metal magnetic monopole.

Furthermore, if direct experimental observation of the magnetic monopole can be achieved, charge quantization can be better explained. Electrons are particles with no internal structure. They can be reshaped to carry orbital angular momentum (OAM). By coupling the center of mass of the wave function with the interior, the total angular momentum information can be obtained from the vortex beam and then manipulated artificially [51]. Similarly, if the magnetic moment of the liquid metal micromotor can be measured to obtain momentum information, it may be manipulated and improved microscopically, and it will even be possible to develop technology based on moving magnetic charges to break through the limitations of current charge engineering and create magnetic materials that exhibit richer behavior.

5. Conclusion

Liquid metal can interact with sound, light, heat, electricity, and magnetism. The present study disclosed for the first time that as a fluidic conductor, liquid metal machines open a generalized way to generate transformable endogenous magnets through tuning their interior rotational configurations. This mechanism is rather difficult to implement through rigid materials otherwise. It may change people' s basic understanding of classical magnetism science. A most noteworthy tool enabled by this finding still lies in that such fluidic magnets suggest a new promising way to realize magnetic monopoles in reality. The fundamental routes can be based on either self-fueled liquid metal motors or the electrically controlled spin motion of liquid metal machines inside the electrolyte. Meanwhile, it should also be pointed out that such liquid metal endogenous magnetism is fundamentally different from conventional magnetic fluids, which were in fact caused by magnetic particles rather than the fluid itself. This raises important fundamental and practical issues waiting to be addressed in the coming time. It also opens perspectives for making new conceptual liquid machines that may find emerging uses in future basic physics, information technology, smart devices, and advanced functional materials. Overall, the reasonable conjecture made on the classical mystery of whether magnetic monopoles exist would shed light on innovating future science and engineering.

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Note: Figure translations are in progress. See original paper for figures.