Revealing the mystery of the cases where Nd–Fe–B magnetic like poles attract each other

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This investigation reveals the mystery of the cases where magnetic like poles attract each other, and unlike poles repel one another. It is identified that for two unequally sized like poles, the pole with a higher $P_c$ (permeance coefficient) causes a localized demagnetization ($LD$) to the pole with a lower $P_c$. If the $LD$ is large enough, the polarity of a localized area can be reversed, resulting in an attraction between these two like poles in the $LD$ area in a small gap. Two unusual behaviors are observed: (1) an inflection point $IP$ appears on the force vs gap curves of all the unequally sized like poles since they have different $P_c$. Normally, the like poles' repelling force increases when the gap decreases, but this $IP$ results in nonmonotonic curves, even an attractive force in a small gap; (2) for some NdFeB magnets with a low coercivity and nonlinear B–H curve in the 2nd quadrant, a repulsion can occur for these unequal sized unlike poles, after previously pairing with their like poles that left an unrecoverable $LD$ and reversed polarity area. The relationship of the $LD$, the $P_c$ ratio, and the B–H curve are also explored in this paper.

The basic law of magnetism is that like poles repel one another, and unlike poles attract each other. Even though Gauss' law for magnetic flux density (B-field) indicates that there is no free magnetic charge, we can still define the effective bound magnetic charges locally from the magnetization of magnetic material. The distribution of positive magnetic charge can be defined as the “north pole”, and correspondingly, the negative magnetic charge can be defined as the “south pole”. The interaction between the local magnetic charges is governed by Coulomb's law so that like charges repel and unlike charges attract. However, George Mizzell observed some cases in which two like poles attracted each other near the central area for a pair of permanent magnets with significantly different dimensions. Mizzell first reported it in May 2007 on YouTube, then reported it again in March 2019. We reported our preliminary investigation for this seemingly unacceptable behaviour in November 2019. Other researchers also reported such a fact in 2019. The phenomenon does not mean that the fundamental laws of magnetism are violated, but it is important to understand the physics underlying the phenomenon. Why do these “like poles” attract each other instead of repelling? To understand the mechanism and reveal the mystery of this unique interaction, a series of experiments were conducted in our labs.

The permeance coefficient ($P_c$) is defined as the ratio of magnetic induction $B_d$ and magnetic field $H_d$ inside a standalone magnet at the operating point, i.e., $P_c = |B_d/H_d|$7,8, which depends on the geometry of the magnet. For example, in the case of cylindrical magnets with the same diameter and same magnetization along the axis, the longer the magnet is, the higher the $P_c$. Combined with the B–H curves, the $P_c$ can determine how easily a magnet will be demagnetized, especially when the B–H curve in the 2nd quadrant is nonlinear. In this work, we find that the $P_c$ and the B–H curves are the key factors to explain the interesting phenomena.

Experiment method

N55 and N48SH samples of Nd–Fe–B, and SmCo30 samples of Sm2Co17 were tested. The dimensions and values of $P_c$ are shown in Table 1, and their demagnetization B–H curves are shown in Fig. 1. These cylindrical magnet pairs with various $P_c$ values range from 0.13 to 24. For the material itself, N55 has a nonlinear B–H curve in the 2nd quadrant, while N48SH and SmCo30 have linear B–H curves in the 2nd and even in part of the 3rd quadrant. SmCo30 was tested so that the surface degradation can be excluded, which may be more obvious for some small or thin Nd–Fe–B magnets.

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These magnet pairs were tested for repelling and attracting forces at the gaps between 0 and 50 mm at the center position, using an Instron 5944 force tester. In order to observe what happened during the test process, four forces were recorded and marked by their testing sequence, $F_1$, $F_2$, $F_3$, and $F_4$, as shown in Fig. 2. $F_1$ and $F_4$ should be all attracting and $F_2$ and $F_3$ should be all repelling, and “$d$” is the gap in between.

Table 1. The magnet samples tested in this investigation (the unit is mm, where OD and L are the diameter and length of the cylinders, respectively).

| Pair ID | OD (mm) | L (mm) | $P_{c1}$ (mm) | OD (mm) | L (mm) | $P_{c2}$ (mm) | N55 | N48SH | SmCo30 |
|---------|---------|--------|---------------|---------|--------|---------------|-----|-------|--------|
| 1-A     | 4       | 2      | 1.41          | 32      | 2      | 0.13          | ✓   | ✓     | ✓      |
| 2-A     | 8       | 2      | 0.61          | 32      | 2      | 0.13          | ✓   | ✓     | ✓      |
| 3-A     | 16      | 2      | 0.28          | 32      | 2      | 0.13          | ✓   | ✓     | ✓      |
| A-A     | 32      | 2      | 0.13          | 32      | 2      | 0.13          | ✓   | ✓     | ✓      |
| 4-A     | 4       | 16     | 24            | 32      | 2      | 0.13          | ✓   | ✓     | ✓      |
| 4-B     | 32      | 4      | 0.28          | 32      | 2      | 0.13          | ✓   | ✓     | ✓      |
| 4-C     | 32      | 8      | 0.61          | 32      | 2      | 0.13          | ✓   | ✓     | ✓      |
| 4-D     | 32      | 16     | 1.41          | 32      | 2      | 0.13          | ✓   | ✓     | ✓      |

Figure 1. The B–H curves of the three magnets in the 2nd and part of the 3rd quadrant, and the working points $B_d/H_d$ marked for N55 and SmCo30 for four load lines with $P_c = 0.13–24$.

Figure 2. Four forces testing setup: $F_1$, $F_2$, $F_3$, and $F_4$ as the above sequence. $F_1$ and $F_4$ should be all attracting and $F_2$ and $F_3$ should be all repelling, and “$d$” is the gap in between.
Results and analysis

Unusual behaviours shown in $F_2$ and $F_4$. Figure 4 plots $F_1$, $F_2$, and $F_4$ forces vs. the gap $d$ for some N55 unequally sized pairs. ($F_3$ is not plotted here as $F_3 \cong F_2$). Two unusual behaviours are observed in the plots: (1) an inflection point $IP$ appears on the curve of $F_2$ vs $d$; (2) $F_4 < F_1$ or even $F_4 < 0$ when $d < \sigma$, and $F_2 > 0$ when $d < \delta$. ($F_3$ is not plotted here as $F_3 \cong F_2$. ($b$) $\delta$ is the point where $F_2 = 0$, and $\sigma$ is the point where $F_4 = 0$.

Three pairs with $P_{c1}/P_{c2} = 4.69$, 10.8 and 185 have $F_4 < 0$ when the gap $d < \sigma$ (2–3 mm), where the force transforms from attraction to repulsion, and only one pair ($P_{c1}/P_{c2} = 2.15$) does not have $F_4 < 0$. This unusual $F_4 < F_1$ does not occur to N48SH and SmCo30, which have linear B–H curves.
Figure 5 shows $F_2$ vs gap $d$ for N55, N48SH, and SmCo30 with both unequally sized and equally sized pairs. An unusual $IP$ is observed for all the magnet pairs, except the equally sized pairs with $P_{c1} = P_{c2}$. Figure 5a,b for N55 show five out of eight pairs having $F_2 > 0$ at $d < \delta (\sim 1$ mm). Figure 5c,d for N48SH display two pairs having $F_2 > 0$ at $d < \delta$. Figure 5e,f for SmCo30 present one pair ($P_{c1}/P_{c2} = 10.8$) with $F_2 = 0$ at $d = \delta (0.05$ mm), which indicates that certain SmCo30 pairs can also have $F_2 > 0$ at a small gap. It is noticeable in Fig. 5 that the higher the $P_c$ ratio is, the higher the $IP$ will be, and the $IP$ ranges from 0.4 to 6 mm when $P_{c1}/P_{c2}$ is 2.1 to 185. When $P_{c1}/P_{c2} = 1$ for the equal sized pairs, the $IP$ disappears (or $IP \rightarrow 0$).
Figure 6 shows the green-tape views for the magnets with $P_c$ ratio of 4.69, before and after the N→←N paring. The reversed polarity is clearly seen on the D32 × 2 magnet after the paring, and no change is observed for the D8 × 2 magnet.

Most of the results are listed in Table 2, from which the unusual behaviours of $F_2$ and $F_4$ can be analysed, and the localized demagnetization $LD$ can be estimated. The data in Table 2 are plotted in Figs. 7 and 8 to make reasonable analyses. Figure 7 shows the force difference $\Delta F_2(=|F_2@d<0.5 − F_2@IP|/F_2@IP|$) vs $Pc_1/Pc_2$. In general, a higher $P_c$ ratio results in a larger $\Delta F_2$, which is as high as 1100% for N55 with $Pc_1/Pc_2=10.8$ in Series #1, and 400% for N55 with $Pc_1/Pc_2=185$ in Series #2. The $\Delta F_2$ is 2–250% for N48SH pairs, and 4–100% for SmCo30 pairs. Figure 8 demonstrates the force difference $\Delta F(=|F_4−F_1|/F_1|)$ vs $Pc_1/Pc_2$ for N55 pairs only, as N48SH and SmCo30 do not have this unusual behaviour of $F_4<F_1$. It is clear that a higher $P_c$ ratio results in a larger $\Delta F$ for both Series #1 with the bottom size fixed and Series #2 with the top size fixed. The $\Delta F$ is as high as 193% for $Pc_1/Pc_2=185$ in Series #2, and 175% for $Pc_1/Pc_2=10.8$ in Series #1. A larger $\Delta F$ or $\Delta F_2$ indicates a greater localized demagnetization $LD$.

**Figure 6.** The green-tape views for N55 pair of D8 × 2 and D32 × 2 ($P_c$ ratio = 4.69) before and after N→←N paring.

| Pair ID | Magnet 1 (Top) | Magnet 2 (Bottom) | For N→S pairs Unusual Force: $F_i<F_j$ (Usually $F_i=F_j$) | For N→→N pairs Unusual Force: $F_i$ vs gap $d$ has an inflection point IP when $d<IP; F_i@IP$ as $d↓; F_j may>0$ (Normally $F_j<0$) |
|---------|---------------|------------------|-------------------------------------------------|-------------------------------------------------|
| 1-A     | 16            | 4                | 1.41                                           | N/A                                             |
| 2-A     | 8             | 0.61             | 2.3                                            | 0.28                                           |
| 3-A     | 16            | 0.28             | 4.07                                           | 0.13                                           |
| A-A     | 32            | 0.13             | N/A                                            | N/A                                             |
| 4-A     | 16            | 4                | 0.32                                           | 0.28                                           |
| 5-B     | 4             | 34               | 0.28                                           | 0.28                                           |
| 5-C     | 8             | 32               | 0.61                                           | 0.61                                           |
| 6-D     | 16            | 1.41             | 0.17                                           | 0.17                                           |

* A larger $\Delta F$ or $\Delta F_2$ indicates a greater localized demagnetization $LD$.
Figure 7. Unusual $\Delta F_2$ for all the magnet pairs with $P_{c1} \neq P_{c2}$: A higher $P_{c1}/P_{c2}$ leads to a higher $\Delta F_2$. All the pairs with $\Delta F_2 > 100\%$ show attraction for $N \rightarrow \leftarrow N$ pairs.

Figure 8. Unusual $F_4 < F_1$ for the N55 pairs with $P_{c1} \neq P_{c2}$: a higher $P_{c1}/P_{c2}$ results in a larger $\Delta F$. Note: All the pairs with $\Delta F > 100\%$ show repulsion for $N \rightarrow S$ pairs.

Figure 9. The surface field @ 1.2 mm above the N side of N55 and SmCo30 after pairing with $P_{c1}/P_{c2} = 4.69$. 
Localized demagnetization LD plots and maps and the determined LD levels. The LD can be visualized using a surface flux density test (the testing setup is illustrated in Fig. 3), from which the LD levels can be determined. Figures 9, 10 and 11 show the flux density at 1.2 mm above the N-side of the bottom magnets of N55 and SmCo30 with three $P_c$ ratios of 4.69, 185, and 17, respectively. The 2D magnetic flux maps are shown on the right, and the curves of flux density vs position and the magnet size are shown on the left. The curves of flux density vs position along a diameter are curves 1 and 2 for N55, and curves 3 and 4 for SmCo30. Curves 1 and 3 are the original fluxes labelled "A", corresponding to Step 1-Scan A in Fig. 3. Curves 2 and 4 are the fluxes after 1 minute of repulsion by the top magnet, labelled "B", corresponding to Step 2-Scan B in Fig. 3. The flux densities at the surface of the magnets with $OD = 32$, as well as the LD values (LD = 100% * $(B_B - B_A)/B_A$) for various pairs are summarized in Table 3. Figure 9 shows pair 2-A with $P_c1/P_c2 = 4.69$, in which N55 has a larger LD (−55%) at the center of curve_2, comparing to original curve_1, while SmCo30 has a small LD (−2.1%). Figure 10 shows the pair 4-A with $P_c1/P_c2 = 185$, and N55 has a huge LD with its polarity being totally reversed at the center (−114%) of curve_2, while SmCo30 has a small LD (−0.44%). Figure 11 shows pair 4-D with $P_c1/P_c2 = 17$, and N55 has LD = −6.1% while SmCo30 has LD = 0.64%. In general, LD on the N-side is higher than that on the S-side. When the $P_c1/P_c2$ ratio = 1 for the A-A pairs, the LD for both N55 and SmCo30 is approximately 0%, and the tiny difference is within the measurement error. Since the flux density was tested at 1.2 mm above the surface, the actual LD should be higher than the levels described in this section.

Figure 10. The surface field @1.2 mm above the N side of N55 and SmCo30 after pairing with $P_c1/P_c2 = 185$.

Figure 11. The surface field @1.2 mm above the N side of N55 and SmCo30 after pairing with $P_c1/P_c2 = 17$. 
The effects of the linearity of B–H curves and the load-lines with working points. As shown in the previous sections, the LD level is related to the \( P_c \) ratio, and it is also linked to the linearity of the B–H curves in the 2nd and part of the 3rd quadrant. Figure 1 shows the B–H curves of N55, N48SH, and SmCo30, and the linearity limits (knee positions) of the B–H curves are 13 kOe, 21.4 kOe, and > 21.5 kOe, respectively. Among all three magnets, SmCo30 has the best linearity of the B–H curve. The small circles at the cross points of the load-lines and the B–H curves in Fig. 1 are the working points (\( B_d/H_d \)), which are listed in Table 4 for some magnets tested in this investigation. When two unequally sized magnets with different \( P_c \) pair with the like poles \( N \rightarrow← N \), the one with a lower \( P_c \), which has an internal self-demagnetization field \( H_d \), will be affected by an external field \( H_{\text{ex}} \) from the one with a higher \( P_c \). The total demagnetizing field is the sum of \( H_d \) and \( H_{\text{ex}} \) as shown in Fig. 12. If the sum exceeds the linearity limits, the B loss will be unrecoverable. Figure 12a shows how a N55 magnet with \( P_c = 0.13 \) loses its flux B after paring as \( N \rightarrow← N \) with a magnet having a higher \( P_c \). The stand-alone magnet has operating point "a", and it drops to point "b" while pairing with one having a higher \( P_c \). After the pair separates, the magnet can only return to point "c" as it needs to return to its stand-alone condition along the line parallel to its relative permeability \( \mu_r = 1.045 \). This large B loss is due to the nonlinear B–H curve of N55, and the working point "a" of this magnet is very close to the knee of the B–H curve. On this aspect, N48SH and SmCo30 would not have such unrecoverable losses as long as the total demagnetizing field is less than 21.4 kOe and 21.5 kOe, respectively, where they are about to lose their linearity of their B–H curves (see Fig. 1 for the Table 4. Working points \( B_d \) and \( H_d \) for the following tested magnets (see Fig. 1 for the B–H curves).

| \( P_c \) or load-line | \( B_d/H_d \) | \( \mu_r \) | N55 | N48SH | SmCo30 |
|------------------------|-------------|----------|-----|-------|--------|
| \( B_d \) (kG)         | \( H_d \) (kOe) |          |     |       |        |
| 0.13                    | 1.6         | 12.4     | 1.59| 12.2 | 1.2    |
| 0.61                    | 5.4         | 8.8      | 5.3 | 8.7   | 4.1    |
| 1.41                    | 8.5         | 6.0      | 8.0 | 5.7   | 6.1    |
| 24                      | 14.2        | 5.9      | 13.7| 5.7   | 10.8   |

Table 3. The LD detected at 1.2 mm above the surface of bottom magnets (\( B_A \) – original testing after magnetization, \( B_B \) tested after repulsion on \( N \rightarrow← N \) pairing).
B–H curve details). Figure 12b shows how a N48SH with $P_c = 0.13$ maintains its flux B after paring $N \rightarrow←← N$ with a magnet with a higher $P_c$. This explains why N48SH and SmCo30 do not show the unusual behaviour of $F_H < F_L$ at a small gap, and this recoverable LD is a unique characteristic to be utilized in some novel applications in the near future.

See Refs. 7,9,10,11 for the concept used in the analysis. It is clear that the linearity of the B–H curve and the magnet’s load-line play important roles in the LD level and its recoverability after the magnet separates from the $N \rightarrow←← N$ paring.

**Summary**

A localized demagnetization (LD) is identified for unequally sized magnetic like poles as their $P_c$ values are different, in which the pole with a higher $P_c$ causes a LD to the pole with a lower $P_c$. If the LD is large enough, the polarity of the localized area can be reversed, resulting in an attraction between two like poles in the LD area in a small gap. Two unusual behaviours are observed in this investigation.

1. An inflection point, $IP$, appears on the curves of the force vs gap for all the unequally sized like poles. The $IP$ results in nonmonotonous curves, even an attraction for the like poles.
2. For some NdFeB magnets with a low coercivity and nonlinear B–H curve in the 2nd quadrant, a repulsion can occur for these unequally sized unlike poles after previously pairing with their like poles that left an unrecoverable LD and a reversed polarity area.

The unusual behaviours are not contradictory to the basic law of magnetism, and they are caused by the localized demagnetization LD. A higher $P_c$ ratio results in a greater $LD$; the linearity of the B–H curves and the load-line also play important roles in the force level in the LD area. The $LD$ level can be visualized and determined by mapping the surface flux.

**Discussion**

The linearity of the B–H curve and the magnet’s load-line play important roles in the LD level and its recoverability after the magnet separates from the $N \rightarrow←← N$ paring. For N55 with a nonlinear B–H curve, especially with small thickness, the LD is mostly unrecoverable. Similar to N55, Alnico magnets may also show the same unusual phenomena. For N48SH and SmCo30 magnets with linear B–H curves in the 2nd and part of the 3rd quadrant, the LD is mostly recoverable after the like pair is separated. If SmCo30 or N48SH pairs have a proper $P_c$ ratio, the like poles can also appear attracting each other; since the LD is recoverable, some novel applications may be developed for utilizing these newly discovered unique characteristics.

Received: 13 April 2021; Accepted: 3 June 2021
Published online: 15 June 2021

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**Author contributions**

H.M. and C.C. designed the experiments, analyzed data, and wrote the paper; G.T. and H.M. preformed the testing and some data analyses; A.S. helped the experiments, did data analyses, and helped writing the paper; M.Q. and Q.W. helped the experiments and did some data analyses; G.M. provided earlier experiment data and edited the paper.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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