Magnetization and magneto-transport staircaselike behavior in layered perovskite \( \text{Sr}_2\text{CoO}_4 \) at low temperature

Qiuhang Li\(^1\), Xueping Yuan\(^2\), Lei Xing\(^3\) & Mingxiang Xu\(^1\)

Polycrystalline layered perovskite \( \text{Sr}_2\text{CoO}_4 \) sample was synthesized by high temperature and high pressure method. The staircaselike behavior has been observed in the magnetization and resistivity versus field curves of \( \text{Sr}_2\text{CoO}_4 \) at low temperature. The main features of the steps can be obtained from the measured results: (i) the positions of the external magnetic field at which steps occur are varying in different measurement runs, (ii) the steps only appear at low temperature and disappear with a slight increase of the temperature, (iii) the steps are dependent on the temperature and field sweep rate. Based on the features of the magnetization and magneto-transport staircaselike behavior in \( \text{Sr}_2\text{CoO}_4 \), the unusual phenomenon can be ascribed to an avalanche of flipping domains in terms of the random field theory.

In recent years, two dimensional compounds with \( \text{K}_2\text{NiF}_4 \)-type structure (a type of tetragonal structures) have generated great interest after the discovery of superconductivity, magnetoresistance (MR), spin/charge stripes in nickelates and manganites\(^1\)-\(^13\). Two-dimensional layer structured perovskite compound \( \text{Sr}_2\text{CoO}_4 \) is one of \( \text{K}_2\text{NiF}_4 \)-type structured materials with space group \( \text{I}4/\text{mmm} \). The structure of \( \text{Sr}_2\text{CoO}_4 \) consists of corner sharing \( \text{CoO}_6 \) octahedra with two-dimension \( \text{CoO}_2 \) planes separated by insulating rock-salt layers of \( \text{SrO} \). In the past reports, both \( \text{Sr}_2\text{CoO}_4 \) single-crystalline thin films and polycrystalline bulks were reported as a metallic ferromagnets with a fairly high Curie temperature \( (\text{TC}) \) of 255 K\(^1\)-\(^3\). The susceptibility data above \( \text{TC} \) of \( \text{Sr}_2\text{CoO}_4 \) can be well fitted to the Curie-Weiss law \( \chi = C/(T + \theta) \). The observed value of the effective magnetic moment per \( \text{Co} \) ion \( \mu_{\text{eff}}(\mu_{\text{B}}/\text{Co}) \) is 4.11, which can approximately coincide with that expected for spin only moment of the intermediate-spin (IS) state \( (t_{2g}^4e_g^0, S = 3/2) \text{Co}^{4+}(3.87 \mu_{\text{B}}/\text{Co}) \) and be quite different from the values of the low-spin (LS) state \( (t_{2g}^6e_g^0, S = 1/2) \text{Co}^{4+}(1.73 \mu_{\text{B}}/\text{Co}) \) and high-spin (HS) state \( (t_{2g}^5e_g^2, S = 5/2) \text{Co}^{4+}(5.92 \mu_{\text{B}}/\text{Co}) \). Below \( \text{T}_c \), a cluster-glass state exists in \( \text{Sr}_2\text{CoO}_4 \) system\(^4\). It has been observed that \( \text{Sr}_2\text{CoO}_4 \) reveals large magnetic anisotropy where the \( c \)-axis is the magnetic easy axis\(^5\). The coercivity \( (H_c) \) of \( \text{Sr}_2\text{CoO}_4 \) is approximately 2.2–2.5 T at 5 K from polycrystalline sample\(^6\) and single-crystalline film\(^7\). It suggests great potential of \( \text{Sr}_2\text{CoO}_4 \) for high quality memory applications\(^7\). The half-metallicity of \( \text{Sr}_2\text{CoO}_4 \) has been predicted\(^8\). Different relationships of the electrical resistivity \( (\rho) \) versus temperature were observed in polycrystalline \( \text{Sr}_2\text{CoO}_4 \) and single-crystalline \( \text{Sr}_2\text{CoO}_4 \) film\(^9\)-\(^12\). The temperature dependence of \( \rho \) in polycrystalline \( \text{Sr}_2\text{CoO}_4 \) exhibits semiconducting characteristics\(^4\). The \( \rho \) above \( \text{T}_c \) for the polycrystalline \( \text{Sr}_2\text{CoO}_4 \) can be well fitted by the variable range hopping (VRH) model \( \rho = \rho_0 \exp(T_d/T)^{1/4} \). By comparison, in single-crystalline \( \text{Sr}_2\text{CoO}_4 \) film, the inter-\( \text{CoO}_2 \)-plane \( \rho \) of \( c \)-axis shows a sharp peak at \( \text{T}_c \), with a metallic behavior below \( \text{T}_c \) and a semiconducting behavior above \( \text{T}_c \). In contrast, the intra-\( \text{CoO}_2 \)-plane \( \rho \) of \( b \)-axis shows metallic characteristics\(^2\). At low temperature, large negative MR was observed in \( \text{Sr}_2\text{CoO}_4 \). The MR reaches a maximum at \( H_c \). Therefore, the magnetic and electrical properties of \( \text{Sr}_2\text{CoO}_4 \) at low temperature, especially below 5 K, will be rather significant to study. Moreover, certain exceptional and unusual physical phenomena were observed frequently at low temperature, such as superconductivity, magnetic jump and quantum tunneling\(^14\)-\(^20\).

An interesting phenomenon, a staircaselike behavior which is analogous to resonant quantum tunneling of magnetization, was indeed observed in our \( \text{Sr}_2\text{CoO}_4 \) polycrystalline sample below 2.8 K. So far, to our knowledge, this is the first time that the staircaselike behavior was observed in \( \text{Sr}_2\text{CoO}_4 \). It may suggest the new application...
The d\( _{2}\) values of Sr\(_{2}\)CoO\(_{4}\) measured at different temperatures. It can be observed that with increasing of the temperature, the quantity of the steps decreases and the positions of the corresponding steps move towards the direction of high field. At 2.8 K, the staircaselike behavior disappears completely. These results suggest that the staircaselike behavior is sensitive excessively to the slight temperature variation. The inset of Fig. 3 shows the three curves in the inset (b) of Fig. 4 are misaligned for different field sweep rates. The positions of the corresponding steps on the \( \rho \)-\( H \) curves also move towards the low field with the increasing of the field sweep rate (see the arrow in the inset (b) of Fig. 4). The steps on the \( \rho \)-\( H \) curves of the same piece of sample are also misaligned under the same measurement condition (figure not shown). These phenomena are consistent with the above magnetic results of Sr\(_{2}\)CoO\(_{4}\).
Three main characteristics of the staircaselike behavior in Sr$_2$CoO$_4$ are concluded from the measured results: (i) the positions of the steps are varying in different measurement runs, (ii) the steps only appear at low temperature ($T < 2.8$ K) and disappear with a slight increase of the temperature, (iii) the steps are dependent on the temperature and field sweep rate. The possible mechanism of the staircaselike behavior will be systematically discussed below.

The similar staircaselike behaviors in hysteresis loops have been also reported in many types of materials, such as Ca$_3$Co$_2$O$_6$\textsuperscript{14,15}, [Mn$_4$]$_2$ dimer\textsuperscript{16}, Fe$_x$Mg$_{1-x}$Cl$_2$\textsuperscript{21}, PrVO$_3$\textsuperscript{22}, UGe$_2$\textsuperscript{23,24}, and amorphous Dy-Cu\textsuperscript{25}. Simultaneously, different theories have been presented to explain the staircaselike behaviors. The main three theories are resonant quantum tunneling\textsuperscript{14–20}, random field\textsuperscript{21–35}, and intrinsic pinning of magnetic domain walls\textsuperscript{36–38}.

Resonant quantum tunneling has been applied to systems involving a large number of identical high-spin materials\textsuperscript{14–20}, as in the case of Ca$_3$Co$_2$O$_6$\textsuperscript{14,15}, and Mn$_{12}$ acetate\textsuperscript{30}. Ca$_3$Co$_2$O$_6$ is a type of perovskite material with K$_4$CdCl$_6$-type structure (an infinite chain-type structure). The analogous steps can be observed from the $M$-$H$ curves of Ca$_3$Co$_2$O$_6$ at low temperature\textsuperscript{14,15}. The steps are resulted from the transformation and change of the

Figure 2. (a) Magnetization versus field ($M$-$H$) curve at 1.8 K with a field sweep rate of 25 Oe/s for the Sr$_2$CoO$_4$. (b) $dM/dH$-$H$ curve at 1.8 K for the Sr$_2$CoO$_4$. The inset of (a) shows the three measurement runs of the same piece of sample obtained under the same measurement condition.

Figure 3. Magnetization versus field ($M$-$H$) curves for the Sr$_2$CoO$_4$ sample at different temperatures with the same field sweep rate of 25 Oe/s. The inset shows $M$-$H$ curves for the Sr$_2$CoO$_4$ at 2 K with different magnetic field sweep rates.

**Discussion**

Three main characteristics of the staircaselike behavior in Sr$_2$CoO$_4$ are concluded from the measured results: (i) the positions of the steps are varying in different measurement runs, (ii) the steps only appear at low temperature ($T < 2.8$ K) and disappear with a slight increase of the temperature, (iii) the steps are dependent on the temperature and field sweep rate. The possible mechanism of the staircaselike behavior will be systematically discussed below.

The similar staircaselike behaviors in hysteresis loops have been also reported in many types of materials, such as Ca$_3$Co$_2$O$_6$\textsuperscript{14,15}, [Mn$_4$]$_2$ dimer\textsuperscript{16}, Fe$_x$Mg$_{1-x}$Cl$_2$\textsuperscript{21}, PrVO$_3$\textsuperscript{22}, UGe$_2$\textsuperscript{23,24}, and amorphous Dy-Cu\textsuperscript{25}. Simultaneously, different theories have been presented to explain the staircaselike behaviors. The main three theories are resonant quantum tunneling\textsuperscript{14–20}, random field\textsuperscript{21–35}, and intrinsic pinning of magnetic domain walls\textsuperscript{36–38}.

Resonant quantum tunneling has been applied to systems involving a large number of identical high-spin materials\textsuperscript{14–20}, as in the case of Ca$_3$Co$_2$O$_6$\textsuperscript{14,15}, and Mn$_{12}$ acetate\textsuperscript{30}. Ca$_3$Co$_2$O$_6$ is a type of perovskite material with K$_4$CdCl$_6$-type structure (an infinite chain-type structure). The analogous steps can be observed from the $M$-$H$ curves of Ca$_3$Co$_2$O$_6$ at low temperature\textsuperscript{14,15}. The steps are resulted from the transformation and change of the
percentage of different magnetism in the materials caused by the applied field at different temperatures\(^1\). The chain-type structure is the key factor to the staircaselike behavior. The intrachain coupling is ferromagnetic and the interchain coupling is antiferromagnetic. However, \(\text{Sr}_2\text{CoO}_4\) is one type of two-dimensional layer structured compound. Obviously, no chain-type structure exists in \(\text{Sr}_2\text{CoO}_4\). On the other hand, the most important characteristic of the staircaselike behavior in quantum-effect system is that the positions of the steps are temperature-independent below a critical temperature\(^17,18\). The results from the Fig. 3 of \(\text{Sr}_2\text{CoO}_4\) show that the steps in the six \(M-H\) curves exhibit no similar characteristic of temperature independence. This result indicates that the staircaselike behavior in \(\text{Sr}_2\text{CoO}_4\) is incompatible with resonant quantum tunneling.

The presence of random fields is another explanation that can lead to staircaselike behavior. Under this mechanism, a given domain is flipped by an external field, thus reversing the magnetization of the neighboring domains and finally resulting in an avalanche of flipping domains\(^21-29\) considering the random field Ising model (RFIM)\(^31-34\). Each jump in one curve corresponds to an avalanche process where the spins (of one or more clusters in the polycrystalline \(\text{Sr}_2\text{CoO}_4\)) align with the applied magnetic field\(^26\). The noteworthy characteristic of the steps in this theory is the randomness. The positions of the steps are varying in different measurement runs. Meanwhile, the steps can be only observed at low temperature. The ferromagnetic clusters in \(\text{Sr}_2\text{CoO}_4\) sample play a crucial role for this phenomenon\(^13,26-28\). Below the critical temperature at which the steps are vanished, the ferromagnetic cluster-sizes in the sample increase, and the cluster percolation process yields an increase in the ferromagnetic correlation length with lowering the temperature\(^26\). The larger cluster-size can result in the bigger avalanche, which gives rise to the distinct jumps. Above the critical temperature, the thermal activation is dominating\(^26\), and the cluster-size is so small, which can only cause small avalanche. As a consequence, the jumps become sightless, and the hysteresis loop becomes smooth. This type of staircaselike behaviors is dependent on temperature, but independent on field sweep rate. Such an explanation has been proposed in site-diluted metamagnet \(\text{Fe}_{x}\text{Mg}_{1-x}\) and the hysteresis loop becomes smooth. This type of staircaselike behaviors is dependent on temperature, but independent on field sweep rate. When the magnetic field changes slowly enough, the energy released in the spin reversal process dissipated tardily\(^35\). With the increasing of the sweep rate, the energy accumulates rapidly and facilitates the reversal of neighboring spins. It results in the sweep rate dependence of the steps. From this point of view, the fundamental reason of the staircaselike behavior in \(\text{Sr}_2\text{CoO}_4\) may be ascribed to an avalanche of flipping domains in terms of the random field theory.

The intrinsic pinning of magnetic domain walls is compatible with the magnetization jumps observed in alloy samples\(^36-38\). The domain walls motioning inside the ferromagnetic domains depend on the pinning effect introduced by foreign elements and the local crystal fields. The pinning effect can result in the creation of energetic barriers, which influence the magnetization process at low temperature\(^36\). In the case of \(\text{EuBaCo}_2\text{M}_{0.05}\text{O}_{1.5-\delta}\) (\(\text{M} = \text{Zn}, \text{Cu}\))\(^37\), \(\text{Zn}^{2+}\) and \(\text{Cu}^{2+}\) are the origin of the pinning of the narrow domain walls. When the magnetic field becomes high enough to overcome the pinning effect, the domain walls tend to disappear and the spins of the ferromagnetic domains are all aligned. This type of the staircaselike behaviors strongly depends on the external magnetic field sweep rate. When the magnetic field changes slowly enough, the \(M-H\) curve becomes normal with no jump\(^38\). This phenomenon was similar to the result from the inset of Fig. 3 in \(\text{Sr}_2\text{CoO}_4\). In the perfect \(\text{Sr}_2\text{CoO}_4\) crystals, no substituted defect results in the effective pinning. However, here, the saturated moment of the \(\text{Sr}_2\text{CoO}_4\) sample (1.02 \(\mu_B/\text{Co}\)) is lower than the calculated value (1.97 \(\mu_B/\text{Co}\))\(^2\). Meanwhile, the \(\mu_{\text{eff}}\) of Co ion (4.11 \(\mu_B/\text{Co}\)) in \(\text{Sr}_2\text{CoO}_4\) is also different from the spin only moments of LS Co\(^{2+}\) (1.73 \(\mu_B/\text{Co}\)), IS Co\(^{4+}\) (3.87 \(\mu_B/\text{Co}\)), and HS Co\(^{4+}\) (5.92 \(\mu_B/\text{Co}\))\(^11,14\). These results suggest that multiple spin states may exist in our \(\text{Sr}_2\text{CoO}_4\) sample.

Figure 4. Resistivity versus field (\(\rho-H\)) curve for the \(\text{Sr}_2\text{CoO}_4\) at 2 K with a field sweep rate of 25 Oe/s. The inset (a) shows \(\rho-H\) curves for the \(\text{Sr}_2\text{CoO}_4\) sample at different temperatures with the same field sweep rate of 25 Oe/s. The inset (b) shows \(\rho-H\) curves for the \(\text{Sr}_2\text{CoO}_4\) sample at 2 K with different magnetic field sweep rates.
The interactions between the neighboring IS or HS Co ions (Co(IS or HS)-O-Co(IS or HS)) are antiferromagnetic\textsuperscript{39,40}, though the ground state of Sr\textsubscript{2}CoO\textsubscript{4} is ferromagnetic.\textsuperscript{6} It means that antiferromagnetism and ferromagnetism are coexistent in Sr\textsubscript{2}CoO\textsubscript{4}, which can lead to multiple magnetic phases. The multiple magnetic phases may result in the intrinsic pinning of magnetic domain walls\textsuperscript{41,42}, and further contribute to the magnetization and magneto-transport staircase-like behavior in the Sr\textsubscript{2}CoO\textsubscript{4}.

In summary, layered perovskite compound Sr\textsubscript{2}CoO\textsubscript{4} polycrystalline sample was synthesized by high temperature and high pressure method. The magnetic and magneto-transport properties of Sr\textsubscript{2}CoO\textsubscript{4} were studied at low temperature. A staircase-like behavior on $M$-$H$ curves was observed in polycrystalline Sr\textsubscript{2}CoO\textsubscript{4} below 2.8 K. The steps appear with a certain degree of randomness in different measurement runs. The staircase-like behavior is dependent on the temperature and the magnetic field sweep rate. The fundamental reason of the staircase-like behavior can be considered as the presence of random fields, leading to an avalanche of flipping domains. The multiple magnetic phases which can result in the intrinsic pinning of magnetic domain walls, may contribute to the magnetization and magneto-transport staircase-like behavior in the Sr\textsubscript{2}CoO\textsubscript{4}.

**Methods**

Polycrystalline sample of composition Sr\textsubscript{2}CoO\textsubscript{4} was synthesized under high pressure at high temperature. Starting materials of Sr\textsubscript{O} and Co were well mixed in a molar ratio of Sr\textsubscript{2}:Co = 2:1. The mixture was sealed into a gold capsule. The capsule was first compressed at 6 GPa in a high pressure apparatus (flat-belt-type-high-pressure capsule). The crystal structure of the polycrystalline sample was identified by the powder X-ray diffraction (XRD, Rigaku Smartlab3), using Cu-K\alpha radiation ($\lambda$ = 1.5418 Å). The morphology of the sample was observed using a scanning electron microscope (SEM). The dc magnetic measurements were investigated using a vibrating sample magnetometer (VSM) integrated in a physical property measurement system (PPMS-9, Quantum Design). The electrical resistivity of the sample was measured with a Quantum Design PPMS-9 system using the standard four-probe ac method.

**References**

1. Wang, X. L. & Takayama-Muromachi, E. Magnetic and transport properties of the layered perovskite system Sr\textsubscript{2-y}Y\textsubscript{y}CoO\textsubscript{4} (0 $\leq$ y $\leq$ 1). Phys. Rev. B 72, 064401 (2005).
2. Matsuno, J. et al. Metallic ferromagnet with square-lattice CoO\textsubscript{2} sheets. Phys. Rev. Lett. 93, 167202 (2004).
3. Wang, X. L., Takayama-Muromachi, E., Dou, S. X. & Cheng, Z. X. Band structures, magnetic properties, and enhanced magnetoresistance in the high pressure phase of Gd and Y doped two-dimensional perovskite Sr\textsubscript{2}CoO\textsubscript{4} compounds. Appl. Phys. Lett. 91, 062501 (2007).
4. Xu, M., Balamurugan, S. & Takayama-Muromachi, E. Magnetic and transport properties and spin states of layered cobalt oxides Sr\textsubscript{1-x}Ho\textsubscript{x}CoO\textsubscript{4} (0 $\leq$ x $\leq$ 1.0). Prog. Theor. Phys. Supp. 159, 349 (2005).
5. Pandey, P. K., Choudhary, R. J. & Phase, D. M. Magnetic behavior of layer perovskite Sr\textsubscript{2}CoO\textsubscript{4} thin film. Appl. Phys. Lett. 103, 132413 (2013).
6. Pandey, S. K. Correlation induced half-metallicity in a ferromagnetic single-layered compound: Sr\textsubscript{2}CoO\textsubscript{4}. Phys. Rev. B 81, 035114 (2010).
7. Pandey, P. K., Choudhary, R. J., Mishra, D. K., Sathe, V. G. & Phase, D. M. Signature of spin-phonon coupling in Sr\textsubscript{2}CoO\textsubscript{4} thin film: a Raman spectroscopic study. Appl. Phys. Lett. 102, 142401 (2013).
8. Wang, X. L., Sakurai, H. & Takayama-Muromachi, E. Synthesis, structures, and magnetic properties of novel Roddlesden-Popper homologous series Sr\textsubscript{n}Co\textsubscript{3n}O\textsubscript{3n+1} (n = 1, 2, 3, 4, and $\infty$). J. Phys. Chem. B 107, 100519 (2005).
9. Lee, K.-W. & Pickett, W. E. Correlation effects in the high formal oxidation-state compound Sr\textsubscript{2}CoO\textsubscript{4}. Phys. Rev. B 73, 174428 (2006).
10. Wu, H. Metal-insulator transition in Sr\textsubscript{1-x}La\textsubscript{x}CoO\textsubscript{4} driven by spin-state transition. Phys. Rev. B 86, 075120 (2012).
11. Yao, Q. et al. Band structures, and magnetic and transport properties of La doped two dimensional Sr\textsubscript{2}CoO\textsubscript{4}. J. Appl. Phys. 101, 09N515 (2007).
12. Yao, Q. et al. Density of states, magnetic and transport properties of Nd doped two dimensional perovskite compound Sr\textsubscript{2}CoO\textsubscript{4}. J. Appl. Phys. 111, 07D708 (2012).
13. Pandey, P. K., Choudhary, R. J. & Phase, D. M. Anomalous temperature dependence in valence band spectra: a resonant photoemission study of layered perovskite Sr\textsubscript{2}CoO\textsubscript{4}. Appl. Phys. Lett. 104, 182409 (2014).
14. Maiguan, A., Michel, C., Masset, A. C., Martin, C. & Raveau, B. Single crystal study of the one dimensional Ca\textsubscript{2}Co\textsubscript{4}O\textsubscript{5} compound: five stable configurations for the Ising triangular lattice. Eur. Phys. J. B 15, 657 (2000).
15. Maigunan, A. et al. Quantum tunneling of the magnetization in the Ising chain compound Ca\textsubscript{2}Co\textsubscript{4}O\textsubscript{5}. J. Mater. Chem. 14, 1231 (2004).
16. Tiron, R., Wernsdorfer, W., Foguet-Albiol, D., Aliaga-Alcalde, N. & Christou, G. Spin quantum tunneling via entangled states in a dimer of exchange-coupled single-molecule magnets. Phys. Rev. Lett. 91, 227203 (2003).
17. Wernsdorfer, W., Bhaduri, S., Boskovic, C., Christou, G. & Hendrickson, D. N. Spin-parity dependent tunneling of magnetization in single-molecule magnets. Phys. Rev. B 65, 180403(R) (2002).
18. Wernsdorfer, W., Aliaga-Alcalde, N., Hendrickson, D. N. & Christou, G. Exchange-biased quantum tunneling in a supramolecular dimer of single-molecule magnets. Nature 416, 406 (2002).
19. Wernsdorfer, W., Bhaduri, S., Tiron, R., Hendrickson, D. N. & Christou, G. Spin-spin cross relaxation in single-molecule magnets. Phys. Rev. Lett. 89, 197201 (2002).
20. Wernsdorfer, W., Sessoli, R. & Gatteschi, D. Nuclear-spin-driven resonant tunnelling of magnetisation in Mn\textsubscript{12} acetate. Europhys. Lett. 47, 254 (1999).
21. Kushauer, J., van Bentum, R., Kleemann, W. & Bertrand, D. Athermal magnetization avalanches and domain states in the site-diluted metamagnet Fe\textsubscript{3}Mg\textsubscript{1}O\textsubscript{4}. Phys. Rev. B 53, 11647 (1996).
22. Tung, L. D. PrVO\textsubscript{3}: an inhomogeneous antiferromagnetic material with random fields. Phys. Rev. B 72, 054414 (2005).
23. Nishioka, T., Motoyama, G., Nakamura, S., Kadoya, H. & Sato, N. K. Unusual nature of ferromagnetism coexisting with superconductivity in UGe\textsubscript{2}. Phys. Rev. Lett. 88, 237203 (2002).
24. Lhotel, E., Paulsen, C. & Huxley, A. D. Comment on “Unusual nature of ferromagnetism coexisting with superconductivity in UGe\textsubscript{2}”. Phys. Rev. Lett. 91, 209701 (2003).
25. Coey, J. M. D., McGuire, T. R. & Tissier, B. Amorphous Dy-Cu: random spin freezing in the presence of strong local anisotropy. Phys. Rev. B 24, 1261 (1981).
Magnetization and magneto-transport staircaselike behavior in layered perovskite Sr$_2$CoO$_4$ at low temperature.

How to cite this article: Li, Q. et al. Magnetization and magneto-transport staircaselike behavior in layered perovskite Sr$_2$CoO$_4$ at low temperature. Sci. Rep. 6, 27712; doi: 10.1038/srep27712 (2016).

This work is licensed under a Creative Commons Attribution 4.0 International License. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in the credit line; if the material is not included under the Creative Commons license, users will need to obtain permission from the license holder to reproduce the material. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/