High Magnetic Field Laboratory of the Chinese Academy of Science

Steady High Magnetic Field Facility (SHMFF, Hefei)

2022 Annual Report

High Magnetic Field Laboratory, CAS
2023.02

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Overview

High Magnetic Field Facilities (HMFF) Project was approved on January 25th, 2007, which was jointly applied by Chinese Academy of Sciences and Ministry of Education. The HMFF Project includes two parts: Steady High Magnetic Field Facility (SHMFF), constructed by Hefei Institutes of Physical Science, CAS; Pulsed High Magnetic Field Facility (PHMFF), constructed by Huazhong University of Science and Technology.

SHMFF started its construction on May 19th, 2008. Partial magnets of SHMFF have been open to users since October 28th, 2010. SHMFF passed national acceptance and was fully put into operation on September 27th, 2017.

SHMFF consists of a world-record 45.22T hybrid magnet, five water-cooled magnets (38.5T/Φ32, 25T/Φ50, 20T/Φ200, 27.5T/Φ32 and 35T/Φ50), four superconducting magnets (10T/Φ100/Φ100, 20T/SMA, 20T/NMR and 9.4T/MRI) and six experimental systems (transport, magnetic, magneto-optical, extremely low temperature, ultrahigh pressure and STM-AFM-MFM combo).

SHMFF gives priority to original fundamental research, applied research with important application prospects and high-tech development to improve technical innovation in China, encourages users to undertake national and ministerial major research projects, and welcomes industrial users. Users have been playing a leading role in its operation and opening, which are conductive to feature scientific objectives, prioritize key research fields, and promote important scientific outcomes.

By the end of 2022, SHMFF has provided 555,099 hours of operation time and executed 3,237 approved user' projects. Users from 183 organizations across the world have carried out research here, and have made series of important research achievements in materials, chemistry, biology science and other disciplines. The users have published more than 2,200 peer-reviewed journal articles, including dozens in Nature, Science, Cell and other top journals.

In 2022, SHMFF completed the operation task, and provided 50,737 hours of operation time. 277 users' projects from 67 organizations carried out research projects and published 242 articles in peer-reviewed journals.

SHMFF focuses on three missions:

1. Advance magnet-related technology, stimulate invention and creation in high magnetic fields.

2. Perform the frontier research of physics, chemistry, biology and material under high magnetic fields.

3. Promote economic development such as pharmaceuticals, medical treatment etc.

Research progress and results

Publications & patents

In 2022, the users of SHMFF published 242 articles in peer-reviewed journals, including 225 in SCI. In addition, they obtained 37 authorized patents and applied for 66 new patents.

Number of Publications and patents related to SHMFF in 2022

SCI	EI and others	Authorized patents	Pending patents	Software copyrights	Nature Index Journal publications
225	17	37	66	2	56

Grant application

In 2022, new in-house research projects were approved for funding, including 3 topics by National Key R & D Programs of China, 10 by NSFC, 5 by CAS and 6 by Anhui Province.

Research highlights

- **Observation of spin－orbit－parity coupled superconducting state in centrosymmetric atomically thin 2M-WS_2**

Scientists from Fudan University investigated the transport properties of atomically thin 2M-WS_2 by SHMFF. The experimental results demonstrated that in-plane upper critical field of 2M-WS_2 not only exceeded the Pauli paramagnetic limit and exhibited a anisotropic two-fold symmetry. Furthermore, tunnelling spectroscopy measurements conducted under high in-plane magnetic fields revealed that the superconducting gap possessed an anisotropic magnetic response along different in-plane magnetic field directions, and it persisted much above the Pauli limit. Theoretical calculations showed that this unusual behavior originated from the spin–orbit–parity coupling （SOPC） arising from the topological band inversion in 2M-WS_2. This work identified the unconventional superconductivity in atomically thin 2M-WS_2, which served as a promising platform for exploring the interplay between superconductivity, topology and SOPC. This work was published in ***Nature Physics*** and recommended by News & Views.(Fig.1)

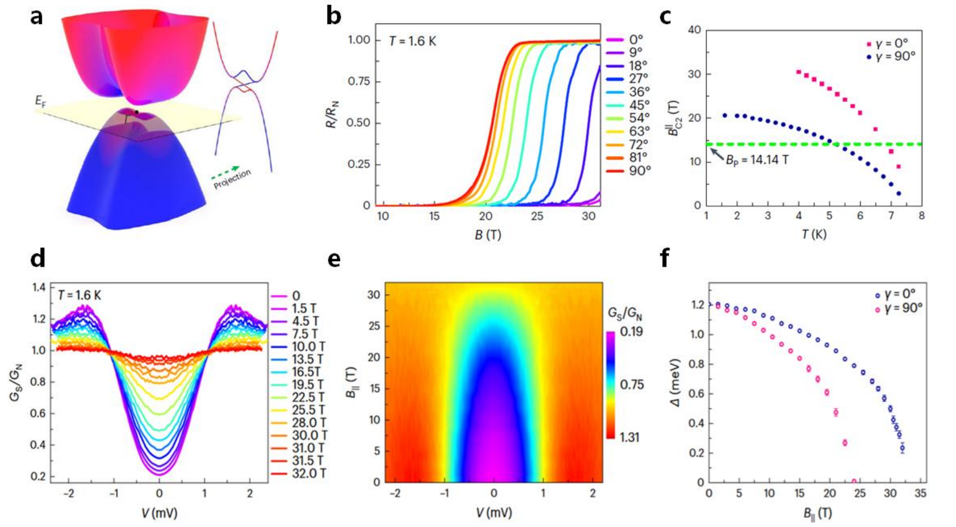

Fig.1. (a)Schematic plot of thin layer 2M-WS_2; (b)Normalized magnetoresistance of a 2M-WS_2 device with the magnetic field; (c)Temperature-dependent critical magnetic field; (d,e)Normalized tunnelling conductance of a 2M-WS_2 under various in-plane magnetic fields; (f)Extracted magnetic-field-dependent superconducting gap with the magnetic field

- **Controlling the superconductivity of $NbSe_2$ through the intercalation method of ionic liquids cations**

Quasi-two-dimensional layered materials exhibit abundant typical properties, which are highly dependent on dimensionality and carrier concentration. Therefore, manipulating dimensionality and carrier concentration is an important pathway to induce novel properties in layered materials. Prof. Zhou Shuyun from Tsinghua University and collaborators, including Prof. Yu Pu, Prof. Duan Wenhui, Prof. Xu Yong, Prof. Xue Qikun, etc. developed a new strategy to engineer both the dimensionality and carrier concentration of layered materials through the intercalation of ionic liquids cations. The as-formed $NbSe_2$ organic-inorganic hybrid crystals exhibit novel superconducting properties beyond both unintercalated bulk crystals and monolayer samples, which were confirmed by WM5 in SHMFF. This work was published in ***Nature Physics*** and recommended by News & Views.(Fig.2)

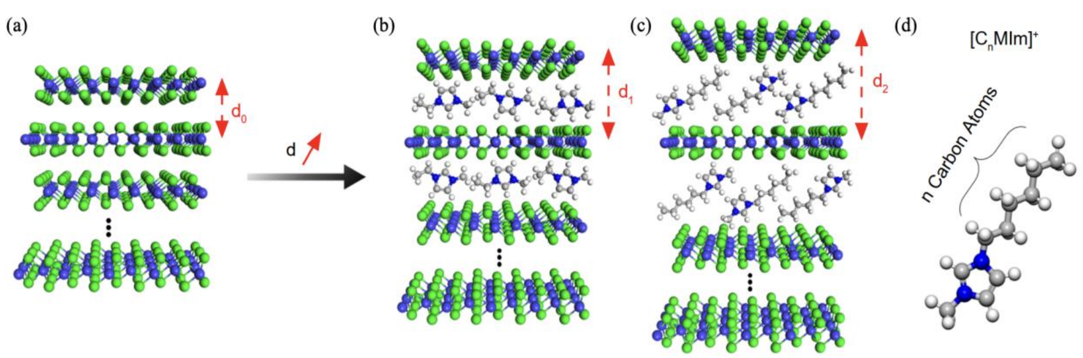

Fig.2. Schematic of dimensionality manipulation of layered materials, like $NbSe_2$, through ionic liquids cations intercalation.

- **Large momentum exciton observed in quasi-one-dimensional metal $TaSe_3$**

Charge neutrality and an expected itinerant nature make excitons potential transmitters of information. The creation in insulators of non-moving excitons (bound states from electrons and holes located at the minimum and maximum of the conduction band and valence band, respectively) by optical excitation is fairly standard and has been widely studied both theoretically and experimentally. Exciton mobility remains inaccessible to traditional optical experiments that only create and detect excitons with negligible momentum or group velocity. Exciting a moving bound state only with light involves a higher order process due to momentum conservation. The cross section of such process scales with the interaction strength that is usually very weak. Thus, excitons with large non-zero group velocity have been rarely investigated. Mobile excitons in metals have been elusive, as screening usually suppresses their formation. Here, the authors demonstrated such mobile bound states in quasi-one-dimensional metallic $TaSe_3$ under SHMFF, taking advantage of its low dimensionality and carrier density. The excitons have intrachain or interchain modes. Interchain excitons are quasi-1D cousins of bilayer excitons in layered 2D materials, such as transition metal dichalcogenides. They are of particular interest as they may have a significantly longer lifetime due to the spatial separation of the particle and the hole and may have possible applications in the future. This work was published in ***Nature Materials.***(Fig.3)

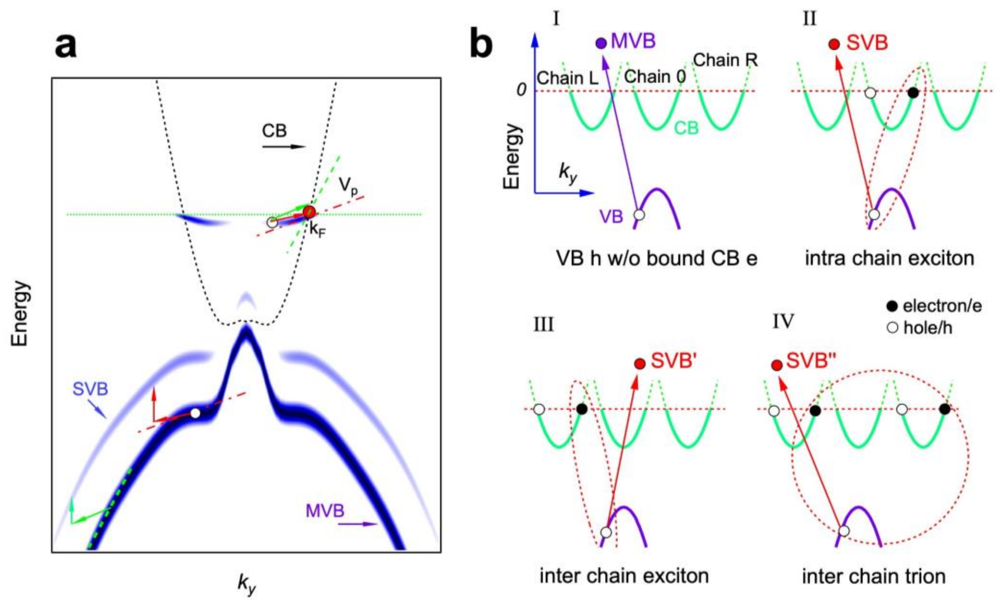

Fig.3. An exciton theoretical model for the formation of stable, large momentum, multi exciton modes in one-dimensional metals

- **Observing a non-monotonic temperature dependent anomalous Hall effect in an Iridate Superlattice**

As a new frontier of scientific research, the combined effect of electronic correlation with nontrivial complex hopping remains poorly understood in the intermediate regime, which calls for real experimental systems that can simulate and unveil the correlation-topology interplay. Prof. Hao Lin from High Magnetic Field Laboratory, Chinese Academy of Sciences(CHMFL), in collaboration with Prof. Jian Liu from University of Tennessee, performed an extensive study on the correlation-topology interlay in moderated correlated electron systems. The researchers showed that the nontrivial electronic topology anticipated at the weak coupling limit leaded to an anomalous Hall effect (AHE), as schematically shown in Fig.4(a). By performing high-field AHE measurements at SHMFF (Fig.4(b)), they revealed that the AHE not only signified Berry curvatures in the Hubbard bands but was also subject to the self-competition of the electron-hole pairing. This work not only revealed the rich topology-correlation interplay but also demonstrated a controllable material platform for such investigations. The strategy of controlling gauge-dependent/-invariant complex hopping through artificial design could provide valuable insights for investigating topology-related physics in other correlated materials. This work was published on ***Physical Review X.***

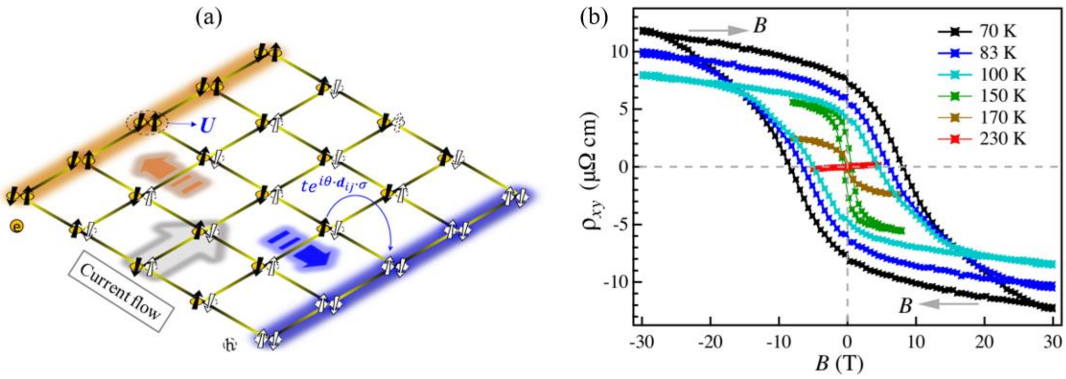

Fig.4. (a) Schematic of anomalous Hall effect in the intermediate coupling regime; (b) Magnetic field dependent Hall measurements at different temperatures

- **Unveiling Berry-curvature dominated linear positive magnetoresistance**

Large linear positive magnetoresistance (LPMR) has been widely reported in topological materials, but the explanations for it are ambiguous. Especially, there still lacks experimental confirmation for the intrinsic mechanisms. The research group led by Prof. Liu Enke from the Institute of Physics, CAS, grew and studied a topological material candidate, cobalt disulfide(CoS_2), which exhibited the largest positive MR among known magnetic topological materials. When the magnetic field was increased to 32T, measured by SHMFF, the positive MR didn't show any signature of saturation. Then they established a physical model of Berry-curvature-dominated LPMR based on a 3D-Weyl-node model, and further provided experimental evidence for this mechanism. This study unveiled the relationship between Berry curvature and LPMR, thus facilitating the understanding and functional design of LPMR materials for magnetic sensing or information storage. Relevant results were published on ***Proceedings of the National Academy of Sciences***. (Fig.5)

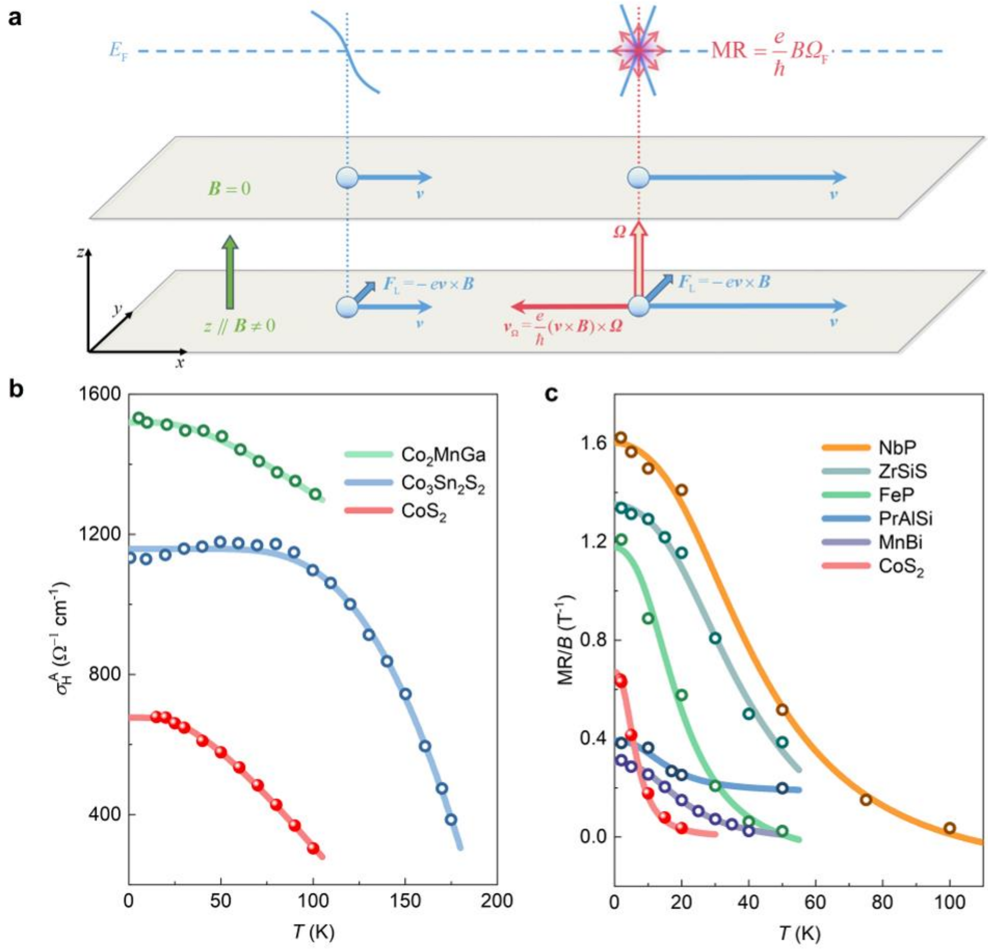

Fig.5. The schematic illustration of Berry curvature induced LPMR and the fitting of experimental data to theoretical equations

- **Magnetic-field-oriented anion-exchange membranes for fuel cells**

Anion exchange membrane fuel cells (AEMFC) are expected to replace their proton exchange counterparts for the advantage of being able to use non-noble-metal catalysts due to the alkaline environment. The design of their core components—anion-exchange membranes (AEM)—is crucial in achieving the desired AEMFC power outputs and performance stability. A research team led by Professor Yin Yan from Tianjin University successfully developed an oriented ferrocenium anion exchange membrane under strong magnetic field. The anion exchange membrane has ion transport channels arranged in the through-plane (TP) direction, which greatly improves the power output of AEMFC. Due to the universal practicability of AEM in fuel cells, as well as water electrolysers, this material may find additional applications in other areas of renewable and clean energy. The results were published in ***Nature Energy.*** (Fig.6)

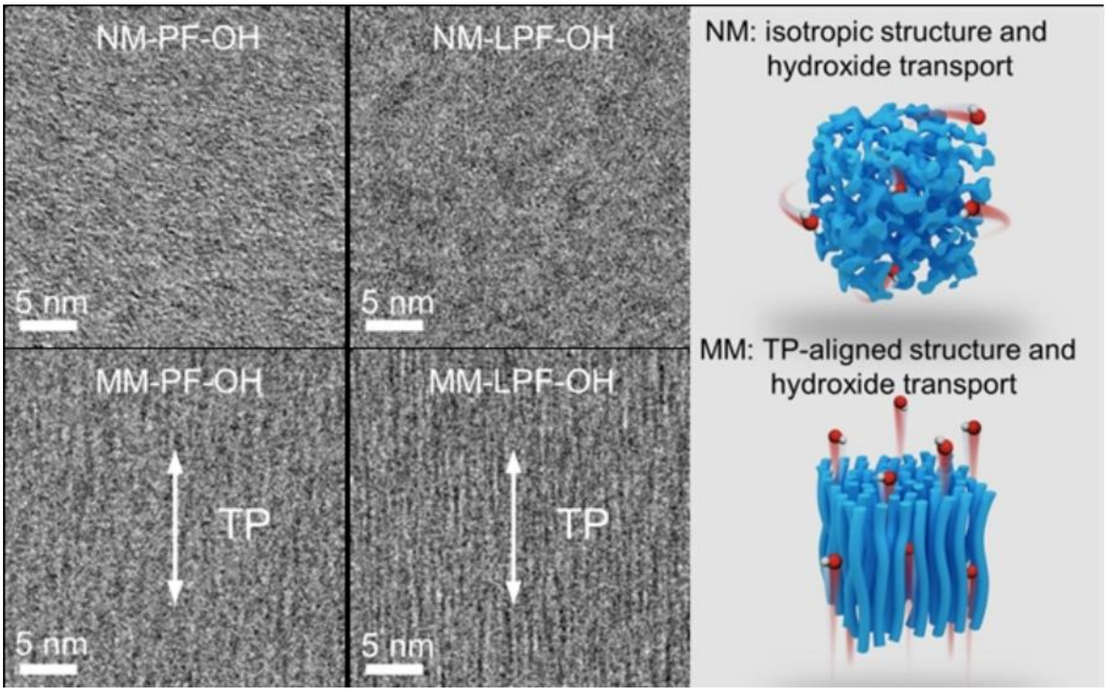

Fig.6. TEM images and schematic diagrams of the microstructure of magnetic-cast membranes (MM) and normal-cast membranes (NM)

- **Construction of novel Two-Dimensional magnetic homogeneous bias device**

Two-dimensional Van der Waals magnetic materials provide an excellent platform for basic magnetic research and low-dimensional magnetic device development. However, the weak interlayer coupling greatly limits the application. A research team led by Sheng Zhigao from CHMFL, cooperated with Professor Zhang Zhenyu from the University of Science and Technology of China found that the two-dimensional Fe_3GeTe_2 with ferromagnetic ground state could be induced into a homogeneous and magnetic heterostructure with ferromagnetic-antiferromagnetic coexistence by uniaxial pressure technology, and the structure had a practical exchange bias effect. Using the superconducting magnet SM1 of SHMFF, magneto-optical Kerr (MOKE) and second harmonic generation (SHG) techniques, combined with high-resolution transmission electron microscopy and first-principles calculations, the research team fully confirmed the pressure-induced phase transition and the origin of its exchange bias. This result not only provides a new idea for the study of the mechanism of exchange bias effect, but also opens up a new way for the design and development of high-performance two-dimensional magnetic devices, which are expected to be the core magnetic components of two-dimensional electronic technology and equipment. The related research results were published in the international journal ***Advanced Materials***.(Fig.7)

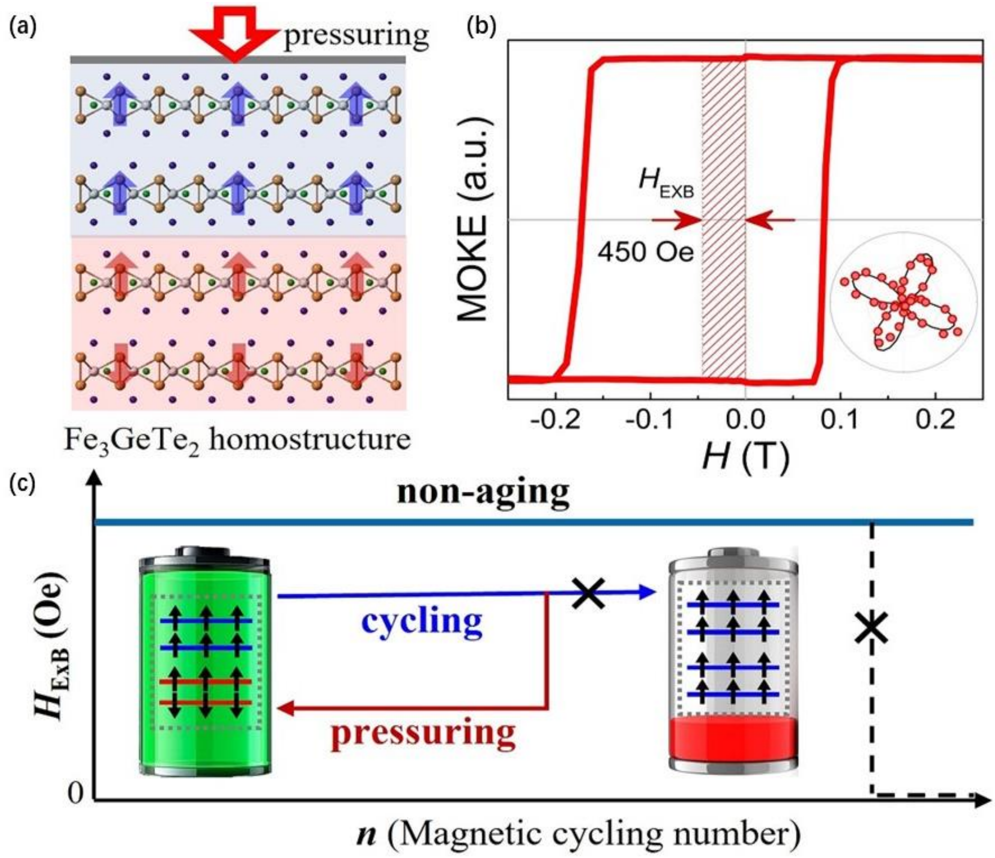

Fig.7. (a) A schematic diagram of the induced FGT magnetic transition after uniaxial compression; (b)Magneto-optical phenomenon of FGT after pressurization; (c) FGT no aging, extendable, recoverable exchange bias effect diagram

- **Iron-catalysed reductive cross-coupling of glycosyl radicals for the stereoselective synthesis of C-glycosides**

Stereochemically defined C-glycosides are prized for their biological activity. Developing a catalytic method that comprises non-precious metals to synthesize these C-glycosides remains challenging. Cooperated with CHMFL, users from the National University of Singapore and Nankai University found that iron-based catalyst promoted the facile generation of glycosyl radicals and successfully produced a diverse array of C-glycoside products functionalized with alkenyl, alkynyl or aromatic anomeric groups across a range of substrates. Mechanistic control and SHMFF experiments indicated that the active catalytic species were a low-valent iron complex formed through Mn reduction. The method was applied in the stereoselective synthesis of bioactive C-glycosides and therapeutically relevant analogues. The research results were published on ***Nature Synthesis***.(Fig.8)

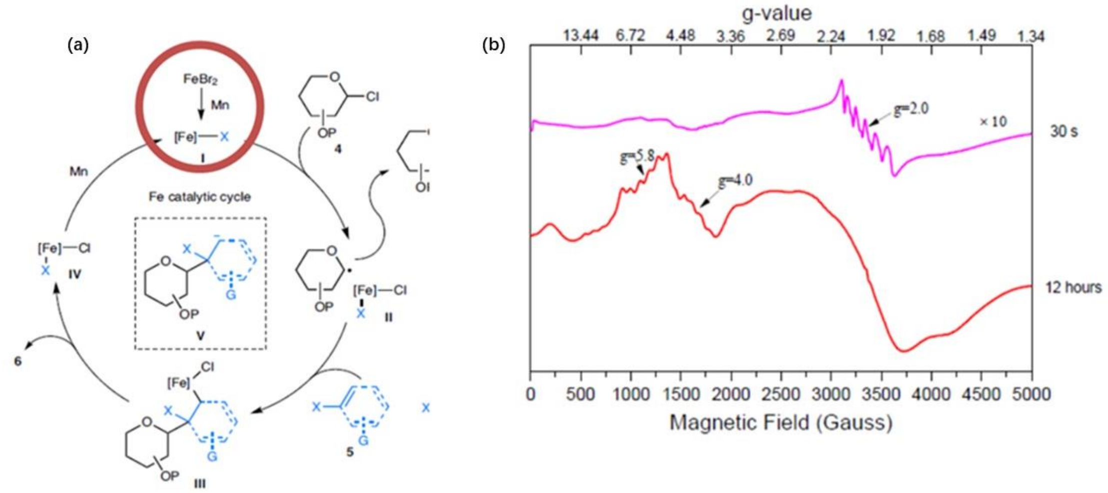

Fig.8. (a) Proposed catalytic mechanism for cross-electrophile coupling to generate C-glycosides; (b) Electron spin resonance (ESR) spectrums at 10K low temperature

- **Mechanistic investigation of the activation cisplatin prodrug under physiological conditions**

Cisplatin is the most widely used anticancer drug, but its application is limited by the side effects and drug resistance. The Pt(IV) prodrug of cisplatin could be a promising substitution and has been extensively studied. However, it is still a challenge to clarify the reduction process of the prodrug under physiological conditions.

Prof. Liu Yangzhong and Prof. Tang Liqin of the University of Science and Technology of China and Prof. Giovanni Natile's team of the University of Bari in Italy designed a ^{19}F-labeled Pt(IV) prodrugs to study the activation and metabolism of cisplatin prodrugs using ^{19}F NMR. NMR is a non-invasive analysis method that can provide information on the dynamic biochemical process of biomolecules under physiological conditions at the atomic level. The reduction and metabolism of Pt(IV) prodrug in different cell environments, in whole blood and in living animals were investigated. The results suggested that ^{19}F NMR could be a general method to study the activation and metabolism of prodrugs in physiological environments. The work was published in ***Angewandte Chemie-International Edition.*** (Fig.9)

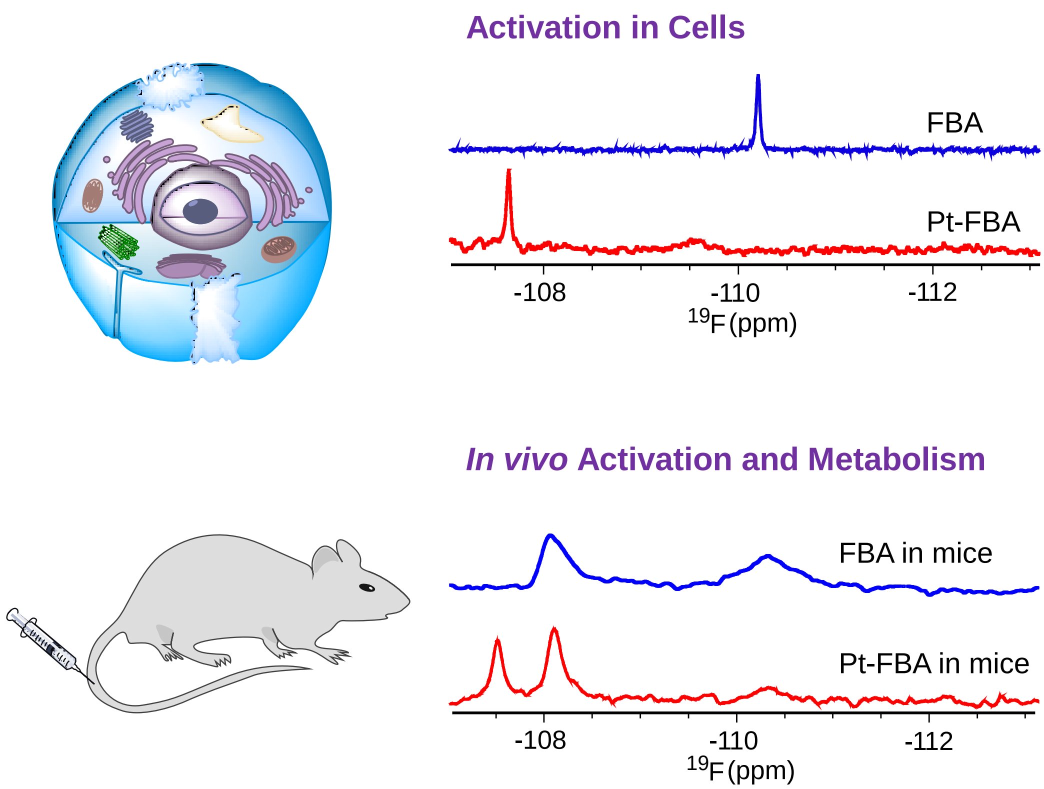

Fig.9. Analysis of the activation process of cisplatin prodrug in cell environment and living animals by ^{19}F NMR

- **Constructing magnetosome-like structures with efficient tumor tissue penetration**

The targeted delivery of antitumor drugs can effectively improve the efficacy of drugs and reduce the toxicity of drugs. Due to the increased interstitial fluid pressure and the dense extracellular matrix (ECM) in tumor tissues, the average tumor targeting efficiency of current nanodrugs is less than 1%, which constitutes one of the bottlenecks in tumor treatment. On the basis of studying the biomineralization mechanism of magnetotactic bacteria in nature, the team of researcher Wang Junfeng from CHMFL biomimicks synthesized soft ferromagnetic magnetosome structure nanomaterials with efficient magnetic targeting and tumor tissue penetration. Relying on SM3 and NMR device of SHMFF, the performance of magnetosomes in tumor tissue penetration and magnetic targeting was verified at the animal level by an order of magnitude. This work not only provided an efficient carrier for the magnetic targeting delivery of nanodrugs, but also provided a new model system for studying the biomineralization mechanism of magnetotactic bacteria in vitro. The results were published in ***Proceedings of the National Academy of Sciences***.(Fig.10)

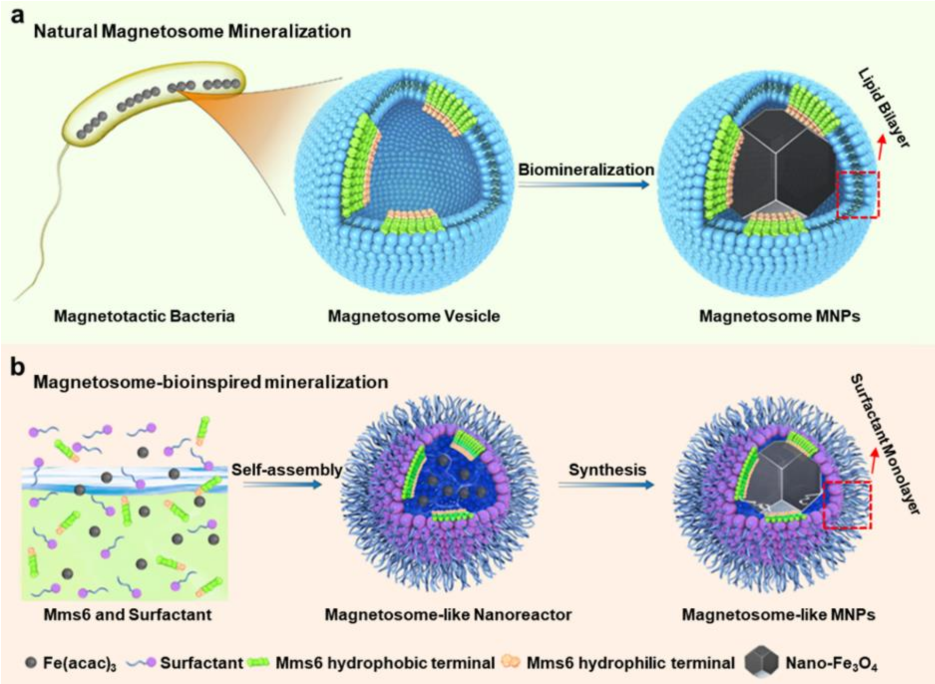

Fig.10. In vitro reconstitution of magnetotactic bacterial nanoreactor based on Mms6 protein

Construction, operation and upgrading

In 2022, SHMFF served users from 67 universities and institutes, covering 277 projects. Planned running time is 48880 hrs, and actual running time is 50737 hrs.

	HW/WM	SM3+NMR	SM4+MRI
Planned time(hrs)	1500	8232	2600
Actual time(hrs)	2070	8294	2602

	Planned time（hrs）	Actual time(hrs)
SM1	2900	2962
SM2	6552	7008
PPMS	6600	6096
Cryostat	880	810
MPMS	7440	7728
ESR	1200	1316
Raman	850	850
FTIR	800	794
XRD	1130	1155
Extreme Low Temperature Transport System	2100	2560
Ultra-pressure Physical Measurement System	1000	1107
STM-MFM-AFM Combo	4096	4336
Condensed Nuclear Magnetic Resonance	1000	1050

Scientific & technical personnel and talent training

CHMFL has a total of 198 employees including 55 professors, 57 associate professors, and 86 other staff. CHMFL also has 30 postdocs and 333 graduate students.

Total number of facility staff	Classified by positions			Classified by professional titles			Students			In-house post-doctor	Introduced talents *
	Operation & maintenance staff	Researchers	Others	People with senior professional title	People with medium professional title	Others	graduated Ph.D	Graduates master	Post-graduate in progress		
198	109	84	5	112	74	12	19	18	333	30	2

Cooperation and exchange

International cooperation and exchanges were carried out mostly online in 2022. Domestic scholars and experts were invited to visit SHMFF and gave academic presentations. The numbers of forums in recent five years are as follows:

Year	**2022**	**2021**	**2020**	**2019**	**2018**	**2017**
No. of presentations	12	9	7	17	23	15

From November 25th to 28th, the 1th Conference of "Magnetic Biology and magnetic Medicine" co-organized by CHMFL was successfully held in Anji, Zhejiang. Focusing on the theme of "important scientific issues in magnetic biology and magnetic medicine", the conference exchanged the latest frontier trends and future development trends in the field, and built a platform for the participants to exchange academic ideas. This conference promotes the cross-integration, cooperation and exchange of different disciplines in the field of magnetic biology and magnetic medicine.

The 1st Conference of "Magnetic Biology and magnetic Medicine"

Chronicle of events

- May. 5th — The first Academic Committee of “Low Power Quantum Material Construction Research Platform” was held.
- May. 27th — The meeting of the SHMFF User Committee was held.
- Jul. 27th — “SHMFF Users’ Workshop of High Field Magnetic Resonance Imaging” was held.
- Aug. 12th — Hybrid Magnet of SHMFF generated 45.22T steady-state magnetic field, setting a new world record for the same type of magnet.
- Oct. 31st — The maintenance and transformation project of water-cooled Magnet in HWM11 and WM3 of SHMFF successfully passed the acceptance.
- Nov. 25th-28th — The 1st Conference of “Magnetic Biology and magnetic Medicine” was held.
- Dec. 25th — “Setting a new world record of SHMFF” was selected as “Top 10 science and technology news in China”.

*Jan.12th,2023 — “Achieving a major breakthrough of SHMFF” was selected as “Top 10 science and technology progress news in China”.