Research on Collaborative Innovation Organization Models of German Research Institutions: Postprint

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Date: 2024-03-27T00:00:00+00:00

Abstract

In the context of the innovation-driven development strategy, uniting various science and technology innovation entities and strengthening collaborative innovation constitute an effective pathway to implement and accelerate the achievement of high-level scientific and technological self-reliance and strength. Currently, China is in a crucial period for promoting the accelerated development of collaborative innovation, and there is a need to learn from successful international experiences. Through methods such as literature analysis and case analysis, and building upon a review of collaborative innovation concepts and organizational models, this article takes the five representative organizational models among Germany' s four major scientific research institutions—project-based, integrated, strategic alliance, platform, and network types—as examples. It analyzes and summarizes the characteristics, advantages, and applicable situations of different organizational models from the perspectives of collaborative innovation objectives, cooperation entities, organizational mechanisms, funding methods, government roles, and cooperation effectiveness, thereby providing references for promoting the collaborative development of scientific and technological innovation in China.

Full Text

Preamble

Citation Format: Ge C L, Pei R M, Zhang Q J. Collaborative innovation organizational modes of major scientific research institutes in Germany. Bulletin of Chinese Academy of Sciences, 2024, 39(2): 345-357, doi: 10.16418/j.issn.1000-3045.20230726006. (in Chinese)

Collaborative Innovation Organizational Modes of Major Scientific Research Institutes in Germany

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Abstract

Against the strategic backdrop of innovation-driven development, uniting various science and technology innovation actors and strengthening collaborative innovation represents an effective pathway to achieve high-level scientific and technological self-reliance. China is currently in a crucial period for accelerating collaborative innovation development and needs to draw upon successful international experiences. Through literature analysis and case studies, this paper examines the connotations and organizational modes of collaborative innovation, focusing on five representative models among Germany' s four major research institutions: project-type, integrated-type, strategic alliance-type, platform-type, and network-type. The study analyzes and summarizes the characteristics, advantages, and applicable scenarios of these different organizational modes from perspectives including collaborative innovation objectives, partnership actors, organizational mechanisms, funding approaches, government roles, and collaborative effectiveness, providing insights for promoting collaborative innovation development in China.

Keywords: Germany, scientific research institutes, collaborative innovation, organizational modes

DOI: 10.16418/j.issn.1000-3045.20230726006
CSTR: 32128.14.CASbulletin.20230726006

1. Collaborative Innovation Theory and Related Research

The evolving paradigms of scientific research and increasingly interdisciplinary trends have heightened the difficulty of technological innovation, deepened its complexity, and accelerated its pace, posing new challenges to traditional single-actor innovation models. Collaborative innovation has gradually become an inevitable choice for scientific and technological development in the "Big Science" era and an important trend for innovation-oriented countries.

Since 2011, when Comrade Hu Jintao first proposed the directive to "actively promote collaborative innovation" [1], Chinese government agencies, universities, research institutions, and enterprises have actively explored and practiced various collaborative innovation organizational approaches, developing new models such as innovation consortia, new R&D institutions, joint R&D platforms, and industrial technology innovation strategic alliances, achieving remarkable results. However, compared with developed countries, China' s collaborative innovation organizational models still suffer from numerous drawbacks, with limited breadth, depth, effectiveness, and sustainability, and have yet to form a long-term mechanism driven by shared interests [2]. Effectively coordinating scientific and technological innovation actors through optimal organizational models is crucial for China to break through key core technologies, accelerate innovation-driven development, and achieve high-level scientific and technological self-reliance.

Germany, as a strong scientific and technological innovation power, possesses a unique innovation system with clearly positioned and well-defined innovation actors that have formed mutually cooperative collaborative innovation relationships. Germany' s four major research institutions—the Max Planck Society (MPG), Fraunhofer Society (FhG), Leibniz Association (WGL), and Helmholtz Association (HGF)—serve as important strategic scientific forces in Germany' s innovation system. Each plays distinct roles along the innovation chain, demonstrating organizational characteristics of collaborative innovation in key technology research and development and achieving significant results. This study examines the collaborative innovation organizational models of Germany' s four major research institutions, analyzing their practices and experiences from perspectives including collaborative innovation objectives, partnership mechanisms, organizational structures, funding approaches, government roles, and collaborative effectiveness, to provide references for China' s collaborative innovation organization building in important scientific and technological fields.

The concept of collaborative innovation emerged with the continuous development of innovation theory. In the 1970s, German physicist Hermann Haken systematically proposed synergy theory, arguing that synergy represents the coordinated, cooperative, or synchronized joint action and collective behavior among subsystems in a system, producing a synergistic effect of 1+1>2. In 2005, MIT scholar Peter Gloor provided the earliest definition of collaborative innovation as "a network of self-motivating individuals who share a common vision, collaborating through network communication of ideas, information, and work status to achieve common goals" [3].

Chinese research on collaborative innovation began in the late 1990s with industry-university-research collaboration. Currently, domestic scholars generally believe that collaborative innovation refers to a process in which different innovation actors, based on shared interests, with resource sharing or complementary advantages as prerequisites, engage in rational division of labor, and through organic coordination of innovation elements and complex non-linear interactions, generate overall synergistic effects that individual elements cannot achieve alone [4].

As a complex innovation organizational approach, collaborative innovation exhibits characteristics of integrity, hierarchy, systematicity, complexity, dynamism, intensiveness, academic nature, organic nature, and self-organization [2]. The organizational forms of collaborative innovation are diverse, and domestic scholars have proposed various classification frameworks. For instance, in 2004, Li Yanyan et al. [5] classified industry-university-research collaboration into four models based on the different roles of innovation actors: government-led (including government directive and government promotion types), enterprise-led (including commissioned development, cooperative development, and co-construction of research institutions), university/research institution-led (including technology transfer and patent sales), and co-led (interest-driven, with equal partners leveraging respective advantages to jointly promote technological innovation and market development, sharing risks and benefits).

In 2012, Lu Ruoyu et al. [6] categorized industry-university-research collaboration into six models based on the closeness of partnerships: technology transfer, commissioned research, joint research, internal integration, co-construction of bases, and co-construction of entities. Technology transfer typically involves universities and research institutions transferring technology to enterprises. Commissioned research refers to enterprises entrusting research tasks to academic institutions. Joint research uses research projects as carriers, with industry-university-research partners conducting collaborative R&D. Internal integration typically takes the form of universities or research institutions establishing enterprises to connect research activities with the real economy. Co-construction of bases and entities involves joint investment by all parties to establish joint R&D institutions, laboratories, or other entities.

In 2015, Wang Zhangbao et al. [7] divided industry-university-research collaborative innovation into five organizational models based on organizational levels and closeness: project-type, co-construction-type, entity-type, alliance-type, and virtual-type. Project-type includes technology transfer, commissioned research, and collaborative research. Co-construction-type includes co-construction of R&D bases, collaborative innovation centers, and high-tech parks. Entity-type includes internal entity models (typified by university enterprises) and external entity models (legal economic entities formed by all parties). Alliance-type is represented by industrial technology alliances, which can be industry-specific, regional, or cross-industry and cross-regional. Virtual-type refers to networked virtual organizations established through modern network technology, such as virtual cooperative education and virtual R&D platforms.

Previous literature has primarily focused on industry-university-research collaborative innovation organizational models, emphasizing government guidance and enterprise centrality, while paying less attention to collaborative innovation organizational models among research institutions at different stages of the innovation chain. This study attempts to analyze the role of research institutions in collaborative innovation from an innovation chain perspective, using multiple collaborative innovation organizational models among Germany' s four major research institutions as examples.

2. The German Research System and Positioning of the Four Major Research Institutions

Germany' s research system comprises three sectors: universities, research institutions, and enterprises. Universities conduct extensive research and play crucial roles in basic theoretical research, applied research, and talent cultivation. Non-profit research institutions represented by the Max Planck Society, Fraunhofer Society, Leibniz Association, and Helmholtz Association constitute important forces in basic and frontier research, serving as primary undertakers of national strategic key research projects. Enterprises mainly conduct application research based on their development needs and represent the main force in product technology innovation.

Among Germany' s research system, the four major research institutions are most representative. Their institutional development after World War II was a key factor in Germany' s rapid recovery of research strength. As important components of Germany' s research system, these four institutions have distinct research positioning and form a complementary organic system with clear division of labor and coordinated planning, jointly establishing Germany' s primary position for addressing major and complex scientific challenges.

(1) **Max Planck Society (MPG):** Established in 1948, MPG primarily conducts cutting-edge basic research and interdisciplinary innovation in natural sciences, biosciences, and humanities and social sciences. It is Germany' s most Nobel Prize-winning research institution, employing a Principal Investigator (PI) system. Approximately 90% of its funding comes from institutional grants provided by the German federal and state governments.

(2) **Fraunhofer Society (FhG):** Founded in 1949 to develop application-oriented research for enterprise needs, Fraunhofer is Germany' s and Europe' s largest applied research organization. Its research activities focus on commissioned research, with 70% of its funding from government and enterprise-commissioned projects and 30% from institutional grants from federal and state governments.

(3) **Leibniz Association (WGL):** Established in 1995, the Leibniz Association is a comprehensive research institution with numerous research entities, primarily conducting application-oriented basic research in social, economic, and ecological fields. Approximately 70% of its funding comes from institutional grants from the German federal and state governments.

(4) **Helmholtz Association (HGF):** Founded in 1995, the Helmholtz Association is Germany' s largest research organization. Oriented toward national medium- and long-term scientific research missions, it conducts large-scale scientific research in six fields—health, energy, earth and environment, key technologies, matter, and aerospace and transportation—using large-scale equipment and research facilities. Its research activities

adopt a project system, with approximately 70% of its funding from institutional grants provided by the German federal and state governments.

As the knowledge and skills required for scientific and technological production become increasingly complex and diverse, Germany' s four major research institutions actively integrate internal and external innovation resources on the basis of their respective divisions of labor. By establishing collaborative innovation models with higher innovation efficiency, they achieve resource sharing and complementary advantages in intelligence, methodology, and interdisciplinary approaches, enhancing scientific research and innovation capabilities and promoting scientific and technological progress.

3. Collaborative Innovation Organizational Modes of Germany' s Four Major Research Institutions

Germany' s four major research institutions exhibit diverse collaborative innovation organizational forms, which can be categorized into five models based on the looseness of cooperative structures: project-type, integrated-type, strategic alliance-type, platform-type, and network-type.

3.1 Project-Type Organizational Mode

The project-type organizational mode is a dynamic, scalable, and flexible cooperation model with compact organizational structure, high-density scientific cooperation among participants, efficient and flexible management, and high collaborative efficiency. Research projects focus on specific scientific problems. A 典型案例 is the joint cooperation program initiated by the Max Planck Society and Fraunhofer Society [Figure 1: see original paper].

(1) Cooperation Objectives: Since 2005, the Max Planck Society and Fraunhofer Society have leveraged their respective core competencies to collaborate at the intersection of basic and applied research, developing new technologies with application potential and transforming world-class basic research results into innovative applications. Through cooperation among two or more Max Planck institutes and Fraunhofer institutes, they complete projects that each could not accomplish independently, filling gaps in the innovation chain.

(2) Organizational Mechanisms: Cooperation projects between the Max Planck Society and Fraunhofer Society adopt internal bidding, internal competition, joint evaluation, and joint funding mechanisms, with project durations of 3–4 years. Projects employ a multi-level evaluation mechanism: first, a review committee composed of three directors from each society conducts written pre-selection, then approximately five project teams are invited to present their proposals. The presidents of both societies make final funding decisions based on the committee' s voting results, approving 2–4 new projects annually. The Max Planck Society and Fraunhofer Society invest over €4 million annually to support cooperation projects.

(3) Government Role: The German federal and state governments provide financial and institutional guarantees for the continuity and deepening of cooperation between the Max Planck Society and Fraunhofer Society. In 2005, the federal and state governments concluded the "Pact for Research and Innovation," committing to continuously increase budgets for non-university research institutions including Germany' s four major research institutions, thereby strengthening their position in Germany' s research system. With stable funding growth, these institutions pledged to take additional measures to further enhance research quality, including deepening cooperation among research institutions and narrowing the gap between basic theoretical research and application [9].

(4) Collaborative Effectiveness: Since its implementation in 2006, the cooperation program has invested approximately €58 million in 55 projects. These projects cover broad themes in important technologies and economically significant fields, including biotechnology, medicine, microelectronics, catalysis research, quantum physics, information and communication, materials, and energy, achieving technological innovations such as new rare-earth-free magnetic materials, dual-comb spectroscopy technology, and attosecond extreme ultraviolet laser pulses.

3.2 Integrated-Type Organizational Mode

The integrated-type organizational mode represents an integrated organization that breaks the dispersed organizational model centered on single institutions from a holistic and strategic perspective. It integrates organizational elements with different functions into an organic whole, aiming to achieve qualitative functional transformation through mutual complementarity, enhancing overall solution provision capabilities and comprehensive competitive advantages while amplifying overall effects. A 典型案例 is the German Research Fab Microelectronics Germany, jointly established by the Fraunhofer Society and Leibniz Association [Figure 2: see original paper].

(1) Cooperation Objectives: In 2017, 11 Fraunhofer institutes and two Leibniz institutes jointly formulated and launched the cross-regional microelectronics and nanoelectronics research project—German Research Fab Microelectronics Germany. The project aims to bridge scientific research, application, processing, and production through cross-regional cooperation, providing users in science and industry with new technologies and one-stop, high-maturity solutions covering the complete innovation chain, thereby driving the development of Germany' s and Europe' s semiconductor and electronics industries.

(2) Organizational Mechanisms: The German Research Fab Microelectronics Germany coordinates over 2,000 researchers and technical R&D equipment from 13 institutes of the two organizations. Research focuses on four future technology areas: "silicon-based technologies," "compound semiconductors," "heterogeneous integration," and "design, testing, and reliability." Additionally, through six technology platforms— "microwaves and terahertz," "power electronics," "design, manufacturing, and system integration of complementary metal-oxide-semiconductor circuits," "optoelectronic systems," "sensor systems," and "micro-electro-mechanical systems actuators"—the Research Fab integrates capabilities across the entire technology value chain from system design to testing, providing customers with comprehensive solutions. A coordination office in Berlin organizes the Research Fab' s business activities and development strategies, comprising the Research Fab director, four technology area managers responsible for planning long-term development directions, several project managers liaising with industrial customers and connecting application topics, and a communications team responsible for promotion and marketing.

(3) Government Role: The German Research Fab Microelectronics Germany is a supporting measure under the pan-European "Important Projects of Common European Interest" (IPCEI) program, representing Germany' s largest investment in microelectronics research since reunification. The German Federal Ministry of Education and Research provides approximately €400 million in funding for R&D projects and infrastructure, including about €350 million for initial equipment renewal and expansion, with Fraunhofer receiving approximately €280 million and the Leibniz Association receiving approximately €70 million.

(4) Collaborative Effectiveness: As Europe' s largest cross-regional microelectronics R&D alliance and the world' s largest technology and intellectual property team in intelligent systems, the German Research Fab Microelectronics Germany has made important contributions to terahertz technology development for communications and sensing, supporting Germany' s successful implementation of "Industry 4.0," digitalization, and future challenges such as resource efficiency.

3.3 Strategic Alliance-Type Organizational Mode

The strategic alliance-type organizational mode is a strategic, loosely-coupled long-term cooperation model formed by two or more organizations with common strategic interests. This model emphasizes partners acting as a unified whole with clear strategic intentions, focusing on long-term interests. A 典型案例 is the Munich Quantum Valley initiative, jointly launched by the Max Planck Society, Fraunhofer Society, German Aerospace Center (DLR), and other institutions [Figure 3: see original paper].

(1) Cooperation Objectives: In 2021, seven institutions—the Max Planck Society, Fraunhofer Society, German Aerospace Center, Bavarian Academy of Sciences (BAdW), Technical University of Munich (TUM), Ludwig Maximilian University of Munich (LMU), and Friedrich-Alexander University Erlangen-Nuremberg (FAU)—jointly launched the Munich Quantum Valley initiative. The plan aims to make Munich one of the world' s leading regions in quantum science and technology within ten years, helping Germany achieve leadership in quantum technology.

(2) Organizational Mechanisms: Munich Quantum Valley explores quantum science and technology from three dimensions: research, development, and talent. First, the Quantum Computing and Technology Center builds and operates superconducting quantum computers and quantum computers based on ion and atomic qubits. The Max Planck Society's institutes conduct groundbreaking basic research in quantum simulators, cold atoms in optical lattices, Rydberg atoms, quantum information processing, and quantum many-body physics, laying the foundation for quantum technology. The Fraunhofer Society focuses on software issues related to quantum computing security, robustness, and optimization, and undertakes engineering, manufacturing, and system integration of key system components, participating comprehensively in Munich Quantum Valley from both software and hardware perspectives. The German Aerospace Center leverages its expertise in optimal control theory and quantum algorithms to numerically optimize qubit control for different hardware systems and algorithms, developing full-stack quantum computers. Second, the Quantum Science and Technology Park provides necessary technical infrastructure and production facilities for research and product development in Munich Quantum Valley. Infrastructure elements from the Max Planck Society' s Semiconductor Laboratory and Fraunhofer' s Institute for Microelectronic Circuits and Systems will be integrated into the park, providing state-of-the-art facilities for quantum technology R&D and translation. Third, the initiative organizes academic education and industry personnel training. Two Max Planck doctoral programs—the International Max Planck Research School for Quantum Science and Technology and the International Max Planck Research School for Quantum Optics and Quantum Information—provide high-level training for PhD students. Max Planck Innovation and Fraunhofer' s venture capital department conduct training and consulting services for researchers to enhance patent awareness. Munich Quantum Valley has established a streamlined organizational management structure, with the seven partner institutions forming a registered association (Munich Quantum Valley e.V.) to guide and coordinate activities and allocate resources. A supervisory board composed of federal and state government representatives and industry representatives oversees Munich Quantum Valley e.V.

(3) Government Role: Munich Quantum Valley serves as Bavaria' s core force for quantum technology development, with the Bavarian state government providing €300 million in funding under the "Bavarian High-Tech Agenda." Additionally, as part of the German federal government' s "Future Plan," Munich Quantum Valley received €80 million in funding from the Federal Ministry of Education and Research and the Federal Ministry for Economic Affairs [10]. The initiative also collaborates with enterprises in the quantum technology field, obtaining industrial funding support.

(4) Collaborative Effectiveness: Munich Quantum Valley achieved considerable progress in its first year, securing federal funding for quantum computer demonstrators and quantum software applications. Interest from local, regional, and international enterprises and academic institutions in collaborating with Munich Quantum Valley continues to grow, including joint personnel exchange programs. Furthermore, Munich Quantum Valley has played a pioneering role in creating an interdisciplinary ecosystem, with researcher numbers nearly doubling from the initial 200, demonstrating the attractiveness of the quantum ecosystem in and around Munich Valley despite global competition for quantum technology talent.

3.4 Platform-Type Organizational Mode

The platform-type organizational mode is constructed by a leading unit and multiple partners, aiming to establish an open, dynamic collaborative platform. Through platform openness, it achieves effective resource integration and cooperation. Partners exhibit strong mobility during platform development, with complementary advantages that mutually reinforce each other, creating a "co-creation and win-win" ecosystem. This model typically adopts a "platform-sub-platform" structure, establishing different sub-platforms according to business divisions. A 典型案例 is the Cyber Valley initiative launched by the Max Planck Society in the artificial intelligence field in 2016 [Figure 4: see original paper].

(1) Cooperation Objectives: Cyber Valley involves 12 cooperative members from German government, scientific community, and industry, including the Baden-Württemberg state government, Max Planck Institute for Intelligent Systems, Fraunhofer Society, University of Stuttgart, University of Tübingen, Amazon, BMW, IAV, Mercedes-Benz, Porsche, Bosch, and ZF. The initiative aims to create a research and entrepreneurship ecosystem, building Germany' s "Silicon Valley."

(2) Organizational Mechanisms: Cyber Valley spans two cities—Stuttgart and Tübingen—and operates in three sub-areas: expertise and talent, economic development, and social impact. In expertise and talent, Max Planck institutes conduct basic research on perception, behavior, and learning in AI systems, while the International Max Planck Research School for Intelligent Systems trains doctoral students. The Fraunhofer Center for Machine Learning bridges basic research and enterprises, conducting manufacturing and service-related research to help SMEs apply modern AI methods. Cyber Valley' s organizational management includes a General Assembly and an Executive Committee. The General Assembly decides on fundamental development issues and strategic interests, with Max Planck Society, Baden-Württemberg state government, and enterprises each holding 33.3% of voting rights. The Executive Committee, composed of three members elected by the General Assembly (representing Max Planck Society, Baden-Württemberg state government and universities, and enterprises), oversees ongoing projects.

(3) Funding Approach: Cyber Valley is jointly invested in by all cooperative members, with Phase 1 investment totaling approximately €165 million. The Baden-Württemberg state government, Max Planck Society, University of Stuttgart, and University of Tübingen fund new research buildings, professorships, research groups, graduate schools, and other major facilities, with the state government as the largest contributor providing over €160 million. Industrial partners provided approximately €7.5 million in support for research groups at Max Planck Institute for Intelligent Systems, University of Stuttgart, and University of Tübingen between 2018–2022, and funded two endowed professorships. Additionally, Cyber Valley receives support from foundations such as the Carl Zeiss Foundation.

(4) Collaborative Effectiveness: Cyber Valley is Europe' s largest AI research organization, enjoying an excellent reputation throughout Germany and internationally, ranking highly in relevant evaluations. Since its establishment, cooperation among partners has fostered prosperity and development of the AI ecosystem in the Stuttgart-Tübingen region, with Baden-Württemberg emerging as a European and global research and innovation center for machine learning, robotics, and computer vision.

3.5 Network-Type Organizational Mode

The network-type organizational mode is the most loosely structured cooperation model, breaking institutional and regional boundaries in organizational form and exhibiting multilateral and three-dimensional characteristics. Nodes are the basic units of network organizations, possessing decision-making capabilities and able to complete tasks independently. Due to its loose structure, network organizations require national guidance and long-term funding to maintain stability, along with a specific coordination management system [11]. A 典型案例 is the six cross-regional, cross-institutional health research centers established by the German federal government between 2009–2012 [Figure 5: see original paper].

(1) Cooperation Objectives: The German Centers for Health Research unite partners from university medical schools and extra-university medical research institutions, whose complementary scientific expertise along the medical innovation chain aims to concentrate research forces nationwide in common disease areas, create a national health research network, improve research quality, and accelerate translation from laboratory to medical services. The six centers focus on translational medical research in diabetes, infectious diseases, cancer, neurodegenerative diseases, lung diseases, and cardiovascular diseases.

(2) Organizational Mechanisms: The health research centers adopt a "working group—site" two-tier structure for research activities. Working groups are divided into scientific and clinical working groups, with partners participating in center research activities by joining working groups. Geographically adjacent working groups jointly form sites to complete research tasks, with each center typically having 5–9 sites. For example, the German Center for Infection Research unites 35 German university and extra-university medical research institutions, the most among all centers, establishing 49 working groups across nine research areas including emerging infectious diseases, HIV, infections in immunocompromised hosts, tuberculosis, and hepatitis, organized into seven sites: Hamburg-Lübeck-Borstel, Hanover-Braunschweig, Bonn-Cologne, Gießen-Marburg-Langen, Heidelberg, Tübingen, and Munich. The centers have decision-making, management, supervisory, and advisory departments, with the General Assembly as the highest authority where all partners decide on research strategies, funding allocation, and personnel appointments.

(3) Government Role: The health research centers were established under the "German Federal Government Health Research Framework Program," receiving long-term funding from federal and state governments at a 90:10 ratio. Annual funding from the federal government and 13 state governments totals approximately €270 million [12].

(4) Collaborative Effectiveness: The health research centers have successfully integrated basic and clinical research, creating optimal conditions for accelerating translation to medical services. In 2020, scientists from the centers led development of the first drug for chronic hepatitis D and a new heart valve technology approved in Europe, making decisive contributions to human welfare.

3.6 Differences and Characteristics of Different Organizational Modes

Germany' s four major research institutions exhibit diverse collaborative innovation forms, with the five models showing differences in structural characteristics, advantages and disadvantages, and applicable scenarios . Based on organizational looseness, these models can be categorized into two types: compact and loose.

(1) Project-type and integrated-type models feature streamlined partners, tight organization, and lean structure. The project-type model offers advantages of strong interactive cooperation, easy implementation, clear responsibilities, and flexible, efficient management, making it suitable for focused, targeted specific research problems. However, its temporary and dynamic nature lacks continuity and stability. The integrated-type model emphasizes overall effects, with integrative characteristics that reintegrate core organizational elements to facilitate unified command and coordination of core interests and key actions, avoiding conflicts and competition among partners. It represents the best path for seeking overall solutions and enhancing comprehensive competitive advantages.

(2) Strategic alliance-type, platform-type, and network-type models feature broad scope and diverse partners. The strategic alliance-type model has clear strategic intentions and objectives, emphasizing strategic cooperation and long-term relationships focused on long-term benefits. Generally launched by multiple actors, it enables resource sharing and technology transfer, shortening R&D cycles and promoting technological innovation. The platform-type model attaches to an institution with strong research capabilities and leadership, maximizing partner value. Its greatest characteristic is organizational openness, though partners maintain relative independence and higher degrees of freedom, making cooperation coordination challenging. The network-type model exhibits network-like characteristics in cross-domain, cross-organizational, and cross-regional partnerships, with dense multilateral connections as its main feature. The diversity and heterogeneity of partners and knowledge make it suitable for comprehensive, large-scale national strategic research tasks. Without an obvious core, network organizations generally adopt collective decision-making by partners, emphasizing consensus-building, resulting in relatively lower decision-making efficiency.

4. Implications and Lessons

Amid rapid scientific and technological development and increasingly complex international scientific and technological competition, aggregating elite national scientific and technological forces to explore and establish more efficient collaborative innovation organizational models in important strategic and key technology fields represents an effective path for China to shape new drivers and advantages for development, enhance independent innovation capabilities, and improve international competitiveness. As important components of Germany' s strategic scientific and technological forces, the collaborative innovation organizational models of Germany' s four major research institutions offer insights and lessons for China to improve its new national system and enhance collaborative innovation effectiveness among national research institutions and national laboratories.

(1) Introduce incremental resources to promote collaborative innovation development. The positioning and division of labor among Germany' s four major research institutions in the national innovation system are clear, with stable government financial support enabling them to adhere to their missions. Since 2006, the German federal and state governments have concluded the "Pact for Research and Innovation," committing to increase funding for the four major research institutions by at least 3% annually while requiring strengthened cooperation among them [9]. The introduction of incremental resources has actively promoted cooperation and linkage among Germany' s four major research institutions and provided important financial guarantees for stable collaborative innovation operation. China should change the current situation where incremental scientific and technological resources are mainly used for competitive projects or new research units. While stabilizing the mission positioning of existing research institutions, China should allocate incremental resources to encourage collaborative innovation among research institutions, forming a national innovation system with clear functional positioning and complementary innovation advantages.

(2) Strengthen full-chain collaborative innovation in comprehensive national research institutions. Diversified innovation actors create necessary space for collaborative innovation. Germany' s four major research institutions extend their mission positioning from cutting-edge basic research to applied technology development, covering the entire innovation chain. Comprehensive national research institutions represented by the Chinese Academy of Sciences should leverage their systematic and institutional advantages of comprehensive disciplinary fields and full innovation chains, breaking barriers between disciplines, fields, and teams. They should actively connect research forces along the innovation chain, leveraging differentiated advantages of different research units to accelerate formation of a research system with clear division of labor, efficient collaboration, independent operational capability, and joint problem-solving capacity for critical research challenges.

(3) Build a strategic scientific and technological force collaboration network led by national laboratories. The Helmholtz Association, with its national laboratory characteristics, occupies a dominant position and plays a leading and aggregating role in collaborative research on major national strategic tasks such as health research. For complex, major scientific and technological collaborative research tasks that are interdisciplinary, cross-field, cross-institutional, cross-regional, long-cycle, and large-investment, China should fully leverage national laboratories as institutionalized national strategic scientific and technological forces to integrate various types of innovation resources. This would form a networked collaborative model with strong integration effects, synergy effects, radiation effects, and amplification effects, significantly enhancing the effectiveness of core technology research systems.

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