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CiteSpace-based Visualization and Analysis of Quantum Information Technology Research in China

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Abstract

In view of the current research situation of quantum information technology in China, this paper examines the quantum information technology related literature in China National Knowledge Infrastructure (CNKI), and derives 874 documents in Chinese. Through CiteSpace, we draw a visual knowledge map of quantum information technology, analyze the number of publications, high-frequency keywords, and the evolution of keyword time sequence, etc., analyze the current status and trend of China's research, and provide quantitative data support for the future research of quantum information technology. The study shows that the number of Chinese literature in the field of quantum information has been increasing in recent years. Chinese quantum information research can be broadly categorized into two areas: quantum communication and quantum computing. In addition, new research hotspots in the field of quantum information continue to emerge, such as quantum entanglement, quantum error correction, and quantum network construction, etc. These indicate that the research in the field of quantum information in China is deepening and developing, and that there is a huge potential for research in quantum information. In order to promote the further development of quantum information, this paper puts forward strategies and suggestions such as strengthening basic research, promoting technological breakthroughs, cultivating human resources, promoting international cooperation and improving policy support. The research in this paper provides a reference for China's strategic layout and scientific research innovation in the field of quantum information, aiming to promote the rapid development of quantum information technology.

Keywords:quantum communication; quantum computing; quantum information; CiteSpace software ; visualization analysis

1 Introduction

Quantum information as an emerging frontier technology is becoming the focus of global scientific and technological competition. The emergence of quantum information not only brings a new theoretical basis and technical means for information science, but also has the potential to trigger a profound technological revolution, changing our traditional knowledge of information processing, transmission and storage.

The concept of quantum information can be traced back to the birth of quantum mechanics in the early 20th century. The emergence of quantum mechanics has enabled our understanding of the microscopic world to reach unprecedented depth and precision. It has revealed such peculiar phenomena as wave-particle duality, quantum entanglement and quantum superposition of microscopic particles, which cannot be explained in classical physics. With the deepening research on quantum mechanics, scientists have begun to explore how to utilize these unique quantum properties to process and transmit information, thus giving rise to the brand-new subject area of quantum information. China has also made important breakthroughs in the field of quantum information, especially in quantum computing, where Chinese scientists have achieved a number of world-leading results. For example, a Chinese research team has successfully developed the "Nine Chapters" optical quantum computing prototype with 76 photons and the 66-bit programmable superconducting quantum computing prototype "Zuchongzhi II", which has enabled China to realize the leap from following the lead to running in parallel, and partially leading in the field of quantum computing. This has enabled China to realize the leap from following to parallelism and partial leadership in the field of quantum computing [1].

Quantum information technology belongs to the cross-technology field of quantum physics and information science, mainly including quantum computing, quantum communication, quantum measurement, quantum metrology and other technical directions. These technologies not only show great potential in scientific research, but also have a wide range of application prospects in information security, communication transmission and computational capability. Quantum communication, as an important part of quantum information technology, mainly contains technologies such as quantum key distribution and quantum invisible state transmission. Quantum key distribution ensures the absolute security of communication through the principle of quantum mechanics, which can effectively prevent the information from being eavesdropped and become an important guarantee of future information security [2]. Quantum computing is a new computing paradigm that realizes information processing based on the basic principles of quantum mechanics. It utilizes the superposition property of quantum states to realize parallel processing of multiple quantum states at the same time. Compared with classical computers, quantum computers have significant speed advantages for specific tasks [3]. Quantum measurements, on the other hand, can realize ultra-precise measurements of physical quantities with the high sensitivity and accuracy of quantum systems, which is of great significance for basic scientific research and high-end manufacturing.

In recent years, the field of quantum information has achieved many remarkable results. 2019, Google announced that it had achieved quantum superiority, and its quantum processor "Suzuki" was much faster than traditional supercomputers on specific tasks [4]. 2020, Pan Jianwei's team at the University of Science and Technology of China (USTC) successfully realized a quantum system based on the "Mo". In 2020, Pan Jianwei's team at the University of Science and Technology of China (USTC) successfully realized star-to-ground quantum communication based on the "Mozi" satellite, marking an important step towards the practicalization of quantum communication technology [5]. These results not only demonstrate the powerful potential of quantum information, but also stimulate the global research on quantum information. However, the development of quantum information also faces many challenges. The fragility of quantum systems and the interference of environmental noise make the storage and transmission of quantum information extremely difficult. The error correction problem of quantum computing, the network construction of quantum communication, and the accuracy improvement of quantum measurement are all key technical challenges that need to be solved at present [6]. In order to overcome these challenges, governments and research institutions have increased their investment in quantum information research, which has promoted the rapid development of quantum information technology.

Based on the above background, this paper will provide a comprehensive overview of the latest research progress, challenges and future development trends of quantum information. In this paper, a systematic review of the relevant research in China is conducted, while the theoretical research on quantum information is used to explore the future development.CiteSpace software, as a tool for literature analysis and data visualization, not only can effectively avoid the subjective problems caused by qualitative analysis, but also its graphic and textual features can help to clarify the research hotspots and development trends. In this paper, we use CiteSpace software as a tool, adopt bibliometric analysis method to dig deep into the selected literature, and read the key literature to show the research hotspots in the field of quantum information in the past 30 years, and put forward the strategies and suggestions to promote the development of quantum information, so as to provide references for China's strategic layout and scientific research and innovation in the field of quantum information.

2 Research Design

2.1 Data sources

CNKI database has a large number of Chinese literature resources, which can comprehensively cover the development history, status and prospect of quantum information technology in China. In this paper, CNKI was searched with "quantum information" as the subject term, and 3,153 academic journal articles were obtained. In order to ensure the quality of the selected literature, the years of the selected literature were limited to 2000-2025, and the abstracts of the literature were systematically enlarged to exclude articles unrelated to the research of quantum information, and finally 874 articles were obtained. The literature data were imported into CiteSpace software, the time span was set to 2000-2025, the time partition was set to 1 year, and the node screening method was selected as g-index (coefficient k=25).

2.2 Analysis method

Bibliometric analysis is a scientific method of assessing a research field by counting and analyzing various data in academic literature, which can comprehensively present the knowledge base, research hotspots, and development trends of the research field [7]. In this paper, we use CiteSpace software for bibliometric analysis to scientifically measure the literature on quantum information in China and to analyze specific literature in depth. In this paper, we first conduct a descriptive analysis of the selected literature in order to understand the overall research on quantum information in China; secondly, we conduct a keyword analysis of the literature with the help of CiteSpace software, analyze the key literature on quantum information based on keyword co-occurrence, keyword clustering and keyword timeline, and then determine the general direction of the research in the light of the frequency of occurrence and the centrality of intermediaries, and finally, we conduct a digging and analysis on the content of the research.

3 Literature statistics and analysis

3.1 Basic knowledge

In order to have a comprehensive understanding of the changes in the quantity and time evolution of the literature in the field of quantum information in China, this paper conducts a descriptive analysis of the selected literature. Quantum" in modern physics originated in the early 20th century and was proposed by Max Planck, a German physicist. Quantum is an important concept in modern physics, which describes the discontinuity and discrete nature of physical quantities in the microscopic world. A physical quantity is called quantum if there exists a smallest indivisible fundamental unit, and this smallest unit is called a quantum. Quantum information is a new way of information based on the principles of quantum mechanics, which is computed, encoded and transmitted information through various coherent properties of quantum systems [8]. Compared with traditional information theory, quantum information shows great advantages in terms of computational capability, communication security, and transmission efficiency. China introduced quantum information science in the 1980s, and after decades of development, it has made world-renowned achievements. In order to explore China's research achievements and future development trend in the field of quantum information, this paper, with the help of the keyword analysis function of the literature, analyzes the content of the literature in a specific way.

The annual publication volume of Chinese academic journals is searched, and the keyword is quantum information, as shown in Figure 1. As can be seen from Figure 1, before 2000, there were very few articles in the field of quantum information, most of which were not published, and the highest number of articles was not more than 10, indicating that it has not yet attracted extensive attention and research. Since the 1990s, with the development of quantum modulation technology, quantum information technology has gradually attracted attention [9]. Since 2000, the number of articles published in related fields has increased significantly, and although the specifics of the number of articles published fluctuate, the overall trend is upward, indicating a significant increase in research activities in the field of quantum information in China.

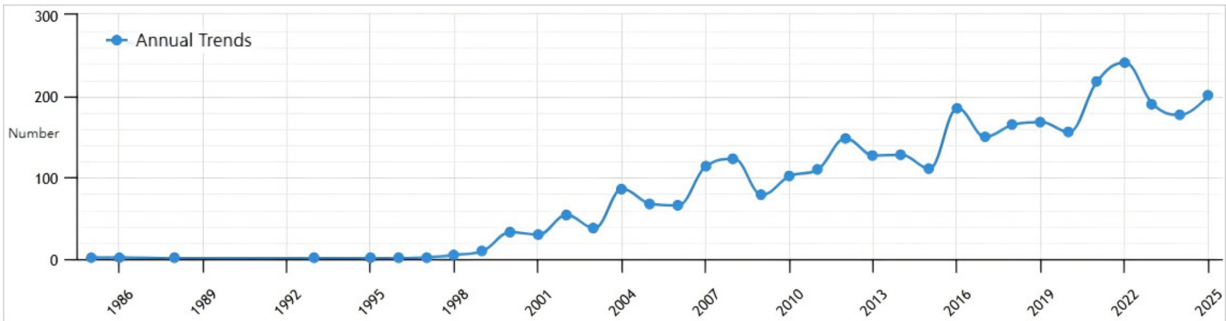

Fig. 1 Annual publication volume of Chinese literature

3.2 Keyword Analysis

3.2.1 High-frequency keyword analysis

In this paper, the literature data are imported into CiteSpace software, the time span is set to 2000-2025, the time division is set to 1 year, and the node type is set to Keyword, so as to construct the literature keyword network and carry out cluster analysis. In this paper, the keywords are selected to name each cluster, and the results are shown in Fig. 2 and Fig. 3. Combining the keyword co-occurrence graph and the keyword clustering graph can get five significant clusters (#0 quantum communication, #1 quantum optics, #2 quantum computation, in which #3 quantum information as a big topic is not counted, #4 quantum entanglement as a basic theory is not counted, and the rest of the clusters are not significant enough).Modularity Q is the evaluation index of network modularity, when Q>0.3, it is the network structure is considered to be more significant; Weighted Mean Silhouette value is used to measure the network homogeneity, and when S>0.5, the clustering result is efficient and convincing. From Fig. 2, it can be seen that the literature keyword network of this paper is well structured (Q=0.5884), the clustering results are reasonable, the quality of clusters is high, the similarity within the clusters is high, and the differences between the clusters are large. (S=0.8818).

Fig. 2 Keyword co-occurrence diagram

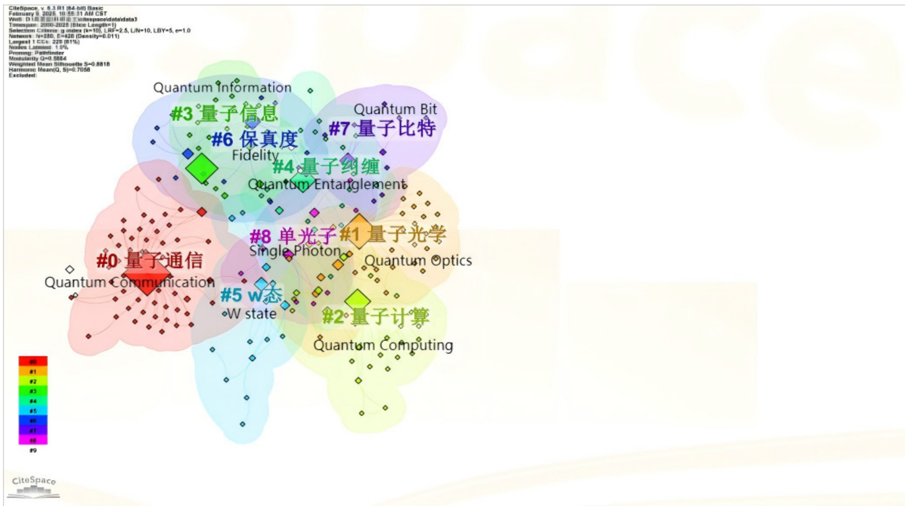

Fig. 3 Keyword clustering diagram

In the keyword co-occurrence graph, the larger the keyword node represents the greater the influence of the topic and the higher the frequency of research. Keywords condense and summarize the key words of the article, and their frequency and centrality can reflect the research hotspots in this field[10], as shown in Table 1. When the mediator centrality >= 0.1, it means that the keyword acts as a "mediator" more often, the greater the importance. Combined with the analysis of keyword co-occurrence graph, keyword clustering graph and keyword intermediary centrality, it can be seen that the research hotspots in the field of quantum information in China can be roughly divided into quantum communication and quantum computing.

Count	Centrality	Year	Keywords
278	0.75	2000	量子通信 Q-communication
162	0.39	2004	量子光学 Quantum Optics
131	0.26	2000	量子信息 Q-Information
82	0.19	2000	量子纠缠 Q-Entanglement
78	0.22	2000	量子计算 Q-computing
29	0.05	2003	保真度 Fidelity
28	0.05	2002	量子比特 Qubit
26	0.04	2004	量子密码 Q-Cryptography

Table 1 Table of high-frequency keywords (Year represents the year in which the keyword first appeared)

(1) Quantum communication. Quantum communication is a new communication technology that utilizes the principle of quantum mechanics to transmit information, and its key lies in the use of the characteristics of quantum states (such as quantum entanglement, non-clonability, etc.) to achieve safe transmission of information. The main applications of quantum communication include quantum key distribution (QKD), quantum invisible transmission, and quantum secure direct communication. These techniques provide unconditional security at the theoretical level, i.e., within the framework of quantum mechanics, any attempt to steal information will be detected, thus guaranteeing the security of communication [11]. Quantum key distribution is one of the most mature technologies in quantum communication, and its basic principle is to transmit quantum bits through a quantum channel to ensure the security of the key distribution by virtue of the unclonability and measurement collapse of quantum states, and one of the early quantum key distribution protocols is the BB84 protocol, which encodes the key information by means of the polarized state of a single photon [12]. The security and transmission distance of quantum key distribution have been significantly improved with the advancement of the decoy state method and the measurement device independent quantum key distribution (MDI-QKD) technology[13]. The Chinese Academy of Sciences (CAS) team has successfully realized the star-ground quantum key distribution by using the decoy state method for thousands of kilometers of quantum key distribution in 2016 by using the Mercurial Science Experiment Satellite [14-16].The paper on quantum invisible state transfer published by Bennett [17]et al. in 1993 is a milestone in the history of quantum information science. It first proposed a theoretical scheme for quantum invisible state transfer, proved its feasibility, and laid an important foundation for the development of quantum communication and quantum computing. Quantum invisible state transfer is another key application of quantum communication, which utilizes quantum entanglement to achieve the transmission of unknown quantum states without the need to transmit solid particles. The core of quantum invisible state transfer lies in the fact that, through the entangled states shared in advance, the sender is able to transmit information about a quantum state to the receiver without actually transmitting the quantum state itself. Quantum secure direct communication belongs to a new classified communication mode, which transmits secret information directly in a quantum channel without the need for keys and ciphertexts. Quantum secure direct communication utilizes the non-clonability and measurement collapse of quantum states to ensure the security of information in the transmission process. The quantum secure direct communication scheme proposed by Long Guilu et al. was verified in experiments and implemented in fiber optics and free space for principle demonstration [18]. In addition to the above core technologies, the construction of quantum communication networks is also one of the hotspots of research. Internationally, the United States, the European Union, Japan and other countries and regions have carried out numerous experiments and pilot projects of quantum communication networks (DARPA Quantum Network in the United States, SECOQC in the European Union, Tokyo QKD Network in Japan) ([19]) , whichprovide a practical basis for the practicalization of quantum communication. China has also achieved remarkable results in the construction of quantum communication networks, such as the completion of the Beijing-Shanghai trunk line quantum communication network, and the initial construction of the star-ground integrated quantum communication network [20]. Quantum communication is a global technology field, which needs to strengthen international cooperation and exchange. Countries can jointly carry out quantum network construction projects, share technology and experience, and promote the internationalization of quantum communication technology [21].

Quantum Computing. Quantum computing is a cutting-edge research direction in the field of modern physics and information technology. As an emerging interdisciplinary discipline, quantum information science covers a wide range of fields such as quantum communication, quantum computing, quantum simulation and quantum precision measurement. Quantum computing, on the other hand, is one of the core applications of quantum information science, which utilizes the basic principles of quantum mechanics, such as quantum superposition and quantum entanglement, to achieve efficient computational processing. Quantum computing has powerful parallel computing and simulation capabilities [22-24], such as the Shor algorithm and the Grover algorithm, which demonstrate the great advantages of quantum computing on specific problems.The Shor algorithm can solve the large integer factorization problem in polynomial time, and it can easily crack the RSA algorithm, which is currently widely used as an asymmetric encryption algorithm for public-key cryptography and e-commerce ([25The Grover algorithm accelerates the search of unorganized databases [26]. The success of these algorithms not only proves the potential of quantum computing, but also pushes the development of quantum information theory. The development of quantum computing has pushed forward the progress of experimental techniques of quantum information, and the continuous improvement of the preparation, manipulation and measurement techniques of quantum bits has made the experimental research of quantum information more in-depth. The development of quantum error-correcting code and fault-tolerant computing technology provides a guarantee for the reliability of quantum computing, and also promotes the deepening of quantum information theory. In addition, the combination of quantum computing and quantum communication, such as quantum key distribution (QKD), provides a new solution for information security.The security of quantum secure communication based on quantum key distribution is independent of the computational complexity, and cannot be cracked even by quantum computers [27]. The development of quantum information theory provides rich theoretical support for quantum computing. Theoretical studies such as quantization of quantum entanglement and metrics of quantum information provide theoretical basis for quantum bit manipulation in quantum computing [28]. Quantum error-correcting codes and fault-tolerant computing techniques in quantum information are the key to realizing reliable quantum computation. The development of these techniques not only improves the stability of quantum computation, but also lays the foundation for the wide application of quantum information [29]. The future development of quantum computing and quantum information will promote each other. Quantum computing is expected to achieve breakthroughs in more fields, such as quantum simulation, quantum optimization and quantum machine learning. The deepening of quantum information theory will provide stronger theoretical support for quantum computing. At the same time, the practical needs of quantum computing will also drive the continuous progress of quantum information experimental technology [30]. With the maturity of quantum computing technology, the construction of quantum networks will become possible, which will further expand the application scope of quantum information.

3.2.2 Hot Spot Timing Analysis

Keywords can reflect the topic information of the article, and its can help us understand the research hotspot. Timeline mapping arranges the keywords in the clusters in the order of the year in which they first appeared, which visualizes the frequency of appearance of specific topics in different time periods and helps to analyze hotspot migration. It provides researchers with an intuitive and dynamic way to analyze and understand the evolution of a research area by introducing a time dimension.

Figure 4 shows the timeline mapping. The time sequence is arranged in order from far to near, and the denseness of the nodes shows the research frequency and hotness of the topic in that time period. The length of the dense area also indicates to some extent the persistence of that research. Each node represents a different keyword under the cluster, and the more nodes indicate the more comprehensive research on the cluster. The right side of the figure lists the cluster numbers and names for each topic, which indicate the collection of literature with similar research content in a specific time period.

From the figure, it can be seen that since 2005, with the increasing emphasis of the state on quantum information technology and industry, there has been a significant increase in research and discussion in the field of quantum information in China. Quantum communication has maintained a high level of research activity throughout the time period, while quantum optics and quantum computing have gradually increased their research activity after 2008. Quantum information and quantum entanglement began to significantly increase research activity after 2010. In terms of research convergence, there are more connections between quantum communication and quantum optics and quantum computing, indicating more cross research between these topics.

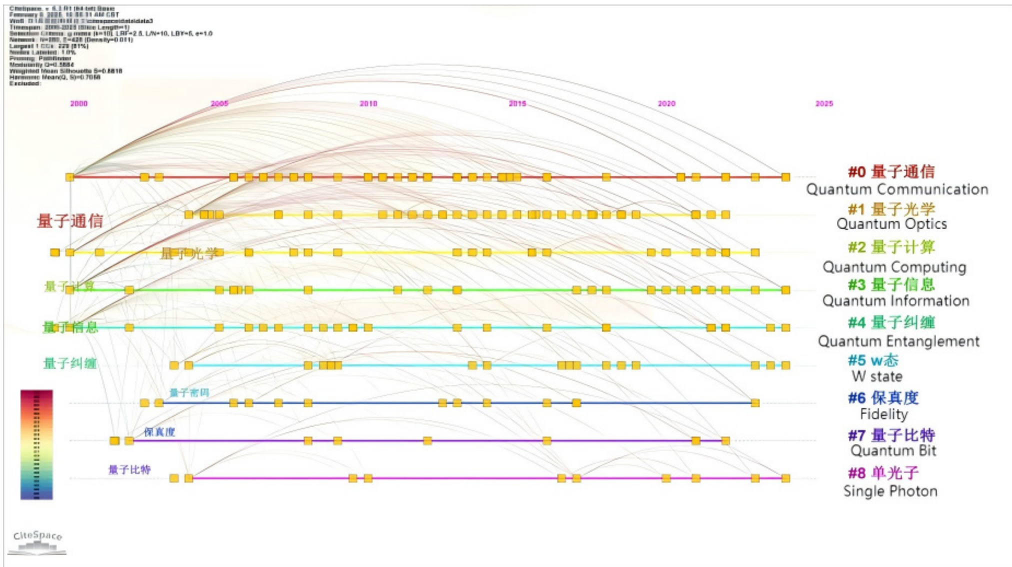

Fig. 4 Keyword timeline graph

Combining the timeline mapping and high-frequency keyword analysis, this paper broadly divides the research of quantum information technology in China into the following four stages.

(1)Theoretical research stage of quantum information

During this period, quantum information, as an emerging field, began to receive academic attention. The relevant research focused on the basic principles of quantum mechanics and its potential use in information processing. Quantum communication, quantum computation and quantum measurement, as the three main aspects of quantum information, gradually became the core of research. However, due to the limitations of technology and theory, the research results in this period are relatively limited, mainly focusing on theoretical research and verification of small-scale experiments as a way to improve the stability and reliability of quantum computation.

(2) Technological exploration stage of quantum information

Along with the continuous maturation of the theory of quantum information and the development of technology, the research activities in this period increased significantly. In terms of quantum communication, especially quantum key distribution technology, it has moved from the laboratory to practical application, reaching a specific distance of quantum secure communication. As far as quantum computing is concerned, the research on quantum algorithms has gained progress, highlighting the advantages of quantum computing in specific problems. Quantum measurement technology has also demonstrated its unique strengths in the field of precision measurement. During this period, China's research in the field of quantum information has gradually formed a certain scale and influence.

(3)Deepening and Expanding Stage of Quantum Information

As the research in the field of quantum information is deepening and expanding, quantum information technology is developing towards more efficient, safer and wider applications. Although quantum computing technology faces many challenges, researchers are working hard to overcome them and promote the practicalization of quantum computing. In addition, research hotspots in the field of quantum information continue to emerge, such as quantum entanglement, quantum error correction, quantum network construction, etc. The research on these hotspots not only promotes the development of the theory of quantum information, but also provides the possibility of the practicalization and industrialization of quantum information technology.

(4)Practicalization and industrialization stage of quantum information

In this stage, the research in the field of quantum information gradually moves from theory to practicalization as well as industrialization. The construction of quantum communication networks has become the focus of research, and many countries and regions have launched experiments and pilot projects on quantum communication networks. Although quantum computing technology is still in its early stages, it has already begun to explore its application in specific fields. Quantum measurement technology is also playing an increasingly critical role in basic scientific research and high-end manufacturing. Over time, China's research in the field of quantum information has not only made theoretical breakthroughs, but also achieved remarkable results in practical applications.

In summary, China's research in the field of quantum information has gone through the stages of theoretical research, technological exploration, deepening and expanding, as well as the current stage of practicalization and industrialization. With the continuous deepening of research and technological progress, the field of quantum information is expected to make more breakthroughs in the future and make greater contributions to China's scientific and technological progress and economic development.

4 Conclusion and Recommendation

4.1 Research Conclusion

In this paper, we use CiteSpace software to analyze the literature in the field of quantum information in the CNKI database from 2000 to 2025, and excavate the research status and dynamic frontier information through bibliometric analysis. Through the analysis, we find that quantum information, as an emerging frontier science and technology field, has occupied an important position in the global science and technology competition. As the two main directions of quantum information research, quantum communication and quantum computation have shown great potential and wide application prospects, and have not only made theoretical breakthroughs, but also made remarkable progress in practical applications.

In terms of the number of published literature, although the number of specific literature fluctuates every year since 2000, the number of literature on quantum information is generally on the rise, indicating that the research in the field of quantum information has continued to receive extensive attention due to the national attention and policy support.

In terms of research content, research in the field of quantum information is mainly focused on quantum communication and quantum computing. Quantum communication provides theoretically unconditionally secure communication based on the unclonable theorem and uncertainty principle of quantum mechanics. Quantum computation utilizes the superposition and entanglement properties of quantum bits, demonstrating a more efficient computational capability than traditional computers.

From the viewpoint of research hotspots, research hotspots in the field of quantum information continue to emerge, such as quantum entanglement, quantum error correction, quantum network construction and so on. The research on these hotspots not only promotes the development of quantum information theory, but also provides a possibility for the practicalization and industrialization of quantum information technology. The cross-fertilization between different disciplines provides a solid theoretical foundation for the development of quantum information science.

4.2 Policy Recommendations

Quantum science and technology is moving from theory to application, and will profoundly affect economic transformation, industrial upgrading and national security. Its development will not only bring opportunities for industrial revolution, but also reshape the shape of future war. On the one hand, quantum information technology has great potential for commercialization and will reconfigure key industrial ecosystems. The U.S. National Strategy Overview for Quantum Information Science states that "the development of quantum information science can help the United States improve its industrial base, create jobs and realize economic and national security benefits" [31]. This says that quantum information technology plays an important role in the economic development of the country. On the other hand, quantum technology will revolutionize the future battlefield in multiple dimensions. Compared with traditional military technology, quantum technology will not only enhance battlefield perception and electronic warfare capability, but also reshape the future information confrontation mode and make significant changes in the form of war [32]. Quantum technology is becoming a strategic high ground for the competition of great powers, and its development not only concerns economic competitiveness, but also determines the initiative of future military and information security.

In recent years, although China has made significant breakthroughs in this field, its road ahead is still full of challenges. In order to deepen the development of quantum information in China, basic research should be strengthened, and research investment in basic theories of quantum information should be continuously increased to provide a solid theoretical foundation for the development of quantum information; technological breakthroughs should be promoted, and cooperation between scientific research institutes and enterprises should be encouraged to jointly overcome technical problems in the field of quantum information, and to push forward the pragmatization and industrialization of quantum information technology; the cultivation of talents in the field of quantum information should be strengthened, and a multi-level and multi-channel talent cultivation program should be established. Multi-level and multi-channel talent cultivation system to provide talent guarantee for the development of quantum information; the government should introduce relevant policies to provide financial support and policy guidance for quantum information research, and create a favorable research environment; strengthen the cooperation and exchange between the state, institutions, scholars, and enterprises, and jointly promote the development of quantum information technology, and contribute to the development of human science and technology.

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