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WORKS ON QUANTUM ENTANGLEMENT

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Who are the dominant players in the experimental field of quantum entanglement? A bibliometric analysis

Y.D. Xie, Q. Wu, X.C. Li, Y. Gao, P. Zhang, S.J. Wu, Y.Y. Liu, N. Zhang

Abstract. **Quantum entanglement is a major research resource in quantum information science, which has obtained increasing attention and has been intensively studied experimentally in recent years. Based on 7089 research papers in the experimental field of quantum entanglement obtained from the Web of Science Core Collection database, this study investigates the 400 top-cited papers which were written by 498 first or corresponding authors from188 institutions in 32 countries/territories. This study not only relies on traditional methods with first author full counting and corresponding author full counting to present the critical authors, institutions, and countries as designers or executors but also uses distinctive methods with first/corresponding author full counting and first/corresponding author fractional counting to find the dominant players in the experimental field of quantum entanglement. Considering authors, A. Zeilinger and J.W. Pan are the most dominant scientists in this field. The University of Vienna has the best institutional performance in this field, and other institutions such as the University of Science and Technology of China also do fairly well. The results show that the USA, Germany, Austria, the UK, and mainland China fit their reputations as dominant players in the field.**

Keywords: *top-cited papers, first/corresponding author, quantum entanglement, experimental field, bibliometric analysis.*

1. Introduction

In recent years, quantum theory has undergone rapid development, and many countries and regions are investing much money to promote theoretical development and seize the lead in quantum information technology. For example, the USA passed the *National Quantum Initiative Act* in 2018 to ensure that the USA maintains a leading position in studying quantum information technology. In addition, China chose quantum information as a key project of its *13th Five-Year Plan* (2015 to 2020), seeking to improve the basic research into applications of quantum information technology. As the essence of the quantum world and the main resource of quantum information processing [1], quantum entanglement has obtained growing attention from academia and governments in the 21st century.

Y.D. Xie, Q. Wu, X.C. Li, Y. Gao, P. Zhang, S.J. Wu, Y.Y. Liu, N. Zhang School of Management, University of Science and Technology of China, 96 Jinzhai Road, Hefei 230026, China; e-mail: qiangwu@ustc.edu.cn

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Discussion of quantum entanglement, known as the god effect [2], originated in the debate about the basic interpretation of quantum mechanics in 1935 [3], although it took over many years for entanglement to really enter the stage of viewing it as a new resource in laboratories that is similar to energy [4]. In 1997, A. Zeilinger's team firstly observed the experimental results of quantum teleportation based on the quantum entanglement, and their work was selected for publication in *Nature: A Celebration of Physics* in 1999, an issue that included only 21 centennial classical papers of physics published in *Nature*. Zeilinger's student, J.W. Pan, who is called the 'Father of Quantum' in China [5] continues his research in the experimental application of quantum entanglement and makes pioneering achievements in China. There is no doubt that the experimental study of quantum entanglement can significantly impact the development of the discipline of quantum information processing, which has great scientific value and prospects. Hence, to obtain a better understanding and achieve an overall view of the experimental field of quantum entanglement, this paper adopts quantitative analysis to confirm the contributions of scholars who have been evaluated by peer review, and to determine scientific guidelines for researchers and governments.

Bibliometric study has been used to assess and map the communication of science in many overall subjects, subfields, and research topics [6]. Many studies of top-citation papers focus on different fields at different levels. For example, the overall subject evaluations include Economics and Business research [7], the subfields' evaluations include operations and management science research [8] and chemical engineering research [9], and the specific topic evaluations include Antarctic research [10] and World War II research [11]. In parallel, some research has involved bibliometric evaluations in the field of physics covering research of regional physics [12, 13], optics [14], nuclear science and technology [15], nanomaterials and nanotechnologies [16, 17], radiation dosimetry [18], and quantum cryptography [19]. In particular, Strumia and Torre [20] used improved bibliometric indicators based on the PageRank algorithm to rank authors, institutions, countries, and so on, in the field of fundamental physics. Although some papers have examined the high-citation papers on space physics in the field of physics [21], it is obvious that there is still a lack of research on top-cited papers, especially those on the hot topics in the field of physics. Therefore, this paper focuses on the top-cited papers in the experimental field of quantum entanglement to fill a bibliometric research gap.

The bibliometric technique is applied to explore the contribution and distribution of different objects such as journals, authors, institutions, and countries/territories (hereafter referred to simply as 'countries'). The well-known methods of full counting and fractional counting are used to measure the participation and contribution of different objects [22]. More importantly, according to [22], the first author and the corresponding author are different in many publications, indicating the important contribution of the corresponding author. There is a consensus that both the first author and the corresponding author play the dominant role and have the important positions in a project [23, 24]. It should be noted that prior studies have focused on the first author and the corresponding author [10, 25, 26]. Ho [27] developed a new index called Y-index including two factors, j and θ, to evaluate scientific productivity of first and corresponding author. The factor j is related to publication quantity of first and corresponding author, and the factor θ represents the publication character of first and corresponding author. In parallel, there are acknowledged problems with identifying the first author or corresponding author. For instance, some papers' authors are arranged in alphabetical order, and some journals do not name the corresponding author of the paper. Unlike the Y-index, the present study uses distinctive and simple methods that have been applied in practice but not tested in theory, called first/corresponding author full counting and first/corresponding author fractional counting in this paper, to give guidance about the dominant players who have reputations in the field.

The major objective of this study is to investigate the distribution and contribution of papers in the experimental field of quantum entanglement, such as experimental detection, measurement, and application of quantum entanglement, based on the Web of Science Core Collection (WoSCC) considering annual production, citations per paper, journals, countries, institutions, and authors. This study not only uses traditional methods with first author full counting and corresponding author full counting to present the critical authors, institutions, and countries as designers or executors in the experimental field of quantum entanglement, but determines the dominant authors, institutions, and countries leading the primary progress of this field via first/corresponding author full counting and first/corresponding author fractional counting.

The present paper is organised as follows. Section 2 presents the data and methods. Section 3 describes the data analysis results regarding annual distribution, citations per paper, journals, authors, institutions, and countries. Finally, Section 4 closes with a discussion of the major conclusions.

2. Data and methods

2.1. Data collection

The data in this paper was derived from the Science Citation Index Extended Edition (SCIE) database, Social Science Citation Index (SSCI) database, and Conference Literature Citation Index Science Citation (CPCI) database in the WoSCC from Thomson Reuters. Using 'TS = (entangl* AND quantum* AND experiment*) AND PY = (1900–2019)' as the retrieval formula, the present study considered all the literature in the experimental field of quantum entanglement from 1900 to 2019. The retrieval data were acquired on December 9, 2020, and a sample of 8635 published papers was obtained. We refer to this as the *basic* sample. Then, all the results used in this paper were manually collected by six graduate students over several months.

The top-cited literature of quantum entanglement in the experimental field was acquired from the basic literature sample of quantum entanglement in the experimental field. First, in order to emphasise originality, the papers with the document types of 'article', 'proceeding paper', and 'note were extracted from the basic sample, and a total of 8330 papers were obtained except for 'early access' and 'retracted publication'. Then, these papers were sorted by the number of citations from high to low, and the top 5% papers were selected as the sample of top-cited papers in the experimental field of quantum entanglement. Hence, a total of 419 top-cited papers were obtained, and the minimum number of citations among these up to the date of collection (December 9, 2020) was 140, which was denoted as TC2019 $\geqslant$ 140. However, considering that there are errors in literature classification in the WoSCC, the study needed to check and reclassify the data [28]. For example, the majority of papers in the journal *Reviews of Modern Physics* belonged to the 'review' category, while many of that journal's papers are classified as 'article' in the WoSCC. On this basis, the study manually excluded 19 papers of that journal. In the end, a total of 400 top-cited papers with TC2019 $\geqslant$ 140, all published since 1992, were extracted.

2.2. Methods

Bibliometric analysis, introduced by [29], is regarded as a comprehensive evaluation method and is being used increasingly in the scientific areas [30]. Due to the qualitative and quantitative advantages of bibliometric analysis, the present study adopted this technique to evaluate the scientific contribution and distribution of journals, countries, institutions, authors, and other entities. The major bibliometric methods, including full counting, fractional counting, and, in particular, first/corresponding author full and fractional counting, were applied to represent the contribution and distribution of the research objects in this study. At present, full and fractional counting are widely used by many scholars and institutions to present the importance of different objects, such as is done in the Nature Index database.

Full counting means that each co-author is recorded as an equal in completing the document, and each co-author's contribution to the document is counted as one. For the contributions of countries/institutions, the statistical method resembles that for authors. Considering that the first author or corresponding author who have primary responsibility for the work, we introduce three methods: *first author full counting, corresponding author full counting*, and *first/corresponding author full counting*. The first two method, *first author full counting* means that each first author has the same weight of one; *corresponding author full counting* means that each corresponding author is also counted as one. Further, if the first or corresponding author of the paper comes from various affiliated institutions or countries, the weight of one is assigned to these institutions or countries.

The third method, *first/corresponding author full counting*, considers only the first author and corresponding author, who are regarded as the dominant players who have reputations in the field. For example, in a co-authored document, a weight of one is assigned to the first author and corresponding author, and other co-authors have a weight of zero. In parallel, for the affiliated countries and institutions of the first author and corresponding author, each country and institution also have a weight of one. As a special case, when authors are arranged in alphabetical order, this paper considers all authors as the first author and gives them each a weight of one.

In contrast, *fractional counting* at the author-level means that each author has the same weight, but the sum of weights must equal one. That is, in a co-authored document, each co-author's contribution to a document is equal regardless of the co-author's ranking. For instance, if a document has *n* co-authors, each co-author's contribution to the document is counted as 1/*n*. Further, if a co-author of the paper comes from *g* countries, the 1/*n* is split equally between the affiliated countries of the co-author. It is similar to the *fractional counting and first/corresponding author full counting*, this paper also builds the *first/corresponding author fractional counting* method.

3. Results

3.1. Publication analysis

As explained above, 400 top 5% cited papers (TC2019 ⩾ 140) since 1992 in the experimental field of quantum entanglement were extracted from the WoSCC. Figure 1 shows the distribution of these 400 top-cited papers and the citations per paper until 2019. As we can see from Fig. 1, there exist great differences in the distribution of top-cited papers by years. The development of top-cited papers started slowly but increased remarkably in 1998 and 2001. The year 2003 had the highest number of top-cited papers, with 35 papers accounting for 8.75%, a performance followed by both 2010 and 2002, with 34 and 30 papers (8.50%; 7.50%), respectively. However, only five top-cited papers were published before 1997, and no top-cited papers were published in 1994 and 2019.

Looking at the performance of citations per paper (CPP), time is necessary for a paper to accumulate citations [31]. Only six years (1993, 1995, 1996, 1997, 1998, and 2001) have CPP of ⩾ 500, all of which are found in the early stage of our study period. In particular, the years 1993 and 1995, each with one paper, has CPP of 1147.00 and 1127.00 citations, respectively, followed by the year 1997 with the CPP of 802.17 citations. These three years mainly rely on the papers entitled Event-Ready-Detectors Bell Experiment via Entanglement Swapping [32], Optical Imaging by Means of 2-Photon Quantum Entanglement [33], and Experimental quantum teleportation [34]. On the contrary, the CPP of recent years are below 300 citations except for 2015, which also reflects the citation advantage of papers published earlier [35].

3.2. Journal analysis

The total of 400 top 5% cited papers were published in 38 journals. Table 1 illustrates the distribution of the top seven journals publishing at least ten top-cited papers, accounting for 87.00% of all top-cited papers. *Physical Review Letters* (IF_{2019} = 8.385) was the most productive journal with a total of 135 papers, accounting for 33.75% of all, followed by *Nature* with 101 top-cited papers accounting for 25.25%, but *Nature* has the highest impact factor (42.779) among all these journals; they are the only two journals with at least 100 top-cited papers. The third journal, with 49 top-cited papers, is *Physical Review A* (IF_{2019} = 2.777), accounting for 12.25%. Although the well-known journal *Science* has the second-highest impact factor, 41.846, it is only ranked fifth with 15 papers (3.75%), which indicates that the top-cited papers may not always be published in multidisciplinary journals with high impact factors [23, 36].

As listed in Table 2, the majority of top-cited papers fall into the category of multidisciplinary physics and then are further classified into multidisciplinary sciences, optics, and other categories. The present study also considered whether these top seven journals are Nature Index journals. Except for the one journal *New Journal of Physics*, the remaining six journals are Nature Index journals, implying that most top-cited papers are distributed in the highly recognised journals.

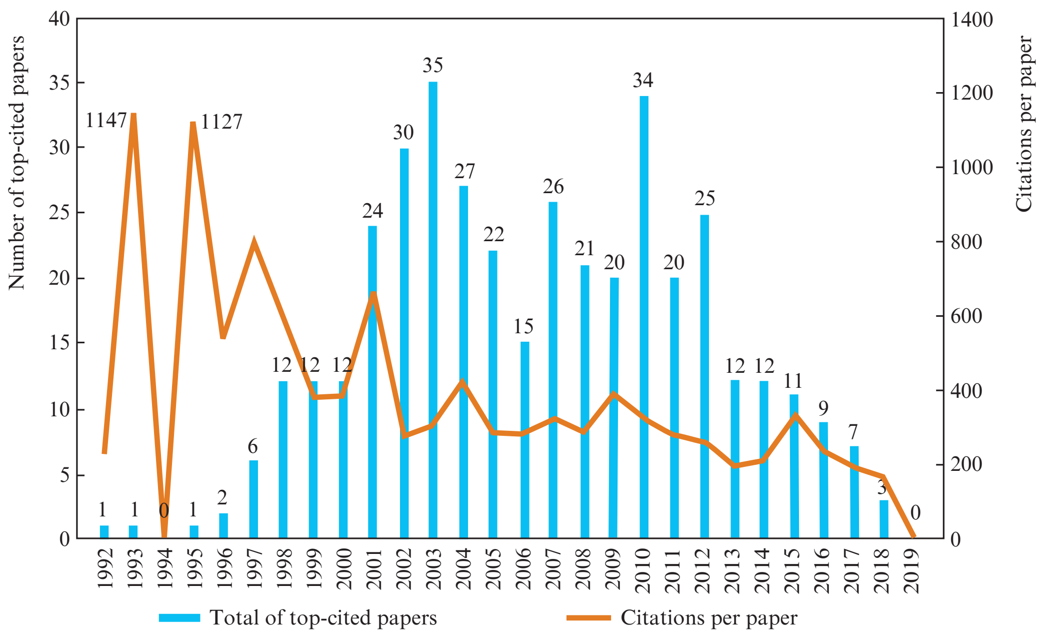

Figure 1. Number of top-cited papers and citations per paper until 2019.

Table 1. Top seven journals with top-cited papers (FUP ⩾ 10).

Journal	TP (%)	IF_{2019}	JCR category	NIJ
Physical Review Letters	135 (33.75)	8.385	Multidisciplinary physics	Yes
Nature	101 (25.25)	42.779	Multidisciplinary sciences	Yes
Physical Review A	49 (12.25)	2.777	Optics; Physics atomic, molecular and chemical	Yes
Nature Physics	28 (7.00)	19.256	Multidisciplinary physics	Yes
Science	15 (3.75)	41.846	Multidisciplinary sciences	Yes
Nature Photonics	10 (2.50)	31.241	Optics; Applied physics	Yes
New Journal of Physics	10 (2.50)	3.539	Multidisciplinary physics	No

Note: TP (%) is the total number and percentage of the top-cited papers; IF_{2019} is the Impact Factor in 2019; JCR category is the Journal Citation Reports category; and NIJ is the Nature Index journals (Yes/No).

3.3. Author analysis

There were 400 top-cited papers, which were written by 498 first or corresponding authors. The top 15 authors with the F/CUP at least four papers are listed in Table 2. There are five (33.33%) top scholars who complete their research in Austria. The USA and mainland China rank second, each having three scholars, followed by Australia with one scientist. The remaining counties include Germany, Netherlands, the UK, France, and Italy, each with one scholar too. J.W. Pan, who published 17 papers in F/CUP, ranks first among all authors, followed by A. Zeilinger with 16 papers; their totals significantly outweigh the others. Moreover, there are great differences in the impact of the other authors. The following scholars are G.J. Pryde with seven papers, M.D. Lukin with six papers, and L.M. Duan, B.P. Lanyon and C.Z. Peng, each with five papers, tie for fifth place. After them, eight scientists rank eighth with four papers. In addition, J.W. Pan and A. Zeilinger are the top two in F/CRP, but their ranking has reversed; there are obvious differences in F/CUP and F/CRP ranking of these scholars. It is concluded that J.W. Pan and A. Zeilinger have higher performance in F/CUP and F/CRP, reflecting their prominent and dominant contributions to the experimental field of quantum entanglement.

Furthermore, using the FUP indicator, the best performance is by J.W. Pan and B.P. Lanyon, each having five papers, followed by L.M. Duan, A. Vaziri, W. Tittel, J.T. Barreiro, S.L. Braunstein, and D. Leibfried, each ranking third with four papers. Other scholars with fewer than two papers rank lower than fifteenth, and S. Haroche and F. Sciarrino have no paper in FUP. Based on the CUP indicator, the first and second scientists in the experimental field of quantum entanglement are A. Zeilinger with 16 papers and J.W. Pan with 13 papers. The third and fourth dominant authors are G.J. Pryde and M.D. Lukin, who have six and five papers, respectively. There are five scholars, L.M. Duan, C.Z. Peng, S. Haroche, F. Sciarrino, and M. Aspelmeyer, who rank fifth, each having four papers; the others publish one to three papers except for W. Tittel with no publication. Combining FUP and CUP indicator, this study found that the majority of dominant scholars contributed to the experimental field of quantum entanglement by the critical role of designer, and especially, J.W. Pan realised the transformation from the executor to the instructor.

3.4. Institution analysis

Altogether, 188 first or corresponding authors' institutions contributed to the 400 top-cited papers. Table 3 shows the top 17 institutions with F/CUP at least seven top-cited papers. The USA, with five top institutions, ranks first, followed by

Table 2. Top 15 authors with F/CUP ⩾ 4.

Author	Country	F/CUP	R	F/CRP	R	FUP	R	CUP	R
Pan J.W	Mainland China	17	1	6.83	2	5	1	13	2
Zeilinger A.	Austria	16	2	7.25	1	2	15	16	1
Pryde G.J.	Australia	7	3	2.75	13	2	15	6	3
Lukin M.D.	USA	6	4	2.42	16	1	45	5	4
Duan L.M.	Mainland China	5	5	4.00	3	4	3	4	5
Lanyon B.P.	Austria	5	5	3.50	4	5	1	2	22
Peng C.Z.	Mainland China	5	5	1.92	31	1	45	4	5
Vaziri A.	Austria	4	8	3.25	5	4	3	1	44
Tittel W.	Netherlands	4	8	3.25	5	4	3	–	–
Barreiro J.T.	USA; Austria	4	8	3.25	5	4	3	1	44
Braunstein S.L.	UK	4	8	3.17	8	4	3	3	10
Leibfried D.	USA	4	8	2.83	12	4	3	2	22
Haroche S.	France	4	8	2.00	20	–	–	4	5
Sciarrino F.	Italy	4	8	1.67	36	–	–	4	5
Aspelmeyer M.	Austria	4	8	1.58	37	1	45	4	5

Note: F/CUP is the total number of the top-cited papers based on first/corresponding author full counting; F/CRP is the total number of the top-cited papers based on first/corresponding author fractional counting; FFUP is the total number of the top-cited papers based on first/corresponding author fractional counting; CUP is the total number of the top-cited papers based on corresponding author full counting; and R is the ranking.

the Austria, having three top institutions, whereas there are two institutions each in Germany and France, and one top institution in each of the UK, mainland China, Italy, Switzerland, and Australia. (For brevity, we use short forms for institution names, as listed in Table 4.) Among these institutions, the most impactful institution is Univ. Vienna, which has 33 papers in F/CUP, followed by Univ. Sci. & Technol. China (25 papers), Univ. Innsbruck (23 papers), and Austrian Acad. Sci. (22 papers). These four institutions are the only ones to publish more than 20 first or corresponding authors' papers. There are six institutions that publish the number of first or corresponding authors' papers between 10 and 19, including Natl. Inst. Stand. & Technol. (19 papers), Max Planck Inst. (18 papers), Univ. Queensland (14 papers), Univ. Munich (14 papers), Harvard Univ. (10 papers), and Univ. Geneva (10 papers). After them, three institutions, Caltech, CNRS, and Ecole Normale Super, rank 11th with 9 papers; Univ. Calif. Los Alamos Natl. Lab. takes the 12th place with 8 papers; and Univ. Oxford, Univ. Roma La Sapienza, and Yale Univ. rank 13th, each having 7 papers. Moreover, Univ. Vienna, Univ. Sci. & Technol. China, and Univ. Innsbruck are also the top three in F/CRP with the same rankings; the others have a smaller gap between their rankings of F/CUP and F/CRP. It is worth noting that the top three institutions ranked by first/corresponding author fractional counting are considered as the most dominant entities.

The top three institutions, based on the FUP indicator, are Univ. Vienna with 32 papers, Univ Innsbruck with 23 papers, and Univ. Sci. & Technol. China with 22 papers. The fourth institutions are Austrian Acad. Sci. and Max Planck Inst., each having 18 papers, followed by five institutions exceeding or equalling 10 papers, including Univ. Queensland (15 papers), Natl. Inst. Stand. & Technol. (14 papers), Univ. Queensland (14 papers), Harvard Univ. (10 papers), and Univ. Geneva (10 papers). Using the CUP indicator, the top three institutions are Univ. Vienna (24 papers), Austrian Acad. Sci. (21 papers), and Univ. Sci. & Technol. China (20 papers); They are the only ones with greater than or equal to 20 papers. The other institutions publish first or corresponding authors' papers with lower than 10 except for Univ. Innsbruck (19 papers), Natl. Inst. Stand. & Technol. (15 papers), Univ. Queensland (12 papers), and Max Planck Inst. (11 papers). Although this CUP ranking with fractional counting method has a few differences compared with the FUP ranking with full counting method, we can conclude that Univ. Vienna, Univ. Sci. & Technol. China, Univ. Innsbruck, and Austrian Acad. Sci. are not only the primary executors in

Table 3. Top 17 institutions with F/CUP $\geqslant$ 7.

University	Country	F/CUP	R	F/CRP	R	FUP	R	CUP	R
Univ. Vienna	Austria	33	1	27.08	1	32	1	24	1
Univ. Sci. & Technol. China	Mainland China	25	2	18.94	2	22	3	20	3
Univ. Innsbruck	Austria	23	3	17.09	3	23	2	19	4
Austrian Acad. Sci.	Austria	22	4	10.26	7	18	4	21	2
Natl. Inst. Stand. & Technol.	USA	19	5	16.30	4	14	6	15	5
Max Planck Inst.	Germany	18	6	11.78	5	18	4	11	7
Univ. Queensland	Australia	14	7	11.14	6	15	5	12	6
Univ. Munich	Germany	14	7	8.40	11	14	6	8	9
Harvard Univ.	USA	10	9	8.55	9	10	9	9	8
Univ. Geneva	Switzerland	10	9	9.29	8	10	9	3	27
Caltech	USA	9	11	8.50	10	9	11	6	13
CNRS	France	9	11	3.64	30	8	13	7	10
Ecole Normale Super	France	9	11	6.18	13	9	11	7	10
Univ. Calif. Los Alamos Natl. Lab.	USA	8	14	7.50	12	7	14	7	10
Univ. Oxford	UK	7	15	6.00	15	7	14	5	16
Univ. Roma La Sapienza	Italy	7	15	5.58	17	6	17	4	21
Yale Univ.	USA	7	15	6.17	14	7	14	5	16

Table 4. Top 12 countries with F/CUP $\geqslant$ 10.

Country	F/CUP	R	F/CRP	R	FUP	R	CUP	R
USA	102	1	93.21	1	98	1	80	1
Austria	60	2	57.43	2	59	2	47	2
Germany	47	3	39.40	3	47	3	32	3
UK	36	4	30.97	4	35	4	27	5
Mainland China	35	5	29.73	5	33	5	28	4
Australia	23	6	19.47	6	22	6	18	6
France	19	7	17.73	7	18	8	16	7
Switzerland	19	7	16.49	9	17	9	9	10
Italy	19	7	17.43	8	19	7	12	8
Japan	17	10	15.94	10	17	9	11	9
Denmark	11	11	9.08	12	11	11	8	11
Brazil	10	12	10.00	11	10	12	7	13

the experimental field of quantum entanglement, but also play the role of designer in this domain.

3.5. Country analysis

The total of 400 top 5% cited papers had geographical sources distributed among 32 first or corresponding authors' countries. Table 5 shows the performance of the top 12 countries with at least ten top-cited papers in F/CUP. The most prominent country is the USA with 102 top-cited papers, which has much greater than the following counties, including Austria (60 papers), Germany (47 papers), the UK (36 papers), and mainland China (35 papers). These top five countries each published more than 30 top-cited papers. The sixth country is Australia, which publishes 23 papers. Three other countries, France, Switzerland, and Italy rank seventh, each having 19 papers. The remaining three countries, including Japan (17 papers), Denmark (11 papers), and Brazil (10 papers), follow in the ranking. The top seven countries in F/CRP are the same as the rankings in F/CUP, and the USA (93.21 papers), Austria (57.43 papers), Germany (39.40 papers), the UK (30.97 papers), and mainland China (29.73 papers) are the only five countries with greater than 20 papers. We can therefore conclude that the USA, Germany, Austria, the UK, and mainland China are regarded as the most dominant countries for publishing top-cited papers in this field when we combine these two counting methods.

Moreover, using first author full counting, the present study shows that the USA with 98 papers also ranks first. Far following the USA is Austria with 59 papers, Germany with 47 papers, the UK with 35 papers, and mainland China with 33 papers. Countries following these in the ranking all published less than 30 papers, including Australia (22 papers), Italy (19 papers), France (18 papers), and others. Based on corresponding author full counting, the USA with 80 papers, Austria with 47 papers, Germany with 32 papers, mainland China with 28 papers, and the UK with 27 papers still rank in the top five (but with mainland China and the UK reversed); the USA also leads other countries by a significant margin. Australia with 18 papers ranks sixth with a much lower total than the UK, indicating the top five countries guide in contributing top-cited papers in the experimental field of quantum entanglement. It should be noted that there are some similarities of the ranking between the results of first/corresponding author full counting, first author full counting, and corresponding author full counting.

4. Conclusions

The present study used data extracted from the WoSCC to investigate the publication of top-cited papers in the experimental field of quantum entanglement. A total of 400 top-cited papers since 1992 were written by 498 first or corresponding authors who were affiliated with 188 institutions, distributed among 32 countries.

First, our total of 400 top-cited papers was classified by years, with 2003 having the most publications (35 papers). The distribution of citations indicates that there is a citation advantage of publishing papers earlier. Moreover, the majority of top-cited papers were published in just nine scholarly journals, and *Physical Review Letters* is the most productive journal, followed by *Nature*, with the latter having the highest impact factor; their totals obviously exceed the others. Among these top seven journals, six are Nature Index journals.

This study not only uses traditional methods with first author full counting and corresponding author full counting to rank important authors, institutions, and countries but also introduces distinctive methods with first/corresponding author full counting and first/corresponding author fractional counting to find the dominant players in the experimental field of quantum entanglement. Scientists A. Zeilinger and J.W. Pan are the most dominant authors in this field; J.W. Pan realised the transformation from the executor to the instructor. There are great differences in the impact of the remaining authors. In terms of publishing papers as first or corresponding author, G.J. Pryde and M.D. Lukin also are highly influential scholars, followed by L.M. Duan, B.P. Lanyon and C.Z. Peng. Moreover, the study has determined that Univ. Vienna, Univ. Sci. & Technol. China, Univ. Innsbruck, and Austrian Acad. Sci. are the most dominant research institutions in the experimental field of quantum entanglement. These five institutions are not only the primary executors, but also play the role of designer in this domain. It is worth noting that the majority of first or corresponding author's papers from China are published by only one institution, which is a research centralisation not seen in the other top countries. Considering countries, there are some similarities of the ranking between the results of first/corresponding author full counting, first author full counting, and corresponding author full counting, and the USA, Germany, Austria, the UK, and mainland China match the wide acknowledgment in the field that these play the dominant roles. Especially, there is an interesting finding that the majority of dominant works in mainland China are done by both the one team and one institution.

To sum up, the current study has explored the subdivision of quantum information science and obtained an overall view of the experimental field of quantum entanglement. The results of this study provide meaningful information for researchers and governments. Based on first author full counting, corresponding author full counting, first/corresponding author full counting, and first/corresponding author fractional counting, the results are useful for finding the most dominant countries, institutions, authors. It should be noted that our quantitative results confirm the contribution of A. Zeilinger and J.W. Pan in the experimental field of quantum entanglement, and further demonstrate the strength of their affiliated institutions (Univ. Vienna, Univ. Sci. & Technol. China) and countries (Austria, mainland China) in this field. This confirmation of widely held opinion solidly affirms our results in this paper. Finally, our work may help subsequent researchers and governments understand the development of the experimental field of quantum entanglement in order to promote future research and development in this field.

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