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BIBLIOMETRIC ANALYSIS OF PUBLICATIONS IN EXPERIMENTAL PARTICLE PHYSICS ON COSMIC RAYS AND WITH ACCELERATORS

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In the first part, the present paper presents a quantitative analysis of physics publications in the domain of experimental particle physics, before the Second World War in the field of cosmic rays physics and for the modern times in the field of accelerator and collision rings experiments. In the second part, a more general study is made on publications in the various fields of physics separating contributions from experiment, theory and techniques. Three aspects of physics are enlightened: physics of exploration, physics of applications, and forefront physics.

Introduction

The study presented originates with a work devoted to a historical study of cosmic ray physics at the time of the mesotron discovery and of its identification.[1] As it is well known, cosmic rays allowed to discover new particles but they have been replaced in that search by studies of interactions of particles furnished by accelerators or by storage rings. This type of research is now one of the best examples of the so-called "big science". In this article, we give informations about these two types of research by a quantitative study of publications in these fields.

Let us first give a rapid historical outline of the development of these domains. Cosmic rays were discovered in 1911 by *Victor Hess* in Österreich, and they began to be extensively studied only after the First World War, notably under the impulsion of *Millikan* in the United States. In 1929, german physicists *Bothe* and *Kolhörster* made an experiment[2] showing that cosmic rays were probably of corpuscular nature and not produced by high energy photons as believed and defended by *Millikan*. This experiment gave rise in Europe and in the United States to an intensification of cosmic ray studies, made namely with *Geiger* counters and with cloud chambers. In the United

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States, experiments led to the discovery of the positive electron in 1932[3] and of the mesotron, our modern lepton μ, in 1937.[4] After the Second World War, cosmic ray studies in Great Britain allowed to discover the π meson and the first "strange" particle in 1947. However, it was soon realized that this domain of production of new particles would be better studied with accelerators producing particles of a known energy. After the construction of the first cyclotron by *Lawrence* in 1930, a synchrocyclotron (cyclotron of higher energy) allowed to create π mesons in Berkeley after the war in 1948. New high energy accelerators were also built in the United States. In 1953 strange particles were first artificially produced at Brookhaven and in 1954 antiproton production was identified at Berkeley. In Europe, countries such as Great Britain and France began to build national accelerators, but they realized soon that a bigger programme would require financial collaboration. Negotiations led to the creation in 1954–1955 of a European center – the CERN-near Geneva. Its first high energy accelerator began to work in 1959. The sixties have seen, thanks to bubble chambers, invented in 1952, the discovery of a lot of new particles. In the same time, new types of accelerators, storage and collision rings have been developed. Instead of producing external beams of particles, the techniques consist to accelerate in a ring two beams of particles circulating in opposite directions and producing head-on collisions. As detectors, bubble chambers have been replaced by electronic detectors which have become more and more complex. By now, one of the highest energy collision rings in the world is the large electron-positron ring called LEP at CERN which has produced in particular Z^0 mesons by e^+e^- collisions.

On the cosmic ray physics, our publications study concerns the years 1929 through 1938, consequent to the study made in an earlier work.[1] For accelerator particle physics publications, we have chosen two years of reference. The first year, 1970, corresponds to an epoch of intensive work with bubble chambers and the second, 1990, twenty years later, corresponds to the incoming of new results from LEP at CERN which began to operate in 1989. We concentrate our attention on the number of publications, their origin and the number of authors involved, taking as main source of reference periodicals dedicated to these domains. This analysis is presented in paragraphs 2 and 3 of this paper.

In the last paragraph, we present a general study of publications in various fields of physics. This last work has been done by scanning the review *Science Abstracts – series A: Physics* – from 1929 through to 1938 corresponding to the first cosmic ray study period and the review *Physics Abstracts – series A* – for 1970 and 1990, years corresponding to the modern particle physics. This second analysis allowed also to check some findings found in the first research.

Number of experimental publications and their origin

In this section we are interested in publications giving experimental results and we have been induced to take some cuts, after reading eventually abstracts of publications. Besides pure theoretical or technical papers, we eliminated papers which can be considered as popularization and papers giving only an outline or a summary of a domain of research. For example, in the modern period, we have excluded papers published in *Physics Today*, *American Journal of Physics*, *Scientific American*, *La Recherce* and most of papers published by *Reviews of Modern Physics* or by *Physics Reports*. We have excluded also these and conference papers since corresponding results, if interesting and complete, have been published in current publications reviews. Short papers giving corrections or comments have also been excluded.

For cosmic ray experiments, we have retained all publications referring to this general topic, as these researches were of exploratory nature in those times. For the years 1970 and 1990, we have retained in this first analysis only results coming from accelerators or collision rings.

For the cosmic ray period, less than 10 papers per year were found from 1929 to 1932 and after this time a slow progression was noted increasing to ca. sixty publications in 1938. This progression was expected as it was due in particular to e^+ and mesotron discoveries and to the development of techniques. Thus, the main global features of these publications have been given in totalizing the results of the 1929–1938 ten-year period.

Tables 1 and 2 give quantitative results of the 1929–1938 cosmic ray period and of the two years 1970 and 1990 for researches with accelerators. We have dispatched our results in categories corresponding to the origin of the publications. As the cosmic ray publications involved few authors, the nationality of physicists or the country where they worked has been retained, independently of possible expeditions to take data. The category of Western European countries contains, in decreasing order, papers coming from Germany, France, Great Britain, Italy, Netherlands, Austria and Sweden. Eastern European Countries are Hungary, USSR, Poland and Romania. A few papers came from other countries, namely Brazil and South Africa, but the corresponding authors were mainly from European countries.

For accelerator periods, experiments are often the result of collaborating of physicists of various laboratories and thus the retained origin is the country of the data taking, i.e. the country where the accelerator is located. A case of exception is a category – mixture of experiments – corresponding to some papers for which an experimental analysis has been made on collecting various data samples.

Table 1

Numbers of publications (Np) on cosmic ray experiments oriented to particle physics for the 1929–1938 period and for various countries. Relative average numbers of authors per paper <Na/Np> are also given with an assumed gaussian error. Supplementary informations can be found in the text

Origin	Western Europe	USA	USSR and Eastern Europe	Japan	Other countries	Total
Np	242	160	19	4	13	438
<Na/Np>	1.3 ± 0.1	1.7 ± 0.1	1.8 ± 0.3	2.5 ± 0.8	1.3 ± 0.4	1.5 ± 0.1

Besides CERN, Western countries are mainly, in 1970, France and Great Britain and, in 1990, Germany with, in particular, results coming from the DESY Hamburg Center.

Results given in tables 1 and 2 deserve some general comments. We see first that for 1970 the number of publications (495) is bigger than for the 1929–1938 period (348) and is also bigger than the 1990-year production (392). These facts are easily explained in the following way: in the cosmic ray period, experiments were carried out by one or two physicists. A change of scale occured with the advent of accelerators where experiments required more manpower. As an example, in the sixties, pictures taken with a bubble chamber were shared among some laboratories for scanning and measuring. After that stage, results were collected for a final analysis. Physicists of the collaboration could thus limit their scanning work and increase the number of their publications, in particular in a period where the research was in a great part of exploratory nature. The peak of this type of research was perhaps reached at CERN in 1973 with the discovery of neutral currents in neutrino interactions (55 authors). Now, since about 1970, pure electronic experiments with colliding rings were developed also and, after the ψ discovery in 1974 in United States, the orientation of the research towards quark physics grew up and the complexity of the experiments increased. Independent of various local situations, a general idea of this tendency can be found in Table 2 by comparing the average numbers of authors <Na/Np> in 1990 for conventional accelerators and for colliding rings. The increasing complexity of the experiments with more specialized goals of research explains a relative stabilization of the number of publications between the years 1970 and 1990.

Table 2

Numbers of publications (Np) for particle physics experiments realized with accelerators or colliding rings. Two years – 1970 and 1990 – are referred to with origins. Relative average numbers of authors per paper <Na/Np> are given with an assumed gaussian error. Supplementary details are given in the text

Reference year and type of experiments	Origin	Western Europe without CERN	CERN without LEP	CERN LEP	USA	USSR and Eastern Europe	Japan	Mixture of experiments	Total
1970 all accelerator experiments	Np	53	107	-	252	39	3	41	495
	<Na/Np>	9.0±0.4	11.5±0.3	-	6.7±0.2	10.2±0.5	12.7±2.1	3.5±0.3	8.0±0.1
1990 experiments with accelerators	Np	10	45	-	65	53	3	6	182
	<Na/Np>	12.8±1.1	50.0±1.1	-	27.0±0.6	14.2±0.5	12.0±2.0	2.0±0.6	28.7±0.4
1990 experiments with storage rings	Np	36	27	70	53	2	20	2	210
	<Na/Np>	74.8±1.4	79.2±1.7	395±3	107±1	22.5±3.3	85.8±2.1	3.0±0.8	194±1

Moreover, with the complexity of the experiments, the number of the authors of publications rose as can be seen by the representation in Table 3 of more detailed results for the 70 papers published in 1990 on the four experiments taking data with LEP at CERN. In addition to the same information as that given in Table 2, we added some other features. Besides the number of the laboratories involved, we counted for each detector experiment the number of individual authors, counting each one only one time, and by the same counting we obtained the number of the authors having signed all papers referred to. From these results, we see in Table 3 that 80% to 90% of the authors have signed all the papers published in 1990. The remaining authors can be due to physicists having made only a part of the analysis but also to engineers playing an important role in the realization of the detector and of its facilities. Now, the differences between the total number of individual authors can be due to differences in techniques involved in addition to the considerations given above which are not in any case normalized in the same manner between experiments.

Table 3
Characteristics of 1990 publications for LEP experiments. Explanations and comments are given in the text

Detector experiment / Characteristics	ALEPH	DELPHI	L3	OPAL
Number of 1990 publications	17	14	20	19
Average number of laboratories	30	39	38	24
Average number of authors/publication	361	495	463	278
Total number of individual authors	414	625	513	302
Number of authors having signed all 1990 papers	324	415	406	245

It is out of the scope of this paper to lead to a worthy judgement of experimental particle physics publications but only to give an idea of the intense effort, independently of financial questions. This effort can be judged from Tables 1 and 2 by the number of publications or by the total number of authors, i.e. by the quantity N_p<Na/Np>. We see that the fields of cosmic ray physics and of particle physics with accelerators were largely dominated by the USA and the Western Europe. The development of experimental particle physics can be judged also by the number of research workers participating in it. For that purpose, we counted the number of individual authors, respectively, for each period. We counted 2202 and 6868 individual authors for 1970 and 1990 publications and only 202 for the publications of the studied cosmic ray period. These numbers are perhaps one of the best indicators of the development in time of this experimental particle physics.

Comparison with other fields of research in physics

As mentioned in the introduction, an investigation of the number of publications has been undertaken with the support of Science Abstracts-series *A* for the 1929–1938 period, and of *Physics Abstract – series A* for the years 1970 and 1990. Note that this choice excludes publications referred to in other series. A *series B* of *Science Abstracts*, devoted to electrical engineering existed before the Second World War and also in 1970 and 1990. A new *series C* of *Physics Abstracts* devoted to Computer Technology was created in 1966 and a fourth series, devoted to Information Technology, exists since 1983. Nevertheless, we can suppose that series *A* gathers all the basic physics, which we are interested in here. Besides experimental papers devoted to experiments or results of observations, we counted also the number of theoretical and technical papers. Theoretical papers are those explaining experimental results or making predictions on them and papers giving basis for a more or less sophisticated model or theory. Technical papers are of two types. They can be centered on methods of experimental or theoretical physics or they can be devoted to applications and are thus sometimes referred to as applied physics. Some papers giving experimental results and discussing their theoretical interpretation are indexed as experimental, as can be the case of some experimental papers giving also description of techniques.

Cuts of the first analysis were also taken here to have a clean sample of research papers. We were obviously led to distinguish different fields of research and we were compelled to make some choices since classifications adopted by *Science* or *Physics Abstracts* varied with time. We adopted a "modern" classification in the following way. The particle physics category is rather clear to-day but in the thirties it was supposed to include basic research on proton, electron and photon as well as cosmic ray physics research centered on the properties of these rays. Note as an example that, in *Science Abstracts*, cosmic ray physics papers of the 1929–1938 period are indexed first in the radioactivity subdivision and after 1932 in the radiation section. If research on cosmic rays was mainly centered on their origin, the corresponding papers were added to astronomy and astrophysics category, subject well identified in all periods. Nuclear physics, as a study of various nuclei, exists in 1970 and 1990 classification of *Physics Abstracts* but, before the World War II, it was mainly found in the radioactivity subdivision. Obviously, researches devoted to the fundamental properties of proton and neutron have been indexed in particle physics category. In the techniques of this category are indexed papers devoted to accelerator developments, even if these papers concerned also nuclear physics. Geophysics is a rather well-defined category if we group together subjects such as geology, seismology, atmospheric studies and meteorology. Biophysics including possibly medical sciences is also a clear category. Following 1970 and 1990 terminology, we adopted also the physical chemistry category even if before the war this category didn't exist as such. All other subjects were indexed in a last category called general physics. That is the case of classical physics subjects such as optics and electromagnetism but also of some new types of researches. As an example environmental science existed only as such in the 1990 classification of *Physics Abstracts*. Quantum mechanics studies were put also in this last category except field theories subjects indexed in the particle physics category. Special relativity subjects were indexed in general physics and general relativity topics in astrophysics.

General results are given in Table 4. At an ~10% level, we found for particle and cosmic ray physics same results as found in the first analysis. We estimated also at ~10% the possibility of a bad classification. On the other hand, the counting rates for a given division of *Science Abstracts* or *Physics Abstracts* were checked if a global control gave an inconsistency greater than 5%. For the total counting, we found a global number a few per cent smaller than the real one but we didn't correct our numbers, as we didn't detect any particular category bias.

Results of Table 4 can be commented on in two directions: development of a research field, remarks about experiments, theory and techniques.

Table 4

Numbers of publications according to categories and classes for different periods. For the 1929–1938 period, cosmic ray physics has been divided in particle physics and astrophysics depending on the aim of the research. Corresponding numbers are put in parentheses. For 1970 and 1990, the number of papers on experimental particle physics without accelerators, (in experimental particle physics category), the number of papers on techniques in accelerators (in techniques of particle physics category) and the number of papers on techniques on fusion or fission reactors (in techniques of nuclear physics category) are put in parentheses

Year period	Category / Class	Particle physics	Nuclear physics	Astronomy and astrophysics	Geophysics	Physical chemistry	Biophysics	General physics	Total
1929–1938	Experiment	390 (284)	1205	1763 (138)	1386	6035	190	8482	19451
	Theory	532 (58)	564	1297 (43)	823	1385	42	5853	10496
	Techniques	101 (47)	434	725 (135)	975	2251	623	12471	17580
	Total	1023 (389)	2203	3785 (220)	3184	9671	855	26806	47527
1970	Experiment	583 (41)	1995	1821	1209	365	262	12000	18235
	Theory	2647	1164	1531	924	145	53	12023	18487
	Techniques	685 (253)	1428 (728)	398	865	526	230	15811	19943
	Total	3915	4587	3750	2998	1036	545	39834	56665
1990	Experiment	431 (21)	1114	3425	2770	826	2362	15352	26280
	Theory	5018	1735	3462	4274	729	830	22354	38402
	Techniques	804 (290)	2564(2080)	758	2072	648	2803	34480	44129
	Total	6253	5413	7645	9116	2203	5995	72186	108811

Development of fields of research

From the crude results given in Table 4, we can extract a progression factor of publication i.e. a ratio of the number of publications per year, for two periods. We give in Table 5 this progression factor for 1970 compared to an average year of the 1929–1938 period and for the year 1990 compared to 1970. In the average this progression factor is ~12 for the first ratio and ~2 for the second. We noted in particular that numbers of publications reviews rose with time. The editors of *Science* or *Physics Abstracts* gave numbers of the publications they analysed, which are 295, 1568 and 3727 for 1936, 1970 and 1990, respectively.

Between the years before war and 1970, the progression factor is ~10 for all experimental physics categories except for physical chemistry where this factor is lower than 1. Two types of explanation can exist for that exception. In the abstract publications, physical chemistry classification exists only in 1970 and 1990. Thus, a personal misclassification may exist with some papers classified in physical chemistry before the war and in general physics in the modern periods. Another type of explanation is the rejection of some articles by the editors of the modern *Physics Abstracts*, leaving this analysing work for the *Chemical Abstracts*. Nevertheless, this low ratio indicates that difficult as can arise with some frontier fields. It is possible that problems exist also in biophysics even if they don't seem to appear from the crude numbers.

For the years 1970 and 1990, we see a progression factor less than 1 for experimental particle physics and experimental nuclear physics and this fact is due to the complexity arising from these sectors. We see also that the progression factor is ~10 for biophysics and this reflects probably a progression of the biology research in our modern times.

Remarks about experiment, theory, and techniques

To judge the relative situation of experiment, theory and techniques, we can proceed in two different directions. We can first consider each of these classes for each category and compare it to the total. From Table 4, we see for example that, in 1990, theoretical particle physics contributed to ~13% of the total theory publications. These comparisons are however limited because what we named general physics represents ~70% of the total and thus this type of a comparison would require to investigate different categories of general physics.

Table 5

Progression factor of publications before the war and those of 1970 and that for 1990 compared to 1970. Assumed gaussian errors (not given) are smaller than 0.1

Period of reference	Category / Class	Particle physics	Nuclear physics	Astronomy and astrophysics	Geophysics	Physical chemistry	Biophysics	General physics	Total
1970 compared to the years before war	Experiment	15.3	16.5	10.3	8.7	0.6	13.8	14.1	9.4
	Theory	50.7	20.6	11.8	11.2	1.0	12.6	20.5	17.6
	Techniques	66.5	32.9	5.5	8.9	2.3	3.7	12.7	11.3
	Total	38.9	20.8	9.9	9.4	1.1	6.4	14.9	11.9
1990 compared to 1970	Experiment	0.7	0.6	1.9	2.3	2.3	9.0	1.3	1.1
	Theory	1.9	1.5	2.3	4.6	5.0	15.7	1.9	2.1
	Techniques	1.2	1.8	1.9	2.4	1.2	12.2	2.2	2.2
	Total	1.6	1.2	2.0	3.0	2.1	11.0	1.8	1.9

Table 6

Proportion of experimental, theoretical and technical publications in 1990 for various categories of researches. Errors given are taken as binominal

Category / Class	Particle physics	Nuclear physics	Astronomy and astrophysics	Geophysics	Physical chemistry	Biophysics	General physics
Experiment (in %)	6.9±0.3	20.6±0.5	44.8±0.6	30.4±0.5	37.5±1.0	39.4±0.6	21.3±0.2
Theory (in %)	80.2±0.5	32.0±0.6	45.2±0.6	46.9±0.5	33.1±1.0	13.8±0.4	31.0±0.2
Techniques (in %)	12.9±0.4	47.4±0.7	9.9±0.3	22.7±0.4	29.4±1.0	46.8±0.6	47.8±0.2

Now, another way is to consider the relative situation of experiment, theory and techniques for a given category. For particle physics we see that, before war, cosmic ray physics was essentially of exploratory nature, as can be checked on by the ratio of theory versus experiment publications which was only 58/389 ≅ 15%. On the contrary, in 1990 this ratio is 5018/431 ≅ 11.5. Thus, after an exploratory period, particle physics has become a forefront physics where the role of theory is more important. On the other hand, it is useful to mention that in particle physics category, techniques have led to applications only in its proper domain of research. The situation is different in nuclear physics where a big part of techniques (~38%) is related to fusion or fission reactor applications.

The best way to visualize the relative situation of categories is perhaps to consider the relative proportions of experiment, theory and techniques. After extraction of the results from Table 4, we give them in the Table 6 for 1990. Apart the case of particle physics and nuclear physics discussed above, biophysics with a rather low proportion of theory and an important proportion of techniques can be assumed to be dominated by explorative physics and by applied physics. The general physics category is dominated also by the techniques proportion, but a more refined analysis would require to distinguish different domains in this category.

Conclusions

Our quantitative study of publications has perhaps cleared up some ways followed by particle physics research. Before the Second World War, cosmic ray physics research was essentially of exploratory nature, with a small role played by theory. Now, particle physics has become a good example of big science where the complexity has required a leading role for theory. A general study of physics publications has made clearly three aspects of physics research: physics of exploration, applied physics and forefront physics. In this last aspect, theory dominates in a given field to get out new ideas of generalization. Clearly, particle physics seems to have entered into this new phase.

Our study was made mainly with the support of the libraries of two Orsay laboratories: the Linear Accelerator Laboratory, (LAL) specialized in particle physics research and the Nuclear Physics Institute (IPN) which has in its possession the collection of *Science Abstracts* for years before the Second World War. Our thanks go to the staff of these libraries.

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