RUTHERFORD'S IMPACT ON SCIENCE OVER THE LAST 110 YEARS: A BIBLIOMETRIC ANALYSIS

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Ernest Rutherford (1871-1937) was a towering figure in scientific research in the first part of the 20th Century. According to John Campbell, Rutherford's biographer [1], "Ernest Rutherford is one of the most illustrious scientists of all time. He is to the atom what Darwin is to evolution, Newton to mechanics, Faraday to electricity and Einstein to relativity." His three major experimental discoveries in atomic physics during that period – the model of the atom from the scattering of alpha and beta particles, nuclear fission, and radioactive decay – could each have earned him a Nobel Prize although he was awarded only one, in Chemistry, in 1908 [2]. Rutherford was the first person to be awarded a Nobel Prize for work completed in Canada. In an obituary published in The New York Times announcing his untimely death in 1937, Rutherford was eulogized as follows: "It is given to but few men to achieve immortality, still less to achieve Olympian rank, during their own lifetime. Lord Rutherford achieved both. In a generation that witnessed one of the greatest revolutions in the entire history of science he was universally acknowledged as the leading explorer of the vast infinitely complex universe within the atom, a universe that he was first to penetrate." However, his scientific achievements and interests went well beyond just these notably huge advances in our knowledge of atomic physics at the time.

Rutherford was awarded the Nobel Prize for explaining radioactivity as the spontaneous disintegration of atoms (McGill University), and in the process identified alpha, beta, and gamma rays. In other equally brilliant experiments performed with colleagues he also determined the structure of the atom (Manchester University) and thereby produced his model of the atom – a minute nucleus (his term) surrounded by a cloud of electrons – and lastly he transmuted the atom by converting nitrogen into oxygen to become the first true alchemist (Manchester and Cambridge Universities).

SUMMARY

Bibliometric methods are applied to determine Rutherford's long term impact on the advancement of science and atomic physics over the last 110 years. This article celebrates the 100th anniversary of Rutherford's model of the nucleus and the beginning of nuclear physics.

Many of his secondary discoveries [1] would have resulted in fame for any other scientist. When Rutherford first blew tobacco smoke into his ionization chamber in McGill University way back in 1899 [3] and observed the resulting change in ionization he led the way to the development of the ubiquitous smoke detector alarm systems found in our buildings today. He pioneered the use of radioactive decay as a time marker for determining the age of the earth and also its subsequent use for dating the earth's artifacts, overcoming much resistance from the scientific establishment in the process. The Rutherford-Geiger detector now known as the Geiger-Muller tube was developed as the first device to detect individual nuclear particles by electrical means. He directed research that led to the development of nuclear accelerators and to the discovery of the chargeless proton or 'neutron', which he and Niels Bohr had postulated must exist to account for the atomic masses of the elements. He also carried out frontier research in wireless electric signal transmission – Rutherford and Howard Barnes were the first to send a wireless signal between a station and a train – and worked on the high-frequency properties of dielectrics.

Here we report on the huge impact of Rutherford's work on scientific developments over the last Century through an analysis of citations to his publications.

METHODOLOGY

The number of citations is often taken as a measure of the attention a paper, a researcher or an institute has attracted. Although citation numbers reflect strengths and shortcomings and are therefore frequently used for research evaluation, the number of citations cannot easily be equated with the overall significance. The question arises as to whether the impact of early pioneers of science like Ernest Rutherford can be quantified by bibliometric methods usually applied to present day scientists. Carefully establishing and interpreting the citations of Rutherford as a case study seems to be a reasonable way to proceed [4].

The data presented here are primarily based on the Science Citation Index (SCI) accessible via the Web of Science (WoS) provided by Thomson Reuters (the former Institute for Scientific Information, ISI) [5]. In addition, the CAPlus

The cartoon at the top of this page, by Alisa Lockwood, shows Rutherford in his famous 'guise' as a crocodile thinking about his nucleus. Rutherford was given this nickname because of his tenacity, always looking forward and not looking back (a crocodile cannot see its tail).

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literature database of the Chemical Abstracts Service (CAS), the INSPEC database for Physics, Electronics, and Computing, and SCIsearch (SCI) accessible via the database provider STN International have been consulted for the present study [6]. In its General Search mode the SCI under the WoS stretches back to 1900. Both CAplus and INSPEC include data sets stretching back some years before 1900.

The WoS offers two search modes: The General Search mode gives access to the papers (no books, no conference proceedings unless they appear in source journals) published since 1900 and covered by the so-called WoS source journals: about 9000 journals currently selected by the staff of Thomson Reuters as contributing significantly to the progress of science. The Cited Reference Search mode gives access to all references appearing in source journal papers (cited either correctly or containing errors). The cited references are not limited to papers published in source journals but include any other published material. In other words: The citing papers are limited to source journal papers published since 1900, but the papers cited therein are not limited concerning document type or publication year (*i.e.*, even citations to the Bible and the Koran, or Quran, can be retrieved).

REFERENCE BASED CITATIONS

The WoS limitations concerning journal coverage and time cause some complexity and extra problems specifically relevant in the case of analyzing early pioneers of science. The WoS General Search for "Rutherford E" as author name revealed 197 papers for the time period 01-01-1900 till 31-12-2009. However, this number is misleading in two aspects: (1) Rutherford's pre-1900 papers are not (fully) covered by the WoS and (2) the 37 papers after 1940 were published by namesakes (these papers have been excluded using the WoS "Refine" function). After the refinement we obtained a total of 160 papers accessible as source records under the WoS. An additional search in the INSPEC database in the time period 1898 till 1940 revealed 145 papers, including one pre-1900 paper. Note that the WoS is a multidisciplinary database, whereas INSPEC covers only the physics literature. The journal coverage of the pre-1950 physics-related literature by the WoS seems to be sufficiently complete to justify the following citation analysis.

We present in Figure 1 the time evolution of the citing papers (rather than the citations) based on the General Search mode, which includes only the impact of the Rutherford papers published since 1900 in WoS source journals. Note that one citing paper may contain more than one citation to a given author (*e.g.* one citing paper may refer to more than one Rutherford paper). Based on the WoS Cited Reference Search mode and the time period 1890-1940 (the publication years relevant for Rutherford), we determined in addition the time evolution of the citing papers of all publications by Rutherford (articles as well as books and any other published material) with the misspelled citations included here. Misspelled citations (*e.g.* incorrect with regard to the numerical data: volume, starting page,

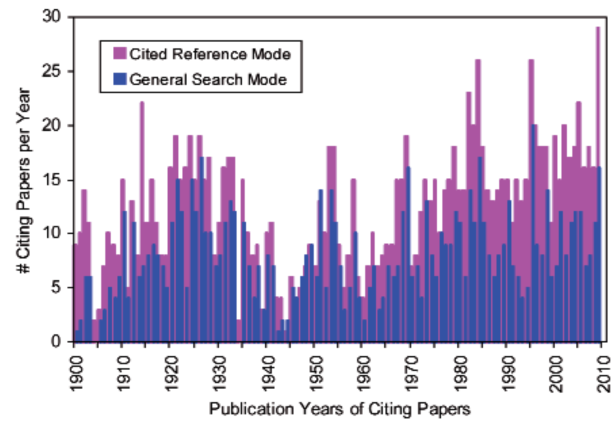

Fig. 1 Time evolution of the citing papers (rather than the citations) of the Rutherford articles as a function of the publication years of the citing papers. The blue bars are based on the General Search mode (including only the formally correct citations of the papers which appeared in WoS source journals since 1900). The red bars are based on the Cited Reference Search mode (including the citations of the pre-1900 papers since 1900, work not published in WoS source journals, and all misspelled citations). Source: Thomson Reuters Web of Science (WoS).

and publication year) are a general problem in citation analysis. The references of earlier papers, however, are particularly susceptible regarding "mutations".

The 160 Rutherford papers published between 1900 and 1931 received 1336 citations within 885 citing papers published till the end of 2009. If the citations of the pre-1900 articles are included we obtain a total of 1468 citations. If all Rutherford

TABLE 1

THE TEN MOST FREQUENTLY CITED ARTICLES BY ERNEST RUTHERFORD

Source: Thomson Reuters Web of Science (WoS)
Date of searching: 17-03-2010.

Author(s)	Journal	Title	# Citations
E. Rutherford	Philosophical Magazine 21, 669-688 (1911)*	The scattering of α and β particles by matter and the structure of the atom	327
E. Rutherford & H. Geiger	Proceedings of the Royal Society of London A 81, 141-161 (1908)	An electrical method of counting the number of alpha-particles from radio-active substances	86
E. Rutherford	Nature 123, 313-314 (1929)	Origin of actinium and age of the earth	64
E. Rutherford	Philosophical Magazine 47, 277-303 (1924)	The capture and loss of elections by alpha particles	58
E. Rutherford & C. Andrade	Philosophical Magazine 28, 263-273 (1914)	The spectrum of the penetrating gamma rays from radium B and radium C	57
M. Curie, A. Debierne, A.S. Eve, H. Geiger, O. Hahn, S.C. Lind, S. Meyer, E. Rutherford, & E. Schweidler	Review of Modern Physics 3, 427-445 (1931)	The radioactive constants as of 1930 - Report of the international radium-standards commission	57
E. Rutherford	Proceedings of the Royal Society of London A 97, 374-400 (1920)	Bakerian Lecture: Nuclear constitution of atoms	57
E. Rutherford	Philosophical Magazine 37, 581-587 (1919)	Collisions of alpha particles with light atoms IV. An anomalous effect in nitrogen	50
E. Rutherford & H. Geiger	Philosophical Magazine 20, 698-707 (1910)	The probability variations in the distribution of alpha particles	45
E. Rutherford & F. Soddy	Philosophical Magazine 4, 370-396 (1902)	Soddy on the cause and nature of radioactivity - Part I	44

* This article is not included as WoS source record because volume 21 is one of the volumes of the Philosophical Magazine not covered, for unknown reasons, by the WoS (see below).

publications (the pre-1900 papers, the publications not covered by the WoS, and also the misspelled citations) are taken into consideration, we obtain 1390 citing papers comprising approximately 2100 citations. The citations of the pre-1900 papers within the time period from the year of publication till 1900 are currently not available.

The citation ranking reveals the ten most frequently cited Rutherford papers, which are presented in Table 1. Note that the citation counts given therein are not time-adjusted with regard to the lower citation rates within the time period of "little science" (see below). For comparison with current papers and researchers, respectively, the number of citations has to be multiplied by a factor between 30 and 40 (see reference [7]).

INFORMAL CITATIONS

Seminal work is often cited by mentioning the author's name or name-based items ("informal citations" [8], also called eponyms) instead of citing the full references as a footnote ("formal citations"). We show in Figure 2 the time curve of the Rutherford "informal citations" based on the CAS and the INSPEC database ("Rutherford" appearing in the titles, the abstracts or the keywords). The corresponding time curve based on the SCI is limited to the past-1990 literature because the abstracts of the earlier records are not available under the WoS.

Chemical Abstracts (CAS) revealed altogether 17430 informal citations (1897-12/2009), Physical Abstracts (INSPEC) revealed a total of 18827 informal citations (1897-12/2009), and Science Citation Index (SCI) under the WoS revealed 9596 informal citations (only 01/1991-12/2009).

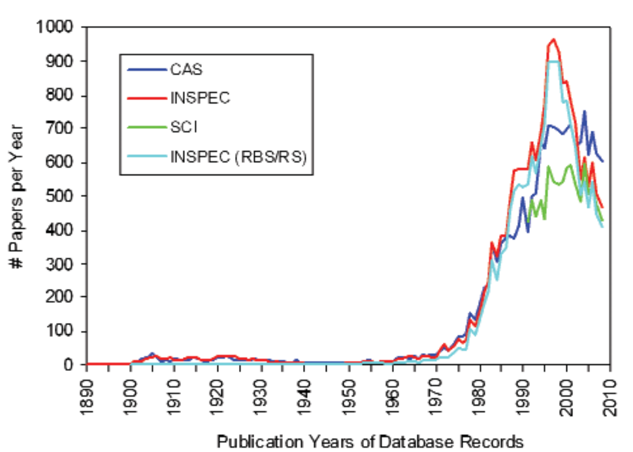

Fig. 2 Time evolution of the Rutherford "informal citations" based on the SCI, CAS and INSPEC databases ("Rutherford" appearing in the titles, the abstracts or the keywords). In the case of INSPEC we have given beside all informal citations mentioning "Rutherford", separately, those mentioning "Rutherford Backscattering" or "Rutherford Scattering" (RBS, RS). Source: CAS literature database CAPlus and INSPEC database under STN International and Thomson Reuters Web of Science (WoS).

Figure 2 demonstrates that most "informal citations" to Rutherford obtained from INSPEC correspond to Rutherford Backscattering (RBS) – 16254 out of 18827 (86.3 %). Particularly interesting is the peak found for the years 1996-1997. A possible origin of this peak may be the similar peak in the time curve of the publications of the INSPEC category of " Atom-, Molecule, and Ion-Surface Impact & Interactions". More than 60% of the RBS papers fall into this classification category of the INSPEC database. Thus the RBS-peak around 1997 is related to decreasing activity in Surface Physics as the corresponding research field.

Here we pose an interesting Gedankenexperiment: If for example the modern atom model or a phenomenon related to radioactivity (his most important achievements) would bear his name, the number of informal citations would be much higher and thus would better give a quantitative measure of the importance of his many fundamental contributions to physics (see also the last section on obliteration by incorporation).

LITTLE SCIENCE VERSUS BIG SCIENCE

The time evolution of citations is a result of two competing phenomena: the aging of the papers (obsolescence, replacement, oblivion) and the growth of the scientific literature. The publications covered by the SCI as well as by INSPEC increased approximately by a factor of a hundred throughout the 20th century. In the first half of the 20th century the number of researchers in the natural sciences was relatively small. Correspondingly, the number of ensuing publications was low, as reflected in the number of database records for these years. For the investigation of the time dependence of the research activities in physics the INSPEC database is particularly appropriate since it encompasses this field of endeavor more completely than *e.g.* the WoS. The time evolution of the physics publications covered by INSPEC is shown in Figure 3.

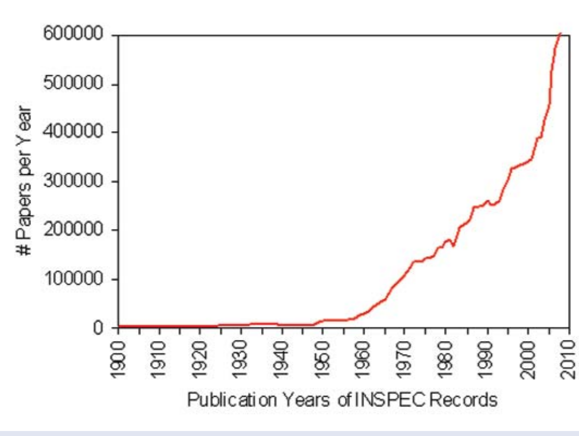

Fig. 3 Time evolution of the yearly publications covered by INSPEC in the field of physics and the related fields. The data include not only regular research articles and reviews but also any other kind of document types (*e.g.* conference proceedings, reports etc.). Source: INSPEC database provided by STN International.

The time evolution curve of Figure 3 shows a remarkable increase in the number of items per year, starting between 1955 and 1960. The time evolution of the chemical literature is similar although the increase is not so pronounced [9]. Following the title of the famous book by Derek de Solla Price [10] we shall speak of the period before 1955 as "little science" whereas the period after 1960 will be referred to as "big science". It is easy to conjecture that the transition from the period of "little science" to that of the "big science" is due to the so-called Sputnik shock [11] that took place upon the placing in orbit of the first satellite by the Soviet Union in 1957. As a reaction to this shock the Western industrial nations, especially the USA, allocated within a short time funds of hitherto unknown amounts to support related scientific research and development. These measures resulted in a rapid increase in the number of scientists and research activities, which reflected itself in a dramatic increase in the number of publications.

The number of publications of the "little science" period was not only low but they were also cited less frequently than those of the "big science" period. This is clearly reflected in the low average number of citations per publication as compared to the present one. The probability of a paper being cited depends, in fact, on the average number of references it musters. For the year 1900 (a total of 810 publications in the physics journals covered by the WoS) the average number of references was 6.0 (arithmetic average; median: 2). The corresponding average for the physics journals covered by the WoS in the year 2000 is 22.2.

CITATION HISTORY OF RUTHERFORD'S MOST-CITED PAPER

The graph displaying the time-dependent evolution of a single paper is sometimes called its citation history. Each paper develops its own life span as it is being cited. With time, the citations per year (citation rate) of papers by ordinary mortals normally evolve following a similar pattern: They generally do not increase substantially until one year after publication. They reach a summit after about three years, the peak position depending somewhat on the research discipline. Subsequently, as the papers are displaced by newer ones and interest in the field wanes, their impact decreases, leading to the accumulation of citations at a lower rate. Finally, most papers are either barely cited or forgotten. Figure 4 shows the citation history of the most-cited Rutherford paper [12] (see Table 1), which differs markedly from this pattern.

Rutherford developed his model of the atom based on his initial observations while at McGill University of the diffused propagation of alpha particles through a thin sheet of mica followed later by further measurements on metal films undertaken first by his assistant Hans Geiger, and then by his student Ernest Marsden, in Manchester. Quoting Cambell [1], "Marsden found that some alpha rays were scattered directly backwards, even from a thin film of gold. It was, a surprised Rutherford stated, as if one had fired a large naval shell at a piece of tissue paper and it had bounced back. In 1911, Rutherford deduced from these results that almost all of the mass of an atom, an object so small that it would take over five million of them side-by-side to cross a full stop on this page, is concentrated in a nucleus a thousand times smaller than the atom itself...The nuclear model of the atom had been born."

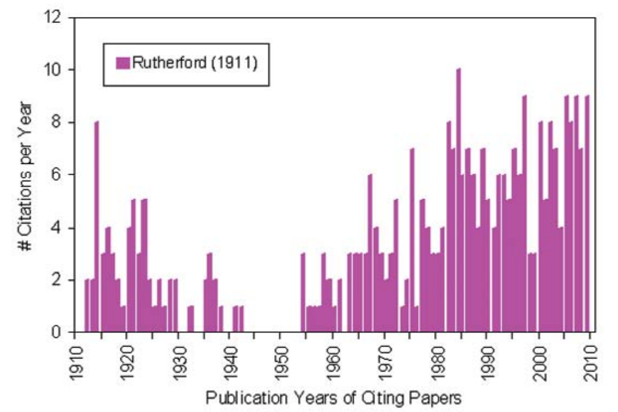

Fig. 4 Time evolution (citation history) of the famous 1911 Rutherford paper on the scattering of alpha and beta particles by matter and the structure of atoms [12] (325 citations till 12/2009). This is a good example of a seminal paper with a long term impact, which receives an increasing number of citations per year following the boom after the Sputnik shock half a century after its publication. Source: Thomson Reuters Web of Science (WoS).

This paper belongs to the rather few papers published at the beginning of the "little science" area that have been remembered throughout half a century and were then increasingly cited within the "big science" epoch. Most of the articles published during the beginning of the 20th century were no longer cited after around 1960. We find in the WoS only 12 citations within the year 1960 to the 810 physics papers published in 1900. Only articles of great significance, such as those of Rutherford, Planck or Einstein, show continuing citation patterns.

Ernest Rutherford at Manchester University ca.1908.

THE H-INDEX OF ERNEST RUTHERFORD

A new index (h-index, h-number) was introduced in 2005 by Jorge E. Hirsch (h = 53) as a measure of the cumulative impact of a researcher's scientific work within a given discipline [13]. It has captured the field of research evaluation in part because of its simplicity. The h-index can be easily obtained under the WoS General Search mode, provided there are either no highly cited namesakes or they can be removed. The h-index is simply defined as the number of papers in source journals that have had h citations or more. The index increases roughly linearly with the scientific age of the researcher and depends on his specific research field. It reflects a researcher's contribution based on a broad body of publications rather than based on a few high-impact papers. This avoids an overestimation of single or a few highly cited papers, sometimes being of a methodological nature, reviews or articles with a large number of coauthors in which it is impossible to assign individual contributions. The h-index is a combined measure of both output (in terms of papers) and impact (in terms of citations) in one single number.

The citation counts of early articles, and hence the h-numbers of pioneers like Ernest Rutherford, are much lower than the citation numbers of current papers and the h-numbers of present top-scientists (*e.g.*, P.W. Anderson, h = 103; R.A. Marcus, h = 85). The increasing number of citable papers within the last century results in increasing average citation rates. The h-index is, however, not only a measure of impact but, in addition, also of output. The publication habits (in particular the average number of papers per year and the average number of coauthors per paper) have increased significantly. Around 1900, scientists like Rutherford used to publish only a few articles per year. Hence, the publication and citation numbers (and thus also the h-numbers) of early scientists are not directly comparable to those of present day researchers. We have to find out in particular, how much more citations around 1900 are worth compared to present day citations.

The WoS General Search mode based on the SCI reveals 160 papers authored by E. Rutherford and published in WoS source journals within the time period 1900-1940. Based on these articles we obtain an unscaled (not time-adjusted) h-index of 20. The Cited Reference Search mode reveals 11 pre-1900 papers with more than 1 citation. These papers have been included into the list of the 160 WoS source journal articles and all papers of the extended list have been ranked by their citation counts. Applying our newly developed scaling method for papers published in the period of "little science" [7] means that all citation numbers of the articles in the final list have to be multiplied by the appropriate reference multiplier. This procedure results for Rutherford in a present day scaled h-index of 91 (using a reference multiplier of 30 based on the *Philosophical Magazine*) and of 93 (using a reference multiplier of 40 based on the *Physical Review*). This is similar to the unscaled h-index of 13 versus the time-adjusted h-index of 85-90 for Max Planck [7].

TABLE 2

THE WOS BASED NUMBER OF PAPERS AND THE H-INDEX OF THE NOBEL LAUREATES FROM NEW ZEALAND OR CANADA, OR WITH CANADIAN PHYSICS CONNECTIONS

Nobel Laureate	Country	Nobel Prize	# Papers (WoS)	h-index
A.G. MacDiarmid	New Zealand	Chemistry 2000	663	93
M.H.F. Wilkins	New Zealand	Medicine 1962	80	38
R.E. Taylor	Canada	Physics 1990	146	38
B.N. Brockhouse	Canada	Physics 1994	89	33
W.F. Giauque	Canada	Chemistry 1949	166	35
G. Herzberg	Canada	Chemistry 1971	206	59
J.C. Polanyi	Canada	Chemistry 1986	282	61
S. Allman	Canada	Chemistry 1989	252	52
R.A. Marcus	Canada	Chemistry 1992	399	85
M. Smith*	Canada	Chemistry 1993	192	56
W. Kohn	Canada and USA	Chemistry 1998	207	61
V.L. Fitch	Canada and USA	Physics 1980	44	14
A. Schawlow	Canada and USA	Physics 1981	203	43
W. S. Boyle	Canada and USA	Physics 2009	37	17

* Because of the large number of namesakes we have limited the search to works done at his main institution (University of British Columbia).

For an interesting comparison, the WoS based number of papers and the h-index of the Nobel Laureates from New Zealand or Canada or with Canadian physics connections are given in Table 2. Note that (1) the papers of the Laureates in the fields of technology and engineering (*e.g.* Boyle) are not completely covered by the WoS and (2) that the h-index values given here are unscaled with regard to the lower citation rates within the time period of "little science".

RUTHERFORD AND THE *PHILOSOPHICAL MAGAZINE*

According to the 1900-2010 WoS count, 63 of Rutherford's 160 papers were published in the *Philosophical Magazine*. Obviously, this journal was his preferred choice for publishing his work, starting in 1896 and ending in 1919. Rutherford ranks 6th in the list of authors most often appearing in the *Philosophical Magazine* behind R.W. Wood (101), G.E. Murch (100), N.F. Mott (99), P.B. Hirsch (73), and D.J. Bacon (71).

This study is affected by some caveats caused by the limited coverage of journals pre-1945. When the WoS had been extended back to 1900 in the Century of Science Project of the ISI (now Thomson-Reuters), not all relevant material was available and could be included. Some volumes of the *Philosophical Magazine* are missing in the database for reasons unknown to us: 1900 (V 50), 1903 (V6), 1904 (V7), 1911 (V21), 1915 (V29) and maybe more. The volumes of the publication years 1913, 1945-1948, and 1950 of the *Philosophical Magazine* are completely missing in the WoS. In addition, many references with the *Philosophical Magazine* as a reference journal do not include volume and page numbers (*e.g.* E. Rutherford, *Philosophical Magazine*, May 1911). Such references are not linked with the corresponding source records and hence are not included in the citation counts given under "Times Cited". Further investigations are needed to find out whether this is only a specific problem caused by the journal (or by Rutherford himself) or even a general problem resulting from the citation practice in the period of "little science".

OBLITERATION BY INCORPORATION

The works of Ernest Rutherford, in particular his famous article about the scattering of alpha and beta particles, are a typical example of "obliteration by incorporation", a phenomenon first described in 1949 by the sociologist Robert K. Merton [14,15]. The process of obliteration or palimpsest (the latter expression referring to a piece of parchment used more than once, that is, being erased to make room for newer work) affects seminal works (*i.e.*, truly ground-breaking research) offering novel ideas that are rapidly absorbed into the body of scientific knowledge. Such work is soon integrated into textbooks and becomes increasingly familiar within the scientific community. As a result of this absorption and canonization, the original sources (mainly articles or books) fail to be cited, either as full references (formal citations) or even as names or subject-specific terms (informal citations).

The ideas survive, sometimes becoming substantial elements of the basis and groundwork of modern science. But building over the groundwork implies obliteration of the sources. For example, the articles by Albert Einstein on the Theory of Relativity (published in 1905 and 1916, respectively) are rarely cited in current research work (as compared to less fundamental articles), although they are the basis of modern cosmology and mainly caused Einstein's popularity. It may even happen that a transmitter, being familiar with the origin of a concept and assuming the same of his readers, brings the idea back to life without citing the source, with the eventual result of becoming identified with its originator.

Eugene Garfield, the inventor of the citation indexes and the founder of ISI (Institute for Scientific Information, Philadelphia), concisely stated in one of his essays [16]: "Obliteration—perhaps even more than an astronomical citation rate—is one of the highest compliments the community of scientists can pay to the author…. It would mean that his contribution was so basic, so vital, and so well-known that scientists everywhere simply take it for granted. He would have been obliterated into immortality." Bearing this in mind, we should not expect that formal or even informal citations of the works of Rutherford can be taken as a real measure of the influence of his ideas in modern science. There are no metrics for quantifying fundamentality, significance or even elegance, which are terms falling under a completely different category.

RUTHERFORD'S IMPACT OVER THE LAST CENTURY

In summary, Rutherford's influence on the course of science and nuclear physics in particular has been immense. This is evidenced through our citation analysis of his published works. It should be noted in this regard that Rutherford seldom coauthored papers published by his students [1], otherwise he would have had even more citations. As it is, he ranks ,in terms of citations, with Max Planck and Albert Einstein [7] as one of the main contributors to the developments of modern physics at the first part of the 20th Century. His name lives on primarily in the Rutherford back scattering technique that was developed subsequent to his most important discovery of the atomic nucleus, but could have been widely applied in many other areas of science. This is a pity. Rutherford's name should be at least as widely quoted in the modern literature as, for example, C.V. Raman, who was active in research in the same time frame as Rutherford and had the Raman effect named after him [8]. The process of scientific obliteration lies at fault here – Rutherford's new ideas and discoveries, although they underpin so much of today's physics and chemistry, were rapidly incorporated into the scientific knowledge and then simply taken for granted.

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