Modern Physics Letters B, Vol. 24, No. 12 (2010) 1151–1163

DOI: 10.1142/S0217984910023992

FROM BECQUEREL TO NANOTECHNOLOGY: ONE CENTURY OF DECLINE OF SCIENTIFIC DISSEMINATION, PUBLISHING AND TECHNOLOGY TRANSFER*

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Received 10 March 2010

2008 marks the 100th anniversary of Henri Becquerel's death, the discoverer of radioactivity and a leading contributor to the birth of modern physics. In addition to well-deserved celebrations, this offers a chance for a sobering look at scientific dissemination then and now and at the evolution of technology transfer. The facts are shocking: both dissemination and technology transfer were much faster and effective at the time of Becquerel, in spite of all the new communication techniques. I briefly speculate on the causes of these dismal failures, arguing that they are primarily rooted in society, academic management and industrial management — and therefore very difficult to reverse.

Keywords: Becquerel; radioactivity; bibliometry; technology transfer.

1. Introduction

Early in 2008, I was invited by Physics World to compose a short article to commemorate the 100th anniversary of the death of Antoine-Henri Becquerel (Fig. 1). I researched the subject in detail and this enabled me to discover some fascinating facts: the incredible rapidity of Becquerel's experiments, his outstanding professionalism and courage — and the unjust treatment of his image by history.

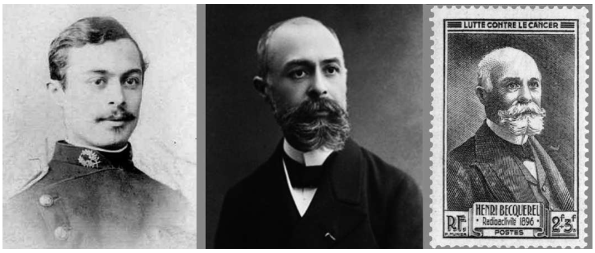

Fig. 1. The three different images of Antoine-Henri Becquerel as a student, a mature researcher and a postage stamp icon.

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*This paper is to appear concurrently in *EPIOPTICS-10: Proceedings of the 43rd Course of the International School of Solid State Physics* published by World Scientific.

Furthermore, it led me to the shocking realization that at Becquerel's time scientific dissemination was much faster and effective than today — in contrast to our illusions about rapid communications, letters, web publishing etc. Similarly, most fundamental discoveries of that time found their way to practical applications and industry much more rapidly and efficiently than today.

These facts, I believe, merit to be known and carefully analyzed. In this paper, I try to go beyond the celebration and the mere narration of historical events — discussing what went wrong with our scientific dissemination and technology transfer strategies compared to one century ago.

2. The Breathtaking Pace of Becquerel's Discovery

The history of the birth of radioactivity is in itself a very fascinating argument.[2–8] There are many misconceptions about it — in particular, that it was merely the result of luck. Quite forgotten is the fact that Becquerel won an international race with outstanding scientists in France and the UK. He won not just because he was lucky, but thanks to of his outstanding professionalism and to an excellent arsenal of samples and techniques.

The discovery took place[2–8] on 1st March 1896 in Paris — and its very effective dissemination started[9] within *one day!* The experiments were triggered by a public discussion that took place only 37 days before the discovery – and had started a couple of weeks before.

The framework for these fast-paced events was provided by an outstanding institution: the French Academy of Sciences (*Académie des Sciences*). Each Monday, the Academy held a regular meeting enabling its members to present their latest results, comments, news and speculations. The results were then disseminated in France and all over Europe by an excellent communication network with other scientific institutions — and published in the Academy journal, the famous "*Comptes Rendus*". Reciprocally, other scientific institutions communicated their latest results through the network and beyond national barriers; such results were presented by the French Academy to its attending members during the Monday meetings.

These two elements, the international communication network and the weekly meetings of the Academy, had a decisive role in Becquerel's work. The first triggered the events leading to the discovery of radioactivity and the second set their fast pace. Note that presenting the latest results during the Monday meetings was a formidable challenge. In a few days (or hours), the author was forced to process and digest the data — and then face a superlatively qualified audience: mediocrity could not easily survive.

The event that triggered Becquerel's work happens[10] on 8th November 1895 in Würzburg: Wilhelm Röntgen (Fig. 2) discovers X-rays and immediately uses them for radiology. The impact on the scientific and general public is tremendous: one could see for the first time bones in living bodies, a philosophical reminder of mortality hidden inside us.

Fig. 2. Wilhelm Conrad Röntgen, whose discovery of X-rays triggered a few weeks later the experiments of Becquerel.

Fig. 3. Henri Poincaré: his ideas about the connection between X-ray emission and florescence triggered Becquerel's experiments.

The scientific network is very effective in disseminating Röntgen's discovery. On Monday, 20th January 1896, the eminent scientist Henri Poincaré (Fig. 3) announces it to the Science Academy. He is also able to show a few radiographs, some received from Röntgen and others very quickly obtained in Paris. The enthusiasm is universal and Poincaré's speech is followed by an exciting discussion: what is the cause of the Röntgen's mysterious rays?

One intriguing fact sparks the debate: in Röntgen's tube, the X-rays seem to originate from the same place as fluorescence. Poincaré argues that X-ray emission could be somewhat related to fluorescence stimulated by illumination with visible light, asking[11] if "*all bodies producing intensive fluorescence, whatever its cause, do not emit, in addition to light rays, Röntgen's X-rays*". We know today that Poincaré was wrong but at that time the idea was not implausible.

Becquerel participates in the discussion (as an Academy member since 1889) — and is very interested in Poincaré's hypothesis. Fluorescence is a family business: he investigated luminescence like his father Alexandre-Edmond and possesses an excellent collection of fluorescent sample, in particular uranium compounds.

The validation of Poincaré's hypothesis is an excellent opportunity to solve serious problems of Becquerel's career — that was both facilitated and complicated by the scientific heritage of his family. Henri's grandfather Antoine-César had discovered diamagnetism, piezoelectricity and the electrolytic extraction of metals from ores. His father Alexandre-Edmond had observed the photovoltaic effect when he was nineteen years old — before pioneering the study of luminescence.

Predecessors of that stature are troublesome for 43 years old Henri Becquerel. His previous results in optics and thermodynamics, however, excellent, are no match to the family traditions. He needs something good enough to definitely establish his own independent identity — like proving the relation between fluorescence and X-rays (with the bonus of a simple and cheap way to produce X-rays for practical uses). And he must solve his problem as soon as possible since his position recently became more troublesome.

This is, paradoxically, a result of his nomination as professor at the *Ecole Polytechnique* in Paris — the famous "X". His family did not flourish at the "X" but at the French Museum of Natural History whose chair in physics had been occupied by Becquerels for three generation: Henri himself replaced his father after serving as an assistant. But being his father's successor did not satisfy him. He graduated at the *Ecole Polytechnique* and considered a chair at his *alma mather* as the only worthy academic objective.

Quite recently, this dream became reality — but in a rather nightmarish way. The physics chair of Alfred Potier became vacant and Henri Becquerel was selected to occupy it. But the call for candidatures failed to produce a good batch of candidates: Henri's nomination was virtually unchallenged. The other physics professor at the *Ecole Polytechnique*, French Academy of Science president Alfred Cornu, vocally criticized the procedure and the selection — and insultingly refused to take part in the final vote.

Henri Becquerel thus continues to be considered as his father's son rather than an eminent scientist on his own merit. Poincaré's hypothesis is the chance to resolve this problem. But Becquerel faces two difficulties. First, he is not alone in the race to validate the idea: in France, Charles Henri and Gaston Henri Niewenglowski start their own tests — and present preliminary results in the first days of February. And in London, Sylvanus P. Thompson (not to be confused with J. J. Thompson) is experimenting with uranium salts (Fig. 4)!

Uranium compound tests are certainly the most promising way to validate Poincaré's idea — and Becquerel's collection of specimens gives him a solid advantage over the competition. But there is a second problem: he has lent his best uranium compound, SO4(UO)K (uranium and potassium double sulfate), to a colleague for experiments. Waiting to get it back, he tests non-uranium specimens with disappointing results but cannot use other uranium salts since they are unstable — they cannot stay in the atmosphere during the long time necessary for exposure to sunlight to stimulate fluorescence.

Fig. 4. Sylvanus Thompson, a dangerous competitor in the race that led to the discovery of radioactivity.

Finally, Becquerel recovers his best specimen. The first test gives him the impression of having seized his dream result. He is wrong, but in the following days he discovers something unexpected and much more fundamental: natural radioactivity — and that changes the very foundations of science.

The experimental procedure is both simple and ingenious. A photographic plate is wrapped with heavy black paper to prevent accidental exposures to visible light. Then, the uranium salt is placed on the wrapped plate. To stimulate phosphorescence and — hopefully — X-ray emission, the salt is exposed to sunlight for long periods of time. After developing the plate, Becquerel observes a clear image that cannot have been produced by visible light — suggesting that sunlight also caused the emission of something else!

Feeling close to success, Becquerel rapidly and professionally completes a series of corroborating tests. A piece of glass between the uranium salt and the plate attenuates the images without eliminating them. A piece of metal causes a shadow in the image. On the strength of these results, Becquerel speaks to the Academy[12] on 24th February (a Monday of course): "*One must thus conclude from these experiments that the phosphorescent substance under investigation emits radiation that goes through paper opaque to light and reduces the silver salts.*"

This is an excellent first step and a strong claim to priority, but Becquerel needs more data to validate Poincaré's hypothesis and convincingly beat the competitors — who are not sleeping. The next deadline is the Academy meeting of Monday, 2nd March (1896 is a leap year). Thus, he prepares a new test by inserting between the salt and the plate a cross-shaped copper sheet — in the hope of obtaining a better-defined shadow image.

But there is a big setback: no constant sunlight is present as clouds dominate the Parisian February. Becquerel only obtains intermitting exposures to sunlight and unreliable exposures to weak ambient illumination, quite different from the well-defined sunlight exposures of the previous week. Frustrated, Becquerel interrupts the tests and stores the wrapped plate with the salt and the copper cross in a dark drawer.

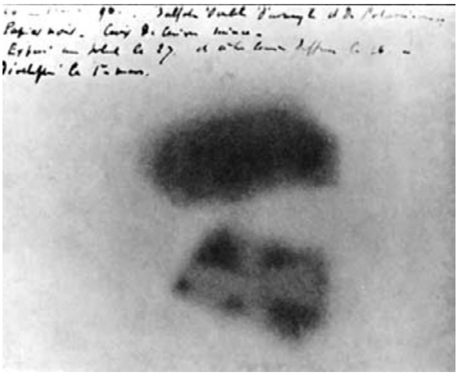


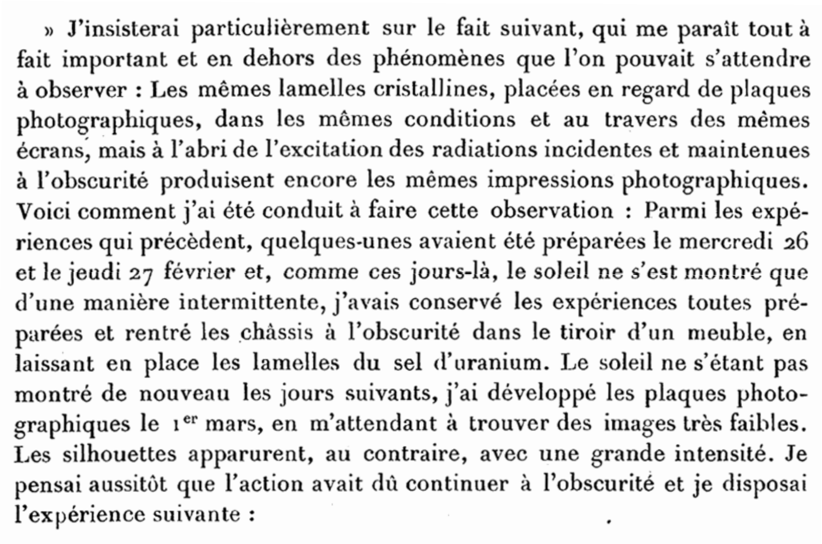
Fig. 5. The image that revealed radioactivity: the uranium salt shape is clearly visible together with the shadow of the copper cross. In Becquerel's handwriting the note: "*Uranyl and potassium double sulfate — Black paper — Thin copper cross — Exposed to the sun on the 27 and to diffuse light on the 26 — Developed on 1st March*".

The cloudy weather continues until on Sunday 1st March Becquerel realizes that he cannot get a good sunlight exposure in time for the Monday meeting. He then makes two critical decisions: first, he replaces the plate with a fresh one in preparation for the eventual return of sunlight. Second, he does not throw away the old plate but develops it.

We can only speculate about the motivations of this choice. One, most likely, is the good laboratory practice of getting complete documentation. Furthermore, Becquerel probably hopes that weak and erratic light exposures anyway produced some kind of faint image to present at the Monday meeting: not much, but better than nothing.

The actual finding is very different and astonishing: the image (Fig. 5) is not weak but comparable to the result of a long sunlight exposure! What should Becquerel do? Let us try to look at things from his point of view. It would be tempting to avoid deductions from the puzzling results or perhaps discard the last image as a freak accidental result. But he does not cede to these temptations and reaches a clear if preliminary conclusion: illumination is not needed for the emission of the mysterious invisible radiation!

Within a few hours, he presents[9] the new results to the Academy (Fig. 6) and the world: "*I would like to stress in particular the following fact that seems to me very important and outside the phenomena that one could expect to observe . . . . I developed the photographic plates on 1st March anticipating to find very weak images. The silhouettes appeared, on the contrary, with great intensity.*" This is, by the way, a timely announcement in the international competition: Sylvanus P. Thompson later claims[13] — with no supporting evidence — to be the independent discovery of radioactivity (in his terms, "hyperphosphorescence") — but learning about Becquerel's announcement abandons his experiments.



» J'insisterai particulièrement sur le fait suivant, qui me paraît tout à fait important et en dehors des phénomènes que l'on pouvait s'attendre à observer : Les mêmes lamelles cristallines, placées en regard de plaques photographiques, dans les mêmes conditions et au travers des mêmes écrans, mais à l'abri de l'excitation des radiations incidentes et maintenues à l'obscurité produisent encore les mêmes impressions photographiques. Voici comment j'ai été conduit à faire cette observation : Parmi les expériences qui précèdent, quelques-unes avaient été préparées le mercredi 26 et le jeudi 27 février et, comme ces jours-là, le soleil ne s'est montré que d'une manière intermittente, j'avais conservé les expériences toutes préparées et rentré les châssis à l'obscurité dans le tiroir d'un meuble, en laissant en place les lamelles du sel d'uranium. Le soleil ne s'étant pas montré de nouveau les jours suivants, j'ai développé les plaques photographiques le 1er mars, en m'attendant à trouver des images très faibles. Les silhouettes apparurent, au contraire, avec une grande intensité. Je pensai aussitôt que l'action avait dû continuer à l'obscurité et je disposai l'expérience suivante :

Fig. 6. Henri Becquerel announces his surprising result to the French Academy of Sciences (Ref. 9).

3. Aftermath

The continuation of Becquerel's work is not as exciting as we could believe. He does perform many important tests to validate his discovery (not yet called "radioactivity"). Most notably, he definitely rules out any connection between the uranium radiation and light exposure — and identifies uranium itself as the emitting component cause. But these experiments come to an end and Becquerel switches to studies of the Zeeman effect.

Why this lack of interest? First of all, everyone seems to discover new types of radiation in those years — some real and others the result of imagination like Blondot's N-rays.[14] Second, X-rays catch all the popular attention because of their use in radiology. Tests to obtain radiographs with the uranium radiation fail (luckily for the potential patients), preventing it from becoming similarly fashionable.

All this is changed in 1898 by a news bombshell: Marie and Pierre Curie's 1898 discovery of the very intense emission of polonium and radium.[15] This kind of emission seems to defy the roots of science, such as the conservation of energy. The popular attention to the phenomenon is overwhelming, also thanks to its final christening as radioactivity by Marie Curie.

Henri Becquerel decides to resume his work on radioactivity and to establish a very fruitful collaboration with the Curies, exchanging samples, results and ideas and socializing with them (Fig. 7). This is not a trivial choice and demonstrates that Becquerel believes in the democracy of science. Social and academic barriers separate a faculty member of the *Ecole Polytechnique* from a professor in a minor school like Pierre Curie and his partner of modest foreign origin — a woman scientist

Fig. 7. The relation between Becquerel (on the left) and Pierre and Marie Curie went beyond scientific collaboration and also became social.

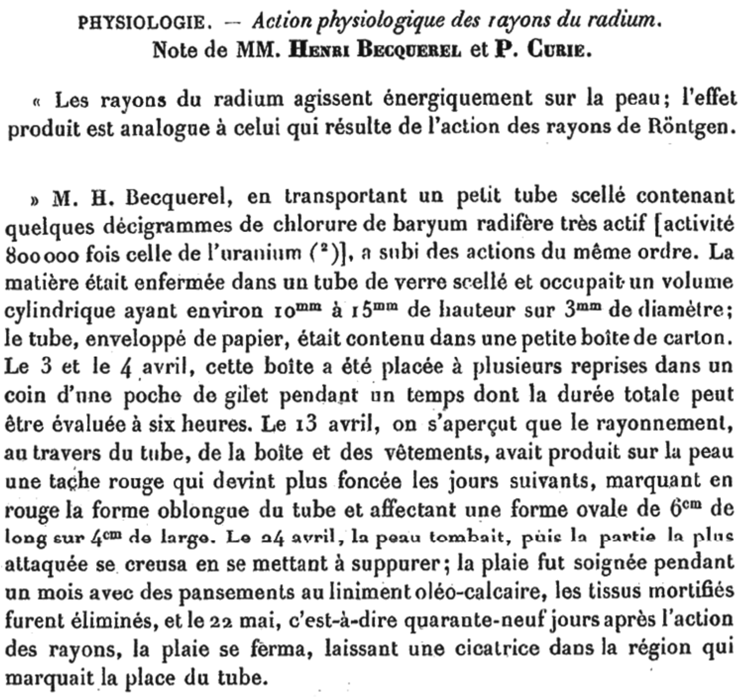
in the bargain! Becquerel brushes prejudice and bigotry aside but Marie Curie will later pay a heavy price because of them.[5]

The results of this collaboration are excellent for science and its applications. In parallel experiments, the Curies and Becquerel discover the physiological effects of radioactivity — specifically, Becquerel gets a burn from the accidental exposure to a radium sample borrowed from the Curies and left in his vest pocket. The Curies follow up voluntarily experimenting with their own bodies! The findings are presented in 1901 (Fig. 8) in a joint Becquerel–Curie article.[16] In the same year, the Saint-Louis Hospital in Paris pioneers radiotherapy — a stunningly rapid transition from discovery to practical applications.

Twelve years later, Marie Curie inaugurates the famous Radium Institute in Paris. But by now she alone: Pierre died of an accident in 1906 and Becquerel in 1908 of a heart attack.

4. Historical Unfairness

For a long period of time, Henri Becquerel's image was not well treated by the public opinion and by the academic community. The fact that he continued to produce excellent results (Fig. 9) did not seem to matter. For example, he identified the β-radiation as electrons and observed the interplay of different elements in radioactivity — that later led Rutherford and Soddy[17] to connect radioactivity with the subatomic transmutation of elements.



PHYSIOLOGIE. — *Action physiologique des rayons du radium.*
Note de MM. **Henri Becquerel** et **P. Curie**.

« Les rayons du radium agissent énergiquement sur la peau; l'effet produit est analogue à celui qui résulte de l'action des rayons de Röntgen.

» M. H. Becquerel, en transportant un petit tube scellé contenant quelques décigrammes de chlorure de baryum radifère très actif [activité 800000 fois celle de l'uranium (2)], a subi des actions du même ordre. La matière était enfermée dans un tube de verre scellé et occupait un volume cylindrique ayant environ 10^{mm} à 15^{mm} de hauteur sur 3^{mm} de diamètre; le tube, enveloppé de papier, était contenu dans une petite boîte de carton. Le 3 et le 4 avril, cette boîte a été placée à plusieurs reprises dans un coin d'une poche de gilet pendant un temps dont la durée totale peut être évaluée à six heures. Le 13 avril, on s'aperçut que le rayonnement, au travers du tube, de la boîte et des vêtements, avait produit sur la peau une tache rouge qui devint plus foncée les jours suivants, marquant en rouge la forme oblongue du tube et affectant une forme ovale de 6^{cm} de long sur 4^{cm} de large. Le 24 avril, la peau tombait, puis la partie la plus attaquée se creusa en se mettant à suppurer; la plaie fut soignée pendant un mois avec des pansements au liniment oléo-calcaire, les tissus mortifiés furent éliminés, et le 22 mai, c'est-à-dire quarante-neuf jours après l'action des rayons, la plaie se ferma, laissant une cicatrice dans la région qui marquait la place du tube.

Fig. 8. The Curie–Becquerel article (Ref. 16) announcing the discovery of the physiological effects of radioactivity and opening the door to radiotherapy.

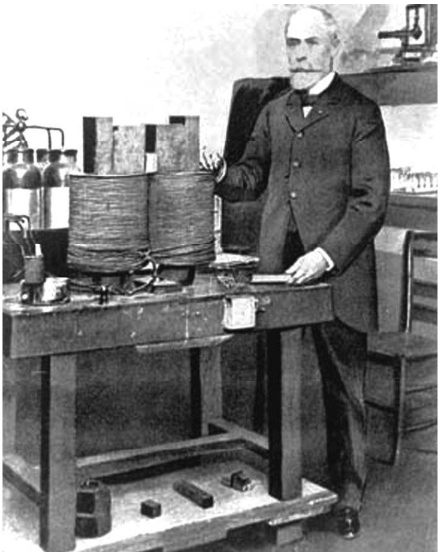


Fig. 9. Becquerel in his laboratory.

Becquerel did obtain the 1903 Nobel prize in physics — shared with the Curies — "*in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity.*" But even this prestigious award could not solve his image problems. For one thing, he suffered from the comparison with the tragic and imagination-catching figures of the Curies. Compared to the backbreaking work that led the Curies to their discovery (and to long-term, serious medical problems), Becquerel's discovery appeared to many just a lucky strike — by the privileged child of a well-established family, member of an exclusive institution.

But the unfairness went beyond the image of luck and privilege. There were for a while incredible and unjust rumors of plagiarism, attributing the original observation of uranium radiation to Abel Niépce, nephew of the photography inventor Nicéphore Niépce, back in 1857.

All this is objectively unjust: luck played only a minor role in Becquerel's discovery. It only accelerated the discovery by providing him with a good reference result before the second erratic experiment. But, considering his highly professional and systematic approach, Becquerel would have sooner or later discovered that uranium radiation has nothing to do with sunlight exposure. Other researchers would have stumbled onto the same findings dismissing them as a freak result. Becquerel had the professional wisdom to recognize the real nature of the "freak" result — and the courage to disseminate it a few hours later. This makes him one of the greatest scientists of all times.

This stature was eventually recognized partially compensating the historical unfairness: "Becquerel" became the SI unit of radioactivity, streets and institutions were named after him and his image appeared in postage stamps. Becquerel would have been shocked by this popularity since he was a rather modest man. The records also show that he was a decent, soft-spoken, urban person, deeply in love with his first wife Lucie Marie Zoé (daughter of Jules Jamin, physics professor at the *Ecole Polytechnique*), devastated by her early death and finding love again only many years later with his second wife Louise Désirée Lorieux. His life was simple, devoted to science and centered around the Natural Science Museum, its magnificent botanical garden and the "*Maison de Cuvier*" where he was born, lived for a long time and discovered radioactivity.

Unfortunately, Becquerel's image suffered again in recent years because of the irrational public attitude towards his discovery. Radioactivity has become a dirty — or at least politically incorrect — word. This overshadows its fundamental importance in the development of modern science.

This central role has two different aspects. First, radioactivity revealed the nuclear-level transmutations of elements, destroying the notion of atoms as unchanging entities — dating back to the Greek philosophers. This conceptual step was fundamental for the development of nuclear and subnuclear physics and of the different forms of nuclear energy.

Even more importantly, radioactivity marked the transition from deterministic science to the modern statistical foundations. Before its discovery, science dealt with deterministic phenomena. The motion of a solid body could be determined with unlimited accuracy given the forces and the initial conditions. The situation was different for liquids and gases, but statistical mechanics related their behavior to the properties of the constituent particles. A statistical treatment was necessary because of the very large number of components — but the behavior of each individual component was still deterministic.

Radioactivity was radically different since individual nuclear events cannot be deterministically predicted. Only the statistical behavior of many nuclei can be treated: radioactivity was thus the first example of intrinsically statistical phenomenon. This realization must be credited to Marie Curie and paved the way to the uncertainly principle, quantum mechanics, atomic physics, chemistry and materials science — in fact, to most of modern physics. And the first step of this historical path was Becquerel's discovery.

5. Why Are We Failing?

My most shocking realization in studying the discovery of radioactivity was that dissemination was much more effective and rapid at that time than today. If Becquerel had discovered radioactivity in 2008, the "safe" method of dissemination would have been publication in a prestigious and "fast" journal like Nature, Science or Physical Review Letters. He would not have dared use other methods for fear of losing priority or even of plagiarism. Dissemination, however, would have started after several weeks or months rather than in a few hours — or even more, considering the problems of peer review.

There are exceptions in this dismal picture and they help us to better understand the phenomenon. Dissemination is still pretty fast in domains like elementary particle physics with its excellent international organization. On the contrary, the widely publicized initiatives in Web publication and open access are still quite ineffective.

One could suspect that fast dissemination was possible in the past because of the small size of the scientific community. However, the rapidity and effectiveness of the new communication technologies should more than offset this factor. Thus, the main reasons must be found elsewhere.

I believe that the real cause of our dissemination failure is the interference of two different and partially conflicting objectives. The first is dissemination itself and the second is the quality evaluation of active scientists. The population size effects are very visible in this second case: due to the large number of cases that must be analyzed, the painstaking work of personal assessment based on a variety of elements is increasingly replaced by computer-assisted "bibliometric" evaluations. This in turn requires a quantitative ranking of journals and articles. The journals are forced to adopt acceptance criteria partly based on non-scientific elements (e.g., the likelihood that the paper will be cited). The implementation of such criteria is unavoidably slow and a major factor in our dissemination failure.

Dissemination in Becquerel's time was effective because the time sequence was reversed: the scientist's quality evaluation occurred first and was recognized by membership in scientific academies. This opened the access to very fast dissemination of the scientist's results. The potential problem was of course the exclusion of newcomers. But this was avoided by granting fast dissemination via an academy member under his/her personal responsibility. Journal ranking and bibliometry were thus irrelevant.

This system could not work under the present situation primarily because the scientist's quality ranking is also related to resource allocation. Most funding agencies claim that the proposed research quality is more important than the authors' quality in their decisions — but reality is different. Because of the pressures on the peer review system, the proposals of an established scientist are scrutinized less severely than those of newcomers — giving the former an objectively unfair advantage.

The need to offset this inequality requires rapid quality evaluations of junior scientists, puts pressure on the entire system and pushes it into the temptation of "quantitative" assessment based on bibliometry. This phenomenon is worsened by the use of scientists' quality evaluations for promotions and candidate selections. The entire machinery is increasingly relying on computer-assisted procedures that cause journal management strategies in conflict with the objective of dissemination.

The second of the above two objectives should indeed be only a secondary goal for the journal management — or no goal at all. Unfortunately, it is becoming instead more and more important, jeopardizing the primary objective of dissemination. The communication forum thus becomes a beauty context in which personal stature is more important than the real quality of work.

There are of course other negative consequences of this trend — such as the tendency to short-term research as opposed to long, difficult and risky efforts. Thus, there would be many good reasons for changing it. But could this be done?

I am afraid I cannot be optimistic. A significant correction would require a radical if not revolutionary change in our "science society" that is not likely to happen. The only chance for a real change would be a drastic deterioration of the publishing situation triggered by financial problems. This could conceivably cause a collapse of the entire journal system and lead to a real revolution. But the occurrence of such events is unpredictable and probably unlikely.

Similar to dissemination, the present situation of technology transfer does not justify optimism. One century ago, a new technology like radiology or the applications of radioactivity arrived into a vacuum and could very rapidly lead to new products and new enterprises. This is not true today in part because of pre-existing technologies. A new radiology technique, for example, would imply a very expensive retooling for the customers and the equipment manufacturers. Innovation is automatically welcome only if it is the result of corporate planning. Otherwise, there is often resistance against new technologies with methods like hostile takeovers. Innovation is still relatively easy when it arrives in a vacuum, but this combination is increasingly rare: our science and technology system, in relative terms, tends to be less innovative today than one century ago.

These are the disappointing but inescapable conclusions of the historical analysis of Becquerel's discovery — and of the very rapid and effective dissemination and technology transfer at that time. They do not lead to optimism, unless a new social and professional conscience develops among scientists — an unlikely but not entirely impossible prospect.

Acknowledgment

This work was supported by the Fonds National Suisse de la Recherche Scientifique and by the EPFL.

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