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Teaching about non-deterministic physics: an almost forgotten fundamental contribution of Marie Curie

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Abstract

The first historical steps of radioactivity research offer an excellent opportunity to teach a key concept of modern physics: non-deterministic phenomena. However, this opportunity is often wasted because of historical misconceptions and of the irrational fear of radioactive effects. We propose here a lecturing strategy - primarily for undergraduate students - based on interesting historical facts. In particular, on a key conceptual contribution by Marie Curie, an attractive figure for the young women and men of today. Paradoxically, this milestone is almost unknown, whereas it should contribute to her immortal fame – perhaps as much as the discovery of radium.

Keywords: Curie, radioactivity, determinism

1. Unreasonable apprehensions and forgotten history

Radioactivity has regrettably become a dirty word, reflecting emotional anxieties—in short, a topic that is better to avoid. This attitude, unfortunately, also percolates into the teaching of physics.

Consider for example the Web site [1] dedicated to lecturing about radioactivity. It is very attractive and full of useful resources. However, only 2 of the 26 chapters deal with the most fundamental consequence of radioactivity: non-deterministic phenomena that require statistical descriptions. Whereas radiation damage and health issues are present a.e.

This is not right: when teaching radioactivity, non-determinism should be the central issue because of its fundamental philosophical importance. Whereas health issues should be marginalized or even excluded. After all, when lecturing about the electrostatic voltage one does not dwell on electrocutions!

Used correctly, radioactivity is a wonderful teaching tool. To exploit its potential, we propose here a comprehensive strategy rooted on our experience. The approach links the early days of radioactivity research to the birth of non-determinism. In particular, it unveils a largely forgotten result of Marie Sklodowska Curie, which played a key role in the downfall of absolute determinism.

Marie Curie was the first woman entombed in the French Pantheon because of her own merit. Is this fame justified? Most students would agree, based on her discoveries of radium and polonium [2] – which were indeed outstanding results rewarded by two Nobel prizes.

But other Nobel laureates who discovered new elements—such as Ramsey, Rayleigh, Seaborg and McMillan - do not enjoy a fame even remotely comparable to that of Marie Curie. To understand this difference, we must realize that polonium and radium were not the only top achievements of her life. There was also the aforementioned key discovery: the atomistic nature of radioactive decays, directly linked to non-determinism.

This result was not even formally published but marginally mentioned in Marie Curie's thesis (we shall discuss later why). As a consequence, it went - and still is -largely unnoticed [2]. By learning about it, the students will realize that Marie Curie was not just a super-chemist, but also an outstanding theorist—at an age not much older than theirs. This will hopefully strengthen her impact as a role model, in particular for young women potentially interested in science.

2. Nature is not deterministic

The starting point of the lectures should be the presentation of determinism. For centuries, scientists believed in the possibility to predict and/or justify all phenomena based on their causes. They specifically thought that any accuracy level could be potentially reached with adequate theories and mathematical techniques.

Optionally, the teacher could also briefly mention some negative consequences of determinism beyond science. Such as the justification of aberrant pseudoscientific racism.

The lectures should then introduce the events that, in the years bridging the 19th and 20th centuries, progressively undermined the absolute faith on determinism:

- The statistical mechanics descriptions of the ideal gas and in particular of entropy [3].
- Einstein's 1905 'heuristic viewpoint' on the existence and role energy quanta of light [4].
- The discovery and study of radioactivity [5–14].

Boltzmann's and Maxwell's statistical mechanics explained the macroscopic properties of thermodynamic systems based on the collective, statistical behavior of their microscopic components. Determinism could appear at risk: opening a pressurized gas bottle, one cannot say for sure that the particles will exit – but only that it is a very probable event.

Objectively, however, statistical mechanics was not a direct challenge to determinism. The micro-components of a macro-system, for example the molecules of a gas, were still thought to behave in a deterministic way. The statistical description of the macro-system was necessary because of the huge number of micro-components and not because of their non-deterministic behavior.

Einstein's bold proposal in 1905 that electromagnetic radiation behaves sometimes as a collection of energy quanta [4]—later baptized 'photons' [15] - posed a more direct challenge to determinism. However, this challenge had puzzling aspects. To explain them, the teacher can discuss with the students the example of an 'isotropic' light source. Its symmetry is easily explained with waves. However, if the emission consists of energy quanta, then the symmetry only applies to the cumulative statistical behavior of many of them – whereas one cannot predict nor justify the direction of each one.

The negative impact on determinism seems clear. However, the non-deterministic, statistical nature of phenomena was so philosophically difficult to digest that Albert Einstein himself rejected it – and tried in vain to undermine its foundations [16].

3. The main actors

By contrast, radioactivity was direct and conclusive in undermining absolute determinism. It must be considered, therefore, not only as a great discovery but also as the beginning of a fundamental philosophical revolution.

This is a key message to the students and must be carefully explained. In a radioactive object, modifications occur in the nuclei of the atoms. One can accurately predict the fraction of the specimen that is modified by radioactivity within a certain time period. On the contrary, the time at which an individual nucleus is modified cannot be predicted nor justified: it occurs at random.

This case is radically different from that of a gas: we have seen that the behavior of each individual gas particle is deterministic and could, in principle, be predicted. Radioactive decays of individual nuclei provided instead the first experimental evidence of intrinsically random phenomena. Their existence contrasted with deep-rooted beliefs about the foundations of scientific knowledge: they triggered indeed a conceptual revolution. And now we know that non-deterministic phenomena dominate the microscopic world of atoms, electrons and nuclei.

The conceptual revolution was primarily caused by the early (1896–1903) research of a few amazing pioneers [5–14]. Their history should be extensively discussed by the teacher.

After its 1896 discovery [11, 14], radioactivity was fashionable and attracted many scientists. The most successful were Henri Becquerel, Pierre and Marie Curie, Ernest Rutherford and Frederick Soddy (figure 1). They had four aspects in common. The first was rather young age: the oldest, Becquerel, discovered radioactivity when he was only 44 [11, 14] (figure 2). Marie and Pierre Curie started their studies at 29 and 37. Rutherford was 25 when radioactivity was announced, and he recruited Soddy at the age of 23.

Second, all except Becquerel did not have good jobs. Becquerel, the exception, discovered radioactivity right after becoming a full professor at a Parisian '*grande école*', his *alma mater* the Ecole Polytechnique. However, he was frustrated for not yet having produced important results like his father and grandfather [14].

Pierre Curie was a professor at the *Ecole Supérieure de Physique et Chimie Industrielles* in Paris, not a prestigious institution at that time. His meager yearly salary was equivalent to about 24,000 euros of today (less than one-half of what he could get now from a 'Marie Curie' European fellowships) [9]. Marie, until 1900, was a student and not a paid employee. Afterwards, she supplemented the low family income with a teaching job at a young ladies' school in Sèvres – wasting much of her precious time [9, 17].

Figure 1. The five leading pioneers of radioactivity: top, left to right: Henri Becquerel, Pierre Curie, Marie Sklodowska Curie: bottom: Ernest Rutherford, Frederick Soddy.

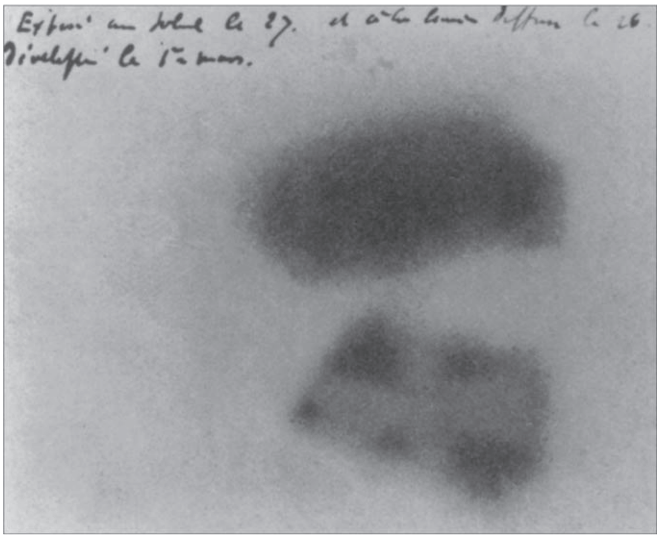


Figure 2. The photographic plate revealing the spontaneous emission from uranyl potassium sulfate, which led Becquerel in 1896 to the surprising discovery of radioactivity [11, 12].

Pierre and Marie Curie were actually paid for teaching and not to do research [9]. Their laboratory was a miserable shack (figure 3) where just surviving was a challenge [6]. This contributed to Pierre's bad health and was a likely factor in Marie's long-term ailments and death [9, 17].

As to Rutherford, he started working on radioactivity when he was still a student in Cambridge [12] (after failing three times to secure a comfortable high-school teaching job) [12]. In

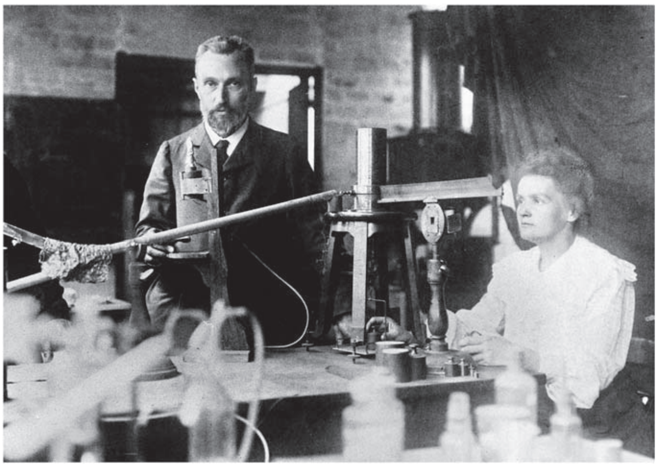


Figure 3. Marie and Pierre Curie in their inadequate, unsafe and unhealthy working space in Paris.

1898, he got a professorship at McGill university in Montreal, Canada. But was unhappy: such a 'colonial' institution cut him out of the physics mainstream in Europe. And Soddy was just his student at McGill and a modest 'demonstrator in chemistry' [12].

The third common feature of the five pioneers was that all of them became Nobel laureates [9, 12, 17]. Becquerel shared one-half of the 1903 physics prize with Pierre and Marie Curie. And Marie got a second one in chemistry in 1911 [9, 17].

Rutherford received a Nobel in chemistry in 1908 [12] – but was disappointed because he preferred physics: '*I have dealt with many different transformations with various periods of time, but the quickest that I have met was my own transformation from a physicist to a chemist*'. On the contrary, the 1921 Nobel in chemistry made Soddy happy [12].

Finally, all five radioactivity pioneers were top-level experimentalists. Particularly remarkable was Becquerel's superb professional competence, which allowed him to realize that radioactivity was a new discovery [11, 14]. He could have trashed his unexpected result as an unexplainable oddity. Instead, he took the incredible risk of presenting it officially as a new phenomenon – *the day after* its first observation [11].

4. Rectifying history

In order to correctly understand the path to non-determinism, the students should learn at this point about the individual contributions of the five pioneers, correcting misconceptions. For example, the wrong belief that only Rutherford and Soddy dealt with conceptual issues, whereas their French colleagues were not interested in theories [18]. Indeed, Pierre and Marie Curie are often regarded just as chemistry practitioners [19]. This diminutive image was reinforced when their main chemical product, radium, became very popular (and also inspired many frauds like that of figure 4).

In reality, Marie and Pierre Curie constantly dealt with sophisticated theoretical ideas, which guided their experimental work – not limited to chemical manipulations but including many conceptual tests [9, 10, 18–20]. The theoretical foundations of their research led them, in particular, to adopt the term 'radioactivity', invented by Marie and implying a new kind of phenomenon [9, 17].

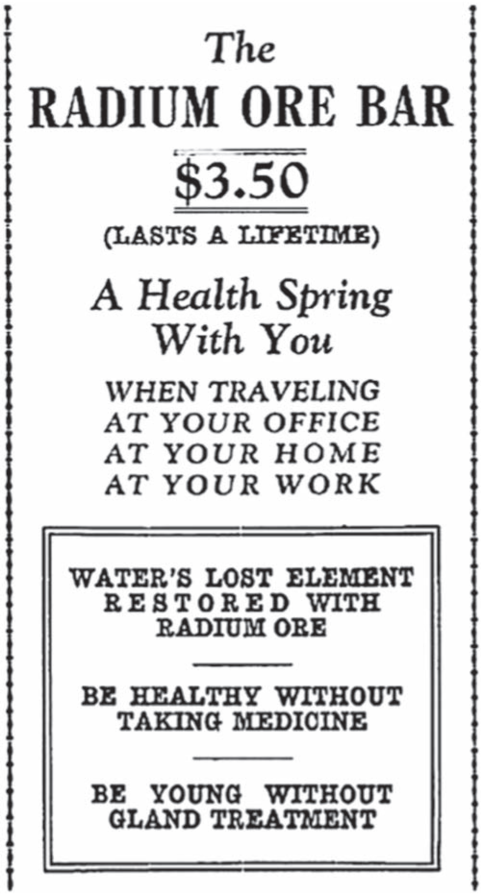


Figure 4. One of the many fraudulent products inspired by the popularity of radium: this one was sold to produce radioactive water, which was advertised to improve the unlucky customers' health!.

Another misconception must be rectified to discover the specific contributions of Marie Curie: the idea that she and Pierre were essentially the same entity, working in a symbiotic collaboration that blurred their individual achievements. This is false: from the very beginning, several of their articles were not co-authored by both of them.

And those by Marie alone reflected her specific accomplishments [10]. This applies in particular to the famous first note on radioactivity (presented by M. Lippmann to the *Académie des sciences* [20]). In which she consistently spoke in the first person: '*I studied the conductibility of air… I investigated if solids… I used for this study…*' – and never mentioned her husband.

Some of the differences between Pierre and Marie were conceptual. And consistent with the intriguing hypothesis [18] that French 'positivist' philosophy influenced the early analysis of radioactive phenomena. Indeed, this notion could be plausible for Pierre, but less so for Marie whose cultural background was strongly Polish.

§ 3. *The Material Nature of the Radiations.*

The view that the ray or rays from any system are produced at the moment the system changes has received strong confirmation by the discovery of the electric and magnetic deviability of the α ray. The deviation is in the opposite sense to the β or cathode-ray, and the rays thus consist of positively charged bodies projected with great velocity (Rutherford, Phil. Mag., Feb. 1903). The latter

Figure 5. Rutherford describes two of the components of radioactivity [5, 22].

5. Towards non-determinism

It is now time for the teacher to deal with Marie Curie's thesis and with the atomistic nature of radioactivity. The path to this milestone was long and very difficult. The Curies' experimental data were complicated by the multiple, simultaneous mixed effects of different radioactive elements and compounds, interacting with each other. This is reflected by the intricate laboratory notes and publications [5–10].

Becoming entangled in this jungle would not be good for teaching. Lecturing should focus instead on a few key points, adopting a simplified version of the conceptual route.

The theoretical side was also complex, in particular because its initial steps were negatively affected by the immense popularity of x-rays. After Roentgen's discovery in 1895 [21], they had attracted the attention of scientists, the general public and the media. Every researcher dreamed to find some new 'rays' that would bring fame and money. This ambition notoriously misled René Blondot to imagine the (non-existent) 'N-rays', damaging his reputation [22].

X-rays did influence Becquerel's work on radioactivity ('uranium rays' in his terminology). He wanted to use it for an alternate approach to radiology. But the images were poor, so he stopped working on radioactive phenomena [14]. Only after the discovery of radium did he change his mind.

X-rays also dominated [9, 20, 21, 23] the early thinking of Pierre and Marie Curie about the radioactivity mechanism. They considered the emission as a release of energy in the form of electromagnetic waves. This notion especially affected Pierre, who was oriented towards energy and thermodynamics [18]. Later, both he and Marie were led by the x-ray results of their friend Georges Sagnac [9, 20, 23] to a bizarre—and wrong - hypothesis. They imagined that radioactivity was triggered by some mysterious x-ray-like radiation from space (or from the 'ether').

To eliminate the initial wrong notions and reach the truth, the essential facts had to be disentangled from the confusing mass of experimental results. Evidence eventually accumulated [5, 13, 24] in favor of random, non-deterministic modifications ('transmutations') of individual atoms.

The path to this revolutionary notion was marked by three milestones that must be discussed in depth by the teacher, produced [5, 24–26] by Rutherford, Soddy, Villard and Marie Curie:

(1) The identification of the components of radioactive emission;
(2) The realization that radioactive decays are atomistic phenomena;
(3) The time dependence of radioactive emission.

The first milestone was reached in 1898–1902 with Rutherford's discovery [18, 24, 25] of alpha and beta rays (helium nuclei and electrons) (figure 5) and with the identification of gamma rays (photons) by Paul Villard [26]. Alpha and beta rays had masses, thus they ruled out radioactivity mechanisms solely based on the emission of massless waves like the x-rays.

6. Marie Curie's forgotten contribution

The second milestone was reached by Marie Curie when she realized that radioactivity is a property of individual atoms [2, 10] – not influenced by their chemical binding in molecules and solids, nor by other external factors. This fact had been somewhat hinted by Becquerel's early results on different uranium compounds. However, the credit for its discovery must go to Marie Curie—and constitutes her most important scientific achievement together with radium and polonium. It is also, arguably, one of the top scientific contributions of all times [2, 10].

We saw that Marie did not publish her remarkable discovery, in particular in her 1898 note to the *Académie des sciences* [20]. The vehicle was her thesis [10]: '*il resulte de l'ensemble de ces mesures que la rdioactivité de ces substabces est bien effectivement une propriété atomique - it results from the combination of these measurements that the radioactivity of these substances is in fact an atomic property*' (figure 6). And the result was explicitly credited to her by Rutherford [24]: '*Mme. Curie's original position, that radioactivity is a specific property of the element, must be considered to be beyond question*'.

The implications of the atomistic nature of radioactivity are fundamental and subtle, so they must be discussed in detail by the teacher. First, it changed the very notion of 'atom', completing a revolution that had started with the discovery of the electron. As we have seen, radioactive emission is not just energy but includes masses (alpha and beta rays). Thus, being an atomistic effect, it requires 'transmutations' of the atoms. Which could not be the 'atoms' of the ancient Greek language, i.e., the immutable and indivisible particles of Democritus and Leucippus.

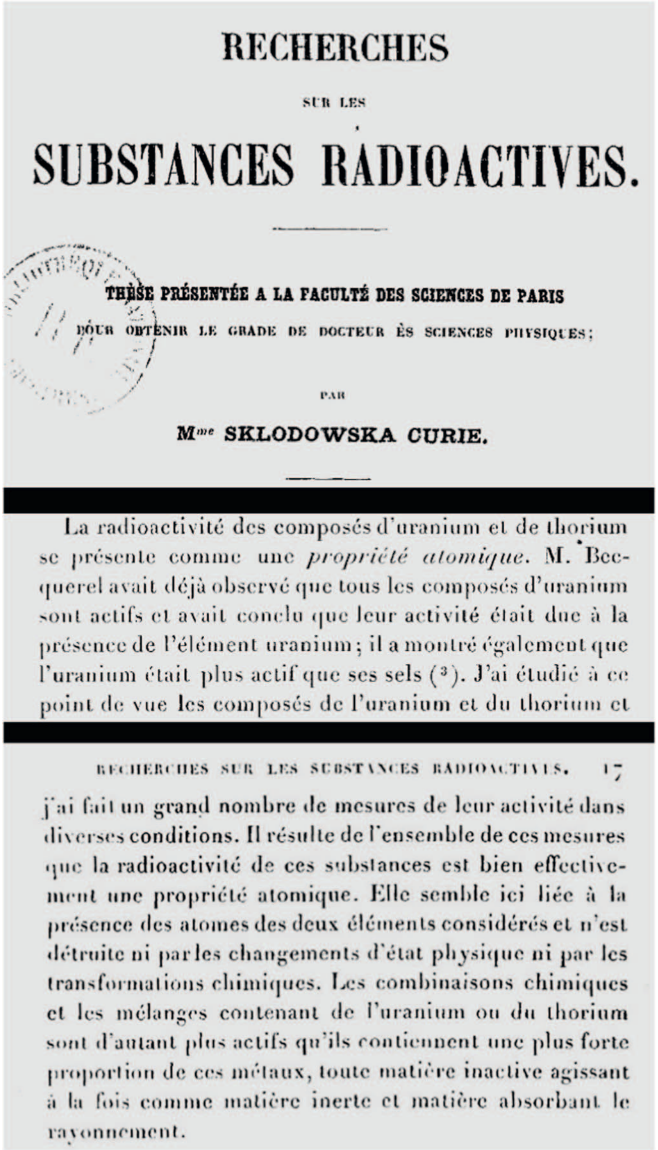
The second implication was non-determinism. Indeed, the experiments revealed that different atoms decay at different times. With no external factors, one had to admit that individual atomistic decays could not be predicted from their causes. So, there was a direct logic link between the atomistic nature of radioactivity and the end of determinism.

Marie Curie did not explicitly present this link in her thesis. And, without a more complete publication, we cannot assess if she initially understood all the implications of her discovery. Later, she forcefully remarked [9] that '*The exponential law has a deep philosophical meaning: it shows that the transformation occurs following the laws of randomness*'.

The 'exponential law' was the time dependence of radioactive emission, the third and final milestone towards non-determinism that corroborated the implications of the atomistic notion. The law was derived by Rutherford and Soddy [5–7, 13, 24] from measurements on the so-called 'emanation', i.e., radon produced by the decay of solid radioactive elements. The corresponding time constant was of the order of days and could thus be handled in practical experiments.

Rutherford and Soddy found that the radioactivity emitted per unit time by a given initial quantity of radon decreases exponentially (figure 7). This implies that the fraction of radon nuclei that transmute per unit time is constant – as statistically expected for decay phenomena occurring *at random* in a population of many micro-components.

With the third milestone, all the pieces of the radioactivity puzzle were fitting together. The decays followed the laws of statistics because of the random, non-deterministic occurrence of individual transmutations, each entirely happening in one atom with no influence of external factors. In Rutherford's words [5]: '*We thus arrive at the conclusion that the configuration of*



RECHERCHES

SUR LES

SUBSTANCES RADIOACTIVES.

THÈSE PRÉSENTÉE A LA FACULTÉ DES SCIENCES DE PARIS

POUR OBTENIR LE GRADE DE DOCTEUR ÈS SCIENCES PHYSIQUES;

PAR

M^{me} SKLODOWSKA CURIE.

La radioactivité des composés d'uranium et de thorium se présente comme une *propriété atomique*. M. Becquerel avait déjà observé que tous les composés d'uranium sont actifs et avait conclu que leur activité était due à la présence de l'élément uranium; il a montré également que l'uranium était plus actif que ses sels (3). J'ai étudié à ce point de vue les composés de l'uranium et du thorium et

RECHERCHES SUR LES SUBSTANCES RADIOACTIVES. 17

j'ai fait un grand nombre de mesures de leur activité dans diverses conditions. Il résulte de l'ensemble de ces mesures que la radioactivité de ces substances est bien effectivement une propriété atomique. Elle semble ici liée à la présence des atomes des deux éléments considérés et n'est détruite ni par les changements d'état physique ni par les transformations chimiques. Les combinaisons chimiques et les mélanges contenant de l'uranium ou du thorium sont d'autant plus actifs qu'ils contiennent une plus forte proportion de ces métaux, toute matière inactive agissant à la fois comme matière inerte et matière absorbant le rayonnement.

Figure 6. Marie Curie's doctoral thesis [10] presents her remarkable discovery that radioactivity is an atomistic phenomenon.

the atom which gives rise to a radiation of energy only occurs in a minute fraction of the atoms present at one time, and is probably governed purely by the laws of probability'.

For the first time in history, a phenomenon could not be predicted with unlimited accuracy because of its intrinsically non-deterministic nature. A revolutionary path was open for science. And, starting in 1925, the 'Copenhagen' interpretation of quantum mechanics put probability and statistics at the center of the knowledge of nature.

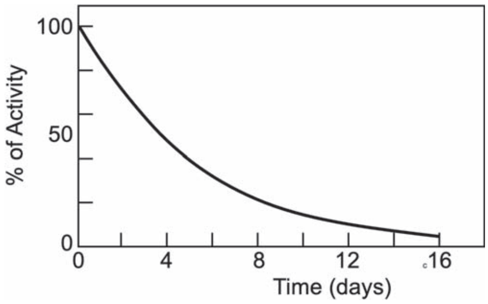


Figure 7. The exponential time dependence of radon radioactivity discovered by Rutherford and Soddy [5, 22].

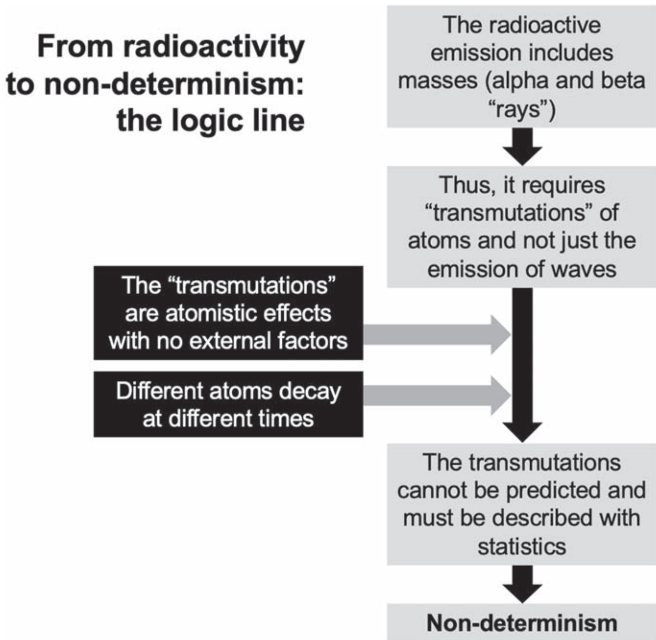


Figure 8. Summary of the logic path of the lectures, from radioactivity to non-determinism.

7. Why marie curie did not advertise her discovery?

The final teaching steps must not dilute the key message about non-determinism but reinforce it. The teacher could present, for example, visible manifestations of randomness in radioactivity. Such as a video showing single-particle detection of low-intensity radioactivity. In which the 'clicks' are not regularly spaced in time but occur, indeed, at random. And the teacher should also point out that the percentage fluctuations of the number of clicks decrease as the number increases, consistent with the principles of statistics.

The lectures could then be wrapped up with a summary of their logic path from radioactivity to non-determinism, shown in figure 8. But I would also suggest adding some fascinating aspects of the Marie Curie personage.

Starting from an intriguing question: why did she not advertise her key theoretical result about the atomistic nature of radioactivity? Even if one assumes that she had not initially grasped all its implications, in the long run a more aggressive presentation would have been justified. Why, then, did she downplay it?

A plausible explanation is prudence. The atomistic nature became dangerous when it was linked to 'transmutations'. Marie could be suspected to flirt with alchemy and see her reputation destroyed.

Rutherford himself was very concerned about this risk [27, 28], so he replaced the term 'transmutation' with 'transformation' [6]. This was a wise precaution: even an eminent scientist like Lord Kelvin vehemently criticized transmutations as alchemy. Prudence was all the more reasonable for Marie Curie, who was at that time only a doctoral student!

These facts can be expanded by describing to the students other difficulties encountered by Marie as a woman, a foreigner and a young person – in addition to her very hard experimental work. They should learn that, contrary to a popular belief, such difficulties did not disappear after she became famous because of radium. She was still viewed by many as a foreigner lacking the 'traditional French values' championed by conservatives. And was the victim of brutal attacks of sexist, xenophobic and even racist nature, by trash fascist tabloids like '*Action française*' and '*La libre parole*'.

But she courageously fought back, becoming an inspiration for the young generations.

Acknowledgments

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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