

LISE MEITNER,  $\beta$ -DECAY AND NON-RADIATIVE ELECTROMAGNETIC  
TRANSITIONS

by

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The current activities in detecting neutrinos as carriers of information from far out in our Universe prompt us to look back on the research activities a century ago that led to the discovery of these weakly interacting particles. One of the leading researchers was Lise Meitner, who observed electrons with well-defined energy, besides the continuous energy spectrum emitted in  $\beta$  decay. These *electron lines* are well understood as radiationless nuclear transitions competing with  $\gamma$ -ray emission. It is proposed to name the electrons resulting out of this so-called *internal conversion* process after Lise Meitner and Charles D. Ellis. The equivalent process within the electronic (atomic) shell is the *Auger effect*, competing with X-ray emission. In this context, the radioactive decay of UX1 or  $^{234}\text{Th}$ , well studied a century ago by Lise Meitner and Charles Ellis, is re-visited, and the mono-energetic electrons are ascribed entirely to the internal conversion process.

**Keywords:** Lise Meitner;  $\beta$  decay;  $^{234}\text{Th}$ ; radiationless electromagnetic transition; internal conversion; Auger effect

## INTRODUCTION

These days, researchers have succeeded in using neutrinos as messenger particles to get information from far out in the Universe, about supernova explosions, black holes, neutron stars etc. Since neutrinos are weakly interacting particles, large instruments are needed as detection systems; one of them is the so-called iceCube in the Antarctic ice.<sup>1</sup> Our present knowledge about the neutrino goes back to the research done almost a century ago, when a puzzling question was worrying the physics world: the energy of the emitted electrons from  $\beta$  decay showed a continuous energy spectrum up to a maximum decay energy. It appeared as if some energy were missing. Could it be that energy is not strictly conserved? The person most deeply involved, who pioneered the research on  $\beta$  decay, was Lise Meitner (figure 1). Therefore, she was addressed and meant in the famous letter that

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<sup>1</sup> See e.g. [https://icecube.wisc.edu/science/highlights/neutrino\\_astronomy](https://icecube.wisc.edu/science/highlights/neutrino_astronomy).

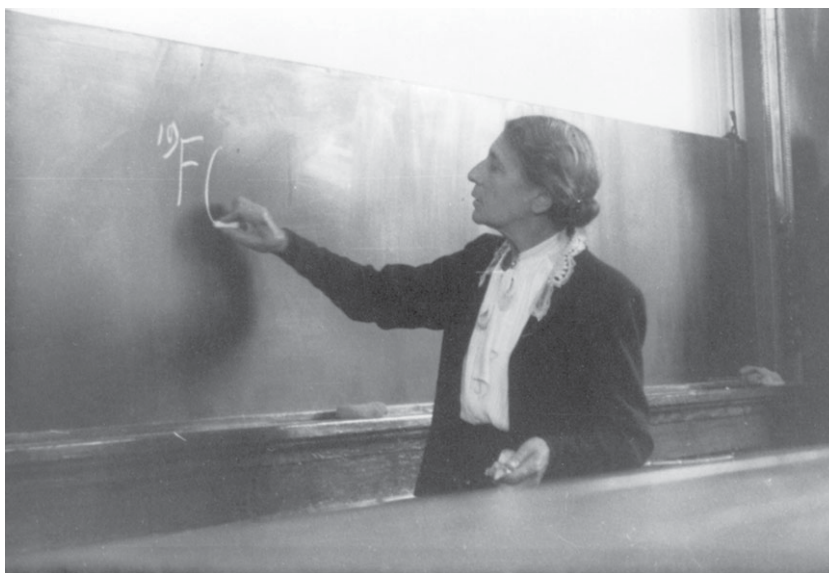


Figure 1. Lise Meitner lecturing in Bonn 1949 (photo: Hans-Hermann Meurers, Koblenz, © Max-Planck-Gesellschaft, Berlin-Dahlem).

Wolfgang Pauli wrote to the participants at a conference held in Tübingen in 1930, in which he proposed the solution of the two major puzzles in understanding  $\beta$  decay, the conservation of energy and the statistics of the nucleus: a new particle, later called the ‘neutrino’, accompanying the electron emission in  $\beta$  decay (‘Liebe Radioaktive Damen und Herren’).<sup>2</sup>

In the years prior to Pauli’s solution, Lise Meitner was one of the key figures in studying  $\beta$  decay by measuring electrons with magnetic spectrometers (as the instruments would be called today). She observed the continuous energy spectra of the emitted electrons in nuclear decays; in contrast to what was seen in the case of  $\alpha$  decays, and in some other instances, she also observed mono-energetic electrons, *electron lines*, superimposed on the continuous spectrum, which she could explain as resulting from electromagnetic transitions within the nucleus, i.e.  $\gamma$  decays or photon emission, finally leading to electron emission from the atom with well-defined kinetic energies. With this research, often in close cooperation with Otto Hahn, who frequently carried out the chemical separation of various radioactive elements, she was in disagreement with Charles D. Ellis in Cambridge (figure 2). They argued about the question of what comes first in the decay—the elemental transformation by the emission of electrons, then followed by a  $\gamma$  decay—or *vice versa*. In addition, Lise Meitner tried to understand from where such electrons are actually ejected: from the nucleus (via a process today called *internal conversion*), or from the atomic (electronic) shells.

In those days, at the beginning of the 1920s, the photo-effect as explained by Albert Einstein<sup>3</sup> was generally understood and accepted, so that the study of  $\gamma$  rays could

2 Sources: cds.cern.ch/record/83282/files/meitner\_0393.pdf and Wolfgang Pauli, *Wissenschaftlicher Briefwechsel mit Bohr, Einstein, Heisenberg u.a./Scientific Correspondence with Bohr, Einstein, Heisenberg a.o.*, ? vols (Springer, Berlin and Heidelberg, 1985), vol. II (ed. K. Meyenn), vol. II, 1930–1939, (Springer, Berlin and Heidelberg, 1985).

3 A. Einstein, *Ann. Phys.* 322 132–148 (1905).



Figure 2. Charles Drummond Ellis, Trinity College Cambridge.

be performed indirectly using different metal foils as absorbers to distinguish them from the emitted electrons of  $\beta$  decay. These experimental procedures prompted Lise Meitner to develop a model anticipating that electrons could be ejected from the electronic shells of the atom instead of X rays, an explanation later experimentally observed by Pierre Auger<sup>4</sup> (figure 3). Lise Meitner proposed this process first in 1922 when describing experiments on the  $\beta$  decay of Th B.<sup>5</sup> In a later publication (1923), she actually interpreted the electrons that she had detected as resulting from transitions within the electronic shells.<sup>6</sup> Both publications are often used as arguments to ascribe the discovery of what is today called the *Auger effect* to Lise Meitner, and to suggest the renaming of this effect as the ‘Meitner–Auger effect’, or something similar,<sup>7</sup> and most recently.<sup>8</sup>

In the following, this issue will be revisited, and the arguments will be reanalysed. Finally, it will be concluded that there is no strong argument for renaming the Auger effect. However, it is suggested that the electrons emitted as the result of internal conversion, a radiationless alternative to the emission of  $\gamma$  rays (from the nucleus), similar to the process in atomic physics with the emission of electrons as an alternative to X-ray emission (fluorescence), be termed *Meitner–Ellis* electrons instead of ‘conversion electrons’.

4 P. Auger, *J. Phys. Radium* **6**, 205–208 (1925).

5 L. Meitner, *Z. Phys.* **9**, 145–152 (1922).

6 L. Meitner, *Z. Phys.* **17**, 54–66 (1923).

7 R. Sietmann, *Phys. Bull.* **39**, 316–317 (1988); O. H. Duparc, *Int. J. Mat. Res.* **100**, 1162–1166 (2009); R. L. Sime, *Lise Meitner, a life in physics* (University of California Press, Berkeley, 1996), p. 91.

8 D. Matsakis, A. Coster, B. Laster and R. Sime, *Phys. Today* **72**, 10–11 (2019).

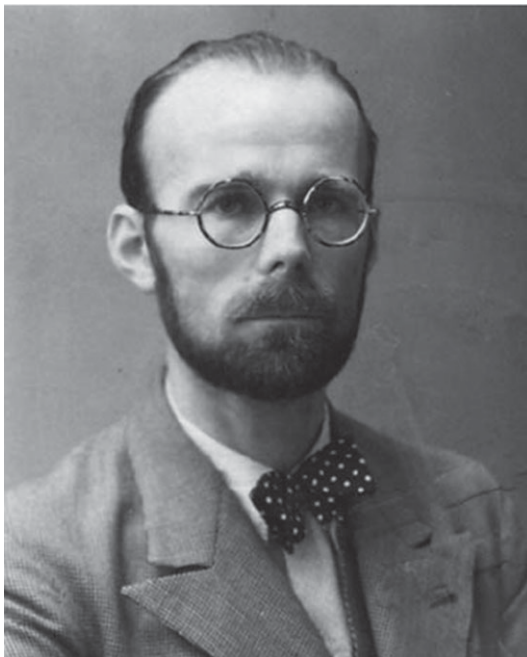


Figure 3. Pierre Victor Auger. Courtesy of the French Academy of Sciences, Institut de France.

#### ELECTRON SPECTROMETRY—ELECTRON LINES IN THE $\beta$ -RAY SPECTRUM

Most of the research on  $\beta$  decay performed and published by Lise Meitner in the early 1920s deals with the question of the origin of the  $\beta$  rays and the connection and relation between  $\beta$  and  $\gamma$  rays, as one of her early publications on those results was titled.<sup>9</sup> The radioactive sources studied were Ra D (i.e.  $^{210}\text{Pb}$ ), Th B (i.e.  $^{212}\text{Pb}$ ) and Th X (i.e.  $^{224}\text{Ra}$  in equilibrium with  $^{212}\text{Pb}$ ), among others. Lise Meitner carefully determined the energy of the electrons detected, assigning their relativistic velocity  $v$  as a fraction  $\beta$  of the speed of light  $c$  to the observed lines. From her interpretation that the electrons are released from the electronic shells of the same atom as a result of the photo-effect by energetic photons, i.e. the  $\gamma$  rays originating from transitions within the nucleus, she could then calculate the initial energy of the  $\gamma$  ray by taking into account the known binding energies of the ejected electrons. Equation (1) gives the relation between the velocity ratio  $\beta$  and the total energy  $E$  of the electrons:

$$\beta^2 = (v/c)^2 = 1 - (m_e c^2/E)^2 \quad \text{or} \quad E = m_e c^2 (1 - \beta^2)^{-1/2}, \quad (1)$$

where  $v$  is the velocity of the ejected electron and  $m_e$  is its rest mass; the total energy  $E$  equals the sum of the rest mass energy and the kinetic energy of the electron (eq. 1 according to A. Einstein's special relativity theory).<sup>10</sup>

<sup>9</sup> Meitner, *op. cit.* (note 5)

<sup>10</sup> A. Einstein, *Ann. Phys.* **322**, 891–921 (1905).

Interpreting the kinetic energy of the electron as the energy transferred from the  $\gamma$  transition to the bound electron of the respective atomic shell, then from equation (2), the  $\gamma$ -ray transition energy  $E_\gamma$  is obtained:

$$E_{cx} = E_\gamma - E_{\text{binding energy}}, \quad (2)$$

where the index c denotes ‘conversion’ and x labels the electronic shell (e.g. K shell, L shell, etc).

While Meitner typically gave the relative velocity values  $\beta$  for the electron lines as derived from the measured deflection in the magnetic field, Ellis went on to calculate the energy of the measured electrons (Eq. 1). In table 1, the major electron lines are presented, with the adopted transition energies as compiled in the *Table of isotopes*.<sup>11</sup> Using the known electron binding energies,<sup>12</sup> the energies of the conversion electrons and their relative velocities are calculated.

Although our table does not present all the lines known today in these decays, it is evident that they are all well understood as the conversion lines of electromagnetic transitions within the nucleus. Meitner and Ellis interpreted the process of conversion as a two-step process: first, a  $\gamma$  transition takes place, and then the emitted photon ejects an electron from the atom’s shells via the photo-effect if the  $\gamma$  energy is sufficient to overcome the electron’s binding energy. And the  $\gamma$  transition was considered a process of rearrangement within the nucleus. It was also not clear to these two pioneers, and heavily disputed between them,  $\beta$  whether nuclear beta decay precedes  $\gamma$  transition or *vice versa*. Finally, all attempts to understand their findings have to be viewed taking into account that the reason for the continuous energy spectrum of the  $\beta$  particles was still not known, and the neutrino had not yet been proposed. With the development and understanding of quantum electrodynamics, where the charges and currents within a nucleus can couple to the charges and currents in the electronic shells, especially for electrons with finite occupation probabilities within the nucleus, the internal conversion process is described as a radiationless process alternative to photon emission. An experimental proof for that is the occurrence of internal conversion for nuclear transitions between two states with zero angular momentum ( $0^+ \rightarrow 0^+$  transitions), which transitions are forbidden for photons, but allowed by internal conversion.

As a consequence of the internal conversion, characteristic X rays should also be emitted, and indeed could be observed, as mentioned by Lise Meitner. In the same article, Meitner continues by proposing the analogous process within the electronic shells, which would be the Auger process, as an alternative to X-ray emission.<sup>13</sup> It is this description which is used as the basis for the idea that Lise Meitner had already discovered the origin of the electrons later found and thoroughly described by Pierre Auger, and thus now called ‘Auger electrons’.

Based on her data for the case of UX1 (i.e. <sup>234</sup>Th, included in table 1), this description of the process occurring in the electronic shells is again suggested in another paper.<sup>14</sup> However,

11 C. M. Lederer, J. M. Hollander, I. Perlman, *Table of isotopes*, 6th edn (J. Wiley & Sons, New York, 1968).

12 *Ibid*; from Table 11 in Appendix III, p. 569.

13 Meitner, *op. cit.* (note 5), p. 147: ‘...Dadurch wird aber die charakteristische Röntgenstrahlung des Atoms angeregt, die natürlich auch ihrerseits wieder Elektronen aus niedrigen Energieniveaus herauswerfen kann’. Translated: ‘Due to this process (i.e. the ejection of an electron), the characteristic X-rays are excited, which, naturally, can in turn eject electrons from less strongly-bound levels as well’.

14 Meitner, *op. cit.* (note 6), p. 61.

Table 1. The most intense internal conversion lines observed in the  $\beta$ -ray spectra studied. In the column 'Ref.' the references are given for the  $\beta$  values in the previous column.

Isotope (historic name)	Isotope	$\gamma$ transition (keV) <sup>a</sup>	$E_{\text{K}}$ (keV)	$\beta$ ( $\nu/\epsilon$ )	$E_{\text{L1}}$ (keV)	$\beta$ ( $\nu/\epsilon$ )	$E_{\text{CM}}$ (keV)	$\beta$ ( $\nu/\epsilon$ )	Element of conversion	$\beta$ (%)	Ref.
<b>Th B</b>	<b>Pb-212</b>	238,6	148,1	0,632	222,2	0,717			Bi	63; 72,3	b
		300,1	209,5	0,705	283,7	0,766			Bi	71,4	b
<b>Ra D</b>	<b>Pb-210</b>	46,5			30,1	0,329	42,5	0,384	Bi	34; 40	b
<b>Radiothor</b>	<b>Th-228</b>	84,4			65,9	0,464	79,6	0,501	Ra	47; 51	b
<b>Ra B</b>	<b>Pb-214</b>	352,0	261,5	0,750	335,6	0,797			Bi		c
		295,2	204,7	0,700	278,8	0,762			Bi		c
<b>Ra C</b>	<b>Bi-214</b>	609,4	515,8	0,867	592,5	0,886			Po	high	d
<b>Radium</b>	<b>Ra-226</b>	185,7	87,3	0,520	167,7	0,658			Rn	52; 65	b
<b>UX<sub>1</sub></b>	<b>Th-234</b>	93,1/93,5			72,0/72,4	0,482	87,7/88,1	0,522	Pa	48; 52	e
		63,2/63,6			42,1/42,5	0,383	57,8/58,2	0,440	Pa		
		29,9			8,8	0,183	24,5	0,300	Pa		

a. The  $\gamma$ -transition energies are taken from Table II in Lederer, *op. cit.* (note 11).

b. L. Meitner, *Z. Phys.* **9**, 131–144 (1922).

c. C. D. Ellis and H. W. B. Skinner, *Proc. R. Soc. Lond. A* **105**, 165–184 (1924); *op. cit.* (note 16).

d. Meitner, *op. cit.* (note 5)

e. Meitner, *op. cit.* (note 6)

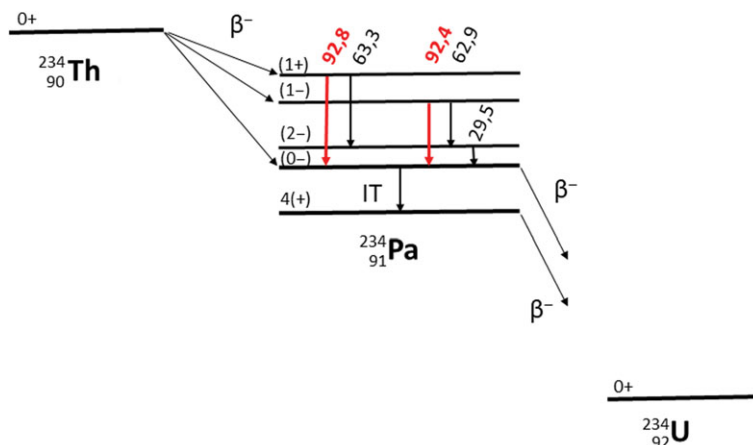


Figure 4. Simplified decay scheme of  $^{234}\text{Th}$  and energy level scheme of the product nucleus  $^{234}\text{Pa}$ . The two relevant  $\gamma$  transitions close in energy and very similar to the K-X-ray lines in thorium are shown in red (transition energies, rounded values, are given in keV). (Online version in colour.)

she was misled by an unfortunate coincidence, as will be discussed more thoroughly in the next section.

#### THE DECAY OF $^{234}\text{Th}$

One of the typical radioactive sources studied in the early 1920s is UX1 or  $^{234}\text{Th}$ . Its  $\beta$  decay has rather low energy, and the following  $\gamma$  transitions are also of low energies. What really could be called an unfortunate coincidence (or ‘bad luck’) is the almost identical energy of one, or even two nuclear transitions between the excited levels in the  $^{234}\text{Pa}$  product nucleus, as compared with the characteristic X-ray energies of Th or Pa, respectively. Figure 4 shows a simplified decay scheme, including the energy levels of  $^{234}\text{Pa}$ , preceded by its  $\beta$ -decay precursor  $^{234}\text{Th}$ , and followed by the decay into  $^{234}\text{U}$ . Two  $\gamma$  transitions are highlighted in red, at 92.4 and 92.8 keV, which are very close to the K X-ray lines of Th,  $K_{\alpha 1} = 93.4$  and  $K_{\alpha 2} = 90.0$  keV (rounded values; for the actual values see [16]). This seems to be the key point in the debate about the ‘naming of the Auger effect’.

The development of high-resolution  $\gamma$ -ray detectors based on Ge(Li) semiconductor technology has allowed high-precision measurements of  $\gamma$ -ray transition energies. Thus, T. E. Sampson and J. Godart and A. Gizon were able to clearly establish the origin of the ‘92’ keV line,<sup>15</sup> namely two  $\gamma$  transitions, i.e. *nuclear* transitions, very close in energy, and very similar in energy to the K-X-ray transitions, i.e. *atomic* transitions, in thorium. Godart and Gizon additionally determined the various internal conversion lines. Their diligently measured spectra led to the now-adopted decay scheme of  $^{234}\text{Th}$  as shown in Figure 4 in a simplified version.

Here, it should be mentioned that Charles Ellis, had already in his publication ‘The interpretation of  $\beta$  ray spectra’,<sup>16</sup> pointed out some problems with the mechanism proposed

15 T. E. Sampson, *Nucl. Instr. Methods* **111**, 209–211 (1973); J. Godart and A. Gizon, *Nucl. Phys. A* **217**, 159–176 (1973).

16 C. D. Ellis and H. W. B. Skinner, *Proc. R. Soc. Lond. A* **105**, 185–198 (1924).

by Lise Meitner, claiming that the energy resolution should have been sufficiently high to detect the well-separated  $K_{\alpha 1}$  and  $K_{\alpha 2}$  X-ray lines (via the electron lines). That Ellis, jointly with Skinner, was right, is confirmed in the review on the early work on nuclear  $\beta$  decay by Carsten Jensen, who summarized the different interpretation in the words: ‘Meitner was led astray by this coincidence in energies..’<sup>17</sup>

Therefore, it is now definitely clear that the electrons observed as electron lines in the  $\beta$ -decay spectrum of  $^{234}\text{Th}$  are internal conversion electrons, resulting from electromagnetic transitions between excited levels in the  $^{234}\text{Pa}$  product nucleus following the  $\beta$  decay of its parent  $^{234}\text{Th}$ . These conversion electrons are the result of the interaction (*electromagnetic interaction*) between the nucleus and the electrons in the atomic shell, an interplay between nuclear physics and atomic physics. This conversion process is an alternative decay mode to the emission of electromagnetic radiation, which in the case of a nuclear transition is called  $\gamma$  transition or  $\gamma$  radiation, independent of the energy of this radiation.

#### CONCLUSION AND RECOMMENDATION

While Lise Meitner presented a diligent description, in her publication on the investigation of UX1, of how electrons could be emitted in radiationless transitions within the *atomic* shells (later called Auger electrons) as an alternative to X-ray emission when filling a vacancy in an inner electronic shell, she did not actually observe such electrons in any of her careful studies of  $\beta$  decay. Instead, superimposed on the continuous spectrum of electrons originating from *nuclear*  $\beta$  decay, she did observe electrons with well-defined energies, i.e. electron lines, which she correctly explained as the result of  $\gamma$  transitions within the nucleus. At that time, this effect was understood as a two-step process (‘inner photo-effect’). It is now correctly interpreted as the radiationless variant of the electromagnetic interaction within the nucleus, interacting with the surrounding charges (electrons) of the atom, leading either to the emission of  $\gamma$  radiation or to the ejection of electrons out of the atomic shells. This ejection of an electron as the result of the so-called internal conversion process thus creates a vacancy in an inner electronic shell.

Evidently, there is no experimental basis for the assumption that Lise Meitner had already observed ‘Auger electrons’ prior to Pierre Auger doing so [4]. She only formulated a model description, a ‘theoretical’ prediction; she lacked the experimental proof.

However, owing to the numerous electron lines observed in radioactive decays of quite a few radioisotopes that she and Charles Ellis independently found and interpreted as ‘ $\gamma$  transitions’, today better known as (internal) conversion electrons, it is very appropriate to give those conversion electrons a personalized name as well, in recognition of the achievements of Meitner and Ellis in understanding both  $\beta$  and  $\gamma$  decay in nuclei: *Meitner–Ellis electrons*.

Such a naming would express a great appreciation of the pioneering work of Lise Meitner and Charles Ellis in developing our basic understanding of our subatomic world and the fundamentals such as the law of energy conservation behind the forces acting even on subatomic scales.

<sup>17</sup> C. Jensen, *Controversy and consensus. Nuclear beta decay, 1911/1934*, (Birkhäuser, Basel, Boston and Berlin, 2000); quote from p. 98.

Finally, it should be noted that internal conversion electrons continue to play a key role in nuclear spectroscopy. When the theory of the process was developed,<sup>18</sup> the determination of the relative probabilities of electron versus photon emission, i.e. the conversion coefficients, and especially their ratios (K to L, or in detail, LI, LII, LIII), turned out to be a useful tool for determining the multipolarities of electromagnetic transitions and therefore nuclear spins and parities of the nuclear levels involved. In this way, nuclear level schemes were established, leading to the development of nuclear models to understand the underlying nuclear structure. Additionally, while the Auger effect plays a role today in standard surface characterizations, conversion-electron Mössbauer spectroscopy is also a specialized tool for studying surfaces and thin-layer structures.

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<sup>18</sup> M. E. Rose, 'Theory of internal conversion', in *Alpha-, beta-, and gamma-ray spectroscopy* (ed. K. Siegbahn), pp. 887–903 (North Holland Publishing Company, Amsterdam, 1968).