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## Part II: Terminology in Nuclear Processes—Misconceptions and Inaccuracies\*

*by Mauro L. Bonardi and David S. Moore*

There are few subjects that evoke a stronger response from most people than those associated with nuclear processes. The "power" of nuclear processes is not only  $E=mc^2$ , but also rhetoric, saber rattling, threats, fear, anguish, and horror. We wonder how much of the vehemence of such a response could be attributed to misunderstandings based on inaccurate and misleading terminology.

For example, using the terminology *atomic* energy to describe the energy produced by *nuclear* processes like



fission is misleading, even if, unfortunately, it continues to belong to common language (e.g., peaceful uses of atomic energy, atomic bomb, atomic explosion, atomic reactor, Euratom, International "Atomic" Energy Agency, and so on). The IUPAC Gold Book, as well as Chapter 16 of the Orange Book, makes this distinction very clear. Terms that have to do with nuclear processes do not include the word "atomic" and vice versa. Similar misunderstandings accompany the use of the terminology "radiopharmaceutical" to designated labelled species for biomedical purposes (radiodiagnostic and metabolic radiotherapy), because no pharmacological effects are expected due to the negligible amounts of substance administered. Indeed, to be used in humans, a labelled compound must undergo a series of analytical and radioanalytical GLP and GMP investigations that are well described in the relevant literature (*National and International Pharmacopeia*).

This article seeks to describe the current situation and provide an understanding of preferred terms.


### Radioanalytical and Nuclear Analytical Techniques vs. Atomic Techniques: How to Avoid Ambiguity?

At the time of their discovery, it was not clear to scientists that the atomic origin of Röntgen's rays (subsequent to *atomic* electron rearrangement) was completely different from that of Becquerel and Curie's rays (subsequent to a *nuclear* decay). As is explained below, today we can formulate an unambiguous distinction among them.

In order to proceed further, some definitions and statements are required. We can classify the field of analytical investigations on the basis of the *chemical-physical origin* of the process in question, rather than in terms of associated energy or time scale. This means roughly dividing the phenomena into *sub-nuclear, nuclear, atomic, molecular, or supra-molecular*. Hence, it is possible to classify the different branches of analytical chemistry and related analytical techniques as *radioanalytical and nuclear* (sometimes called nuclear analytical techniques or NATs) on one side and *atomic/molecular* on the other. However, no sub-nuclear processes are presently used on a routine basis for radioanalytical purposes. Therefore, the nuclear processes that are applied in nuclear and radiochemistry (N&R), and through related radioanalytical techniques, only involve the excitation or de-excitation of *nuclear* levels and not *atomic* or *molecular* levels, which are *subsequent* to spontaneous (radioactive decay) or induced nuclear reactions (either manmade or natural). Often, these nuclear processes are *followed* at different time scales by significant atomic and molecular modifications, fruitfully adopted as probes for analytical and structural investigations.<sup>1-5</sup>

In most cases, the processes concerning nuclear transition or transmutation involve much larger amounts of energy (several keV to many MeV or more, [i.e.,  $1 \text{ eV} = 1.60218 \cdot 10^{-13} \text{ J}$  or  $96 \cdot 485 \text{ J}\cdot\text{mol}^{-1}$ ]) than atomic and molecular processes (less than a few eV) and the *radiation* (both electromagnetic and corpuscular) associated with these processes is, as a rule, classified as "directly ionizing radiation," like X-rays or fast electron/charged-particle/heavy ion beams accelerated in high-energy acceleration devices (betatrons, Van de Graff, cyclotrons, synchrotrons, LINAC). These types of radiation must be distinguished from radiation that does not have sufficient energy for the *direct* ionization or excitation of the irradiated material or entity. As a useful figure, 30 eV is the average energy that is necessary to induce formation of an ionization/excitation entity in a material, compared to the first ionization energy of He (25 eV), the energy of Group 1 and 2 elements (4–9 eV), and the energy gap of TiO<sub>2</sub> photocatalyst (3.2 eV for anatase). This means that radiations from processes less energetic than UV light (less than a few eV) are not able to induce directly these phenomena and consequently are usually classified as "non-ionizing" radiation or simply by a term or abbreviation implying their energy range (NIR, UV, visible, IR, microwaves, radiowaves, cosmic background, etc.).

We believe the more correct approach to classifying the processes involved is not to describe the associated energy or the time scale, but the physical origin of the process itself. In fact, gamma rays originate from the decay (de-excitation) of nuclear levels in spite of the energy involved, while X rays originate from electronic rearrangements at the atomic levels. From the time-scale viewpoint, plenty of metastable nuclear levels are known and profitably used (radioisomers), with half-lives from fractions of seconds to many years.<sup>6,7</sup> On the basis of this simple classification it is possible to distinguish without any ambiguity between nuclear and atomic/molecular processes, even in the cases in which nuclear and atomic phenomena affect each other and cause significant chemical-physical effects on the chemical environment.



Surprisingly, the half-life of a radionuclide can be influenced by the atomic-electronic environment, especially if decay modes like electron capture or internal conversion on the innermost atomic shells are involved, because the decay probability of a radionuclide depends on the overlap between the nuclear and atomic wave functions. Unexpectedly, the half-life of metastable levels of nuclides is also affected by the chemical surroundings of the nuclides. The *hyperfine interaction* between nuclear levels and the *chemical microenvironment (chemical isomer shift)* is the basis of *Mössbauer spectroscopy* (MÖSSPEC, MOSPEC), a powerful radioanalytical tool for structural and analytical purposes. The interaction of decay emitted positrons, and the *positronium* quasi-atomic species Ps formed by binding with atomic electrons, is affected by the chemical environment as well, giving rise to *positron annihilation spectroscopy* (PAS) and related radioanalytical techniques. On the other hand, other exotic quasi-atomic species like *muonium* and *antiatoms* have resulted to date in negligible analytical potentialities. These electronic effects following nuclear decay or nuclear reactions are, of course, not of direct nuclear origin and are normally called *extra-nuclear* or *atomic effects of nuclear transformations*. Among such effects are the emission of X-rays and Auger (and Coster-Kronig) monoenergetic electronic cascades after the rearrangement of electronic shells that occurs before most nuclear decay processes that are able to create electronic vacancies in the innermost atomic shells. Even *Bremsstrahlung* radiation (external and internal) generated by the deceleration/centripetal acceleration of fast particles through matter and Cherenkov shockwave visible radiation are not precisely of nuclear origin, but must be classified as atomic effects subsequent to a nuclear process.

In this framework, X rays and the X-ray based analytical techniques for chemical analysis in the energy range from some keV to some hundreds of keV have proved incapable of inducing nuclear processes. Let's remember that the binding energy of an alpha particle at rest is 28.3 MeV (or 7 MeV.nucleon<sup>-1</sup>), and the binding energy per nucleon of the 2 850 nuclides presently known varies from 2.2 MeV for the less stable, like <sup>2</sup>H, to 8.8 MeV for the more stable: Fe, Co, and Ni. Hence, analytical techniques based on the use of fast ion or electron beams with energy insufficient to induce nuclear reactions are normally called Ion Beam Analytical (IBA) techniques and are not nuclear techniques at all. Among them are PIXE, RBS, and a range of techniques based on the use of synchrotron radiation, even in the X-ray energy range (SRXRF, EXAFS, XANES).<sup>1</sup> Thus, elemental analysis techniques based on X-ray fluorescence, like XRF, TXRF, or ED-XRF, are not of nuclear origin, even if they are based on the use of radiogenic equipment or radioactive sources as excitation devices, which are incidentally installed at nuclear centers. Conversely, nuclear activation methods, like delayed and prompt neutron and charged particle *activation analysis*—in both instrumental or radiochemical versions, are properly classified as nuclear analytical techniques, because, in spite of the occasional low-energy projectile involved, they lead to a nuclear reaction on target nuclei, with delayed or prompt emission of de-excitation gamma rays or fast particles of nuclear origin (nucleons or clusters of nucleons). Further, due to their nature as neutral particles, neutrons can induce nuclear reaction even at the most

probable thermal energy of only 0.025 eV (i.e.,  $\langle E \rangle = \frac{1}{2} m_n v^2 = k.T$ ).

As a final comment, it is known that some nuclear levels have energies well below the typical energies of X rays of atomic origin: In this framework, the discovery of a nuclear level at 3.5 eV of the radioisomer  $^{229m}\text{Th}$  led to the invention of the term "nuclear light" to stress the evidence that the energy of this nuclear phenomenon is of the same order of magnitude of typical UV radiation. Later on, the nuclear metastable level at 14 keV of stable nuclide  $^{57}\text{Fe}$ , successfully used in MOSPEC for radioanalytical purposes, lies well below the atomic X-ray energy range of heavier elements, which are easily—even roughly—predictable by Moseley's equation, confirming the conclusion that the classification of these phenomena on the energy scale is quite misleading.

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\*[Part I](#) focused on the role of radionuclides and radiochemistry in society (Nov-Dec 2007 Cf).