APPENDIX

CROSS SECTIONS AND YIELDS: DEFINITIONS

The terms cross section and yield, widely used in practical radioisotope production, often differ from basic definitions used in nuclear reactions theory. Different application oriented groups use these terms in a non-standard way. In order to avoid misinterpretation of the data in the present database we briefly summarize definitions of the most important quantities describing nuclear reactions in the field of practical radioisotope production and activation technology.

Production cross section

When an accelerated charged particle interacts with a target nucleus a nuclear reaction takes place, ultimately leading to a stable or radioactive product nucleus. A nuclear reaction is characterized by a cross section, a geometrical quantity given in barn ($10^{-24}cm^2$), describing a probability that a particle, with a beam intensity of 1 particle per 1 cm^2, incident on 1 target nucleus will lead to a specific physical process, where the incident particle, target nucleus, reaction channel and the final nucleus are exactly specified.

In isotope production and application of monitor reactions, usually the activity of the product radioisotope is measured. The related quantity of interest is then the integral cross section or the production cross section. It refers to a sum of cross sections of all reaction channels on a well-defined target nucleus, which lead to direct production of the final nuclide. The same final nuclide can also be produced indirectly via the decay of progenitors produced simultaneously on the target nucleus. In many cases the separation of direct and indirect routes becomes unimportant and one uses the cumulative production cross section to describe these two routes together. This becomes even more complicated when one uses a natural multi-isotopic target element where different reaction channels on different target nuclei can contribute to the production of the same final radioisotope. In this case one uses the elemental production cross section to describe all production routes together. It should be noted that in doing so one must properly calculate the number of target nuclei, by summing nuclei of all contributing target isotopes. If one considers also indirect production routes, the elemental cumulative production cross section should be used. Similarly, the notation isotopic production cross section is used to describe reactions with mono-isotopic target elements.

The present document aims to address the needs of every day practice, where one uses elemental targets that are generally multi-isotopic and sometimes mono-isotopic. Throughout this document we consistently use the term cross section. For beam monitor reactions, this term means cumulative elemental production or cumulative isotopic production cross section of the final nuclide. For medical radioisotope production, this term means elemental production or isotopic production cross section of the final nuclide.

Production yield

A thin target has a thickness so small that the reaction cross section can be considered as constant through the whole target. This is equivalent to the energy loss being negligible when compared to the energy range needed to see significant changes in the reaction cross section. A thick target has its thickness comparable or larger than the range of the incident particle in the target material.

The yield for a target having any thickness can be defined as the ratio of the number of nuclei formed in the nuclear reaction to the number of particles incident on the target. It is termed as the physical yield, Y. It is customary to express the number of radioactive nuclei in terms of the activity, and the number of incident particles in terms of the charge. Thus, Y can be given as activity per Coulomb, in units of GBq/C. The analytical meaning of the physical yield is the slope (at the beginning of the irradiation) of the curve of the growing activity of the produced radionuclide versus irradiation time.

Radioisotopes disintegrate during the bombardment, therefore for practical applications other yield definitions are used taking into account this effect. The activity at the end of a bombardment performed at a constant 1μA beam current on a target during 1 hour is closely related to the measured activity in every day isotope production by accelerators, the so called 1h-1μA yield, A_1. In practice, this latter quantity can be used when the bombardment time is significantly shorter than or comparable with the half-life of the produced isotope.

When the irradiation time is much longer than the half-life of the produced isotope, a saturation of the number of the radioactive nuclei present in the target is reached, and their activity becomes practically independent of the bombardment time (at a constant beam current). This activity produced by a unit number of incident beam particles is the so-called saturation yield, A_2.

There are close relationships between the above mentioned yields. Using the decay constant of the radionuclide λ and the irradiation time t one gets

$$Y = A_1 \frac{\lambda}{1-e^{-\lambda t}} = A_2 \lambda .$$

Several other definitions are often used. Differential or thin target yield is defined for negligibly small (unit) energy loss of the incident beam in the thin target material. Thick target yield is defined for a fixed macroscopic energy loss, E_{in}-E_{out}, in a thick target. Integral yield is defined for a finite energy loss down to the threshold of the reaction, E_{in}-E_{th}. The thin target yield is easily related to the reaction cross section and the stopping power of the target material for the beam considered, see Bonardi [1].

For medical radioisotope production, the three above mentioned yield quantities were calculated, namely the physical yield Y, activity in 1 hour activation with 1 μA intensity beam A_1, and saturation activity in 1 μA irradiation A_2. To this end, recommended cross sections discussed in the present document were used. In addition, the target stopping powers of Ziegler [2, 3] and Andersen and Ziegler [4] and nuclear decay data of Browne and Firestone [5] were used. In the tables and figures we give physical yields Y in 0.5 MeV or 1 MeV energy steps, except for cases where only cumulative cross sections are known. In those cases only saturation yields are given.

The yield for any target thickness, Y_{thick} can be obtained from the simple formula

$$Y_{thick}(E_{in}\text{-}E_{out}) = Y(E_{in})\text{-}Y(E_{out}),$$

where E_{in} is the incident particle energy and E_{out} is its outgoing energy. For a more detailed discussion and for practical calculations we refer to the extensive list of references in the literature (cf. Bonardi [1] and Dmitriev [6]).

Remark:

For radioisotopes formed via contributions from various nuclear decay processes, the yield and activities were calculated from the total production cross sections (i.e. cross sections measured after total decay of possible isomeric states and/or parent nuclei). Actual production yields can be deduced from the data given in the tables only after the complete decay of isomeric states and/or parent nuclei (cf. ^{81}Rb, ^{111}In, ^{123}Cs, ^{201}Pb).

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