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Monte Carlo Method for Simulating a Technique for Measuring the Proton Beam Energy from a Commercial Cyclotron

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1. Introduction

Cyclotrons have prepared various radioisotopes that can be applied in single photon emission computed tomography (SPECT) or positron emission tomography (PET). Therefore, the production of radiopharmaceuticals using radioisotopes produced in cyclotrons has been an area of great global demand today.

Most radioisotopes used in PET scans can be obtained in large quantities in cyclotrons with a relatively small energy range, between 9 and 19 MeV. The quantity and quality of radioisotopes a cyclotron produces are closely related to the correct beam energy. For this reason, in commercial installations, it is essential that the beam energy is regularly measured and calibrated [1].

To accurately determine the kinetic energy of a beam of electrically charged particles, several techniques have been developed and presented [2,3,4,5]. This work presents a study using the Monte Carlo Method, a relatively simple technique for determining the kinetic energy of a proton beam from a commercial cyclotron in the range from 15 to 18 MeV.

2. Methodology

Most techniques used to measure the energy of a proton beam accurately require high-resolution gamma spectrometry, which requires time and expensive equipment (an HPGe detector, for example) not available in most radioisotope-producing centers.

Irradiation of a single thin foil of a given element with protons over a known time interval can produce one or more radioisotopes, depending on the isotopic purity of the foil. For a specific radioisotope “j”, the activity (A_j) can be calculated, in principle, by the following expression:[4]

$$A_j = N\, I\, \sigma_j\, x \left(1 - e^{-\lambda_j t}\right) \tag{1}$$

Where A_j is the activity (Bq) of radioisotope "j"; N is the density of atoms in the target ($1/cm^3$); I the proton flux (1/sec) that reaches the target; σ_j is the cross-section for the production of radioisotope "j"; x is the thickness (cm) of the target; λ_j is the nuclear decay constant for radioisotope "j"; and t is the irradiation time.

By measuring the activities produced by the same radioisotope “j” in two identical thin foils irradiated simultaneously but with slightly different energies, the energy of the incident beam can be determined relatively quickly, as long as the energy-dependent cross sections are well established. The idea is to irradiate two thin foils, and between them, an energy degrader is positioned so that the second foil is irradiated with lower energy than the first one. Figure 1 illustrates this concept and the geometry that was used in this work.

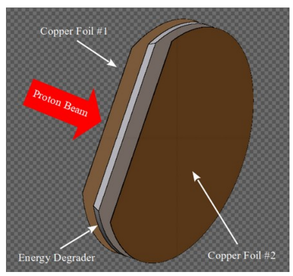

Figure 1: two thin copper foils interspersed by an energy degrader was the geometry used in simulations to determine the energy of a proton beam.

Let $A_{1,j}$ and $A_{2,j}$ be the activities of the radioisotope "j" produced in the thin foils during irradiation, and considering that N, I, x, λ, and t will be practically constant for both cases, equation (1) leads to:

$$\frac{A_{1,j}}{A_{2,j}} = \frac{\sigma_{1,j}}{\sigma_{2,j}} = r \tag{2}$$

In equation (2), $A_{1,j}$ is the activity (Bq) of radioisotope "j" in the first foil (foil #1); $A_{2,j}$ is the activity (Bq) of the same radioisotope in the second foil (foil #2); $\sigma_{1,j}$ is the cross section (mb) for the production of radioisotope "j" in the first foil; and $\sigma_{2,j}$ is the cross section (mb) for the production of the same radioisotope in the second foil.

For the energy range from 15 up to 18 MeV, the nuclear reaction chosen was $^{nat}Cu(p,n)^{63}Zn$ ($T_{1/2}$ = 38.1 min, with β^+ decays and gamma photons of 670, 962 and 1412 keV, respectively), whose excitation function is well known [6], as shown in Figure 2. With the experimental data provided by the International Atomic Energy Agency (IAEA), the ratio "r" that appears in equation (2) can be calculated with standard values of energy, and a function of the type E=E(r) can be written. This function will later be used to determine the beam energy value that caused the thin foils nuclear reactions.

Based on the choice of nuclear reaction, the thin foils were natural copper, whose isotopic composition is 69.15% ^{63}Cu and 30.85% ^{65}Cu, and the material chosen for the energy degrader was aluminum, which has a relatively low cross-section in the range of energy that will be analyzed and also because it does not produce isotopes with a long half-life. A computer program called "*Stop and Range of Ions in Matter*" (SRIM) [7] was used to determine the best thicknesses of the copper foils and the aluminum degrader. For all cases analyzed, the thickness of the copper foils was 25 µm. And, for the thickness of the aluminum degrader, two thicknesses were calculated: 200 µm for energy between 15 and 16.2 MeV and 400 µm for energy between 16.6 and 18 MeV. These choices were based so that the functions E=E(r) were as smooth as possible. Knowing the values of the incident energies on the first copper foil, the value of the cross-section is determined by consulting the experimental data provided by the IAEA. However, after the proton beam passes through the first copper foil and the energy degrader, it will reach the second copper foil with energy, in principle, unknown, and therefore, the value of the cross-section for the production of ^{63}Zn in this foil will also be unknown. This situation is overcome through a simulation using a program based on the Monte Carlo method called FLUKA [8], where a particle flow detector is positioned immediately before the second copper foil. This detector provide information about the energy and the number of protons that reach that position. The geometry and detectors used for these analyses is constructed using another computer program called FLAIR [9]. With the data obtained from the energies of the protons incident on each copper foil and the values of the cross-sections, provided by the IAEA, it is possible to calculate the ratio of the cross-sections and determine the equation E=E(r) through a convenient curve fit, as shown in equation (3) for the interval from 15 up to 16.2 MeV and equation (4) for the interval from 16.6 up to 18 MeV.

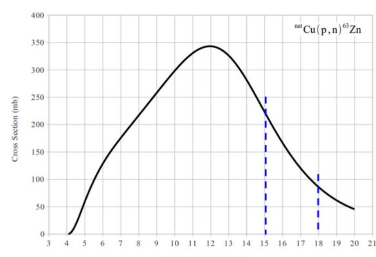

Figure 2: Excitation function for the $^{nat}Cu(p,n)^{63}Zn$ nuclear reaction obtained from experimental data provided by the IAEA.

$$E(r) = 17.66\, r^2 - 36.52\, r + 31.80 \quad (3)$$

$$E(r) = 196.72\, r^2 - 194.34\, r + 64.16 \quad (4)$$

In equations (3) and (4), "r" is the ratio between the cross sections obtained with equation (2).
After obtaining the equations for E=E(r) for the two energy ranges studied, simulations were conducted again using the Monte Carlo method (FLAIR and FLUKA) to determine the ^{63}Zn activities produced in each copper foil. For this purpose and all cases analyzed, the foils plus the energy degrader set was irradiated with a 10 µA proton beam for 300 sec. The activities obtained in the simulations are measured (at EOB) using two volumetric detectors surrounding each foil.

3. Results and Discussion

The results obtained with these simulations are presented in Table I, where the energy values calculated by equations (3) and (4) can also be observed, where the ratio "r" was calculated by the first term on the left in equation (2). The data presented in Table I show that in the range between 15.0 and 16.6 MeV the proposed method appears to be quite satisfactory and can be improved by significantly increasing the number of primaries used in the simulations, bearing in mind that the Monte Carlo method is essentially a statistical method and by increasing the number of possible iterations, the tendency is for errors and discrepancies to decrease. Another way to improve these results would be to reduce the intervals between the energy values analyzed, to 0.2 or 0.1 MeV, making the functions that represent E=E(r) a little smoother concerning the functions obtained in this work. For the interval between 17.0 and 18.0 the energy differences are not satisfactory and this cannot be credited solely to the number of primaries used in the method, other more relevant factors are certainly strongly influencing the results obtained. In the same way as mentioned for the interval between 15.0 and 16.6 MeV, decrease the interval between the analyzed energies, perhaps to 0.1 MeV or less, increase the number of primaries and also increase the thickness of the energy degrader, so that the energy in the foil #2 will be closest to 13.0 MeV where the cross section for ^{63}Zn production is larger.

Table I: Activity values (*EOB*) of ^{63}Zn obtained in simulations with 300 sec irradiation and 10 μA beam current. The simulated energies were calculated using equations (3) and (4) and the ratio "r" of the activities.

Energy (MeV)	Foil #1 Activity (MBq)	ERROR (%)	Foil #2 Activity (MBq)	ERROR (%)	Ratio "r" (A_1/A_2)	ERROR (+/-)	Simul. Energy	ERROR +/- (MeV)	ΔE (MeV)
15.0	128.54	0.86	180.89	0.67	0.71	0.07	14.8	0.8	-0.2
15.4	126.00	0.87	189.06	1.29	0.67	0.08	15.3	1.0	-0.1
15.8	107.56	0.55	185.42	0.54	0.58	0.05	16.6	0.8	+0.8
16.2	91.28	1.25	178.88	1.10	0.51	0.07	17.8	1.3	+1.6
16.6	75.69	1.65	178.81	0.96	0.42	0.07	17.1	1.5	+0.5
17.0	64.07	0.68	184.93	0.38	0.35	0.05	17.8	1.3	-0.8
17.4	54.59	0.76	181.13	0.56	0.30	0.06	17.9	1.5	-0.5
17.8	48.69	0.90	184.76	0.55	0.26	0.05	18.7	1.5	-0.9
18.0	45.49	0.97	184.61	0.51	0.25	0.06	19.1	1.5	-1.1

In Table I, the errors in the ^{63}Zn activity measurements are calculated and provided by the FLUKA application; the errors in the ratio "r" of the activities and the errors for the energies obtained through the simulations were calculated using the Error Propagation Theory[10].

4. Conclusions

Part of the results presented in this work show that the proposed method could be a very useful tool to guide cyclotron maintenance in those tasks of calibrating proton beam extraction systems, so that their kinetic energy is always that required for the production of the desired radioisotope. As demonstrated, it is enough for the laboratory to have activity meters (there is no need for calibration, as only the reason for the activities will be important), which are simpler and cheaper equipment when compared to an HPGe type detector and some copper thin foils and aluminum plates, which are also easily found on the specialized market. This work will be extended to measure the energy of a proton beam from a commercial cyclotron with energy varying between 15 and 30 MeV.
In the future, validation of the simulations is expected with the 30 MeV and 18 MeV cyclotron accelerators installed at the Nuclear and Energy Research Institute (IPEN).

Acknowledgements

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