A simple calibration-independent method for measuring the beam energy of a cyclotron

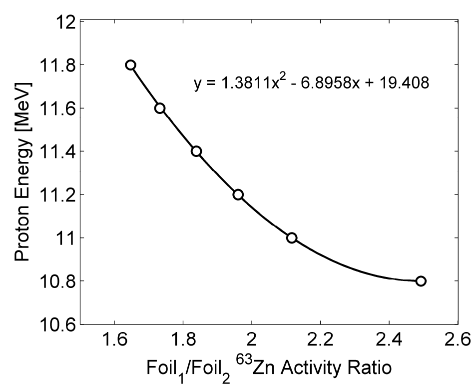
K. Gagnon[1], M. Jensen[2], H. Thisgaard[2+], J. Publicover[3++], S. Lapi[3+++], S.A. McQuarrie[1] and T.J. Ruth[3]

[1]Edmonton PET Centre, Cross Cancer Institute, University of Alberta, Edmonton, AB, CANADA
[2]Hevesy Laboratory, Risoe-DTU, Technical University of Denmark, Roskilde, DENMARK
[3]TRIUMF, Vancouver, BC, CANADA
[+]Presently at PET and Cyclotron Unit, Odense University Hospital, Odense, DENMARK
[++]Presently at University Health Network, Toronto, ON, CANADA
[+++]Presently at Mallinckrodt Institute of Radiology, Washington University, St. Louis, MO, USA

Introduction: When used for medical radionuclide production, both new and old cyclotrons need to have their beam energy checked periodically. This is not only part of good manufacturing practice and quality assurance but is also necessary for optimising target yields and minimising the radiation dose overhead of radionuclide production. As the production targets for most medical cyclotron configurations sit more or less straight on the vacuum tank with no room for beam diagnostics, an off-line approach for evaluating the beam energy of a medical cyclotron is required. Although beam monitor reactions have been extensively published, evaluated, and used for many years, the reliable use of these methods, at present, requires access to and knowledge of a well calibrated (typically HPGe) detector system.

Aim: Develop a simple method for evaluating the beam energy of a cyclotron to an accuracy of a few tenths of an MeV without using complex data analysis methods or sophisticated equipment.

Theory: To overcome the need for gamma spectroscopy and high quality efficiency calibrations, this study suggests the irradiation of two thin monitor foils of the same material interspaced by a thick energy degrader. By carefully selecting both the monitor foil material and degrader thickness, the differential activation of the two monitor foils may be used to determine the beam energy. The primary advantage to this technique is that by examining the ratio of two identical isotopes produced in the two monitor foils (e.g. $^{63}Zn/^{63}Zn$) as opposed to, for example, the $^{62}Zn/^{63}Zn$ ratio resulting from proton irradiation of a single copper monitor foil, all detector efficiency calibration requirements are eliminated. The energy can thus be monitored by experimentally measuring the activity ratio and comparing this value with activity ratios predicted using published cross section data (σ) as given by: $\frac{A_{Foil1}}{A_{Foil2}} = \frac{\sigma_{Foil1}}{\sigma_{Foil2}}$. A sample plot of the predicted ^{63}Zn activity ratio is given [right] for a 350 μm aluminum degrader, 25 μm copper monitor foils, and a 25 μm aluminum vacuum foil.



Methods: The proposed strategy was evaluated using 25 μm ^{nat}Cu monitor foils, a 25 μm aluminum window, and an aluminum energy degrader for protons in the 11–19 MeV range on the Edmonton PET Centre's (EPC) TR 19/9 cyclotron and the tandem Van de Graaff at Brookhaven National Lab (BNL). As the sensitivity of this technique depends upon the degrader thickness employed, this technique assumes prior knowledge of the beam energy (within ~ 1 MeV). The degrader thicknesses employed in this study are given in the table [top right]. For the blind BNL measurements, the energy range was specified so that an appropriate degrader thickness could be selected.

Assumed Energy Range [MeV]	Al Degrader Thickness [μm]	A	B	C
10.8 – 11.8	350	1.3811	-6.8958	19.408
12.0 – 12.8	500	0.7058	-4.0449	17.795
13.0 – 13.8	625	0.5352	-3.1150	17.527
14.0 – 14.8	750	0.5223	-2.7947	17.696
15.0 – 15.6	875	0.5254	-2.5192	17.837
15.8 – 16.4	1000	0.7218	-2.8021	18.380
16.6 – 17.2	1125	1.1060	-3.3724	19.029
17.4 – 18.0	1250	2.1607	-4.7938	19.934
18.2 – 18.8	1375	4.5682	-7.3352	21.028

Prior to irradiation, the predicted activity ratios were determined using the IAEA recommended $^{nat}Cu(p,x)^{63}Zn$ cross sections (www-nds.ipen.br/medical/) and simulations performed in the TRIM module of SRIM (www.srim.org), v.2008.04. From these predicted ratios, we present in the above table the coefficients (A, B, and C) necessary for determining the proton energy incident on the aluminium vacuum window, $E(MeV) = Ar^2 + Br + C$, where r is the experimental ^{63}Zn activity ratio measured between the front and back copper foil. In obtaining these coefficients we have assumed the presence of a 25 μm Al vacuum window, the Al degrader, and two 25 μm Cu monitor foils.

Following irradiation, the ^{63}Zn activity ratios were measured using Capintec™ CRC-15PET (EPC) and CRC-15W (BNL) dose calibrators set to an arbitrary calibration setting of 100. As ^{62}Cu and ^{62}Zn production is also possible during irradiation of ^{nat}Cu, activity measurements were made at: (i) a single time-point roughly 1-hour post-EOB to ensure minimal ^{62}Cu contribution, and (ii) multiple time-points from 20 minutes to 3 hours post-EOB where the ^{63}Zn activity reading contribution was determined through exponential curve fitting to account for both the ^{62}Cu and ^{62}Zn contributions.

Results: The table [bottom right] summarizes the incident energies evaluated using the ^{63}Zn activity ratio measured using either the single 1-hour post-EOB time-point or exponential stripping of the ^{63}Zn activity contribution via curve-fitting. All energies are reported as the energy incident on the vacuum foil and were calculated using the coefficients provided above. The excellent agreement noted with the nominal energy for the 1-hr measurements up to 17 MeV suggests that half-life discrimination is not necessary below this energy.

	E [MeV] Nominal	E [MeV] 1 hr	E [MeV] Curve
EPC	10.9	10.9	10.9
EPC	11.1	11.2	11.2
EPC	11.3	11.4	11.4
EPC	11.6	11.6	11.7
EPC	11.8	11.9	11.9
EPC	13.8	13.8	13.9
EPC	14.6	14.5	14.6
EPC	15.4	15.4	15.5
EPC	16.2	16.2	16.4
EPC	17.0	16.9	17.2
EPC	17.8	17.5	17.9
EPC	18.6	18.1	18.5
BNL	11.00	10.93	10.96
BNL	13.50	13.47	13.45
BNL	16.00	15.92	16.10
BNL	18.00	17.56	18.17
BNL	Blind (12.3)	12.32	12.32
BNL	Blind (14.4)	14.36	14.42

Conclusions: The new, simple, calibration-independent method proposed for measuring the beam energy of a cyclotron was found to provide an accurate determination of proton energies in the 11–19 MeV range without the need for sophisticated equipment. To facilitate the adoption of this technique into routine evaluation of the cyclotron beam energy, we have included a look-up table of recommended aluminum degrader thicknesses as well as a list of the corresponding curve fit data for evaluation of the proton energy using the measured ^{63}Zn activity ratio.

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