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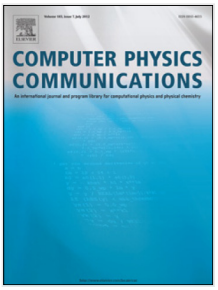

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Activity Computer Program for Calculating Ion Irradiation Activation

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February 2017

Abstract

A computer program, Activity, was developed to predict the activity and gamma lines of materials irradiated with an ion beam. It uses the TENDL[1] proton reaction cross section database, the Stopping and Range of Ions in Matter (SRIM)[2] code, a Nuclear Data Services (NDS) radioactive decay database [3] and an ENDF gamma decay database [4]. An extended version of Bateman's equation is used to calculate the activity at time t, and this equation is solved analytically, with the option to also solve by numeric inverse Laplace Transform as a failsafe. The program outputs the expected activity and gamma lines of the activated material.

Program Summary

Authors: Ben Palmer
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Progam Title: Activity
Licensing provisions: GNU
Programming Language: Fortran
Recommended computer: PCs or HPCs
Operating System: Linux (tested on Debian)
RAM: 250MB per process + 200MB overhead
Parallelization: OpenMPI
Recommended Processes: 1-4
Nature of Problem: To calculate the predicted activity of an ion irradiated target. The expected range of ion energies is between 1 MeV and 200 MeV; this is the range of the available ion cross section data.
Solution Method: The program loads cross section data from the TENDL database and trajectory data points from a SRIM simulation exyz output file. It uses this input to calculate the production/loss rate of each isotope in the simulated target. Radioactive decay equations are used to calculate the amounts and activity of each radioactive isotope at the specified time.
Restrictions: None.
Unusual Features: No unusual features or requirements.
Running Time: Typically the Activity program runs each input from seconds to no more than several minutes.
Source code: https://github.com/BenPalmer1983/activity
Keywords: Ion Irradiation Activation Bateman Transmutation Decay

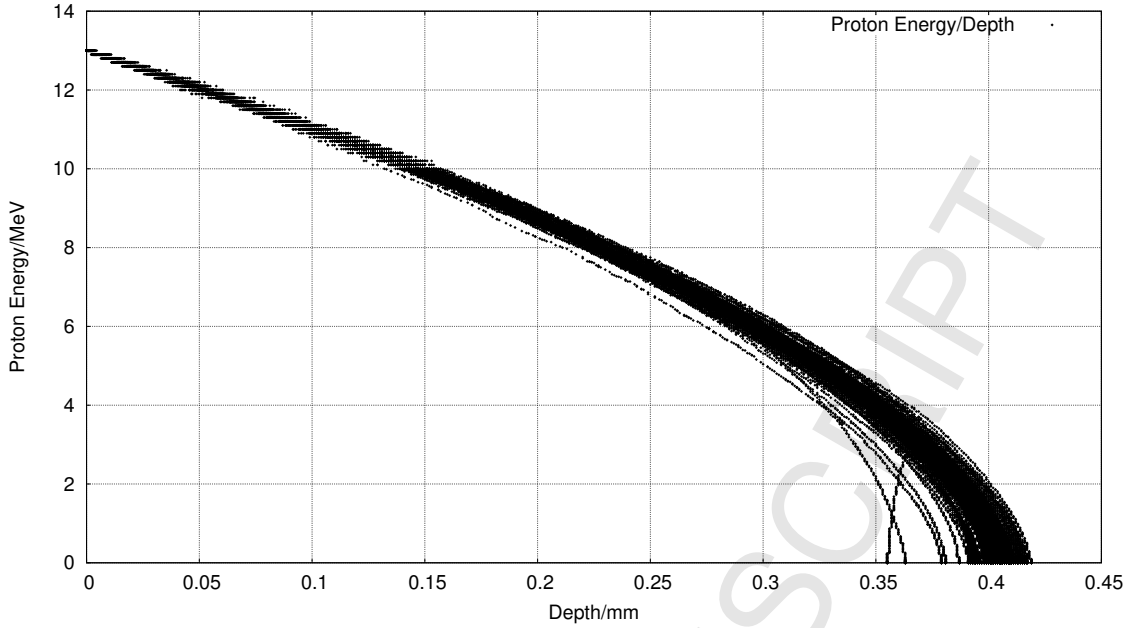

Figure 1: One hundred simulated 13MeV proton energy loss curves in Fe simulated with SRIM [2]

Background

Ion Irradiation at the University of Birmingham

The Scanditronix MC-40 Cyclotron is used at the University of Birmingham to create a beam of protons or other light ions. The energies of these ions are typically between 10 MeV and 60 MeV with beam currents ranging up to 50 microamps ($3.1\text{x}10^{14}$ protons per second). Target materials are irradiated by this cyclotron for a number of reasons, including purposely creating radioactive isotopes for the nearby Queen Elizabeth Hospital, investigating ion irradiation damage and emulating neutron irradiation.

The Cyclotron is usually used to create radioactive isotopes for medical use, but an additional beam line has been devoted to material science investigations into radiation damage. While the creation of radioactive isotopes is desired in some cases, material being tested for radiation damage should preferably have low levels of radioactivity.

It is expensive to arrange the irradiation of target materials by high energy neutrons sources, whereas it is relatively inexpensive to irradiate using an ion beam on the MC-40 Cyclotron. The energies can be controlled, and a set dose at a single energy, or a range of energies, can be precisely deposited into the target material.

The Activity code discussed here was developed to calculate the activity of a target material irradiated by a proton beam. It has been developed in Fortran and uses data from the TENDL-2013 proton cross section database, SRIM ion transport code and NDS radioactive decay database.

Simulating Ion Irradiation with SRIM

A package of ion transport codes, SRIM, is freely available to download and use to investigate the transport of ions through matter. SRIM uses the binary collision approximation (BCA) to simulate the passage of ions in a material. It is an approximate method, and one key restriction is that it does not take into account the structure of the material, and this approximation is therefore also imposed on the Activity code.

One file that SRIM creates is of importance to the Activity code, and that is the trajectory file that contains the energy and x,y,z co-ordinate data points for simulated ions moving through matter. Figure 1 shows the

trajectory of one hundred 13MeV protons entering and passing through an Iron target, and it is this set of data points (together with the cross section database) that the Activity code uses to calculte the reaction rates for the transmutation of nuclei in the target. At higher energies, the ions slow as they lose energy due to electronic stopping, but as the ion energy drops the mechanism of loss through nuclear collisions becomes important. The spreading of ion depths at lower energies is a result of the higher momentum transfer during nuclear collisions, as can be seen in Figure 1.

Transmutation of Nuclei by Ion Irradiation

Considering a simplified nuclear potential well, energetic protons approaching a nucleus may overcome the Coulomb potential barrier. They are captured by the nucleus and held within the potential well by the strong nuclear force. This process may leave the nucleus in an excited and unstable state, depending on the input energy of the proton and configuration of nucleons. The process is probabilistic, and the average chance of a reaction (the microscopic cross section) may be measured as a function of the projectile, projectile energy and target, either experimentally or by optical model potential calculations. The reaction rate is calculated from the microscopic cross section using the following equation:

$$R = \frac{J}{e} n_t \sigma \cdot 10^{-28} \delta t \tag{1}$$

- R Reaction Rate (reactions per second)
- J Beam current (A)
- n_t Number density of target (atoms per cubic metre)
- σ Microscopic reaction cross section (barns)
- e Elementary charge (1.602177E-19C)
- δT Target thickness (m)

Radioactive Decay

Radioactive decay is the random change in nucleons or energy state of an unstable nucleus. It is impossible to predict when a single nucleus will decay, but the decay of a collection of nuclei is statistical in nature. The radioactivity and number of unstable nuclei at time t can be predicted using the decay constant, λ, for the radioactive isotope. This constant is defined as follows:

$$\lambda = -\frac{N'(t)}{N(t)} \tag{2}$$

The number of radioactive nuclei N(t) at time t is given by the following equation, where N(0) is the starting number of nuclei:

$$N(t) = N(0) \exp(-t\lambda) \tag{3}$$

The activity A(t) of the radioactive nuclei is predicted at time t by using the following equations, where N'(t) is the change in amount of nuclei with respect to time:

$$A(t) = -N'(t) = \lambda N(t) \tag{4}$$

$$A(t) = \lambda N(0) \exp(-t\lambda) \tag{5}$$

Bateman Equation for Radioactive Decay

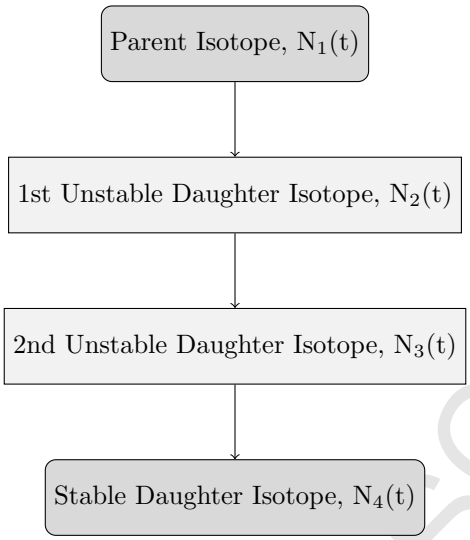

Figure 2: An example decay chain from an unstable parent isotope, through unstable daughter isotopes ending with a stable daughter isotope.

The English mathematician Harry Bateman derived an equation (6) to calculate the amount of each isotope in a decay chain, illustrated in Figure 2, at time t.

$$N_n(t) = \sum_{i=1}^{i=n} \left(\left(\prod_{j=i}^{j=n-1} \lambda_{(ij+1)} \right) \sum_{j=i}^{j=n} \left(\frac{N_{i0} \exp(-\lambda_j t)}{\prod_{p=i,p\neq j}^{p=n} (\lambda_p - \lambda_j)} \right) \right) \tag{6}$$

When a radioactive isotope decays, there may be more than one mode of decay, and this leads to branching factors. Pb-214 only decays via beta decay to Bi-214, giving a branching factor of 1.0, whereas Bi-214 has a 99.979% chance of decaying to Po-214 by beta decay and a 0.021% of emitting an alpha particle and decaying to Tl-210 (branching factors of 0.99979 and 0.00021 respectively) [5].

When a target material is irradiated, there is a source term for transmuted nuclei due to the irradiation. The daughter isotopes of these transmuted isotopes will also be affected by the irradiation and will transmute further, giving a source term for each daughter isotope as a result of the irradiation. Sources for each isotope in the decay chain, and branching factors between a parent isotope and its daughter isotope/s must be accounted for.

The Bateman equation was derived using Laplace transforms, and this same method has been used to develop a modified equation that incorporates branching factors and production rates for each isotope in the decay chain, as illustrated by Figure 3.

Laplace Transform

Laplace Transforms (7) are a useful mathematical tool, and allow ordinary differential equations to be solved by simple algebraic manipulation in the s domain. Bateman took advantage of Laplace Transforms in deriving his equation, and this is the method that has been taken here as well.

$$F(s) = \int_0^\infty f(t) \exp(-st) dt \tag{7}$$

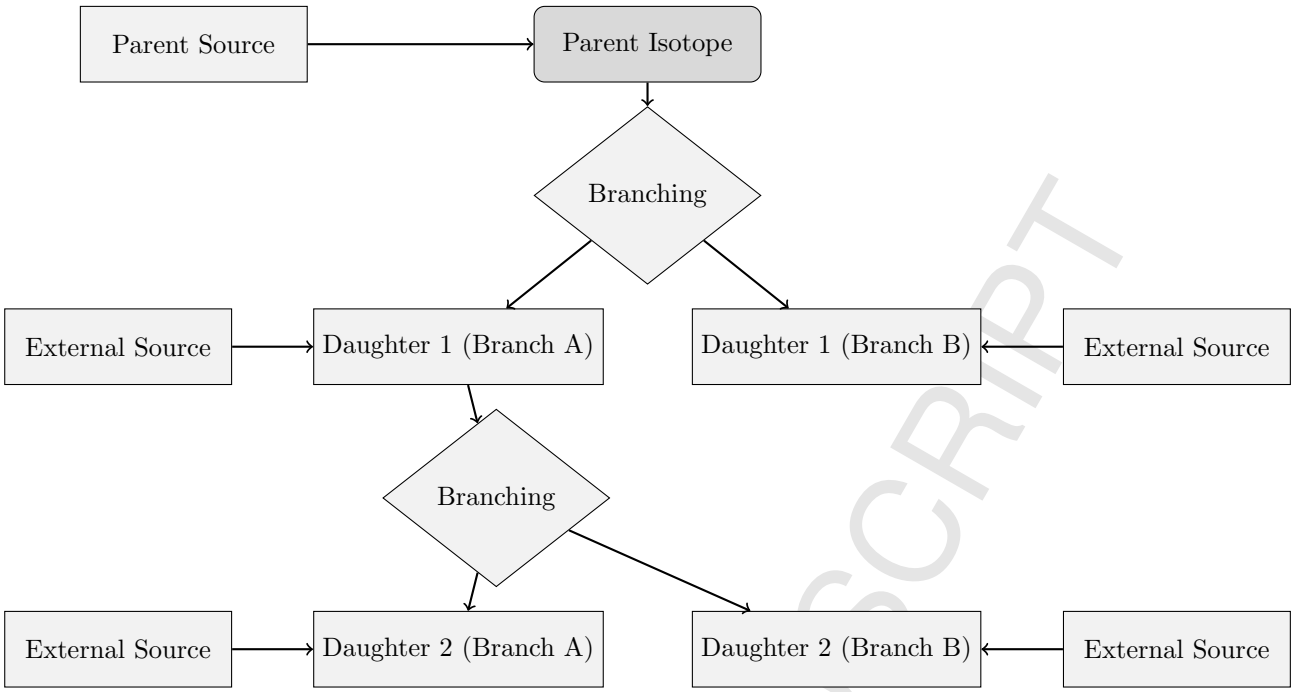

Figure 3: An example of several decay chains including branching factors and possible external source terms for each isotope on each chain.

Constructing the Differential Equations

The first step is to set up differential equations for the parent isotope, unstable daughter isotopes and stable daughter isotope. The parent isotope has a source term, due to production, and a loss term, due to decay. The unstable daughter isotopes have two source terms, from the production by irradiation induced transmutation and the decay of preceding isotopes in the decay chain, and a loss term, due to decay. Finally, the stable daughter that finalizes the decay chain has two source terms (the same as the unstable daughters) but no loss term.

The variables (and vectors) used in these equations are defined as follows:

- $\vec{\lambda}$ vector containing isotope decay constants λ_i
- $\vec{b}$ vector containing isotope to isotope branching factors b_i
- $\vec{w}$ vector containing isotope production rates w_i
- t time at which activity/amount of isotope is measured
- $N_i(0)$ starting amount of the i^{th} isotope
- $N_i(t)$ amount of the i^{th} isotope at time t
- $N_i'(t)$ change in amount of the i^{th} isotope, with respect to time, at time t

The differential equations for the parent isotope (first isotope), unstable daughter isotopes (i^{th} isotopes) and stable, final, daughter isotope (zth isotope) in the time domain are as follows:

$$N_1'(t) = \omega_1 - \lambda_1 N_1(t) \tag{8}$$

$$N_i'(t) = \omega_i + b_{i-1}\lambda_{i-1}N_{i-1}(t) - \lambda_i N_i(t) \tag{9}$$

$$N_z'(t) = \omega_z + b_{z-1}\lambda_{z-1}N_{z-1}(t) \tag{10}$$

Applying the Laplace Transform to these three differential equations allows them to be manipulated and solved algebraically in the s-domain.

$$N_1(s) = \frac{1}{s+\lambda_1}N_1(0) + \frac{1}{s(s+\lambda_1)}\omega_1 \tag{11}$$

$$N_i(s) = \frac{1}{s(s+\lambda_i)}\left(\omega_i\right) + \frac{1}{s+\lambda_i}\left(b_{i-1}\lambda_{i-1}N_{i-1}(s)\right) + \frac{1}{s+\lambda_i}N_i(0) \tag{12}$$

$$N_z(s) = \frac{1}{s^2}\omega_z + \frac{1}{s}b_{z-1}\lambda_{z-1}N_{z-1}(s) + \frac{1}{s}N_z(0) \tag{13}$$

Numerical Inversion of the Laplace Transform

The Gaver-Stehfest[6] algorithm was developed in the 1960s and 1970s and is a method of calculating the inverse of a Laplace Transform in the real number domain. It is an easy to implement and reasonably accurate method, although it is an approximation to the real value. A comparison between an analytic and numeric inversion for the unstable isotope Po-218 is discussed at the end of this section (figure 4).

$$f(t) \approx f_n(t) = \frac{\ln(2)}{t}\sum_{k=1}^{2n} a_k(n)F(s) \text{ where } n \geq 1, t > 0 \tag{14}$$

$$s = \frac{k\ln(2)}{t} \tag{15}$$

$$a_k(n) = \frac{(-1)^{(n+k)}}{n!}\sum_{j=Floor(\frac{k+1}{2})} j^{n+1}\binom{n}{j}\binom{2j}{j}\binom{j}{k-j} \tag{16}$$

The equation for the i$^{\text{th}}$ isotope may be calculated by recursively calculating the equations by numeric inversion, starting from the first (parent isotope) and inserting the result into each subsequent recursion until the i$^{\text{th}}$ isotope is reached (changing the equations appropriately for the parent, unstable daugher and stable daughter isotopes).

Analytic Solution by Partial Fraction Expansion

The equation for the i$^{\text{th}}$ isotope in the s domain can be written in full by substituting the preceding equation until the parent isotope is reached, and this full equation may be rearranged with the production amount of each isotope and starting amount of each isotope in individual terms. Each of these terms is multiplied by a fraction that can be expanded, using partial fractions, and inverted analytically.

This is illustrated with an example unstable isotope, fourth in the decay chain (including the parent isotope):

$$
\begin{aligned}
N_4(s) = &\frac{1}{(s+\lambda_1)(s+\lambda_2)(s+\lambda_3)(s+\lambda_4)} b_2 b_3 b_4 \lambda_1 \lambda_2 \lambda_3 N_1(0) \\
&+ \frac{1}{(s+\lambda_2)(s+\lambda_3)(s+\lambda_4)} b_3 b_4 \lambda_2 \lambda_3 N_2(0) \\
&+ \frac{1}{(s+\lambda_3)(s+\lambda_4)} b_4 \lambda_3 N_3(0) \\
&+ \frac{1}{(s+\lambda_4)} N_4(0) \\
&+ \frac{1}{s(s+\lambda_1)(s+\lambda_2)(s+\lambda_3)(s+\lambda_4)} b_2 b_3 b_4 \lambda_1 \lambda_2 \lambda_3 \omega_1 \\
&+ \frac{1}{s(s+\lambda_2)(s+\lambda_3)(s+\lambda_4)} b_3 b_4 \lambda_2 \lambda_3 \omega_2 \\
&+ \frac{1}{s(s+\lambda_3)(s+\lambda_4)} b_4 \lambda_3 \omega_3 \\
&+ \frac{1}{s(s+\lambda_4)} \omega_4
\end{aligned}
\tag{17}
$$

An example stable isotope, fourth (last) in the decay chain (including the parent isotope):

$$
\begin{aligned}
N_4(s) = &\frac{1}{s(s+\lambda_1)(s+\lambda_2)(s+\lambda_3)} b_2 b_3 b_4 \lambda_1 \lambda_2 \lambda_3 N_1(0) \\
&+ \frac{1}{s(s+\lambda_2)(s+\lambda_3)} b_3 b_4 \lambda_2 \lambda_3 N_2(0) \\
&+ \frac{1}{s(s+\lambda_3)} b_4 \lambda_3 N_3(0) \\
&+ N_4(0) \\
&+ \frac{1}{s^2(s+\lambda_1)(s+\lambda_2)(s+\lambda_3)} b_2 b_3 b_4 \lambda_1 \lambda_2 \lambda_3 \omega_1 \\
&+ \frac{1}{s^2(s+\lambda_2)(s+\lambda_3)} b_3 b_4 \lambda_2 \lambda_3 \omega_2 \\
&+ \frac{1}{s^2(s+\lambda_3)} b_4 \lambda_3 \omega_3 \\
&+ \frac{1}{s^2} \omega_4
\end{aligned}
\tag{18}
$$

By using partial fraction expansion and standard Laplace Transforms, the set of equations below is used to calculate the amount of the m^{th} isotope in the decay chain, providing the m^{th} isotope is unstable.

$$
N_m(t; \vec{\lambda}, \vec{b}, \vec{w}) = \sum_{k=1,m} r(k; \vec{\lambda}, \vec{b}) \left[f(t; k, m, \vec{\lambda}) N_k(0) + g(t; k, m, \vec{\lambda}) w_k \right] \tag{19}
$$

$$
r(k, m, \vec{\lambda}) = \begin{cases} \prod_{i=k,m-1} (b_{i+1} \lambda_i), & \text{if } k < m \\ 1, & \text{if } k = m \end{cases} \tag{20}
$$

$$
f(t; k, m, \vec{\lambda}) = (-1)^{m-k} \sum_{i=k,m} \left[\exp(-\lambda_i t) \prod_{j=k,m; j \neq i} \left(\frac{1}{\lambda_i - \lambda_j} \right) \right] \tag{21}
$$

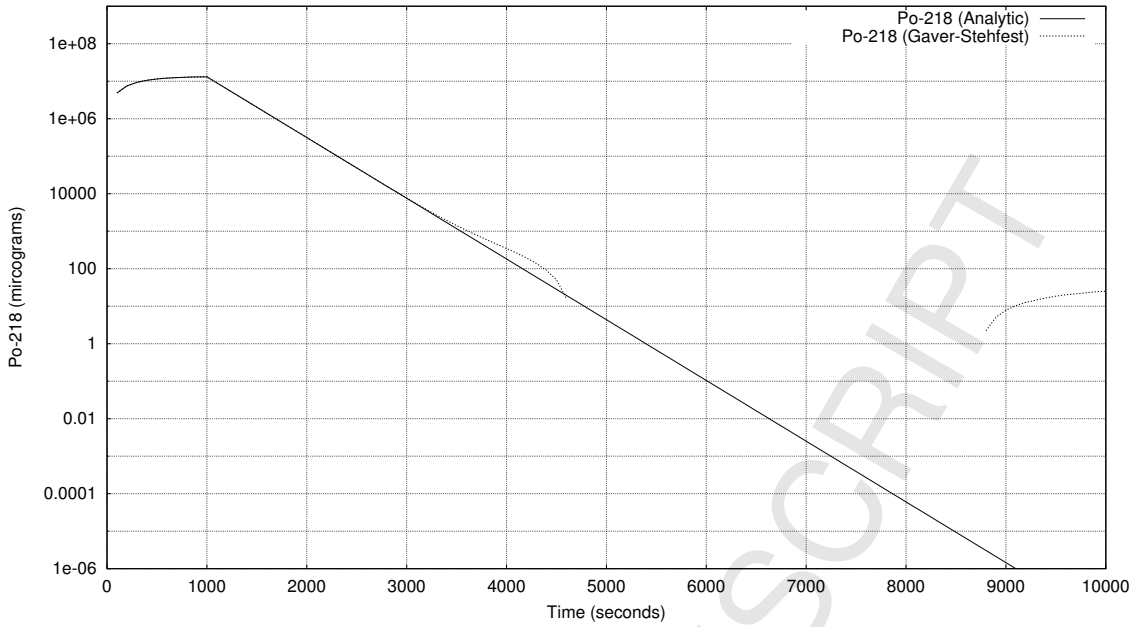

Figure 4: Decay of Po-218: Analytice and Gaver-Stehfest Calculations [5]

$$g(t;k,m,\vec{\lambda}) = \frac{1}{\prod_{i=k,m}\lambda_i} + (-1)^{m-k+1}\sum_{i=k,m}\left[\frac{1}{\lambda_i}\exp(-\lambda_i t)\prod_{j=k,m;j\neq i}\left(\frac{1}{\lambda_i-\lambda_j}\right)\right] \tag{22}$$

The set of equations below is used to calculate the amount of the m^{th} isotope in the decay chain, where the m^{th} isotope is stable.

$$N_m(t;\vec{\lambda},\vec{b},\vec{w}) = N_m + w_m t + \sum_{k=1,m-1} r(k;\vec{\lambda},\vec{b})\left[f(t;k,m-1,\vec{\lambda})N_k(0) + g(t;k,m,\vec{\lambda})w_k\right] \tag{23}$$

$$r(k,m,\vec{\lambda}) = \begin{cases}\prod_{i=k,m-1}\left(b_{i+1}\lambda_i\right), & \text{if } k<m\\ 1, & \text{if } k=m\end{cases} \tag{24}$$

$$f(t;k,m,\vec{\lambda}) = \frac{1}{\prod_{i=k,m}\lambda_i} + (-1)^{m-k+1}\sum_{i=k,m}\left[\frac{1}{\lambda_i}\exp(-\lambda_i t)\prod_{j=k,m;j\neq i}\left(\frac{1}{\lambda_i-\lambda_j}\right)\right] \tag{25}$$

$$g(t;k,m,\vec{\lambda}) = \frac{1}{\prod_{i=k,m}\lambda_i}t + \frac{\sum_{i=k,m}\left[\prod_{j=k,m;j\neq i}\lambda_j\right]}{\prod_{i=k,m}\lambda_i^2} + (-1)^{m-k+1}\sum_{i=k,m}\left[\frac{1}{\lambda_i^2}\exp(-\lambda_i t)\prod_{j=k,m;j\neq i}\left(\frac{1}{\lambda_i-\lambda_j}\right)\right] \tag{26}$$

Preference: Analytic over Numeric

The numeric solution only requires the equation to be solved in the s-domain; the Gaver-Stehfest algorithm performs the inversion. It is worth the extra effort to derive and implement an analytic solution, as the numeric is only an approximation. Examples of the pitfalls of the numeric solution are that it can give negative amounts of an isotope and the difference between the numeric and analytic calculated amounts can become quite large when the isotope decays away to a very small value. Figure 4 shows the predicted decay of a sample of Po-218 irradiated for 1,000s, and sampled until 10,000s. In the region between 4,000s and 9,000s the amount from the numeric calculation drops below zero, whereas the analytic calculation remains above zero, as would be expected.

Computational Methods

The Activity program has been developed in Fortran and takes advantage of MPI (Message Parsing Interface) to speed up calculation times by allowing the use of multiple processes in parallel. It has a self contained maths library, although this could be improved in the future by using optimised maths libraries for certain functions (e.g. matrix operations).

The code was developed on a Debian based distribution of Linux, but it should be supported on other variants of Linux and Unix, and does not require any specialist hardware.

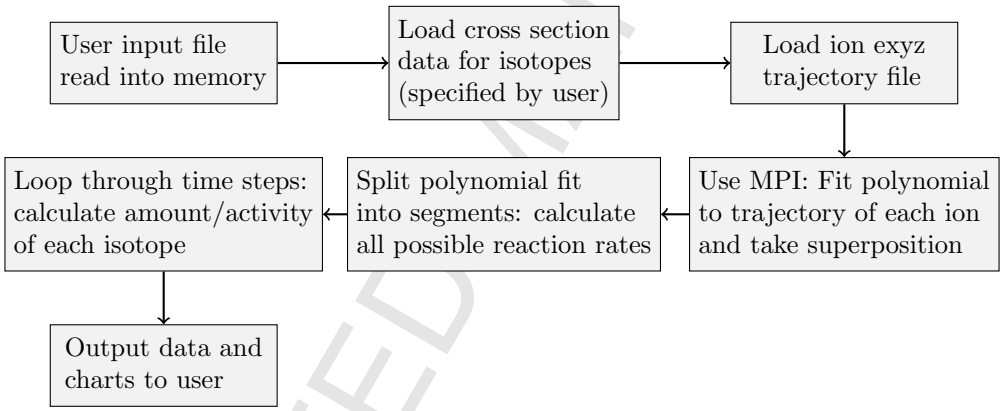

Figure 5: Flow chart of major processes in the Activity code

The user is required to prepare an input file that contains the instructions required to perform a calculation. In addition to the input file, the user must provide an EXYZ ion trajectory file output by SRIM. Activity will read in the user input file, and the SRIM and data files listed within, before performing the calculation. Figure 5 shows a flowchart of the major steps the code performs.

There are various settings in the user input file, but the main ones relating to the simulated experiment are:

- Element composition of target (percentage by mass).
- Beam flux (current), energy, duration and area on target.
- Activity measurement time (end of the "experiment").
- Material density.
- Target thickness.

Several data files are generated by Activity and, if the user has matplotlib [7], charts will be created too. The most relevant to the user are:

- gammaLines.dat - tally into discrete bins of predicted gamma counts.
- ionTraj.dat - the averaged ion trajectory used in the calculation.
- isotopeActivityFileG.dat - a large data file detailing the activity of every predicted radioactive isotope in the target at user specified times following irradiation.

The charts include:

- activityTop5.png - activity of the top 5 active isotopes as a function of time after irradiation starts.
- gammaLines.png - predicted gamma spectrum expected at the "experiment end time".

The Activity code uses the equations derived above to calculate the amount and activity of each isotope in the calculation. One problem with the original Bateman equation that also exists in the set of modified Bateman equations is that two different isotopes with the same decay constant will cause a singularity and a halt in the calculation. The activity code loops through all the decay constants in use before it attempts to run the calculation. If any isotope decay constants match they are varied by a small amount relative to the decay constant. It repeats this process until all decay constants are unique before proceding.

Approximations

The accuracy of the Activity code is dependant on the input files provided by the user and the method used to calculate the reaction rates and resulting activity. The TENDL proton database consists of experimental measured cross sections as well as values calculated using the optical model potential. Using the latest database is recommended.

SRIM uses the binary collision approximation to simulate ion transport. It is a well tested code that has been used for many years. One limitation is that the structure of the material is not taken into account. This would have an impact on a user of the Activity program if they were trying to calculate, for example, whether a FCC (face centered cubic) steel would be irradiated differently when compared to a BCC (body centered cubic) steel. The Activity code would determine the activity of the steel as a function of the ion current, ion type and the density, thickness and composition of the steel, not its structure.

This version of the Activity code averages the path of all the SRIM simulated ions, rather than treating each ion differently. This may or may not have an impact on the results. If a new version of the code is developed there would be an option to calculate reaction rates for each induvidual simulated ion, and a comparison could then be made to the calculations using the averaged path of a set of ions.

The final approximation would be to use the numeric solution to the activity equations, although the analytic solution is forced within the code unless it returns a failed result.

Results

A target of high purity Iron was irradiated with 36 MeV protons by the University of Birmingham Scanditronix MC-40 Cyclotron. The target was 0.5mm thick and was irradiated at a current of 0.5 micro Amps for 300 seconds, irradiating approximately 0.25g of Iron. A high purity Germanium detector was used to measure the gamma peaks three days after irradiation.

The peak that dominated the readings was the 931 keV Cobalt 55 line. After calibrating the detector and adjusting the readings, this peak was measured at 44,300Bq+/-2,000Bq. The activity of this peak as predicted by the Activity code was 44,565Bq.

Table 1: Gamma peaks predicted and measured for a 13 MeV ion irradiated sample of Mo

Gamma Energy (keV)	Predicted Activity (Bq)	Experimental Activity (Bq)
766	4.45E6	5.11E5+/-2.5E4
778	6.14E6	1.36E6+/-6.8E4
812	5.04E6	1.15E6+/-5.8E4
850	6.00E6	1.39E6+/-7.0E4
126	9.33E5	2.10E5+/-1.1E4

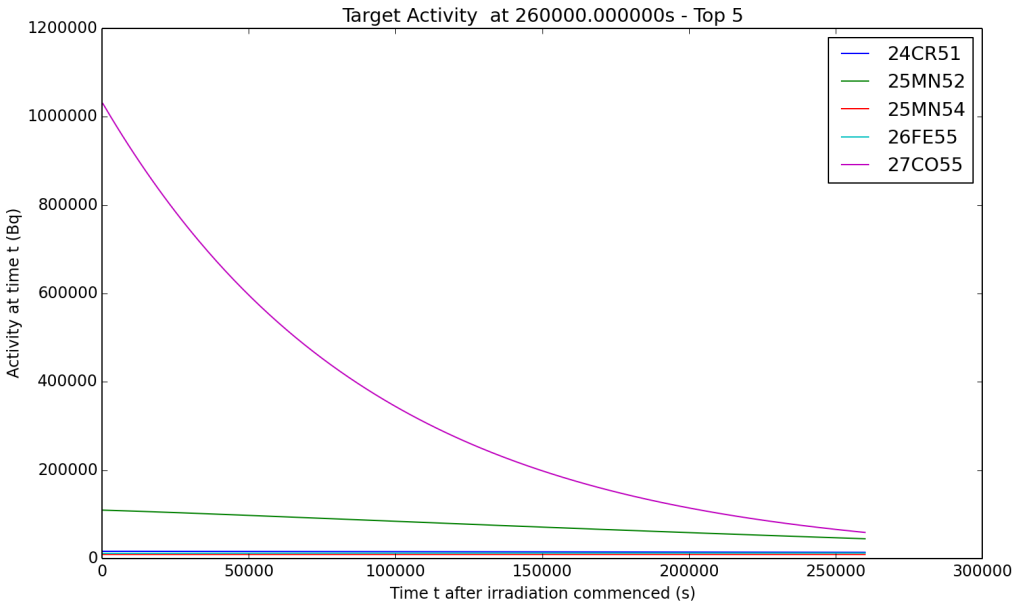

Figure 6: Sample Activity code output chart for the top five most active isotopes for Iron irradiated by 36MeV protons.

A target of high purity Molybdenum was irradiated with 13 MeV protons by the University of Birmingham Scanditronix MC-40 Cyclotron. The target was 0.5mm thick and was irradiated at a current of 5 micro Amps for 1500 seconds, irradiating approximately 0.3g of Molybdenum. A high purity Germanium detector was used to measure the gamma peaks three days after irradiation.

Five peaks were of interest, and these are listed in Table 1.

There was the possibility of the high purity Geranium detector introducing errors due to detector dead time, where by a source that is too active floods the device with gammas. The samples were safe to handle, and did not appear to flood the detector in any way, but there was still the possibility of counts being missed due to dead time. The probabilistic nature of radioactive decay also introduced inherent errors to the experimental activity measurements.

Conclusions

The Activity program is an easy to use Fortran compiled executable that can be built and run, for free, on a Linux computer. It takes advantage of multi-core processors, and typical calculations take from seconds to minutes.

Using the SRIM code and TENDL database, the code has been used to predict the activity of Iron and Molybdenum targets that have been irradiated with a proton beam. The prediction of the 931 (keV) Cobalt 55

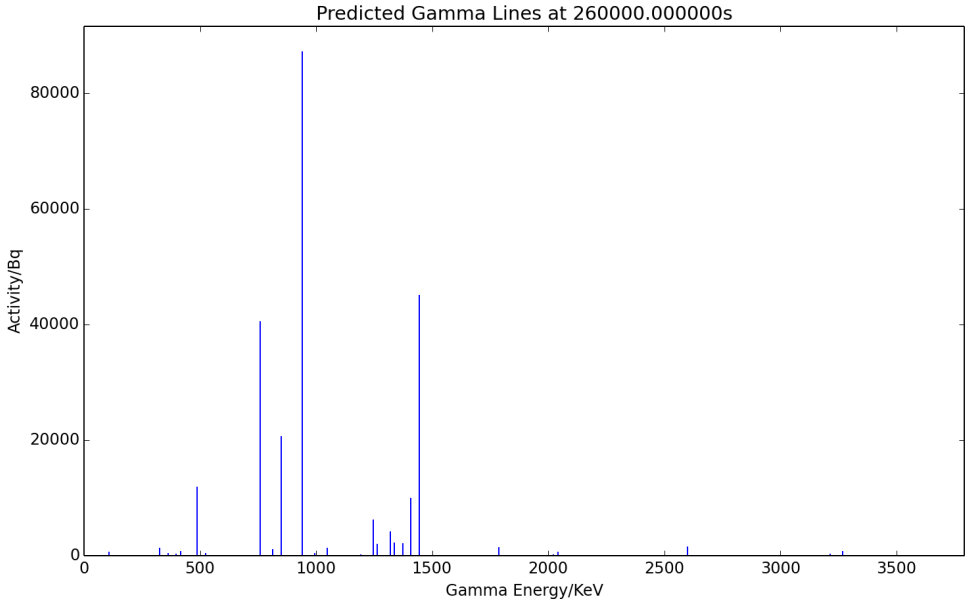

Figure 7: Sample Activity code output chart for the expected gamma lines to be measured for Iron irradiated by 36MeV protons.

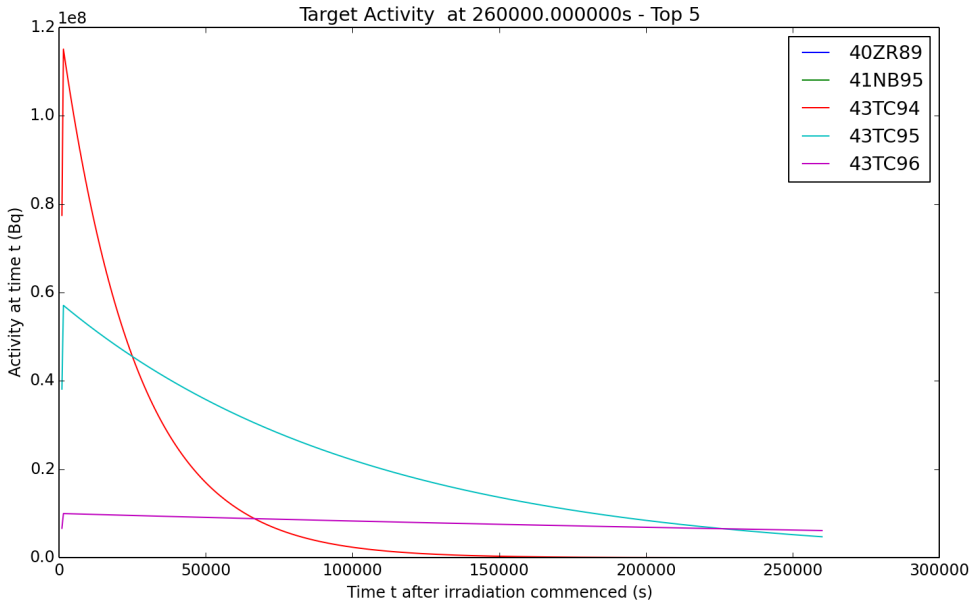

Figure 8: Sample Activity code output chart for the top five most active isotopes for Molybdenum irradiated by 13MeV protons.

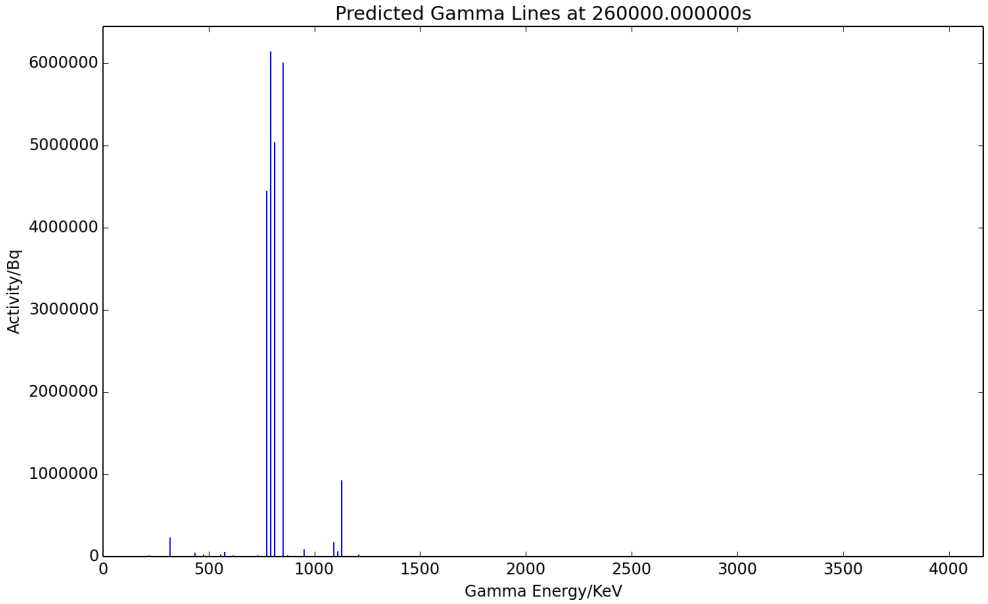

Figure 9: Sample Activity code output chart for the expected gamma lines to be measured for Molybdenum irradiated by 13MeV protons.

gamma activity of irradiated Iron was very close to the measured value. The five predicted gamma activities for ion irradiated Molybednum were up to a factor of 5-10 away from the measured activities.

There are a number of improvements that would be considered in a future version of the Activity code. These improvements would include the following:

- A more readable output with less information printed, as too much may confuse the user.
- A file containing the top five radioactive isotopes with their top five gamma lines.
- Individual ion trajectories used to calculate the reaction rates, rather than the average path.
- Experimental ion activation data for a wider range of elements to test the Activity code against.
- Expand to include deuterons (this would require the TENDL deuteron cross section database).

Acknowledgements

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- Dr Chris Cooper and John Hewett for irradiation activation data points.
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References

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Program title: Activity

Catalogue identifier: AFBS_v1_0

Program summary URL: http://cpc.cs.qub.ac.uk/summaries/AFBS_v1_0.html

Program obtainable from: CPC Program Library, Queen's University, Belfast, N. Ireland

Licensing provisions: GNU GPL v3

No. of lines in distributed program, including test data, etc.: 688828

No. of bytes in distributed program, including test data, etc.: 71056048

Distribution format: tar.gz

Programming language: Fortran.

Computer: PCs or HPCs.

Operating system: Linux (tested on Debian).

Has the code been vectorised or parallelized?: OpenMPI

RAM: 250MB per process + 200MB overhead

Classification: 2.2, 17.8.

Nature of problem:
To calculate the predicted activity of an ion irradiated target. The expected range of ion energies is between 1MeV and 200MeV; this is the range of the available ion cross section data.

Solution method:
The program loads cross section data from the TENDL database and trajectory data from a SRIM [1] simulation exyz data file. It uses this data to calculate the production/loss rate of each isotope in the simulated target. Radioactive decay equations are used to calculate the amounts and activity of each radioactive isotope at the set time.

Running time:
Typically the Activity program runs each input from seconds to no more than several minutes.

References:

[1] SRIM - The stopping and range of ions in matter (2010). Ziegler, James F., Ziegler, M. D. and Biersack, J. P. 2010, Nuclear Instruments and Methods in Physics Research Section B, Vol. 268, pp. 1818-1823.