R.P. Note 102

A Calculation of Activity Produced by an AmBe Source in the Reaction ${}_{26}Fe^{54}(n,p){}_{25}Mn^{54}$

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Recently, there has been much discussion at Fermilab of the matter of defining Radioactive Materials Management Areas (RMMA). A RMMA is loosely defined as an area in which a non-radioactive item can become radioactivated or contaminated. The motivation for performing this calculation is to consider whether the use of a neutron source, such as AmBe, might cause an area to become a RMMA due to the production of measurable radioactivity.

The reaction ${}_{26}Fe^{54}(n,p){}_{25}Mn^{54}$ was chosen because ${}_{25}Mn^{54}$ is commonly found in radioactive waste at Fermilab and the cross sections for this reaction are typical of neutron activations.

The activation formula is given by Barbier[1] as

$$-\frac{d n_{\nu}}{d t_{c}} = \Phi \frac{N_0}{A} \sigma_{\nu,t} \left[1 - \exp\left(-\frac{t_i}{t_{\nu}}\right)\right] \exp\left(-\frac{t_c}{t_{\nu}}\right) \qquad (1).$$

It gives the decay rate of a particular isotope ν which has been irradiated for a time t_i and left alone to decay during a "cooling time" t_c. In eq. (1),

n_{ν} = the number of radioactive nuclei of isotope ν per gram of target material produced per unit time.

t_i = the irradiation time

t_c = the cooling time

t_{ν} = the mean life of isotope ν (450.4 days for Mn^{54})

[1]Marcel Barbier, *Induced Radioactivity*, John Wiley & Sons, Inc., New York, (1969).

F = the neutron flux (# per unit area per unit time)

N_0 = Avogadro's number (6.022 ∞ 10^{23} per mole)

A = the atomic weight of the target material (55.85 for iron).

$\sigma_{\nu,T}$ = the activation cross section for target nucleus *T* to isotope ν.

Consider neutrons in the energy range from E_a to E_b. The neutron flux in this range is given by

$$\Phi_{ab} = \Phi \int_{E_a}^{E_b} y(E)\, dE \qquad (2).$$

The energy distribution function *y(E)* is the fraction of the total number of neutrons emitted whose energy lies in the range *E* to *E* + *dE*. The activation cross section in this energy range is a function of the energy:

$$\sigma_{\nu,T} = \sigma_{\nu,T}(E) \qquad (3).$$

Hence, the activation rate for a source emitting neutrons over a continuous energy range is obtained by combining eqs. (1), (2) and (3).

$$-\frac{dn_\nu}{dt_c} = \Phi \frac{N_0}{A}\left[1 - \exp\left(-\frac{t_i}{t_\nu}\right)\right]\exp\left(-\frac{t_c}{t_\nu}\right)\int_{E_a}^{E_b} y(E)\,\sigma_{\nu,T}(E)\, dE \qquad (4).$$

The neutron energy distribution has been measured for an AmBe source.[2] The data in reference 2 are presented as a histogram. In order to obtain the function *y(E)*, bins were plotted at regular intervals and a polynomial function was fitted to them (Figure 1) using the Cricket Graph program on a Macintosh computer. The error was taken to be the square root of the number of events in the bin. The histogram must be normalized so that the area underneath it, and therefore the area underneath the fitted curve, is unity. Thus, the area underneath the curve between any two points E_a and E_b multiplied by a normalization constant is simply the fraction of the total neutron flux emitted with energies in that range.

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[2] Robert B. Schwartz, Draft International Standard ISO/DIS 8529, *Neutron Reference Radiations for Calibrating Neutron Measuring Devices Used for Radiation Protection Purposes and for Determining Their Response as a Function of Neutron Energy*, (1986).

Cross sections for the reaction $_{26}Fe^{54}(n,p)_{25}Mn^{54}$ have been compiled by Goldberg *et. al.*[3] for a range of neutron energies. Data from this compilation were also plotted with Cricket Graph and fitted to a polynomial function (Figure 2).

The function fitted to the neutron spectrum is a fourth-order polynomial; the function fitted to the cross section plot is a fifth-order polynomial. The coefficients are listed in figures 1 and 2, respectively. Note that this fit has no validity outside the range for which data are plotted.

By multiplying these two polynomials together, an approximation of the integrand in eq. (4) is obtained. The integrand is thus expressed as a ninth-order polynomial in *E* and the integral can be expressed as 10 simple integrals of constant coefficients times powers of *E*. The integral from eq. (4) then becomes

$$\int_{E_a}^{E_b} y(E)\sigma_{v,T}(E)dE =$$
$$3.319\int_0^{10} dE - 35.87\int_0^{10} E dE + 10.39\int_0^{10} E^2 dE + 5.444\int_0^{10} E^3 dE -$$
$$1.049\int_0^{10} E^4 dE + 7.136\times 10^{-2}\int_0^{10} E^5 dE + 1.036\times 10^{-2}\int_0^{10} E^6 dE + \qquad (5).$$
$$1.369\times 10^{-3}\int_0^{10} E^7 dE + 7.815\times 10^{-5}\int_0^{10} E^8 dE + 1.599\times 10^{-6}\int_0^{10} E^9 dE$$

The limits of integration, taken from figure 1, are expressed in MeV. Evaluating the integrals,

$$\int_{E_a}^{E_b} y(E)\sigma_{v,T}(E)dE = 4.841\times 10^{5} \qquad (6).$$

The normalization constant for *y(E)* is 0.2546 and the conversion factor from mb to cm^2 is 10^{-27}.

The most active AmBe source currently in use at Fermilab is Am241Be-7.2-1. The neutron flux from this source is 2.00 ∞ 10^7 s^{-1}.[4] When in use, the typical exposure time for this

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[3] Murrey D. Goldberg *et. al.*, BNL 325, Second Edition, Supplement No. 2, *Neutron Cross Sections Volume IIA, Z = 21 to 40*, (1966).

source is about one hour. Using one hour for t_i and setting t_c equal to zero, the numbers cited above can be used to compute an induced activity immediately after the use of this source. Consider the activity induced in a cubic centimeter of iron at a distance of one meter from the source. A cubic centimeter subtends 10^{-4} sr at one meter, hence

$$-\frac{dn_v}{dt_c} = \left(\frac{2.00\times10^{7}}{4\pi}\times10^{-4}\right)\frac{6.022\times10^{23}}{55.85}\times \left[1-\exp\left(-\frac{1}{10810}\right)\right]\left(0.2546\times10^{-27}\right)\left(4.841\times10^{5}\right) \quad (7).$$

$$= 1.96\times10^{-2}$$

This figure is in disintegrations per second per gram, seen in 10^{-4} sr at 1 meter. Converting to curies, the specific activity is

$$A = \left(1.96\times10^{-2}\,\mathrm{s^{-1}\,g^{-1}}\right)\left[\frac{1\,\mathrm{Ci}}{3.7\times10^{10}\,\mathrm{s^{-1}}}\right]\left[\frac{4\pi}{10^{-4}}\right] \quad (8).$$
$$= 66.6\ \mathrm{nCi\,g^{-1}}$$

The total number of decays due to this amount of activation is three orders of magnitude less than the nominal "minimal" count rate detectable by survey meters at Fermilab, 2000 cpm.[5] No attempt is made here to consider the activation of a larger object due to the added complexities of self-shielding, attenuation, buildup and variations of the flux density with distance. Furthermore, the efficiency and geometry of the survey meter is not taken into account. However, even a simplistic study such as this is sufficient to demonstrate that the neutron sources at Fermilab will not produce a detectable amount of induced radiation during normal use.

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[4] F. Krueger, Calibration of Radioactive Sources Used by Fermilab ES&H Section for Instrument Calibration and Characterization, R. P. Note 83 (1992).

[5] J. D. Cossairt and A. J. Elwyn, *Response of 1 2/2" by 1" NaI(Tl) with Respect to a Release Criterion*, R. P. Note 87 (1991).

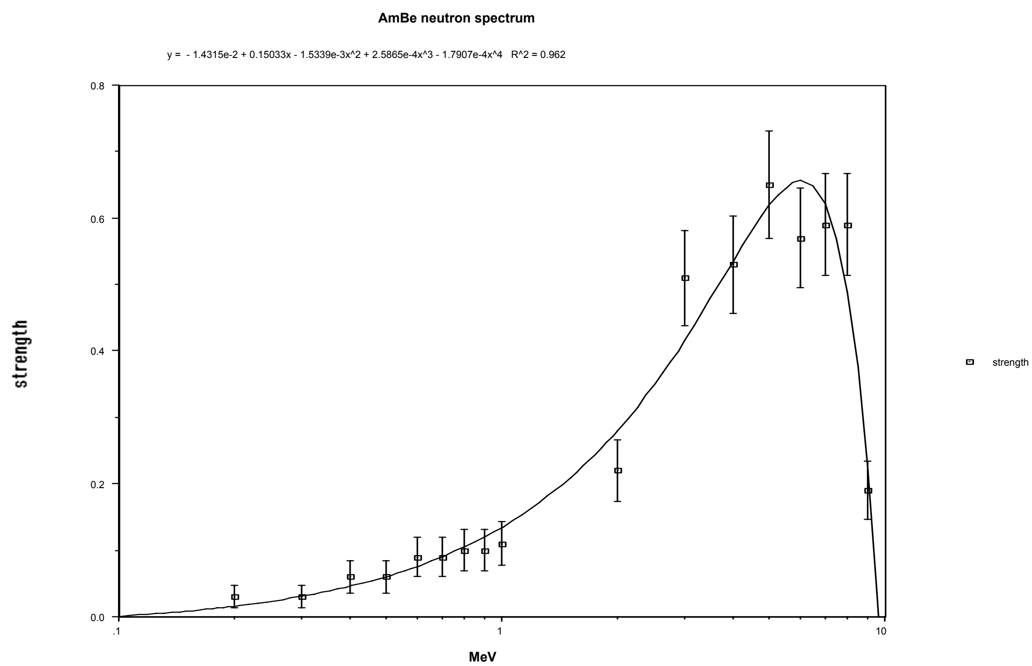

Figure 1. Fitted AmBe Spectrum

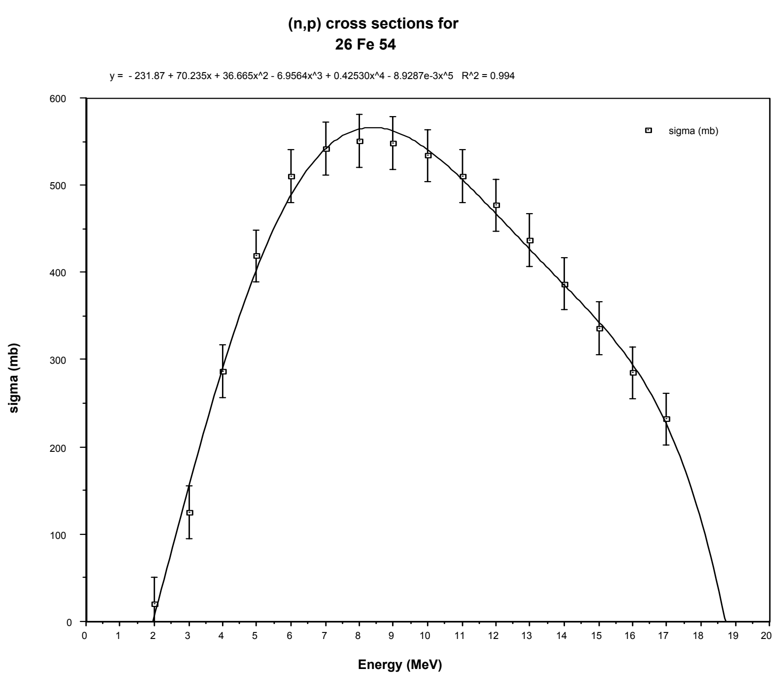

Figure 2. Fitted Cross Section Curve