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Correction to Account for the Isomer of ^{87}Y in the ^{87}Y Radiochemical Diagnostic

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Here we summarize the need to correct inventories of ^{87}Y reported by the Los Alamos weapons radiochemistry team. The need for a correction arises from the fact that a 13.37 hour isomer of ^{87}Y, that is strongly populated through $(n, 2n)$ reactions on ^{88}Y and isomers of ^{88}Y, has not been included in the experimental analyses of NTS data. Inventories of ^{87}Y reported by LANL's weapons radiochemistry team should be multiplied by a correction factor that is numerically close to 0.9. Alternatively, the user could increase simulated values of ^{87}Y by 1.1 for comparison with the original method for reporting NTS values. If the inventories in question were directly reported by LLNL's radiochemistry team, care must be taken to determine whether or not the correction factor has already been applied.

Yttrium is used as a radiochemical diagnostic for the 14 MeV neutron flux in a burning plasma. ^{89}Y is loaded into the system prior to burn, and both ^{88}Y and ^{87}Y are produced via $(n, 2n)$ nuclear reaction that take place during the burn, Fig. 1. The ^{87}Y/^{88}Y ratio is the main diagnostic for determining the 14 MeV neutron fluence. A complication arises in reporting the measured ^{87}Y/^{88}Y ratio because ^{87}Y has an excited state isomer that decays 100% to the ground state of ^{87}Y, with a half-life of 13.37 hours. This ^{87}Y isomer is strongly populated in the $(n, 2n)$ reaction on ^{88}Y [1]. Historically, the importance of this isomer was not known and its contribution to the total ^{87}Y ground state production in measurements, made several days after the shot, was not originally taken into account. Thus, the original method used to back-out inventories at the time of the shot (T=0) from inventories of the ^{87}Y ground state measured at time T=t is equivalent to writing,

$$N^{87}_{g.s.}(T = t) = \exp(-\lambda_{\mathrm{g.s.}}\mathrm{t}) \left[\mathrm{N}^{87}_{\mathrm{g.s.}}(\mathrm{T} = 0) + \mathrm{N}^{87}_{\mathrm{m}}(\mathrm{T} = 0)\right]$$

or equivalently,

$$N^{87}_{g.s.}(T = 0) = \exp(\lambda_{\mathrm{g.s.}}\mathrm{t})\mathrm{N}^{87}_{\mathrm{g.s.}}(\mathrm{T} = \mathrm{t})/\left[1 + \mathrm{X}\right] \quad , \tag{1}$$

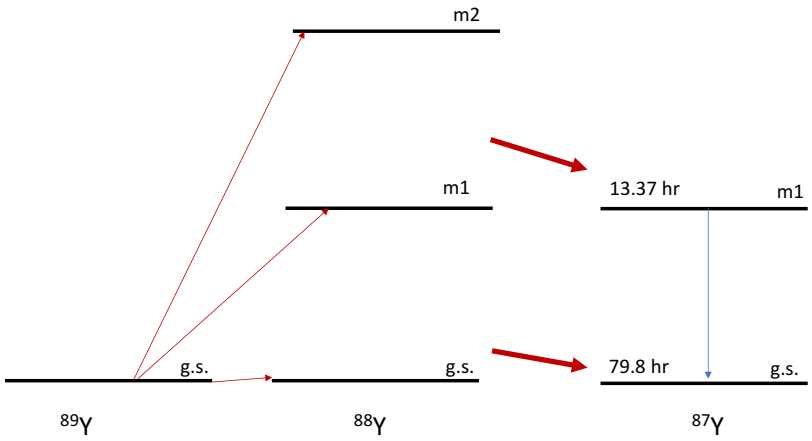

FIG. 1: Schematic of the Yttrium reaction chain, in which the ground state and isomers of ^{88}Y and ^{87}Y are populated. The thick arrows from A=88 to A=87 represent all possible paths populating the g.s. and isomer of ^{87}Y. The isomer of ^{87}Y is strongly populated via $(n, 2n)$ reactions on ^{88}Y and decays to the ground state in 13.37 hours. Historically, this fact was not taken into account in backing out the total production of ^{87}Y at the time of the shot from inventories measured several days later. For this reason a correction must be applied to reported ^{87}Y inventories.

where $X = N_m^{87}(T=0)/N_{g.s.}^{87}(T=0)$ is the ratio of the isomer to ground state population of ^{87}Y at the time of the shot.

However, if we solve the coupled decay equations for the isomer and g.s. of ^{87}Y,

$$\begin{aligned} \frac{dN_{g.s.}^{87}}{dt} &= -\lambda_{g.s.} N_{g.s.}^{87}(t) + \lambda_m N_m^{87}(t) \\ \frac{dN_m^{87}}{dt} &= -\lambda_m N_m^{87}(t) \ , \end{aligned} \tag{2}$$

we find

$$N_{g.s.}^{87}(T=t) = \exp(-\lambda_{\mathrm{g.s.}}\mathrm{t})\mathrm{N}_{\mathrm{g.s.}}^{87}(\mathrm{T}=0)\left[1+\frac{\lambda_{\mathrm{m}}}{\lambda_{\mathrm{m}}-\lambda_{\mathrm{g.s.}}}\left[1-\exp(-(\lambda_{\mathrm{m}}-\lambda_{\mathrm{g.s.}})\mathrm{t})\right]\mathrm{X}\right] \ . \tag{3}$$

Plugging the numerical values for the decay constants $\lambda_{g.s.}$ and λ_m into the above equation, we get,

$$N_{g.s.}^{87}(T=0) \approx \exp(\lambda_{\mathrm{g.s.}}\mathrm{t})\mathrm{N}_{\mathrm{g.s.}}^{87}(\mathrm{T}=\mathrm{t})/\left[1+1.20\left(1-\exp(-0.0432\ \ \mathrm{hr}^{-1}\ \mathrm{t}\right)\mathrm{X}\right]. \tag{4}$$

Because the timescale for NTS radiochemical measurements was typically days after the shot, the term $\left(1-\exp(-0.0432\ \ \mathrm{hr}^{-1}\ \mathrm{t}\right)$ is approximately equal to 1. Comparing eq. (1) to eq. (4), we see that we need to apply a correction factor that is approximately $(1+X)/(1+1.2X)$ to the original method of reporting ^{87}Y inventories. If the ground state and isomer of ^{87}Y are equally populated, so that $X=1$, we get a correction of 0.9. Alternatively, a direct comparison between the reported value and a simulated value can be made by multiplying the simulated value by 1.1.

In terms of the available measurements for population of the isomer of ^{87}Y, Prestwood *et al.* [1] measured the $(n,2n)$ cross sections for $^{88}\mathrm{Y}_{g.s.}$ at 14.19±0.04 MeV and at 14.8±0.1 MeV, and found isomer ratios $\left(\frac{m}{m+g.s.}\right)$ of 0.7±0.05 and 0.74±0.05, respectively. Measurements of the isomer-to-ground-state ratio from $(n,2n)$ reactions on the isomers of ^{88}Y are not available. Shaughnessy *et al.* [2] have proposed that very high yield capsules at the National Ignition Facility could be used for such studies.

Finally, we comment on how the correction to ^{87}Y inventories are currently being treated. At Los Alamos, a decision was made that the weapons radiochemistry group (now C-NR) would continue to report ^{87}Y inventories without correcting for the isomer, and the user (now XTD-Div) would include a $(1+1.2X)/(1+X) \approx 1.1$ multiplicative correction to their simulated value for the total production of ^{87}Y. It is very important to note that LLNL did not necessarily choose to follow this method and when using LLNL ^{87}Y measured values the user needs to check which number is being reported, i.e., an uncorrected or a corrected value.

[1] Rene J. Prestwood, Kimberly W. Thomas, David R. Nethaway, and Norman L. Smith, Phys. Rev. **C 29**, 805 (1984).
[2] D. Shaughnessy, Lawrence Livermore National Laboratory, *private communication*, and D. Shaughnessy, NEDPC (2017).