ORIGIN OF *r*-PROCESS RADIONUCLIDES IN THE EARLY SOLAR SYSTEM. S.P. Marcum[1], Q.R. Shollenberger[2], M.R. Mumpower[3], J.M. Miller[3], T.M. Sprouse[3], and E.D. Young[1], [1]Department of Earth, Planetary, and Space Sciences, UCLA, USA (smarcum13@ucla.edu, eyoung@epss.ucla.edu), [2]Lawrence Livermore National Laboratory, Livermore, CA, USA (shollenberger@llnl.gov), [3]Los Alamos National Laboratory, Los Alamos, NM, USA (mumpower@lanl.gov, jonahm@lanl.gov, tmsprouse@lanl.gov).

Introduction: The birth environment of the Solar System can be understood through a combination of astronomical observations, astrophysical modeling, and meteoritic measurements of short- and long-lived radionuclides. Understanding the origins of radionuclides produced via the rapid neutron capture process (*r*-process) of nucleosynthesis is important because many isotopes born from this process serve as chronometers that constrain the origin and evolution of our galaxy. The astrophysical setting for the *r*-process had often been thought to be core-collapse supernovae [1]. However, the recent observation of the gravitational wave event GW170817 [2] and the inference of lanthanide elements in the ejecta demonstrate that kilonova events (*e.g.,* neutron star mergers, neutron star-black hole mergers) are potential production sites of *r*-process elements [3, 4].

Two general models have been put forth by cosmochemists to explain the abundances of Solar System radionuclides [5]. The first is a one-phase model of the interstellar medium (ISM) in which single, discrete events are responsible for the solar abundances deduced from studies of meteoritical materials [6, 7]. The ISM is populated by long-lived nuclides as a result of these discrete nucleosynthetic events and it is enriched in short-lived radionuclides (SLRs) from the most recent event. This model is described by the equation

$$\frac{N_\mathrm{R}}{N_\mathrm{S}} = \left[\frac{P_\mathrm{R}}{P_\mathrm{S}}\,\frac{\delta t}{T}\left(1+\frac{\mathrm{e}^{-\delta \mathrm{t}/\tau}}{1-\mathrm{e}^{-\delta \mathrm{t}/\tau}}\right)\right]\mathrm{e}^{-\Delta t/\tau} \quad (1)$$

where N_i and P_i are the number and production rates for radionculides (R) and stable isotope partner (S), δt is the average time between events, T is the age of the Galaxy at the time of Solar System birth, Δt is the time interval between the most recent event and the beginning of the Solar System, and τ is the mean life of R. This equation is completely general, and does not require P_R and P_S to represent the same events. Recent studies invoking kilonovae sources of *r*-process nuclides have focused on this type of model (*e.g.,*[8]). The alternative model, involving a two-phase ISM, suggests that the Solar System sampled averages accrued over time in the star-forming region in which the Sun formed [9]. This model is described by the expression

$$\log\left(\frac{N_\mathrm{R,MC}}{N_\mathrm{S,MC}}\right) - \log\left(\frac{P_\mathrm{R}}{P_\mathrm{S}}\right) = 2\log\tau - \log\left[(1-x_\mathrm{MC})\tau_\mathrm{MC}+\tau\right] - \log T, \quad (2)$$

where the abundances of radionuclides and their stable partners are contained in molecular clouds. The parameters τ_{MC} and x_{MC} are the residence time in clouds and mass fraction of the Galaxy contained within. Actinides are not the best arbiters for these two models, but they are used for cosmochronology, the dating of the Galaxy. Here we use modern nucleosynthesis simulations of potential *r*-process sites, including neutron star mergers and a neutron star-black hole merger, to obtain the production ratios of specific actinides in these events and determine if these new production ratios are consistent with meteorite data and established cosmochronology constraints (*i.e.,* the 10 to 13 Gyr age of the Galaxy).

Methods: Nucleosynthesis simulations were run using the reaction framework Portable Routines for Integrated nucleoSynthesis Modeling (PRISM) developed by T. Sprouse and M. Mumpower. PRISM can simulate the production of individual isotopes given a set of trajectories that describe the astrophysical parameters of a given nucleosynthesis event and their associated initial conditions. This allows for the extraction of production ratios of the radionuclides of interest. It is important to use ratios normalized to a stable, reference nuclide to account for the differences in the chemistry between the nuclides. In the case of the actinides, there is no stable reference, so the long-lived isotope ^{232}Th is used as the reference nuclide. After the production ratios are determined, the solar abundance ratios of the radionuclides normalized to ^{232}Th are divided by the production ratios. This accounts for variations in the production ratios for the different nuclides. The resulting value is a normalized relative abundance (α) that can be plotted vs the mean lives (τ) of the radionuclides. Comparison with Eqns. (1) and (2) suggests that α should depend only on the mean life. Comparing the simulation values from various nucleosynthesis events with the ISM model curves may suggest a most likely astrophysical site of *r*-process nuclides in the Solar System.

In this work, we ran four different *r*-process events through PRISM: simple dynamical ejecta trajectory sets of two neutron star merger environments, a neutron star-

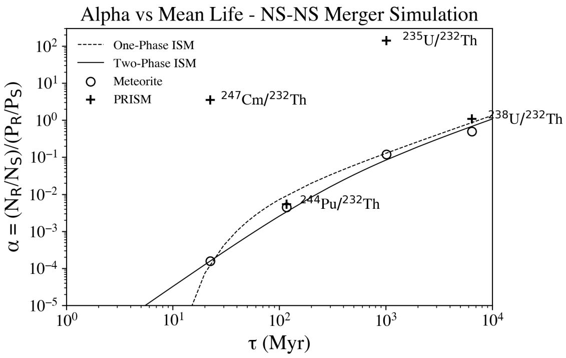

Figure 1: The normalized abundance ratio α vs mean life τ for four actinides from a simulation of the accretion disk of a neutron star merger event. The ^{244}Pu and ^{238}U values obtained from PRISM (pluses) match well with the values used by cosmochemists (circles), but the values of ^{247}Cm and ^{235}U are radically different. The one-phase and two-phase ISM curves are shown for an age of 13 Gyr for our Galaxy.

black hole merger event [10], a simulation of the accretion disk of a neutron star merger [11], and a collapsar simulation [12]. The outputs from these events were used to extract the production ratios for the isotopes of interest, including ^{235}U/^{232}Th, ^{238}U/^{232}Th, ^{244}Pu/^{232}Th, and ^{247}Cm/^{232}Th.

Results: The normalized abundance ratios (α) vs mean life (τ) for four actinides produced by the *r*-process from a neutron star merger event are shown in Figure 1. The α values for ^{238}U/^{232}Th and ^{244}Pu/^{232}Th are in good agreement with those predicted by models for a Galactic age of 13 Gyr [5]. However, there is significant disagreement between the values for ^{235}U/^{232}Th and ^{247}Cm/^{232}Th predicted by our models and predictions based on the age of the Galaxy [5]. The output of the dynamical ejecta of two neutron star merger environments and the neutron star-black hole event (Figure 2) give similar results to those presented in Figure 1. The collapsar simulation does not produce significant amounts of the actinides.

Discussion and Conclusions: The fact that the collapsar simulation does not produce actinides whereas the neutron star merger events and the neutron star-black hole event do may prove useful for understanding the site(s) of *r*-process element production. Nonetheless, there is still uncertainty in the modeling of these events and collapsars cannot be ruled out as possible *r*-process production sites.

The results obtained from the neutron star merger events and the neutron star-black hole event in this work demonstrate that three actinides out of five (^{232}Th, ^{238}U, ^{244}Pu) are predicted to be produced at a level that is consistent with previous production ratios estimated from supernova environments [5]. In these cases, the kilonova origin is consistent with constraints from cosmochronology. Conversely, the predictions for ^{235}U and ^{247}Cm are inconsistent with cosmochronology constraints (Figures 1 and 2); their relative abundances cannot be reconciled with reasonable ages for the Galaxy. Either the models are incomplete, or these nuclides were not produced in kilonova events. This work demonstrates that in some cases the actinide production ratios of *r*-process nuclides are indistinguishable from previous supernova estimates, but in other cases large discrepancies exist. Examining the production ratios obtained for other environments, such as magnetorotational supernovae, will be useful to further assess the possible site(s) of the *r*-process.

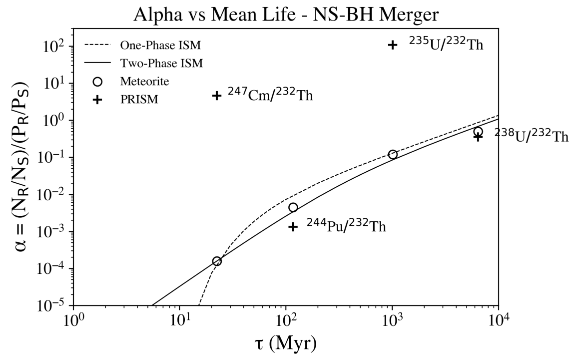

Figure 2: The normalized abundance ratio α vs mean life τ for four actinides from a neutron star-black hole merger event. The ^{244}Pu and ^{238}U values obtained from PRISM (pluses) match well with the values used by cosmochemists (circles), but the values of ^{247}Cm and ^{235}U do not. The one-phase and two-phase ISM curves are shown for an age of 13 Gyr for our Galaxy.

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