ORIGIN OF *r*-PROCESS RADIONUCLIDES IN THE EARLY SOLAR SYSTEM.

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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 kilanova events (*e.g.,* neutron star 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. 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]. 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 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). PRISM can simulate the production of individual isotopes given a set of trajectories that describe the astrophysical parameters of a given nucleosyhthesis 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. 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). Here we ran four different *r*-process events through PRISM: simple dynamical ejecta trajectory sets of two neutron star merger environments, a neutron star-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 of interest (*i.e.,* ^{235}U/^{232}Th, ^{238}U/^{232}Th, ^{244}Pu/^{232}Th, and ^{247}Cm/^{232}Th).

Results and discussion: For the neutron star merger events and the neutron star-black hole event, 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 collapsar simulation does not produce significant amounts of the actinides.

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; 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. Nonetheless, 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.

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