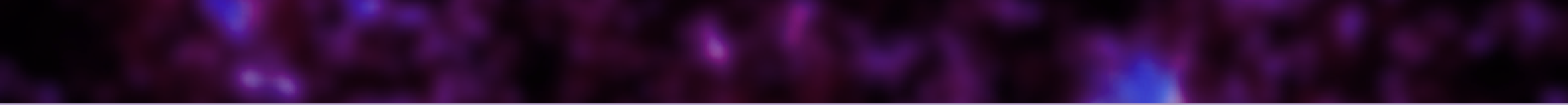


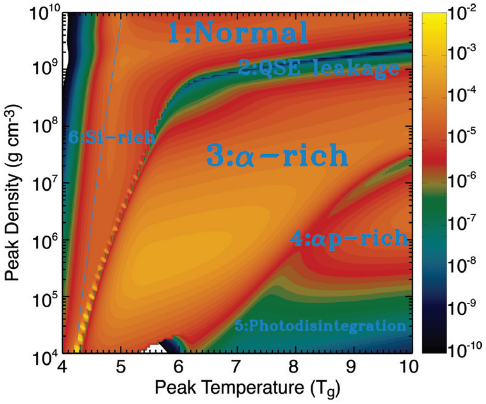
Nucleosynthesis in the Universe, Understanding ^{44}Ti

Chris Fryer, CCS-2; Guy Dimonte, XCP-5; Carola Ellinger, Arizona State University; Aimee Hungerford, XTD-6; Bob Kares, XCP-8; Georgios Magkotsios, Notre Dame University; Gabriel Rockefeller, CCS-2; Frank Timmes, Arizona State University; Paul Woodward, University of Minnesota; Patrick Young, Arizona State University

Understanding the origin of the elements remains one of the greatest mysteries in the universe. LANL scientists have brought together a broad team to better understand the origin of the elements, focusing on the production of a particularly difficult-to-explain radioactive isotope of titanium. Using detailed theoretical models combining nuclear physics, computational physics, and turbulence theories, LANL scientists will compare the production of this isotope to observations from the upcoming NASA satellite NuSTAR. This comparison of theory and observations will help scientists to understand the production of titanium and a broad set of related elements injected into the universe by supernovae.

Mankind, the earth we live in, and the solar system are all composed of the debris from supernova explosions. Understanding how supernovae produce these elements and inject them into the universe to form planets like the Earth remains one of the major research areas of nuclear astrophysics. LANL scientists have leveraged LANL expertise in computational radiation-hydrodynamics, turbulence, and nuclear physics (both theory and experiment) to advance our understanding of the production of these elements in the universe.

Fig. 1. Titanium production (color-coded) as a function of peak temperature and density in the supernova shock. In this production, we identified six separate regions where different nuclear rates played primary roles in determining the ultimate titanium yield.



The process in which stars and supernova fuse hydrogen into heavier elements and inject them into the universe is known as nucleosynthesis. One of the key pieces to understanding the nucleosynthetic-yield puzzle is the production of the radioactive isotope of titanium (^{44}Ti). Titanium-44 is believed to be formed in the same place as a radioactive nickel isotope (^{56}Ni)[1]. On the surface, it appears that ^{44}Ti is a typical alpha element, produced in the supernova shock, as it reassembles alpha particles (^{4}He) into heavier elements. Past models predicted a fairly constant ratio of ^{44}Ti/^{56}Ni production. But explaining the high value of the ratio of ^{44}Ti/^{56}Ni in supernova remnants has proved to be extremely difficult for theoretical models.

Fully understanding the production of ^{44}Ti requires combining a broad set of physics and astrophysics—nuclear physics, stellar evolution, and supernova explosion models (and the radiation-hydrodynamics and turbulent mixing required to model supernova explosions). This full understanding also requires strong ties to observational diagnostics. This year, LANL scientists brought together a broad scientific effort study to include all aspects of ^{44}Ti production in the universe. This effort includes experts in nuclear physics, turbulence, and computational science. In early 2012, NASA will launch the satellite NuSTAR (Nuclear Spectroscopic Telescope Array) to study ^{44}Ti production in supernovae. One of the primary goals of this satellite is to map out the ^{44}Ti yield from the supernova remnant Cassiopeia A. Members of our team have joined the NuSTAR science team, and this year we focused our theory efforts on providing detailed predictions for these Cassiopeia A observations.

As a first step, LANL worked closely with nuclear astrophysicists at Arizona (F. Timmes) and Notre Dame (G. Magkotsios, M. Wiescher) Universities to study the effect of nuclear uncertainties on the ^{44}Ti yield. Contrary to previous beliefs, the ^{44}Ti yield is not just sensitive to the triple-alpha nuclear rate[1]. This study showed that ^{44}Ti is produced through a variety of processes, and a range of nuclear-rate uncertainties are important in predicting the ultimate production of ^{44}Ti. Figure 1 shows the titanium yield as a function of the peak temperature and density in a supernova shock. We identified six regions of titanium production, all sensitive to different nuclear reaction rates. These different regions each have yields sensitive to different reactions, explaining why the observed ^{44}Ti and ^{56}Ni production are not as tightly correlated as the simplified models assumed. The Facility of Rare Isotope Beams at Michigan State University will help reduce many of the uncertainties in our ^{44}Ti production knowledge, and we are now working closely with these scientists to develop experimental strategies to drive down these uncertainties.

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[1] ^{56}Ni ultimately decays into iron and it is this particular isotope that makes up the bulk of the iron we have on earth.

For more information contact Chris Fryer at fryer@lanl.gov.

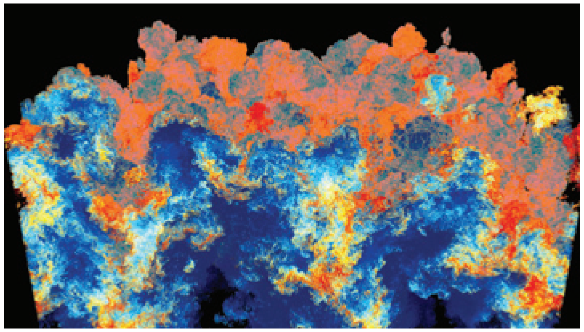

Fig. 2. Three-dimensional material boundary surfaces (color-coded) of a Rayleigh-Taylor turbulence simulation of an initial broadband perturbation spectrum. The growth rate of the bubbles and plumes is critical in determining the outward mixing of titanium within the supernova ejecta. This particular simulation used the Woodward PPM code and began with a resolution of 8000x8000x1000 and was allowed to coarsen and expand (in the y axis) as the perturbations grew. It ran on more than 8400 ranks of the Roadrunner machine for nearly a week. We use these simulations to verify our supernova explosion codes.

Understanding the nuclear burning is only one piece of the nucleosynthetic yield puzzle. To compare with the planned observations of NuSTAR, we must also calculate how these nuclear products are dispersed into the universe in supernova explosions. Supernova explosions are incredibly turbulent, developing both Rayleigh-Taylor and Richtmeyer-Meshkov instabilities. To understand this turbulence, our astrophysics team leveraged LANL's expertise in turbulent mixing. Led by Guy Dimonte and working with Paul Woodward, our team used Woodward's PPM code to run the highest resolution Rayleigh-Taylor mixing problem on the Cell BE-based Roadrunner machine. Figure 2 shows the results of a calculation of Rayleigh-Taylor instabilities using a broadband initial spectrum. The initial broadband spectrum allows mode coupling that accelerates the growth rate of both plumes and bubbles in the convection. Accurate calculations of this mixing are essential in comparing to both laboratory experiments and, ultimately, our astrophysical supernova experiment. This calculation ran on over 8400 ranks of the Roadrunner machine for over 1 week. With these detailed calculations, we are able to verify our supernova explosion codes, increasing our confidence in their performance in characterizing supernova mixing.

Our supernova explosion codes must cover a broad range of size scales to follow the shock at 10^9 cm out to the remnant sizes of 10^{18} cm. In addition, we must calculate the nuclear burning in this matter as the shock moves through the star. The SNSPH code, a parallel 3D smoothed particle hydrodynamics code [2], is ideally suited for such calculations. Working with Patrick Young at Arizona State University, LANL scientists have homed in on the progenitor of the Cassiopeia A remnant system. Working with LANL scientists to incorporate a 19-isotope network in the SNSPH code, Carola Ellinger of Arizona State University has calculated the titanium ejecta in the Cassiopeia A supernova remnant. Figure 3 shows the results of a 50-million particles calculation, focusing on the ^{44}Ti yields. This calculation is the largest smooth particle hydrodynamics supernova calculation ever run. This work will be post-processed using more detailed networks and including the uncertainty calculations studied by Magkotsios et al. [1]. These results, in turn, will be passed through NuSTAR detector filters, allowing us to make direct predictions for the NuSTAR observations of Cassiopeia A.

In this project, we have combined detailed nuclear physics studies with turbulence models and astrophysical calculations. In this way, we move from turbulent studies of laboratory experiments to studies of the nucleosynthetic yields from an astrophysics supernova experiment.

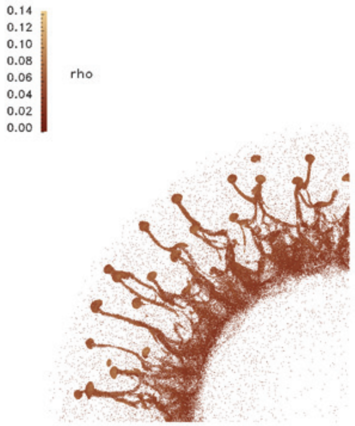

Fig. 3. Titanium density (color-coded) from a symmetric supernova explosion (one octant of a 4π calculation). Rayleigh-Taylor and Richtmeyer-Meshkov instabilities mix outward the titanium yield. This image is from a 50-million particle smooth particle hydrodynamics calculation (using the SNSPH code) and marks one of the largest supernova calculations using this technique.

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[2] Michael Wiescher, a nuclear experimentalist at Notre Dame University is also one of the principal investigators of the Joint Institute of Nuclear Astrophysics and a major player in the Facility for Rare Isotope Beams and Michigan State University.

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[1] Magkotsios, G., et al., *Astrophys J Suppl* **191,** 66 (2010).
[2] Fryer, C.L., et al., *Astrophys J* **643,** 292 (2006).

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