

calculation and movie by Erika Holmbeck, nsm trajectory from Just+2015

 σ

nuclear data required for r -process simulations

seed assembly charged particle reactions e.g., ${}^4\mathsf{He}(\alpha\eta,\gamma) {}^9\!\mathsf{Be}$

masses beta-decay rates beta-delayed neutron emission probabilities neutron capture rates

> fission rates fission product distributions neutrino interactions

sensitivity study review: Mumpower, Surman, McLaughlin, Aprahamian Progress in Particle and Nuclear Physics 86 (2016) 86

R Surman

R Surman

 σ

r-process abundance pattern signatures

nuclear data required for r -process simulations

seed assembly charged particle reactions e.g., ${}^4\mathsf{He}(\alpha\eta,\gamma) {}^9\!\mathsf{Be}$

masses beta-decay rates beta-delayed neutron emission probabilities neutron capture rates

> fission rates fission product distributions neutrino interactions

sensitivity study review: Mumpower, Surman, McLaughlin, Aprahamian Progress in Particle and Nuclear Physics 86 (2016) 86

R Surman

nuclear data required for r -process simulations

Progress in Particle and Nuclear Physics 86 (2016) 86

R Surman

required nuclear data: ${}^4He(\alpha n, \gamma) {}^9Be$

required nuclear data: masses

nuclear masses from AME 2016

R Surman

Notre Dame

-47 TM

 $\frac{1}{2}$

masses beta-decay rates beta-delayed neutron emission probabilities neutron capture rates

> fission rates fission product distributions neutrino interactions

required nuclear data: masses

nuclear masses from AME 2016

R Surman

Notre Dame

-47 TM

 $\frac{1}{2}$

masses

while (n, γ) – (γ, n) equilibrium holds, the neutron separation energies determine the abundances along an isotopic chain:

$$
\frac{Y_{eq}(Z, A+1)}{Y_{eq}(Z, A)} = \frac{G(Z, A+1)}{2G(Z, A)} n_n \left(\frac{2\pi \hbar N_A}{m_n kT} \right)^{3/2} \exp \left[\frac{S_n(Z, A+1)}{kT} \right]
$$

r-process uncertainties: masses

r-process uncertainties: masses

SKM*

SLY4

 $SKP-3$

SV-MIN

UNFDF0

NEDF1

Surman, Mumpower, McLaughlin 2016

masses from massexplorer.frib.msu.edu: Olsen, Nazarewicz:

see also Martin+2016

experimental prospects at FRIB: masses

AME 2016 FRIB Day 1 reach FRIB design goal

TITTILILILILILI

experimental prospects at FRIB: masses

required nuclear data: beta decay

beta decay properties from NUBASE 2016

R Surman

Notre Dame

-47 TM

 $\frac{1}{2}$

masses beta-decay rates beta-delayed neutron emission probabilities neutron capture rates

> fission rates fission product distributions neutrino interactions

required nuclear data: beta decay

beta decay properties from NUBASE 2016

R Surman

Notre Dame

-47 TM

 $\frac{1}{2}$

beta-decay rates

determine the relative abundances of the isotopic chains through the steady beta flow condition:

 $\lambda_{\beta}(Z, A_{path})Y(Z, A_{path}) \sim$ constant

r-process uncertainties: beta decay rates $S₃$ 102 *r*-process nuclearity of the state anos italiaise, pota aooay ratoo $\frac{1}{2}$ \cdot upoortointiga: hota

R Surman Notre Dame -47 TM $\frac{1}{2}$

r –process uncertainties: beta decay rates We take *µ* = 0 and = ln(1*.*4) which yields a spread in heta decay rates corre

r-process uncertainties: beta decay rates

experimental prospects at FRIB: beta decay

NUBASE 2016 FRIB Day 1 reach FRIB design goal

THEFT LITTLE

experimental prospects at FRIB: beta decay

required nuclear data: neutron capture rates

neutron capture rates from

KADONIS database

R Surman

Notre Dame

-47 TM

 $\frac{1}{2}$

masses beta-decay rates beta-delayed neutron emission probabilities neutron capture rates

> fission rates fission product distributions neutrino interactions

r-process uncertainties: neutron capture rates

experimental prospects at FRIB: neutron capture

TIJT

KADONIS $FRIB(d,p)$ **FRIB beta Oslo**

VIIIIIIIIIIIIIIIIIIIIIIIII

ITTLE

experimental prospects at FRIB: neutron capture

ШI

Example 3: August binary mergers discussed by the compact of the *reprocess* uncertainties: fission

9

of 0.2–0.4 *c*, electron fractions below ⇠ 0*.*1, and entropies per baryon of a few *k*B. The considered $\tilde{\Xi}$ mergers produce $\tilde{\Xi}$

R Surman

Notre Dame

-47 TM

 $\frac{1}{2}$

cantly larger masses, 0.035–0.08 *^M*, with very low entropies (*<*⇠ ¹*k*^B per nucleon), because this $m \angle E = 1$

2. Ejecta from the Merger Phase

11

12.5 13 13.5

Fig. 1.4— Final abundances of the integration and the second and α their relative shortcomings. However, it is important to FIRE: Fission In R−process Elements Although there are many uncertainties in the as-US DOE/NNSA Topical Collaboration

relative contributions of each r-process model based upon

ies (Shen et al. 2015; van de Voort et al. 2015) along with better r-process hydrodynamic models (Winteler et al. 2012; Perego et al. 2014; Rosswog et al. 2014; Wanajo, et al. 2014; Goriely et al. 2015; Just et al.

required input data: neutrinos

masses beta-decay rates beta-delayed neutron emis¹⁰⁻³ neutron capture rates

fission rates TISSION rates
fission product distributions \overline{z} neutrino interactions

the rare earth peak

Its formation mechanism is sensitive to both the astrophysical conditions of the late phase of the r process and the nuclear physics of the nuclei populated at this time

Surman, Engel, Bennett, Meyer 1997

rare earth peak formation

Mumpower, McLaughlin, Surman 2012

rare earth peak formation $m_{\rm{max}}$ mode continuo patterns, as in the **in Fig. 2. Such fragment distributions in Fig. 2. Support in Fig. 2.** scale of neutron capture becomes longer than a few sec-

of the 110 & A & 170 nuclei in the decompression of NS

matter, present and unexpected double and unexpected double \mathcal{P}_max

rare earth peak formation and nuclear masses

rare earth peak formation and nuclear masses

Neodymium ($Z = 60$) isotopic chain

reverse-engineering rare earth masses to rare e-opoino oring rare oarth mass os is verse engineering rare carefullaces

mass modification parameterization:

R Surman

Notre Dame

-47 TM

 $\frac{1}{2}$

 $\mathcal{C}(\mathcal{C})$

too low. A standard supernova neutrino wind is a hot

tidal tails of neutron star mergers is both cold and very

neutron rich. We apply our Monte Carlo procedure to

gion in which we are interested, we require a theoretical

 $\mathbf{F}_{\mathbf{r}}$

 $\mathcal{P}_\mathcal{A}$.

masses away from stability in the rare earth region. To

 $\sqrt{2}$

 \mathbf{r}_c

of *r*
r
process si

 $\frac{5}{5}$

 $\frac{1}{2}$

 \mathcal{A}

$$
M(Z, N) = M_{DZ}(Z, N) + a_N e^{-(Z-C)^2/2f}
$$

reverse-engineering rare earth masses

rare earth peak formation comparison

theory-only predicted mass surfaces

Neodymium ($Z = 60$) isotopic chain

summary

Evidence increasingly suggests compact object mergers are the primary site of synthesis of the heaviest elements, though many uncertainties remain.

On the nuclear physics side, current and next-generation radioactive beam facilities will continue to push the boundaries of measurements of extremely neutron-rich nuclei. current and next-generation
continua to push tha boundarias **at FRIB**

As nuclear physics uncertainties are reduced, we can exploit details of the r -process abundance pattern, such as the rare earth peak, to explore the nature of r process environments.

R Surman

Notre Dame

-47 TM

 $\frac{1}{2}$

