PROCEEDINGS OF SCIENCE

Neutrinos and their impact on the nucleosynthesis in binary neutron star mergers

Vimal Vijayan,[a,b,*] **Andreas Bauswein**[a,c] **and Gabriel Martínez-Pinedo**[a,c,d]

[a] *GSI Helmholtzzentrum für Schwerionenforschung,*
Planckstraße 1, 64291 Darmstadt, Germany

[b] *Department of Physics and Astronomy, Ruprecht-Karls-Universität Heidelberg,*
Im Neuenheimer feld 226, 69120 Heidelberg, Germany

[c] *Helmholtz Forschungsakademie Hessen für FAIR, GSI Helmholtzzentrum für Schwerionenforschung,*
Planckstr. 1, 64291 Darmstadt, Germany

[d] *Institut für Kernphysik (Theoriezentrum), Department of Physics, Technische Universität Darmstadt,*
Schloßgartenstraße 7, 64289 Darmstadt, Germany

E-mail: v.vijayan@gsi.de

The first observation of gravitational waves and electromagnetic emission from a neutron star merger in August 2017 highlighted the importance of these events for element formation through the rapid neutron capture process. We describe simulations of neutron star mergers with an advanced treatment of weak interactions, which are important to obtain reliable predictions of the composition of the outflows from these events. Our simulation data are post-processed by nuclear network calculations to obtain the abundance pattern in the ejecta.

FAIR next generation scientists - 7th Edition Workshop
23-27 May 2022
Paralia, Pieria, Greece

*Speaker

PoS(FAIRness2022)061

1. Introduction to BNS mergers

Neutron stars (NSs) are the final remnant product of the collapsed core of a massive star formed in core-collapse supernova. They are one of the most dense objects found in the universe with a mass of 1-2 $M_\odot$ and a radius of about 10-15 km. This implies densities that exceed several times the nuclear saturation density. A binary system of NSs consists of two neutron stars that inspiral for millions of years and finally merge within the timescale of a few milliseconds. Depending on the equation of state (EoS) of high-density matter, they either promptly collapse into a black hole (BH) or become a massive differentially rotating NS [1]. The gravitational wave signal emitted from these binary neutron star (BNS) mergers provides immediate constraints on the EoS, which is not precisely known. In addition, BNS mergers are progenitors of short gamma ray burst (sGRB). The ejecta from mergers provide favourable conditions for the rapid neutron capture process (r-process), which forms about half of all heavy nuclei. So far, BNS mergers are the only confirmed astrophysical site, where this process takes place [2].

2. Observational evidence

The first unambiguous multi-messenger detection of a BNS merger was GW170817 [3, 4]. It was observed not only by graviational waves but also through gamma, X-rays, UV, optical, IR, radio emission with the optical transient, the so called kilonova [5, 6], being visible over days. The kilonova is generated by thermal emission from an initially opaque, hot, expanding ejecta cloud, which becomes transparent on the timescale of days, i.e. the luminosity peaks on these timescales. The emission shifts from blue to red, which is often interpreted as originating from different ejecta components, where the blue emission stems from lanthanide poor material and the reddish emission from lanthanide rich material that has a high opacity (e.g. [7]). The spectrum of the kilonova shows broad absorption features, which were associated with strontium [8]. Strontium is an element which is produced by the r-process, providing strong evidence that this nucleosynthesis process took place in the ejecta of GW170817. Considering estimated merger rates and the estimated ejecta mass of GW170817 suggests that BNS mergers are one of the major sources of heavy element production in the Universe.

3. Dynamical simulation with neutrinos

The interpretation of kilonovae is heavily based on numerical simulations. To simulate BNS merger systems, we use a relativistic smoothed particle hydrodynamics code [9] that employs the conformal flatness condition to solve the Einstein field equations. Here, we consider a 1.35-1.35 $M_\odot$ binary system described by the SFHo [10] or DD2 EOS [11, 12]. The simulation is ran until $\sim 20\,ms$ after the merger took place. Regarding the r-process, a key parameter to quantify the amount of neutrons is the electron fraction Y_e, since it determines the neutron to seed ratio [2]. The large temperatures occurring during the merger lead to weak interactions modifying the electron fraction in a fair portion of the ejecta. These changes are attributed to the large amount of neutrinos produced at those temperature and their interaction with free protons and free neutrons, which changes the ejecta composition in a significant amount. Most important are beta reactions:

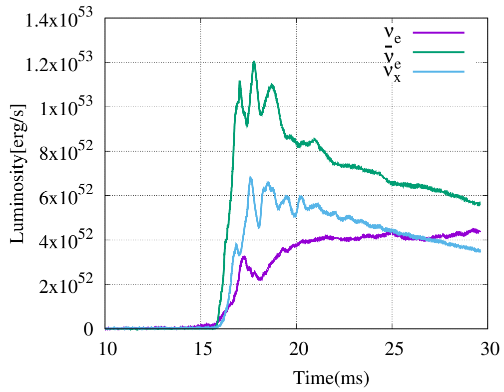

Figure 1: Luminosity of different neutrino species (electron neutrino, electron anti-neutrino and a single heavy neutrino species) as function of time for a 1.35-1.35M$_\odot$ BNS system with the SFHo EoS.

$$\nu_e + n \leftrightarrow p + e^- \tag{1}$$
$$\bar{\nu}_e + p \leftrightarrow n + e^+. \tag{2}$$

Also, the high temperatures lead to numerous electron-positron pairs, and in particular positron captures on neutrons increase Y_e [2]. These considerations exemplify the importance of including these reactions in hydrodynamical merger simulations.

We use a state of the art neutrino treatment. The ILEAS scheme (Improved Leakage Equilibration Absorption scheme) [13] includes three types of neutrinos: electron neutrinos ν_e, electron anti-neutrinos $\bar{\nu}_e$ and ν_x represents the heavy neutrinos combined as a single type. Unlike traditional leakage schemes [14], this method takes into account not only the leakage of energy and neutrinos from the optically thick region, but also the re-absorption of neutrinos in optically thin regions using a sophisticated ray-tracing algorithm. Finally, at each time step of the simulation, the scheme includes an equilibration step to conserve the lepton number in the optically thick region. The complete details of the scheme can be found in [13].

Once the simulation finished, for post-processing and nuclear network calculations, we extract the trajectories (the evolution of the density, temperature and Y_e) of each of the individual unbound fluid elements (because of the SPH method we often use the term 'particle' to refer to a specific fluid element). Ejecta particles are identified by considering an energy criterion comparing kinetic, thermal and gravitational energy to judge which fluid elements become gravitationally unbound [9].

Figure 1(a) shows the luminosity of each of the individual neutrino species, i.e. electron neutrino, electron anti-neutrino and a single species of heavy neutrinos. We note that neutrino emission is stronger in the polar directions compared to the equatorial ones, which results in more significant change of Y_e along the poles e.g. [13].

4. Network calculation

We start a time-dependent nuclear network calculation for each SPH particle when the temperature of the ejected particle drops to 1 MeV ($\sim 10^{10} K$). If the temperature of the particle is still above

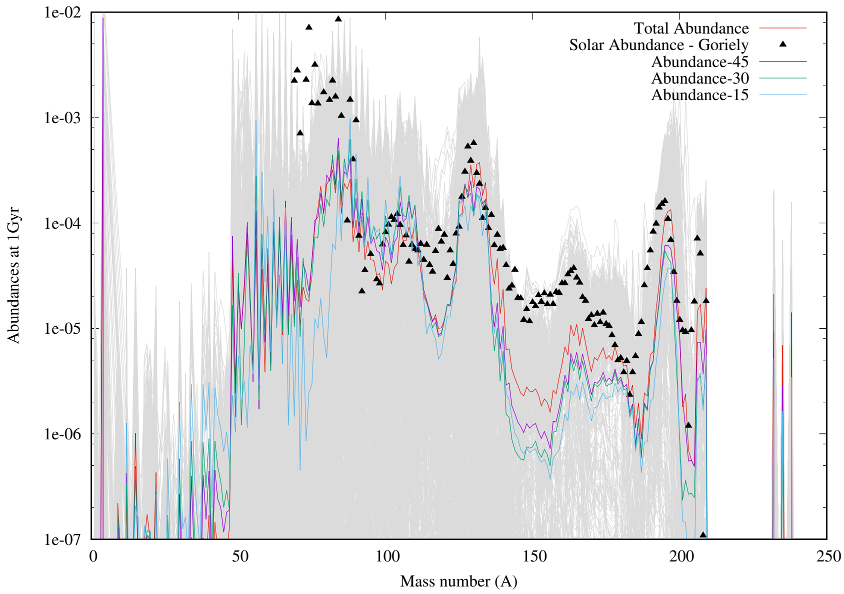

Figure 2: The combined total abundance from each ejected particle for a 1.35-1.35M$_\odot$ BNS system with the SFHo EoS compared to the solar abundance. The blue, green and purple lines display the abundance for the ejecta binned by their polar angle θ (blue: $0° < \theta < 15°$, green: $0° < \theta < 30°$ and purple: $0° < \theta < 45°$). The grey lines visualize the abundance pattern of all individual trajectories.

1 MeV at the end of the simulation, we use the temperature reached at the end of the hydrodynamical simulation. And, we use the same nuclear reaction network as in [15]. In these calculations, Y_e is taken to be the value reached at the end of the hydrodynamical simulation as it already reached a plateau at these times for most of the ejected particles. For the given temperature and Y_e the initial ejecta composition is obtained by assuming nuclear statistical equilibrium (NSE) together with the density from the SPH data. Since the nucleosynthesis calculations cover a period of time beyond the end of the hydrodynamical simulation, the density evolution is extrapolated assuming homologous expansion that fulfills the condition $\rho(t)r(t)^3 = \rho_0 r_0^3$. Here $r(t) = r_0 + v_0(t - t_0)$ with r_0 and v_0 being the radial position and velocity at time t_0 at the end of the simulation time ($\sim 20\,ms$ after merger). The density evolution is obtained using the expression

$$\rho(t) = \rho_0 \left(\frac{\Delta + t_0}{\Delta + t}\right)^3 \tag{3}$$

where $\Delta = \frac{r_0}{v_0} - t_0$.

From the nucleosynthesis network calculations, we finally obtain the abundance for each individual trajectory. We combine all trajectories to compute the total abundance, which is compared to the solar abundance. This is shown in Fig. 2 for a 1.35-1.35M$_\odot$ binary system with the SFHo EoS and in Fig. 3 for the same setup with the DD2 EoS. In addition, we assess the abundance pattern with respect to different polar angles. Figure 2 and Fig. 3 show the abundance pattern for trajectories being binned by their polar angle θ, $0° < \theta < 15°$, $0° < \theta < 30°$ and $0° < \theta < 45°$. Along the polar directions, the ejecta is predicted to have a low lanthanide fraction. Correspondingly, higher Y_e also

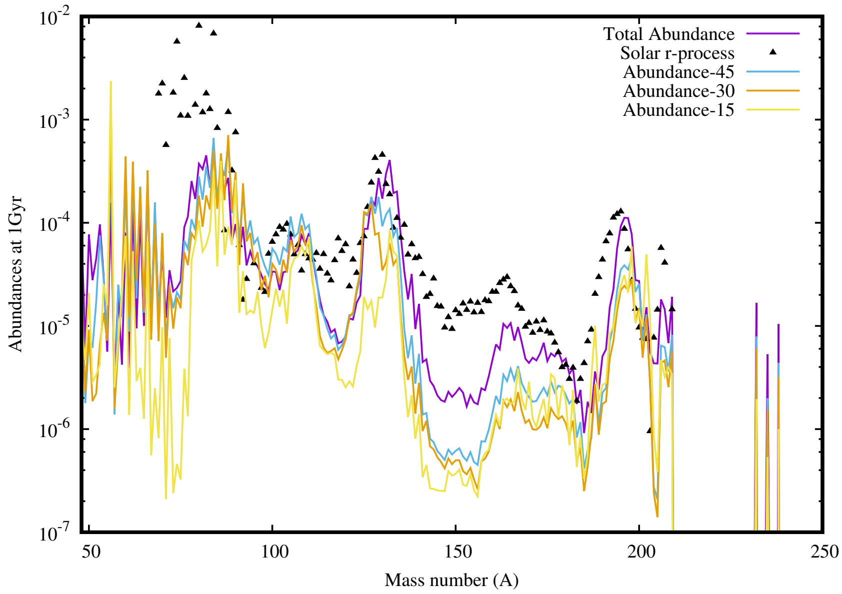

Figure 3: The combined total abundance from each ejected particle for a 1.35-1.35$M_\odot$ BNS with the DD2 EoS compared to the solar abundance. The yellow, orange and blue lines display the abundance for the ejecta binned by their polar angle θ (yellow: $0° < \theta < 15°$, orange: $0° < \theta < 30°$ and blue: $0° < \theta < 45°$).

lead to a significant decrease of the abundance of heavy elements. We observe that there exists a clear correlation between the initial Y_e composition of the ejecta and the produced heavy elements, which aligns with literature results (see [2] for a review). Our nuclear network calculations also yield the heating rate by radioactive decays, which are used for advanced kilonova modelling by radiative transfer codes [16].

5. Conclusions

We successfully ran full BNS merger simulations that include neutrinos with a state of the art leakage-equlibration-absorption scheme and did full nucleosynthesis network calculations based on trajectories extracted from the simulations. The results corroborate that BNS mergers are an important site for r-process nucleosynthesis. Our calculations are used for sophisticated kilonova modelling. A large set of runs for a parameter study with different binary masses and EoSs will be done in the future together with nucleosynthesis and radiative transfer calculations.

Acknowledgments

VV and AB acknowledge support by DFG - Project-ID 138713538 - SFB 881 ("The Milky Way System", subproject A10). AB acknowledge support by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program under grant agreement No. 759253. AB, G.M.-P acknowledge support by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - Project-ID 279384907 - SFB 1245. AB and G.M.-P acknowledge support by the State of Hesse within the Cluster Project ELEMENTS. G.M.-P acknowledge support by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (ERC Advanced Grant KILONOVA No. 885281).

References

[1] A. Bauswein and N. Stergioulas, *Spectral classification of gravitational-wave emission and equation of state constraints in binary neutron star mergers*, *Journal of Physics G Nuclear Physics* **46** (2019) 113002 [1901.06969].

[2] J.J. Cowan, C. Sneden, J.E. Lawler, A. Aprahamian, M. Wiescher, K. Langanke et al., *Origin of the heaviest elements: The rapid neutron-capture process*, *Reviews of Modern Physics* **93** (2021) 015002 [1901.01410].

[3] B.P. Abbott, et al. (LIGO Scientific Collaboration and Virgo Collaboration), *GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral*, *Physical Review Letters* **119** (2017) 161101 [1710.05832].

[4] B.P. Abbott, et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Multi-messenger Observations of a Binary Neutron Star Merger*, *Astrophys. J. Lett.* **848** (2017) L12 [1710.05833].

[5] L.-X. Li and B. Paczyński, *Transient Events from Neutron Star Mergers*, *Astrophys. J. Lett.* **507** (1998) L59 [astro-ph/9807272].

[6] B.D. Metzger, G. Martínez-Pinedo, S. Darbha, E. Quataert, A. Arcones, D. Kasen et al., *Electromagnetic counterparts of compact object mergers powered by the radioactive decay of r-process nuclei*, *Mon. Not. R. Astron. Soc.* **406** (2010) 2650 [1001.5029].

[7] V.A. Villar, J. Guillochon, E. Berger, B.D. Metzger, P.S. Cowperthwaite, M. Nicholl et al., *The Combined Ultraviolet, Optical, and Near-infrared Light Curves of the Kilonova Associated with the Binary Neutron Star Merger GW170817: Unified Data Set, Analytic Models, and Physical Implications*, *Astrophys. J. Lett.* **851** (2017) L21 [1710.11576].

[8] D. Watson, C.J. Hansen, J. Selsing, A. Koch, D.B. Malesani, A.C. Andersen et al., *Identification of strontium in the merger of two neutron stars*, *Nature* **574** (2019) 497 [1910.10510].

[9] R. Oechslin, S. Rosswog and F.-K. Thielemann, *Conformally flat smoothed particle hydrodynamics application to neutron star mergers*, *Phys. Rev. D* **65** (2002) 103005.

[10] A.W. Steiner, M. Hempel and T. Fischer, *Core-collapse Supernova Equations of State Based on Neutron Star Observations*, *Astrophys. J.* **774** (2013) 17 [1207.2184].

[11] S. Typel, G. Röpke, T. Klähn, D. Blaschke and H.H. Wolter, *Composition and thermodynamics of nuclear matter with light clusters*, *Phys. Rev. C* **81** (2010) 015803.

[12] M. Hempel and J. Schaffner-Bielich, *A statistical model for a complete supernova equation of state*, *Nucl. Phys. A* **837** (2010) 210 [0911.4073].

[13] R. Ardevol-Pulpillo, H.T. Janka, O. Just and A. Bauswein, *Improved leakage-equilibration-absorption scheme (ILEAS) for neutrino physics in compact object mergers*, *Mon. Not. R. Astron. Soc.* **485** (2019) 4754 [1808.00006].

[14] M. Ruffert, H.T. Janka and G. Schaefer, *Coalescing neutron stars - a step towards physical models. I. Hydrodynamic evolution and gravitational-wave emission.*, *Astron. Astrophys.* **311** (1996) 532 [astro-ph/9509006].

[15] J.d.J. Mendoza-Temis, M.-R. Wu, K. Langanke, G. Martínez-Pinedo, A. Bauswein and H.-T. Janka, *Nuclear robustness of the r process in neutron-star mergers*, *Phys. Rev. C* **92** (2015) 055805.

[16] C.E. Collins, A. Bauswein, S.A. Sim, V. Vijayan, G. Martínez-Pinedo, O. Just et al., *3D radiative transfer kilonova modelling for binary neutron star merger simulations*, *arXiv e-prints* (2022) arXiv:2209.05246 [2209.05246].