PROCEEDINGS OF SCIENCE

Electromagnetic Counterparts of Neutron Star Mergers: Signatures of Heavy r-Process Element Nucleosynthesis

Andreas Flörs,[a,*] **Gerrit Leck,**[a,b] **Ricardo da Silva,**[c,d] **Luke Shingles**[a] **and Gabriel Martínez-Pinedo**[a,b,e]

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

[b] *Institut für Kernphysik (Theoriezentrum), Technische Universität Darmstadt, Schlossgartenstraße 2, 64298 Darmstadt, Germany*

[c] *Laboratório de Instrumentação e Física Experimental de Partículas, Av. Prof. Gama Pinto 2, 1649-003 Lisboa, Portugal*

[d] *Universidade de Lisboa, Faculdade de Ciências, Rua Ernesto de Vasconcelos, Edifíco C8, 1749-016 Lisboa, Portugal*

[e] *Helmholtz Forschungsakademie Hessen für FAIR, GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany*

E-mail: a.floers@gsi.de

It has long since been established that observable actinides in the universe originate from the r-process. In 2017, the electromagnetic counterpart to the gravitational wave detection of two merging neutron stars was observed. From the light curve alone it was possible to characterise two ejecta components: one that contains low-Y_e material such as lanthanides and possibly actinides, and a high-Y_e component with low lanthanide abundances.
The dividing characteristic between the two components is the opacity of the material: lanthanides have a ~ 100 times higher opacity than iron-group material. The opacity of actinides is expected to be on a similar level as that of the lanthanides, or, possibly, even higher. To identify specific elements, spectroscopic information is required. However, so far no clear detection of individual lanthanides or actinides has been made in the electromagnetic counterpart following the neutron star merger AT2017gfo.
A great challenge for spectroscopic modelling of kilonovae using radiative transfer codes is the almost non-existent atomic data currently available for lanthanides and actinides. I will present how converged lanthanide and actinide opacities affect the kilonova spectrum compared to iron-group or light r-process elements. I will then use this collection of atomic data to show how we can use radiative transfer simulations to identify signatures or place constraints on the amount of heavy r-process material synthesized in kilonovae.

FAIR next generation scientists - 7th Edition Workshop (FAIRness2022)
23-27 May 2022
Paralia (Pieria, Greece)

[*] Speaker

PoS(FAIRness2022)015

1. Introduction

One of the most promising sites in the universe capable of producing the heaviest elements are binary neutron star (BNS) mergers. In BNS mergers, nucleosynthesis occurs through the rapid neutron capture process (r-process) [1] due to extreme neutron fluxes. In contrast to the s-process (slow neutron capture process), neutron capture events occur much faster than the typical beta-decay timescale of the synthesised nuclei, allowing for the production of the heaviest elements.

There has not been a direct detection of an r-process production site yet, however, the observed signal of the kilonova AT2017gfo – the electromagnetic counterpart following the gravitational wave event (GW170817) [2] – suggests at least some r-process material was produced [see 3, for a summary of the observations]. The electromagnetic emission from the first observed kilonova was studied extensively in visible and near-infrared (NIR) bands by ground-based telescopes for about two weeks until it became too faint even for the 8-10 m-class facilities. The tail of the quasi-bolometric light curve of AT2017gfo is in good agreement with the energy release rate from radioactive decays of r-process elements. The rapid spectral evolution from a blue and nearly featureless continuum to a red (peaking in the NIR) spectrum rich in absorption and emission lines as well as the evolutionary time scale of the light curve indicate that high-opacity material must have been created, with opacities much higher than those typical for the iron group elements (IGE).

So far, only a single element – strontium – has been firmly identified in the kilonova AT2017gfo [4]. In particular, no r-process elements of the second or third peaks have been found. Unsuccessful searches involve caesium/tellurium [5] and gold/platinum [6]. Identification of a lanthanide or actinide would settle the debate about whether BNS mergers are responsible for the abundance of heavy elements seen in the Universe, and, if so, whether they are the dominant channel. A straightforward, albeit very challenging approach to element identification, is through radiative transfer modelling of the observed spectra of AT2017gfo.

Radiative transfer models in their simplest form still require precise knowledge of level energies and bound-bound transitions which make up the bulk of the photon opacity in the r-process enriched ejecta. It is expected that lanthanide and actinide ions each have of order 10^6 relevant transitions (a factor of 10–100 more than IGE ions) [see e.g. 7], whereas only a tiny fraction has been measured for a few selected ions [8]. It is not experimentally feasible to measure a full set of opacities for all quasi-neutral ions from the IGE to the actinides, and thus the only way of obtaining atomic data is through theoretical atomic structure calculations.

2. Calculation of lanthanide atomic data

The reason for the high opacity of lanthanides compared to the iron group is the open f-shell (compared to the open d-shell) of the former. Atomic structure calculations of open f-shell ions are thus orders of magnitudes more computationally demanding. As a result, only a few sources of lanthanide atomic data are available in the literature [e.g. 7, 9].

The most important atomic parameters for radiative transfer simulations are level energies and oscillator strengths of electric dipole (E1) as well as forbidden electric quadrupole (E2) and magnetic dipole (M1) transitions. In Local Thermodynamical Equilibrium (LTE), which is assumed

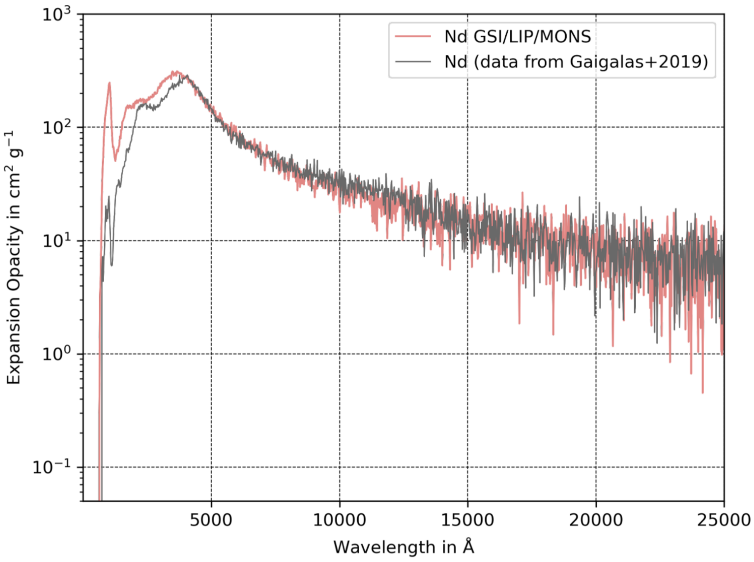

Figure 1: Expansion opacities of Nd at $T = 5000\,\mathrm{K}$, $\rho = 10^{-13}\,\mathrm{g\,cm^{-3}}$ and $t = 1\,\mathrm{day}$ computed with the atomic structure code FAC. For comparison, the expansion opacity computed from the atomic data from the GRASP2K code published in [9] is shown in black.

to hold for at least several days after the explosion [10], these quantities are enough to compute radiative transfer models of kilonovae.

Due to the sparsity of published lanthanide data, we compute level energies and oscillator strengths using the publicly accessible Flexible Atomic Code (FAC), which employs a Relativistic Configuration Interaction (RCI) method. In FAC, configuration state functions (CSF) are computed self-consistently while an effective potential is employed.

Using the calculated level energies and oscillator strengths one can determine the opacity of lanthanides. In an expanding atmosphere, the Sobolev optical depth [11, 12] is given by

$$\tau_l^{\mathrm{Sob}} = \frac{\pi e^2}{m_e c} n_l \lambda_l f_{lu} t_{\mathrm{exp}} \tag{1}$$

where n_l is the number density of ions in the lower level of a transition l, λ_l is the wavelength of the transition, f_{lu} is the oscillator strength and t_{exp} is the time since the merger event. From the line optical depths, one can compute the wavelength-dependent expansion opacity

$$\kappa_{\mathrm{exp}} = \frac{1}{\rho c t_{\mathrm{exp}}} \sum_i \frac{\lambda_i}{\Delta\lambda} (1 - e^{-\tau_l^{\mathrm{Sob}}}). \tag{2}$$

In Figure 1 we show a comparison of the expansion opacity from the atomic data computed with FAC compared to published atomic data for neodymium [9]. Over the optical and NIR wavelengths our opacities are in excellent agreement with those from [9].

3. Radiative transfer modelling of AT2017gfo

Finally, we show an emergent spectrum from the atomic data computed in the previous section using the 1D open-source Monte-Carlo radiative transfer spectral synthesis code TARDIS [13]. We start with a model that is in good agreement with the 1.4 day spectrum of AT2017gfo observed with the XSHOOTER spectrograph at ESO's Very Large Telescope, similar to the model from [4] and use an exponential density profile

$$\rho(v, t_{\exp}) = \rho_0 \left(\frac{t_0}{t_{\exp}}\right)^3 \left(\frac{v}{v_0}\right)^{-\Gamma} \tag{3}$$

with a power-law index of $\Gamma = 3$. In this model, the ejecta above the photosphere contain strontium with an abundance such that the strengths of the P-Cygni features match the observed features.

We find that at temperatures of around T=5000 K, which at this epoch of AT2017gfo was obtained by fitting a black body to the spectrum, the neodymium is either singly or doubly ionised. A low abundance of neodymium affects the spectrum only at short wavelengths near 5000 Å where the opacity peaks and line blanketing takes place. The spectrum at longer wavelengths is not affected by the addition of neodymium.

Increasing the abundance of neodymium quickly leads to a spectrum that is in complete disagreement with the observed 1.4 day spectrum (see Fig. 2). Due to the high opacity of singly ionised neodymium most of the black body radiation released from the inner boundary (which can be thought of as a 'photosphere') is reprocessed and emitted at longer wavelengths. Features in the emergent spectrum are, in contrast to those from strontium, caused by a plethora of Doppler-smeared transitions. While there is still a long way to go to identify individual r-process signatures in kilonovae, one can use the high opacity of lanthanides and actinides to place limits on their abundances by finding the values for which the models start diverging from the observed spectrum of AT2017gfo.

References

[1] Cowan, J. J. and 7 colleagues 2021. Origin of the heaviest elements: The rapid neutron-capture process. Reviews of Modern Physics 93. doi:10.1103/RevModPhys.93.015002

[2] Abbott, B. P. and 3676 colleagues 2017. Multi-messenger Observations of a Binary Neutron Star Merger. The Astrophysical Journal 848. doi:10.3847/2041-8213/aa91c9

[3] Pian, E. 2021. Binary neutron star mergers: a multi-messenger revolution. Frontiers in Astronomy and Space Sciences 7. doi:10.3389/fspas.2020.609460

[4] Watson, D. and 17 colleagues 2019. Identification of strontium in the merger of two neutron stars. Nature 574, 497–500. doi:10.1038/s41586-019-1676-3

[5] Smartt, S. J. and 121 colleagues 2017. A kilonova as the electromagnetic counterpart to a gravitational-wave source. Nature 551, 75–79. doi:10.1038/nature24303

[6] Gillanders, J. H., McCann, M., Sim, S. A., Smartt, S. J., Ballance, C. P. 2021. Constraints on the presence of platinum and gold in the spectra of the kilonova AT2017gfo. Monthly Notices of the Royal Astronomical Society 506, 3560–3577. doi:10.1093/mnras/stab1861

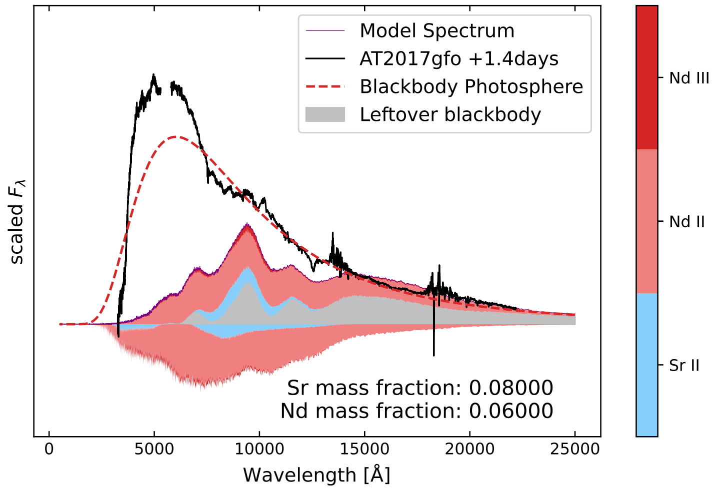

Figure 2: Spectral decomposition plot of our TARDIS [13] model using the 1.4 day XSHOOTER spectrum. Negative contributions indicate absorption, and positive contributions show emission from ions. The remaining black body is shown in grey. For this model, the strength of the Sr II feature was fixed similar to [4]. Additionally, a high abundance of Nd was added. The additional opacity from Nd leaves a spectral signature that is in strong disagreement with the observed data.

[7] Tanaka, M., Kato, D., Gaigalas, G., Kawaguchi, K. 2020. Systematic opacity calculations for kilonovae. Monthly Notices of the Royal Astronomical Society 496, 1369–1392. doi:10.1093/mnras/staa1576

[8] Kramida, A., Ralchenko, Yu., Reader, J., and NIST ASD Team. 2021. NIST Atomic Spectra Database (ver. 5.9). [Online]. Available: `https://physics.nist.gov/asd` [2022, September 15]

[9] Gaigalas, G., Kato, D., Rynkun, P., Radžiūtė, L., Tanaka, M. 2019. Extended Calculations of Energy Levels and Transition Rates of Nd II-IV Ions for Application to Neutron Star Mergers. The Astrophysical Journal Supplement Series 240. doi:10.3847/1538-4365/aaf9b8

[10] Pognan, Q., Jerkstrand, A., Grumer, J. 2022. NLTE effects on kilonova expansion opacities. Monthly Notices of the Royal Astronomical Society 513, 5174–5197. doi:10.1093/mnras/stac1253

[11] Sobolev, V. V. 1957. The Diffusion of Lα Radiation in Nebulae and Stellar Envelopes.. Soviet Astronomy 1, 678.

[12] Sobolev, V. V. 1960. Moving envelopes of stars. Cambridge: Harvard University Press, 1960.

[13] Kerzendorf, W., and 80 colleagues 2022. tardis-sn/tardis: TARDIS v2022.06.19. https://doi.org/10.5281/zenodo.6662839