Kilonova:
Multimessenger and Multiphysics

774. WE-Heraeus-Seminar

28 November – 01 December 2022

hybrid

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 774. WE-Heraeus-Seminar:

In 2017, a multimessenger era started with the first gravitational wave detection from the merger of two neutron stars (GW170817) and the rich electromagnetic follow-up. The most exciting electromagnetic counterpart was the kilonova. This provides an answer to the long-standing question of how and where heavy elements are produced in the universe. The neutron-rich material ejected during the neutron star merger (NSM) undergoes an r-process (rapid neutron capture process) that produces heavy elements and generates energy that is radiated as a kilonova. Therefore, one can use the kilonova as a direct observable of the matter ejected in NSM and learn about the extreme conditions that are reached in these events. This requires combing full general relativity simulations with state-of-the-art microphysics for the high-density equation of state and neutrinos, nucleosynthesis calculations involving extreme and still unknown neutron-rich nuclei, radiation transport models for the kilonova with detailed atomic physics information, and multimessenger observations.

The goal of this interdisciplinary seminar will be to bring together a group of experts from different fields and approaches to understand the microphysics and macrophysics of kilonovae and how to use observations to learn about these exciting multimessenger events. We aim to start and strengthen collaborations between atomic physics and astrophysics (atomic astrophysics) following the successful example of nuclear astrophysics. The time line of the seminar is critical, since new nuclear and atomic physics data from experiments and advanced theoretical models are now becoming available together with improved astrophysical models and larger samples of observations.

Scientific Organizers:

Prof. Dr. Almudena Arcones	TU Darmstadt & GSI Helmholtzzentrum für Schwerionenforschung, Germany E-mail: almudena.arcones@physik.tu-darmstadt.de
Prof. Dr. Camilla Juul Hansen	Universität Frankfurt, Germany E-mail: hansen@iap.uni-frankfurt.de
Prof. Dr. Kenta Hotokezaka	University of Tokyo, Japan E-mail: kentah@g.ecc.u-tokyo.ac.jp
Prof. Dr. Thomas Stöhlker	Helmholtz-Institut Jena & GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany E-mail : t.stoehlker@hi-jena.gsi.de

Introduction

Administrative Organization:

Dr. Stefan Jorda
Elisabeth Nowotka

Wilhelm und Else Heraeus-Stiftung
Postfach 15 53
63405 Hanau, Germany

Phone +49 6181 92325-12
Fax +49 6181 92325-15
E-mail nowotka@we-heraeus-stiftung.de
Internet: www.we-heraeus-stiftung.de

Venue:

Physikzentrum
Hauptstrasse 5
53604 Bad Honnef, Germany

Conference Phone +49 2224 9010-120

Phone +49 2224 9010-113 or -114 or -117
Fax +49 2224 9010-130
E-mail gomer@pbh.de
Internetwww.pbh.de

Taxi Phone +49 2224 2222

Registration:

Elisabeth Nowotka (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday
morning

Program

Program

Sunday, 27 November 2022

17:00 – 20:00	Registration	
18:00	*BUFFET SUPPER and informal get-together*	

Monday, 28 November 2022

08:00	*BREAKFAST*	
09:00	Scientific organizers	**Welcome words**
09:10 – 09:55	Masaru Shibata	**Modeling neutron-star mergers by long-term numerical relativity simulation**
09:55 – 10:40	Jonah Miller	**Impact of neutrinos in post-merger accretion flows**
10:40 – 11:10	*COFFEE BREAK*	
11:10 – 11:55	Stephan Rosswog	**Neutron star merger simulations with the Lagrangian numerical relativity code SPHINCS_BSSN**
11:55 – 12:20	Anna Neuweiler	**Long-term simulations of dynamical ejecta: Homologous expansion and ilonova properties**
12:20 – 12:45	Maximilian Jacobi	**Nuclear matter properties in neutron star mergers**
12:45	*LUNCH*	

Program

Monday, 28 November 2022

14:00 – 14:45	Nicole Vassh	**r process in neutron star mergers and the impact of nuclear physics uncertainties**
14:45 – 15:30	Gabriel Martinez-Pinedo	**3D radiative transfer kilonova modelling with detailed nuclear and atomic input**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	Ann-Cecile Larsen	**Experiments for the *r* process**
16:45 – 17:30	Oliver Just	**R-process conditions and neutrino flavor mixing in neutrino-cooled accretion disks**
17:30 – 17:45	Stefan Jorda	**About the WE-Heraeus-Foundation**
17:45 – 18:30	**Discussion: Simulations and nucleosynthesis** with Rodrigo Fernandez and Nicole Vassh	
18:30	*DINNER*	

Program

Tuesday, 29 November 2022

08:00	*BREAKFAST*	
09:00 – 09:25	Giulia Stratta	**A comparison between short GRB optical counterparts and kilonova AT2017gfo**
09:25 – 09:50	Sho Fujibayashi	**Mass ejeciton and nucleosynthesis in binary neutron star mergers leaving short-lived massive neutron stars**
09:50 – 10:35	Masaomi Tanaka	**Radiative transfer simulations for kilonovae**
10:35 – 11:00	*COFFEE BREAK*	
11:00 – 11:25	Vsevolod Nedora	**Modeling kilonova afterglows: Effects of the thermal electron population and interaction with GRB outflows**
11:25 – 11:50	Nina Kunert	**Model selection of GRB 211211A through multi-wavelength analyses**
11:50 – 12:15	Brendan O'Connor	**The locations and environments of short GRBs**
12:15 – 12:40	Nanae Domoto	**Signatures of heavy elements in near-infrared spectra of kilonova**
12:40 – 12:50	**Conference Photo** (in the front of the lecture hall)	
12:50	*LUNCH*	

Program

Tuesday, 29 November 2022

14:00 – 14:45	Daiji Kato	**NIFS database for non-equilibrium plasmas and Japan-Lithuania opacity database for kilonovae**
14:45 – 15:30	**Poster flash**	
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 17:30	**Poster session**	
17:30 – 18:30	**Discussion: Kilonova models and observations** with Eleonora Troja and Eli Waxman	
18:30	*DINNER*	

Program

Wednesday, 30 November 2022

08:00	*BREAKFAST*	
09:00 – 09:45	Henrik Hartman	**Experimental atomic radiative data for kilonova spectroscopy**
09:45 – 10:30	Stephan Fritzsche	**An atomic approach to the opacity of open d- and f-shell elements**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Sonja Bernitt	**X-ray astrophysics in the laboratory**
11:45 – 12:10	Khwaish Kumar Anjum	**Laser-microwave double-resonance spectroscopy to perform g-factor measurements of heavy, highly charged ions at ARTEMIS in HITRAP**
12:10 – 12:35	Ricardo Ferreira da Silva	**Calculation of atomic inputs of r-process elements for kilonova modelling**
12:35	*LUNCH*	

Program

Wednesday, 30 November 2022

14:00 – 14:45	Stefan Schippers	**Laboratory astrophysics with storage rings and synchrotron light sources**
14:45 – 15:30	Darach Watson	**Element identification in, and geometry of, the kilonova AT2017gfo associated with GW170817**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	V. Ashley Villar *(online)*	**Kilonova observations enabled by the Vera C. Rubin Observatory**
16:45 – 17:30	Asa Skúladóttir	**Two sources of the r-process: quick and delayed**
17:30 – 18:30	**Discussion: Atomic physics for kilonova models and experiments** with James Gillanders and Yuri Litivnov	
18:30	*DINNER HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Thursday, 01 December 2022

08:00	*BREAKFAST*	
09:00 – 09:45	Anne Noer Kolborg	**R-process mixing in the early Universe**
09:45 – 10:10	Quentin Pognan	**NLTE spectra of kilonovae**
10:10 – 10:35	Smaranika Banerjee	**Early kilonova from neutron star merger**
10:35 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Imre Bartos	**Near-future multi-messenger observations of kilonovae**
11:45 – 12:30	Tim Dietrich	**Multi-messenger astrophysics studies of merging neutron star**
12:30 – 12:40	Scientific organizers	**Closing words**
12:40	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Friday; however, a self-service breakfast will be provided on Friday morning

Posters

Posters

Arthur Alencastro Puls	**Chrono-chemo-dynamics of red giants in the Kepler field**
Andrey Bondarev	**Calculations of expansion opacities of Ce ions within the configuration interaction plus many-body perturbation theory approach**
Alessandro Camilletti	**Simulations of the neutron star merger GW190425: can we get constraints from the lack of the kilonova?**
Leonardo Chiesa	**Nucleosynthesis of light elements in BNS mergers**
Andreas Flörs	**Towards spectral modelling of kilonovae: Atomic data for Nd and U**
Federico Maria Guercilena	**Long term modelling of binary neutron star mergers ejecta: an efficient numerical framework**
Hamid Hamidani	**Cocoon emission in neutron star mergers**
Eleonora Loffredo	**Muons in the aftermath of neutron star mergers and their impact on trapped neutrinos**
Angelo Pidatella	**Experimental design of opacity measurements in the PANDORA plasma trap relevant for Kilonovae signals**
Giacomo Ricigliano	**Semi-analytic modeling of kilonovae**
Federico Schianchi	**Implementation of first-order multipolar neutrino transport in Numerical Relativity code BAM**
Paramvir Singh	**Kilonova mining project**
Shuxing Wang	**Dielectronic recombination experiments of Kr25+ ions at the CSRm and CSRe**
Binghui Zhu	**X-ray emission study Performed for hydrogen-like lead Ions at the electron cooler of CRYRING@ESR**

Abstracts of Talks

(in alphabetical order)

Laser-Microwave Double-Resonance Spectroscopy to Perform g-Factor Measurements of Heavy, Highly Charged Ions at ARTEMIS in HITRAP

K. Anjum[1,2], P. Baus[3], G. Birkl[3], M. Chambath[1,4], J. Hellmann[1,7], Kanika[1,5], J. Klimes[1,5,6], A. Krishnan[1,3], W. Quint[1,5,8], B. Reich[1,5,8] and M. Vogel[1]

[1]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[2]Physikalisch-Astronomische Fakultät, Friedrich Schiller Universität, Jena, Germany
[3]Institut für Angewandte Physik, TU Darmstadt, Darmstadt, Germany
[4]NMAM Institute of Technology, Mangalore, India
[5]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[6]International Max Planck Research School for Quantum Dynamics in Physics, Chemistry and Biology, Heidelberg, Germany
[7]Technische Hochschule Mittelhessen, Gießen, Germany
[8]Max Planck Institut für Kernphysik, Heidelberg, Germany

In **ARTEMIS** (**A**symmet**R**ic **T**rap for measurement of **E**lectron **M**agnetic moment in **I**on**S**) [**1**], at HITRAP, we aim to measure the magnetic moments of both electrons and nuclei in heavy, highly charged ions (HCIs), such as $^{209}Bi^{82+}$ at our cryogenic Penning trap facility in GSI, Darmstadt. This allows the test of the theoretical predictions made by quantum electrodynamics (QED), one of the most precisely tested physical theories, in the exotic conditions of hydrogen-like bismuth or uranium (up to field strengths of $\mathbf{10^{16}\ V\ cm^{-1}}$ and $\mathbf{10^4\ T}$). We plan to perform this test of QED in such HCIs using laser microwave double-resonance spectroscopy - by shifting the hyperfine structure and Zeeman transitions to the optical and microwave regimes, respectively [**2**]. A closed optical cycle is used as a probe of successful induction of spin flips by microwave stimulus.

References

[1] W. Quint et al., Phys. Rev. A 78, 032517 (2008).
[2] D. von Lindenfels et al., Phys. Rev. A 87, 023412 (2013).

Early kilonova from neutron star merger

Smaranika Banerjee[1,2] **and Masaomi Tanaka**[1] **and**
Kyohei Kawaguchi[3] **and Daiji Kato**[4] **Gediminas Gaigalas**[5]

[1]*Tohoku University, Aoba, Sendai 980-0845, Japan*
[2]*Stockholm University, AlbaNova, SE-10691 Stockholm, Sweden*
[3]*ICRR, The University of Tokyo, Chiba 277-8582, Japan*
[3]*NIFS, Gifu 509-5292, Japan*
[3]*Vilnius University, LT-10257 Vilnius, Lithuania*

In binary neutron star (BNS) mergers, the radioactive decay of freshly synthesized heavy elements produces emissions in the ultraviolet-optical-infrared range, producing a transient called a kilonova. The observational properties of the kilonova (light curve and spectra) depend on the bound-bound opacity of the heavy elements. Hence, a detailed opacity calculation is necessary to model the realistic kilonova light curve and spectra. However, such calculations for opacity, and correspondingly, the realistic light curve, were unavailable for the conditions suitable at an early time ($t < 1$ day). Understanding the kilonova starting from an early time is important because the early emission can reveal the abundance in the outermost layer of the ejecta (at an early time, the photons can escape only from the outermost layer).

In this work, we perform the detailed atomic opacity calculation for BNS merger ejecta for all the elements from Ca - Ra (Z = 20 - 88), including the lanthanides (open f-shell elements with Z = 57 - 71, expected to increase the opacity and affect the light curve significantly). **Using the new opacity, we calculate the realistic early kilonova with and without the presence of lanthanides**. Our results show that for the lanthanide-free ejecta, the radioactive heating is enough to produce the early kilonova observed from the BNS merger (AT2017gfo). Also, we find that, in the presence of the lanthanides, the early light curve is fainter by a factor of ~ four compared to the lanthanide-free ejecta at t ~ 0.1 day. Our work provides the foundation for a more detailed study from the future observation of kilonova at an early time.

References

[1] Banerjee, S., Tanaka, M., Kawaguchi, K., Kato, D., et al., 2020, ApJ, 901, 29
[2] Banerjee, S., Tanaka, M., Kato D., Gaigalas G., et al., 2022, ApJ, 934, 117

Near-future Multi-messenger Observations of Kilonovae

I. Bartos[1]

[1]University of Florida, Gainesville FL, USA

The physics and cosmological insight we can extract from kilonovae largely depends on the number of observations as well as the messengers we detect from individual events. I will discuss near-future prospects of the rate and type of expected observations, focusing in particular on gravitational waves and long-term radio observations of neutron star mergers.

X-ray Astrophysics in the Laboratory

S. Bernitt[1,2]

[1] *Helmholtz-Institut Jena, Germany*
[2] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany*

Emission and absorption spectra of hot astrophysical plasmas in the UV and X-ray bands are often dominated by electronic transitions in highly charged ions (HCI). Observations with the newest generation of high-resolution instruments onboard current and future satellite observatories have the potential to reveal previously inaccessible details of the processes in such environments. This is essential for advancing our understanding of extreme environments and the evolution of the universe. However, what can be reconstructed from spectra is currently limited by the availability and quality of atomic data [1] used for plasma modelling. Laboratory experiments are required to provide data and benchmark atomic structure theory.

For many years, electron beam ion traps (EBITs) [2] have been valuable tools for laboratory measurements with HCI, providing a wide range of atomic data, like transition energies [3] and rates of ionization and recombination processes. Here, various X-ray spectroscopy experiments with EBITs are presented, including measurements in which radiation from ultrabrilliant X-ray free-electron laser (FEL) [4] or synchrotron [5, 6, 7] light sources is used to resonantly excite electronic transitions in trapped HCI, and subsequent fluorescence or changes of ion charge state are detected. This can provide spectroscopic data with unprecedented resolving powers and signal-to-noise ratios.

References

[1] G. Bentancourt-Martinez *et al.*, arXiv:1903.08213 (2019)
[2] P. Micke *et al.*, Rev. Sci. Instrum. **89**, 063109 (2018)
[3] J. K. Rudolph *et al.*, Phys. Rev. Lett. **111**, 103002 (2013)
[4] S. Bernitt *et al.*, Nature **492**, 225-228 (2012)
[5] M. Togawa *et al.*, Phys. Rev. A **102**, 052831 (2020)
[6] S. Kühn *et al.*, Phys. Rev. Lett. **124**, 225001 (2020)
[7] S. Kühn *et al.*, arXiv:2201.09070 (2022)

Multi-messenger astrophysics studies of merging neutron star

T.Dietrich[1,2], **et al.**

[1]*Institut für Physik und Astronomie, Universität Potsdam, D-14476 Potsdam, Germany*
[2]*Max Planck Institute for Gravitational Physics, Am Mühlenberg 1, D-14476 Potsdam, Germany*

Our knowledge about dense matter explored in the cores of neutron stars remains limited, but, fortunately, the detection of gravitational waves emitted from the merger of neutron stars and the corresponding electromagnetic signals provide a new way of studying supranuclear-dense material.
Through a general-purpose multi-messenger framework, we combine the information obtained from gravitational-wave observations, the electromagnetic counterparts of merging neutron stars with the information provided by NICER, radio pulsar observations, and heavy-ion collision experiments to derive new constraints on the neutron-star equation of state and the Hubble constant.
In this talk, we will also discuss how numerical-relativity simulations enter in our analysis and how they forecast the amount and properties of the ejected material, which is a key element to constrain the source properties of the binary neutron star systems from kilonova observations.

References

[1] T. Dietrich et al., Science 370 (2020) 6523, 1450-1453
[2] S. Huth et al., Nature 606 (2022) 276-280
[3] Pang et al., arXiv: 2205.08513

Signatures of heavy elements in near-infrared spectra of kilonova

Nanae Domoto[1]

[1]*Astronomical Institute, Tohoku University, Sendai, Japan*

Although the observations of GW170817/AT2017gfo have provided us with evidence that binary neutron star mergers are sites of rapid neutron capture nucleosynthesis [e.g., 1], no trace of individual elements has been identified from the observed spectra yet, except for strontium [2, 3]. We investigate the kilonova spectra in photospheric phase over the entire wavelength range toward elemental identification [4]. We systematically calculate the strength of bound-bound transitions for all the elements by constructing a hybrid line list that is accurate for important strong transitions and complete for weak transitions. We find that the elements at the left side of the periodic table, such as Ca, Sr, Y, Zr, La, and Ce, can become strong absorption sources in neutron star merger ejecta, due to their atomic properties. We then perform radiative transfer simulations, and find that La III and Ce III appear in the near-infrared spectra, which can explain the absorption features at λ ~ 12000–14000 A in the spectra of GW170817/AT2017gfo. Using these absorption features, we give the first direct estimates of the mass fractions of La and Ce.

References

[1] M. Tanaka et al., PASJ **69**, 102 (2017)
[2] D. Watson et al., Nature **574**, 497 (2019)
[3] N. Domoto et al. ApJ, **913**, 26 (2021)
[4] N. Domoto et al. ApJ, **939**, 8 (2022)

Calculation of atomic inputs of r-process elements for kilonova modelling

R. Ferreira da Silva[1], A. Flörs[2], G. Leck[2,4], P. Amaro[3], J. M. Sampaio[1], G. Martínez-Pinedo[2,4,5], J. P. Marques[1]

[1]Laboratório de Instrumentação e Física Experimental de Partículas (LIP) and Faculdade de Ciências, Universidade de Lisboa (FCUL), Portugal
[2]GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany
[3]Laboratory for Instrumentation, Biomedical Engineering and Radiation Physics (LIBPhys-UNL), Department of Physics, NOVA School of Science and Technology, NOVA University Lisbon, 2829-516 Caparica, Portugal
[4]Institut für Kernphysik (Theoriezentrum), Fachbereich Physik, Technische Universität Darmstadt, Schlossgartenstraße 2, 64289 Darmstadt, Germany
[5]Helmholtz Forschungsakademie Hessen für FAIR, GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany

Given the recent detection of multiple neutron-star merger events, a more complete description of nuclear and atomic properties as well as advanced astrophysical simulations are needed to accurately predict *r*-process nucleosynthesis yields and electromagnetic signals when presented with observational data. In this talk, we present results for large-scale calculations of data needed to compute astrophysical opacities for important *r*-process elements, including actinides, which are projected to have an opacity similar to, if not greater than, lanthanides [1]. We focus mainly on the results for the first ionization stages of neodymium and uranium. The atomic data was obtained using the Flexible Atomic Code (FAC) [2], as it allows for structure calculations of radiative and collisional data needed for kilonova modelling in different stages of its evolution. Structure calculations are carried out by employing a configuration interaction approach with a local central potential defined by minimizing the energy of a mean fictitious configuration. We investigate how this central potential model affects our calculations and how it can be systematically improved in order to increase computation accuracy and consistency with experimental data.

References

[1] R. Ferreira da Silva, J. Sampaio, P. Amaro, A. Flörs, G. Martínez-Pinedo, J. Marques, Atoms **10**, 18 (2022)

[2] M. Gu, Can. J. Phys. **86**(5), 675 (2008)

An atomic approach to the opacity of open d- and f-shell elements

S. Fritzsche and A. Bondarev

Helmholtz Institut, Jena, 07743, Germany
Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität, Jena, 07743, Germany
email: s.fritzsche@gsi.de

Opacities are often utilized in astrophysics for studying solar and photospheric models, (solar) neutrino observations or, more recently, neutron star mergers. The opacity of an atomic ion hereby quantifies how the photons are absorbed or re-scattered by the plasma ions, while propagating through the medium. The opacity of different ion sources also enters explicitly the radiation transport in different environments, such as stellar interiors, fusion devices or short-wavelength plasma light sources, at least, if local thermodynamic equilibrium (LTE) conditions can be assumed.

From the viewpoint of atomic physics, opacity calculations first of all request to compute a good (or even large) number of fine-structure levels, based on reasonably well-correlated state functions. For the (heavy) r-process elements beyond iron, this often enforces large-scale computations owing of the extended fine-structure of most open d- and f-shell elements. From several recent case studies, it has been seen that rather high optical and NIR opacities need to be expected for the lanthanides and, perhaps, even larger opacities for selected actinides [1,2]. Until the present, however, the precision and reproducibility of opacity computations have both raised recurrent debates, starting from low-Z elements on.

In practice, the ionic opacities are often discussed and applied in quite different forms, either (frequency- or) wavelength-resolved or in terms of *mean* – Planck or Rosseland – opacities. The Rosseland opacity, for example, averages over the mean free path $s(\omega) = 1/[\rho\ \kappa(\omega)]$ of photons with frequency ω, built upon a black-body photon distribution. They all depend more or less sensitively on the level density just above the ground state, and often also on photoionization, photorecombination and scattering processes. Apart from its wavelength dependence, however, little is known how the (expansion) opacity $\kappa(\lambda, \Delta\lambda; T; \rho_{ion}, t_{obs}$, [level population], plasma model) depends on the other parameters, such as temperature T, ion density ρ_{ion}, observation time t_{obs}, or the level population and others. In non-LTE conditions, furthermore, difficulties arise from the local dynamics, the ionic balance, or simply the plasma-density shifts to the rates and cross sections of interest.

To better understand the sensitivity and role of (different) opacities in modelling the light curves from kilonovae, the Jena Atomic Calculator (JAC) has been expanded in order to compute, analyze and discuss these dependencies. JAC [3,4] is based on Julia, a new programming language for scientific computing, and which provides an easy-to-use but powerful platform to extent atomic theory towards new (astrophysical) applications for almost all atoms and ions across the periodic table. Apart from opacities, we shall also demonstrate the flexibility of these tools for dealing with atomic cascade processes of different sort and complexity [5].

References

[1] G. Gaigalas et al., ApJS **240**, 29 (2019).
[2] C.J. Fontes et al., MNRAS **493**, 4143 (2020).
[3] S. Fritzsche, Comp. Phys. Commun. **240**, 1 (2019); https://github.com/OpenJAC/JAC.jl
[4] S. Fritzsche, User Guide & Compendium to JAC (unpublished, 2022).
[5] S. Fritzsche, P. Palmeri & S. Schippers, Symmetry **13**, 520 (2021).

Mass ejeciton and nucleosynthesis in binary neutron star mergers leaving short-lived massive neutron stars

S. Fujibayashi[1], K. Kiuchi[1,2], S. Wanajo[1], K. Kyutoku[2,3], Y. Sekiguchi[4], and M. Shibata[1,2]

[1] *Max Planck Institute for Gravitational Physics, Potsdam, Germany*
[2] *Center for Gravitational Physics and Quantum Information, Yukawa Institute for Theoretical Physics, Kyoto, Japan*
[3] *Department of Physics, Kyoto University, Kyoto, Japan*
[4] *Department of Physics, Toho University, Funabashi, Japan*

By performing general relativistic hydrodynamics simulations with an approximate neutrino-radiation transfer, the properties of ejecta in dynamical and post-merger phases are investigated for the cases in which the remnant massive neutron star collapses into a black hole in <20 ms after the onset of the merger [1]. The dynamical mass ejection is investigated in three-dimensional simulations. The post-merger mass ejection is investigated in two-dimensional axisymmetric simulations with viscosity using the three-dimensional post-merger systems as the initial conditions. We show that the typical neutron-richness of the dynamical ejecta is higher for the merger of more asymmetric binaries; hence, heavier r-process nuclei are dominantly synthesized. The post-merger ejecta is shown to have only a mild neutron-richness, which results in the production of lighter r-process nuclei, irrespective of binary mass ratios. Because of the larger disk mass, the post-merger ejecta mass is larger for more asymmetric binary mergers. Thus, the post-merger ejecta can compensate for the underproduced lighter r-process nuclei for asymmetric merger cases. As a result, by summing up both ejecta components, the solar residual r-process pattern is reproduced within the average deviation of a factor of three, irrespective of the binary mass ratio. Our result also indicates that the (about a factor of a few) light-to-heavy abundance scatter observed in r-process-enhanced stars can be attributed to variation in the binary mass ratio and total mass. For the case in which the merger remnant is a long-lived massive neutron star [2], in contrast, light r-process nuclei are overproduced and the resulting abundance pattern deviates from that of the solar r-residuals. An implication of our results associated with the mass distribution of compact neutron star binaries is discussed.

References

[1] S. Fujibayashi *et al.*, accepted for publication in ApJ (arXiv: **2205.05557**).
[2] S. Fujibayashi et al., ApJ **901**, 122 (2020)

Experimental atomic radiative data for kilonova spectroscopy

H. Hartman[1]

[1]*Malmö university, Sweden*

Modeling of the spectroscopic observations of kilonova rely on radiative data to have a good coverage. Experimental data is sparce for these elements thought to be responsible for the opacity in the kilonova spectra.
We will review the technique behind a successful combination of experiments and calculation for lighter elements Magnesium and Silicon [1]. This has been successful in providing evaluated data sets for applications to stellar spectroscopy. For heavier elements, experiment can easily provide accurate wavelengths for complex spectra with a huge number of lines, but only accurate intensities for a limited number. Calculations, on the other hand, can provide line strengths for many lines, but with a less accuracy in wavelength.
We will discuss the possible routes to combine experiment and calculations to provide broad data sets for kilonova spectroscopy.

References

[1] A. Pehlivan Rhodin, H. Hartman, H. Nilsson, and P. Jönsson, A&A **598**, A102 (2017); and submitted to A&A

Nuclear matter properties in neutron star mergers

M. Jacobi[1] , F. Guercilena[2,3], S. Huth[1] , and A. Arcones[1,4]

[1] Institut für Kernphysik, Technische Universität Darmstadt, Germany
[2] INFN-TIFPA, Trento Institute for Fundamental Physics and Applications, Italy
[3] Dipartimento di Fisica, Università di Trento, Italy
[4] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

Merging binary neutron stars (BNS) typically emit gravitational waves (GWs) and eject matter that undergoes r-process nucleosynthesis. As demonstrated by the joint observation of GWs and electromagnetic transients from a BNS merger in August 2017, this makes them ideal sources for multi-messenger astronomy. The dynamics of the merger, the properties of the ejected matter, as well as the spectral features of emitted GWs sensitively depend on the equation of state (EOS) of dense matter. Therefore, numerical simulations of BNS mergers are an excellent means to constrain the highly uncertain nuclear EOS.

In this work, we systematically investigate the influence of the nuclear physics input on BNS merger simulations by varying the nuclear matter properties in the employed EOS independently. We identify several important effects of the effective nucleon mass and incompressibility on the merger dynamics as well as the ejection of matter. Furthermore, we demonstrate that the dependence of the post-merger gravitational wave spectrum on the EOS can be inferred solely based on its nuclear matter properties.

R-process conditions and neutrino flavor mixing in neutrino-cooled accretion disks

Oliver Just[1]

[1]*GSI Helmholtzzentrum, Darmstadt, Germany*

Neutrino-cooled accretion disks can be formed after the coalescence of two neutron stars or a neutron star and a black hole as well as in the core of a collapsing, strongly rotating star. The outflows launched from these disks can be massive enough for these systems to represent substantial contributors to the galactic chemical enrichment, however, the question of whether these disks are the main sources of a range of, or possibly even all, r-process elements remains elusive. The role of these disks for galactic chemical evolution depends sensitively on the neutron-richness of the outflows, which is determined by the detailed thermodynamic and weak-interaction conditions in the disk. In this contribution I will report our recent efforts to systematically investigate the weak-interaction conditions of neutrino-cooled disks and how these conditions are affected by fast neutrino-flavor conversions.

References

[1] O. Just, S. Goriely, H.-Th. Janka, S. Nagataki, A. Bauswein, MNRAS 509, 1377 (2022)
[2] O. Just, S. Abbar, M.-R. Wu, I. Tamborra, H.-Th. Janka, F. Capozzi, PRD 105, 083024 (2022)
[3] O. Just, M.-A. Aloy, M. Obergaulinger, S. Nagataki, ApJL, 934, L30 (2022)

NIFS database for non-equilibrium plasmas and Japan-Lithuania opacity database for kilonovae

D. Kato[1,2], I. Murakami[1], M. Tanaka[3], S. Banerjee[3],

G. Gaigalas[4], L. Radžiūtė[4], and P. Rynkun[4]

[1]National Institute for Fusion Science (NIFS), Toki, Japan
[2]Kyushu University, Kasuga, Japan
[3]Astronomical Institute, Tohoku University, Sendai, Japan
[4]Institute of Theoretical Physics and Astronomy, Vilnius University, Vilnius, Lithuania

NIFS has developed and released a numerical database of collision cross sections and rate coefficients for atoms and molecules [1,2], which are necessary to construct spectroscopic models of non-equilibrium plasmas. The problem of radiative cooling by impurity ions in fusion plasmas was the original motivation for the database development, and working groups of domestic and foreign atomic collision researchers were organized to collect and evaluate the data.

We have recently constructed optical absorption data of r-process element ions, which are in high demand for the analysis of kilonova observation associated with neutron star mergers. The data were developed by theoretical calculations in cooperation of Japan and Lithuanian experts, and made a database available at NIFS [3,4].

In this talk, I will introduce these databases.

References

[1] NIFS DATABASE at URL=http://dbshino.nifs.ac.jp/

[2] I. Murakami, M. Kato, M. Emoto, D. Kato, H. A. Sakaue, T. Kawate, Atoms 8 (2020) 71.

[3] D. Kato, I. Murakami, M. Tanaka, S. Banerjee, G. Gaigalas, L. Radžiūtė, P. Rynkun, Japan-Lithuania Opacity Database for Kilonova (2021), http://dpc.nifs.ac.jp/DB/Opacity-Database/, (version 1.0)

[4] M. Tanaka, D. Kato, G. Gaigalas, K. Kawaguchi, "Systematic opacity calculations for kilonovae", Monthly Notices of the Royal Astronomical Society 496 (2020) 1369-1392.

R-process mixing in the early Universe

Anne N. Kolborg[1,2]

[1]*DARK, Niels Bohr Institute, University of Copenhagen, Copenhagen Denmark*
[2] *Department of Astronomy and Astrophysics, University of California Santa Cruz, Santa Cruz, USA*

The r-process is the source of approximately half of the elements heavier than iron. Despite its undoubted importance many open questions remain about how and where these elements are formed. In this talk I will focus on recent advances in our understanding of the transport of metals and what this can teach us about the likely primary site of the r-process.

Model selection of GRB 211211A through multi-wavelength analyses

N. Kunert[1] and S. Antier[2] and Vsevolod Nedora[9] and Mattia Bulla[3] and Michael Coughlin[4] and Peter T. H. Pang[6,7] and Ingo Tews[8] and Weizmann Kiendrebeogo[2,5] and Meili Pilloix[2] and Jennifer Barnes[10] and Tim Dietrich[9]

[1]*Institute of Physics and Astronomy, University Potsdam, Potsdam, Germany*
[2]*Artemis Observatoire de la Côte d'Azur, Université Côte d'Azur, Nice, France*
[3]*Nordita, KTH Royal Institute of Technology and Stockholm University, Stockholm, Sweden*
[4]*School of Physics and Astronomy, University of Minnesota, Minneapolis, USA*
[5]Laboratoire de Physique et de Chimie de l'Environment, Université Joseph KI-ZERBO, Ouagadougou, Burkina Faso
[6]*Nikhef, Science Park, Amsterdam, The Netherlands*
[7]*Institute for Gravitational and Subatomic Physics, Utrecht University, Utrecht, The Netherlands*
[8]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, USA*
[9]*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Potsdam, Germany*
[10]*Kavli Institute for Theoretical Physics, University of California, Santa Barbara, USA*

GRB 211211A poses great challenges on the classification of GRB signals being one of the closest gamma-ray bursts discovered to date with partially inconclusive electromagnetic signatures. In this study, we assume four different astrophysical scenarios as possible progenitor systems: a binary neutron star system, a black hole - neutron star system, a supernova, and a collapsar. We use the nuclear physics and multi-messenger astronomy framework "NMMA" to perform several Bayesian multi-wavelength analyses based on different models, priors, and data sets to investigate which astrophysical sources and processes might have been related to the detection of GRB 211211A. Our analysis supports previous studies in which the presence of an additional component, likely a related r-process nucleosynthesis, is required to explain the observation of GRB 211211A, as it cannot solely be explained as an GRB afterglow. Fixing the distance to about 350 Mpc, we find statistical preference for a binary neutron star merger and estimate the component masses to be $1.57^{+0.42}_{-0.35} M_{\odot}$ and $1.32^{+0.21}_{-0.28} M_{\odot}$.

Experiments for the *r* process

Ann-Cecilie Larsen[1]

[1] *Department of Physics, University of Oslo, Oslo, Norway*
a.c.larsen@fys.uio.no

We live in a very exciting time, as we come closer and closer to unravel the mysteries of how half of the elements heavier than iron has been made in the Universe. A major breakthrough was achieved in 2017, when the electromagnetic transient, a “kilonova”, was measured following a neutron star collision, confirming that neutron star mergers are capable of producing lanthanides in significant amounts. However, we are still far from seeing the complete picture. It could well be that there are other possible sites where the rapid neutron capture process (r process) can take place, a complete end-to-end description of a neutron-star merger is still lacking, and the uncertainties connected to the needed nuclear input are substantial.

In this contribution, I would like to highlight one aspect of the nuclear physics uncertainties, namely the neutron-capture reaction rates. I will present some recent efforts to provide experimental constraints to these neutron-capture reaction rates [1], some new data on neutron-rich rare-earth nuclei measured this fall at Argnne National Laboratory, and some future prospects for detector development and experiments at existing and upcoming radioactive beam facilities.

References

[1] A.C. Larsen, A. Spyrou, S. N. Liddick, M. Guttormsen, Prog. Part. Nucl. Phys. **107**, 69 (2019)

3D radiative transfer kilonova modelling with detailed nuclear and atomic input

L. J. Shingles[1], A. Flörs[1], G. Martínez-Pinedo[1,2], A. Bauswein[1], C. E. Collins[1], G. Leck[1,2], V. Vijayan[1,3], S. A. Sim[4], R. F. Silva[5,6], J. M. Sampaio[5,6], P. Amaro[7], and J. P. Marques[5,6]

[1]GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany
[2]Institut für Kernphysik (Theoriezentrum), Fachbereich Physik, Technische Universität Darmstadt, Schlossgartenstraße 2, 64298 Darmstadt, Germany
[3]Department of Physics and Astronomy, Ruprecht-Karls-Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany
[4]Astrophysics Research Center, School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, Northern Ireland, UK
[5]Laboratório de Instrumentação e Física Experimental de Partículas (LIP), Av. Prof. Gama Pinto 2, 1649-003 Lisboa, Portugal
[6]Faculdade de Ciências, Universidade de Lisboa, Rua Ernesto de Vasconcelos, Edifíco C8,1749-016 Lisboa, Portugal
[7]Laboratory for Instrumentation, Biomedical Engineering and Radiation Physics (LIBPhys-UNL), Department of Physics, NOVA School of Science and Technology, NOVA University Lisbon, 2829-516 Caparica, Portugal

Kilonova observations provide unique opportunities to characterize the in-situ operation of the r-process and the dynamics of the astrophysical environment supplying complementary information to gravitational wave observations. This was confirmed by the observation of a kilonova electromagnetic transient, AT2017gfo, associated with the gravitational wave event GW170817. Further progress requires the development of kilonova models that connect the light curve and spectral predictions to neutrino radiation hydrodynamical models via nucleosynthesis network calculations. In this talk, we will present LTE 3D Monte Carlo radiative transfer models based on the code ARTIS. These models follow the long-term decay from nucleosynthesis products corresponding to the dynamical ejecta of a neutron star merger modelled with 3D smooth-particle hydrodynamics including neutrino interactions. We consider energy produced by alpha and beta decays with detailed gamma-ray transport and time-dependent particle deposition. Photon transport is done using detailed line-by-line opacities for all ions at the relevant ionization stages. Electron energy deposition is treated using a thermalization efficiency prescription benchmarked against results of ref. [1]. We use line-by-line atomic bound-bound opacities as given by ref. [2]. We will also present a new set of opacity calculations that include the contribution of actinides.

References

[1] J. Barnes, D. Kasen, M.-R. Wu, G. Martínez-Pinedo, ApJ, 829, 110 (2016)
[2] M. Tanaka, D. Kato, G. Gaigalas, K. Kawaguchi, MNRAS, 496, 1369 (2020)

Impact of Neutrinos in Post-Merger Accretion Flows

Jonah M. Miller[1,2,*]

[1] *Center for Theoretical Astrophysics, Los Alamos National Laboratory, Los Alamos, NM, USA*
[2] *CCS-2, Los Alamos National Laboratory, Los Alamos, NM, USA*

The 2017 detection of the in-spiral and merger of two neutron stars was a landmark discovery in astrophysics. Through a wealth of multi-messenger data, we now know that the merger of these ultracompact stellar remnants is a central engine of short gamma ray bursts and a site of r-process nucleosynthesis, where the heaviest elements in our universe are formed. The radioactive decay of unstable heavy elements produced in such mergers powers an optical and infra-red transient: The kilonova.

One key driver of nucleosynthesis and resultant electromagnetic afterglow is wind driven by an accretion disk formed around the compact remnant. Neutrino transport plays a key role in setting the electron fraction in this outflow, thus controlling the nucleosynthesis. I present recent progress in modeling this system, with an emphasis on uncertainties, degeneracies with the rest of the modeling process, and opportunities for the future.

* jonahm@lanl.gov

Modeling kilonova afterglows: Effects of the thermal electron population and interaction with GRB outflows

V. Nedora[1 2], T. Dietrich[1,2], M. Shibata[1,3] M. Pohl [2,4], L. C. Menegazzi[1]

[1]Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Am Muhlenberg 1, Potsdam 14476, Germany
[2] Institute for Physics and Astronomy, University of Potsdam, Potsdam 14476, Germany
[3]Center for Gravitational Physics and Quantum Information, Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto, 606-8502, Japan,
[4]Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany

One of the fundamental multidisciplinary questions in physics concerns the properties of matter at supranuclear densities. These properties become exposed when neutron stars collide and a fraction of matter is ejected. The ejecta then emits quasi-thermal electromagnetic radiation, kilonova, releasing the energy produced in rapid neutron capture nucleosynthesis. Additionally, the interaction between the ejecta and interstellar medium produces non-thermal, synchrotron radiation, so-called kilonova afterglow. This long-lived electromagnetic signature provides a new window into the properties of ejected matter, and ultimately on the neutron star equation of state.
Thus, it is of paramount importance to develop models of kilonova afterglow, using results of first-principles studies of physics at shocks, numerical relativity simulations of merging neutron stars, and observations. To this end, we consider kilonova afterglow when (i) ejecta has angular and velocity structure; (ii) electrons behind the shock follow thermal and non-thermal distributions; (iii) interstellar medium has been modified by passing gamma-ray burst ejecta. We assess the importance of these factors and provide prospects for observations. These results further emphasize the importance of kilonova afterglow in the multimessenger picture of neutron star mergers.

Long-Term Simulations of Dynamical Ejecta: Homologous Expansion and Kilonova Properties

A. Neuweiler[1], T. Dietrich[1,2], M. Bulla[3,4], S. V. Chaurasia[4], S. Rosswog[3,5], and M. Ujevic[6]

[1]Institut für Physik und Astronomie, Universität Potsdam, Haus 28, Karl-Liebknecht-Str. 24/25, 14476, Potsdam, Germany
[2]Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Am Mühlenberg 1, Potsdam 14476, Germany
[3]The Oskar Klein Centre, Department of Astronomy, Stockholm University, AlbaNova, SE-10691 Stockholm, Sweden
[4]Department of Physics and Earth Science, University of Ferrara, via Saragat 1, 44122 Ferrara, Italy
[5]Sternwarte Hamburg, Gojenbergsweg 112, 21029 Hamburg, Germany
[6]Centro de Ciências Naturais e Humanas, Universidade Federal do ABC, Santo André 09210-170, SP, Brazil

Ejecta data from numerical-relativity simulations of compact binary mergers can be used as input to radiative transfer simulations to compute kilonova light curves. While most radiative transfer simulations subsequently assume homologous expansion of the outward flowing material, this condition might not always be met at the end of the usually very short numerical-relativity simulations.

To investigate when and to what extent this condition is satisfied, we adapt the infrastructure of our numerical-relativity code BAM to allow for longer simulations of the dynamical ejecta component. We find that the deviations from a perfect homologous expansion at ~ 100 ms after merger are slightly less than 30%. In order to determine the impact of these deviations on the computation of the kilonova light curves, we use the ejecta data for different reference times as input to radiative transfer simulations. Our results show that the light curves for extraction times later than 100 ms after the merger deviate by 0.4 mag and are mostly consistent with numerical noise.

References

[1] A. Neuweiler, T. Dietrich, M. Bulla, S. V. Chaurasia, S. Rosswog, M. Ujevic, arXiv e-prints, p. arXiv:2208.13460 (2022)

The locations and environments of short GRBs

B. O'Connor[1,2]

[1] *The George Washington University, Washington, DC, USA*
[2] *University of Maryland, College Park, MD, USA*
E-mail: oconnorb@gwmail.gwu.edu

Short gamma-ray bursts (sGRBs) were unambiguously connected to binary neutron star (BNS) mergers through the simultaneous detection of GW170817 and GRB 170817A. As such, sGRBs play a significant role in astrophysics with far-reaching implications, from the rate of detectable gravitational wave events to the production of heavy elements in the Universe (the kilonova). Their environments and distance scales yield important information as to their progenitors and their formation channels, complementing the constraints derived from gravitational wave astronomy. We performed a systematic follow-up campaign targeting all sGRBs without a host galaxy association. Here, we present the results of our observing campaign, including deep Gemini, Keck and HST imaging of 31 new short GRBs. Our study doubles the sample of well-studied sGRB galaxies. We have uncovered evidence for a redshift evolution in their locations within their hosts, and for a significant population of high redshift events. The larger high redshift population suggests that BNS mergers have shorter time delays than previously expected, and therefore their kilonovae could have been responsible for polluting the early Universe with heavy metals.

NLTE Spectra of Kilonovae

Q. Pognan[1], A. Jerkstrand[1], and J. Grumer[2]

[1] *Oskar Klein Center, Department of Astronomy, Stockholm University, Stockholm , Sweden*

[2] *Theoretical Astrophysics, Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden*

The radioactively powered electromagnetic transient following a binary neutron star merger is known as a kilonova (KN). Owing to rapid expansion velocities and small ejecta masses, KNe rapidly transition into the nebular phase where Non-Local Thermodynamic Equilibrium (NLTE) processes define the physical conditions producing the emission[1]. Spectra in this regime are expected to be dominated by atomic emission lines, providing an excellent opportunity to identify individual or groups of species present in the ejecta. However, accurate modelling of NLTE physics in KN ejecta is challenging and requires the consideration of many physical processes. I will outline here the main steps needed for spectral modelling of the nebular phase, and present some preliminary results of NLTE spectra of KN.

References

[1] Q. Pognan et al, MNRAS **513**, 5174 (2022)

Neutron star merger simulations with the Lagrangian Numerical Relativity code SPHINCS_BSSN

Stephan Rosswog

University of Hamburg, Observatory, Germany

Simulations of merging neutron stars in full General Relativity are formidable computational physics challenges. To date, practically all fully general relativistic simulations are performed with Eulerian methods. An exception is the recently developed Numerical Relativity code SPHINCS_BSSN which evolves the spacetime on a hierarchy of grids according to the BSSN formulation of General Relativity, but evolves the fluid with freely moving Lagrangian Particles.
In this talk I will describe the new elements of this code and I will discuss recent neutron star merger simulations performed with SPHINCS_BSSN.

Laboratory Astrophysics with Storage Rings and Synchrotron Light Sources

S. Schippers[1]

[1]*Justus-Liebig-University Giessen, Institute of Experimental Physics I,*
Heinrich-Buff-Ring 16, 35392 Giessen, Germany
Email: schippers@jlug.de

The modeling of nonequilibrium plasmas requires the knowledge of cross sections of the basic atomic collision processes that occur in plasmas. The electron-ion merged-beams technique as implemented at the electron coolers of heavy-ion storage rings is a versatile and reliable method for measuring cross sections for electron-impact ionization and electron-ion recombination on absolute scales [1]. Likewise, the photon-ion merged-beams technique [2] yields absolute cross section for photoionization and photoabsorption. In my talk, I will introduce these experimental techniques and outline their potential for providing atomic cross sections for collision processes involving the heavy elements that are relevant for the understanding of kilonovae.

References

[1] S. Schippers, Nucl. Instrum. Methods Phys. Res. B **350**, 61 (2015)
[2] S. Schippers, A. L. D. Kilcoyne, R. A. Phaneuf, A. Müller, Contemp. Phys. **57**, 215 (2016)

Modeling neutron-star mergers by long-term numerical relativity simulation

M. Shibata

Max Planck Institute for Gravitational Physics at Potsdam, Germany

Long-term numerical-relativity simulation is the key for modeling neutron-star mergers. I will present our latest results for seconds-long radiation magnetic hydrodynamics simulation in general relativity both for black hole-neutron star binaries [1] and binary neutron stars. I will show how the magnetohydrodynamics turbulence plays an important role in the post-merger mass ejection and relativistic outflow along the spin axis of the remnant black holes.

References

[1] K. Hayashi et al., Phys. Rev. D 106, 023008 (2022)

Two sources of the r-process: quick and delayed

Ása Skúladóttir[1]

[1]*University of Florence, Italy*

The origin of heavy elements such as europium (Eu), and gold (Au) remains mystery, and the astrophysical site hosting the rapid neutron-capture process (r-process; high neutron flux) remains unclear to this day. With spectroscopic observations of individual stars in the Milky Way and the dwarf galaxy satellites, it becomes clear that (at least) two distinct r-process sites are needed to explain the data: a quick source with timescales comparable to core-collapse supernovae, and a delayed source with characteristic timescales of a few ~Gyr, most probably originating in neutron star mergers. In this talk I will go over the data and the arguments leading to this result and show that only by looking at all the available data in many galaxies will we be able to solve the puzzle that is the r-process.

A comparison between short GRB optical counterparts and kilonova AT2017gfo

G. Stratta[1,2,3]

[1]Institut für Theoretische Physik, Goethe Universität, Frankfurt am Main, Germany
[2] Istituto di Astrofisica e Planetologia Spaziali, Rome, Italy
[3] Osservatorio di Astrofisica e Scienze dello Spazio, Bologna, Italy
E-mail: stratta@physik.uni-frankfurt.de

The optical transient AT2017gfo has been associated with the binary neutron merger GW170817 that originated the short gamma-ray burst GRB 170817A (Abbott et al. 2017). AT2017gfo has been robustly identified with a kilonova (KN) emission thanks to an unprecedented extensive monitoring in time using both photometry and spectroscopy (e.g. Smartt et al. 2017, Pian et al. 2017). Previously, only a few kilonova candidates have been observed against the glare of short GRB afterglows. In this talk I will present the results from a comparison of AT2017gfo luminosity evolution with the optical/NIR counterparts of 39 short GRB with known redshift (Rossi et al. 2020). The GRB sample was carefully selected in order to be consistent with compact binary merger progenitors not only on the basis of the prompt duration, and with robust redshift measurement. Moreover, in the comparison we accurately accounted for cosmological corrections by using AT2017gfo VLT/X-Shooter spectra taken at 10 different epochs, resulting in a great improvement in time and spectral coverage over similar analysis based on less accurate spectral energy distribution extrapolation. Finally, we identify for each GRB a potential blue (<900nm) and red (>900nm) component, in analogy with the AT2017gfo modeling. Our work led to a plausible range of blue and red kilonova luminosities in a completely model-independent way, that can be used to constrain the parameter space of kilonova simulations, as well as to forecast kilonova distance reaches with current and future facilities.

References

[1] B.P. Abbott et al., ApJL, **848**, L13 (2017)
[2] S.J. Smartt et al., Nature, **551**, 79 (2017)
[3] E. Pian et al., Nature, **551**, 67 (2017)
[4] A. Rossi et al., MNRAS, **493**, 3379 (2020)

Radiative transfer simulations for kilonovae

M. Tanaka[1], D. Kato[2,3], G. Gaigalas[4], L. Radžiūtė[4], P. Rynkun[4], S. Banerjee[1], N. Domoto[1], K. Kawaguchi[5], and K. Hotokezaka[6]

[1]Astronomical Institute, Tohoku University, Sendai, Japan
[2]National Institute for Fusion Science (NIFS), Toki, Japan
[3]Kyushu University, Kasuga, Japan
[4]Institute of Theoretical Physics and Astronomy, Vilnius University, Vilnius, Lithuania
[5]Institute for Cosmic Ray Research, The University of Tokyo, Chiba, Japan
[6]Research Center for the Early Universe, The University of Tokyo, Tokyo, Japan

Kilonova is electromagnetic emission from neutron star merger, powered by radioactive decays of newly synthesized r-process nuclei. Properties of kilonovae are largely controlled by atomic properties of synthesized heavy elements, and thus, we can study the heavy element nucleosynthesis in neutron star mergers by decoding observational signatures of kilonovae. To have a better link between theory and observations, we have systematically constructed atomic data of heavy elements [1,2,3]. In this talk, we will introduce these new atomic data and recent progress of our radiative transfer simulations for kilonovae.

References

[1] M. Tanaka, D. Kato, G. Gaigalas, K. Kawaguchi, MNRAS, **496**, 1369-1392 (2020)

[2] S. Banerjee, M. Tanaka, K. Kawaguchi, D. Kato, G. Gaigalas, ApJ, **901**, 29 (2020)

[3] S. Banerjee, M. Tanaka, D. Kato, G. Gaigalas, K. Kawaguchi, N. Domoto, ApJ, **934**, 117 (2022)

r process in neutron star mergers and the impact of nuclear physics uncertainties

N. Vassh[1]

[1]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*

This year marks 65 years since Burbidge, Burbidge, Fowler, and Hoyle (B2FH) charted the initial roadmap for nuclear astrophysics [1]. At the time of B2FH the rapid neutron capture process (r-process) showed itself to synthesize exotic, heavy nuclei far from stability largely via its signature on the Solar abundances. Nowadays we have a wealth of observational information to assimilate, from metal-poor star abundances to neutron star merger light curves. In this talk I will discuss how nuclear physics will play a central role in addressing the question of heavy element origins over the next decade, with world-wide campaigns fixing their aim at new measurements and new theoretical calculations of the properties of still unprobed neutron-rich nuclei. The timeliness and importance of such work is demonstrated through r-process studies which synergize efforts across multiple disciplines when seeking to decipher r-process observables. Since nucleosynthesis outcomes encode the interplay between nuclear physics and astrophysics, such studies present valuable opportunities for theory, experiment, and observation to inform one another and drive progress in each area.

References

[1] E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, Rev. Mod. Phys. **29**, 547 (1957)

Kilonova Observations Enabled by the Vera C. Rubin Observatory

V. Ashley Villar

[1]*Penn State University, Pennsylvania USA*

In early 2025, the Vera C. Rubin Observatory will begin its decade-long Legacy Survey of Space and Time (LSST). This survey will begin an unprecedented era in observational astrophysics, capture deep imaging of the entire southern sky every few days. Two years later, gravitational wave observatories will have reached design sensitivities, allowing for detections of binary neutron star mergers out to 325 Mpc. The union of these datasets will lead to multi-messenger observations of a dozen kilonovae annually. Here I review observational strategies with LSST to make these discoveries possible and highlight synergies with other future missions.

Element identification in, and geometry of, the kilonova AT2017gfo associated with GW170817

D. Watson[1,2]

[1] *Niels Bohr Institute, University of Copenhagen, Denmark*
[2] *Cosmic Dawn Center*

AT2017gfo, associated with the gravitational wave event GW170817, is the only well-studied kilonova to date. The spectral series of the evolving kilonova are of high-quality, but are complex and so far only one line has been identified -- Sr, a light neutron capture element. This is the first, and so far only, identification of freshly-formed neutron capture matter in situ and demonstrates unequivocally that neutron star mergers make neutron capture elements. However, the rest of the spectrum is still a mystery. I present here our recent work on the kilonova spectra, from the identification of Sr, to showing how we can use the spectra to measure the geometry of the explosion and measure the distance to kilonova to sub-percent accuracy.

Abstracts of Posters

(in alphabetical order)

Chrono-chemo-dynamics of red giants in the Kepler field

Arthur Alencastro Puls[1,2,3], Luca Casagrande[2,3], Stephanie Monty[2,3,4], David Yong[2,3], Fan Liu[5], Dennis Stello[3,6,7], Victor Aguirre Børsen-Koch[7] and Ken C Freeman[2,3]

[1]Goethe University Frankfurt, Institute for Applied Physics, Max-von-Laue Str. 11, 60438 Frankfurt am Main, Germany
[2] Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT 2611, Australia
[3] ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO3D), Australia
[4]Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK
[5]School of Physics & Astronomy, Monash University, Clayton VIC 3800, Australia
[6] School of Physics, University of New South Wales, Sydney, NSW 2052, Australia
[7] Stellar Astrophysics Centre (SAC), Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark

In this poster we show results already published[1], where we combine information from solar-like oscillations gathered from Kepler light curves, high-resolution spectroscopy from Keck/HIRES, and Gaia astrometry. Stellar ages, chemical abundances and kinematics are derived for a group of seven metal-poor Red Giants in order to characterise them in a multidimensional chrono-chemo-dynamical space. For the abundances, 1D LTE ATLAS atmospheres were emplyed together with spectral synthesis and equivalent widths. Fundamental stellar parameters such as masses and ages were interpolated in a grid of BaSTI models, taking advantage of asteroseismic information from Kepler. Galpy was emplyed toghether with Gaia EDR3 astrometric solutions to derive the dynamics. Our results suggest that stellar ages are sensitive to the choice of zero-point calibration in Gaia parallaxes, and that the uncertainties of Gaia (E)DR3 may be underestimated. We also identify two potentially evolved blue stragglers. Finally, four stars in our sample have characteristics that suggest membership on the accreted Milky Way halo.

References

[1] Alencastro Puls et al. (2022), MNRAS **510** 1733

Calculations of expansion opacities of Ce ions within the configuration interaction plus many-body perturbation theory approach

A. Bondarev[1,2] and S. Fritzsche[1,2,3]

[1]*Helmholtz-Institut Jena, D-07743 Jena, Germany*
[2]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany*
[3] *Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany*

After detecting gravitational waves from the neutron star merger GW170817 and its electromagnetic counterpart AT2017gfo, a lot of attention has been devoted to calculations of opacities of r-process elements. Different atomic approaches and codes such as GRASP, HULLAC, FAC, and others have been used to calculate spectra and bound-bound transition oscillator strengths for these elements [1-4]. The vast amount of generated atomic data needed for further kilonova modeling is usually visualized and compared using the expansion opacity formalism [5].

In this contribution, we present the recent results of calculations of the expansion opacities in low-ionized Ce ions, which are expected to be produced in neutron star mergers. The calculations are based on the combination of configuration interaction and the many-body perturbation theory approach [6]. This approach has been successfully used a lot in the past in high-precision evaluations of energies of low-lying levels and amplitudes of transitions between them in ions with a complex electronic structure (see, e.g., [7,8]). Within the current approach, the effect of accurate treatment of core-valence and core-core correlations on the opacities is studied in detail. Also, the obtained results are compared to the results available in the literature.

References

[1] M. Tanaka, D. Kato, G. Gaigalas, K. Kawaguchi, MNRAS 496, 1369 (2020).
[2] C. J. Fontes, C. L. Fryer, A. L. Hungerford, R. T. Wollaeger, O. Korobkin, Mon. Not. R. Astron. Soc. 493, 4143 (2020).
[3] H. Carvajal Gallego, P. Palmeri, P. Quinet, MNRAS. 501, 1440 (2021).
[4] R. F. Silva, J. M. Sampaio, P. Amaro, A. Flörs, G. Martínez-Pinedo, J. P. Marques, Atoms 10, 18 (2022).
[5] P. A. Pinto and R. G. Eastman, Astrophys. J. 530, 757 (2000).
[6] V. A. Dzuba, V. V. Flambaum, M. G. Kozlov, PRA 54, 3948 (1996).
[7] C. Cheung, M. S. Safronova, S. G. Porsev, M. G. Kozlov, I. I. Tupitsyn, A. I. Bondarev, PRL 124, 163001 (2020).
[8] M. G. Kozlov, I. I. Tupitsyn, A. I. Bondarev, D. V. Mironova, PRA 105 052805 (2022).

Simulations of the neutron star merger GW190425: can we get constraints from the lack of the kilonova?

Alessandro Camilletti*[1,2], Leonardo Chiesa[1,2], Giacomo Ricigliano[3], Albino Perego[1,2], Lukas Chris Lippold[4], Surendra Padamata[5,6], Sebastiano Bernuzzi[4], David Radice[5,6,7], Domenico Logoteta[8,9] and Federico Maria Guercilena[1,2]

[1] *Dipartimento di Fisica, Universitá di Trento, Via Sommarive 14, 38123 Trento, Italy*
[2] *INFN-TIFPA, Trento Institute for Fundamental Physics and Applications, via Sommarive 14, I-38123 Trento, Italy*
[3] *Technische Universität Darmstadt, Institut für Kernphysik, Schlossgartenstr. 2, D-64289 Darmstadt, Germany*
[4] *Theoretisch-Physikalisches Institut, Friedrich-SchillerUniversität Jena, 07743, Jena, Germany*
[5] *Institute for Gravitation & the Cosmos, The Pennsylvania State University, University Park PA 16802, USA*
[6] *Department of Physics, The Pennsyvlania State University, University Park, PA 16802, USA*
[7] *Department of Astronomy & Astrophysics, The Pennsyvlania State University, University Park, PA 16802, USA*
[8] *Dipartimento di Fisica, Università di Pisa, Largo B. Pontecorvo, 3 I-56127 Pisa, Italy*
[9] *INFN, Sezione di Pisa, Largo B. Pontecorvo, 3 I-56127 Pisa, Italy*

GW190425 was the second gravitational wave (GW) signal compatible with a binary neutron star (BNS) merger detected by the Advanced LIGO and Advanced Virgo detectors. Since no electromagnetic counterpart was identified, whether the associated kilonova was too dim or the localisation area too broad is still an open question. We simulate 28 BNS mergers with the chirp mass of GW190425 and mass ratio $1 \leq q \leq 1.67$, using numerical-relativity simulations with finite-temperature, composition dependent equation of state (EOS) and neutrino radiation.

The energy emitted in GWs is less than $0.083\,\mathrm{M}_\odot c^2$ with peak luminosity of 1.1 - $2.4 \times\ 10^{58}/(1+q)^2 \mathrm{erg\ s}^{-1}$. Dynamical ejecta and disc mass range between $5 \times\ 10^{-6}$ - 10^{-3} and 10^{-5} - 0.1 $\mathrm{M}_\odot$, respectively. Asymmetric mergers, especially with stiff EOSs, unbind more matter and form heavier discs compared to equal mass binaries. The angular momentum of the disc is 8 - $10\,\mathrm{M}_\odot\ GM_{\mathrm{disc}}/c$ over three orders of magnitude in M_{disc}.

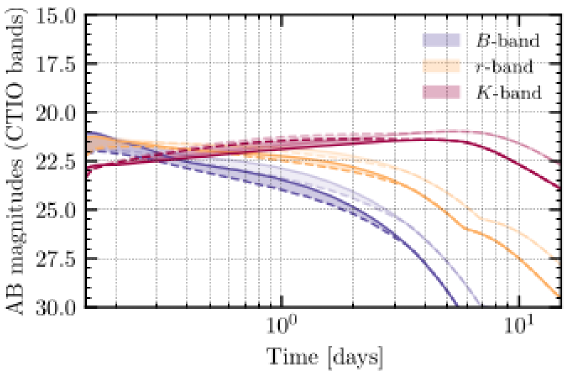


Figure 1: AB magnitudes in the blue, red and IR bands of CTIO telescope as a function of time for the simulation with DD2 EOS and $q = 1.33$.

While the nucleosynthesis shows no peculiarity, the simulated kilonovae (e.g. Fig. 1) are relatively dim compared with GW170817. For distances compatible with GW190425, AB magnitudes are always dimmer than ~ 20 mag for the B, r and K bands, with brighter kilonovae associated to more asymmetric binaries and stiffer EOSs. We suggest that, even assuming a good coverage of GW190425's sky location, the kilonova could hardly have been detected by present wide-field surveys and no firm constraints on the binary parameters or EOS can be argued from the lack of the detection.

*e-mail: a.camilletti@unitn.it

Nucleosynthesis of light elements in BNS mergers

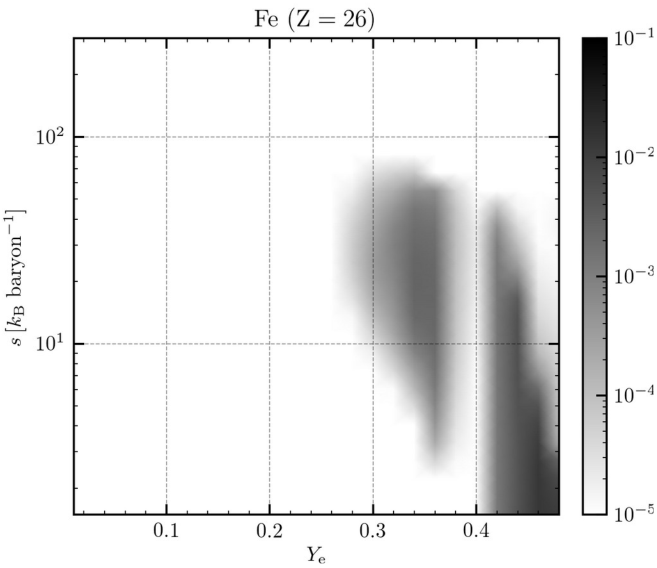
L. Chiesa[1,2], A. Perego[1,2] and F. Guercilena[2]

[1]Dipartimento di Fisica, Università di Trento, Via Sommarive 14, I-38123 Trento, Italy
[2] INFN-TIFPA, Trento Institute for Fundamental Physics and Applications, Via Sommarive 14, I-38123 Trento, Italy
E-mail: leonardo.chiesa@unitn.it

Nucleosynthesis studies in binary neutron star (BNS) mergers usually focus on the production of heavy elements across the characteristic three-peak r-process pattern, being the primary yields in this kind of events. However, the presence of high electron fraction (Ye) regions in the ejecta could extend this pattern by producing lighter elements among the final yields (see e.g. [1]). The impact on kilonova spectra of these elements in principle is easier to identify due to the smaller number of associated atomic transitions. In view of an eventual future observability, light elements could play an important role in constraining the physics of compact binary mergers, since their production is less robust than the standard heavy r-process pattern when comparing differing BNS models.

In this study, we investigate at a quantitative level the production of light elements (Z<30) in the dynamical ejecta of BNS mergers. The work is an extension of the nucleosynthesis analysis presented by *Perego et al.* in [2]. We first explore the typical thermodynamics conditions that favor the production of these elements by performing extensive calculations with the nuclear reaction network *SkyNet*. Then, we compute the actual yields in dynamical BNS ejecta by combining the nucleosynthesis output with a set of numerical BNS simulations targeted to GW170817-like binaries.

We find that elements lighter than calcium (with the exception of H and He) are severely under-produced for any typical condition realized in BNS ejecta. Focusing on slightly heavier nuclides, iron-group elements are produced only in relatively high-Ye matter and therefore are more abundant in BNS models with equal NS masses and soft nuclear EOSs, where the contribution of the leptonized shock-heated ejecta is greater.



References

[1] J. Lippuner and L. Roberts, Astrophys. J. **815**, 82 (2015)
[2] A. Perego et al., Astrophys. J. **925**, 22 (2022)

Towards Spectral Modelling of Kilonovae: Atomic Data for Nd and U

A. Flörs[1], **R. Ferreira da Silva**[2], **G. Leck**[1,3], **G. Martínez-Pinedo**[1,3,4]

[1] GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany
[2] Laboratório de Instrumentação e Física Experimental de Partículas (LIP) and Faculdade de Ciências, Universidade de Lisboa (FCUL), Portugal
[3] Institut für Kernphysik (Theoriezentrum), Fachbereich Physik, Technische Universität Darmstadt, Schlossgartenstraße 2, 64289 Darmstadt, Germany
[4] Helmholtz Forschungsakademie Hessen für FAIR, GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany

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 [1]. 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 only observed neutron star merger. A great challenge for spectroscopic modelling of kilonovae is the almost non-existent atomic data currently available for lanthanides and actinides. While some progress has been made with regard to lanthanide atomic data recently [2,3], there is currently no publicly available detailed atomic data for actinides.
I will present converged and calibrated atomic structure calculations using the FAC code [4], focusing on two of the most important lanthanides and actinides possibly present in kilonova ejecta: neodymium and uranium. For these exemplary elements, I will present line-by-line and grey opacity data as well as their calibration to measured atomic data and their convergence behavior.

References

[1] Kasen D., Metzger B., Barnes J., Quataert E., Ramirez-Ruiz E., Nature, **551**, 80 (2017)
[2] Tanaka M., Kato D., Gaigalas G., Kawaguchi K., MNRAS, **496**, 1369 (2020)
[3] R. Ferreira da Silva, J. Sampaio, P. Amaro, A. Flörs, G. Martínez-Pinedo, J. Marques, Atoms **10**, 18 (2022)
[4] M. Gu, Can. J. Phys. **86** (5), 675 (2008)

Long term modelling of binary neutron star mergers ejecta: an efficient numerical framework

F. Guercilena[1], **M. Jacobi**[2] **and A. Arcones**[2,3]

[1]TIFPA-INFN, Trento, Italy
[2] TU Darmstadt, Darmstadt, Germany
[3] GSI, Darmstadt, Germany

The dynamics of binary neutron star (BNS) mergers is a complex interplay of many physical processes, making it rich of non trivial features in every phase of the system evolution. Some of the dynamics however can only be accurately modelled by considering the long term evolution of a BNS system in the post merger phase. This is in particular true for the evolution of the ejecta. While so-called dynamical ejecta, powered by mechanical torques and shock heating in the outer layers of the stars, happen on a timescale of a few tens of milliseconds, neutrino driven winds and magnetically driven winds operate on much longer timescales (~100 ms), and can eject a far greater amount of matter; viscous effects lead to further ejection of matter on timescales of seconds; finally, one second is also the typical timescale of neutron freeze-out in r-process nucleosynthesis, when nuclear reactions slow and effectively cease to release energy in the ejected matter [1]. Due to their complex geometry, BNS mergers require three-dimensional simulations to be modelled; however, the computational cost of such simulations limits the timescale that they can realistically reach to ~100 ms after merger [2]. However in the post merger phase the geometry of the system simplifies and can reasonably be thought of as axisymmetric and therefore two-dimensional. We show how can this observation can be leveraged to turn a 3D BNS evolution code into a much cheaper 2D one by means of the Cartoon technique [3]. We discuss details of the initial data setup and of our implentation of the evolution framework in the open source EinsteinToolkit [4]. Finally, we demostrate the significat reduction in computational cost coming from the reduction in the dimensionality of the model, and the ability to carry out long-term simulations of the post-merger phase of BNS systems.

References

[1] B. Metzger, Living Reviews in Relativity, Volume 23, Issue 1, id.1
[2] L. Baiotti, L. Rezzolla, Rep. Prog. Phys. 80 096901 (2017)
[3] M. Alcubierre et al, Int.J.Mod.Phys. D10 (2001) 273-290
[4] https://doi.org/10.5281/zenodo.6588641

Cocoon emission in neutron star mergers

H. Hamidani[1,2] **and K. Ioka**[2]

[1] *Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
[2] *Astronomical Institute, Tohoku University, Aoba, Sendai 980-8578, Japan*

In the gravitational wave event GW170817, there was a ∼10 hours gap before electromagnetic (EM) observations, without detection of the cocoon [1]. The cocoon is heated by a *short* gamma-ray burst (*s*GRB) jet propagating through the ejecta of a Neutron Star (NS) merger, and a part of the cocoon escapes the ejecta with an opening angle of 20º–30º. Here we model the cocoon and calculate its EM emission. Our 2D hydrodynamic simulations suggest that the density and energy distributions, after entering homologous expansion, are well-fitted with power-law functions, in each of the relativistic and non-relativistic parts of the escaped cocoon. Modeling these features, we calculate the cooling emission analytically. We find that the cocoon outshines the r-process kilonova/macronova at early times (10–1000 s), peaking at UV bands. The relativistic velocity of the cocoon's photosphere is measurable with instruments such as Swift, ULTRASAT and LSST. We also imply that energetic cocoons, including failed jets, might be detected as X-ray flashes. Our model clarifies the physics and parameter dependence, covering a wide variety of central engines and ejecta of NS mergers and *s*GRBs in the multi-messenger era.

References

[1] M. Kasliwal, et al., Science, 358, 1559 (2017)

Muons in the aftermath of Neutron Star mergers and their impact on Trapped Neutrinos

E. Loffredo[1,2,3], **A. Perego**[4,5], **D. Logoteta**[6,7], **M. Branchesi**[1,2,3]

[1]Gran Sasso Science Instititue, L'Aquila, Italy
[2] INFN-Laboratori Nazionali del Gran Sasso, L'Aquila, Italy
[3] INAF-Osservatorio Astronomico d'Abruzzo, Teramo, Italy
[4] Dipartimento di Fisica-Università di Trento, Trento, Italy
[5] INFN-TIFPA, Trento, Italy
[6] Dipartimento di Fisica-Università di Pisa, Pisa, Italy
[7] INFN-Sezione di Pisa, Pisa, Italy
Email: eleonora.loffredo@gssi.it

The joint detection of GW170817 together with a short gamma-ray burst and a kilonova (KN) from a Binary Neutron Star (BNS) merger marked the birth of multi-messenger astronomy including gravitational waves (GWs). GW detectors LIGO, Virgo, and KAGRA, are expected to further improve their sensitivity before the upcoming runs and to increase the number of detected BNS mergers. Moreover, next-generation interferometers, such as the Einstein Telescope and Cosmic Explorer, will significantly enlarge the horizon of detectable BNS mergers and dramatically improve parameter estimation, enhancing the chances to detect electromagnetic (EM) counterparts. In this context, theoretical modeling and numerical simulations play a pivotal role. On the one side, they are mandatory to interpret the collected data and eventually constrain the microphysics of the merger. On the other side, they provide reliable predictions about GW and EM signals, which are necessary to develop multi-messenger detection strategies. State-of-the-art simulations of BNS mergers do not include muons in the EOS, even though muons give a relevant contribution to the thermodynamics of protoneutron stars, cold NSs, and Core-Collapse Supernovae. Moreover, present simulations often neglect the contribution of trapped neutrinos to the system's pressure and energy. The aim of our work is to investigate the impact of muons and trapped neutrinos in the aftermath of BNS mergers. We post-process the outcome of four numerical relativity simulations, considering three different nuclear Equations of State (EOS) and two different mass ratios. We find that in the central region of the remnant, the fraction of muons is always above 30% of the electron fraction, with a maximum between 50% and 70% depending on the nuclear EOS. Muons change the flavor hierarchy of trapped neutrinos, so that muon anti-neutrinos are the most abundant, followed by electron anti-neutrinos. Finally, muons modify the remnant pressure up to 7%. These changes correlate in a non-trivial way with the EOS and the system's density and temperature.

Experimental design of opacity measurements in the PANDORA plasma trap relevant for Kilonovae signals

A. Pidatella[1] *on behalf of the PANDORA collaboration*

[1]*INFN - LNS, Catania, Italy*

Joint observations of gravitational-wave (GW) event to compact binary objects mergers, and of their electromagnetic counterpart, known as kilonova (KN) lead to a new avenue in the multi-messenger astronomy era to constrain the astrophysical origin of the r-process elements and the equation of state of dense nuclear matter [1]. KNe act as spectral probes to explore the merger environment, hence of fundamental relevance for future detection and for providing sounder nucleosynthetic yields occurring in these loci [2]. However, largely heterogeneous post-merging ejecta composition, of both light- and heavy-r process nuclei, propagates strong effects on the KN light-curve prediction through the ejecta opacity, till today hard to be fully addressed by theoretical models. Within the PANDORA (Plasmas for Astrophysics Nuclear Decays Observation and Radiation for Archaeometry) project [3], we intend to provide, in the forthcoming years, critical new nuclear and atomic physics inputs from experiments and advanced theoretical models. In particular, the in-plasma atomic physics knowledge on the opacity of several metallic nuclei from r-process will allow to extend the understanding on the microphysics of KNe. We report on the paradigm of early-stage timescale KN emission expected at optical wavelengths from light r-process ejecta component, and we present the work carried out in the framework of the PANDORA collaboration [3] to support first-of-its-kind experimental measurements of plasma opacity with in-laboratory plasmas resembling these KN-stage conditions [4]. In this view, the results of recently performed experiments at the INFN-LNS to reproduce stable early-stage ejecta thermodynamical conditions of under-dense and low-temperature plasmas are here reported [5]. These are the grounds to tackle the astrophysical problem in laboratory plasmas with an interdisciplinary approach, and some of the critical experimental aspects are here discussed.

References

[1] Rosswog S., *International Journal of Modern Physics D* ***24*** *1530012 (2015).*

[2] Kasen D., *et al. Nature* ***551*** *80–84 (2017).*

[3] Mascali D., *et al. Universe* ***8*** *(2022).*

[4] Pidatella A., *et al. Il Nuovo Cimento C* ***44*** *4 (2021)*.

[5] Pidatella A., *et al. Frontiers in Astronomy and Space Sciences,* ***9*** *225 (2022).*

Semi-analytic modeling of kilonovae

G. Ricigliano[1], A. Arcones[1,2], A. Perego[3,4], L. Lippold[5], S. Bernuzzi[5], A. Camilletti[3,4] and L. Chiesa[3,4]

[1]*Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstr. 2, 64289 Darmstadt, Germany*
[2]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, 64291 Darmstadt, Germany*
[3]*Dipartimento di Fisica, Università di Trento, Via Sommarive 14, 38123 Trento, Italy*
[4]*INFN-TIFPA, Trento Institute for Fundamental Physics and Applications, Via Sommarive 14, 38123 Trento, Italy*
[5]*Theoretisch-Physikalisches Institut, Friedrich-Schiller Universität Jena, 07743 Jena, Germany*

Matter expelled from binary neutron star (BNS) and black hole-neutron star (BHNS) mergers is one confirmed site capable of harboring r-process nucleosynthesis in the universe, due to its extreme conditions and abundance of neutrons. The freshly produced nuclei are unstable and undergo nuclear decay, releasing an amount of energy sufficient to power a thermal transient known as kilonova (KN). A kilonova shines from a few hours ("blue" KN) to a few weeks ("red" KN) after merger and represents a major electromagnetic counterpart to gravitational wave signals.
We present a numerical-relativity-informed KN model derived from an analytic solution of the radiative transfer equations. The model considers multiple ejecta components, the general anisotropy of their dynamic properties and the projection in the observer viewing direction. The impact of the ejecta composition on the light curves is explored by employing parametrized radioactive heating rates derived from nuclear reaction network calculations and grey opacities obtained with atomic structure calculations. We compare our results with those of other semi-analytic models [1] and full radiative transfer calculations. Finally, we show a first model application where AB magnitudes are computed for a set of BNS merger simulations targeted on the gravitational wave signal GW190425 [2].

References

[1] Z. Wu et al, *Monthly Notices of the Royal Astronomical Society* **512**, 1, 328-347 (2022)
[2] A. Camilletti et al, *Monthly Notices of the Royal Astronomical Society* **516**, 4, 4760–4781 (2022)

Implementation of first-order multipolar neutrino transport in Numerical Relativity code BAM

Federico Schianchi[1], **Henrique Gieg**[2], **Vsevolod Nedora**[3], **Maximiliano Ujevic**[2], and **Tim Dietrich**[1,3]

[1]*Institut für Physik und Astronomie, Universität Potsdam, Haus 28, Karl-Liebknecht-Str. 24/25,14476, Potsdam, Germany*
[2]*Centro de Ciências Naturais e Humanas, Universidade Federal do ABC, 09210-170, Santo André, São Paulo, Brazil*
[3]*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Am Mühlenberg 1, Potsdam 14476, Germany*

Numerical-relativistic simulations of Binary Neutron Star (BNS) mergers have a key role in Multimessenger Astronomy, e.g., for modeling gravitational and electromagnetic emissions connected to those events. For an accurate description of electromagnetic counterparts, one needs to know the properties of the matter ejected during and shortly after the merger. Inside this material, heavy elements are synthesized depending on the electron fraction of the outflowing matter. The radioactive decay of these elements produce an observable thermal emission from BNS mergers. All these phenomena are highly dependent on weak interactions between baryons and neutrinos.

Our work consists of implementing a code that tracks the propagation of such particles and their interaction with matter during merger and postmerger. It will be part of our Numerical Relativity code BAM. The aim is to get a more accurate estimate of the ejecta properties, mostly of the electron fraction. Recent studies revealed that neutrino emission/absorption also influences the mass and velocity of the ejected material [1] [2].

The scheme is based on a first-order multipolar (M1) transport equation [3] [4]. It consists of evolving the energy and momentum densities of neutrinos without solving a full and too expensive Boltzmann equation.

The advantage of transport formalisms with respect to the Leakage scheme currently implemented in BAM is the possibility to take into account for the neutrinos to be reabsorbed by the fluid in another point of the simulation domain, with transfer of energy, momentum and lepton number.

References

[1] Tim Dietrich and Maximiliano Ujevic. In: *Classical and Quantum Gravity* 34.10 (2017), p. 105014.

[2] Vsevolod Nedora et al. In: *Classical and Quantum Gravity* 39.1 (2021), p. 015008.

[3] Masaru Shibata et al. In: *Progress of Theoretical Physics* 125.6 (2011), pp. 1255–1287.

[4] Kip S Thorne. In: *Monthly Notices of the RoyalAstronomical Society* 194.2 (1981), pp. 439–473.

Kilonova Mining Project

Paramvir Singh[1,2], Giulia Stratta[1,2,3,4,5], Andrea Rossi[3],
David Alexander Kann[1,2], Mattia Bulla[6,7] and Luciano Rezzolla[1,8,9]
[1]*Institute for Theoretical Physics, Goethe University Frankfurt, 60438 Frankfurt am Main, Germany*
[2]*Hessian Research Cluster ELEMENTS, Giersch Science Center, Goethe University Frankfurt, 60438 Frankfurt am Main, Germany*
[3]*INAF-Osservatorio di Astrofisica e Scienza dello Spazio, 40129 Bologna, Italy*
[4]*INAF- Institute of Space Astrophysics and Planetology, 00133, Rome, Italy*
[5]*INFN-National Institute for Nuclear Physics Rome, 00185 Rome, Italy*
[6]*Department of Physics and Earth Science, University of Ferrara, 44122 Ferrara, Italy*
[7]*The Oskar Klein Centre, Department of Astronomy, Stockholm University, AlbaNova, SE-10691 Stockholm, Sweden*
[8]*School of Mathematics, Trinity College, Dublin 2, Ireland*
[9]*Frankfurt Institute for Advanced Studies, 60438 Frankfurt am Main, Germany*

The binary neutron star merger GW170817 at a distance of 40 Mpc was the pivotal event for multi-messenger astronomy. The proximity of this merger allowed for extensive observations and follow up. Due to the low detection rate of such a well sampled event, a similar merger could be difficult to be observed in near future. In our envisioned work, we will analyze past short GRBs with known redshift, coupled with the state of the art models to explore the Kilonova parameter space. We intend to construct an updated database of optical counterparts in the UV/optical/NIR bands, extending it with X-ray and publicly available data [1]. We aim to model the non-thermal component, fitting synthetic multi-band light curves to the short GRBs in our sample using the python package Afterglowpy [2]. Whereas to identify any thermal contribution, we use the time-dependent three-dimensional Monte Carlo code POSSIS for modelling the radiation transport in supernovae and Kilonovae [3]. As a result, we evaluate our sample of short GRBs, constraining any evidence of Kilonovae and their properties according to our best fit template.

References

[1] A. Rossi, Monthly Notices of the Royal Astronomical Society, **Volume 493**, Issue 3, pp.3379-3397 (2020)

[2] G. Ryan, The Astrophysical Journal, **Volume 896**, Issue 2, id.166, 23 pp. (2020)

[3] M. Bulla, Monthly Notices of the Royal Astronomical Society, **Volume 489**, Issue 4, p.5037-5045 (2019)

Dielectronic recombination experiments of Kr^{25+} ions at the CSRm and CSRe

S. X. Wang[1,2], Z. K. Huang[3], W. Q. Wen[3], L. F. Zhu[1] and X. Ma[3]

On behalf of the DR collaboration group at HIRFL in Lanzhou

[1]University of Science and Technology of China, Hefei, China
[2] I. Physikalisches Institut Justus-Liebig-Universität Gießen, Gießen, Germany
[3]Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China

DR rate coefficients for Na-like Kr^{25+} have been measured at the CSRm and CSRe in the energy range of 0-150 eV. Strong DR resonances due to $3s \rightarrow 4l$ core excitations forming $4l4l'$ intermediate states are observed. Theoretical calculations can reproduce these resonances with satisfactory accuracy only when the strong mixing between the adjacent $4l4l'$ and $3lnl'$ states are included. The observed $4l4l'$ resonances contribute prominently to the plasma recombination rate coefficients at low temperatures. The experimental rate coefficients provide benchmark for testing and developing atomic codes. The successful calibration DR measurement with Kr^{25+} indicates that CSRe could become a promising platform for carrying out electron-ion collision experiments with heavy highly charged ions.

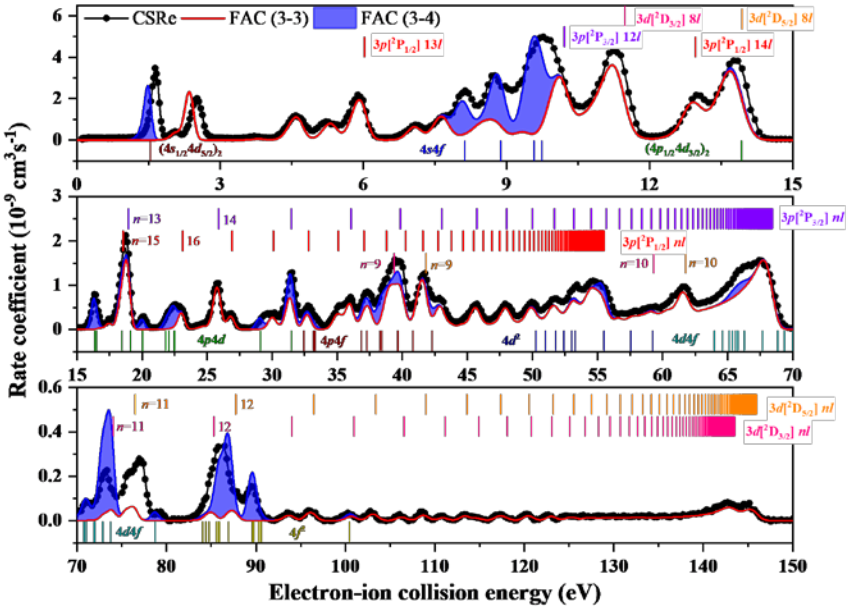


Figure 1: Comparison between the CSRe data and the FAC calculation.

References

[1] Z. K. Huang et al., Phys. Rev. A 102, 062823 (2020)

X-ray Emission Study Performed for Hydrogen-like Lead Ions at the Electron Cooler of CRYRING@ESR

B. Zhu[1,2,3], A. Gumberidze[2], T. Over[1,3], G. Weber[2], Z. Andelkovic[2], A. Bräuning-Demian[2], R. Chen[2], D. Dmytriiev[2], O. Forstner[1,2,3], C. Hahn[1,2,3], F. Herfurth[2], P.-M. Hillenbrand[2], A. Kalinin[2], F. M. Kröger, M. Lestinsky[2], Yu. A. Litvinov[2], E. B. Menz[1,2,3], W. Middents[1,2,3], T. Morgenroth[1,2], N. Petridis[2], Ph. Pfäfflein[1,2,3], M. S. Sanjari[2], R. S. Sidhu[2], U. Spillmann[2], S. Trotsenko[1,2], L. Varga[2], G. Vorobyev[2] and Th. Stöhlker[1,2,3]

[1]Helmholtz Institute Jena, Jena, Germany
[2] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[3] IOQ, Friedrich-Schiller-Universität Jena, Jena, Germany

The study of x-ray emission associated with Radiative Recombination (RR) at ultra-cold cooling conditions, as it prevails at electron cooler devices at ion storage rings allows for a stringent test of atomic structure and the investigation of subsequent x-ray emission characteristics. In particular, for highly charged ions at high Z it enables us to probe in detail the prevailing cascade decay dynamics and gain more insight into the final state population of the recombination process itself.

We report on an experiment where bare lead ions were decelerated down to 10 MeV/u in the ESR storage ring at GSI, Darmstadt and injected into CRYRING@ESR [1] and, subsequently, the x-ray emission of H-like lead ions associated with the RR process were studied at the electron cooler. For this purpose, at the extension part of cooler section dedicated vacuum chambers were used, equipped with beryllium view ports allowing for x-ray detection under 0° and 180° with respect to the ion beam axis. The x-ray detection was accomplished by using two standard high-purity germanium x-ray detectors. In order to suppress the dominant background, stemming from bremsstrahlung caused by cooler electrons and the natural background, an ion detector was operated downstream to the cooler, enabling to record x-rays in coincidence with down-charged Pb^{81+} ions from electron cooler section.

In this experiment, we observed for the very first time for stored ions the full x-ray emission pattern. Most remarkably, at 0° no line distortion effect due to delayed emission are present in the well resolved spectra, spanning over a wide range of x-ray energies (from about 5 to 100 keV) which enable to identify fine-structure resolved Lyman, Balmer as well as Paschen x-ray lines along with the RR transitions into the K-, L- and M-shell of the ions. To compare with theory, an elaborate theoretical model has been applied taking into account the initial population distribution via RR for all atomic levels up to Rydberg states with principal quantum number n = 165 in combination with cascade calculations based on time-dependent rate equations. Most notably, this comparison sheds light on the contribution of prompt and delayed x-ray emission to the observed x-ray spectra, originating in particular from Yrast-cascade transitions into inner shells.

References

[1] B. Zhu *et al*., Phys. Rev. A **105**, 052804 (2022)