# On the impact of compact binary merger ejecta opacity on Kilonova transient signals

*Angelo* Pidatella[1,*] for the PANDORA collaboration

[1]Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud, Catania - Italy

**Abstract.** Returns of gravitational wave astronomy will largely benefit from the detection and identification of electromagnetic (EM) signatures to gravitational-wave sources. Kilonovae (KNe) are promising EM counterparts to compact binary mergers, offering to astronomers and nuclear astrophysicists a unique window to advance knowledge on the heavy-element nucleosynthesis and merger-driven mass ejection. However, extremely heterogeneous post-merging ejecta composition of both light- and heavy-*r* process nuclei, implies strong effects on the KNe light-curve identification due to the varying opacity of the system. Hence, large uncertainties on the *r*-process final abundance via spectroscopic analysis of KNe signals are still present, hardly fixed by theoretical models. Here we will present some peculiar features of KNe studies, focusing on the opacity issue, from the atomic and plasma physics perspectives. In this view, efforts have been made recently at INFN-LNS, trying to put constraints on plasma opacity of interest for early-stage KNe emission. We will present the experimental progress on the problem, including instruments and methods which could open an interdisciplinary approach to tackle astrophysical problems in laboratory plasmas.

## 1 Introduction

Matter ejected from the coalescence of compact binary objects, such as neutron-stars mergers, is thought to be among the major cosmic nuclei factories for the production of elements heavier than iron through the *r*-process nucleosynthesis [1–3]. Radioactive nuclei in the ejecta can feed thermal transients diffusing through the ejecta and the radiation can escape once when a translucent stage of the expanding ejecta is reached. These signals, known as *Kilonovae* (KNe), are electromagnetic (EM) counterparts of GW (Gravitational-Wave) events [4] and can last from days to weeks [5]. Their light-curves peak in different range of the EM spectrum [6], depending on many peculiar thermodynamic conditions of the ejecta, on the merging dynamics [5], and especially on the post-merging *r*-process nucleosynthesis pattern and final ejecta composition [7]. A good analysis of these signals becomes crucial for an efficient identification of GW signals, and for advancing knowledge on the equation of state of neutron stars. Moreover, KNe turn to be exceptional probes to give sounder constraints on the *r*-process nucleosynthesis yields. In the study of KNe, two fundamental inputs are requested [8]: (1) *r*-process yields (fixing the *heating rate*), (2) *opacity* (fixing the exchange of energy between plasma and radiation). The time-scale dynamics at which the KNe peak

*e-mail: pidatella@lns.infn.it

occurs depends on the opacity [2]. However, due to a strongly heterogeneous ejecta composition, opacity from theoretical models suffers from large uncertainty, with incomplete and uncertain atomic transition strength, and blending of plethora of transition lines, largely requesting for experimental data [7, 8]. The KN emission is reprocessed by atomic opacities (mainly bound-bound transitions) to optical and infra-red wavelengths. At the INFN-LNS, we propose an experimental design for plasma opacity measurements via spectroscopic techniques, in particular Optical Emission Spectroscopy (OES) analysis of emitting plasma with thermodynamic conditions resembling the astrophysical scenario, aiming at estimating the mean opacity for several light $r$-process metals abundant in the KNe diffusion stages [9, 10]. A feasibility study, to bound such experimental survey on typical laboratory plasmas used as plasma sources for accelerators, has been framed within the PANDORA project and research infrastructure, underlining that several physics cases are suitable for the study and envisaging the experimental design for the measurements [9]. The study opened the route to experimental measurements connecting nucleosynthesis ($r$-process), plasma physics, and nuclear astrophysics in the multi-messenger astronomy era. Experimental progresses have been done in terms of plasma parameters characterization via OES techniques as a function of several plasma source parameters [11], the summary of which is presented in the following section.

## 2 Experimental results

Before performing any of the planned opacity measurements, a robust plasma characterization is needed, attempting to reproduce and stabilize plasma conditions of interest. This must be done in respect of the several plasma trap parameters determining each experimental configuration. Since PANDORA is still under construction, we carried out these measurements on the Flexible Plasma Trap (FPT) [12] for only gaseous plasmas, as starting case, and adopted the methodologies employed in the OES to estimate the average electron energy (temperature $k_b T_e$), and density $\rho_e$ along the line-of-sight of the detection system - see Fig. 1(a). A spectrometer coupled to a CCD detector has been used to acquire the $H_2$/Ar plasma emissions in the optical range (300-700 nm), tuning the gas pressure ($10^{-3} \div 10^{-2}$ mbar), microwave power ($40 \div 400$ W), frequency, and the confining magnetic field in the trap. By using the *line ratio method* [13] we were able to estimate $k_B T_e$ and $\rho_e$ for several stable configurations. Resulting data are summarily shown in Fig. 1(b), with more details on the experimental setup, configurations, and data analysis available in [11]. The peculiar distribution of the measured average electron temperatures ($z$-axis) and densities ($y$-axis) of plasmas explored as a function of microwave power ($x$-axis) is very promising in resembling the astrophysical conditions, desired to perform opacity measurements in the framework of the KNe. The strict requirement is on temperature, that must be at most few eV. Only few power/gas pressure configurations ($H_2$-Ar gas mixing, low RF power, $40 \div 200$ W, and pressure $\sim 10^{-2}$ mbar) allow these temperatures, providing a good track for the next future experimental setup. Plasma ejecta density condition of $10^{16 \div 18}$ m$^{-3}$ are clearly fulfilled, independently on the RF power. The relative error calculated on the measurements is at most within the 50 % [11].

## 3 Conclusion

To conclude, we reported on the experimental plasma characterization whose work has been motivated by the possibility to reproduce in laboratory plasma ejecta conditions typical of a compact binary object post-merging phenomenon. The experimental survey served as a ground-state for the future experimental activity, with the aim to provide first-of-its-kind experimental opacity data useful for the KNe study. The measured data stressed the possibility to have controlled and monitored trapped plasmas with the desired thermodynamic and plasma parameters.

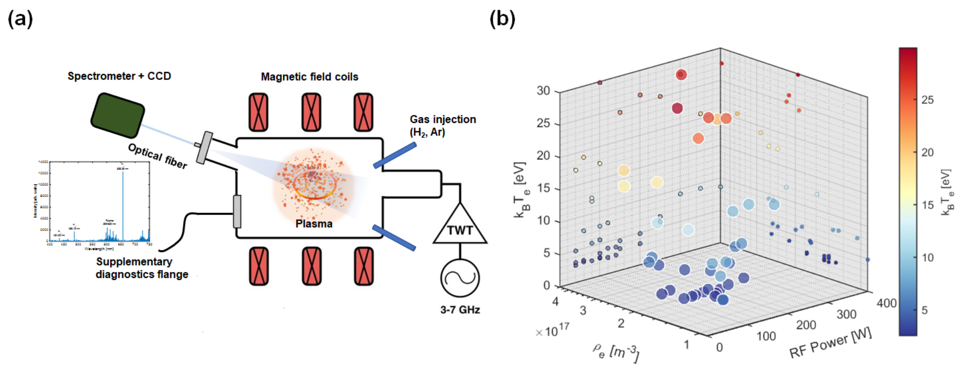


**Figure 1.** **(a)** Scheme of the experimental setup - further details in [11]. **(b)** Plasma electron energy (temperature, $k_B T_e$) [eV] (on z-axis) from OES measurements of $H_2$-Ar plasma emission in the FPT at the INFN-LNS. Data are displayed in the electron density $\rho_e$ [$m^{-3}$] - microwave power $P_{RF}$[W] $xy$-plane. Projections onto $yz$-plane ($k_B T_e$ vs. $\rho_e$), and $xz$-plane ($k_B T_e$ vs. $P_{RF}$) are also shown. Data were collected for different experimental configurations in terms of power and gas pressure $p_g$. From projections, plasmas at low $k_B T_e \leq 3$ eV and $\rho_e \sim 1 \div 2 \cdot 10^{17}$ $m^{-3}$ result only from $H_2$-Ar plasma, with $P_{RF} \leq 200$ W and high-pressure $p_g \sim 10^{-2}$ mbar.

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