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Heavy element atomic data for multi-messenger observations of neutron star mergers

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Neutron star mergers are one of the most promising sites for heavy element nucleosynthesis in the Universe. By synthesizing heavy elements, they give rise to electromagnetic emission, so called kilonova, thermal emission powered by radioactive decays of newly synthesized r-process nuclei.

Thanks to the “multi-messenger” observations of gravitational waves and electromagnetic waves in 2017, heavy element nucleosynthesis in the neutron star mergers has been directly confirmed. Observational properties of kilonova are largely affected by bound-bound opacities of heavy elements. Thus, it is essential to understand atomic properties of heavy elements to link the observed signals with nucleosynthesis of neutron star mergers.

Aiming at (1) evaluating the heavy element opacities in the ejected material from neutron star mergers, and (2) extracting elemental information from the spectra of kilonova, we have been constructing atomic data of heavy elements through the collaboration between astrophysicists and atomic physicists.

For the opacities, we have systematically calculated atomic structure of heavy elements covering neutral atoms up to triply ionized ions [1]. Our results show that the average opacities for lanthanides can be as high as 20-30 cm^2 g^{-1} (Figure 1), which is higher than the opacity of Fe group elements by more than one order of magnitude. Such a high opacity nicely reproduces the properties of the kilonova observed in 2017. Our datasets are publicly available through the “Japan-Lithuania Opacity Database for Kilonova” [2].

By extending these works, atomic data for highly ionized heavy elements have also been constructed [3,4]. These results show that the opacity of highly ionized lanthanides can be even higher by another order of magnitudes due to the complex atomic structure of two open shells. This has an impact to the ultraviolet emission from kilonova within a few hours after the merger.

Based on these new atomic data, we also study the spectral features of kilonovae. By using/constructing atomic data with accurate transition wavelengths, we show that the spectra of kilonovae tend to show absorption features of Ca, Sr, La, and Ce [5,6]. These elements are located at the left side of the periodic table, and they show a relatively simple atomic structure, causing the strong individual transitions. Decoding these absorption features in kilonova spectra enables us to confirm the presence of individual elements and to quantify the mass fraction of these elements in the ejected material from neutron star mergers.

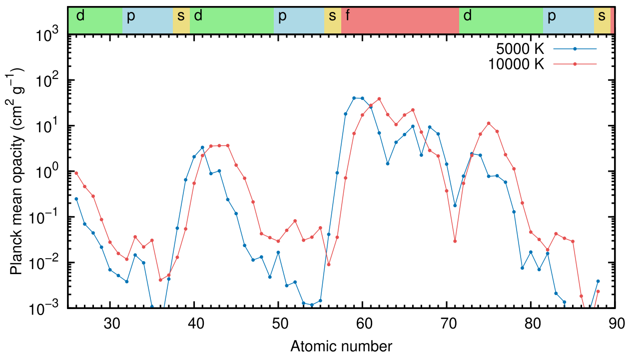

Figure 1: Planck mean opacities for all the heavy elements [1]. The opacities are calculated by assuming $\rho=10^{-13}$ g cm^{-3}, and t=1 day after the merger. Blue and red lines present the opacities for T = 5000 and 10 000 K, respectively.

References

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