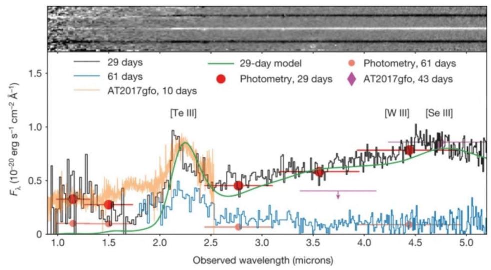
Modelling Tellurium Emission from Late Stage Kilonovae

Patrick Flint[1], Connor Ballance[2], Steven Bromley[1], Niamh Ferguson[3], Evan Garbe[4], Niall McElroy[2], Leo Mulholland[2], Catherine Ramsbottom[2], Phillip Stancil[4], Stuart Loch[1]
Auburn University US[1], Queen's University Belfast UK[2], University of Strathclyde UK[3], University of Georgia US[4]

AUBURN UNIVERSITY
College of Sciences and Mathematics

Introduction

One of the main sources of r-process elements are Neutron Star Mergers (NSMs). In the 2017 AT2017gfo and 2023 AT2023vfi detection there is a strong peak found near 2.1 μm in the nebular phase of the kilonova, with possible identifications being Te III (Levan et al. 2024) or other possible elements (Gillanders and Smartt 2025).



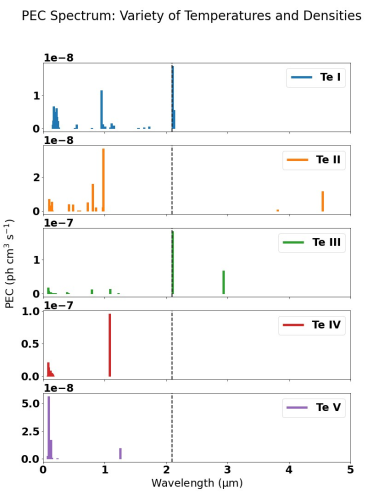
From Levan *Nature* **volume 626**, pages 737–741 (2024)

JWST/NIRSpec spectroscopy of the counterpart of GRB 230307A.

Aims

In this poster we used recently calculated atomic data to answer three main questions:

1. When are Saha Local Thermodynamic Equilibrium (LTE) approximations valid?
2. Is recombination an important populating mechanism for the spectral line emission?
3. Can spectral line ratios be used to constrain the plasma parameters?



Description of the Model

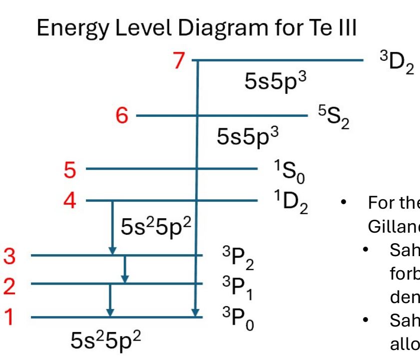
Generalized Collisional-Radiative (GCR) theory with no reabsorption of the radiation field (Summers et al. 2006) can be used to accurately model the nebular phase of the kilonova. The ColRadPy code (Johnson 2019) uses atomic data to model spectral line intensities.

The excitation data used in this poster was generated by L. P. Mulholland et al. (2024) using the R-matrix method for Tellurium. Recombination data was generated with the AutoStructure code (private communication Niall McElroy).

Acknowledgements

This work was supported by grants from NSF-AAG and NASA-APRA

Saha-LTE Approximation Validity?

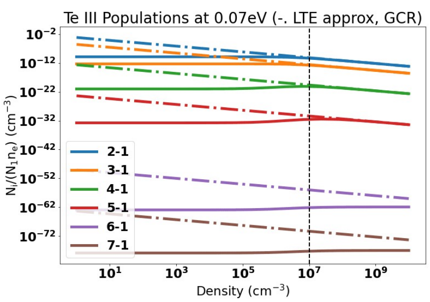


Opacity

For the forbidden Te III transitions (2-1, 3-2, 4-3) it is likely optically thin, however for the allowed Te III transitions (7-1) it is likely optically thick (Mulholland et al. 2024).

Population Modeling

- For the electron temperature assumed by Gillanders et al. (2023)
  - Saha LTE approximations are valid for the forbidden transitions above an electron density of $10^7\ cm^{-3}$
  - Saha LTE approximations are not valid for allowed transitions



Saha-LTE Approximation:

$$\frac{N_u}{N_l n_e} = \frac{2J_u+1}{2J_l+1}\frac{1}{n_e}e^{-\frac{E_u-E_l}{k_B T}}$$

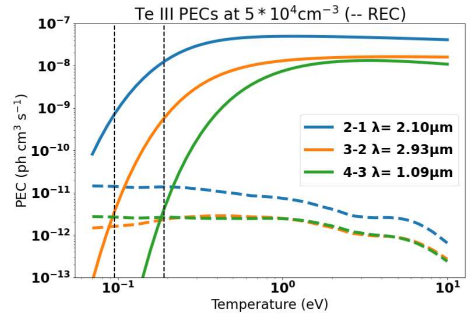
Conclusions

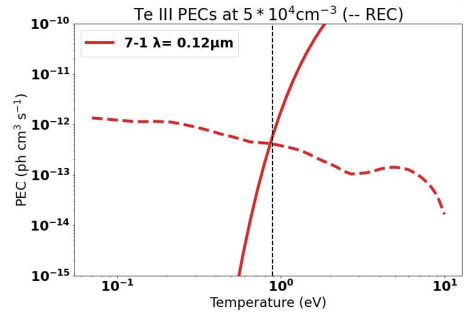
- We have shown that the forbidden transitions in Te III would not have LTE populations below an electron density of $10^7\ cm^{-3}$
- Recombination is likely not a significant populating mechanism for the forbidden transitions in Te III
- Recombination makes allowed transitions much stronger despite low temperature
- Theoretical line ratios using the new atomic data puts constraints on the electron temperature of the late-stage kilonova spectra of lower than 1 eV

The Significance of Recombination?

The spectral line intensity can be separated in GCR theory into a contribution from excitation and a contribution from recombination:

$$I^{Te\ III}_{u\to l} = \int_{LOS}\left(n_e N_{Te^{2+}} PEC^{ex}_{u\to l} + n_e N_{Te^{3+}} PEC^{rec}_{u\to l}\right) ds$$





- The plots include radiative and dielectronic recombination rates.
- The electron density was taken from a relationship given by A. Sneppen et al. (2024).

Forbidden Transitions:

- 2.10 μm likely does not have a significant contribution from recombination
- For 2.93 μm, recombination may dominate below 0.095 eV
- For 1.09 μm, recombination may dominate below 0.19 eV

Resonance Line Transition:

- For 0.12 μm, recombination may dominate below 0.89 eV

Future Work

- Repeating the analysis for other r-process elements to see how general the conclusions are
- Plasma spectroscopy experiments involving tellurium will be performed at Auburn University
- Using Steady State Ionization Balances to better constrain the plasma and find relative abundances
- Explore beta decay effects in these environments

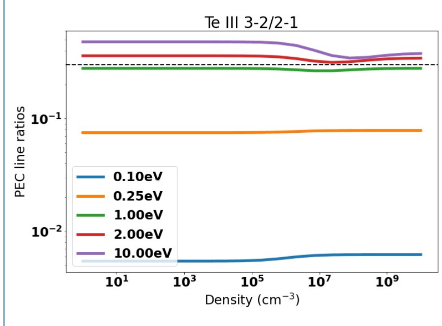
Diagnosing Plasma Parameters?

Generally, if two lines are present in a given spectrum of a kilonova, the line ratios can be compared to the measured intensities to:

- Diagnose plasma parameters (electron temperature and density)
- Help with element identification and abundance calculation

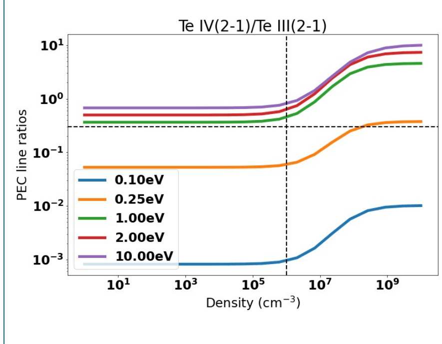
$$\frac{I^{ion\,1}_{i\to j}}{I^{ion\,2}_{k\to l}} = \frac{\int_{LOS}\left(PEC^{ex,ion\,1}_{i\to j} + \frac{N_{ion\,1^{+1}}}{N_{ion\,1}}PEC^{rec,ion\,1}_{i\to j}\right)N_{ion\,1}ds}{\int_{LOS}\left(PEC^{ex,ion\,2}_{k\to l} + \frac{N_{ion\,2^{+1}}}{N_{ion\,2}}PEC^{rec,ion\,2}_{k\to l}\right)N_{ion\,2}ds}$$

- May use a Steady State Ionization Balance (SSIB) for same element abundance ratios
- Neglecting recombination below



Transitions within Te III

- No abundance ratio needed
- With the lack of detection of a 2.93 μm line from the 3-2 transition, there is a constraint on the electron temperature
  - If the temperature was greater than approximately 1 eV, one would expect to see the 2.93 μm line



Transitions between Te III and Te IV

- Te IV Transition
  - $5s^25p\,(^2P_{\frac{3}{2}}) \rightarrow 5s^25p(^2P_{\frac{1}{2}})$
- Assumes equal abundances of Te III and IV (no data available for Te SSIB)
- There was not a 1.08 μm detection from the Te IV 2-1 transition which implies one of:
  - Electron temperatures are lower than 1 eV
  - Very low Te IV abundance compared to Te III
- If the electron density is above $10^6\ cm^{-3}$ this puts an even stricter constraint on the electron temperature