# Atomic data and spectral modeling constraints from high-resolution X-ray spectroscopic observations of the Perseus cluster with Hitomi

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## Abstract

High-resolution X-ray spectroscopy is a key to understand nature of cosmic plasmas, as it provides direct measurements of temperature and velocity structures, chemical abundances, and charge-state distributions. It also opens a window for new spectral features. Plasma codes are indispensable to carry out high-resolution spectroscopy as any spectral analysis uses a plasma code to derive physical parameters. The first high-resolution X-ray spectrum of the Perseus cluster has been obtained with the Soft X-ray Spectrometer on the Hitomi X-ray satellite. It covers major spectral features in 2–9 keV, including K-shell emission lines of abundant elements Si through Ni. The Hitomi spectrum can be used for the first practical benchmark of plasma codes. One of our purposes is to evaluate systematic uncertainties in calculations of spectra and their impacts on deriving physical parameters. Another purpose is to investigate possibilities to detect new spectral features, for instance charge-exchange (CX) emission or characteristic emission line ratios due to interactions with non-thermal electrons.

Starting from the same dataset as presented by Hitomi Collaboration et al. (2016a, b), empirical corrections for energy scale, effective area, and low-energy redistribution matrix were first applied. The baseline model was defined based upon the corrected data with the SPEX package version 3.03.03. It is mainly a hot gas component of 4-keV plasma at collisional ionization equilibrium (CIE) affected by possible resonance scattering, interstellar absorption, and spectral broadening due both to thermal and turbulent motions. The other component is emission from the central active galactic nucleus. It consists of a power-law continuum and Gaussians for the neutral Fe-K lines, whose parameters have been kept frozen throughout the analysis.

Systematic uncertainties of the spectral parameters were estimated as deviations from the best-fit values with the baseline model. Among the systematic effects considered in our analysis, the choices of plasma codes and atomic data behind codes showed major impacts. In the comparison of the codes, it is found that the relative difference between SPEX and APEC is usually within 10%. The origins depend on the lines, either different line wavelengths or different emission rates. An emission rate is determined by a combination of charge-state distribution and transition rate. On transition rates, we take the He-like Fe-K multiplet lines as a test case to assess errors. For the resonance and inter-combination lines, predominantly formed by electron impact excitation from the ground state and radiative decay back there, the rates by the major databases (SPEX, APEC, and CHIANTI) and the theoretical calculation by the FAC agree well with each other within 10%. On the other hand, for the forbidden line, the relative difference is found to be as large as 40%, likely because of its complexity having multiple forming channels.

New spectral features are also under investigation. One is the CX emission from the colliding surface between hot and cool gas components, characterized by high-shell transition lines. With the baseline model, we found two line-like residuals near at 3.4 and 8.6 keV. These energies are consistent with high-shell transition lines of S XVI and Fe XXV, respectively, although the significances are below $3\sigma$. The presence of non-thermal electrons can also modify line emission for instance by changing inner-shell transition rates. By using a capability of the SPEX CIE model to handle this, we obtained upper-limits of the relative density to thermal population as a function of the mean energy, with a quasi-thermal assumption where the non-thermal distribution is approximated by a Maxwellian.

All the results are currently being reviewed and updated with the final version of the pipeline products, software tools, and calibration database, and will be published in a full separate paper.

Key words: : atomic data — atomic processes — clusters: individual (Perseus) — galaxies: intergalactic medium — X-rays: galaxies: clusters