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# Enigmatic photon absorption in plasmas near solar interior conditions

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ABSTRACT

Large systematic discrepancies between theoretical and experimental photon absorption of Fe plasmas applicable to the solar interior were reported [Bailey et al., Nature 517, 56 (2015)]. The disagreement is examined in the context of the Thomas–Reiche–Kuhn f-sum rule. The analysis identifies several anomalies in the experimental results.



## 1. Introduction

Plasma radiative properties are integral to the study of astrophysics, inertial and magnetic confinement, and warm dense matter. The opacity calculations for these problems, however, entail approximations to myriad atomic processes. Furthermore, models for fundamental phenomena, such as continuum lowering and spectral line broadening, remain mostly untested. Hence, there is interest in assessing theoretical opacities by comparisons to photon absorption measurements. In response, experiments were done at the Sandia National Laboratories Z-machine to measure the photon transmission of plasmas at conditions applicable to the solar interior. An important goal of the experiments was to address discrepancies between helioseismic observations and solar models, which can be reconciled by ~15% increases in the opacity near the solar radiation-convection boundary [1].

Although models agreed well with earlier measurements [2], there are significant systematic discrepancies with more recent data at higher densities and temperatures [3]. As an example, Fig. 1 compares the Fe experimental absorption and the effective opacity (see Appendix) from the Topaz code [4]. The disagreement is not unique to Topaz and other models yield similar discrepancies [3]. The disagreement in Fig. 1 is examined in context with the Thomas–Reiche–Kuhn f-sum rule [5]. This sum rule follows from general principles and constrains the sum of oscillator strengths. The analysis identifies several anomalies in the recent Sandia data [3] absent in the earlier measurements [2].

## 2. Analysis and discussion

The spectrum in Fig. 1 is predominantly absorption by L-shell electrons in Fe. The Sandia data show 2p-4d absorption lines from Ne-like ($\lambda \approx 12.2$ Å), F-like ($\lambda \approx 11.4$ Å), and O-like Fe ($\lambda \approx 10.6$ Å) [3]. The Topaz calculation assumes local thermal equilibrium and yields an average ionization charge $\langle Z \rangle = 16.9$ for Fe and displays similar 2p-4d lines. Furthermore, there is good correspondence, except for overall strength, between the spectral lines in the data and the model suggesting reasonable agreement in the ion charge distribution.

A possible error in the opacity models is the calculation of photon absorption cross-sections by L-shell electrons. As a test, Fig. 2 presents the Topaz photon ionization cross-section for the ground configuration of atomic Cr-like Fe in good agreement with the cold solid density data, $\sigma_{cold}$ [6]. The figure also presents calculations for ground configurations (single-configuration approximation without term structure) for several other Fe ions. These calculations reproduce the known result that removing M-shell electrons increases the ionization threshold without further impacting the cross-section [7]. It is only when L-shell electrons are removed that the cross-section, which is proportional to the number of L-shell electrons, is reduced. Although not explicitly displayed here, these results extend to configurations with excited electrons. For example, the cross-section for Ne-like Fe with one

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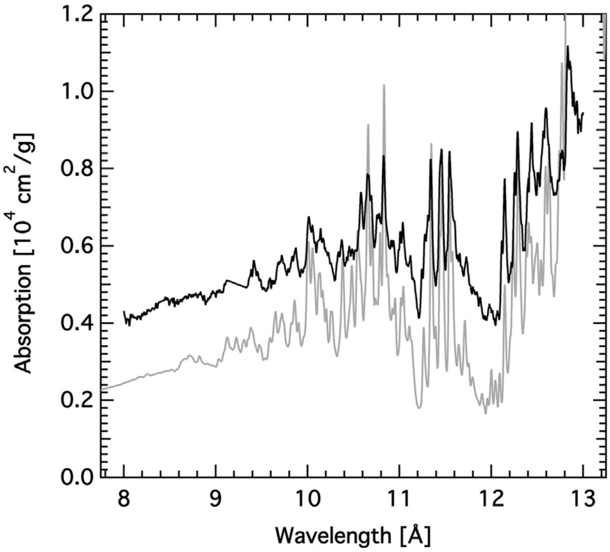


**Fig. 1.** Comparison of experimental and theoretical Fe photon absorption cross-section as a function of wavelength at electron temperature and density of 182 eV and $3.1 \times 10^{22}$ cm$^{-3}$: Sandia data [3] (*black*) and Topaz effective opacity (*grey*).

excited electron is similar (except for threshold energy) to the cross-section for the ground configuration of F-like Fe.

The absorption in solids at photon energies above ~50 eV (avoids valence orbitals or bands) are atomic-like except near thresholds where features associated with the solid state can appear [8]. In plasmas, there is not only continuum lowering [9] but there are fluctuations [10] that smooth the absorption at energies below the isolated ionization threshold. The smoothing conserves the oscillator strength density, $df/d\varepsilon$, where $f$ and $\varepsilon$ are the oscillator strength and photon energy, respectively, of the bound–-bound transitions in the isolated ion [11–13].

To proceed, consider the f-sum rule [5],

$$\sum_{\beta} f_{\alpha\beta} = N \tag{1}$$

This equation applies provided relativistic effects are small (valid for Fe [14]) and refers to an atomic system containing $N$ bound electrons and the oscillator strength sum for transitions from state $\alpha$ to all final states $\beta$ including the continuum. Although full configuration interactions (CI) effects do not impact the sum rule in Eq. (1), if they are negligible or neglected then Eq. (1) extends to partial sums over subshells [5],

$$\sum_{n'\ell'} f_{n\ell,n'\ell'} = N_{n\ell} \tag{2}$$

where $N_{n\ell}$ is the $n\ell$ subshell electron occupation ($n$ and $\ell$ are principal and orbital quantum numbers). Since the Topaz code neglects full CI [15] and excited electronic configurations are delocalized in solid Fe, both the Topaz calculations and the cold data satisfy Eq. (2).

As the examples in Fig. 2 show, the Topaz cross-sections above the ionization threshold are similar to $\sigma_{cold}$ for Fe ions with full L-shell configurations. Accordingly, the bound–bound contributions should reproduce the remaining portion of the sum in Eq. (2). For partially filled L-shell ions the sum in Eq. (2) is proportionally smaller than for $\sigma_{cold}$. Therefore, recalling that the oscillator strength density is conserved [11–13], a smoothed cross-section obtained by the following convolution is constrained to have $\sigma_{cold}$ as a maximum,

$$K(\lambda) = \int_{-\infty}^{\infty} d\lambda' \, G(\lambda - \lambda')\kappa(\lambda') \le \sigma_{cold}(\lambda) \tag{3}$$

where $\kappa(\lambda)$ is the absorption cross-section at photon wavelength $\lambda$ and $G(\lambda)$ is an arbitrary, normalized response function with variance sufficiently large to smear features in the spectrum. The idea is illustrated in Fig. 3 using a Gaussian response function where the photon absorption from ground configurations of C- and Mg-like Fe are compared to $\sigma_{cold}$. These Topaz calculations assumed the same electron temperature and density as Fig. 1 for the plasma effects and used intermediate coupling for the configuration term structure.

Plots of $K(\lambda)$ are displayed in Fig. 4 for the recent Sandia data [3] and Topaz opacity (not the Topaz effective opacity since it

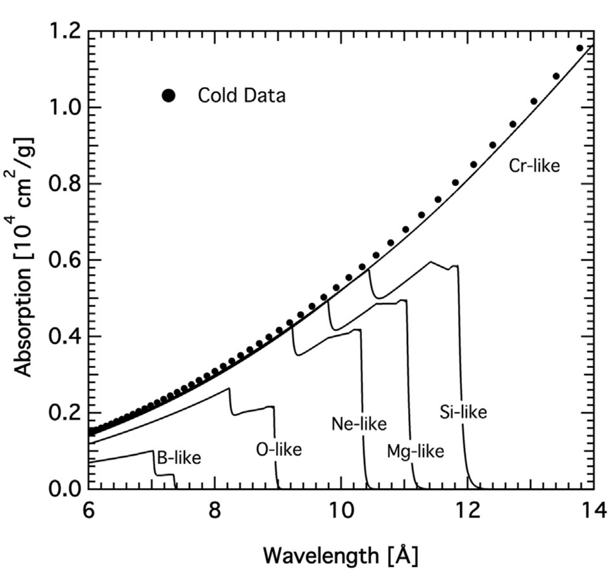


**Fig. 2.** Comparison of the Fe cold absorption cross-section as a function of wavelength and Topaz calculations for ground configurations of various Fe ions indicated in the figure.

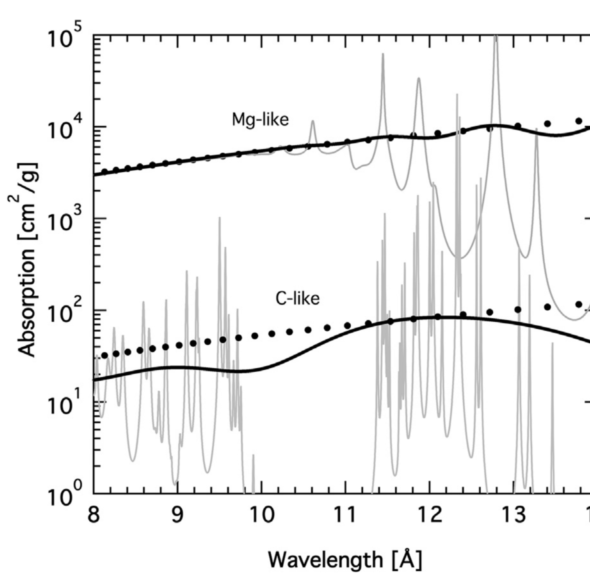


**Fig. 3.** The Topaz photon absorption cross-section as function of wavelength for the ground configuration of C- and Mg-like Fe (*grey*) and smoothed using Eq. (3) (*black*) are compared to $\sigma_{cold}$ (*dots*). The C-like results are scaled by 0.01 for clarity.