Abstract

We present a systematic measurement of the X-ray emission asymmetries in the K-shell dielectronic, trielectronic, and quadruelelectronic recombination of free electrons into highly charged ions. Iron ions in He-like through O-like charge states were produced in an electron beam ion trap, and the electron–ion collision energy was scanned over the recombination resonances. Two identical X-ray detectors mounted head-on and side-on with respect to the electron beam propagation recorded X-rays emitted in the decay of resonantly populated states. The degrees of linear polarization of X-rays inferred from observed emission asymmetries benchmark distorted-wave predictions of the Flexible Atomic Code for several dielectronic recombination satellite lines. The present method also demonstrates its applicability for diagnostics of energy and direction of electron beams inside hot anisotropic plasmas. Both experimental and theoretical data can be used for modeling of hot astrophysical and fusion plasmas.

Key words: atomic data – atomic processes – line: formation – methods: laboratory: atomic – plasmas – polarization

Supporting material: machine-readable tables

1. Introduction

The major part of all visible matter in the universe is in a state of highly ionized hot plasma. In most astrophysical plasmas, the electrons reach thermodynamic equilibrium where their velocities are distributed isotropically following the Maxwell–Boltzmann law. Such plasmas emit isotropic and unpolarized radiation. However, at very high electron energies, the electron velocity distribution may become anisotropic. Anisotropic plasmas are found prominently in solar flares (Haug 1972, 1979, 1981; Emslie et al. 2008). X-rays emitted from such plasmas are usually highly anisotropic and polarized (Inal & Dubau 1987, 1989). Anisotropic plasmas are also found in pulsars (Weisskopf et al. 1976, 1978; Vadawale et al. 2018), in neutron stars (Weisskopf et al. 2006), and around accreting black holes (Dovciak et al. 2004, 2008; Nayakshin 2007; see also Kallman 2000 and references therein). They also appear prominently in laboratory plasmas where electron–ion collisions are directional, e.g., tokamak plasmas (Fujimoto et al. 1996), electron cyclotron resonance plasmas (Iwamae et al. 2005), and laser-produced plasmas (Kieffer et al. 1991). Since the X-ray polarization is caused by the plasma anisotropy, polarization measurements can provide valuable and often unique insights into the physical conditions of such plasmas. They can reveal the distributions of nonthermal or suprathermal electrons, an orientation of electron or ion beams in plasmas, and or tell us the orientations of magnetic fields present inside the plasmas. Indeed, in astrophysics, X-ray polarization measurements are the only way to derive information on the geometry of angularly unresolved sources (Krawczynski et al. 2011).

Interpretation of the spectral features from hot anisotropic plasmas requires an understanding of different atomic excitation mechanisms that can lead to polarized X-ray emission. A polarized X-ray continuum can be produced by bremsstrahlung and radiative recombination (RR; Tashenov et al. 2006, 2011, 2014); at the same time, direct electron impact excitation, radiative cascade, and dielectronic recombination (DR) can produce characteristic polarized X-ray lines (Takács et al. 1996; Beiersdorfer et al. 1996, 1997; Shlyaptseva et al. 1998, 1999; Nakamura et al. 2001). The construction of a reliable model requires a systematic understanding of each of these components, and calculations of them have to be benchmarked against experiments. The aim of this paper is to study the polarization of Fe Kα X-ray lines produced by DR and provide experimental benchmarks under well-controlled conditions.

DR (Burgess 1964) is the dominant electron–ion collision process, active in both photoionized and collisionally ionized high-temperature plasmas. As a line formation mechanism in plasmas, the total cross sections of DR surpass those of all other processes by orders of magnitude. DR is a resonant two-step process, in which a free electron is captured into an ion while a bound electron is simultaneously excited. Thereby, an intermediate excited (autoionizing) state, or resonance, is formed. The DR process is completed by radiative emission, which is the dominant channel in highly charged ions, as opposed to Auger emission. It strongly influences total recombination rates and thus the charge balance of hot plasmas (Dubau & Volonte 1980). DR also provides resolved spectral lines that can be utilized for plasma temperature and density diagnostics (Widmann et al. 1995; Kato et al. 1998; Porquet et al. 2010). Therefore, exact knowledge of DR cross sections is needed not just to understand astrophysical
observations (e.g., the recent results of Hitomi Collaboration et al. 2016) but also to benchmark widely used X-ray spectral models such as AtomDB (Foster et al. 2012), SPEX (Kaastra et al. 1996), and CHIANTI (Del Zanna et al. 2015) for hot collisional plasmas.

Beyond DR, more exotic higher-order resonant recombinations such as trielectronic recombination (TR) or quadruplelectronic recombination (QR) are also relevant. Here, a minimum two or even three bound electrons can be simultaneously excited upon the capture of a free electron, leading to TR and QR, respectively; see Figure 1. The recombination rates in low-temperature photoionized plasmas were shown to be dominated by intra-shell \((n = 2 – 2)\) TR (Schnell et al. 2003; Orban et al. 2010). Similarly, inter-shell \((n = 2 – 1)\) TR was recently measured and found to have a sizable and even greater strength compared to DR for astrophysically relevant low-Z ions (Beilman et al. 2011, 2013b). It is therefore also necessary to include these channels in the plasma model to accurately predict ionization balance (Beiersdorfer 2015; Shah et al. 2016).

Several experimental and theoretical investigations were performed on DR of highly charged ions. The intra-shell low-energy DR rate coefficients were measured at storage rings (Savin et al. 2002, 2003, 2006; Lukić et al. 2007; Orban et al. 2010), while inter-shell high-energy DR strengths and rate coefficients were measured at electron beam ion traps (EBITs; Beiersdorfer et al. 1992; Fuchs et al. 1998; Smith et al. 2000; Yao et al. 2010; Ali et al. 2011; Hu et al. 2013). However, due to the directionality in electron–ion collisions, as well as the geometry of these devices, emitted X-rays are usually anisotropic and polarized. In such cases, accurate values of line polarization are important for interpreting high-resolution measurements and extracting accurate recombination rate coefficients.

Apart from the application relevance of DR in plasmas, the interest in DR also arises from the point of view of understanding electron–electron interaction in the strong Coulomb fields of highly charged ions. The relativistic effect in the electron–electron interaction is known as the Breit interaction (Breit 1929). It includes magnetic interactions and the retardation in the exchange of a virtual photon between the electrons. While its effect on energy levels is considered a modest correction, it significantly changes the DR cross sections and the polarization of DR X-rays for high-Z ions (Nakamura et al. 2008; Fritzsche 2010).
et al. 2009; Hu et al. 2014; Shah et al. 2015; Nakamura 2016; Amaro et al. 2017).

Here we present a comprehensive experimental and theoretical study on the polarization of X-rays produced by KLL DR of highly charged Fe ions. In KLL DR, a bound K-shell electron is excited to the L shell by recombination of a free electron from the continuum to the L shell. An entire set of observed resonances, a higher energy resolution is required. Therefore, in this case, we improved the energy resolution by application of an evaporative cooling technique (Penetrante et al. 1991b) in combination with a moderate electron beam current (70 mA here) sufficient for an efficient ionization and recombination yield. This was achieved by lowering the axial potential well applied to the drift tubes. The ion dump cycle was shortened to 5 s to reduce the accumulation of unwanted heavy ionic species, like tungsten and barium, emitted from the hot cathode of the electron gun. Additionally, this helped to shift the ionization balance toward lower charge states where TR and QR are more prominent. With this method, an excellent electron–ion collision energy resolution of 6 eV FWHM at 5 keV was achieved. We note that the resolution in this energy range was better than that in any previously reported measurements and allowed us to distinguish well-resolved TR and QR along with DR resonances. A list of the operational parameters of the FLASH-EBIT is summarized in Table 1.

To observe the X-ray emission asymmetry, the radiative decay of resonantly excited states has been simultaneously observed by two identical liquid nitrogen–cooled solid-state germanium detectors aligned parallel (0°) and perpendicular (90°) to the electron beam propagation axis; see Figure 1. Both detectors have an intrinsic X-ray energy resolution of approximately 550 eV FWHM at 13 keV. The X-ray detectors at EBITs are typically mounted perpendicular to the electron beam propagation axis. For this experiment, a beryllium window was installed behind the electron beam collector in order to place another identical germanium detector there along the electron beam axis. However, at this observation point, solid-angle and X-ray flux are both significantly reduced as compared to the detector mounted perpendicular to the electron beam propagation axis. The solid angle of detection was 8.7 × 10^{-3} sr for the detector at 90°, whereas the solid angle for X-ray detection along the electron beam was 7.3 × 10^{-3} sr. Hence, the detector at 0° covered less solid angle compared to the one at 90° by a factor of ≈11.9.

The intensity of X-rays observed at 0° with respect to electron beam propagation direction is shown in the inset of Figure 1 as a function of the electron beam and X-ray energies. A similar histogram was obtained for the detector at 90°. The X-ray energy was calibrated using the X-ray radiation from an americium-241 radioactive isotope, whereas the electron beam energy was calibrated using theoretical resonance energies. The visible bright spots are KLL DR resonances in He-like to O-like iron ions. Each resonance is usually identified by the initial charge state of iron in which resonant recombination occurred. X-rays due to RR into the L shell (n = 2) appear as a background. The RR X-ray energy is equal to the sum of the electron energy $E_e$ and the binding energy $E_b$ of the L shell; see Figure 1.

3. Data Analysis and Results

The X-ray intensity as a function of electron beam energy was obtained by integrating the X-rays observed within the X-ray energy interval of the KLL resonances. In this way, X-rays emitted in bremsstrahlung and RR into K, M, and higher shells...
Table 1

| Parameter                      | Value                                  |
|-------------------------------|----------------------------------------|
| Electron beam current         | (a) 100 mA (b) 70 mA                   |
| Magnetic field                | 6 T                                    |
| Trap offset potential         | (a) 110 V (b) 20 V                     |
| Scan energy                   | 4.5–5.2 keV                            |
| Sweep rate                    | 1.16 eV s⁻¹                            |
| Beam radius                   | ≈24.4 μm (Hermann 1958)                |
| Trap length                   | 22.6 ± 4.2 μm (see Section 5)          |
| Trap length                   | 50 m                                   |
| Dump cycle                    | (a) 20 s (b) 5 s                       |
| Pressure of gas injector      | (a) 1.2 × 10⁻⁶ mbar                    |
|                              | (b) 1.1 × 10⁻⁷ mbar                    |

Note. (a) and (b) correspond to two different measurements.

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were excluded. This procedure is essential to reduce the background and observe weak resonances. Several resonantly excited X-ray transitions due to DR, TR, and QR were observed in the region of interest; see Figure 2. They were identified by extensive and detailed calculations using FAC (Gu 2008). The computational details are described in Section 4. Corresponding theoretical resonance strengths were also calculated in order to quantify the relative weights that unresolved excited states contribute to the X-ray lines. Figure 2 shows several well-resolved DR, TR, and QR satellite transitions.

The electron beam energy can be described by the sum of all accelerating potentials that are applied minus the net space charge potential due to the negatively charged electrons of the beam, as well as the positively charged ions accumulated in the trap volume. The energy-dependent part of the space charge potential was calculated at maximum and minimum acceleration potentials and can be considered to be constant along the energy scan (Penetrante et al. 1991a). Thus, the electron beam energy scale can be calibrated using theoretical resonance energies. The electron beam energy scale of measurement (a) in Figure 2 was calibrated using X-ray lines 1 and 8, corresponding to energies of 4554.4 and 4697.8 eV, respectively. Similarly, for measurement (b), the X-ray lines 20 (4858.9 eV) and 31 (4952.2 eV) were employed for the calibration.

The observed spectra need to be corrected for the detector solid angles and the background arising from the L-shell RR. We consider the intensity of RR as a linear function of the electron beam energy, which we fit and subtract from the total intensity. The solid-angle factor can be corrected using a DR transition theoretically known to be isotropic. For measurement (a), we selected the DR resonance [1s2p⁴]₁/₂ (line 1) of initially He-like ions to obtain \( \Omega_{0f}/\Omega_{0g} = 0.09 \pm 0.02 \). In measurement (b), the observed isotropic transitions have very low intensities. Hence, we calculated the detector solid angles using line 31—the TR resonance [1s2p⁴]₁/₂ [2p⁶]₃/₂ \( J=3/2 \) of initially C-like ions. It has a theoretical intensity ratio of \( I_{0f}/I_{0g} = 1.55 \). We selected it for its higher resonance strength and null influence of the Breit interaction on its angular distribution (Gail et al. 1998). Moreover, our previous experiments on Kr have confirmed the theoretical ratio for this line (Shah et al. 2016). The measured ratio of solid angles was found to be \( \Omega_{0f}/\Omega_{0g} = 0.082 \pm 0.003 \). In both cases, used normalization resonances are well separated from the neighboring transitions. After correction for these effects, the corresponding intensity differences indicate an anisotropic X-ray emission for most of the resonances. The red shaded area in Figure 2 represents the X-ray intensity along the direction of the electron beam multiplied by the solid-angle factor.

Since the electron beam energy spread follows a normal distribution and the natural width of the excited state is much lower than this energy spread, spectral resonances can be well described by a Gaussian function. The amplitude and energies \( E_{res} \) of the resonance lines, including partially blended resonances, were obtained by fitting the measured spectrum with the Gaussian functions. Since the fine-structure splitting scales with \( Z^2 \), resonances in low-Z elements, such as iron, are not well resolved. Therefore, the selected energy region contains a high density of excited states. For this reason, we used the following criterion to avoid unwanted spurious effects due to possible interference between two or more excited states in the fitting process. We considered only those excited states having energy differences larger than half of the collision energy resolution—namely, for part (a), 5 eV, and for part (b), 3 eV. Moreover, the excited states having relative resonance strengths smaller than \( \approx5\% \) compared to the neighboring lines were not considered in the fitting procedure.

By applying the above criteria, the amplitudes and centroids corresponding to each resonance were fitted to the spectrum of X-rays observed perpendicular to the electron beam propagation direction. Due to the larger solid angle of this detector, this spectrum had significantly higher statistics. In the first step of the fitting procedure, the line positions and amplitudes were set free, while the widths were fixed to the measured electron beam energy resolution. In the second step, a similar procedure was performed for the spectrum observed along the electron beam propagation direction. However, in this step, the line centroids were fixed to the ones obtained in the first step. The extracted intensities were corrected for the detector solid-angle factor. We stress that the high statistics collected in this experiment allowed us to reliably extract both the line centroids and the intensities of even blended strong resonance lines.

From Figure 2, it is apparent that most observed X-ray transitions are anisotropic, as their intensities differ when observed along and perpendicular to the electron beam axis. We quantify the emission asymmetries by the ratio

\[ R = \frac{I(90°) - I(0°)}{I(90°)}. \]  

The experimental emission asymmetries \( R \) are extracted for each fitted recombination transition and summarized in Table 2, as well as in the uppermost inset of Figure 2. Uncertainties in the emission asymmetries are taken as a quadrature sum of the uncertainty of measured intensity and the uncertainty of the detector solid-angle correction. Moreover, a finite thermal velocity component of the electron beam has a systematic effect on measured emission asymmetries (Gu et al. 1999; Beiersdorfer & Slater 2001). For each of the resonances, we have estimated its effect and found that the measured emission asymmetries were indeed reduced, but only within the uncertainty limits of our measurement. Thus, no corrections for \( R \) were made in this part of the analysis. However, by making a rigorous statistical analysis of the total data set of observed resonances, we can nonetheless determine the thermal velocity component of the electron beam. We demonstrate this in Section 5.
4. Comparison with Theory

In the following theoretical treatment, we consider DR as a two-step resonant process:

$$e^{-}(E_{\text{c}},J_{i}) \rightarrow A^{q+}(\alpha_{i},J_{i}) \rightarrow A^{(q-1)+*}(\alpha_{f},J_{f}) + h\omega.$$  

Here the first step is the resonant capture of a free electron with energy $E_{\text{c}}$ and total angular momentum $J_{i}$ by an initial ion $A^{q+}$ in the charge state $q$. This capture leads to the formation of an excited ion $A^{(q-1)+*}$, which has a charge state reduced by one unit. In the second step, this excited ion decays to the ground state under emission of characteristic X-rays. In Equation (2), $J_{i}$, $J_{f}$, and $J_{\text{f}}$ represent the total angular momenta of the initial, intermediate excited, and final states, respectively. Additional quantum numbers needed for a full-state characterization are collected in variables $\alpha_{i}$, $\alpha_{f}$, and $\alpha_{\text{f}}$.

4.1. Resonance Energy and Strength

We computed the electronic structure of each ground and excited state of the ion with FAC version 1.1.1 in a fully relativistic way and used the distorted-wave approximation for the interaction with continuum states (see Gu 2008 and references therein). We included the full relativistic form of the electron-electron interaction (Coulomb + Breit interaction) in the atomic potential perceived by the free, incoming (distorted) electron (Breit 1929). Higher-order electronic processes cannot be described by the independent particle model; these processes can only be mediated by configuration mixing of the intermediate bound states. Thus, to treat them, full-order configuration mixing between the excited states was included in our calculations. For the present KLL DR calculations, $1s^{2}(2l)^{r}$, $1s^{2}(2l)^{r+2}$, and $1s^{2}(2l)^{r+1}$ configurations were included for the initial, intermediate, and final states, respectively. From He-like to O-like charge states, the number of electrons $e$ in the L shell changes from none to six. Furthermore, extended sets of configurations were included in the initial ionic configuration space in order to assign higher-order resonances unidentified in a previous experiment (Beilmann et al. 2013a). In an extended calculation, configurations with principal quantum numbers up to $n = 5$ and all their possible angular momentum $l$ states were included. By that, we take all possible higher excited states, such as KLM, KLN, KLO, etc., into account. However, we note that it causes negligible changes in the originally predicted values.

The DR cross sections and resonance strengths were calculated in the isolated resonance approximation. The DR strength can be written as

$$S_{\text{DR}} = \frac{\pi^{2}e^{3}}{m_{e}E_{\text{res}}} \frac{g_{d}A_{d}}{2g_{i}} \frac{\sum A_{r}}{\sum A_{r} + \sum A_{d}},$$

where $m_{e}$ is the electron mass, $g_{i}$ and $g_{d}$ are the statistical weights of the initial and intermediate states, $E_{\text{res}}$ is the resonance energy,
Table 2

| Label | Initial Ion | Process | Intermediate Excited State | $E_{\text{ex}}$ (Th.) | $E_{\text{ex}}$ (Exp.) | $R$ (Exp.) | $R$ (Th.) |
|-------|-------------|---------|-----------------------------|------------------------|------------------------|-----------|-----------|
| 1     | He          | DR      | $(1s2^3s^1p_{1/2}^1h_{1/2})$ | 4554.4                 | 4607.8 ± 0.5           | −0.05 ± 0.15 | 0.00      |
| 2     | He          | DR      | $(1s2^3p_{3/2}^1p_{1/2}^1h_{1/2})$ | 4632.1                 | 4626.8 ± 0.7           | −0.13 ± 0.16 | 0.00      |
| 3     | He          | DR      | $(1s2^3p_{3/2}^1p_{1/2}^1h_{1/2})$ | 4638.5                 | 4636.9 ± 1.8           | 0.51 ± 0.07  | 0.50      |
| 4     | Li          | DR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4646.8                 | blend                  | 0.43 ± 0.08 | 0.43      |
| 5     | He          | DR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4658.3                 | blend                  | 0.31 ± 0.10 | 0.50      |
| 6     | Li          | DR      | $(1s2^3p_{3/2}^1p_{1/2}^1h_{1/2})$ | 4675.5                 | blend                  | −0.47 ± 0.20 | −0.61     |
| 7     | He          | DR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4697.8                 | calib.                 | 0.12 ± 0.12 | 0.00      |
| 8     | Li          | DR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4712.0                 | blend                  | 0.11 ± 0.12 | 0.32      |
| 9     | Li          | DR      | $(1s2^3p_{3/2}^1p_{1/2}^1h_{1/2})$ | 4713.8                 | blend                  | −0.22 ± 0.17 | −0.38     |
| 10    | Li          | DR      | $(1s2^3p_{3/2}^1p_{1/2}^1h_{1/2})$ | 4745.7                 | blend                  | 0.14 ± 0.12 | 0.20      |
| 11    | Li          | DR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4749.9                 | blend                  | 0.29 ± 0.11 | 0.28      |
| 12    | Li          | DR      | $(1s2^3p_{3/2}^1p_{1/2}^1h_{1/2})$ | 4750.0                 | blend                  | 0.49 ± 0.07 | 0.56      |
| 13    | Be          | DR      | $(1s2^3p_{3/2}^1p_{1/2}^1h_{1/2})$ | 4755.8                 | blend                  | −0.32 ± 0.19 | −0.36     |
| 14    | Li          | DR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4775.5                 | blend                  | 0.08 ± 0.15 | −0.02     |
| 15    | Be          | TR      | $(1s2^3p_{3/2}^1p_{1/2}^1h_{1/2})$ | 4815.6                 | fusion                 | 0.38 ± 0.14 | 0.54      |
| 16    | B           | DR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4829.0                 | fusion                 | 0.41 ± 0.06 | 0.50      |
| 17    | B           | DR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4856.9                 | calib.                 | 0.39 ± 0.05 | 0.42      |
| 18    | B           | TR      | $(1s2^3s_{1/2}^1p_{1/2}^1h_{1/2})$ | 4858.9                 | calib.                 | 0.26 ± 0.09 | 0.23      |
| 19    | B           | DR      | $(1s2^3p_{3/2}^1p_{1/2}^1h_{1/2})$ | 4862.6                 | calib.                 | 0.42 ± 0.06 | 0.44      |
| 20    | B           | DR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4869.7                 | 4869.3 ± 0.2           | −0.17 ± 0.24 | −0.20     |
| 21    | B           | DR      | $(1s2^3p_{3/2}^1p_{1/2}^1h_{1/2})$ | 4874.3                 | blend                  | −0.16 ± 0.02 | −0.23     |
| 22    | B           | DR      | $(1s2^3p_{3/2}^1p_{1/2}^1h_{1/2})$ | 4875.7                 | blend                  | −0.43 ± 0.05 | −0.45     |
| 23    | B           | DR      | $(1s2^3p_{3/2}^1p_{1/2}^1h_{1/2})$ | 4877.4                 | blend                  | 0.18 ± 0.03 | 0.08      |
| 24    | B           | TR      | $(1s2^3s_{3/2}^1p_{1/2}^1h_{1/2})$ | 4888.3                 | 4887.3 ± 0.1           | −0.43 ± 0.05 | −0.45     |
| 25    | Be          | TR      | $(1s2^3p_{3/2}^1p_{1/2}^1h_{1/2})$ | 4908.6                 | fusion                 | −0.35 ± 0.66 | −0.68     |
| 26    | Be          | TR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4923.2                 | 4919.5 ± 0.4           | 0.41 ± 0.12 | 0.44      |
| 27    | C           | DR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4925.7                 | 4925.6 ± 0.1           | 0.37 ± 0.05 | 0.43      |
| 28    | C           | TR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4935.5                 | fusion                 | −0.29 ± 0.52 | −0.70     |
| 29    | C           | DR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4937.7                 | fusion                 | −0.06 ± 0.44 | 0.00      |
| 30    | C           | TR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4952.2                 | calib.                 | 0.18 ± 0.03 | 0.08      |
| 31    | C           | TR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4962.2                 | blend                  | 0.24 ± 0.17 | −0.03     |
| 32    | B           | TR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4974.0                 | 4971.7 ± 1.1           | 0.05 ± 0.21 | −0.11     |
| 33    | B           | TR      | $(1s2^3p_{1/2}^1p_{1/2}^1h_{1/2})$ | 4986.7                 | 4984.0 ± 1.0           | 0.03 ± 0.21 | −0.11     |
| 34    | N           | DR      | $(1s2^3s_{3/2}^1p_{1/2}^1h_{1/2})$ | 5010.5                 | 5010.2 ± 0.5           | −0.03 ± 0.13 | −0.03     |
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Table 2
(Continued)

| Label | Initial Ion | Process | Intermediate Excited State | E_{res} (Th.) | E_{res} (Exp.) | \mathcal{R} (Exp.) | \mathcal{R} (Th.) |
|-------|-------------|---------|-----------------------------|--------------|---------------|------------------|------------------|
| 36    | N           | DR      | \{1s^2 2p_{1/2}^2 2p_{3/2}^0 \} | 5018.0       | 5017.7 ± 0.8  | −0.01 ± 0.18     | −0.04            |
| 37    | N           | TR      | \{1s^2 2p_{1/2}^2 2p_{3/2}^0 \} | 5036.7       | 5036.0 ± 1.0  | 0.20 ± 0.21      | 0.12             |
| 38    | C           | QR      | \{1s^2 2p_{1/2} 2p_{3/2}^2 \} | 5079.0       | fixed         | −0.10 ± 0.53     | −0.20            |
| 39    | O           | DR      | \{1s^2 2p_{1/2}^2 2p_{3/2}^2 \} | 5080.1       | 5081.1 ± 0.7  | 0.01 ± 0.12      | 0.00             |

Note. The first column identifies the resonances in Figure 2 made of a single or an ensemble of unresolved intermediate excited states. The initial ionic charge state before the recombination and the order of the recombination are given in the next two columns. Intermediate excited states are given in j–j coupling notation. Parentheses stand for the angular momentum of the coupled subshells and subscripts after the square brackets denote the total angular momentum of the state. Measured resonance energies \( E_{res} \) (in eV) from the fits (except fixed, blended, and calibrated ones) are presented. Extracted emission asymmetries \( \mathcal{R} \) are compared with the FAC predictions. Experimental uncertainties are given as 1σ.

\( A_u \) represents the autoionization rate from the intermediate excited state to the initial state, and \( A_r \) represents the radiative rate from the intermediate state to the final state.

Tables 4–10 in the Appendix list all calculated resonances, energies (\( E_{res} \)), and resonance strengths (\( S^{DR} \)) for initially He-like to O-like Fe ions labeled by the order of the recombination processes, such as DR, TR, and QR.

For each resonance observed in the present experiment, the extracted resonance energies are compared with the FAC calculations in Table 2. We found an excellent agreement between theory and experiment. For well-resolved resonances, an average deviation of \(-1.3\) eV was found between theory and experiment.

4.2. X-Ray Anisotropy and Polarization

In the following theoretical treatment, we calculate X-ray polarization only for allowed electric dipole \( E1 \) transitions. This channel usually dominates the radiative decay for low-Z few-electron ions where contributions from higher-order multipole components are negligible compared to the \( E1 \) component.

In DR, the resonant capture of an electron by an ion usually leads to a nonstatistical population of magnetic sublevels. Thus, the X-rays following resonant–capture processes are anisotropic and polarized (Chen & Scofield 1995; Beiersdorfer et al. 1996). The nonstatistical magnetic sublevel population of the intermediate excited states is most naturally described in terms of alignment parameter \( A_2 \). Following the density matrix formalism described by Steffen & Alder (1975), for the resonant capture of an unpolarized electron, the alignment parameter \( A_2 \) can be expressed in the form of

\[
A_2(\lambda_d) = \sum_m (-1)^{\lambda_d + m} \sqrt{S(2\lambda_d + 1)} \left( \frac{\lambda_d}{-m} \right)^2 \sigma_m.
\]

Here the quantity in large parentheses represents the Wigner 3-j symbol, \( m \) is the magnetic quantum number, and \( \sigma_m \) is the partial magnetic sublevel cross section, normalized such that \( \sum_m \sigma_m = 1 \). Since both the electron beam and the ions are unpolarized, \( \sigma_m = \sigma_m \). In this case, as in the present experiment, intermediate excited states with \( \lambda_d = 0 \) or \( \lambda_d = 1/2 \) cannot be aligned, and they decay emitting isotropic and unpolarized X-rays. Here the partial magnetic sublevel cross sections \( \sigma_m \) were evaluated using the distorted-wave formalism used in the FAC, and the relativistic corrections to the electron–electron interaction were accounted for by including the Breit interaction in the zero-energy limit for the exchanged virtual photon (cf. FAC v1.1.1 manual and Gu 2008).

Owing to the alignment of the intermediate excited ion, subsequent DR X-ray emission is polarized and anisotropic. Thus, for \( E1 \) transitions, the degree of polarization and angular distribution are given by Balashov et al. (2000) and Surzhykov et al. (2006),

\[
p^{DR}(\theta) = -\frac{3A_2 \alpha_2^{df} \sin^2 \theta}{2 - A_2 \alpha_2^{df} (1 - 3 \cos^2 \theta)},
\]

where \( \theta \) denotes the angle of the X-rays with respect to the direction of the electron beam propagation (quantization axis), \( P_2(\cos \theta) \) is the second-order Legendre polynomial, and \( \alpha_2^{df} \) represents an intrinsic anisotropy parameter that is completely determined by the total angular momentum of the intermediate excited state \( \lambda_d \) and the final state \( \lambda_f \). It can be expressed as (Balashov et al. 2000)

\[
\alpha_2^{df}(\lambda_d, \lambda_f) = (-1)^{\lambda_d + \lambda_f - 1} \sqrt{\frac{3(2\lambda_d + 1)}{2}} \left( \begin{array}{ccc} \lambda_d & \lambda_f & 2 \\ -m & m & 0 \end{array} \right) A^{df}_m.
\]

where the quantity in large parentheses denotes the Wigner 6-j symbol. It should be noted that the intermediate excited state in DR usually decays into several close-lying different final states with various degrees of polarization. The energy resolution of the Ge detector used in the present experiments was insufficient to resolve the energy splitting between these final states. Therefore, only the superpositions of individual intermediate-to-final-state transitions were observed. Due to this fact, we calculated radiative transition rate weighted “effective” intrinsic anisotropy parameters \( \tilde{\alpha}_2^{df} = \sum_m A^{df}_m / \sum_{-m} A^{df}_m \).

We extracted the emission asymmetries \( \mathcal{R} \) by observing X-ray intensities at two different angles with respect to the electron beam propagation axis. According to Equations (1) and (6), in the present experiment, we have determined the product \( A_2 \tilde{\alpha}_2^{df} \). Previously, this was also referred to as anisotropy parameter \( \beta \) by Chen & Scofield (1995), Surzhykov et al. (2002), and Weber et al. (2010). The product is given in terms of the experimental \( \mathcal{R} \) by

\[
A_2 \tilde{\alpha}_2^{df} = -\frac{2\mathcal{R}}{3 - \mathcal{R}}.
\]

The same product \( A_2 \tilde{\alpha}_2^{df} \) also defines the X-ray polarization; see Equation (5). Therefore, within the leading \( E1 \) approximation, the degree of linear polarization of X-rays emitted at the angle \( \theta \) with respect to the electron beam propagation axis...
can be expressed as

\[ P(\theta) = \frac{R \sin^2 \theta}{1 + R \cos^2 \theta}. \]  

This equation indicates that the linear polarization of characteristic X-rays emitted in the direction perpendicular to the collision axis coincides with the emission asymmetry, i.e., \( P(90^\circ) = R \). Therefore, the degree of linear polarization of the DR X-rays can be obtained easily by using our angle-resolved measurements.

The comparison of experimental values of \( R \) with the FAC results is outlined in Table 2, as well as in the top panel of Figure 2. Note that in the case of an unresolved intermediate excited state (blended resonance), the “weighted” emission asymmetry \( R \) is compared with the experimental value. It is calculated according to the following formula:

\[ R = \frac{\sum S_{i}^{\text{DR}} R_{i}}{\sum S_{i}^{\text{DR}}}. \]  

Here \( S_{i}^{\text{DR}} \) is the resonance strength calculated according to Equation (5). Moreover, we found negligible influence of the Breit interaction on the degree of linear polarization and resonance strengths for Fe ions when compared to the calculations without the Breit interaction.

All calculated theoretical values of alignment parameters \( A_{2} \), intrinsic anisotropy parameters \( \alpha_{DR} \), and degrees of linear polarization \( P_{DR} \) of X-rays are listed in Tables 3–10 in the Appendix.

4.3. Synthetic Spectrum

Table 2 compares experiment and theory for each of the individual resonances observed. Further, in order to account for all unresolved and weak transitions, we compare the experimental spectra with the synthetic one constructed with the help of all theoretical values presented in the Appendix; see the bottom panels of Figure 2.

The differential resonance strength \( dS/d\Omega \) shown in Figure 2 was obtained by multiplying the total resonance strengths with the angular correction factors at respective angles 90\(^\circ\) and 0\(^\circ\) and with the charge state distribution present in the experiment. By taking the ratio of the observed intensity of a “well-resolved” resonance formed by a particular initial ionic state \( I_{CS} \) to the theoretical strength of that resonance \( S_{CS} \), we obtained the normalized ion abundance \( n_{CS} \) from our experiment. For example, in the case of He-like initial ions, the normalized ion abundance can be expressed by

\[ n_{He} = \frac{I_{He}(90^\circ)}{S_{He}(90^\circ)} \cdot \frac{\sum I_{CS}(90^\circ)}{\sum S_{CS}(90^\circ)}. \]  

where CS refers to charge states from He-like to O-like iron ions.

According to this equation, for scan (a), we have obtained a distribution with 17% He-like, 12% Li-like, and 13% Be-like Fe ions. Likewise, for scan (b), fractional abundances of 20%, 25%, 24%, and 15% were found for B-, C-, N-, and O-like Fe ions, respectively. With this, the charge-state normalized differential resonance strengths \( dS/d\Omega \) were obtained for each resonance. We considered \( dS/d\Omega \) as line amplitudes and resonance energies \( E_{\text{res}} \) as line centroids, and then both were convoluted to widths equal to the experimental electron beam energy resolution in order to construct the synthetic spectra (a) and (b). The bottom panel of Figure 2 shows that with some exceptions, these calculations indeed very well agree with the present experiment. Some caveats with respect to the modeled spectrum can be seen in part (a) of the spectrum. This could be due to the lower collision energy resolution in measurement (a), where many blended resonances introduce errors in the reliable extraction of ion abundances. The isolated resonance approximation in the theoretical strength calculations also ignores the possible interference between two resonances. We also note that the interference between RR and DR was not included in constructing synthetic spectra. However, it is expected to be negligible for low-Z ions.

5. Application of Present Data: Diagnostic of Electron Cyclotron Motion in the Hot Plasmas

As discussed before, anisotropic and polarized line radiation can be produced by ions excited by interactions with a directional beam of electrons. Thus, the presence of a directional electron component in a laboratory and astrophysical plasma can be confirmed by a polarization measurement. Here we use the resonant recombination polarization data to diagnose the electron cyclotron energy component of the electron beam propagating through the magnetic field of the EBIT. For the analysis, we combined our present Fe XIX–XXV polarization data with the previously reported Kr XXIX–XXXV polarization data by Shah et al. (2016) and Amaro et al. (2017).

In the EBIT, the electron beam is not truly laminar and unidirectional, since it is produced at the hot cathode. The latter emits electrons with a nonvanishing thermal component. This causes electrons to gyrate perpendicular to the magnetic field lines and follow helical paths collinear with the electron beam direction. This situation may also exist in astrophysical plasmas such as solar flares, where electrons spiral around strongly directed magnetic field lines (Haug 1972, 1979, 1981). The electron beam properties of an EBIT can be described using the nonlaminar optical theory of Herrmann (1958). According to this theory, a transverse velocity component of a given electron in motion is related to its radial distance from the cathode center and its velocity at birth on the cathode; and the magnitude of this velocity component is inversely proportional to the radius of cathode images formed at different locations along the beam axis. This means that the product of transversal energy \( E_{\perp} \) and electron beam area is constant along the beam propagation direction, i.e., \( E_{\perp} \cdot 2\pi r^{2} \) \( \approx \) constant (Herrmann 1958; Beiersdorfer et al. 1996; Beiersdorfer & Slater 2001). Therefore, by using the cathode temperature \( (k_{B}T_{e}) \) and the ratio of the beam radius at the cathode \( (r_{c}) \) to the beam radius at the trap center \( (r_{t}) \), we can estimate \( E_{\perp} \) at the trap center. It can be expressed as

\[ E_{\perp} = k_{B}T_{e} \text{[eV]} \left( \frac{r_{c}}{r_{t}} \right)^{2}. \]  

Because of this transversal component, the instantaneous velocity vector is no longer aligned with the magnetic field or \( z \)-axis of the EBIT, but it deviates by an angle \( \gamma \) from the \( z \)-axis, as shown in Figure 3. This pitch angle between the \( z \)-
axis and electron velocity vector $\mathbf{v}_e$ can be given as

$$\gamma = \sin^{-1} \left( \frac{E_y}{\sqrt{E_z^2 + E_y^2}} \right), \quad (13)$$

where $E_y$ is the total electron beam energy.

As shown in Figure 3, the ions interact with electrons with velocity vectors at an angle $\gamma$, which introduces a new quantization axis to the electron–ion collision system. Because of this, X-ray detectors see either an increase or a decrease in the total intensity of the emitted X-rays. This is the case in the present experiment. A modified expression of Equation (6) can be derived to characterize this change, according to Gu et al. (1999). Considering electrons in an EBIT with a pitch angle distribution $f(\cos \gamma)$ normalized according to $\int_{-1}^{1} f(\cos \gamma) \, d(\cos \gamma) = 1$, the resulting angular distribution of DR X-rays produced by a spiraling beam of electrons can be written as

$$f^{DR}(\theta, \gamma) \propto 1 + C_2 A_2 c_2^{df} P_2(\cos \theta), \quad (14)$$

where

$$C_2 = \int_{-1}^{1} f(\cos \gamma) \, d(\cos \gamma) P_2(\cos \gamma). \quad (15)$$

For a typical pitch angle $\gamma_0$ in an EBIT, the pitch angle distribution can be described by a Dirac delta function, i.e., $f(\cos \gamma) = \delta(\cos \gamma - \cos \gamma_0)$ (Gu et al. 1999). In this case, according to Equations (14) and (15), the observed emission asymmetry $R$ of DR X-rays can be expressed as

$$R = \frac{I(90^\circ, \gamma) - I(0^\circ, \gamma)}{I(90^\circ, \gamma)} = \frac{3 A_2 c_2^{df}(1 - 3 \cos^2 \gamma)}{4 + A_2 c_2^{df}(1 - 3 \cos^2 \gamma)}. \quad (16)$$

In the ideal case, we would assume that the electron beam propagating inside an EBIT is perfectly unidirectional and the pitch angle $\gamma$ is zero ($\gamma = 0$). The emission asymmetry $R_0$ would then be expressed as

$$R_0 = \frac{I(90^\circ) - I(0^\circ)}{I(90^\circ)} = -\frac{3 A_2 c_2^{df}}{2 - A_2 c_2^{df}}, \quad (17)$$

where $f(\cos \gamma) = \delta(\cos \gamma - 1)$, i.e., according to Equation (15), $C_2 = 1$. Under the actual conditions, by combining equations Equations (16) and (17), the real emission asymmetry $R$ takes the form of

$$R = \frac{R_0(3 \sin^2 \gamma - 2)}{R_0 \sin^2 \gamma - 2}. \quad (18)$$

We now compare the values of $R$ determined from the experiment (where $\gamma$ is not zero) to the theoretical $R_0$ value for which $\gamma$ was assumed to be zero. Thereby, we determine the experimental value of the transversal energy component $E_y$ and corresponding pitch angle $\gamma$ of the electron beam:

$$\gamma = \sin^{-1} \left( \frac{2(R - R_0)}{\sqrt{R_0(R - 3)}} \right), \quad (19)$$

$$E_y = \frac{2(R - R_0)}{R_0(R - 3)} E_e. \quad (20)$$

For each well-resolved (not blended) resonance, we determined values of $E_y$ and $\gamma$ by applying Equations (19) and (20). The experimental uncertainties are computed as a quadrature sum of errors associated with quantities in these equations. The extracted values of $E_y$ and $\gamma$ from each resonance are graphically shown in Figure 4. According to Equation (13), the transversal energy component of the electron beam does not change drastically over a certain electron beam energy range. For a complete scan range of both Fe and Kr measurements ($E_e = 4–10$ keV), we give a single weighted average value of $E_y$, which is found to be $534 \pm 124$ eV. For the pitch angle $\gamma$, we present separate weighted average values for both experiments because it changes over the scan range of electron beam energies (see Equation (19)). In the case of the electron beam energy of 4.5–5.1 keV in the Fe measurement, we obtained the average value of $\gamma = 16.3^\circ \pm 5.4^\circ$, whereas in the energy range of 8.8–9.6 keV, used in the Kr measurement, we obtained $\gamma = 17.2^\circ \pm 2.8^\circ$. The weighted average values are shown as red shaded areas in Figure 4.

The theoretical values of $E_y$ and $\gamma$ can be estimated based on the electron beam conditions. The cathode with a diameter of 3 mm is heated to approximately 1200–1400 K, resulting in a transverse thermal energy component of $\approx 0.10–0.12$ eV at the cathode. As mentioned before, the electron beam of the FLASH-EBIT is compressed by the magnetic field with a strength of 6 T. During the measurements, we positioned the electron gun and used a correction coil surrounding the electron gun to ensure a nearly zero residual magnetic field at the cathode. However, this residual magnetic field is not very well known. Based on the observed beam diameter, which is close to the Herrmann value for a negligible residual magnetic field, we estimate an upper bound of the order of a few hundred $\mu$T ($300–500 \mu$T assumed here). With these assumptions, theoretical values of $E_y$ and $\gamma$ were estimated according to Equations (12) and (13). They are shown as the blue shaded area in Figure 4. It can be seen that the theoretical estimates according to Herrmann’s optical theory are in good accord with the experimentally determined average values of $E_y$ and $\gamma$. Furthermore, the electron beam radius $r_e$ at the trap was also deduced using the experimental value of $E_y$ and Equation (12). The radius was found to be $22.6 \pm 4.2 \mu$m, which is also in very good agreement with Herrmann’s theory; see Table 1. This validation reassures our measurements and estimates, since the optical theory of Herrmann was used as one of the first principles in the design of the EBIT (Levine et al. 1988). For comparison, we also estimated the transversal energy component of the electron beam based on the principle of adiabatic magnetic flux invariance, i.e., $\nu^2 / B \approx$ constant. According to this, $E_y$ was estimated to be 1578 eV. Such a large value of transversal energy does not agree with our measured value. This can be explained, since the EBIT has a nonuniform magnetic field along the electron beam propagation axis. The electrons travel across strong magnetic field gradients from a few $\mu$T magnetic field at the electron gun to 6 T at the trap. Such gradients invalidate the applicability of the principle of adiabatic magnetic flux invariance (Beiersdorfer & Slater 2001).

6. Summary and Conclusions

In this work, we have performed comprehensive experimental and theoretical studies on the polarization of X-rays produced by KLL DR of highly charged He-like to O-like iron ions. The emitted radiation was recorded along and perpendicular to the electron beam propagation axis, and the X-ray polarization of DR satellite lines was extracted from the measured emission asymmetries. The presented experimental technique greatly
Figure 3. Emission asymmetry of the emitted photons with an introduction of the pitch angle $\gamma$, which is an angle between the magnetic field line (quantization axis) and electron velocity vector $\vec{v}_e$.

Figure 4. Experimental $E_\perp$ and corresponding $\gamma$ as a function of the electron beam energy (see Equations (19) and (20)). The red shaded area represents the weighted average value and contains uncertainty. The blue shaded area represents the theory estimated according to the experimental electron beam conditions: cathode radius $r_c = 1.5$ mm, magnetic field $B = 6$ T, residual magnetic field at cathode $B_r = 300-500$ $\mu$T, and cathode temperature $T_c = 1200-1400$ K.

reduces the time required for comprehensive measurements compared to direct polarization measurements, which are time-consuming and require an X-ray polarimeter (Shah et al. 2015; Weber et al. 2015). Our method is simple to implement at EBIT’s, and it allows us to scan all ions relevant to astrophysical and fusion research. It can be applied not only to the DR process but also to measuring X-ray polarization due to other atomic processes. With a few exceptions, we found excellent agreement between the experiment and distorted-wave predictions of the FAC. We thus show that this code is reliable to a high degree and can be used to produce large sets of atomic data and develop reliable astrophysical plasma models. A contribution of ubiquitous but hitherto unrecognized higher-order channels, such as TR, was found to be as strong as the dielectronic process in B- and C-like Fe ions, and it should play an important role in the charge balance determination of hot plasmas (Beilmann et al. 2011; Beiersdorfer 2015). Recently, TR channels have also been proven to play a dominant role in the measurable X-ray polarization of a common type of astrophysical and laboratory plasmas (Shah et al. 2016).

In addition, we have demonstrated the suitability of resonant recombination polarization measurements for diagnostics of anisotropies of hot plasmas, such as plasmas of solar flares (Haug 1972, 1979). In our demonstration, we probed the electron cyclotron motion component of the electron beam propagating through a strong magnetic field of the FLASH-EBIT. The electron cyclotron energy accounted for $534 \pm 124$ eV of the total electron beam energy. Furthermore, the electron beam radius at the trap center was determined to be $22.6 \pm 4.2$ $\mu$m. Both values agree exceptionally well with the predictions of the optical theory of electron beams by Herrmann (1958). Such agreement shows that the Herrmann theory can be used to predict the systematic effect of the electron cyclotron motion component on polarization measurements. This analysis is far more complex and extracts even greater details of the plasma anisotropies than the one that would be required to detect the directional component of the hot plasmas of a solar flare or tokamak fusion plasma. Therefore, the present work opens up numerous possibilities for diagnostics of the anisotropies of hot laboratory and astrophysical plasmas.

With the next generation of X-ray satellites, namely the X-ray Astronomy Recovery Mission (XARM) and Athena, exceptional spectral energy resolutions will be reached with higher sensitivity (Hitomi Collaboration et al. 2016; Kelley et al. 2016). The present data will be particularly useful for interpreting high-resolution microcalorimeter-based X-ray spectra in the future (Hitomi Collaboration et al. 2017). It can also be used to benchmark spectral modeling codes for hot collisional plasmas such as SPEX (Kaastra et al. 1996), CHIANTI (Del Zanna et al. 2015), and AtomDB (Foster et al. 2012). Furthermore, these results may also be applicable to model X-ray line polarization data from future X-ray polarimetry missions, such as the ESA M4 class mission XIPE (Soffitta et al. 2013), NASA Small Explorer mission PRAXyS (Jahoda et al. 2014), and IXPE (Weisskopf et al. 2016). For example, the photoelectric gas polarimeter (Costa et al. 2001) of XIPE will not resolve individual X-ray line transitions. Such limitations are rather general even when the high-resolution detector will be utilized, because Doppler shifts will most likely obscure the signal. In such instances, the line polarization will contain contributions from many transitions induced by different atomic processes. This calls for more quantitatively reliable experimental and theoretical atomic data of X-ray polarization of all contributing channels.

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Appendix

KLL DR Calculations of Fe XIX–XXV

Here we present the theoretical DR data that are tested and benchmarked within the present experiment. The following quantities are presented in Tables 3–10. The first column of Tables 4–10 represents the energy level index. The second column identifies the order of the recombination processes: DR, TR, and QR. An intermediate excited-state configuration of the ion is given in the third column. Standard $j$–$f$ coupling notations are used here to define atomic configurations. The subscript following the parentheses denotes the angular momentum of the coupled subshells, and another subscript following the square brackets denotes the total angular momentum of the given state. Resonance energies $E_{\text{res}}$ in eV and total resonance strengths $S_{\text{DR}}$ in units of cm$^2$ eV are given in the fourth and fifth columns, respectively. The former value is the energy difference between the initial and intermediate excited ionic states, and the latter value is calculated using Equation (3). To calculate the degree of linear polarization, the alignment parameter $A_2$ is given in the sixth column, taking the frequency-independent Breit interaction into account, and the intrinsic anisotropy parameter $\alpha_2^{\text{df}}$ for the X-ray transition from the intermediate excited state to the final states is given in Table 3. As discussed in Section 4, the intermediate excited state produced by DR usually decays to several final states. Final-state configurations are given in the seventh column; accordingly, the X-ray energies $E_{\text{X-ray}}$ and radiative decay rates $\lambda_{\text{f}}$ (in s$^{-1}$) are provided in the next two columns. Finally, the polarization of X-rays $P_{\text{DR}}$ is calculated according to Equation (5) and is given in the last column. Note that for the experimental comparison, we used the “effective” intrinsic anisotropy parameter $\alpha_2^{\text{eff}}$, which is weighted by given radiative rates $\lambda_{\text{f}}$.

| Table 3 | Intrinsic Anisotropy Parameter $\alpha_2^{\text{df}}$ (Equation (7)) Characterizing X-Ray Polarization and Anisotropy |
|---------|--------------------------------------------------------------------------------------------------|
| $J_I$ | $J_f$ | $\alpha_2^{\text{df}}$ | $J_I$ | $J_f$ | $\alpha_2^{\text{df}}$ |
| 0 | 1 | 0 | 1/2 | 1/2 | 0 |
| 1 | 1 | $-1/2$ | 3/2 | 1/2 | 1/2 |
| 1 | 2 | $1/10$ | 3/2 | 3/2 | $-2/5$ |
| 2 | 1 | $\sqrt{7}/210$ | 3/2 | 5/2 | 1/10 |
| 2 | 2 | $-7/210$ | 5/2 | 3/2 | $\sqrt{7}/510$ |
| 2 | 3 | $1/\sqrt{7}$ | 5/2 | 5/2 | $-4/\sqrt{7}$ |
| 3 | 2 | $\sqrt{3}/510$ | 5/2 | 7/2 | $1/214$ |
| 3 | 3 | $-\sqrt{3}/4$ | ... | ... | ... |
| 3 | 4 | $-1/\sqrt{3}$ | ... | ... | ... |

| Table 4 | Fe XXV Theoretical Data |
|---------|-------------------------|
| $i$ | Process | Intermediate Excited State | $E_{\text{res}}$ (eV) | $S_{\text{DR}}$ (cm$^2$ eV) | $A_2$ | Final State | $E_{\text{X-ray}}$ (eV) | $\lambda_{\text{f}}$ (s$^{-1}$) | $P_{\text{DR}}$ |
| 4 | DR | $1s(2s^2)h_{1/2}$ | 4554.41 | 1.982E–20 | 0.000 | $1s^22p_{1/2}h_{1/2}$ | 6552.00 | 9.95E+12 | 0.000 |
| 5 | DR | $1s(2s^2)2p_{1/2}h_{1/2}$ | 4565.87 | 6.439E–23 | 0.000 | $1s^22p_{1/2}h_{1/2}$ | 6611.86 | 4.96E+12 | 0.000 |
| 6 | DR | $1s(2s^2)2p_{1/2}h_{1/2}$ | 4569.59 | 3.885E–22 | $-1.000$ | $1s^22p_{1/2}h_{1/2}$ | 6615.57 | 1.59E+13 | 0.600 |
| 8 | DR | $1s(2s^2)2p_{1/2}h_{1/2}$ | 4607.76 | 5.469E–20 | 0.000 | $1s^22p_{1/2}h_{1/2}$ | 6653.75 | 3.38E+14 | 0.000 |
| 9 | DR | $1s(2s^2)2p_{3/2}h_{1/2}$ | 4616.73 | 8.229E–22 | $-1.000$ | $1s^22p_{3/2}h_{1/2}$ | 6662.72 | 5.04E+14 | 0.600 |
| 10 | DR | $1s(2p_{1/2}^2)h_{1/2}$ | 4624.16 | 8.286E–23 | 0.000 | $1s^22p_{1/2}h_{1/2}$ | 6621.75 | 2.05E+13 | 0.000 |
| 11 | DR | $1s(2p_{1/2}^2)2p_{1/2}h_{1/2}$ | 4631.21 | 6.119E–20 | 0.000 | $1s^22p_{1/2}h_{1/2}$ | 6677.20 | 1.78E+14 | 0.000 |
| 12 | DR | $1s(2p_{1/2}^2)2p_{1/2}h_{1/2}$ | 4632.38 | 8.744E–22 | $-1.000$ | $1s^22p_{1/2}h_{1/2}$ | 6629.97 | 4.36E+10 | 0.600 |
| 13 | DR | $1s(2p_{1/2}^2)2p_{1/2}h_{1/2}$ | 4634.52 | 9.435E–23 | $-1.000$ | $1s^22p_{1/2}h_{1/2}$ | 6680.51 | 4.37E+11 | 0.600 |
| 14 | DR | $1s(2p_{1/2}^2)2p_{1/2}h_{1/2}$ | 4639.46 | 4.142E–20 | $-1.069$ | $1s^22p_{1/2}h_{1/2}$ | 6620.18 | 3.26E+13 | 0.500 |
| 15 | DR | $1s(2p_{1/2}^2)2p_{1/2}h_{1/2}$ | 4658.34 | 2.071E–19 | $-1.000$ | $1s^22p_{1/2}h_{1/2}$ | 6655.93 | 3.33E+14 | 0.600 |
| 16 | DR | $1s(2p_{1/2}^2)2p_{1/2}h_{1/2}$ | 4659.29 | 1.674E–21 | $-1.000$ | $1s^22p_{1/2}h_{1/2}$ | 6656.87 | 5.67E+14 | 0.000 |
| 17 | DR | $1s(2p_{1/2}^2)2p_{1/2}h_{1/2}$ | 4663.92 | 2.817E–19 | $-1.069$ | $1s^22p_{1/2}h_{1/2}$ | 6645.64 | 2.21E+14 | 0.000 |
| 18 | DR | $1s(2p_{1/2}^2)2p_{1/2}h_{1/2}$ | 4677.48 | 6.461E–20 | $-1.000$ | $1s^22p_{1/2}h_{1/2}$ | 6675.06 | 9.44E+12 | 0.600 |
| 19 | DR | $1s(2p_{1/2}^2)2p_{1/2}h_{1/2}$ | 4697.79 | 2.452E–20 | 0.000 | $1s^22p_{1/2}h_{1/2}$ | 6695.38 | 1.21E+13 | 0.000 |

Note. Initial (ground) state: $[1s^2]$.

(This table is available in its entirety in machine-readable form.)
| i | Process | Intermediate | Excited State | $E_{\text{ex}}$ (eV) | $g^\text{DR}$ (cm$^{-2}$ eV) | $A_2$ | Final State | $E_{\text{X-ray}}$ (eV) | $A_\beta^\text{DR}$ (s$^{-1}$) | $\rho^\text{DR}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 11 | DR | $[1s2s^22p_{1/2}]_0$ | 4644.94 | 7.96E–22 | 0.000 | $[1s^22p_{1/2}2p_{1/2}]_0$ | 6490.08 | 8.57E+12 | 0.000 |
| 12 | DR | $[1s2s^22p_{1/2}]_1$ | 4646.84 | 1.136E–20 | 0.694 | $[1s^22p_{1/2}2p_{3/2}]_1$ | 6597.86 | 3.76E+13 | −0.975 |
| | | | | | | | | | | |
| 13 | DR | $[1s2s^22p_{3/2}]_1$ | 4660.00 | 4.94E–21 | −0.839 | $[1s^22p_{3/2}2p_{3/2}]_1$ | 6479.63 | 3.90E+12 | −0.975 |
| | | | | | | | | | | |
| 14 | DR | $[1s2s^22p_{3/2}]_2$ | 4661.60 | 1.091E–21 | −0.012 | $[1s^22p_{3/2}2p_{3/2}]_2$ | 6478.33 | 6.44E+12 | −0.639 |
| | | | | | | | | | | |
| 15 | DR | $[1s2s^22p_{3/2}]_3$ | 4669.08 | 5.725E–22 | −0.652 | $[1s^22p_{3/2}2p_{3/2}]_3$ | 6570.35 | 4.02E+11 | 0.321 |
| | | | | | | | | | | |
| 16 | DR | $[1s2s^22p_{3/2}]_4$ | 4675.49 | 6.897E–21 | −0.990 | $[1s^22p_{3/2}2p_{3/2}]_4$ | 6659.61 | 3.77E+12 | 0.012 |
| | | | | | | | | | | |
| 17 | DR | $[1s2s^22p_{3/2}]_5$ | 4678.21 | 2.718E–21 | 0.678 | $[1s^22p_{3/2}2p_{3/2}]_5$ | 6565.78 | 7.58E+12 | −0.006 |
| | | | | | | | | | | |
| 18 | DR | $[1s2s^22p_{3/2}]_6$ | 4708.60 | 1.012E–21 | 0.000 | $[1s^22p_{3/2}2p_{3/2}]_6$ | 6632.23 | 4.59E+14 | −0.946 |
| | | | | | | | | | | |
| 19 | DR | $[1s2s^22p_{3/2}]_7$ | 4712.00 | 3.451E–20 | −0.635 | $[1s^22p_{3/2}2p_{3/2}]_7$ | 6616.18 | 6.05E+13 | −0.379 |
| | | | | | | | | | | |
| 20 | DR | $[1s2s^22p_{3/2}]_8$ | 4713.81 | 1.175E–19 | −0.599 | $[1s^22p_{3/2}2p_{3/2}]_8$ | 6617.99 | 3.37E+14 | 0.334 |
| | | | | | | | | | | |
| 21 | DR | $[1s2s^22p_{3/2}]_9$ | 4717.67 | 1.630E–19 | −0.990 | $[1s^22p_{3/2}2p_{3/2}]_9$ | 6610.49 | 2.35E+14 | 0.439 |
| | | | | | | | | | | |
| 22 | DR | $[1s2s^22p_{3/2}]_{10}$ | 4718.78 | 6.221E–20 | −0.706 | $[1s^22p_{3/2}2p_{3/2}]_{10}$ | 6626.78 | 1.97E+12 | 0.600 |
| | | | | | | | | | | |
| 23 | DR | $[1s2s^22p_{3/2}]_{11}$ | 4725.96 | 4.555E–20 | −0.780 | $[1s^22p_{3/2}2p_{3/2}]_{11}$ | 6650.06 | 4.70E+12 | −0.428 |
| | | | | | | | | | | |
| 24 | DR | $[1s2s^22p_{3/2}]_{12}$ | 4735.38 | 1.379E–20 | −0.007 | $[1s^22p_{3/2}2p_{3/2}]_{12}$ | 6643.39 | 2.73E+12 | 0.000 |
| | | | | | | | | | | |
| 25 | DR | $[1s2s^22p_{3/2}]_{13}$ | 4737.35 | 3.690E–22 | 0.000 | $[1s^22p_{3/2}2p_{3/2}]_{13}$ | 6659.35 | 5.60E+12 | −0.639 |
| | | | | | | | | | | |
| 26 | DR | $[1s2s^22p_{3/2}]_{14}$ | 4745.66 | 5.521E–20 | −1.171 | $[1s^22p_{3/2}2p_{3/2}]_{14}$ | 6653.80 | 1.14E+12 | −0.006 |
| | | | | | | | | | | |
| 27 | DR | $[1s2s^22p_{3/2}]_{15}$ | 4749.63 | 1.132E–20 | −0.010 | $[1s^22p_{3/2}2p_{3/2}]_{15}$ | 6654.24 | 1.53E+14 | 0.001 |
| | | | | | | | | | | |
| 28 | DR | $[1s2s^22p_{3/2}]_{16}$ | 4751.03 | 3.026E–22 | −0.840 | $[1s^22p_{3/2}2p_{3/2}]_{16}$ | 6575.16 | 6.62E+12 | 0.448 |

Table 5
Fe XXIV Theoretical Data

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| $i$ | Process | Intermediate Excited State | $E_{res}$ (eV) | $g_{int}$ (cm$^{-2}$ eV) | $A_i$ | Final State | $E_{x-ray}$ (eV) | $\Delta v^\circ$ (s$^{-1}$) | $p_{int}$ |
|-----|---------|---------------------------|---------------|-----------------|------|-------------|---------------|----------------|---------|
| 29  | DR      | [1s$^2$2p$^2_{1/2}$]     | 4757.35       | 2.022E–20       | -1.185 | [1s$^2$2p$^2_{1/2}$] | 6552.27       | 1.97E+11       | -0.639  |
| 30  | DR      | [1s$^2$2p$^2_{1/2}$]     | 4767.47       | 1.790E–21       | -0.566 | [1s$^2$2p$^2_{1/2}$] | 6675.47       | 8.84E+11       | 0.500   |
| 31  | DR      | [1s$^2$2p$^2_{1/2}$]     | 4775.60       | 7.841E–21       | 0.000  | [1s$^2$2p$^2_{1/2}$] | 6679.78       | 3.31E+11       | 0.000   |
| 32  | DR      | [1s$^2$p$^2_{1/2}$]      | 4780.23       | 1.984E–22       | 0.697  | [1s$^2$p$^2_{1/2}$] | 6631.88       | 2.40E+14       | 0.000   |
| 33  | TR      | [1s$^2$p$^2_{1/2}$]      | 4781.77       | 3.771E–22       | -0.840 | [1s$^2$p$^2_{1/2}$] | 6605.91       | 2.27E+14       | 0.448   |
| 35  | TR      | [1s$^2$p$^2_{1/2}$]      | 4792.14       | 1.081E–22       | 0.695  | [1s$^2$p$^2_{1/2}$] | 6624.92       | 4.81E+13       | -0.977  |
| 36  | TR      | [1s$^2$p$^2_{1/2}$]      | 4800.91       | 6.939E–22       | -0.840 | [1s$^2$p$^2_{1/2}$] | 6625.05       | 6.61E+11       | 0.448   |
| 37  | TR      | [1s$^2$p$^2_{1/2}$]      | 4805.85       | 3.760E–22       | 0.000  | [1s$^2$p$^2_{1/2}$] | 6629.99       | 2.43E+14       | 0.000   |
| 38  | TR      | [1s$^2$p$^2_{1/2}$]      | 4807.77       | 1.155E–21       | 0.700  | [1s$^2$p$^2_{1/2}$] | 6640.55       | 4.21E+12       | -0.986  |
| 39  | TR      | [1s$^2$p$^3_{1/2}$]      | 4815.61       | 1.348E–21       | -0.840 | [1s$^2$p$^3_{1/2}$] | 6639.75       | 7.97E+12       | 0.448   |
| 40  | TR      | [1s$^2$p$^3_{1/2}$]      | 4830.83       | 3.221E–23       | 0.557  | [1s$^2$p$^3_{1/2}$] | 6781.85       | 3.29E+11       | -0.736  |

**Note.** Initial (ground) state: [1s$^2$2s$^1$]$_{1/2}$.
(This table is available in its entirety in machine-readable form.)
| \(i\) | Process | Intermediate States | \(E_{ex}\) (eV) | \(a^{DR}\) (cm\(^2\) eV) | \(A_2\) | Final States | \(E_{x_{ex}}\) (eV) | \(A_e^Y\) (s\(^{-1}\)) | \(p^{DR}\) |
|----|--------|------------------|-------------|-----------------|------|--------------|-------------|-----------------|------|
| 16 | DR    | \(1s^22p_{1/2}^2\) | 4755.78     | 9.320E-22       | 0.000 | \(1s^22p_{1/2}^2\) | 6552.85     | 3.07E+13       | 0.000 |
| 17 | DR    | \(1s^22p_{1/2}^2\) | 4764.68     | 3.164E-23       | -1.000 | \(1s^22p_{1/2}^2\) | 6561.75     | 4.18E+10       | 0.600 |
| 18 | DR    | \(1s^22p_{1/2}^2\) | 4770.34     | 5.382E-21       | -1.069 | \(1s^22p_{1/2}^2\) | 6552.83     | 2.82E+13       | 0.500 |
| 19 | DR    | \(1s^22p_{1/2}^2\) | 4780.91     | 2.017E-26       | -1.069 | \(1s^22p_{1/2}^2\) | 6522.24     | 3.49E+12       | 0.000 |
| 20 | DR    | \(1s^22p_{1/2}^2\) | 4789.06     | 1.076E-20       | 0.000  | \(1s^22p_{1/2}^2\) | 6515.66     | 3.77E+12       | 0.000 |
| 21 | DR    | \(1s^22p_{1/2}^2\) | 4789.42     | 1.215E-19       | -1.000 | \(1s^22p_{1/2}^2\) | 6586.49     | 3.10E+14       | 0.600 |
| 22 | DR    | \(1s^22p_{3/2}^2\) | 4794.37     | 1.457E-19       | -1.069 | \(1s^22p_{3/2}^2\) | 6576.86     | 2.07E+14       | 0.500 |
| 23 | DR    | \(1s^22p_{3/2}^2\) | 4806.94     | 4.325E-20       | -1.000 | \(1s^22p_{3/2}^2\) | 6589.42     | 5.98E+14       | -0.750 |
| 24 | DR    | \(1s^22p_{3/2}^2\) | 4812.49     | 4.085E-20       | 0.000  | \(1s^22p_{3/2}^2\) | 6604.01     | 8.92E+12       | 0.600 |
| 25 | TR    | \(1s^22p_{3/2}^2\) | 4828.96     | 2.202E-23       | -1.000 | \(1s^22p_{3/2}^2\) | 6577.13     | 2.93E+14       | 0.600 |
| $i$ | Process | Intermediate State | $E_{\text{ex}}$ (eV) | $g_{\text{th}}$ (cm$^2$ eV$^{-1}$) | $A_2$ | Final State | $E_{\text{kin}}$ (eV) | $A_2^0_2$ (s$^{-1}$) | $p_{\text{th}}$  |
|-----|---------|---------------------|-------------------|-----------------|-----|-----------|-----------------|-----------------|-----------|
| 26  | TR      | $[(1s^22p_{1/2})h/2](2p_{3/2}^2)_{1/2}$ | 4830.06          | 6.299E$-26$    | -1.069 | $[1s^2(2d_{5/2})_h/2]_{p_{3/2}}_{h/2}$ | 6519.16        | 7.39E$+11$   | 0.600 |
| 27  | TR      | $[(1s^22p_{1/2})h/2](2p_{3/2}^2)_{1/2}$ | 4831.20          | 2.507E$-23$    | 0.000 | $[1s^2(2d_{5/2})_h/2]_{p_{3/2}}_{h/2}$ | 6571.40        | 2.28E$+14$   | 0.000 |
| 29  | TR      | $[(1s^22p_{1/2})h/2](2p_{3/2}^2)_{1/2}$ | 4837.08          | 9.292E$-23$    | -1.000 | $[1s^2(2d_{5/2})_h/2]_{p_{3/2}}_{h/2}$ | 6571.83        | 2.76E$+14$   | 0.143 |
| 30  | TR      | $[(1s^22p_{1/2})h/2](2p_{3/2}^2)_{1/2}$ | 4883.33          | 2.412E$-24$    | 0.000 | $[1s^2(2d_{5/2})_h/2]_{p_{3/2}}_{h/2}$ | 6571.83        | 1.15E$+13$   | 0.000 |
| 31  | TR      | $[(1s^22p_{1/2})h/2](2p_{3/2}^2)_{1/2}$ | 4850.28          | 2.246E$-25$    | -1.069 | $[1s^2(2d_{5/2})_h/2]_{p_{3/2}}_{h/2}$ | 6571.83        | 2.29E$+14$   | 0.143 |
| 32  | TR      | $[(1s^22p_{1/2})h/2](2p_{3/2}^2)_{1/2}$ | 4850.55          | 5.855E$-23$    | -1.000 | $[1s^2(2d_{5/2})_h/2]_{p_{3/2}}_{h/2}$ | 6591.61        | 2.94E$+12$   | 0.000 |
| 33  | TR      | $[(1s^22p_{1/2})h/2](2p_{3/2}^2)_{1/2}$ | 4867.52          | 5.552E$-22$    | -1.000 | $[1s^2(2d_{5/2})_h/2]_{p_{3/2}}_{h/2}$ | 6591.88        | 2.37E$+12$   | 0.600 |
| 34  | TR      | $[(1s^22p_{1/2})h/2](2p_{3/2}^2)_{1/2}$ | 4872.27          | 7.573E$-28$    | -1.069 | $[1s^2(2d_{5/2})_h/2]_{p_{3/2}}_{h/2}$ | 6571.40        | 3.94E$+14$   | 0.000 |
| 35  | TR      | $[(1s^22p_{1/2})h/2](2p_{3/2}^2)_{1/2}$ | 4876.08          | 1.924E$-22$    | -1.000 | $[1s^2(2d_{5/2})_h/2]_{p_{3/2}}_{h/2}$ | 6631.60        | 2.23E$+12$   | 0.000 |
| i  | Process | Intermediate Excited State | $E_{exc}$ (eV) | $S_{tot}$ (cm² eV) | $A_2$ | Final State | $E_{kin}$ (eV) | $A_0^p$ (s⁻¹) | $p_{tot}$ |
|----|---------|-----------------------------|----------------|-------------------|-----|-------------|----------------|----------------|---------|
| 36 | TR      | $[1s^22p_{3/2}h_1/2(2p_{1/2}^22p_{3/2})]_1/2$ | 4881.28        | 3.383E-23         | 1   | $[1s^22p_{3/2}h_1/22p_{3/2}h_1/2]$ | 6617.41        | 1.38E+12       | -0.750 |
| 37 | TR      | $[1s^22p_{3/2}h_1/2(2p_{1/2}^22p_{3/2})]_1/2$ | 4883.16        | 4.564E-23         | 1   | $[1s^22p_{3/2}h_1/22p_{3/2}h_1/2]$ | 6612.61        | 2.95E+11       | -0.750 |
| 38 | TR      | $[1s^22p_{3/2}h_1/2(2p_{1/2}^22p_{3/2})]_1/2$ | 4888.40        | 1.242E-26         | 1   | $[1s^22p_{3/2}h_1/22p_{3/2}h_1/2]$ | 6631.33        | 6.86E+11       | 0.000  |
| 39 | TR      | $[1s^22p_{3/2}h_1/2(2p_{1/2}^22p_{3/2})]_1/2$ | 4895.51        | 5.451E-23         | 1   | $[1s^22p_{3/2}h_1/22p_{3/2}h_1/2]$ | 6658.39        | 4.13E+14       | 0.000  |
| 40 | TR      | $[1s^22p_{3/2}h_1/2(2p_{1/2}^22p_{3/2})]_1/2$ | 4897.90        | 1.171E-21         | 1   | $[1s^22p_{3/2}h_1/22p_{3/2}h_1/2]$ | 6663.84        | 3.41E+11       | -0.750 |
| 41 | TR      | $[1s^22p_{3/2}h_1/2(2p_{1/2}^22p_{3/2})]_1/2$ | 4908.55        | 1.589E-21         | 1   | $[1s^22p_{3/2}h_1/22p_{3/2}h_1/2]$ | 6643.30        | 4.32E+10       | 0.143  |
| 42 | TR      | $[1s^22p_{3/2}h_1/2(2p_{1/2}^22p_{3/2})]_1/2$ | 4912.38        | 6.465E-22         | 1   | $[1s^22p_{3/2}h_1/22p_{3/2}h_1/2]$ | 6653.71        | 1.83E+11       | 0.000  |
| 43 | DR      | $[1s^22p_{3/2}h_1/2(2p_{1/2}^22p_{3/2})]_1/2$ | 4923.25        | 1.484E-24         | 0   | $[1s^22p_{3/2}h_1/22p_{3/2}h_1/2]$ | 6565.97        | 2.18E+14       | 0.500  |
| 44 | QR      | $[1s^22p_{3/2}h_1/2(2p_{1/2}^22p_{3/2})]_1/2$ | 4933.39        | 3.293E-25         | 0   | $[1s^22p_{3/2}h_1/22p_{3/2}h_1/2]$ | 6715.87        | 4.59E+10       | -0.750 |

(Continued)
### Table 6

(Continued)

| \( \ell \) | Process | Intermediate Excited State | \( E_{\text{res}} \) (eV) | \( \delta_{\text{OR}} \) (cm\(^2\) eV) | \( A_2 \) | Final State | \( E_{X\text{-ray}} \) (eV) | \( A_0^\theta \) (s\(^{-1}\)) | \( P^\text{OR} \) |
|---|---|---|---|---|---|---|---|---|---|
| 45 | DR | \([1s^22s^2(2p_{1/2}^2)h_1/2] \) | 4936.68 | 1.447E-23 | 0.000 | \([1s^22p_{1/2}2p_{1/2}^3 h_1/2] \) | 6534.64 | 2.99E+11 | 0.600 |
| 46 | DR | \([1s^22s^2(2p_{3/2}^2)h_1/2] \) | 4951.02 | 1.711E-24 | -1.000 | \([1s^22s^22p_{1/2}^2 h_1/2] \) | 6733.50 | 1.84E+11 | -0.750 |
| 47 | QR | \([1s^22p_{1/2}2p_{3/2}^3 h_1/2] \) | 4955.44 | 6.369E-24 | -1.069 | \([1s^22s^22p_{1/2}^3 h_1/2] \) | 6737.92 | 6.15E+10 | 0.500 |
| 48 | QR | \([1s^22p_{1/2}^22p_{3/2}^2 h_1/2] \) | 4963.14 | 4.678E-24 | -1.000 | \([1s^22s^22p_{1/2}^3 h_1/2] \) | 6605.87 | 2.99E+12 | -0.750 |
| 49 | QR | \([1s^22p_{1/2}2p_{3/2}^3 h_1/2] \) | 4963.93 | 2.826E-23 | 0.000 | \([1s^22s^22p_{1/2}^3 h_1/2] \) | 6761.00 | 1.30E+11 | 0.000 |
| 50 | QR | \([1s^22p_{3/2}^3 h_1/2] \) | 4989.87 | 1.090E-22 | 0.000 | \([1s^22s^22p_{1/2}^3 h_1/2] \) | 6772.35 | 1.17E+11 | 0.000 |

**Note.** Initial (ground) state: \([1s^22s^2] h_1/2 \).

(This table is available in its entirety in machine-readable form.)
| \( i \) | Process | Intermediate State | \( E_{\text{ex}} \) (eV) | \( g_{\text{DR}} \) (cm\(^{-1}\) eV) | \( A_2 \) | Final State | \( E_{\text{ex}} \) (eV) | \( A^\text{DR} \) (s\(^{-1}\)) | \( \rho_{\text{DR}} \) |
|---|---|---|---|---|---|---|---|---|---|
| 21 | DR | \([1s^23p^23s^22p_{3/2}^2]_h\) | 4830.72 | 5.975E–22 | −0.897 | \([1s^23p^23p_{3/2}^22p_{3/2}^2]_h\) | 6509.07 | 9.96E+12 | 0.474 |
| 22 | DR | \([1s^23p^23s^22p_{3/2}^22p_{3/2}^2]_h\) | 4856.94 | 4.736E–20 | −0.684 | \([1s^23p^23p_{3/2}^22p_{3/2}^22p_{3/2}^2]_h\) | 6544.47 | 2.85E+14 | 0.584 |
| 23 | DR | \([1s^23p^23p_{1/2}^23s^23p_{3/2}^2]_h\) | 4858.90 | 5.790E–20 | −0.977 | \([1s^23p^23p_{1/2}^22p_{3/2}^22p_{3/2}^2]_h\) | 6537.26 | 2.13E+14 | 0.599 |
| 24 | DR | \([1s^23p^23p_{1/2}^23s^23p_{3/2}^2]_h\) | 4862.63 | 2.611E–20 | −0.990 | \([1s^23p^23p_{1/2}^22p_{3/2}^22p_{3/2}^2]_h\) | 6535.50 | 1.76E+14 | 0.439 |
| 25 | DR | \([1s^23p^23p_{1/2}^23s^23p_{3/2}^2]_h\) | 4869.65 | 7.145E–21 | −0.630 | \([1s^23p^23p_{1/2}^22p_{3/2}^22p_{3/2}^2]_h\) | 6557.19 | 2.48E+13 | 0.547 |
| 26 | DR | \([1s^23p^23p_{1/2}^23s^23p_{3/2}^2]_h\) | 4874.35 | 5.027E–21 | 0.000 | \([1s^23p^23p_{1/2}^22p_{3/2}^22p_{3/2}^2]_h\) | 6552.70 | 2.39E+14 | 0.000 |
| 27 | DR | \([1s^23p^23p_{1/2}^23s^23p_{3/2}^2]_h\) | 4867.74 | 1.964E–20 | 0.619 | \([1s^23p^23p_{1/2}^22p_{3/2}^22p_{3/2}^2]_h\) | 6554.09 | 3.33E+12 | 0.344 |
| 28 | DR | \([1s^23p^23p_{1/2}^23s^23p_{3/2}^2]_h\) | 4877.43 | 1.696E–20 | 0.013 | \([1s^23p^23p_{1/2}^22p_{3/2}^22p_{3/2}^2]_h\) | 6564.97 | 7.32E+11 | 0.014 |
| 29 | TR | \([1s^23p^23p_{1/2}^2]_h\) | 4888.31 | 1.087E–20 | 0.629 | \([1s^23p^23p_{1/2}^22p_{3/2}^2]_h\) | 6566.67 | 3.31E+12 | 0.349 |
| \( i \) | Process | \( \text{Intermediate Excited State} \) | \( E_{\text{res}} \) (eV) | \( S_{\text{tot}} \) (cm\(^2\) eV) | \( A_2 \) | \( \text{Final State} \) | \( E_{\text{res},\text{f}} \) (eV) | \( A_0^\prime \) (s\(^{-1}\)) | \( \sigma_{\text{tot}} \) |
|---|---|---|---|---|---|---|---|---|---|
| 30 | TR \[1s^22p^3_{3/2}2p^1_{1/2}2p^1_{3/2}\] | 4989.85 | 9.576E–21 | −0.534 | \[1s^22p^1_{1/2}2p^3_{1/2}\] | 6359.49 | 7.90E+11 | 0.349 |
| 31 | TR \[1s^22p^3_{3/2}2p^1_{1/2}2p^1_{3/2}\] | 4902.11 | 9.434E–27 | −0.990 | \[1s^22p^2_{3/2}2p^1_{1/2}\] | 6531.53 | 2.25E+14 | 0.000 |
| 32 | TR \[1s^22p^3_{3/2}2p^1_{1/2}2p^1_{3/2}\] | 4911.29 | 2.208E–25 | −0.758 | \[1s^22p^2_{3/2}2p^1_{1/2}\] | 6502.47 | 7.16E+11 | 0.000 |
| 33 | TR \[1s^22p^3_{3/2}2p^1_{1/2}2p^1_{3/2}\] | 4915.18 | 1.337E–24 | −0.707 | \[1s^22p^2_{3/2}2p^1_{1/2}\] | 6506.35 | 1.73E+11 | 0.073 |
| 34 | TR \[1s^22p^3_{3/2}2p^1_{1/2}2p^1_{3/2}\] | 4946.93 | 4.540E–23 | −0.871 | \[1s^22p^2_{3/2}2p^1_{1/2}\] | 6576.35 | 2.10E+12 | −0.699 |
| 35 | TR \[1s^22p^3_{3/2}2p^1_{1/2}2p^1_{3/2}\] | 4949.60 | 3.820E–23 | −0.709 | \[1s^22p^2_{3/2}2p^1_{1/2}\] | 6579.02 | 2.02E+11 | 0.073 |
| 36 | QR \[1s^22p^3_{3/2}2p^1_{1/2}2p^1_{3/2}\] | 4952.42 | 4.130E–26 | −0.990 | \[1s^22p^2_{3/2}2p^1_{1/2}\] | 6581.84 | 3.17E+11 | 0.000 |
| \( i \) | Process | Intermediate Excited State | \( E_{\text{res}} \) (eV) | \( S_{\text{tr}} \) (cm² eV) | \( A_2 \) | Final State | \( E_{\text{res}} \) (eV) | \( A_0^0 \) (s⁻¹) | \( \rho_{\text{tr}} \) |
|---|---|---|---|---|---|---|---|---|---|
| 37 | QR | \(| (1s^22p_{1/2}^1h_1/2)(2p_{3/2}^1h_1/2) | 4954.71 | 2.092E-23 | -0.899 | \(| l^2s^22p_{1/2}^1l_1/2 \rangle \) | 6584.12 | 1.68E+12 | -0.695 |
| 38 | QR | \(| (1s^22p_{1/2}^1h_1/2)(2p_{3/2}^1h_1/2) | 4958.11 | 1.286E-23 | -0.709 | \(| l^2s^22p_{1/2}^2l_1/2 \rangle \) | 6587.52 | 4.59E+11 | 0.073 |
| 39 | QR | \(| (1s^22p_{1/2}^1h_1/2)(2p_{3/2}^1h_1/2) \langle 0 | 4959.57 | 9.756E-23 | 0.000 | \(| l^2s^22p_{1/2}^2l_1/2 \rangle \) | 6550.75 | 2.67E+14 | 0.000 |
| 40 | TR | \(| (1s^22p_{1/2}^1h_1/2)(2p_{3/2}^1h_1/2) | 4973.99 | 2.888E-22 | -0.709 | \(| l^2s^22p_{1/2}^2l_1/2 \rangle \) | 6603.40 | 1.24E+11 | 0.073 |
| 41 | TR | \(| (1s^22p_{1/2}^1h_1/2)(2p_{3/2}^1h_1/2) | 4976.63 | 2.794E-24 | -0.734 | \(| l^2s^22p_{1/2}^2l_1/2 \rangle \) | 6567.81 | 4.79E+11 | 0.399 |
| 42 | TR | \(| (1s^22p_{1/2}^1h_1/2)(2p_{3/2}^1h_1/2) \langle 0 | 4985.60 | 2.466E-22 | 0.000 | \(| l^2s^22p_{1/2}^2l_1/2 \rangle \) | 6567.81 | 9.23E+11 | 0.544 |
| 43 | QR | \(| (1s^22p_{1/2}^1h_1/2)(2p_{3/2}^1h_1/2) | 4986.66 | 3.514E-22 | -0.784 | \(| l^2s^22p_{1/2}^2l_1/2 \rangle \) | 6577.84 | 2.81E+11 | 0.423 |

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Table 7
(Continued)

| $i$ | Process | Intermediate Excited State | $E_{\text{res}}$ (eV) | $S_{\text{tr}}$ (cm$^2$ eV) | $A^2$ | Final State | $E_{\text{res,fr}}$ (eV) | $A^0$ ($s^{-1}$) | $\sigma_{\text{tr}}$ |
|-----|---------|-------------------------------|------------------------|-----------------------------|------|-------------|--------------------------|-------------------|-----------------|
| 44  | QR      | [(1s$2s$2p$_{1/2}$)h/2(2p$_{3/2}$)h/2] | 4988.54                | 1.323E-22                   | −0.709 | [(1s$2s$2p$_{1/2}$)h/2] | 6516.28                | 1.31E+14          | 0.423           |
|     |         |                               |                        |                             |       | [(1s$2s$2p$_{1/2}$)h/2] | 6579.72                | 5.88E+11          | 0.073           |
|     |         |                               |                        |                             |       | [(1s$2s$2p$_{1/2}$)h/2] | 6562.33                | 4.30E+11          | 0.601           |
|     |         |                               |                        |                             |       | [(1s$2s$2p$_{1/2}$)h/2] | 6561.28                | 4.63E+10          | −0.430          |
|     |         |                               |                        |                             |       | [(1s$2s$2p$_{1/2}$)h/2] | 6559.17                | 7.40E+13          | 0.073           |
|     |         |                               |                        |                             |       | [(1s$2s$2p$_{1/2}$)h/2] | 6539.05                | 2.35E+14          | −0.430          |
|     |         |                               |                        |                             |       | [(1s$2s$2p$_{1/2}$)h/2] | 6534.79                | 5.89E+13          | 0.073           |
|     |         |                               |                        |                             |       | [(1s$2s$2p$_{1/2}$)h/2] | 6518.16                | 1.83E+12          | −0.430          |
| 45  | QR      | [(1s$2s$2p$_{1/2}$)h/2(2p$_{3/2}$)h/2] | 5001.97                | 1.159E-22                   | −0.709 | [(1s$2s$2p$_{1/2}$)h/2] | 6593.15                | 1.58E+12          | 0.073           |
|     |         |                               |                        |                             |       | [(1s$2s$2p$_{1/2}$)h/2] | 6575.76                | 4.80E+11          | 0.601           |
|     |         |                               |                        |                             |       | [(1s$2s$2p$_{1/2}$)h/2] | 6574.71                | 4.93E+11          | −0.430          |
|     |         |                               |                        |                             |       | [(1s$2s$2p$_{1/2}$)h/2] | 6572.60                | 1.42E+12          | 0.073           |
|     |         |                               |                        |                             |       | [(1s$2s$2p$_{1/2}$)h/2] | 6552.48                | 4.95E+12          | −0.430          |
|     |         |                               |                        |                             |       | [(1s$2s$2p$_{1/2}$)h/2] | 6548.22                | 5.23E+14          | 0.073           |
|     |         |                               |                        |                             |       | [(1s$2s$2p$_{1/2}$)h/2] | 6531.59                | 3.06E+14          | −0.430          |
| 46  | QR      | [(1s$2s$)h$_0$2p$_{3/2}$]     | 5011.65                | 4.428E-23                   | 0.000  | [(1s$2s$)h$_0$2p$_{3/2}$] | 6584.39                | 1.15E+12          | 0.000           |
|     |         |                               |                        |                             |       | [(1s$2s$)h$_0$2p$_{3/2}$] | 6541.27                | 4.24E+14          | 0.000           |
| 47  | TR      | [(1s$2s$)$^2$2p$_{3/2}$]     | 5051.42                | 5.625E-26                   | −0.854 | [(1s$2s$)$^2$2p$_{3/2}$] | 6534.09                | 3.12E+14          | −0.652          |
|     |         |                               |                        |                             |       | [(1s$2s$)$^2$2p$_{3/2}$] | 6522.60                | 1.14E+14          | 0.454           |
|     |         |                               |                        |                             |       | [(1s$2s$)$^2$2p$_{3/2}$] | 6511.87                | 3.11E+13          | −0.652          |
|     |         |                               |                        |                             |       | [(1s$2s$)$^2$2p$_{3/2}$] | 6541.93                | 2.37E+14          | 0.055           |
|     |         |                               |                        |                             |       | [(1s$2s$)$^2$2p$_{3/2}$] | 6530.77                | 1.53E+14          | 0.473           |
|     |         |                               |                        |                             |       | [(1s$2s$)$^2$2p$_{3/2}$] | 6530.44                | 9.83E+13          | −0.310          |
|     |         |                               |                        |                             |       | [(1s$2s$)$^2$2p$_{3/2}$] | 6519.72                | 3.63E+13          | 0.055           |
|     |         |                               |                        |                             |       | [(1s$2s$)$^2$2p$_{3/2}$] | 6490.50                | 1.79E+11          | 0.473           |
| 49  | QR      | [(1s$2p$_{1/2}$)2p$_{3/2}$]   | 5068.26                | 5.516E-24                   | 0.000  | [(1s$2p$_{1/2}$)2p$_{3/2}$] | 6539.43                | 4.59E+14          | 0.000           |
| 50  | QR      | [(1s$2p$_{1/2}$)2p$_{3/2}$]   | 5078.79                | 1.601E-23                   | −0.322 | [(1s$2p$_{1/2}$)2p$_{3/2}$] | 6720.17                | 9.71E+10          | 0.307           |
|     |         |                               |                        |                             |       | [(1s$2p$_{1/2}$)2p$_{3/2}$] | 6561.45                | 8.82E+12          | 0.034           |
|     |         |                               |                        |                             |       | [(1s$2p$_{1/2}$)2p$_{3/2}$] | 6550.29                | 9.86E+10          | 0.307           |
|     |         |                               |                        |                             |       | [(1s$2p$_{1/2}$)2p$_{3/2}$] | 6549.96                | 1.61E+13          | −0.181          |
|     |         |                               |                        |                             |       | [(1s$2p$_{1/2}$)2p$_{3/2}$] | 6539.23                | 6.92E+14          | 0.034           |
|     |         |                               |                        |                             |       | [(1s$2p$_{1/2}$)2p$_{3/2}$] | 6510.01                | 1.55E+14          | 0.307           |

Note. Initial (ground) state: [(1s$2s$2p$_{1/2}$)h/2].
(This table is available in its entirety in machine-readable form.)
| $i$ | Process | Intermediate | Allowed State | $E_{\text{ex}}$ (eV) | $g^{\text{DR}}$ (cm$^2$ eV$^{-1}$) | $A_2$ | Final State | $E_{\text{ex}}$ (eV) | $A_{\text{DR}}^\text{T}$ (s$^{-1}$) | $p_{\text{DR}}$ |
|-----|---------|--------------|---------------|----------------|----------------|-------|-------------|----------------|----------------|--------|
| 16  | DR      | $|1s^22p_{1/2}^2(2p_{3/2}^1)_{2}h_{1/2}$ | 4925.71 | 3.800E−20 | −1.069 | $[1s^22p_{1/2}^2(2p_{3/2}^1)_{2}h_{1/2}]$ | 6497.29 | 2.04E+14 | 0.500 |
| 17  | DR      | $[(1s^22p_{1/2})_{h}(2p_{3/2})_{2}h_{1/2}]$ | 4935.53 | 9.324E−21 | −1.000 | $[1s^22p_{1/2}^2(2p_{3/2}^1)_{2}h_{1/2}]$ | 6507.10 | 2.42E+14 | −0.750 |
| 18  | DR      | $|1s^22p_{1/2}^2(2p_{3/2}^1)_{2}h_{1/2}$ | 4937.75 | 7.103E−21 | 0.000 | $[1s^22p_{1/2}^2(2p_{3/2}^1)_{2}h_{1/2}]$ | 6509.32 | 2.28E+14 | 0.000 |
| 19  | TR      | $|1s^22p_{1/2}^2(2p_{3/2}^1)_{2}h_{1/2}$ | 4952.23 | 1.715E−20 | −1.000 | $[1s^22p_{1/2}^2(2p_{3/2}^1)_{2}h_{1/2}]$ | 6523.81 | 5.98E+12 | −0.750 |
| 20  | TR      | $[(1s^22p_{1/2})_{h}(2p_{3/2}^1)_{2}h_{1/2}]$ | 4956.72 | 3.107E−22 | −1.069 | $[1s^22p_{1/2}^2(2p_{3/2}^1)_{2}h_{1/2}]$ | 6528.29 | 6.93E+11 | 0.500 |
| 21  | TR      | $[(1s^22p_{1/2})_{h}(2p_{3/2}^1)_{2}h_{1/2}]$ | 4962.19 | 5.244E−21 | 0.000 | $[1s^22p_{1/2}^2(2p_{3/2}^1)_{2}h_{1/2}]$ | 6531.75 | 3.55E+14 | 0.000 |
| 22  | TR      | $[(1s^22p_{1/2})_{h}(2p_{3/2}^1)_{2}h_{1/2}]$ | 4963.99 | 9.444E−21 | −1.000 | $[1s^22p_{1/2}^2(2p_{3/2}^1)_{2}h_{1/2}]$ | 6535.56 | 4.02E+12 | −0.750 |
| 23  | QR      | $|1s^22p_{1/2}^1(2p_{3/2})_{1/2}$ | 4980.27 | 3.971E−23 | 0.000 | $[1s^22p_{1/2}^2(2p_{3/2}^1)_{2}h_{1/2}]$ | 6551.84 | 8.35E+10 | 0.000 |
| 24  | TR      | $[(1s^22p_{1/2})_{h}(2p_{3/2})_{2}2p_{3/2}^1h_{1/2}]$ | 5021.40 | 3.038E−26 | −1.069 | $[1s^22p_{1/2}^2(2p_{3/2}^1)_{2}h_{1/2}]$ | 6500.12 | 3.05E+14 | −0.889 |
Table 8  
(Continued)

| \(i\) | Process | Intermediate Excited State | \(E_{\text{res}}\) (eV) | \(S^\text{th} \) (cm\(^2\) eV) | \(A_2\) | Final State | \(E_{\text{res}}\) (eV) | \(A^\text{th} \) (s\(^{-1}\)) | \(p_{\text{th}}\) |
|---|---|---|---|---|---|---|---|---|
| 25 | TR | \(|(1s2s)\,2p_{1/2}^3\,2p_{3/2}^1h_1/2\) | 5028.92 | 6.737E–23 | –1.000 | \([1s^2(2s2p_{1/2})h\,2p_{3/2}^1\,b_1/2]\) | 6436.97 | 3.39E+11 | 0.500 |
| 26 | QR | \(|(1s2s)\,2p_{1/2}^3\,2p_{3/2}^4h_1/2\) | 5035.42 | 1.925E–23 | 0.000 | \([1s^2(2s2p_{1/2})h\,2p_{3/2}^4\,b_1/2]\) | 6505.74 | 3.76E+14 | 0.000 |
| 27 | TR | \(|(1s2s)\,2p_{1/2}^3\,2p_{1/2}^1h_1/2\) | 5060.14 | 1.790E–22 | –1.000 | \([1s^2(2s2p_{1/2})h\,2p_{1/2}^1\,b_1/2]\) | 6538.86 | 4.28E+12 | 0.143 |
| 28 | TR | \(|(1s2s)\,2p_{1/2}^3\,2p_{1/2}^1h_1/2\) | 5063.48 | 8.992E–23 | 0.000 | \([1s^2(2s2p_{1/2})h\,2p_{1/2}^1\,b_1/2]\) | 6531.06 | 1.76E+12 | 0.000 |
| 29 | QR | \(|(1s2s)\,2p_{1/2}^3\,2p_{3/2}^4h_1/2\) | 5079.02 | 1.037E–22 | –1.000 | \([1s^2(2s2p_{1/2})h\,2p_{3/2}^4\,b_1/2]\) | 6546.61 | 2.46E+11 | 0.600 |
| 30 | QR | \(|(1s2s)\,2p_{1/2}^3\,2p_{3/2}^4h_1/2\) | 5086.05 | 1.223E–23 | 0.000 | \([1s^2(2s2p_{1/2})h\,2p_{3/2}^4\,b_1/2]\) | 6556.37 | 6.34E+10 | 0.000 |
| 31 | QR | \(|1s^22p_{3/2}^4h_1/2\) | 5173.74 | 3.187E–24 | 0.000 | \([1s^2(2s2p_{3/2})h\,2p_{3/2}^4\,b_1/2]\) | 6500.32 | 4.48E+14 | 0.000 |

Note. Initial (ground) state: \([1s^22s^22p_{3/2}^2\,b_0]\).  
(This table is available in its entirety in machine-readable form.)
Table 9
Fe XX Theoretical Data

| i | Process | Intermediate Excited State | \(E_{\text{res}}\) (eV) | \(\xi^\text{DR}\) (cm² eV) | \(A^\text{2}\) | Final State | \(E_{X-ray}\) (eV) | \(A^\text{2}'\) (s⁻¹) | \(p^\text{DR}\) |
|---|---------|-----------------------------|-------------------------|--------------------------|----------------|----------------|------------------|----------------|----------------|
| 11 | DR | \([1s^22p^4_{1/2}^32p^3_{1/2}]_l\] | 5010.46 | 3.597E–21 | -0.100 | \([1s^22p^4_{3/2}^32p^3_{1/2}]_l\] | 6466.76 | 2.97E+14 | 0.348 |
| 12 | DR | \([1s^22p^4_{3/2}^32p^3_{1/2}]_l\] | 5017.98 | 1.721E–21 | 0.143 | \([1s^22p^4_{3/2}^32p^3_{1/2}]_l\] | 6474.28 | 2.26E+14 | 0.059 |
| 13 | TR | \([1s^22p^4_{1/2}^32p^3_{1/2}]_l\] | 5026.69 | 4.567E–23 | 0.000 | \([1s^22p^4_{3/2}^32p^3_{1/2}]_l\] | 6471.95 | 4.37E+14 | 0.000 |
| 14 | TR | \([1s^22p^4_{1/2}^32p^3_{1/2}]_l\] | 5036.69 | 1.268E–21 | -0.496 | \([1s^22p^4_{3/2}^32p^3_{1/2}]_l\] | 6492.99 | 7.99E+12 | 0.059 |
| 15 | TR | \([1s^22p^4_{3/2}^32p^3_{1/2}]_l\] | 5127.18 | 7.243E–24 | 0.101 | \([1s^22p^4_{3/2}^32p^3_{1/2}]_l\] | 6483.74 | 6.00E+11 | 0.723 |
| 16 | TR | \([1s^22p^4_{3/2}^32p^3_{1/2}]_l\] | 5156.16 | 1.268E–23 | 0.000 | \([1s^22p^4_{3/2}^32p^3_{1/2}]_l\] | 6471.68 | 6.58E+14 | 0.059 |

Note. Initial (ground) state: \([1s^22p^6_{3/2}^22p^5_{1/2}]_l\].
(This table is available in its entirety in machine-readable form.)

Table 10
Fe XIX Theoretical Data

| i | Process | Intermediate Excited State | \(E_{\text{res}}\) (eV) | \(\xi^\text{DR}\) (cm² eV) | \(A^\text{2}\) | Final State | \(E_{X-ray}\) (eV) | \(A^\text{2}'\) (s⁻¹) | \(p^\text{DR}\) |
|---|---------|-----------------------------|-------------------------|--------------------------|----------------|----------------|------------------|----------------|----------------|
| 13 | DR | \([1s^22p^4_{1/2}^32p^3_{1/2}]_l\] | 5080.14 | 3.968E–21 | 0.000 | \([1s^22p^4_{3/2}^32p^3_{1/2}]_l\] | 6434.99 | 4.26E+14 | 0.000 |

Note. Initial (ground) state: \([1s^22p^6_{3/2}^22p^5_{1/2}]_l\].
(This table is available in its entirety in machine-readable form.)

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