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Atomic Data for Hollow Atom Production by High Brightness X-Rays and Its Applications

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Abstract

We perform a theoretical study for x-ray emission from the inner-shell states and hollow atoms of S and Fe ions excited by black-body radiation of x-ray sources. We discuss the measurement of x-ray temperature by x-ray emission from the inner-shell excited states hollow atoms. These will be useful for x-ray astrophysics.

Keywords:

hollow atom, inner-shell excited state, inner-shell ionization, high intensity x-ray source, x-ray temperature, x-ray astrophysic

1. Introduction

Since the interaction of atoms or ions with high brightness x-ray sources often takes place in the universe, high brightness x-ray sources play an important role in x-ray astrophysics. Recently, 'photo-ionized plasmas' have received attention due to x-ray binary stars such as Cyg X-3 [1,2] where many atoms or ions transfer from a star to a black hole via accretion by gravitation because the star is located near a black hole. On the other hand, high intensity x-rays are emitted from the black hole. After ions are inner-shell photo-ionized by x-rays, characteristic x-rays are emitted from inner-shell excited states (IES) and hollow atoms (HA). Until now, only the Ly_α, He_α, and K_α x-rays of heavy ions such as Si, S, and Fe have been discussed because of the lack of high-resolution x-ray detector in the satellites 'Chandra' or 'Asca' [1,2]. We expect that x-ray emission from inner-shell excited states will become important for the analysis of the mechanism of x-ray binary stars because the satellite 'Astro-E2', which has an x-ray detector with a higher resolving power, will be launched in future [3]. In order to understand x-ray binary stars, we should know x-ray temperatures (T_B) of the x-ray sources.

Moribayashi *et al.* [4] have found a new characteristic for the production of IES and HA by high-intensity short-pulse x-rays. They have devised a new x-ray laser scheme using hollow atoms, which originate from inner-shell ionization x-ray lasers pumped by very high intensity x-rays. In this case, inner-shell ionization processes surpass any other atomic processes such as auto-ionization and radiation transition processes. As a result, multiple-inner-shell ionizations predominate, leading to the formation of HAs. On the contrary, for an ordinary x-ray source, since auto-ionization, or radiation transition processes are much faster than photo-ionized processes, further inner-shell ionizations from IES seldom occur. From this characteristic, we predict that x-ray emissions from HA inform us of the x-ray intensities of high intensity x-ray sources. In our previous papers, we treated x-ray emissions from IES of Fe ions [5] and HA of Si [6]. We have shown the shape of an x-ray spectrum would tell us T_B [5]. Further, we have found that the x-ray emission from HA may be used for the measurement of intensities of high-intensity short-pulse x-ray sources produced by high-intensity lasers [6]. Here, we treat x-ray emissions from HA in addition to those from IES of Ne-like Fe ions in order to understand the production processes of photo-ionized plasmas and to propose a method of analysis of the x-ray spectra measured by satellites in the cosmos.

2. Atomic processes

We calculate x-ray spectra emitted from IES and HA of Fe ions in black-body radiation. The initial state of ions is assumed to be the ground state of Ne-like ion. We consider photo-ionization (PI), radiative transition (A_r), and auto-ionization (A_a) processes. We have calculated the atomic data using Cowan's code [7]. In a

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real simulation, we have adapted the atomic data averaged over the quantum numbers of spin angular momentum (S), orbital angular momentum (L), and total angular momentum (J) as follow. The transition energy (E_{av}) and the atomic data for A_a and A_r are given by,

$$E_{av}(1s2s^2 2p^6 \rightarrow 1s^2 2s^2 2p^5) = \frac{\sum_{S,L,J} g_{SLJ} \sum_{S',L',J'} A_{rSLJS'L'J'} E_{SLJS'L'J'}}{\sum_{S,L,J} g_{SLJ} \sum_{S',L',J'} A_{rSLJ,S'L'J'}}, \quad (1)$$

and

$$A_{av} = \frac{\sum_{S,L,J} g_{SLJ} A_{SLJ}}{\sum_{S,L,J} g_{SLJ}}, \quad (2)$$

respectively, where g_{SLJ} expresses the statistical weight atoms and the transition of $Ar_{SLJS'L'J'}$ and $E_{SLJS'L'J'}$ is $1s2s^2\ 2p^6\ {}^SL_J \rightarrow 1s^2\ 2s^2\ 2p^5\ {}^{S'}L'_{J'}$. The reason why we apply Eq. (1) is as follows. If we employ the direct averaged values such as in Eq. (2), the energies of forbidden transitions and transitions with very small values of Ar are included. In order to remove such transition energies, we apply the exception values for photo emission, that is, the inclusion of the effect of A_r. Table I and II list the rates for $A_{r\,av}$, and $A_{a\,av}$ processes of IES and HA of Fe ions, respectively.

With these atomic rates, the population dynamics of the various atomic states may be investigated by the following rate equations:

$$\frac{dP_k}{dt} = -\alpha_k P_k + \sum_{m(>k)} \beta_{mk} P_m, \quad (3)$$

where P_k, α_k and β_{mk} are the population, decay constant in the k'th state, and the transition rate from the m state to k state, respectively. The photon number (Ph) is given by

$$Ph_k = \int_0^\infty P_k A_r dt. \quad (4)$$

3. Results and discussions

Figure 1 shows x-ray intensities from HA of Fe ions as a function of wavelengths listed in Table I, respectively. The marks in the figures correspond to T_B (500 eV–10 keV) of the black body radiation. As shown in Ref.[5], the x-ray intensities from IES of F-like ions ($1s2s^2\ 2p^6$) are much smaller than those from the He-like ions ($1s2p$) at T_B < 3 keV, while at $T_B \geq$ 3 keV, both intensities become almost the same. From the results, we pointed out that the spectra may give us an information of T_B. Here we show that the x-ray emission from hollow atoms may give us information about x-ray sources and this may be useful for the analysis of x-ray spectra in x-ray binary stars as well as the measurement

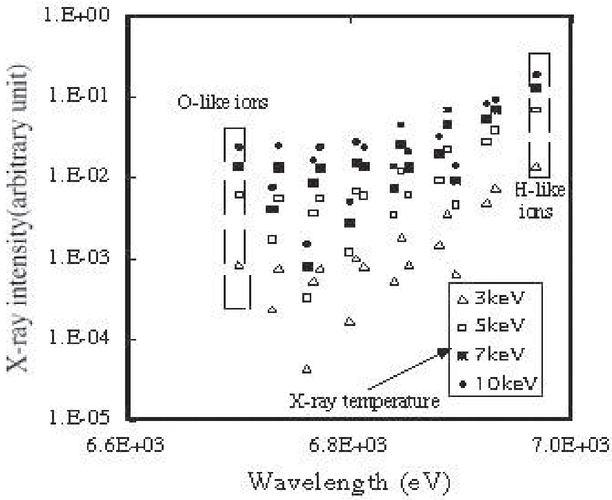

Fig. 1 X-ray emission from HA of Fe ions vs. wavelength listed in Table II for various x-ray temperatures. Enclosed by dashed lines are the x-ray emissions from $2s^2 2p^6$ (left side) and 2p (right side).

of the x-ray intensity (temperature) of high brightness x-ray sources. The x-ray intensities from HA depend on T_B more strongly than those from IES. There is a big different between the x-ray intensities at T_B = 1 keV and 3 keV. This comes from the following fact: Since A_a or A_r is much larger than PI for T_B < 3 keV, the decay processes for inner-shell excited states dominate. On the other hand, for large $T_B \geq$ 3 keV, PI overcomes A_a or A_r. As a result, a lot of hollow atoms are produced through process (3) from IES [4].

Figure 2 shows the ratios of x-ray intensities from IES to those from HA for Fe ions. The states of IES (HA) correspond to $1s2s^2 2p^6 (2s^2 2p^6)$ and, $1s2s^2 2p^2 (2s^2 2p^2)$. We found that the ratios increase as the number of the outer electrons becomes smaller. This

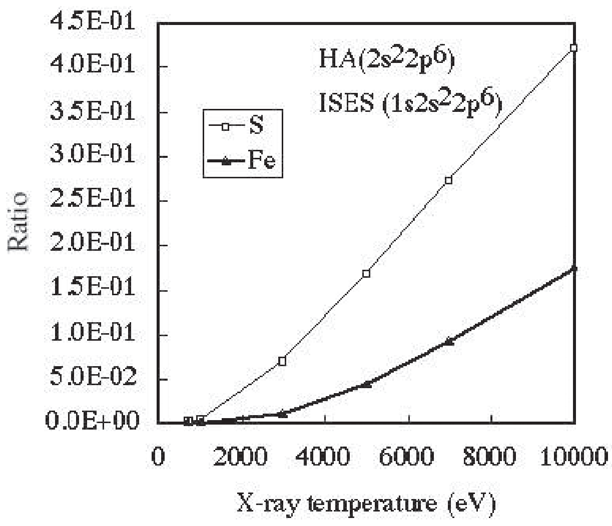

Fig. 2 The ratio of the x-rays from HA ($2s^2 2p^6$) with those from IES ($1s2s^2 2p^6$) for S and Fe.

Table I Atomic data for wavelengths, A_r, and A_a from the IES of Fe. They are used in Eqs. (1) and (2).

IES	wavelength (cm^{-1})	wavelength (eV)	Ar (1/s)	Aa $(2p^2)^{-1}$ (1/s)	Aa $(2s2p)^{-1}$ (1/s)	Aa $(2s^2)^{-1}$ (1/s)
$1s\ 2s^22p^6$	5.193E+04	6.439E+03	6.10E+14	3.13E+14	1.53E+14	4.97E+13
$1s\ 2s^22p^5$	5.218E+04	6.469E+03	5.22E+14	3.64E+14	1.69E+14	6.26E+13
$1s\ 2s^22p^4$	5.247E+04	6.506E+03	4.33E+14	2.32E+14	1.42E+14	6.50E+13
$1s\ 2s^22p^3$	5.278E+04	6.544E+03	3.37E+14	1.23E+14	1.12E+14	6.76E+13
$1s\ 2s^22p^2$	5.310E+04	6.584E+03	2.33E+14	4.36E+13	7.77E+13	7.00E+13
$1s\ 2s^2\ 2p$	5.349E+04	6.631E+03	2.33E+14	–	4.06E+13	7.27E+13
$1s\ 2s\ 2p^6$	5.214E+04	6.464E+03	6.25E+14	5.37E+14	1.01E+14	–
$1s\ 2s\ 2p^5$	5.243E+04	6.500E+03	5.40E+14	3.81E+14	8.89E+13	–
$1s\ 2s\ 2p^4$	5.273E+04	6.538E+03	4.48E+14	2.43E+14	7.44E+13	–
$1s\ 2s\ 2p^3$	5.305E+04	6.577E+03	3.48E+14	1.29E+14	5.84E+13	–
$1s\ 2s\ 2p^2$	5.338E+04	6.618E+03	2.41E+14	4.56E+13	4.06E+13	–
1s 2s 2p	5.372E+04	6.661E+03	1.66E+14	–	2.12E+13	–
$1s\ 2p^6$	5.238E+04	6.494E+03	6.46E+14	5.64E+14	–	–
$1s\ 2p^5$	5.269E+04	6.532E+03	5.58E+14	4.00E+14	–	–
$1s\ 2p^4$	5.300E+04	6.571E+03	4.63E+14	2.55E+14	–	–
$1s\ 2p^3$	5.333E+04	6.611E+03	3.60E+14	1.35E+14	–	–
$1s\ 2p^2$	5.367E+04	6.654E+03	2.49E+14	4.75E+13	–	–
1s 2p	5.402E+04	6.698E+03	2.62E+14		–	–

Table II Atomic data for wavelengths, A_r, and A_a from HA.

HA	wavelength (cm^{-1})	wavelength (eV)	Ar (1/s)	Aa $(2p^2)^{-1}$ (1/s)	Aa $(2s2p)^{-1}$ (1/s)	Aa $(2s^2)^{-1}$ (1/s)
$2s^22p^6$	5.404E+04	6.700E+03	1.38E+15	1.12E+15	4.34E+14	1.33E+14
$2s^22p^5$	5.433E+04	6.736E+03	1.19E+15	7.89E+14	3.79E+14	1.38E+14
$2s^22p^4$	5.463E+04	6.773E+03	9.83E+14	5.02E+14	3.17E+14	1.43E+14
$2s^22p^3$	5.495E+04	6.812E+03	7.63E+14	2.66E+14	2.48E+14	1.48E+14
$2s^22p^2$	5.528E+04	6.853E+03	5.26E+14	9.36E+13	1.73E+14	1.54E+14
$2s^22p$	5.562E+04	6.895E+03	2.72E+14	–	8.92E+13	1.59E+14
$2s2p^6$	5.428E+04	6.730E+03	1.42E+15	1.17E+15	2.27E+14	–
$2s2p^5$	5.458E+04	6.767E+03	1.23E+15	8.28E+14	1.98E+14	–
$2s2p^4$	5.489E+04	6.806E+03	1.02E+15	5.27E+14	1.65E+14	–
$2s2p^3$	5.522E+04	6.846E+03	7.88E+14	2.78E+14	1.29E+14	–
$2s2p^2$	5.556E+04	6.888E+03	5.43E+14	9.72E+13	8.98E+13	–
2s2p	5.591E+04	6.931E+03	2.81E+14	–	4.66E+13	–
$2p^6$	5.454E+04	6.761E+03	1.47E+15	1.22E+15	–	–
$2p5^5$	5.484E+04	6.800E+03	1.27E+15	8.66E+14	–	–
$2p^4$	5.517E+04	6.839E+03	1.05E+15	5.49E+14	–	–
$2p^3$	5.550E+04	6.881E+03	8.13E+14	2.90E+14	–	–
$2p^2$	5.585E+04	6.924E+03	5.61E+14	1.02E+14	–	–
2p	5.620E+04	6.968E+03	2.90E+14	–	–	–

comes from the fact that A_a and A_r become larger with respect to the increase in the number of the outer electrons (see Tables I and II). The x-ray emission from the $2s^2\ 2p^2$state (HA) becomes comparable (the ratio > 0.5) with that from the $1s2s^22p^2$(IES) for $T_B \geq 5$ keV and 10 keV, respectively. On the other hand, in the case of the $1s2s^22p^6$ and $2s^2\ 2p^6$, he same feature occurs for $T_B > 10$ keV in S ions. Thus, when we measure the x-ray emission from IES and HA for various states of various ions, we may gain information on T_B of x-ray sources.

4. Conclusions

We study x-ray emission from the inner-shell states and hollow atoms of Fe ions excited by high intensity x-ray sources. We found that the ultrafast inner-shell ionization processes, which depend on the intensity or temperature of x-ray sources, would produce hollow atoms. In other words, the hollow atom production is sensitive to the x-ray intensity or temperature. The comparable intensities of x-rays emitted from the $2s^2\ 2p^2$state (hollow atom) with those from the inner-shell excited states (the $1s2s^22p^2$) indicate 10 keV. This may be useful for the characterization of x-ray binary stars.

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