Theoretical Analysis of $3d$ Electron Correlation Effects in $4p$-$4d$ Lines for Nickel-like X-ray Laser Emissions

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Since the first demonstration of of a strong x-ray laser emission in 1984[1, 2], electron collision x-ray lasers that use Ne-like and Ni-like ions of various elements in laser produced plasmas have been developed[3, 4, 5, 6]. The lasing wavelengths are in the range of 90 nm[7] to 3 nm[3]. The soft-xray lasing from Ni-like ions involves higher atomic-number elements when compared with the Ne-like species. Once the lasing can be observed, the lasing line is a very good tool for diagnostics of radiation processes and the population distribution in a hot dense plasma. This is because the population inversion causes exponential amplification, while the intensity of a non-lasing line is at most proportional to the product of Einstein A coefficient and the upper level population. Furthermore, the lasing lines are hardly de-tuned or broadened by plasma environment in their wavelengths, because the one path lasing requires the exact match of energies in optical transitions of ions.

The wavelengths of the lasing lines are well coincides with those of the optical emissions from isolated and unperturbed atomic ions. Therefore, soft x-ray lines from this type of Ni-like lasers are quite a good workbench of a very sophisticated precise calculation of the transition energies between well defined configurations in highly-charged high atomic-number elements.

Recently, Daido et al[8] carried out a precise wavelength measurement for $J = 0 - 1$ lasing transitions for the elements: Nd, Sm, Gd, Dy, Ho, Yb, Hf, and Ta, of which atomic numbers are ranging from 60 to 73. The measured wavelengths are compared with the results of precise atomic structure calculation using an unpublished version of GRASP(General Purpose Relativistic Atomic Structure Program)[9] family codes, GRASP2[10]. They obtained a complete agreement between the theory and experiment within the experimental accuracy.

They realized that any empirical artificial-energy-shifts were not necessarily be introduced in their theory to obtain an agreement with experiment, which, Scofield and MacGowan[11] have introduced in their analysis of the data.

In the present paper, we extend our theoretical calculation using GRASP92[12] and RATIP (Relativistic Atomic Transitions and Ionization Properties)[13]. Although the difference of GRASP92 from its older version is basically restricted to the user interfaces in the practical procedure of calculations, the newer version has a great advantage in the evaluation of electron correlations. Using GRASP92, we could take into account the electron correlations in somewhat automatic manner.

The transitions in Ni-like soft x-ray laser are $3d^9 4p[5/2,3/2]_1 - 3d^9 4d[3/2,3/2]_0$ (for longer wavelength lines) and $3d^9 4p[3/2,1/2]_1 - 3d^9 4d[3/2,3/2]_0$ (for shorter wavelength lines). We should note that the $3d$ sub-shell are kept open throughout the transitions. And, further on, we must note that the correlations between the $3d$ and $4d$ orbitals are much stronger than between the $3d$ and $4p$ orbitals. We, therefore, have to take into account the inter as well as intra d sub-shell electron correlations properly.

Our preliminary calculation has suggested that these correlation energies coincides to the empirical artificial-energy-shifts employed by Scofield and MacGowan[11].

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