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SENSING THE DE FONTENAU-AUX-ROSES TOKAMAK PLASMA PARAMETERS BY MEANS X-RAY THEORETICAL SPECTROSCOPY METHOD: NEW ADVANCED SCHEME

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Abstract

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A new advanved high-accuracy theoretical spectroscopy scheme is developed and used for sensing and diagnostics the de Fontenau-aux-Roses tokamak (TFR) plasma parameters. New numerical results on sensing the tokamak plasma parameters (electron temperature etc.) and wavelengths of satellite spectrum for the He-like ions from Ar, Sc, V are presented and are in a excellent agreement with the TFR measurements data.

Key words: sensing tokamak plasma, high-accuracy spectroscopy scheme.

Резюме

ДЕТЕКТУВАННЯ ПАРАМЕТРІВ ПЛАЗМИ ТОКАМАКА DE FONTENAU-AUX-ROSES НА ОСНОВІ ТЕОРЕТИЧНОГО МЕТОДУ РЕНТГЕНІВСЬКОЇ СПЕКТРОСКОПІЇ: НОВА СХЕМА

Е. П. Гурницька

Нова високоточна теоретична схема рентгенівської спектроскопії використана у задачі детектування і діагностики параметрів плазми токамака de Fontenau-aux-Roses (TFR). Наведені нові дані параметрів плазми токамака та довжин хвиль переходів у сателітних спектрах Не-подібних іонів Ar,Sc,V,які знаходяться у добрій згоді з даними TFR вимірювань.

Ключові слова: детектування плазми токамака, високоточна спектроскопічна схема.

Резюме

ДЕТЕКТИРОВАНИЕ ПАРАМЕТРОВ ПЛАЗМЫ ТОКАМАКА DE FONTENAU-AUX-ROSES НА ОСНОВЕ ТЕОРЕТИЧЕСКОГО МЕТОДА РЕНТГЕНОВСКОЙ СПЕКТРОСКОПИИ: НОВАЯ СХЕМА

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Новая высокоточная теоретическая схема рентгеновской спектроскопии использова-на в задаче детектирования и диагностики параметров плазмы токамака de Fontenau-aux-Roses (TFR). Приведены новые данные параметров плазмы, длин волн переходов в сателлит-ных спектрах Не-подобных ионов Ar,Sc,V, которые находятся в хорошем согласии с данными TFR измерений.

Ключевые слова: детектирование плазмы токамака, высокоточная спектроскопическая схема.

In last years it is of a great interest the experimental and theoretical studying the ion levels lifetimes and developing the new methods of their determination (c.f. [1-18]). Similar interest is also stimulated by importance of this information for correct determination of the characteristics for plasma in thermonuclear (tokamak) reactors, searching new mediums for X-ray range lasers. The X-ray laser problem has stimulated a great number of papers devoting to development of theoretical methods for the modelling the elementary processes in a collisionally pumped plasma. There is a hope to find lasing effects on the transitions in the Ne-, Cl- Ni-like plasma. A great progress in development of laser technique, tokamaks and accelerators experiments resulted to a new class of problems. Recently an excellent experiment employed a heavy ion storage ring (TSR at Heildelberg) [1]. There are measured and theoretically calculated the lifetimes for some levels in the ions of Fe, Co, Ni,Cu. There was given an analysis of the heavy ion storage ring determination of the lifetimes in the cobalt and nickel ions and present the results of our theoretical calculation within new scheme [8,9]. Unique possibilities are given by studying multicharged speactra in the Tokamak plasma [1-4]. The electron temperatures and particle confinement times in tokamak plasmas permit the ionization of the heavy impurity elements up to the He-like (eventually H-like) charge state. High resolution X-ray spectroscopy of the line emission of these ions is a powerful technique for definition of the electron and ion temperatures T_e and T_i , the macroscopic plasma movement and dynamics of the plasma impurity transport. In ref. [3] there are presented the rresults of the experimental measurements by means of Bragg crystal spectrometers, high quality spectral analysis for diagnostic-relevant impurities at several large tokamaks: Ti^{20+} and Fe^{24+} (Princeton Large Torus), Cr^{22+} (tokamak de Fontenau-aux-Roses=TFR) etc [1-4]. The TFR measurements of the plasma parameters and wavelengths, atomic characteristics of satellite spectrum of the He-like ions from Ar^{16+} to Mn^{23} (Ar, Sc, V,Cr, Mn) are accurately carried out and presented in ref. [3]. New scheme of theretical spectroscopic calculation has been presented in ref. [6] and used in studying the cited spectra.

In ref. [18-23] two new consistent QED versions for calculations of the spectroscopic characteristics of the multicharged ions in plasma have been developed. Here we use these high resolution X-ray theoretical spectroscopy scheme [14,15] for sensing and diagnostics the tokamak plasma parameters. We present high-accuracy numerical illustrations regarding sensing the tokamak plasma parameters (electron temperature etc.) and calculation results for wavelengths atomic characteristics of satellite spectrum of the He-like ions from Ar^{16+} to Mn^{23} , which are in an excellent agreement with the TFR measurements and significantly more accutate in comparison with theoretical data [3,6].

Let us present the key moments of the new consistent QED perturbation theory (PT) version for calculations of spectra of the multicharged ions in plasma, which have been developed in ref. [14-18]. It bases on the gauge invariant QED energy approach to construsction of the relatifictic functions basis's [10,13] and using the Green's function method for accounting of the complex exchange-correlation, radiation and others corrections. Our version allows to take into account the QED, radiative effects. Let us also note that, for example, methods [3,6] do not allow to account in the entire degree the correlation effects and the QED effects. The procedure for calculation is constructed by the standard way. We start from the electron wave functions zeroth basis, which is found from the Dirac equation solution with the general potential. The latter includes the core ab initio potential, electric, polarization potentials of nucleus (the gaussian form for charge distribution in the nucleus is used). One can write the DF-like equations for a two and three-electron system $1s^2nlj$ (He- and Li-like spectra). Further formally they fall into one-electron Dirac equations for the orbitals $1s,nlj$ with potential: $V(r)=2V(r|1s)+V(r|nlj)+V_{ex}+V(r|R)$. This potential includes the electrical and polarization potentials of the nucleus. The part V_{ex} accounts for exchange inter-electron interaction. The main exchange effect will be taken into account if in the equation for the $1s$ orbital we assume $V(r)=V(r|1s)+V(r|nlj)$ and in the equation for the nlj orbital $V(r)=2V(r|1s)$. The core electron density is defined by iteration algorithm within the Glushkov-Ivanov gauge invariant QED procedure [10,13]. All correlation corrections of the PT second and high orders (electrons screening, particle-hole interaction etc.) are accounted for by the Green's function method (see details in ref. [16-18]). This is a main differing in comparison with scheme [6]. Procedure for approximative acocount of the QED efects is in details is descibed in ref.[23]. Other aspects of the procedure, including definition of the matrix elements of the QED PT with effective account of the exchange-correlation effects are presented in refs. [14-18].

As in ref.[3,6], the spectral lines we are concerned with in this paper the characteristic lines w,x,y,z, ($1s^{21}S_0$-$1s2p\ ^1P_1$, $^3P_2$, $^3P_1$, $1s2s\ ^3S_1$) of the He-like ion and associated satellte lines of the Li-like type $1s^22l$-$1s2l2p$. They are produced by dielectronic recombination to, or inner-shell excitation of, the lithium-like ion. The tables1 and 2 give the most prominent He-like and satellite Li-like lines. According to ref.[3], with respect to the intensities of the spectral lines the line, say, q (table 1) is mainly due to collisional excitation of the Li-like ion. Neglecting recombination and cascade effect for w, the ratio of the local emissivities of these lines is $\varepsilon_q/\varepsilon_w \sim 2/3n_{Li}/n_{He}$, where n_{Li} and n_{He} are the densities of the Li- and He-like ions, respectively (from optically thin plasmas the ratio of the line-of-sight integrated emissivities is observed) [2,3]. For a satellite (s) line which is excited mainly by dielectronic recombination from the He-like to the Li-like ion it can be written: $\varepsilon_q/\varepsilon_w = F_1(s, T_e)F_2^*(s)/C_w(T_e)$, $F_1(s, T_e)=(1,65\cdot 10^{-22})T_e^{-3/2}exp(-E_s/T_e)$, where E_s and T_e are in eV; $F_2^*(s)$ is a line-specific intensity factor (look table 1); E_s is the difference in energy of the satellite state in the recombined ion and the ground state in the recombining ion; $C_w(T_e)$ is the rate coefficient (in cm^3/s) for collisional excitation of line w [2,3,6]. The $\varepsilon_q/\varepsilon_w$ ratio is usually used as a diagnostic for electron temperature (for the Maxwellian electron velocity distribution). According to ref. [3,6], the $\varepsilon_q/\varepsilon_w$ ratio increases very rapidly with increasing nuclear charge of the ion due to mainly Z^4 dependence of the radiative transition probability A_r in the expansion $F_2^*(s)$. It is instructive to make use of a z-scaling law for the $C_w(T_e)$ of two elements A and B as $C_w^A(T_e)=\gamma^{3/2}C_w^B(\gamma^2, T_e)$ with where $\gamma=(Z_B-0,5)/(Z_A-0,5)$.

Table 1

Calculated wavelengths and satellite intensity factors (λ in Å; F_2^* in 10^{13} s^{-1}): Ar

Line	Array	λ [3]	λ[6]	λ (present)	F_2^*
w	$1s2p^1P_1$ - $1s^{21}S_0$	3,9457	3,9461	3,9459	-
x	$1s2p^3P_2$ - $1s^{21}S_0$	3,9632	3,9636	3,9633	-
s	$1s2s2p^2P_{3/2}$ - $1s^22s\,^2S_{1/2}$	3,9648	3,9652	3,9650	1,78
t	$1s2s2p^2P_{1/2}$ - $1s^22s\,^2S_{1/2}$	3,9660	3,9665	3,9662	3,34
m	$1s2p^{2\,2}S_{1/2}$ - $1s^22p\,^2P_{3/2}$	3,9629	3,9634	3,9631	2,58
y	$1s2p^3P_1$ - $1s^{21}S_0$	3,9671	3,9674	3,9672	-
q	$1s2s2p^2P_{3/2}$ - $1s^22p\,^2S_{1/2}$	3,9784	3,9787	3,9785	0,97
k	$1s2p^{2\,2}D_{3/2}$ - $1s^22p\,^2P_{1/2}$	3,9875	3,9878	3,9876	16,61
r	$1s2s2p^2P_{1/2}$ - $1s^22s\,^2S_{1/2}$	3,9808	3,9811	3,9810	2,74
a	$1s2p^{2\,2}P_{3/2}$ - $1s^22p\,^2P_{3/2}$	3,9831	3,9835	3,9833	3,46
j	$1s2p^{2\,2}D_{5/2}$ - $1s^22p\,^2P_{3/2}$	3,9917	3,9923	3,9919	22,89
z	$1s2sp\,^3S_1$ - $1s^{21}S_0$	3,9916	3,9919	3,9917	-

In table 1 we present theoretical data for wavelengths and satellite intensity factors (λ in Å; F_2^* in 10^{13}s^{-1}) for the multicharged ion of Ar (from refs. [3,6] and our ones). The corresponding data [3,6] have been received on the basis of calculations within the multi-configuration intermediate-coupling scheme with a statistical Thomas-Fermi potential (ref. [2]) and relativistic PT scheme [6]. A detailed comparison with experiment [2,3] shows that our data are in more good agreement with experimental data than data from refs. [3,6]. In table 2 we present our results of calculating the wavelengths and satellite intensity factors (λ in Å; F_2^* in 10^{13}s^{-1}) for the multicharged ion of Sc and V. For comparison there are also presented the results [6]. Numerical estimate for the most prominent satellite line j (see table 1) shows that $\varepsilon_q/\varepsilon_w \sim z^n$, where n=7,06 (n is very weakly T_e dependent parameter in the interval [10^3 –$2\cdot 10^3$eV]. The evaluated value of the electron temperature is 1590 eV, which is in an excellent agreement with experimental value [2]. So, we have developed and used a new advanced high-accuracy theoretical spectroscopy scheme to make sensing and diagnostics the TFR tokamak plasma parameters and presented new data of the tokamak plasma parameters and wavelengths of the He (Li)-like satellite spectra for ions Ar, Sc, V, which are the most accurate in comparison with available data in literature. We believe that our approach can be used for high-accuracy sensing and diagnostics the plasma parameters in tokamaks and other techniques.

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Table 2

Calculated (this paper) wavelengths and satellite intensity factors (λ in Å; F_2^* in 10^{13} s^{-1}): Sc, V

Line	Array	λ (Sc) [6]	λ (Sc) present	F_2^*(Sc) present	λ (V) [6]	λ (V) present	F_2^*(V) present
w	$1s2p^1P_1 - 1s^{21}S_0$	2,8699	2,8696	-	2,3790	2,3787	-
x	$1s2p^3P_2 - 1s^{21}S_0$	2,8807	2,8803	-	2,3869	2,3867	-
s	$1s2s2p^2P_{3/2} - 1s^22s\,^2S_{1/2}$	2,8818	2,8815	2,42	2,3880	2,3876	2,55
t	$1s2s2p^2P_{1/2} - 1s^22s\,^2S_{1/2}$	2,8829	2,8826	6,71	2,3889	2,3885	8,91
m	$1s2p^{2\,2}S_{1/2} - 1s^22p\,^2P_{3/2}$	2,8813	2,8810	3,52	2,3879	2,3877	4,13
y	$1s2p^3P_1 - 1s^{21}S_0$	2,8846	2,8842	-	2,3910	2,3908	-
q	$1s2s2p^2P_{3/2} - 1s^22p\,^2S_{1/2}$	2,8903	2,8999	0,42	2,3943	2,3941	0,18
k	$1s2p^{2\,2}D_{3/2} - 1s^22p\,^2P_{1/2}$	2,8953	2,8949	25,85	2,3979	2,3975	30,79
r	$1s2s2p^2P_{1/2} - 1s^22s\,^2S_{1/2}$	2,8928	2,8925	3,92	2,3971	2,3968	4,83
a	$1s2p^{2\,2}P_{3/2} - 1s^22p\,^2P_{3/2}$	2,8931	2,8928	6,47	2,3965	2,3962	8,71
j	$1s2p^{2\,2}D_{5/2} - 1s^22p\,^2P_{3/2}$	2,8991	2,8987	35,50	2,4015	2,4011	43,25
z	$1s2sp\,^3S_1 - 1s^{21}S_0$	2,9005	2,9001	-	2,4031	2,4027	-

References

1. Trabert E., Saathoff G., Wolf A., M1/E2 decay rates in CoXI, NiXII, Cu XIII measured at a heavy-ion storage ring// J.Phys.B.At.Mol.Opt.Phys. — 2004. — Vol. 37(4). — P.945-952.
2. Rosmej F.B., Hoffman D.H., Geissel M. et al, Advanced X-ray diagnostics based on an observation of high-energy Rydberg transitions from autoionizing levels in dense laser-produced plasmas// Phys. Rev.A. — 2001-Vol.63. — P.063409-063418.
3. TFR group, Cornille M., Dubau J., Loulergue M. Chare-dependent wavelengths shifts & line in-tensities in dielectronic satellite spectra of He-like ions// Phys.Rev.A-1985. — Vol.32-P.3000-3010.
4. Chenais-Popovics C., Rancu O., Renaudin P., Gauthier J.C. X-ray Spectroscopy of Laser-Produced Hot Dense Plasmas// Phys.Scripta. — 1996. — Vol.65,N1. — 163-168.
5. Glushkov A.Deuterium lines spectra analysis in Tokamak// Proc.24th Europ. Conf. on Thermonucl. Fusion and Plasma Physics (Garching, Germany). — 1996.
6. Chernyakova Yu.G., Ignatenko V.M.,Vitavetskaya L.A., Sensing the tokamak plasma parameters by means high resolution X-ray theoretical spectroscopy method: new scheme// Sensor Electr. & Microsyst. Techn. — 2004. — N2. — P.20-24.
7. Mohr P.J. Quantum Electrodynamics Calculations in few-Electron Systems// Phys.Scripta. — 1993. — Vol.46,N1. — P.44-52.
8. Blundell S.A. Ab initio Calculations of QED Effects in Li-like, Na-like and Cu-like Ions// Phys.Scripta. — 1993. — Vol.46,N1. — P.144-150.
9. Ivanova E.P., Ivanov L.N. Modern Trends in Spectroscopy of Multicharged Ions// Physics Rep. — 1991. — Vol.166,N6. — P.315-390.
10. Glushkov A.V., Ivanov L.N., Ivanova E.P. Radiation decay of Atomic States: generalized Energy Approach// Autoionization Phenomena in Atoms. — M.: Moscow Univ. — 1986. — pp.58-160.
11. Ivanov L.N., Ivanova E.P., Knight L. Energy Approach to consistent QED theory for calculation of electron-collision strengths//Phys.Rev.A. — 1993. — Vol.48,N6. — P.4365-4374
12. Glushkov A.V. Negative Ions of Inert Gases// JETP Lett. — 1992. — Vol.55, N2- C.95-98.
13. Glushkov A.V., Ivanov L.N. Radiation Decay of Atomic States: atomic residue and gauge non-invariant contributions// Phys. Lett.A. — 1992. — Vol.170,N1. — P.33-37.
14. Glushkov A.V., Gurnitskaya E.P., New QED approach to calculation of the superheavy ions // Proc. of the International conference on Quantum Systems. — Spetses, Greece (2004).
15. Gurnitskaya E.P., New QED approach to calculation of the superheavy ions: Programs complex// Preprint of NIIF, I.I.Mechnikov National University, Odessa. №A-3 (2004).
16. Glushkov A.V., Gurnitskaya E.P., Ambrosov S.V., Loboda A.V., Prepelitsa G.P., Consistent QED approach to calculation of electron-collision excitation cross-sections and strengths: Ne-like ions // Int. Journ.Quant.Chem. — 2005. — Vol.104, N4 . — P. 562-569.
17. Glushkov A.V., Gurnitskaya E.P., Malinovskaya S.V., Loboda A.V.,Korchevsky D.A., Diagnostics of the collisionally pumped plasma and search of the optimal plasma parameters of x-ray lasing// J.Phys.CS. — 2005. — Vol.11. — P.188-198
18. Glushkov A.V., Ambrosov S.V., Loboda A.V., Gurnitskaya E.P., Khetselius O.Yu., QED calculation of heavy multicharged ions with account for the correlation, radiative and nuclear effects// Progress of Theor. Phys. and Chem. — 2005. — Vol.41. — P.315-324.