Rydberg matter: properties and decay

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ABSTRACT

Rydberg matter is a condensed excited state made of highly excited atoms. State of art of research in the field of Rydberg matter is briefly reviewed. Special attention is focused on the contribution of Russian and Swedish scientists' groups to the analysis of this problem. Most attention is concentrated on physical principles of pseudopotential method and density functional theory used to describe the Rydberg matter. The description of Rydberg matter as an excited state becomes viable after the formal replacement of excited atoms by ground state pseudoatoms. This procedure has been used to find parameters of Rydberg matter made of highly excited cesium atoms. Theoretical estimations conform to experimental data available.

Keywords: Excited states, density functional theory, pseudopotential, condensed excited states, decay, cesium.

1. INTRODUCTION

Both pseudopotential and density functional methods are among the most powerful approaches to describe electronic structure of matter. A combination of pseudopotential approach with density functional theory leaded to the pseudopotential-density functional method (PDFM) widely used in solid state physics[1]. PDFM currently is one of most popular methods, which is applied to determine properties of materials including nanostructures and other complex confined systems[1, 2].

The pseudopotential model of a solid treats matter as a sea of valence electrons moving in a background of ion cores[2]. This approach is based on exact accounting for the valence electron wave function in the spatial region away from the core and approximate within the core. The pseudopotential model uses so-called model pseudopotentials, which correctly describe the behaviour of the smoothly varying part of wave function in the chemically active bonding regions. The pseudo wave function determined by the model pseudopotential is taken to be identical to the appropriate all-electron wave function in outer core regions. A possible approximation to find out an optimal pseudopotential is to fit calculated results to experimental data, but currently most pseudopotentials are calculated using PDFM[1, 2].

DFT reduces the many body problem to an one-electron one accounting effects of exchange and correlation through an one electron potential that depends only on the charge density. The chief limitation of density functional theory is that is appropriate only for the ground states and cannot be used to describe excited states without other approximations.

The purpose of this paper is to indicate a particular case of excited states that can be described by DFT without additional approximations. This is the case of Rydberg matter or condensed exited state, namely of the condensed state consisting entirely of highly excited atoms. Describing *ab initio* excited atoms by suitable pseudopotentials we are treating them as some objects – pseudoatoms in ground state. Hence we can construct from these pseudoatoms a solid-like state, describing it in aconventional way, e.g. using DFT and leaving excitation problems to a suitable pseudopotential choice. We will demonstrate below that the structure of Rydberg matter can be determined by DFT incorporating suitable pseudopotentials. This enables calculation and corresponding comparison of some estimated parameters with recent experimental data from[3-16].

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2. RYDBERG MATTER

A confined system of present interest is the Rydberg matter, a condensed state consisting of highly excited atoms condensed into a liquid-like material[3-23]. Rydberg matter is formed because the condensed state energetically is more favourable comparing a system of isolated atoms. The nature of bonding in Rydberg matter is much similar to metallic bond in alkali. Like other metallic states Rydberg matter can be treated as a sea of valence electrons moving in a background of ion cores. The quantitative difference presents characteristic lengths at which are changing the interaction potentials and density of electrons. Qualitative difference makes the fact that inner states (cores) of ions actually are empty: the valence electrons have always the possibility to recombine to lower energetic states. Hence Rydberg matter is a long-lived metastable state of matter[17].

Interaction of a highly excited valence electron with other ions and electrons of the system plays a crucial role in determining properties of Rydberg matter[23]. E. Fermi was the first who considered theoretically the state of a highly excited atom taking into account interaction of highly excited electron with surrounding atoms and introducing the concept of pseudopotentials[24]. In this paper Fermi noted that it not necessary to know the details of the scattering potential since any number of efficient potentials which reproduce the phase shifts of interest would yield similar scattering events. This concept yet modified is applied to understand and describe currently many quantum-mechanical systems.

There are interactions both with surrounding atoms and other valence electrons of Rydberg matter. The interactions with other ions can be characterised by a very smooth potential, corresponding to weak interaction forces that are also slowly changing by distance. This is due to the fact that valence electrons in Rydberg matter spend almost all time far from their ions, the classical orbit increasing its radii as square of main quantum number that for Rydberg atoms is high. At far distances from an ion the potential is almost Coulomb, deviations being accounting by quantum defect of excited states[18]. Since the distances are large, the potential becomes weak and smooth, and its gradient is also small. However this is true until the electrons remain in the chemically active bonding regions, e.g. far from inner core states. The situation changes drastically if the electron moves to the inner areas of ions. Despite in the Rydberg matter core states remain empty the wave function of an exited electron here exhibits a large number of oscillations caused by the nature of a given excited state: the wave function remains orthogonal to all below-lying energetic states like in any excited atom. This is due to the nature of Rydberg matter, it is a condensed state made of exited atoms, which differs the Rydberg matter from a non-ideal plasma consisting of cooled electrons and ions. Fast oscillations of electron wave function like in conventional solids over-compensate the gain in potential energy for inner core states. Indeed fast oscillations of wave function correspond to a large kinetic energy, thus the resulting interaction potential demonstrates an efficient repulsion in this area. This is well known result in solid state physics which serves as a rationale to apply empty core or hard core model pseudopotentials, called Heine-Abarenkov pseudopotentials. Thus the interaction of a valence electron in the Rydberg matter can be characterised by a large volume of an almost constant potential, where actually the electron spend practically all time, and a system of efficiently "hard" cores where despite electron can penetrate, it has a large kinetic energy and being energetically unfavourable is practically avoided by valence electrons.

Fig. 1 schematically presents a pseudopotential picture of a conventional alkali and of a Rydberg matter. Pseudopotentials treat internal core states of an alkali as inert and give exact description of the chemically active, valence electrons. Similarly pseudopotential describes the Rydberg matter giving exact picture of outer core areas where valence electrons are located practically all time providing chemical bonding of structure.

The interaction of valence electrons with others is described by so-called exchange-correlation term, or functional. This term has two contributions: the first is due to quantum-mechanic exchange effects and the second is due to Coulomb correlation interactions. In principle this interaction is non-local by nature, but in a so-called local density approximation is described by an effective local potential, which is stronger in regions where the density of electrons is higher[1, 2, 20, 22, 23]. This interaction is often described by an efficient interaction of the valence electron by an exchange-correlation hole. The exchange-correlation hole represents an opposite (positive) charge distribution around each electron in the electronic sea of Rydberg matter. Resulting exchange-correlation interaction is negative, thus contributing to further diminishing of total energy of system. Since the electrons have a wide possibility to avoid each other, efficiently the exchange-correlation interaction gives a substantial contribution to binding energy of Rydberg matter. Moreover since this interaction occur on the background of a very weak Coulomb interaction with ions (see above) it can even change the overall interaction potential contributing to confinement of electrons in areas far from ions. This diminishes further the probability of penetration of valence electrons into inner core areas, which in Rydberg matter is small initially.

The overall result of interactions of valence electrons with ions and other electrons is the substantial decrease of energy of system comparing a system of isolated highly excited atoms and efficient confinement of electrons in areas far from inner core states. The consequence of this is the formation of a stable metal-like condensate, which although having a density of a gas is metallic in nature and has a significant long lifetime.

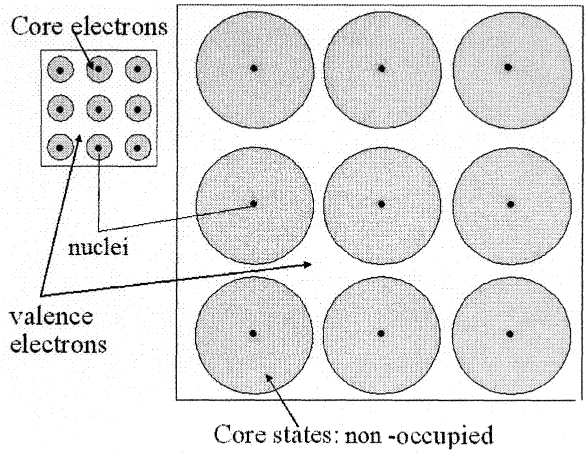

Figure 1: Pseudopotential schematic of condensed matter.
Left – schematic representation of an alkali metal (adopted from[1, 2]). Right representation of a Rydberg matter.

3. PESEUDOPOTENTIALS OF EXCITED STATES

Pseudopotentials are routinely used in DFT and quantum chemical applications and consequently there exists a large literature and continued research effort on the subject[1-23]. The combination of DFT with pseudopotential theory in solid state physics gives a considerable simplification in most cases due to separation of core and valence electrons trough replacement of core real potential by *ab initio* or model pseudopotential. Model pseudopotential are attractive due to their simplicity and application of fitting procedures to one known parameter, e.g. valence electron wave function in outer core area, to describe other, e.g. chemical binding, phonon spectrum, etc.

Exited atoms also can be described by using pseudopotential conception. Consider an excited atom. We can start dividing the wave function of a valence electron into the smooth part (without oscillations) and one subjected to many oscillations due to the orthogonality to lower states including core states (inner or "c"-states):

$$|\psi\rangle = |\phi\rangle - \sum_c |\psi_c\rangle\langle\psi_c|\phi\rangle . \quad (1)$$

For the smooth part of wave function $|\phi\rangle$ we have the exact equation:

$$(T + V_{ps})|\phi\rangle = E|\phi\rangle , \quad (2)$$

where T is the operator of kinetic energy. Equation (2) is similar to Schrodinger equation except that the potential V has been replaced by the pseudopotential V_{ps}

$$V_{ps} = V + \sum_c (E - E_c)|\psi_c\rangle\langle\psi_c| . \quad (3)$$

The above transformations are exact, thus (3) gives the exact pseudopotential of an excited atom. It has the same form as for a non-excited atom. Nevertheless the pseudopotential of an excited atom differs from one of a non-excited atom. The quantitative difference is that there are much more inner, e.g. "c"-states accounted by formula (3) and these are much less localised to the nucleus comparing an non-excited atom. Moreover by the increase of the excitation level the space occupied by the inner states becomes rapidly more and more large, hence the radius of pseudopotential increases correspondingly. Hence quantitatively the pseudopotentials of excited atoms are much larger. This reflects the known fact that excited atoms are efficiently much larger comparing non-excited atoms. The qualitative difference between the pseudopotentials of excited atoms and of non-excited ones makes the fact that most of inner states of highly-excited atoms are non-occupied. This however is "unknown" to the wave function of a valence electron that ought to be orthogonal to all below states, hence we have mathematically exact the same pseudopotential for an empty core atom as for a non-excited atom. The significant exception is that since the inner core states are empty the valence electrons have always the possibility to recombine to lower energy states. It means we shall take into account the recombination and ensure that recombination times are not too small.

Further simplification of exact formula (3) can be achieved through the replacement of this actually non-local pseudopotential (*ab initio* pseudopotential) by a model local pseudopotential. One of the simplest and most powerful approximations is so-called model or Heine-Abarenkov pseudopotential. It is equal to a certain constant within the inner region and is Coulomb out of this core. Hence it gives almost exact wave function out of inner core areas. This is particular true for highly excited states of atoms when the deviations from Coulomb potential are described by introducing effective quantum defects[25]. The model pseudopotential has two fitting parameters: the height of inner core and its radius R_c. Assuming its inner core with a nil height (empty core or Ashcroft pseudopotential) we have only one fitting parameter, e.g. R_c.

$$V_{ps} = \begin{cases} 0, & \mathrm{r} < \mathrm{R_c} \\ -1/r, & \mathrm{r} \geq \mathrm{R_c} \end{cases} \tag{4}$$

Requiring the same energy spectrum for valence electrons as of a real excited atom we can find out optimal radii R_c. Table I gives parameters of Ashcroft model pseudopotentials of cesium atoms, e.g. for comparison of its ground state and several excited states.

Table I. Ashcroft pseudopotentials for cesium atoms (atomic units).

Excitation level	Radius of Ashcroft pseudopotential, R_c
Ground state (6S)	3
10	54
11	76
12	102
13	132
14	165
15	203
16	244

We can now replace real excited atoms by Ashcroft pseudoatoms. These have the same wave functions out of inner regions and smooth wave functions in the regions, where are localized lower excited and non-occupied states and core electrons. What however is the most important is that the Ashcroft pseudoatoms are not excited species. These represent non-degenerated ground state structures to be readily described within DFT without additional approximations.

4. DFT APPROCH TO PSEUDOATOMS

DFT is one of most useful methods for studying many electronic systems. Since it uses the ground sate density of electrons as basic variable in place of many body wave function the description of many electron systems simplifies considerable. The reduction of many body equations to enough tractable description on the base of density in principle is exact and general. DFT is based on two theorems proved by Hohenberg and Kohn: the first theorem establishes that all ground non-degenerate state properties of the system are unique functionals of the density, and the second one that for a given external potential the energy functional assumes a minimum value for the true density[26].

The energy functional can be written as the sum of the kinetic energy, the classical Coulomb self-energy of the electrons, the exchange-correlation (XC) energy and the energy of electrons in the external potential v_a:

$$E[\rho] = T[\rho] + \frac{1}{2}\int \frac{\rho(\vec{r})\rho(\vec{r}')}{|\vec{r}-\vec{r}'|} d\vec{r} d\vec{r}' + E_{xc}[\rho] + \int v_a(\vec{r})\rho(\vec{r}) d\vec{r} \tag{5}$$

The external potential can arise, for example from a set of nuclei or in our case from pseudoatoms. Hence both the density ρ and the energy E of a ground state can be variationaly determined by minimizing the energy with respect to the trial densities, also taking into account normalization condition as a constraint.

Kohn and Sham[27] extended Hartree's approximate theory to a formal exact one by replacing actual system of electrons by a system of non-interacting fermions moving under a static effective self-consistent one-particle potential:

$$v_{eff}(\vec{r}) = v(\vec{r}) + \int \frac{\rho(\vec{r}')}{|\vec{r} - \vec{r}'|} d\vec{r}' + \frac{\delta E_{xc}[\rho]}{\delta\rho} \tag{6}$$

Non-interacting electrons are moving in the common effective local potential and have the same density as that of the original interacting system.

The Hohenberg-Kohn theorems were found to be valid for degenerate states as well (the mapping between external potential and the density in this case in not one-to-one). Moreover they were extended to excited states by introducing the composite energy functional and composite density (see reference[28]). To describe Rydberg matter we will use rather pseudoatoms than excited atoms. This permits to apply DFT directly avoiding additional approximations. Hence the external potential v_a in formula (5) is replaced by the sum of pseudopotentials from (4).

We replaced real highly-excited atoms by pseudoatoms in the meaning that real potential and real wave function are replaced by pseudopotentials and smooth wave function which are exact only in outer regions of chemical bonding. For numeric estimations we applied the Ashcroft empty-core model when the pseudopotential of an individual excited atom is assumed equal to zero inside of a sphere with the given radius R_c and equal to Coulomb potential out of this sphere. This pseudopotential is validated by so-called compensation theorem: if the radius R_c is close to the radius of inner shell the pseudopotential inside of the sphere is practically equal to zero. The radius R_c is found from the fitting of energy terms of a real atom and pseudoatom.

Assume Rydberg matter is made up of excited atoms from the same exited state. In this case in the general DFT formula the external potential v_a is the sum of individual pseudopotentials of each atom from (4). Accordingly with the variational approach we may use a parametric form of the trial density function ρ and minimise the energy functional (5) with respect to variations of these parameters.

Additional approximations are necessary in order to estimate numerically the parameters of Rydberg matter. First of all it is necessary to have some reasonable approximations for functionals $T[\rho]$ and $E_{xc}[\rho]$. We used both the local and the non-local approximations for functionals $T[\rho]$ and $E_{xc}[\rho]$. Local density approximation has been found to be valid if the radii of the pseudopotentials (model Ashcroft pseudopotential) are smaller than $1000a_0$, where a_0 is the Bohr radius[22].

The functional of kinetic energy in local density approximation is given by expression:

$$T[\rho] = \int t(\rho)\rho(\vec{r})d\vec{r}\,, \tag{7}$$

where $t(\rho)$ on the base of Hartree - Fock approximation is given by formula:

$$t(\rho) = \frac{3}{10}(3\pi^2\rho)^{2/3} + \frac{|\nabla\rho|^2}{8\rho^2} - \frac{\Delta\rho}{4\rho} \tag{8}$$

The expression for the kinetic energy consists of three terms, the first one is used in the Thomas-Fermi statistical theory and the second correction has been introduced by Weizsacker. The best agreement is observed taking into account all three terms.

The functional of exchange-correlation energy in local density approximation is given by expression:

$$E[\rho] = \int \varepsilon_{xc}(\rho)\rho(\vec{r})d\vec{r} \tag{9}$$

The exchange-correlation (XC) density is derived using homogeneous electron gas approximation and is given by the sum of two terms:

$$\varepsilon_{xc}(\rho) = -\frac{3}{4\pi}(3\pi^2\rho)^{1/3} - 0.44(\frac{4\pi}{3}\rho)^{1/3} \tag{10}$$

The first term is due to exchange interactions whereas the second one arises from correlation effects. We are using the Wigner expression for correlation energy of homogeneous gas, taking into account that Rydberg matter has a very low density of electrons[22].

The formula (10) can be named as exchange-correlation (XC) potential with negative sign. One can see that electron is attracted to the point of maximum electron density. One might think that in this case the electron density suffers a collapse. That is not so. The first term in (8) is the main value of kinetic energy with positive sign. So there is a balance between the kinetic energy and XC potential in the definite point (see Fig. 2).

The most accurate approximation to calculate both kinetic energy and exchange-correlation energy functionals is the weighted-density approximation. This approximation is based on application of pair correlation functions and XC charge density. The parameters of XC charge density are found in every point of space in accordance with corresponding sum rules. The weighted-density approximation has been used in order to determine the accuracy of local density approximation and to find out limits of its application. As we pointed out the local density approximation is justified for Ashcroft pseudopotentials with R_c<1000[22].

5. APPLICATION OF PSEUDOPONETIAL AND DFT METHODS TO THE RYDBERG MATTER

Numeric parameters of Rydberg matter can be estimated for many exited atoms and molecules. An advantage of highly-excited atoms is that these are hydrogen-like hence we can obtain many generic results without specifying the nature of atoms. The most interesting results have been found for cesium excited atoms[8, 11, 14, 15, 16, 19, 20], despite experimental results have been obtained for hydrogen and potassium also[3-7, 9, 10, 12, 13, 22]. For calculations we used spherical-cell method, which works well for *sp*-bands. Moreover the local density approximation in DFT can be used for cesium excited atoms up to 30-th excitation level. As a trial density function we used a single parameter Gaussian profile with the center near the border of spherical Wigner-Seitz cell. Table II illustrates equilibrium properties of Rydberg matter made of excited cesium atoms. These were estimated applying the DFT in combination with Ashcroft pseudopotentials.

Table II: Parameters of Rydberg matter made of excited cesium atoms.

Excitation level	Equilibrium density, 1/cm^3	Binding energy, K	Bulk modulus, dyn/cm^2	Surface tension, erg/cm^2	Melting temperature, K
Ground state (6S)	$9.1\ 10^{21}$	9590	$2\ 10^{10}$	85	302
10	$6.5\ 10^{18}$	2600	$2\ 10^{7}$	1	390
11	$2.5\ 10^{18}$	1990	$8\ 10^{6}$	0.4	390
12	$1.1\ 10^{18}$	1590	$4\ 10^{6}$	0.2	450
13	$5.3\ 10^{17}$	1310	$2\ 10^{6}$	0.1	460
14	$2.8\ 10^{17}$	1120	$1\ 10^{6}$	0.06	520
15	$1.6\ 10^{17}$	960	$6\ 10^{5}$	0.03	540
16	$9.2\ 10^{16}$	840	$4\ 10^{5}$	0.02	610

*Such states do not melt being thermally destroyed before achieving melting temperature.

Binding energies diminishes by the increase of excitation level. Enough high melting temperatures however are quite unusual. These increase with the increasing of the excitation level. Rydberg matter made of enough highly excited atoms (levels higher than 18-th) cannot be melted since melting temperature becomes higher than binding energy. It means that these states are always solid-like and by heating are destroyed before achieve melting temperature. As has been demonstrated in[8, 11, 14, 15, 16] there is a satisfactory coincidence of most measured parameters of caesium Rydberg matter with calculated data from Table II.

6. RYDBERG MATTER LIFETIME

Rydberg matter as a metastable form of matter has a limited lifetime. One can expect very short lifetimes for Rydberg matter taking into account that electron-electron interactions cause rapid recombination via Auger effects. However more accurate consideration gives us solid arguments on a much extended lifetime by the increase of excitation levels of atoms constituting the Rydberg matter. The main cause of this is due to the space separation of valence electrons of Rydberg matter and final decay states of electrons, e.g. inner states. Second cause of extended Rydberg matter lifetime is the formation of a broad barrier between these states due to exchange-correlation interactions discussed above. The valence electrons in Rydberg matter are confined far out of inner cores so that they practically very rarely penetrate into the inner regions of ions. This occurs only by tunneling through the broad separating potential barrier.

The valence electrons of Rydberg matter are moving in the common effective local potential that can be found from general formula (6). Fig. 2 shows this effective potential calculated for Rydberg matter made of cesium atoms excited in the level 10-S. The valence electrons are pressed toward the boundaries of the unit cells by exchange-correlation interaction. This effect is described by the effective one-particle exchange-correlation potential (third term in formula (6)), which in local density approximation differs from known Slater exchange potential only by a numeric factor.

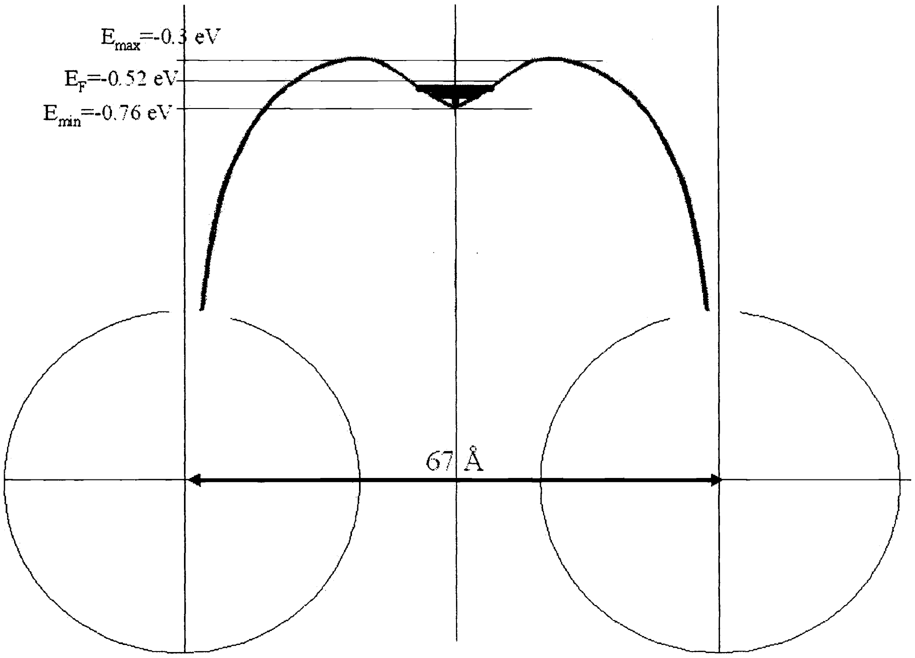

Figure 2. Potential of valence electrons in the Rydberg matter made of excited cesium atoms (10S state).

The confinement of electrons far from inner regions is an effect that can occur only at enough large excitation levels, e.g. corresponding large R_c (see Table I). Confinement may occur when the background Coulomb interaction with ions is enough weak (see Fig. 2). The larger distance from an ion the weaker this interaction. Numeric estimations show that confinement can be observed only if the pseudopotential radii of excited atoms are higher than 30. This means that an extension of Rydberg matter lifetime is unlike if R_c <30. For larger R_c the efficient potential (screened) of valence electrons has a distinguished well located at boundaries of elementary cells. Appearance of these wells is due to exchange-correlation interactions. The confinement of valence electrons in these wells is not complete, since there are topological pathways to other similar wells.

The most of inner core states of a highly-excited atom are un-occupied. Hence the valence electrons in Rydberg matter have always the possibility to recombine to lower energy states. Consider the recombination pathways to assess the Rydberg matter lifetime[17, 18]. The initial states of valence electrons in Rydberg matter differ from atomic states of primary excited atoms from which this matter was created. First of all the valence electrons in Rydberg matter are delocalized and do belong to all ions in the system like in any metallic system. However the valence electrons are distributed in space rather non-uniform and this makes a big difference with simple metals. There is a tendency for the increase of non-uniformity of electron charge distribution by the increasing excitation level of atoms. As the excitation levels n increase, the Bohr radius increases as n^2 and the Broglie wavelength increases only as n. Hence the higher n the higher the inhomogeneity of charge distribution in an excited atom. In the Rydberg matter this tendency is yet strengthened. This is due to additional exchange-correlation interactions of valence electrons with their exchange-correlation holes. The higher density of valence electrons the higher density of exchange-correlation hole. Hence electrons efficiently prefer areas with initial higher charge distribution enhancing initial density. As we see from Fig. 2 this may lead to a self-confinement of electrons near cell boundaries. In this case valence electrons in Rydberg matter spend almost all time far away from inner core states, e.g. in areas near cell boundaries.

The non-uniform distribution of valence electrons in Rydberg matter causes an upward shift of inner states of Rydberg matter ions. The Hartree potential (second term in formula (6)) within the elementary cell is almost constant decreasing near the boundary of the cell to equalize Coulomb potential (cells are neutral). The exchange-correlation potential is practically nil in the region of inner states. Thus the low-lying inner (recombination) states in the Rydberg matter are shifted upwards by a constant value, approximately equal to the average value of the Hartree potential within the elementary cell[18]. Possible decay states of a valence electron in Rydberg matter are determined by condition:

$$I_{n,l} + U_H \le E_e, \tag{11}$$

where $I_{n,l}$ are the term values of an isolated atom, U_H is the average Hartree potential. Using known term values we can find all permitted decay states. One can see that for Rydberg matter spontaneous decay is possible only into inner states with quantum numbers much lower than initial quantum number of primary excited atoms from which this matter has been created. The probabilities of both radiation and Auger decay of Rydberg matter have been calculated numerically for cesium atoms[18]. In the Table III one can see the probabilities for radiation and Auger decay of Rydberg matter formed from excited cesium atoms.

Table III: Decay states and probabilities for Rydberg matter made of excited cesium atoms.

Excitation level	Most likely decay state	Radiation decay probability, s^{-1}	Auger decay probability, s^{-1}
10	$7^2S_{1/2}$	11	650
11	$8^2S_{1/2}$	2.5	1540
12	$8^2S_{1/2}$	0.003	0.04
13	$9^2S_{1/2}$	0.002	0.2
14	$9^2S_{1/2}$	$6\ 10^{-7}$	$3.5\ 10^{-6}$
15	$10^2S_{1/2}$	$1.3\ 10^{-7}$	$2.8\ 10^{-5}$
16	$10^2S_{1/2}$	$4\ 10^{-11}$	$2.9\ 10^{-10}$

The non-radiation decay process predominates for all states of excited cesium atoms. Therefore the decay of Rydberg matter can be explained as a non-radiation transition of valence electrons into an inner orbital of the atom with the maximum possible quantum number (accordingly to condition (11)), which is followed by the relaxation of inner excitation of cesium atom. Since the inner atomic states of cesium are practically unchanged except their upward shift of energy, the radiation spectrum of Rydberg matter may be undistinguished from atomic spectrum of cesium atoms. But the lifetime of Rydberg matter increases rapidly with increasing of excitation level: for example it exceeds 10 hours for excitation level 15S. The most probable mechanism of the decay of Rydberg matter is the recombination through impurities[18]. Exception can be high-vacuum conditions achieved in experiments[8, 11, 14, 15, 16]. These have confirmed the effect of significant extension of lifetime of Rydberg matter comparing excited atoms. Finally, for more details see in references[29-37]. Optical and nonlinear optical properties of RM can be found in[32-35]. Ultracold Rydberg plasma produced by photoionization of laser cooled xenon atoms is considered in[36]. Optically induced condensation of impurity excitation in transparent solids is contained in[37].

7. CONCLUSIONS

Highly excited atoms condensate and form a more favourable long-lived state, e.g. Rydberg matter. We demonstrated that the structure of Rydberg matter can be described using the density functional theory in combination with pseudopotentials. This has been done applying the formal replacement of excited atoms by pseudoatoms in ground state. Parameters of Rydberg Matter made of highly excited cesium atoms were found by using this procedure. Comparison of theoretical estimations with experimental data showed satisfactory coincidence, including anomalous long lifetime for condensed excited states.

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