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RELATIVISTIC THEORY OF SPECTRA OF PIONIC ATOMS WITH ACCOUNT OF THE RADIATIVE CORRECTIONS: HYPERFINE STRUCTURE

A new theoretical approach to the description of spectral parameters pionic atoms in the excited states with precise accounting relativistic, radiation and nuclear effects is applied to studying spectral structure for pionic nitrogen. Energies and probabilities of radiation transitions between hyperfine structure lines components, such as 5f-4d, in the spectrum of the pion nitrogen are calculated and analyzed.

Our work is devoted to the application of earlier developed new theoretical approach to the description of spectral parameters pionic atoms in the excited states with precise accouting relativistic, radiation to studying energy parameters of the hyperfine structure of pionic atoms. As introduction let us remind that at present time studying the exotic hadronic atomic systems such as pionic atoms is of a great interest for further development of atomic and nuclear theories as well as new tools for sensing the nuclear structure and fundamental pion-nucleus strong interactions. In the last few years transition energies in pionic atoms [1] have been measured with an unprecedented precision. Besides, light pionic atoms can additionally be used as a new low-energy X-ray standards [1]. More over, their spectra studying allows to determine the pion mass using the highest accuracy in comparison with other methods. TO nowadays, new advanced experiments are been preparing in order to make sensing the electromagnetic and strong interaction effects in different pionic atoms.

The most popular theoretical models are naturally (pion is the Boson with spin 0, mass m_{π^-} =139.57018 МэВ, r_{π^-}=0.672±0.08 fm) based on the using the Klein-Gordon-Fock equation, but there are many important problems connected with accurate accounting for as pion-nuclear strong interaction effects as QED radiative corrections (firstly, the vacuum polarization effect etc.). This topic has been a subject of intensive theoretical and experimental interest (see [1-14]). The perturbation theory expansion on the physical; parameter αZ is usually used to take into account the radiative QED corrections, first of all, effect of the polarization of electron-positron vacuum etc. This approximation is sufficiently correct and comprehensive in a case of the light pionic atoms, however it becomes incorrect in a case of the heavy atoms with large charge of a nucleus Z.

So, there is a high necessity to develop non-perturbative methods in order to account the QED effects. Besides, let us underline that more correct accounting of the finite nuclear size and electron-screening effects for heavy pionic atoms is also very serious and actual problem. At last, a development of the comprehensive theory of hyperfine structure is of a great interest and importance in a modern theory of the pionic atom spectra.

As usually, the relativistic dynamic of a spinless boson particle should be described on the basis of the Klein-Gordon-Fock (KGF) equation. The electromagnetic interaction between a negatively charged pion and the atomic nucleus can be taken into account introducing the nuclear potential A_v in the KG equation via the minimal coupling $p_v \to p_v - qA_v$.

The wave functions of the zeroth approximation for pionic atoms are determined from the KGF equation [1]:

$$m^2c^2\Psi(x) = \{\frac{1}{c^2}[i\hbar\partial_t + eV_0(r)]^2 + \hbar^2\nabla^2\}\Psi(x) \quad (1)$$

where h is the Planck constant, c the velocity of the light and the scalar wavefunction $\Psi_0(x)$ depends on the space-time coordinate x = (ct,r). Here it is considered a case of a central Coulomb potential ($V_0(r)$, 0). The corresponding stationary equation looks as:

$$\{\frac{1}{c^2}[E + eV_0(r)]^2 + \hbar^2\nabla^2 - m^2c^2\}\varphi(x) = 0 \quad (2)$$

where E is the total energy of the system (sum of the mass energy mc^2 and binding energy ε_0). In principle, the central potential V_0 should include the central Coulomb potential, the radiative (in particular, vacuum-polarization) potential as well as the electron-screening potential in the atomic-optical (electromagnetic) sector. Surely, the full solution of the pionic atom energy especially for the low-excited state requires an inclusion the pion-nuclear strong interaction potential. However, if a pion is on the high orbit of the atom, the strong interaction effects can not be accounted because of the negligible value.

The important nuclear effect is the finite size one (the Breit-Rosenthal-Crawford-Schawlow effect). We will use the widespread Gaussian model for nuclear charge distribution. This is the smooth function, and as result it has a advantage in comparison with usually used model of a uniformly charged sphere [2-5]. It is obvious that it simplifies the calculation procedure and permits to perform a flexible simulation of the real distribution of the charge in a nucleus. The Gauss model is determined as follows:

$$\rho(r|R) = (4\gamma^{3/2}/\sqrt{\pi})\exp(-\gamma r^2), \quad (3)$$

where $\gamma = 4\pi/R^2$, R is an effective radius of a nucleus.

The next important topic is connected with a correct accounting the radiation QED corrections and, first of all, the vacuum polarization correction. We firstly introduce into the theory the Flambaum-Ginges radiative potential. In includes

the standard Ueling-Serber potential and electric and magnetic form-factors plus potentials for accounting of the high order QED corrections such as [15]:

$$\Phi_{rad}(r) = \Phi_U(r) + \Phi_g(r) + \Phi_f(r) +$$
$$+ \Phi_l(r) + \frac{2}{3}\Phi_U^{high-order}(r) \quad (4)$$

where

$$\Phi_U^{high-order}(r) = -\frac{2\alpha}{3\pi}\Phi(r)\frac{0.092Z^2\alpha^2}{1 + (1.8 \ r/r_C)^4} \quad (5)$$

$$\Phi_l(r) = -\frac{B(Z)}{e}Z^4\alpha^5 m \ ^2 e^{-Z \ /a_B} \quad (6)$$

Here e – a proton charge and universal function $B(Z)$ is defined by expression: $B(Z)=0.074+0.35Z\alpha$.

The next step is an account of the electron screening effect. It should be noted that the electron shells are not survived in the light pionic atoms during the cascade processes accompanying the formation of a pionic atom. However, in a case of the heave systems, the internal electron shells survive and this fact should be reflected in a precise theory. Our procedure for accounting this effect is a standard one and includes addition to the total interaction potential SCF potential of the electrons, which can be determined within the Dirac-Fock method by solution of the standard relativistic Dirac equations. To realize this step, we have used the QED perturbation theory formalism for relativistic many-electron atom. Further in order to calculate probabilities of the Radiative transitions between energy level of the pionic atoms we have used the relativistic energy approach [16].

The final topic of the theory is calculation of the hyperfine structure parameters. Here one could use the standard theory of hyperfine structure of the usual multi-electron atom. As usually, the hyperfine structure is arisen because of the interaction of the orbital pion with a magnetic dipole moment μ and quadruple electric moment Q of a nucleus. Hitherto, only magnetic contribution has been studied. The quadruple interaction is not treated hitherto. One could consider energy of the hyperfine interaction, which looks as:

$$W = W_\mu + W_Q = -\mu \cdot H(0) + \frac{1}{6}e\sum_{\alpha\beta}Q_{\alpha\beta}\frac{\partial^2\varphi}{\partial x_\alpha \partial x_\beta} \quad (7)$$

Here H and φ are defined as, respectively, the magnetic field and electrostatic potential produced by an electron (pion) in the position of the nucleus. Following to the standard procedure, after multiple transformations the final expression for the energy of the hyperfine splitting (magnetic part of) the energy levels of the atom in the pion:

$$E_1^{nlF} = \frac{\mu_I \mu_N e \mu_0 \hbar c^2}{4\pi \left(E_0^{nl} - \langle nl|V_0(r)|nl\rangle\right)} \times \left[\frac{F(F+1)-I(I+1)-l(l+1)}{2I}\right]\langle nl|r^{-3}|nl\rangle \quad (8)$$

Here $\mu_N = e\hbar/2m_p c$; other notations are standard. In a consistent precise theory it is important allowance for the contribution to the energy of the hyperfine splitting of the levels in the spectrum of the pion atom due to the interaction of the orbital momentum of the pion with the quadrupole moment of the atomic nucleus. The corresponding part looks as follows:

$$< LIFM|W_Q|LIFM >= \Delta + BC(C+1) \quad (9)$$

where

$$C=F(F+1)-L(L+1)-I(I+1), \quad (10)$$

$$B = -\frac{3}{4}\frac{e^2 Q}{I(2I-1)}\frac{(\gamma \cdot L\|\eta_2\|\gamma \cdot L)}{\sqrt{L(L+1)(2L-1)(2L+1)(2L+3)}} \quad (11)$$

$$\Delta = \frac{e^2 Q(I+1)}{(2I-1)}\frac{(\gamma \cdot L\|\mu_2\|\gamma \cdot L)L(L+1)}{\sqrt{L(L+1)(2L-1)(2L+1)(2L+3)}} \quad (13)$$

Here L – is orbital moment of pion, F is a total moment of an atom.

As example of application of the presented approach, in table 1 we present our data on the energies (in eV) of transitions between hyperfine structure components 5f-4d in the spectrum of the pion nitrogen (our data)

The analogous computing energies of transitions between hyperfine structure components 5f-4d in the spectrum of the pion neon has demonstrated physically reasonable agreement with other theoretical data by Indelicato et al and measured results. So, the received data can be considered as sufficiently accurate ones and used in the corresponding applications.

Energy (in eV) transitions between hyperfine structure components 5f-4d in the spectrum of the pion nitrogen (our data)

F-F'	ΔE, Our data	P, Our data.
4-3	4057.6819	4.57×10^{13}
3-2	4057.6915	3.16×10^{13}
3-3	4057.6799	2.98×10^{13}
2-1	4057.6978	2.13×10^{13}
2-2	4057.6905	2.25×10^{13}
2-3	4057.6789	0.01×10^{13}

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Abstract

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Key words: relativistic theory, hyperfine structure, pionic atom

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РЕЛЯТИВИСТСКАЯ ТЕОРИЯ СПЕКТРОВ ПИОННЫХ АТОМОВ С УЧЕТОМ РАДИАЦИОННЫХ ПОПРАВОК: СВЕРТОНКАЯ СТРУКТУРА

Резюме

Новый теоретический подход к описанию спектральных параметров пионных атомов в возбужденном состоянии с учетом релятивистских, радиационных эффектов применен к изучению спектральной структуры пионного азота. Рассчитаны и проанализированы значения энергий и вероятностей радиационных переходов между компонентами линий сверхтонкой структуры (типа 5f-4d) в спектре пионного азота.

Ключевые слова: релятивистская теория, сверхтонкая структура, пионный атом

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РЕЛЯТИВІСТСЬКА ТЕОРІЯ СПЕКТРІВ ПІОННИХ АТОМІВ З УРАХУВАННЯМ РАДІАЦІЙНИХ ПОПРАВОК: НАДТОНКА СТРУКТУРА

Резюме

Новий теоретичний підхід до опису спектральних параметрів піонних атомів у збудженому стані з урахуванням релятивістських, радіаційних ефектів застосовано до вивчення спектральної структури піонного азоту. Розраховані і проаналізовані значення енергій і ймовірностей радіаційних переходів між компонентами ліній надтонкої структури (типу 5f-4d) в спектрі піонного азоту.

Ключові слова: релятивістська теорія, надтонка структура, піонний атом