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ELECTROMAGNETIC AND STRONG INTERACTIONS EFFECTS IN NUCLEAR SPECTROSCOPY OF HADRONIC ATOMS

Theoretical studying transition energies and widths from X-ray spectroscopy of hadronic atoms is carried out. The electromagnetic and strong interaction effects in nuclear spectroscopy of hadronic (kaonic) atoms are analyzed from the pointview of a new tool for studying nuclear structure.

1. Introduction

Theoretical and experimental studying exotic hadronic atomic systems such as kaonic or pionic or hyperonic atoms represents a great fundamental and applied interest as for further development of atomic and nuclear theories as for search of a new tools for investigation a nuclear structure and strong pion-hyperon-kaon- nuclear interaction etc. Surely, studying these complex systems gives a new low-energy key to understanding and even further check of the Standard Model [1-16]. In the last few years transition energies in the kaonic atoms [1-7] have been measured with an unprecedented precision. The spectroscopy of kaonic hydrogen allows to study the strong interaction at low energies by measuring the energy and natural width of the ground level with a precision of few meV [6,7]. Let us remind about well-known application of the light kaonic atoms as the new low-energy X-ray standards and unique possibility to evaluate the kaon (pion) masses using methods of theoretical and experimental high accuracy X-ray spectroscopy. The known example of the experimental studying is the E570 collaboration experiment [6,7] on measurement of the X-ray energies in the kaonic helium atom, which is an atom consisting of a kaon (a negatively charged heavy particle) and a helium nucleus. Another impressive experiment is with DEAR allowed to perform an improved measurement of kaonic hydrogen [4] (look fig.1). It has been received significantly higher precision and smaller shift and width values than the KpX experiment [11], still for the given precision the results are compatible. The similar experiments are performed or in a status of preparing for the pionic systems (look c.g. [1,2,9,10]). It is important to note that because of the tiny strong interaction effect the study of pionic hydrogen and other elements calls for an X-ray spectrometer system with ultimate precision - provided by a crystal spectrometer which is feasible due to the huge pion beam intensity provided at PSI - whereas kaonic hydrogen can be studied with X-ray detectors like CCDs or SDDs directly. Batty et al [5] had carried out performed theoretical and experimental studying the strong-interaction effects in spectra of high Z kaonic atoms. Now new exciting experiments are been preparing in order to make sensing the strong interaction effects in other hadronic atoms.

Studying the low-energy kaon-nuclear strong interaction with strangeness have been performed by measurements of the kaonic atom X-rays with atomic numbers Z=1-92 [1]. It is known that the shifts and widths due to the strong interaction can be systematically understood using phenomenological optical potential models. Nevertheless, one could mention a large discrepancy between the theories and experiments on the kaonic helium 2p state. A large repulsive shift (about -40 eV) has been measured by three experimental groups in the 1970's and 80's, while a very small shift (< 1 eV) was obtained by the optical models calculated from the kaonic atom X-ray data with Z>2 [1-6]. This significant disagreement (a difference of over 5 standard deviations) between the experimental results and the theoretical calculations is known as the "kaonic helium puzzle". A possible large shift has been predicted using the model assuming the existence of the deeply bound kaonic nuclear states. However, even using this model, the large shift of 40 eV measured in the experiments cannot be explained. A re-measurement of the shift of the kaonic helium X-rays is one of the top priorities in the experimental research activities. In the theory of the kaonic and pionic atoms there is an important task, connected with a direct calculation of the X-ray transition energies. The standard way to solution the hadronic atom problem is using the Klein-Gordon-Fock equation. Here one deal with important problem of the accurate accounting for as kaon-nuclear strong interaction effects as QED radiative corrections (firstly, the vacuum polarization effect etc.) [1-13].

In the present paper awe present the results of theoretical studying transition energies and widths from X-ray spectroscopy of hadronic atoms. The electromagnetic and strong interaction effects in nuclear spectroscopy of hadronic (kaonic) atoms are analyzed from the pointview of a new tool for studying nuclear structure

2. Electromagnetic and strong effects in spectroscopy of kaonic atoms

Earlier we presented the detailed description of approach to kaonic atom spectra problem, so here we are stopping only at the key fundamental topics [11-15]. All available theoretical models to treating the hadronic (kaonic, pionic) atoms are naturally based on the using the Klein-Gordon-Fock equation. Its stationary version is as follows (in atomic units!):

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

Here α is the fine structure constant, E is the total energy of the system, V_0 is a central potential, which contents the nuclear electric potential (due to the charge distribution in a nucleus), potential, provided by the radiative (QED) effect of vacuum polarization and, at last, the strong kaon-nuclear interaction potential (for example, the optical model potential). Earlier we computed spectral characteristics of some hadronic systems using the nuclear charge distribution in the Gaussian form (c.f. [12]). The advantage of the Gaussian form nuclear charge distribution is provided by using the smooth function instead of the discontinuous one as in the model of a uniformly charged sphere [16]. 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 new important topic is connected with a correct accounting the radiation QED corrections and, first of all, the vacuum polarization correction. Procedure for an account of the radiative QED corrections in a theory of the multi-electron atoms is given in detail in refs. [11,12]. Regarding the vacuum polarization effect let us note that this effect is usually taken into account in the first PT order by means of the Uehling-Serber potential:

$$U(r) = -\frac{2\alpha}{3\pi r}\int_1^\infty dt \exp\left(-2rt/\alpha Z\right)\left(1 + 1/2t^2\right)\frac{\sqrt{t^2 - 1}}{t^2} \equiv$$

$$= -\frac{2\alpha}{3\pi}C(g) \qquad (2)$$

where $g = \frac{r}{\alpha Z}$.

In our calculation we usually use more exact approach [16]. The Uehling-Serber potential, is usually derived determined as a quadrature (2.). Nevertheless, [10, 17], it can be approximated with high precision by a definite analytical function. The use of new approximation of the cited potential [17] permits one to decrease the computing error for this term down to 0.5 – 1%. Besides, using such a simple analytical function form for approximating the Uehling-Serber potential allows its easy inclusion into the general system of differential equations [12,14,15].

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3. Some results for heavy systems and conclusions

In ref. [11-15] we have presented some results of calculation for a selection of kaonic atom transitions. The kaon mass was assumed to be 493.677±0.013MeV [1]. In table 1 we present the calculated electro-magnetic (EM) X-ray energies of kaonic atoms for transitions between circular levels.

Table 1

Calculated electromagnetic (E_c) and measured (E_m) energies (keV) of the X-ray transitions in the KA: the Batty et al theory EM1,2 [5] with using simple cascade Fermi-Teller model (Leon-Seki code), data by Indelicato et al (theory EM3) [3,4] and theory [11] (theory EM4) and our work (EM5).

KA	Transition	E_c, our theory EM4	E_c, [5] theory EM1	E_c, [5] theory EM2
W	8-7	346.586	346.54	-
Pb	8-7	426.175	426.15	426.201
U	8-7	538.520	538.72	538.013
KA	Transition	E_c, [3,4] theory EM3	This work EM5	E_m , [1,12]
W	8-7	346.571	346.603	346.624(25)
Pb	8-7	426.180	426.198	426.221(57)
U	8-7	537.44	538.945	538.315(100)

The transitions are identified by the initial (n_i) and final (n_f) quantum numbers. The calculated values of transition energies are compared with available measured (E_m) and other calculated (E_c) values [1-7].

It is easily to understand that when there is the close agreement between theoretical and experimental shifts, the corresponding energy levels are not significantly sensitive to strong nuclear interaction, i.e the electromagnetic contribution is dominative. In the opposite situation the strong-interaction effect is very significant.

The detailed analysis of theoretical and separated experimental data shows that indeed there is a physically reasonable agreement between the cited data. But, obviously, there may take a place the exception too as it is shown on example of the kaonic uranium. Further one can perform the comparison of the theoretically and experimentally determined transition energies in the X-ray spectra and further to find the strong interaction contribution into transition energy. From the other side, solution of the Klein-Gordon-Fock equation with directly implemented kaon-nucleon (say, from optical model) potential with a set of parameters allows to estimate the correctness of their definition. parameters using Eqs. (8)-(11). Moreover, such a way will make more clear the true values for parameters of the kaon -nuclear potentials and correct the disadvantage of widely used parameterization of the cited potential. Let us also in conclusion to note that the known perspective can be opened on the way of sensing the parity non-conservation in the heavy hadron atomic systems, in particular, kaonic atoms. Obviously, this effect will be small in the light hadronic systems as K^-- H, K^-- N, but its contribution is increasing as Z^3, so one could wait for the increased contribution in the high-Z atoms (as K^-- Pb, K^-- W , K^- -U etc.).

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Abstract

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Key words: X-ray spectroscopy, hadronic systems, kaon-nuclear interaction

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ЭФФЕКТЫ ЭЛЕКТРОМАГНИТНОГО И СИЛЬНОГО ВЗАИМОДЕЙСТВИЙ В ЯДЕРНОЙ СПЕКТРОСКОПИИ АДРОННЫХ АТОМОВ

Резюме

Проведено теоретическое изучение энергий переходов и ширин в рентгеновской спектроскопии адронных атомов. С точки зрения выявления новых инструментов изучения структуры ядра проведен анализ эффектов электромагнитного и сильного взаимодействия в ядерной спектроскопии адронных (каонных) атомов.

Ключевые слова: Рентгеновская спектроскопия, адронные системы, каон-ядерное взаимодействие

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ЕФЕКТИ ЕЛЕКТРОМАГНІТНОЇ ТА СИЛЬНОЇ ВЗАЄМОДІЇ В ЯДЕРНОЇ СПЕКТРОСКОПІЇ АДРОННИХ АТОМІВ

Резюме

Проведено теоретичне вивчення енергій переходів і ширин в рентгенівської спектроскопії адронних атомів. З точки зору виявлення нових інструментів вивчення структури ядра проведено аналіз ефектів електромагнітної та сильної взаємодії в ядерній спектроскопії адронних (каонних) атомів.

Ключові слова: Рентгенівська спектроскопія, адронні системи, каон-ядерна взаємодія