ОПТИЧНІ, ОПТОЕЛЕКТРОННІ І РАДІАЦІЙНІ СЕНСОРИ

OPTICAL, OPTOELECTRONIC AND RADIATION SENSORS

PACS 32.15RM;
УДК 539.184

ON POSSIBILITY OF SENSING NUCLEI OF THE RARE ISOTOPES BY MEANS OF LASER SPECTROSCOPY OF HYPERFINE STRUCTURE

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Abstract

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It is presented the the effective theoretical scheme with possibility of advancing corresponding nuclear technology for sensing different parameters for nuclei of the rare, for ezxample, cosmic, isotopes available in the little quantitites. As example, the nuclei of elements uranium and also Be, C, Al, which have rare, cosmic isotopes, are studied.

Keywords: sensing, laser technology, hyperfine structure, rare isotopes, nuclear properties

Анотація

ПРО МОЖЛИВІСТЬ ДЕТЕКТУВАННЯ ЯДЕР РІДКИХ ІЗОТОПІВ МЕТОДАМИ ЛАЗЕРНОЇ СПЕКТРОСКОПІЇ ПОНАДТОНКОІ СТРУКТУРИ

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Розглянута ефективна теоретична схема з можливістю удосконалення відповідної ядерної технології детектування параметрів ядер рідких изотопів, доступних у малих кількостях. Як приклад розглянуті ядра урану, а також Be, C, Al, що мають рідкі, космічні ізотопи.

Ключові слова: детектування, лазерна технологія, теорія надтонкої структури, рідкі ізотопи, ядерні параметри

Аннотация

О ВОЗМОЖНОСТИ ДЕТЕКТРОВАНИЯ ЯДЕР РЕДКИХ ИЗОТОПОВ МЕТОДАМИ ЛАЗЕРНОЙ СПЕКТРОСКОПИИ СВЕРХТОНКОЙ СТРУКТУРЫ

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Рассмотрена эффективная теоретическая схема с возможностью усовершенствования соответствующей ядерной технологии детектирования параметров ядер редких изотопов, доступных в малых количествах.. В качестве иллюстрации рассмотрены уран, а также ядра Be, C, Al, имеющих редкие, космические изотопы.

Ключевые слова: детектирование, лазерная технология, теория сверхтонкой структуры, редкие изотопы, ядерные параметры

1. Introduction

Developing the effective nuclear schems and technologies for sensing different nuclear properties, creation of the corresponding nuclear sensors is of a great importance in the modern nuclear physics and sensor science [1-19]. Among the most important problems one could mention the studying of nuclei, which are available in the little quantities (rare cosmic isotopes of the ^{10}Be, ^{14}C, ^{26}Al, radioactive nuclei far of the stability boundary), search of the superdence nuclei and its sensing, laser governing by parameters of the proton and other beams and sensing their characteristics etc. Such possibilities are provided by the modern laser methods and technologies (see, for example, [1,2]). An actual task here is developing the effective corresponding theoretical schemes and technical realization of sensing technologies on their basis. The high sensibility and resolution ability of laser spectroscopy methods allows investigating the characteristics of nuclei available in the little quantities, including the rare cosmic isotopes. As an example (see ref. [13-15]) one can mention the CERN technical device for studying the short-tlived nuclei which are obtained on the mass-separator in the line with synchrocyclotrone on 600 MeV (ISOLDE apparatus [1]). The shocking results have been obtained in studying of the odd neutron-deficited non-stable isotopes of $^{182-190}$Hg. The intensity of the ion beams of these isotopes with life tiome 1-60 min was 10^7-10^9 ions/s. Under excitation of fluorescence by dye pulsed laser radiation the second harmonics of radiation was tuning to region of 2537A and the measurement of the hyperfine structure for this line of Hg was carried out during 1-2 min disposing about 10^8 of the mercury isotop atoms. During transition from micleus ^{186}Hg to nucleus ^{185}Hg it has been discovered the sharp changing of the middle square of the nuclear radius which is interpreted as sharp changing of the nuclear form (increasing of non-soherity and electic quadrupole moment) during decresing the neutrons number. In ref. [13] (see also [11,12,23,24]) we have developed new effective theoretical scheme with possibility of advancing corresponding nuclear technology for sensing different parameters for nuclei available in the little quantitites. It is based on the experimental receiving the isotope beams on the CERN ISOLDE type apparatus (see detailed description in refs. [1,3,4]) and the precised theoretical and laser spectroscopy empirical estimating the hyperfine structure parameters, magnetic and electric moments of a nuclei of isotopes. We have carried out sensing and estimating the hyperfine structure parameters, magnetic and electric moments of a nucleus for ^{235}U and ^{201}Hg . Theory of the hyperfine structure cslculation is based on developed earlier gauge-invariant QED PT with an account of correlation (interelectron interaction corrections), nuclear and QED effects [20-29]. Here we consider a possibility of using new effective theoretical scheme [14,23,24] with possibility of advancing corresponding nuclear technology for sensing different parameters for nuclei of the rare, for example, cosmic, isotopes available in the little quantitites. Speech is, most of all, about cosmic isotopes of the ^{10}Be, ^{14}C, ^{26}Al. These isotopes, which are created in the upper layers of atmosphere, are hardly detected by usual (radiometric and on accelerators) methods. The isotopes of ^{14}Be are created during nuclear reaction of the galaxy cosmic rays with N and O; isotopes of ^{14}C are created due to the nuclear reaction of secondary neutrons with N. The isotopes of ^{26}Al are created due to the splitting of Ar. These cosmic isotopes cover the Earth surface and ocean and condence, for example, in the bottom layers. It is obvious that under definite conditions it is possible to measure a content of ^{10}Be, ^{14}C, ^{26}Al relatively the stable isotopes ^{9}Be, ^{13}C, ^{27}Al and further to define temporary variations of the cosmic rays and, in particular, variations , connected with changing the sun activity etc. In this paper, as example and test, we consider nuclei of elements Be, C, Al, U, which have above cited rare, cosmic isotopes.

Regarding calculating the hyperfine structure parameters and nuclear quadrupole moments one could mention as follows. This task is of a great importance as it is provided by necessity of infromation ragrding these properties for creating nuclear sensors and new nuclear technologies and also further developing the modern as atomic and as nuclear theories. From the other side, a great progress in experiments has been achieved [1-16]. Recent accurate measurements of the hyperfine structure parameters for a whole number of heavy isotopes (see [1,6,14,15] not only provide the possibility for testing the quantum electrodynamics (QED) in strong fields, but also sensing the hyperfine structure parameters of spectra for heavy atomic systems, electric charge and magnetic moment distributions inside the nucleus [5-10]. Theoretical calculations fulfilled during the last several years apart from the basis Fermi-Breit relativistic contributions also include the magnetic dipole moment distribution inside the nucleus (Bohr-Weisskopf effect) and radiative QED corrections (e.g. [20-29]). In calculations of the heavy ions the well known multi-configuration (MC) Dirac-Fock (DF) approach is widely used (e.g.[14,15,18,19]). More effective method, based on the QED perturbation theory (PT) [20,26-29], has been developed in the series of papers [6,11-13,20-25].

2. Theoretical approach to calculating hyperfine structure parameters

Let us describe the key moments of the theoretical scheme. Full details of the whole method of calculating the hyperfine structure constants can be found in [6,11-13,20-25]. The wave electron functions zeroth basis is found from the Dirac equation solution with potential, which includes the core ab initio potential, electric, polarization potentials of nucleus (the gaussian form for charge distribution in the nucleus is used). All correlation corrections of the second and high orders of PT (electrons screening, particle-hole interaction etc.) are accounted for [3,6,26-29]. We set the charge distribution in the nucleus by the Gaussian function:

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

Here $\gamma = 4/\pi R^2$; R is an effective nucleus radius.. As it has been shown in many papers (e.g. [14,15,11-13] and refs there), the models with the Fermi and Gauss charge distribution in a nucleus are most widespread and more correct in comparison with the model of homogeneous ball charge distribution. For example, let us mention that a difference in values of the spectra levels energies is about several cm^{-1}. The most advanced model must be based on the direct solving of the corresponding nuclear task. One could mention different versions of the shell model with the Woods-Saxon-type and spin-orbit potentials (e.g. refs.[7-10,18-21]). Further let us suppose that the point-like nucleus posseses by some central potential *W(R)*. The transition to potential of the finite nucleus is realized by substituition *W(r)* on

$$W(r|R) = W(r)\int_0^r dr\, r^2\rho(r|R) + \int_r^\infty dr\, r^2 W(r)\rho(r|R).$$

In our case the Coulomb potential for spherically symmetric density $\rho(r|R)$ is:

$$V_{nucl}(r|R) = -\left((1/r)\int_0^r dr' r'^2\rho(r'|R) + \int_r^\infty dr' r'\rho(r'|R)\right).$$

Further one can write the Dirac-Fock -like equations for a multi-electron system {core-*nlj*}. Formally they fall into one-electron Dirac equations for the orbitals *nlj* with potential: $V(r)=2V(r|SCF)+V(r|nlj)+V_{ex}+V(r|R)$. It includes the electrical and polarization potentials of a nucleus. The part V_{ex} accounts for exchange inter-electron interaction. The exchange effects are accounted for in the first two PT orders by the total inter-electron interaction [20,21,29]. The core electron density is defined by iteration algorithm within QED procedure [26]. The radiative QED (the self-energy part of the Lamb shift and the vacuum polarization contribtuion) are accounted for within the QED formalism [8,18]. The hyperfine structure constants are defined by the radial integrals (c.f.[6,30,31]):

$$A=\{[(4,32587)10^{-4}Z^2\chi g_I]/$$

$$/(4\chi^2-1)\}\int_0^\infty drr^2F(r)G(r)U(1/r^2,R),$$

$$B=\{7.2878\ 10^{-7}\ Z^3Q/$$

$$/[(4\chi^2-1)I(I-1)\}\int_0^\infty drr^2[F^2(r)+G^2(r)U(1/r^2,R).$$

Here I is a spin of nucleus, g_I is the Lande factor, Q is a quadruple momentum of nucleus; radial integrals are calculated in the Coulomb units (=3,57 $10^{20}Z^2m^{-2}$; = 6,174 $10^{30}Z^3m^{-3}$). Radial parts F and G of two components of the Dirac function for electron, which moves in the potential $V(r,R)+U(r,R)$, are defined by solution of the Dirac equations (PT zeroth order). The electric quadrupole spectroscopic hyperfine structure constant B of an atomic state related to the electric field gradient q and to electric quadrupole moment eQ of the nucleus as: $B=eqQ/h$. So, to obtain the corresponding value of Q one must combine the hyperfine structure constants data with the electric field gradient obtained in our approach from the QED PT calculation.

3. Estimating the hyperfine structure parameters and discussion

As example and test, we have considered the nuclei of elements Be, C, Al, U, which have above cited rare, cosmic isotopes. We carried out calculation (the Superatom package [3,4,6,20-29] is used) the hyperfine structure parameters, in particular, the hyperfine splitting of levels for ^{9}Be ($^1S_0$), ^{13}C ($^3P_0$) and ^{27}Al ($^2P_{1/2}$) and also ^{235}U. In tables 1-3 we present the values of the hyperfine splitting Δν(F, F') (in MHz) of levels for ^{9}Be ($^1S_0$), ^{13}C ($^3P_0$) and ^{27}Al ($^2P_{1/2}$) together with available experimental results [31]. Let us also present futher the results of studying is the hyperfine structure of spectral line 5915,3 A of the transition $f^3ds^2\ {}^5L_6 \rightarrow f^3dsp\ {}^7M_7$ for uranium ^{235}U. This line is correrspondig to permitted transition from the ground state into one from many excited states.

Table 1

The hyperfine splitting Δν(F, F') (in MHz) of levels for ^{9}Be ($^1S_0$) (nuclear spin 3/2)

Isotope	Electron Term	Quantum numbers of full moment F, F'	Hyperfine splitting Δν(F, F'), MHz	Hyperfine splitting: Theory, Present paper
^{9}Be ($^1S_0$), 3/2	2 $^3P_1$ 2 $^3P_2$	(5/2, 3/2) (3/2, 1/2) (7/2, 5/2) (5/2, 3/2) (3/2, 1/2)	354,44 202,95 435,48 312,02 187,62	352,18 201,31 432,52 310,88 185,94

The cited transition is often used for isotopically selected excitation of the uranium atoms for industrial isotopes and nuclear isomers separation. In table 4 we present the values of the HFS constants, magnetic dipole moment μ and electric quadrupole moment Q for the ^{235}U nucleus, obtained experimentally and theoretically (MCDF method) [13,31]. The key quantitative factor of agreement between theory and experiment is connected with the correct accounting for the interelectron correlations, finite size niclear, Breit and QED radiative corrections [10-20]. The well-known MCDF method is not gauge-invariant one and an accounting of multi-electron correlations is not fully fulfilled, though, for example, in ref. [19] it was used the gauge-invariant local DF version in calculating the N-like ion of Bi. The contribution of the nuclear core-polarization effects and also the high order QED corrections can correspond the difference between theory and experiment for the nuclear moments.

Table 2

The hyperfine splitting Δν(F, F') (in MHz) of levels for ^{13}C ($^3P_0$) (nuclear spin 1/2)

Isotope, ground state term, nuclear spin	Electron Term	Quantum numbers of full moment F, F'	Hyperfine splitting Δν(F, F'), MHz	Hyperfine splitting: Theory, Present paper
^{13}C ($^3P_0$), 1/2	2 $^3P_1$ 2 $^3P_2$	(3/2, 1/2) (5/2, 3/2)	4,3 372,6	4,08 370,47

Table 3

The hyperfine splitting Δν(F, F') (in MHz) of levels for ^{27}Al($^2P_{1/2}$) (nuclear spin 5/2)

Isotope, ground state term, nuclear spin	Electron Term	Quantum numbers of full moment F, F'	Hyperfine splitting Δν(F, F'), MHz	Hyperfine splitting: Theory, Present paper
^{27}Al ($^2P_{1/2}$), 5/2	3 $^2P_{1/2}$ 3 $^2P_{3/2}$	(3, 2) (4, 3) (3, 2)	1506,1 392 ---	1501,32 391,01 272,24

Table 4

The HFS constants, magnetic dipole moment μ and electric quadrupole moment Q for the ^{235}U nucleus

HFS constants (cm^{-1}), Moments	Experiment	Theory MCDF	Present QED PT
$J=6$, $-A_6$	0,00125	0,001	0,00118
$J=6$, $-B_6$	0,1185	-	0,1138
$J=7$, A_7	0,00464	0,0038	0,00437
$J=7$, B_7	0,05588	-	0,05370
$-\mu/\mu_N$	0,315	0,289	0,305
Q (10^{-24}cm^2)	6, 398	-	6,201

In conclusion let us note that we have considered and used an effective theoretical scheme for estimating the hyperfine structure parameters, magnetic and electric moments of a nucleus for for ^{9}Be ($^{1}S_{0}$), ^{13}C ($^{3}P_{0}$) and ^{27}Al ($^{2}P_{1/2}$) and also ^{235}U and reached sufficiently high accuracy. Such theoretical estimates should be used in interpretation of the laser spectroscopy method measurement of isotope atoms spectra. One can use further a scheme of the multi-stepped excitation with using isotopic shift on two-three steps of low-stripe laser radiation. A scheme , based on a combination of the isotopic-selcetive ionization with mass-separation of obtained ions, is an example of perspective method else for sensing the rare, cosmic isotopes.

Acknowledgement. The author would like to thank prof.A.Glushkov for invaluable advices and useful crtitical comments.

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