ОПТИЧНІ, ОПТОЕЛЕКТРОННІ І РАДІАЦІЙНІ СЕНСОРИ

OPTICAL, OPTOELECTRONIC AND RADIATION SENSORS

PACS 32.15RM; УДК 539.184

ON SENSING NUCLEI OF THE LANTHANIDE ISOTOPES BY MEANS OF LASER SPECTROSCOPY OF HYPERFINE STRUCTURE: ^{165}Ho, ^{169}Tm

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Abstract

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It is presented the effective theoretical scheme with possibility of advancing corresponding nuclear technology for sensing different parameters for nuclei of the lanthanide isotopes. As example, the nuclei of elements ^{165}Ho and ^{169}Tm are considered.

Key words: sensing, laser technology, hyperfine structure, lanthanide isotopes

Анотація

ПРО ДЕТЕКТУВАННЯ ЯДЕР ІЗОТОПІВ ЛАНТАНІДІВ МЕТОДАМИ ЛАЗЕРНОЇ СПЕКТРОСКОПІЇ НАДТОНКОІ СТРУКТУРИ: ^{165}Ho, ^{169}Tm

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Розглянута ефективна теоретична схема з можливістю удосконалення відповідної ядерної технології детектування параметрів ядер ізотопів лантанідів. Як приклад розглянуті ізотопи ^{165}Ho і ^{169}Tm.

Ключові слова: детектування, лазерна технологія, теорія надтонкої структури, ізотопи лантанідів

Аннотация

О ДЕТЕКТРОВАНИИ ЯДЕР ИЗОТОПОВ ЛАНТАНИДОВ МЕТОДАМИ ЛАЗЕРНОЙ СПЕКТРОСКОПИИ СВЕРХТОНКОЙ СТРУКТУРЫ: ^{165}Ho, ^{169}Tm

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Рассмотрена эффективная теоретическая схема с возможностью усовершенствования соответствующей ядерной технологии детектирования параметров ядер изотопов лантанидов. В качестве иллюстрации рассмотрены изотопы ^{165}Ho и ^{169}Tm.

Ключевые слова: детектирование, лазерная технология, теория сверхтонкой структуры, изотопы лантанидов

1. Introduction

Developing the effective nuclear schemes 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 (for example, the lanthanides isotopes, radioactive nuclei far of the stability boundary), search of the super dense 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. As an example (see ref. [13-15]) one can mention the CERN technical device for studying the short-lived 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-deficit non-stable isotopes of $^{182-190}$Hg. The intensity of the ion beams of these isotopes with life time 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 isotope atoms. During transition from nucleus ^{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 electric quadrupole moment) during decreasing the neutrons number. In refs. [13,14] (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 quantities. 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 prйcised theoretical and laser spectroscopy empirical estimating the hyperfine structure parameters, magnetic and electric moments of a nucleus of isotopes. We have carried out sensing and estimating the hyperfine structure parameters, magnetic and electric moments of a nucleus for ^{235}U, ^{201}Hg and rare cosmic isotopes. Theory of the hyperfine structure calculation is based on developed earlier gauge-invariant QED PT with an account of correlation (inter electron interaction corrections), nuclear and QED effects [20-29, 13,14]. 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 isotopes available in the little quantities, namely, the lanthanides isotopes. In this paper, as example and test, we consider nuclei of ^{165}Ho and ^{169}Tm 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 information regarding 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 [6,11-14,20-25].

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 [6,11-14,20-25]. 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. All correlation corrections of the second and high orders of PT (electrons screening, particle-hole interaction etc.) are accounted for [3,6,26-29]. The concrete nuclear model is used as described below. A quantitative estimate of the nuclear moments demands realistic proton single-particle wave functions which we obtain by employing the relativistic mean-field (RMF) model for the ground-state calculation of the nucleus. Though we have no guaranty that these wave-functions yield a close approximation to nature, the success of the RMF approach supports our choice (c.f.[31-35). These wave functions do not suffer from known deficiencies of other approaches, e.g., the wrong asymptotics of wave functions obtained in a harmonic oscillator potential [31]. The RMF model has historically been designed as a renormalizable meson-field theory for nuclear matter and finite nuclei. The realization of nonlinear self-interactions of the scalar meson led to a quantitative description of nuclear ground states. As a self-consistent mean-field model (for a comprehensive review see Ref. [6-9,31-35]), its ansatz is a Lagrangian or Hamiltonian that incorporates the effective, in-medium nucleon-nucleon interaction. Recently [6,31], self-consistent models have undergone a reinterpretation which explains their quantitative success in view of the facts that nucleons are composite objects and that the mesons employed in RMF have only a loose correspondence to the physical meson spectrum. They are seen as covariant *Kohn-Sham schemes* and as approximations to the true functional of the nuclear ground state. As a Kohn-Sham scheme, the RMF model can incorporate certain ground-state correlations and yields a ground-state description beyond the literal mean-field picture. RMF models are effective field theories for nuclei below an energy scale of 1GeV, separating the long- and intermediate-range nuclear physics from short-distance physics, involving, i.e., short-range correlations, nucleon form factors, vacuum polarization etc, which is absorbed into the various terms and coupling constants. As it is indicated in refs.[6,31] the strong attractive scalar (*S:* -400 MeV) and repulsive vector (*V:* +350 MeV) fields provide both the binding mechanism (*S + V:* -50 MeV) and the strong spin-orbit force (*S — V:* -750 MeV) of both right sign and magnitude. In our calculation we have used so called NL3 (c.f.[31]), which is among the most successful parametrizations available.

Let us note further that the point-like nucleus possesses by some central potential *W(R)*. The transition to potential of the finite nucleus is realized by substitution *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 of the following type (c.f.[6,30,31]):

$$A=\{[(4,32587)10^{-4}Z^2\chi g_I]/(4\chi^2-1)\}\times$$
$$\times\int_0^\infty drr^2F(r)G(r)U(1/r^2,R),$$

$$B=\{7.2878\ 10^{-7}\ Z^3Q/[(4\chi^2-1)I(I-1)\}\times$$
$$\times\int_0^\infty drr^2[F^2(r)+G^2(r)U(1/r^2,R),,$$

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 other details can be found in refs. [3-6,11-14, 20-26].

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 ^{165}Ho and ^{169}Tm. In tables 1,2 we present the values of the hyperfine splitting Δν(*F*, *F'*) (in MHz) of levels for ^{169}Tm ($^2F_{7/2}$) and ^{165}Ho ($^4I_{15/2}$) together with available theoretical (MCDF) and experimental or compilation data [31].

Table 1

The hyperfine splitting Δν(*F*, *F'*) (in MHz) of levels for ^{169}Tm ($^2F_{7/2}$) (nuclear spin 1/2)

Isotope; Spin of nucleus	Electron Term	Quantum numbers of full moment *F*, *F'*	Hyperfine splitting Δν(*F*, *F'*), MHz [31]	Hyperfine splitting: Theory, MCDF	Hyperfine splitting: Theory, Present paper
^{169}Tm ($^2F_{7/2}$) ; 1/2	4 $^2F_{7/2}$	(4, 3)	1496,55	1484,8	1496,12

Table 2

The hyperfine splitting Δν(*F*, *F'*) (in MHz) of levels for ^{165}Ho ($^4I_{15/2}$) (nuclear spin 7/2)

Isotope Spin of nucleus	Electron Term	Quantum numbers of full moment *F*, *F'*	Hyperfine splitting Δν(*F*, *F'*), MHz [31]	Hyperfine splitting: Theory, Present paper
^{165}Ho ($^4I_{15/2}$) 7/2	4 $^4I_{15/2}$	(5, 4)	4309,3	4308,74
		(6, 5)	5096,3	5095,72
		(7, 6)	5842,4	5841,80
		(8, 7)	---	6540,25
		(9, 8)	---	7184,16

The key quantitative factor of agreement between theory and experiment is connected with the correct accounting for the inter electron correlations, nuclear, 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.

In conclusion let us note that we have considered and used an effective theoretical scheme for estimating the hyperfine structure parameters of the lanthanides isotopes ^{165}Ho, ^{169}Tm and reached sufficiently high accuracy. Such theoretical estimates should be used in interpretation of the laser spectroscopy method measurement of lanthanide isotopes 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-selective ionization with mass-separation of obtained ions, is an example of perspective method for sensing the lanthanide isotopes.

Acknowledgement. The author would like to thank Prof. A.Glushkov for invaluable advices and useful critical comments. The support of the Abdus Salam International Centre for Theoretical Physics (Trieste, Italy) is very much acknowledged.

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