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ON SENSING NUCLEI OF THE ^{207}Bi AND ^{207}Pb ISOTOPES BY MEANS OF LASER SPECTROSCOPY OF HYPERFINE STRUCTURE

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Abstract. It is presented the new theoretical scheme for sensing different parameters of nuclei of the Bi, Pb isotopes on the basis of hyperfine structure spectroscopy of the corresponding atoms.

Keywords: sensing, laser technology, hyperfine structure, isotopes of Bi, Pb

О ДЕТЕКТРОВАНИИ ЯДЕР ИЗОТОПОВ ^{207}Bi И ^{207}Pb МЕТОДАМИ ЛАЗЕРНОЙ СПЕКТРОСКОПИИ СВЕРХТОНКОЙ СТРУКТУРЫ

О. Ю. Хецелиус

Аннотация. Рассмотрена новая теоретическая схема детектирования параметров ядер изотопов Bi, Pb на основе спектроскопии сверхтонкой структуры соответствующих атомов

Ключевые слова: детектирование, лазерная технология, теория сверхтонкой структуры, изотопы Bi, Pb

ПРО ДЕТЕКТУВАННЯ ЯДЕР ІЗОТОПІВ ^{207}Bi ТА ^{207}Pb МЕТОДАМИ ЛАЗЕРНОЇ СПЕКТРОСКОПІЇ НАДТОНКОЇ СТРУКТУРИ

О. Ю. Хецеліус

Анотація. Розглянута нова теоретична схема детектування параметрів ядер ізотопів Bi, Pb на основі спектроскопії надтонкої структури відповідних атомів.

Ключові слова: детектування, лазерна технологія, теорія надтонкої структури, ізотопи Bi, Pb

1. Introduction

A development of the effective nuclear schemes and technologies for sensing different nuclear properties, creation of the corresponding nuclear sensors are of a great importance in the modern nuclear physics and sensor science [1-11]. It allows further developing the modern as atomic and as nuclear theories too. Among the most important problems one could mention studying the nuclei, which are available in the little quantities, a search of the super dense nuclei, a laser governing by parameters of the proton and other beams and sensing their characteristics etc. An special interest attracts a study of the lanthanides isotopes, radioactive nuclei far of the stability boundary and other nuclei. The useful possibilities are provided by the modern laser methods and technologies (see, for example, [1,2]). Here an actual problem is a development of the accurate theoretical schemes for estimating the nuclear parameters and technical realization of the sensing technologies on their basis. The high sensibility and resolution ability of laser spectroscopy methods allows to investigate characteristics of the nuclei, which are available in the little quantities or complex nuclei, including the radioactive isotopes. As an example in ref. [12-14] it has been mentioned the CERN technical device for studying the short-lived nuclei, which are obtained on the mass-separator in the line with synchrocyclotron on 600 MeV (ISOLDE apparatus [1]). The shocking results have been obtained for odd neutron-deficit non-stable isotopes of $^{182-190}$Hg. During excitation of fluorescence by dye pulsed laser radiation the second harmonics of radiation were 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. It has been discovered the sharp changing of the middle square of the nuclear radius under transition from the nucleus of ^{186}Hg to the nucleus of ^{185}Hg. This changing has been interpreted as a sharp changing of the nuclear form (increasing the non-spherity and electric quadrupole moment) during decreasing the neutrons number. In refs. [11-16] we have developed a new effective theoretical scheme for sensing different parameters of nuclei, which are available in the little quantities with possibility of advancing corresponding nuclear technology. First of all, the speech is about an effective technology of separating the corresponding isotopes and nuclear isomers. In a whole the corresponding scheme is based on the experimental receiving the isotope beams on the CERN ISOLDE type apparatus (see detailed description in refs. [1-3]) and the prйcised theoretical and laser spectroscopy empirical estimating the hyperfine structure parameters, magnetic and electric moments of the isotope nucleus. Earlier we have estimated the hyperfine structure constants, magnetic and electric moments of a nucleus for the ^{235}U, ^{201}Hg and rare cosmic isotopes. Theory of the hyperfine structure calculation is based on the gauge-invariant quantum electro-dynamical (QED) perturbation theory (PT) with an account of the correlation (inter electron interaction corrections), nuclear and radiation QED effects [17,18]. In this paper we consider a possibility of using new effective theoretical scheme [13,14] for sensing different parameters for nuclei of the ^{207}Bi and ^{207}Pb isotopes. An attractive possibility is arisen to make more advanced the corresponding nuclear technology of the isotopes and isomers separation.

2. Hyperfine structure theory and generalized RMF model

The detailed description of calculating the hyperfine structure parameters and nuclear quadrupole moments has been earlier presented in refs. [11,17,18]. 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. [4-11]). Let us describe the key moments of the nuclear theoretical scheme. Full details of the whole method of calculating the hyperfine structure constants can be found in [4,11-16]. 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 [11]. The concrete nuclear model is based on 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 [20,21]. 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. The RMF model has 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. [20]), its ansatz is a Lagrangian or Hamiltonian that incorporates the effective, in-medium nucleon-nucleon interaction. Recently [4,18,20] the 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.[6,20] 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-NLC (see details in refs. [4,19,20]), which is among the most successful parameterizations available.

Further let us note 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

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

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. The core electron density is defined by iteration algorithm within QED procedure [17]. The radiative QED (the self-energy part of the Lamb shift and the vacuum polarization contribtuion) are accounted for within the QED formalism [18]. The hyperfine structure constants are defined by the radial integrals of the following type:

$$A=\{[(4,32587)10^{-4}Z^2\chi g_I]/(4\chi^2-1)\}\times$$
$$\times\int_0^\infty drr^2F(r)G(r)U(1/r^2,R),$$
$$B=\{7.2878\ 10^{-7}\ Z^3Q/[(4\chi^2-1)I(I-1)\}\times$$
$$\times\int_0^\infty drr^2[F^2(r)+G^2(r)U(1/r^2,R).$$

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).

3. Results and conclusions

As a studying object, we have considered the nuclei of isotopes of ^{207}Pb and ^{209}Vi. In the PT zeroth-order expansion the one-proton state (^{209}Bi) and one neutron hole state (^{207}Pb) are given as follows:

$$|^{209}\ \mathrm{Bi}>=\hat{a}^{+}_{1h9/2}\ |\ ^{208}Pb>$$

$$|^{207}\ \mathrm{Pb}>=\hat{b}_{3p3/2}\ |\ ^{208}Pb>$$

where $|\ ^{208}Pb>$ is the core ground state wave function and a^+ creates a proton (neutron) valence particle (hole). The charge density is defined in ref.[4, 18, 20]. The proton density is constructed from RMF model and normalized on the charge number Z. In ref. [4] there are given the corresponding model parameters for the RMF calculation. We carried out calculation (the Superatom-ISAN and RMF-G package [17,18] are used) the hyperfine structure parameter for ^{207}Pb and ^{209}Bi isotopes. In tables 1 we present the estimated values of the hyperfine structure and nuclear magnetic moment (in μ_N) calculated with the RMF parameter set HS, NL3, NLC together with available theoretical and experimental or compilation data [4].

Table 1

The hyperfine structure splitting Δν (in eV) and nuclear magnetic moment (NMM, in μ_N) for ^{207}Pb and ^{209}Bi isotopes

Parameter RMF set	Δν ^{209}Bi	Δν ^{207}Pb	NMM ^{209}Bi	NMM ^{207}Pb
HS [4]	6,349	1,383	5,064	0.672
NL3 [4]	5,664	1,375	4,519	0,668
Present	5,2820	1,3351	4,1792	0,6675
Experiment [21]	5,0840	1,2166	4,1106	0,6661

The key quantitative factor of agreement between our theory and experimental data is connected with the correct accounting for the inter electron correlations, nuclear, Breit and QED radiative corrections [10-20]. But, a non-account for the high-order correlations of p-h excitations (nuclear-core polarization effects etc.) probably provides a discrepancy between theoretical and experimental results. The obtained results allow us to conclude that the presented theory is quite effective approach to estimating the hyperfine structure parameters of such complex isotopes as the studied ^{207}Pb and ^{209}Bi isotopes. The obtained data about the hyperfine splitting should be used in order to give an accurate interpretation of the laser spectroscopy method measurement of the ^{207}Pb and ^{209}Bi isotopes spectra. The next step is in application of the laser multi-stepped photo-excitation scheme with using the isotopic shift on two or three step of low-stripe laser radiation. The high perspective method for sensing the studied isotopes (and more complex isotopes too) is based on a combination of the isotopic-selective ionization scheme with mass-separation technology of the obtained ions. In any case, its perspective from the theoretical point of view is absolutely obvious.

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