LASER SPECTROSCOPY ON THE HEAVY ION BEAMS*

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In the presented report the perspectives of the study of the electric charge and current space distributions in the nuclei by laser spectroscopy methods on the beams of the fast multiple charged ions are discussed. The calculations of both the level energies and widths in the H-like and He-like ions and of the isotopic shifts and hyperfine splitting in the optical spectra of these ions are performed . The project of the experimental set-up for these measurements is considered.

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Three main sources of information about the structure of the atomic nuclei are known:

1. radioactive decay;
2. nuclear reactions;
3. optical spectra of atoms and ions.

Some of the important nuclear properties (spins, electromagnetic moments, charge radii) have been observed for the first time using the third method. The laser spectroscopy is a modern variant of the classical optical spectroscopy, which, historically, has had a major impact on studies of the basic nuclear properties. The development of the dye laser with their:

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- high power density: > 10 mW/cm^2 or 10^{17} photons/cm$^2\cdot$ s,
- high spectral resolution: of the order of 1 MHz,
- perfect collimation: divergence < 20 mrad,
- tunability in a large spectral range: 400–800 nm,

revitalized the study of the optical spectra of the atoms as a source of nuclear information. The contemporary laser spectroscopic methods with their high resolution and high sensitivity solved the problem how to access to the basic nuclear ground and isomeric states in an efficient and unique way. Laser spectroscopic experiments have been performed in the last years on a large amount of nuclides (> 600) in long isotopic chains including short lived nuclei ($T_{1/2} > 1$ ms) and with a production rate down to 10^4 s^{-1} [1–3]. Different experimental methods are used for laser spectroscopic measurements, *e.g.* based on the resonance fluorescence, multi step ionization, or nuclear polarization. The high resolution laser spectrometer in the Flerov Laboratory of Nuclear Reactions at JINR is an example of an experimental setup using the laser-induced resonance fluorescence in an atomic beam. With this spectrometer, measurements of the isotope shift (IS) and hyperfine splitting (hfs) for more than 50 isotopes of 10 elements (Na, Ti, Zr, Nd, Sm, Eu, Gd, Hf, U, Am) have been performed. The results for the $^{44-50}$Ti isotope chain [4] and for the odd–odd ^{22}Na isotope [5] are of special interest. In the first case, an essential difference between Ti and Ca isotopes has been observed, concerning the general trend of the charge radii changes versus N at $N < 24$: a decrease of $\langle r^2 \rangle$ in the case of Ca and an increase for the Ti nuclei. In the second case, we succeeded in obtaining the sign and the value of the electric quadrupole moment of ^{22}Na, and thus, in determining the shape of this nucleus. The obtained value of the quadrupole deformation parameter $\beta_2 = 0.441(24)$ is lower than the one for the neighbouring ^{23}Na. At the same time, as follows from the IS data, these isotopes have practically the same ms charge radii ($\langle r^2 \rangle = 0.04$ fm^2). Both examples (Ti and Na) point to a broadening of the spatial distribution of the nuclear electric charge when approaching the proton drip line. Such effects are expected to be more important for light nuclei at the boundary of nuclear stability. Some of them have an unusually large spatial distribution of the last weekly bound nucleons (*e.g.* the neutron halo in ^{11}Li, ^{11}Be or the proton halo in ^{8}B [6]), which reflects on their charge radii, electric, and magnetic multipole moments. These are nuclear parameters which could be determined by laser spectroscopic measurements of the IS and hfs [7]. However, the interpretation of the IS in the light elements is subject to two major difficulties: *(i)* the field shift is negligible within the experimental errors and the value of

the IS is dominated by the mass shift; *(ii)* the specific mass shift is large and hard to allow for [8].

An effective way to overcome this hindrance seems to be the laser spectroscopy of multiple-charged H-like and He-like ions instead of the neutral atoms or single-charged ions. The much more simple energy level schemes of such multiple-charged ions allow precise calculations of the effects induced by the size and the mass of the nucleus, including the specific mass shift. The following peculiarities, concerning the spectroscopy of such ions must be emphasized:

1. Electronic levels: a part of the energy level scheme of H- and He-like ions is shown in Fig. 1 [9,10]. The levels $2^2S_{1/2}$ in H-like and 2^1S_0, 2^3S_1 in He-like ions are long-lived metastable states. As can be seen, they are situated close to the excited p-levels ($2^2P_{1/2}$ and $2^2P_{3/2}$ in H-like, 2^1P_1 and 2^3P_j, $j = 0, 1, 2$ in He-like ions). The wave-lengths necessary for excitation of the corresponding S–P transitions are presented in Table I. There are

TABLE I

Characteristics of the metastable levels of H-and He-like ions, and the laser radiation wavelengths to excite the p-levels.

Ion	Level term	E_m [keV]	τ_m [s]	$\lambda(s \to p)$ [nm]
Li^{+1}	$^1S_0$	0.061	$5.6 \cdot 10^{-4}$	956
	$^3S_1$	0.059	$4.5 \cdot 10^{1}$	548
Be^{+2}	$^1S_0$	0.122	$5.5 \cdot 10^{-5}$	617
	$^3S_1$	0.119	$1.7 \cdot 10^{0}$	372
B^{+3}	$^1S_0$	0.203	$1.2 \cdot 10^{-5}$	448
	$^3S_1$	0.199	$1.3 \cdot 10^{-1}$	283
C^{+1}	$^1S_0$	0.304	$3.0 \cdot 10^{-6}$	353
	$^3S_1$	0.299	$2.0 \cdot 10^{-2}$	227
N^{+5}	$^1S_0$	0.425	$1.3 \cdot 10^{-6}$	288
	$^3S_1$	0.420	$3.5 \cdot 10^{-3}$	191
O^{+6}	$^1S_0$	0.569	$4.3 \cdot 10^{-7}$	246
O^{+7}	$^2S_{1/2}$	0.654	$4.6 \cdot 10^{-7}$	6990
F^{+8}	$^2S_{1/2}$	0.825	$2.9 \cdot 10^{-7}$	4480
Ne^{+9}	$^2S_{1/2}$	1.02	$1.2 \cdot 10^{-7}$	2850
Na^{+10}	$^2S_{1/2}$	1.24	$8.2 \cdot 10^{-8}$	1940
Mg^{+11}	$^2S_{1/2}$	1.47	$4.1 \cdot 10^{-8}$	1365
Al^{+12}	$^2S_{1/2}$	1.73	$2.9 \cdot 10^{-8}$	990
Si^{+13}	$^2S_{1/2}$	2.04	$1.6 \cdot 10^{-8}$	740
P^{+14}	$^2S_{1/2}$	2.30	$1.1 \cdot 10^{-8}$	556
S^{+15}	$^2S_{1/2}$	2.62	$7.2 \cdot 10^{-9}$	450
Ar^{+17}	$^2S_{1/2}$	3.31	$4.5 \cdot 10^{-9}$	266
Ca^{+19}	$^2S_{1/2}$	4.10	$1.8 \cdot 10^{-9}$	174

many cases of transitions in the optical range which are accessible for lasers of different type. For the light elements He–Ne it is convenient to use He-like ions ($2^1S_0 \rightarrow 2^1P_1$ and $2^3S_1 \rightarrow 2^3P_0$ transitions) and for the more heavy ones Ne–Ar ($2^2S_{1/2} \rightarrow 2^2P_{3/2}$ transitions) and Ca–Sn ($2^2S_{1/2} \rightarrow 2^2P_{1/2}$ transitions) the H-like ions.

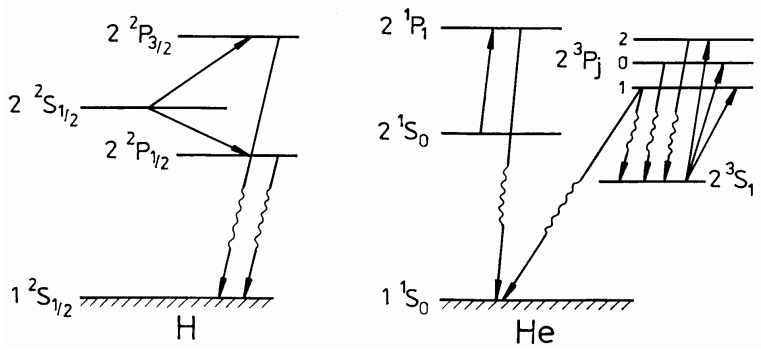

Fig. 1. Level scheme of H-like and He-like ions

2. Resolution. Since the parity of the p-levels is negative, they decay to the ground $1s$ and to the metastable $2s$ by E1-transitions. As a rule, the half-lives of the p-levels are very short ($< 10^{-11}$ s) and their widths are large (> 100 GHz). This is obviously a factor limiting the accuracy of the IS and hfs measurements for the transitions including the p-levels. However, this is not the case for the 2^3P_0 and 2^3P_2 levels in He-like ions, for which the transitions to the $1s$ ground state are forbidden by the selection rules and only the low energy transitions to the 2^3S_1 metastable state are allowed. This results in larger half-lives and smaller widths (< 100 MHz for elements with $Z < 10$) of the p-levels in question and, therefore, high accuracy could be obtained by excitation of these levels.

3. Extraction of mean square radii changes. The most simple case are the H-like ions. As known [1], the specific mass shift is induced by the correlated movement of the electrons in the Coulomb field of the nucleus and in the case of a single electron it is zero. Thus, only the normal mass shift between two isotopes 1 and 2

$$\Delta\nu_{\mathrm{MS}} = \frac{c}{\lambda}\frac{m(M_1 - M_2)}{M_1 M_2}, \tag{1}$$

is important and can be calculated from Eq. (1) with high precision. Here λ is the wave-length of the radiation, c — the light speed, m — the mass of the electron, M_1 and M_2 — the isotope masses. The field shift of a given atom

or ion level depends on the level quantum numbers. In the case of the H- and He-like ions considered here, the field shift of the $2s$-levels is the most important one. Its value, *e.g.* for the H-like $^2S_{1/2} \rightarrow^2 P_{1/2,3/2}$ transition, is determined by the relation [8]

$$\Delta\nu_{\mathrm{FS}} = 1.21 \cdot 10^{-4} Z^4 \Delta\langle r^2\rangle \ \mathrm{GHz/fm^2}\,, \tag{2}$$

where $\Delta\langle r^2\rangle$ is the mean-square charge radii change ($\langle r^2\rangle = 3/5 \cdot R^2$). The dependence of the field shift on Z according to Eq. (2) at $\Delta\langle r^2\rangle = 1\ \mathrm{fm}^2$ is shown in Fig. 2. The situation for the He-like ions with two electrons is more complicated. The mass and field shifts for $1s$-, $2s$- and $2p$-electrons have been calculated first by the non-relativistic Hartree–Fock method, followed by a number of corrections, *e.g.* relativistic effects and vacuum polarization [8]. The obtained dependence of the $\Delta\nu_{FS}$ on Z for He-like ions is nearly the same as for H-like one (see Fig. 2). For comparison the field shift of the neutral alkali atoms is also presented in Fig. 2. As can be seen, the ion field shift is much larger than the one of the neutral atoms. The difference grows rapidly with increasing Z. This effect is connected with the more strong electron-nucleus interaction due to the shorter distance between $2s$ electron and the nucleus.

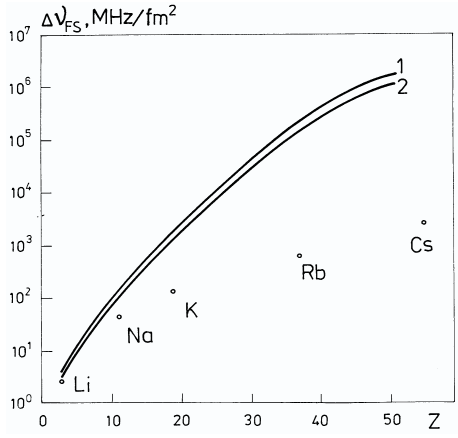

Fig. 2. Dependence of the volume shift on the atomic number Z: 1 — H-like ions, 2 — He-like ions, dots — neutral atoms.

4. Hyperfine splitting. The small distance between the nucleus and the $1s$-electrons in H-like ions induces a strong level hfs. The splitting between both hfs components $F_1 = F - 1/2$ and $F_2 = F + 1/2$ (F is the total angular momentum) can be expressed by the relation:

$$\Delta\nu(F_1, F_2) = \frac{4}{3}\frac{(2I+1)hc\mathrm{Ry}\mu\alpha^2 Z^3}{I}\,. \tag{3}$$

Here Ry is the Rydberg constant,μ — the magnetic dipole moment of the nucleus, α — the fine structure constant. The $\Delta\nu(F_1, F_2)$ value increases very fast with Z and for elements with $Z > 50$ it is in the region of the optical transitions, *i.e.* a laser excitation, and, therefore, precise measurements of the hfs become possible. This means that the nuclear magnetic moments could be determined with a high accuracy and interesting information about the spatial distribution of the electric current in the nucleus could be obtained.

5. Ion production. H- and He-like ions could be produced by different methods:

(a) in the process of laser radiation-matter interaction using high power pulse lasers;

(b) in ECR ion sources using high energy electrons for atom ionization;

(c) in the transmission of accelerated ion beams through thin targets.

The first two ways are suitable for the production of H- and He-like ions of light nuclei: with $Z < 20$. For heavier elements (up to uranium) the third method seems be to the most effective one. It is possible to obtain a dominating yield of H- or He-like ions, selecting the appropriate energy of the accelerated ion beam.

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