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High-Resolution Laser Spectrometer for Fundamental and Applied Research

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Abstract—The first Russian high-resolution tunable laser spectrometer based on a high-power cw Ar^+ pump laser is briefly described. The spectrometer is intended for precise nuclear physics investigations of hyperfine interactions. The spectrometer design and the block diagram of the laser experimental setup are considered. The main directions of fundamental and applied research are listed.

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INTRODUCTION

Fabrication of tunable laser spectrometers opened a new stage in the development of optical methods for investigating structures and properties of atomic nuclei on the basis of precise measurements of isotopic shifts and hyperfine splitting of optical lines in the spectra of atoms or ions [1]. It is known that effects of isotopic shifts and hyperfine splitting arise mainly as a result of isotopic differences in the distribution of the charge radii of nuclei and electromagnetic interaction between the electron shell of an atom and its nucleus, respectively. Unique properties of laser radiation (intensity, monochromaticity, and coherence) made it possible to significantly increase the precision and sensitivity of laser measurements and perform experiments with samples containing extremely small numbers of studied nuclei (atoms): to 10^6. As a result, it became possible to study radioactive nuclei lying at the boundary of nucleon stability and formed in nuclear reactions with low cross sections or existing in isomeric states of unusual nature, for example, having a high-spin state or an anomalously large deformation parameter [1–3].

High sensitivity of laser methods makes it possible to perform applied research in a wide range: in particular, study the nanostructure of materials; search for trace amounts of various environmental elements; separate isotopes; and apply laser radiation in medicine, optical holography, and control and data systems [4, 5].

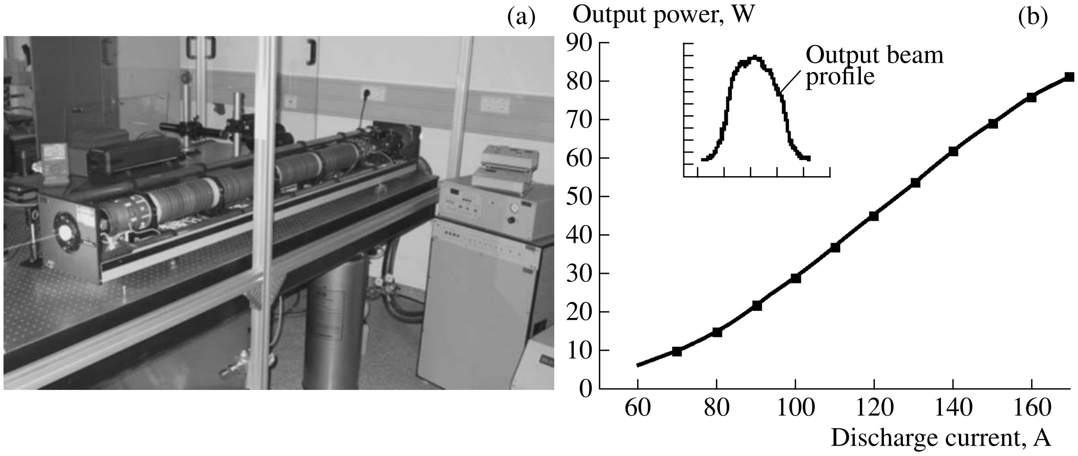

Fig. 1. (a) General view of the Inversion Ar pump laser (gas-discharge tube without a housing) and (b) the dependence of the output laser power on the discharge current through the tube. The output beam profile is shown in the inset, with the distance from the beam center and the beam intensity plotted on the *X* and *Y* axes, respectively.

SPECTROMETER DESIGN

A high-resolution tunable laser spectrometer for fundamental and applied research in nuclear physics is being developed at the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research (LNR JINR) (Dubna), with support of the Faculty of Physics of Adam Mickiewicz University (Poznan) and direct participation of the OOO Inversiya–Lazery, Institute of Automatics and Electrometry (Novosibirsk) and OOO Tekhnoskan, Novosibirsk State University. The spectrometer includes a blue-green ($\lambda = 488–514$ nm) Inversion cw Ar-ion pump laser (Novosibirsk) (Fig. 1) [6] with an output power of 12–15 W (at a discharge current of 100 A) and a DYE-SF-07 (or DYE-SF-077) single-frequency ring dye laser (Tekhnoskan) (Fig. 2) with smooth frequency scanning in a range of 5 GHz. At high-power pumping of the dye laser by the Inversion Ar laser, its output power in the single-frequency mode reaches 1 W. Figure 3 shows a schematic diagram of the arrangement of the pump laser and the dye laser with a frequency doubler.

The Inversion Ar laser produced in Russia differs from conventional pumped gas lasers produced abroad (Coherent Radiation, Spectra Physics) by two specific features: a large (7 mm) diameter of the discharge channel and a slow argon flow through the gas-discharge tube. The large channel diameter allows, first, to reach a high output laser power at a relatively small tube length, and, second, make the gas-discharge tube easily demountable (an important feature for long-term operation and replacement of units). The presence of a slow gas flow reduces accumulation of harmful impurities in the discharge tube.

The optical system of the argon laser consists of a double-mirror cavity with a length of about 130 cm. Replaceable internal mirrors with a diameter of 20 mm and a thickness of 7 mm have dielectric coatings, which makes it possible to select blue-green or blue lasing ranges, depending on the dye type used in the tunable laser and the choice of the fundamental transverse mode in the concave–convex optical configuration. The discharge tube lifetime -is no less than 2000 h.

The power supply of the Ar$^+$ laser consists of two blocks: a thyristor rectifier and a remote control unit. The operating current was set at a level of 120–140 A. Heat removal from the laser (at a level of no less than 40 kW) is performed using a self-regulating cooler—water–water heat exchanger with forced circulation of the cooling mixture through the internal circuit, directly connected with the heat-emitting laser elements, under a pressure of 2–2.5 atm and a flow rate of 30 l min^{-1}. Generally, the internal circuit of the heat exchanger is filled with a 30% solution of ethylene glycol in distilled water. Use of this mixture increases the discharge tube resource.

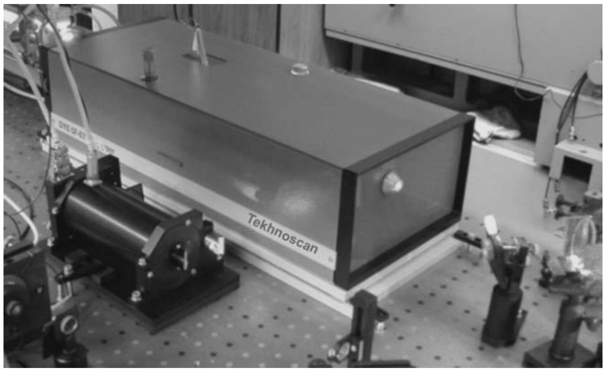

Fig. 2. General view of the DYE-SF-07(077) single-frequency ring laser in the housing.

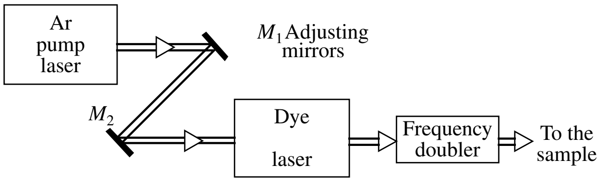

Fig. 3. Schematic arrangement of the main spectrometer components.

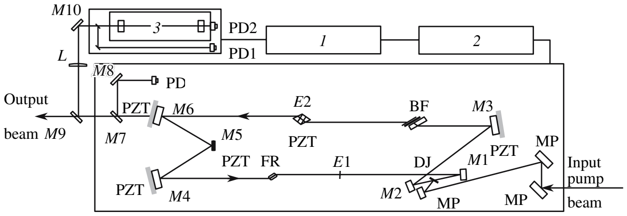

Fig. 4. Optical scheme of the DYE-SF-07(077) single-frequency-stabilized ring laser.

Figure 4 shows a schematic diagram of the optical elements of the DYE-SF-07 single-frequency cw ring dye laser (Russia): MP are pump mirrors, *M*1 and *M*2 are spherical mirrors (R = 75 mm, transmission $T <$ 0.2%), *M*3–*M*5 are flat mirrors ($T < 0.2\%$), *M*6 is a flat output mirror (T = 6–7%), *M*7–*M*10 are auxiliary (additional) mirrors, *L* is a adjusting lens; BF is a three-component birefringent filter, *E*1 is a thin Fabry–Perot reference (thickness $h = 0.1–0.5$ mm), *E*2 is a thick Fabry–Perot reference (h = 8 mm), FR is a polarization plane rotator based on the Faraday effect, PD are photodetectors, PZT are piezoelectric transducers, and DJ is the dye jet. The dye laser is pumped by a cw Ar$^+$ laser (488–514 nm) and its wavelength can be tuned in the range 570–700 nm.

The DYE-SF-077 single-frequency stabilized cw dye laser is an improved development, which expands possibilities of laser spectroscopy in investigation of hyperfine interactions. The mean-square output linewidth of this laser is less than 0.5 MHz, while the DYE SF 07 linewidth radiation is 10 MHz. The difference between these lasers is that the DYE-SF-077 laser is frequency-stabilized. This laser is equipped with two additional electronic control blocks (1 and 2 in Fig. 4), one of which provides operation in the single-frequency mode and the other controls the system of frequency stabilization. The stabilization system provides reliable locking of the output laser frequency and a sufficiently high noise immunity with the use of a reference interferometer. In other words, DYE-SF-077 is an actively frequency-stabilized laser, while DYE-SF-07 is a passively stabilized laser, whose frequency stability is set mainly by the laser cavity rigidity. The parameters of the interferometer used in the DYE-SF-077 laser are as follows: the free dispersion region is 750 MHz and the transmission peak width is 2–3 MHz. The line drift (no more than 40 MHz h^{-1}) is caused by a slow variation in the base of the reference interferometer due to the change in the surrounding air temperature. The interferometer is actively thermostated; however, the residual temperature instability leads to a slow drift of the lasing frequency. Actually, it does not exceed 20–25 MHz h^{-1}; nevertheless, a value smaller than 40 MHz h^{-1} is indicated in specification. For the U. Coherent laser, this parameter is generally 60 MHz h^{-1}.

The laser cavity has a horizontal orientation.

The laser spectrometer developed in Dubna will be equipped with a frequency doubler to ensure operation in the UV range, a data collection and processing system, power and wavelength meters, and a microprocessor control unit.

EXPERIMENTAL TECHNIQUE

It is planned to use the laser spectrometer described above in a wide range of experimental studies aimed at determining the charge and magnetic radii of nuclei, nuclear magnetic dipole and electrical quadrupole moments, and deformation parameters, including investigations on radioactive nuclei and fission fragments (within the Dubna Radioactive Ion Beams project) [7]. Measurement of the hyperfine structure (HFS) in optical spectra of atoms (ions) is one of the main methodical research lines in these investigations.

As was noted above, electromagnetic interaction between the nucleus and electron shell of an atom leads to hyperfine splitting of the thin multiplet components and, therefore, to the formation of HFS. The frequency spacing $\Delta\nu$ between the HFS resonances and the multiplet centroid can be written as [1]

$$\Delta\nu = \frac{A}{2}[F(F+1) - I(I+1) - J(J+1)] + O(F, I, J), \tag{1}$$

where $\mathbf{F}$ is the total momentum of the system, which is equal to the vector sum of the nucleus spin $\mathbf{I}$ and the electron shell spin $\mathbf{J}$; A is the of dipole magnetic hyperfine interaction constant, determined by the relation $A = g_I\frac{H_e(0)}{J}$ ($g_I = \frac{\mu_I}{I}$ is the gyromagnetic ratio, μ_I is the magnetic moment of a nucleus with a spin $I \neq 0$); and $O(F, I, J)$ is the coefficient of additional splitting caused by the higher order moments at quadrupole, octupole, and other interactions. Thus, the HFS of optical spectra relates atomic and nuclear physics and makes it possible to establish a number of nuclear characteristics.

A number of techniques will be used to determine the HFS arising in interaction of laser radiation with atoms, such as fluorescence of atoms or ions in a beam, a gas cell, or an electromagnetic trap; multistep ionization of atoms; optical pumping; light-induced drift; etc. The detailed description of these methods can be found in reviews [8, 9].

During the last three decades, experiments for investigation of nuclear characteristics have been performed with wide application of the method of laser fluorescence in a parallel atomic beam with the use of collinear [10] or orthogonal [10] measurement geometry. The resonant fluorescence cross section is on average about 10^{-12} cm^2. The attainable intensity of frequency-scanned laser radiation is ≥100 mW cm^{-2}, a value corresponding to a photon flux of about 10^{18} cm^{-2} s^{-1} and an excitation rate of a single atom of ~10^6 s^{-1}. This fact indicates that each atom entering the region of laser radiation action undergoes resonant excitation after 10^{-6} s, and, passing through the laser beam, is involved in several thousands of excitation–relaxation events.

In the orthogonal geometry, which will be used in the laser spectrometer developed in Dubna, atoms are excited at a right angle to the atomic beam direction. In this case, the laser frequency is not Doppler-shifted in the coordinate system of the moving atom; this is an important condition since the main requirement for experimental technique is a high resolution in lasing frequency, which makes it possible to determine HFS constants with a minimum possible error. Resonant fluorescence is measured at an angle of 90° to the propagation directions of the atomic and laser beams. Figure 5 shows a block diagram of the experimental laser setup. The beam of the DYE-SF-07 tunable dye laser pumped by the Inversion Ar$^+$ laser is resonantly scattered from the atomic beam emitted by the sample under study (Fig. 3). Two methods of atomization of the samples studied are used: their evaporation in a tantalum crucible heated by an electric current and irradiation by an LTIPCh high-power IR pulsed laser (peak power about 5 MW). The atomic beam is collimated by a system of diaphragms; its divergence in the laser radiation zone is about 0.015 rad. The fluorescence signal is detected by an FEU-136 photomultiplier operating in the single-photon count mode. The dependence of the resonance fluorescence intensity on the laser frequency (scanned in the specified range) is experimentally measured. This circumstance makes it possible to obtain a spec-

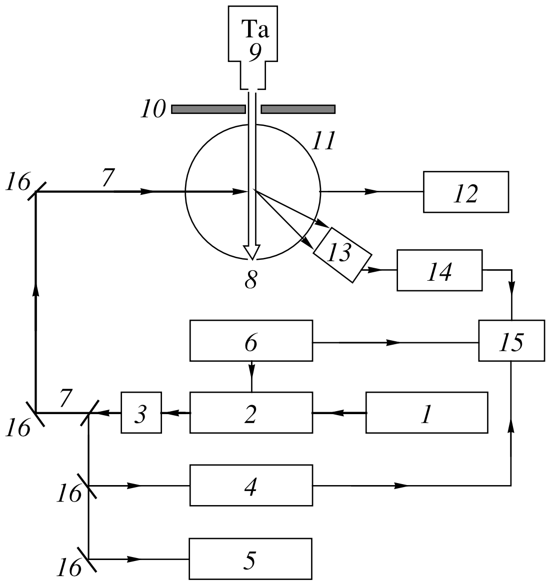

Fig. 5. Schematic of the experimental laser setup: (*1*) Ar pump laser, (*2*) dye laser, (*3*) frequency doubler, (*4*) confocal interferometer, (*5*) wavelength meter, (*6*) λ scanner, (*7*) laser beam, (*8*) atomic beam, (*9*) tantalum crucible, (*10*) collimator, (*11*) spherical mirror, (*12*) power meter, (*13*) photomultiplier, (*14*) amplifier, (*15*) personal computer, and (*16*) plane mirror.

trum including all HFS components for the element isotopes under study. A confocal Fabry–Perot interferometer with a constant of 150 MHz, whose frequency marks are recorded simultaneously with the measured spectrum, can be used for frequency calibration. The measured spectra are stored in the memory of a personal computer for subsequent treatment. A more detailed description of a similar experimental setup was given in [11, 12].

CONCLUSIONS

It should be noted that the improvement of the DYE-SF-077 ring dye laser will make it possible, as showed the developments in Novosibirsk, to reduce the mean-square lasing linewidth to 100 kHz. This reduction will significantly increase the laser spectrometer resolution and greatly extend its possibilities for investigating hyperfine interactions in nature.

In addition, the relatively simple demountable design of the gas-discharge tube in the Ar pump laser, gas flow mode, and the presence of a self-regulating heat exchanger for removing thermal load from the tube significantly simplify the argon laser operation. This circumstance allows one to use the spectrometer not only in fundamental and applied research but also for student training.

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