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Spectroscopy: from atoms to cosmic objects

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Abstract. A review is given of spectroscopic research pursued in the Division of Optics at the P N Lebedev Physical Institute (FIAN), which has yielded significant results in recent years. A case in point is primarily the development of instrumentation installed on board artificial Earth satellites and intended for the ultraviolet and X-ray spectroscopy of the solar corona. Furthermore, progress is reviewed in the area of precision atomic spectroscopy, where an arsenal of state-of-the-art techniques enables observing optical resonances ranging in width from several hertz to several hundred hertz.

1. Introduction

The research pursued in the Division of Optics at the P N Lebedev Physical Institute (FIAN in *Russ. abbr.*) of the Russian Academy of Sciences is widely diversified. The lines of research were developed by outstanding scientists. Sergei Ivanovich Vavilov, the founder of FIAN, supervised the activities of the Laboratory of Luminescence, which pursued extensive investigations of the processes accompanying the luminescence phenomenon in various media. Crucial experiments were conducted in this laboratory to elucidate the nature of the glow emerging in the motion of charged particles through media, which later received the name Vavilov–Cherenkov radiation and was awarded a Nobel Prize in Physics 1958. The Laboratory of Luminescence was engaged in the development of 'cold' light sources — luminescent lamps (which culminated in their production startup), which was awarded a State Prize in 1951. Outstanding scientists — V L Levshin, M D Galanin, and some others — were members of the laboratory staff. The USSR's first ruby laser was launched there. The Laboratory of Luminescence was succeeded by the S I Vavilov Department of Luminescence, which now leans heavily on luminescence techniques.

At the time FIAN was founded, the Optical Laboratory was set up, which was headed by Grigorii Samuilovich Landsberg — the co-discoverer of combination light scattering[1] (jointly with another outstanding FIAN staff member, Leonid Isaakovich Mandel'shtam). Owing to extensive research, in the Optical Laboratory the combination scattering effect turned into a powerful technique for the structural analysis of molecules. During the 'laser era', the Optical Laboratory was involved in research aimed at the development of new laser sources and the application of lasers to studying nonlinear light–medium interaction phenomena. Outstanding scientists were staff members of this laboratory: P A Bazhulin, I L Fabelinskii, M M Sushchinskii, S G Rautian, and some others. The successor of the Optical Laboratory is the G S Landsberg Optical Department, in which research is now pursued in different fields of modern optics, including nonlinear and quantum optics.

When commemorating the 75th anniversary of FIAN, there is good reason to enlarge on the achievements of the Department of Spectroscopy — one of the subdivisions of the Division of Optics. The Department of Spectroscopy is the heritor of the Laboratory of Spectral Analysis (more recently — the Laboratory of Spectroscopy), which was organized in 1944 and headed by Sergei Leonidovich Mandel'shtam.

2. Ultraviolet and X-ray spectroscopy of the Sun

With the advent of the 'space age' in our country, S L Mandel'shtam was the first to realize the promise of spectral investigations of cosmic objects employing instrumentation on board missiles and artificial Earth satellites. Even the second artificial satellite launched in the USSR in November 1957 accommodated instrumentation for recording X-ray solar radiation, which was developed and made at the FIAN Laboratory of Spectroscopy; the description of the instrumentation appeared in Ref. [1] even prior to the launch of the satellite (see also review [2]). Since then, extra-atmo-

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[1] In the international literature, combination light scattering is commonly referred to as Raman scattering. (*Translator's note.*)

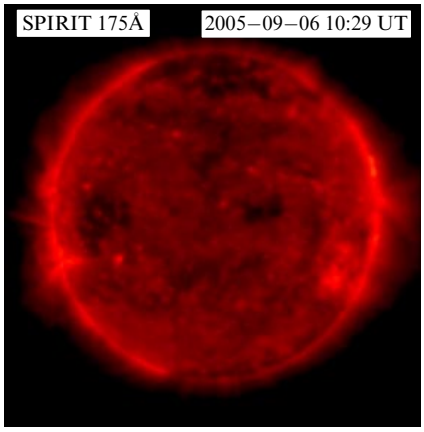

Figure 1. Solar image in emission of the (175 ± 5) Å spectral range, obtained using the short-wave UV telescope aboard the CORONAS-F satellite. The layer of quiet corona is easily discernible, as are numerous active regions heated to temperatures of about 10^6 K.

spheric spectroscopic observations of different cosmic objects has become vastly wider; the first solar image in X-rays was obtained [3].

When S L Mandel'shtam resigned to become Director of the Institute of Spectroscopy, which he had founded, the development of space instrumentation for studying the processes occurring on the Sun and in the solar corona was continued with the active support of I I Sobel'man, the Director of the Division of Optics. These investigations have yielded invaluable data on the mechanisms of the solar corona heating up to several million degrees, the generation and acceleration of the solar wind, and the nature of solar flares. Only X-ray radiation is capable of providing direct information about the current state of the highly inhomogeneous coronal plasma in the temperature range from dozens of thousands to several million degrees.

In the framework of the Complex Orbital Circumterrestrial Observations of Solar Activity (CORONAS in *Russ abbr.*) Program, several generations of instruments were developed and fabricated at the Department of Spectroscopy, which operated successfully aboard the CORONAS-I (1994) [4] and CORONAS-F (2001–2005) [5, 6] satellites and which started to operate aboard the CORONAS-Foton satellite launched in January 2009. The great bulk of data — 300,000 solar images with spectral, spatial, and temporal resolution — was obtained during the execution of the SPIRIT (Spectroheliographic Investigations using an X-Ray Imaging Telescope) experiment aboard the CORONAS-F satellite. The FIAN research instrumentation comprised four facilities [7]:

(1) A telescope for sequential recording of solar images in four spectral ranges: 175 ± 5 Å, 195 ± 6 Å, 284 ± 8 Å, and 304 ± 8 Å. Emitting in these ranges are the He II (304 Å) and Fe IX (171 Å) ions of the quiet corona, and the Fe XV (284 Å) and Fe XII (192 Å) ions of the active regions. These images bear information about coronal regions with temperatures ranging from 5×10^4 to 2×10^6 K. The image angular resolution is 2.5 seconds of arc (which is nearly one thousandth of the solar angular diameter). Figure 1 shows a solar image in radiation of the (175 ± 5) Å wavelength range, which is dominated by ion lines with excitation temperatures of about 10^6 K. The coronal lower layer with numerous active regions is clearly visible.

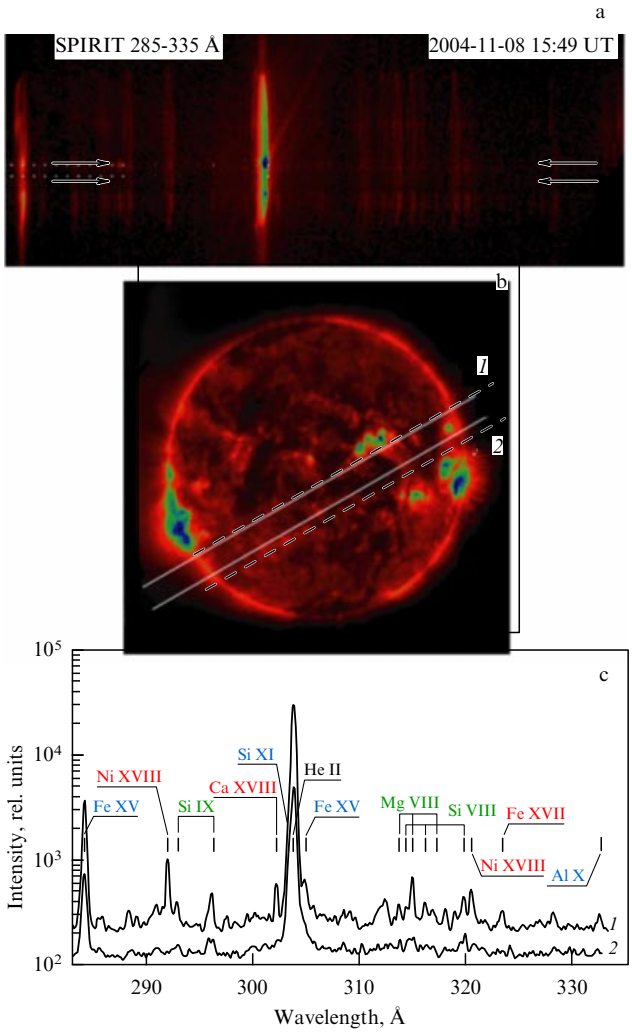

Figure 2. Solar spectroheliogram (reversed image) in the 285–335 Å wavelength range (a) and simultaneous solar image in emission with a wavelength of 175 Å (b). Two spectra (c) correspond to the integral luminosity of the regions disposed along dashed lines *1* and *2* in Fig. 2b.

(2) A coronagraph (telescope) for the simultaneous recording of solar images in two spectral ranges, (171 ± 3) Å and (304 ± 15) Å, with an angular resolution of 2.6 seconds of arc. This telescope is equipped with aperture stops, which enable screening the solar disk and thereby obtaining corona images at considerable distances from the disk (up to 5 solar radii).

(3) A spectroheliograph intended for recording solar spectra in two wavelength ranges: 177–207 Å, and 285–335 Å. This is a slitless spectrograph with a low angular image magnification in the direction of spectral dispersion. Emission lines of several dozen ions are observed in the above spectral ranges, allowing their use for the detailed diagnostics of individual coronal plasma regions in the temperature range from 5×10^4 to 1.5×10^7 K. This range spans virtually all temperature layers of the solar corona. Figure 2a displays a solar spectroheliogram in the 285–335 Å wavelength range, and Fig. 2b presents a simultaneous disk image in emission with a wavelength of 304 Å dominated by the He II line; the two spectra in Fig. 2c with the indication of the several classified emission lines correspond to the integral luminosity of the regions disposed along the dashed lines *1* and *2*. Using the spectroheliographic data, the list of observable lines

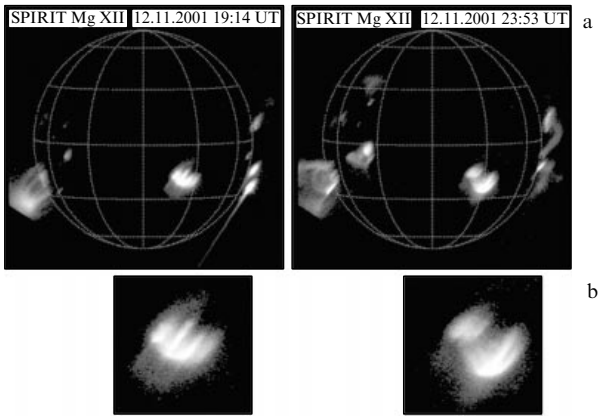

Figure 3. (a) Two solar corona images in 8.4 Å emission (Mg XII line) recorded at an interval of several hours. One can see only flare events with a temperature of about 8×10^6 K, which are remote from the photosphere — up to 0.3 solar radii. (b) Scaled-up individual flare images.

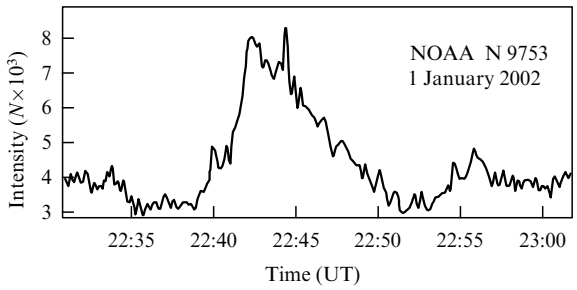

Figure 4. Time dependence of the radiation intensity from the NOAA 9753 active region of coronal plasma in the 8.42 Å line of Mg XII recorded on 1 January 2002, which clearly exposes the minute-scale dynamics of the plasma with a temperature of about 8×10^6 K. (N is the number of counts.)

was broadened (from 100 to 160), and it was possible to diagnose the electron density, the ionic and chemical composition, and the differential emission measure of different structures of the solar corona, including coronal holes and flares.

(4) A heliograph for recording solar images in the Mg XII ion emission at a wavelength of 8.42 Å. This line is excited at plasma temperatures of $(8-10) \times 10^6$ K. Figure 3 shows two sequential solar images recorded with this instrument. One can see that the plasma with the above temperature appears in the form of local coronal regions lying quite remote from the photosphere (up to 0.3 solar radii). Some of the discovered high-temperature plasma objects exist in the form of bursts with the periods of several minutes and several hundred minutes. The mechanism of plasma heating to a temperature of several million degrees remains an intriguing enigma of solar physics.

A characteristic feature of the modern instrumentation developed in the FIAN Department of Spectroscopy for ultraviolet (UV) and X-ray solar research is the application of matrix radiation detectors — CCD arrays (a CCD is a charge-coupled device). In combination with a special-purpose on-board computer, not only do these detectors provide a high spatial resolution, but they also enable observing the dynamics of local events in a time down to several seconds. This is particularly important for the recording of relatively infrequent and unpredictable events like solar flares.

During the operation of the CORONAS-F satellite, about one hundred flare spectroheliograms were obtained, with more than twenty flares belonging to the highest-power category X. Furthermore, the polarization of radiation was measured for more than 90 flares, including the most intense ones in October–November 2003. The X-ray radiation of the X10 class flare on 29 October 2003 was recorded to possess a high (up to 80%) degree of polarization. These data are of paramount importance in the diagnostics of processes involving explosive energy release in the solar corona. Figure 4 depicts the time dependence of the 8.42 Å line radiation intensity from the NOAA 9753 active region of coronal plasma recorded on 1 January 2002. One can see that plasma heated to a temperature above 4×10^6 K is formed within several minutes.

The developers of the research instrumentation for the CORONAS-F satellite solar observatory were awarded a 2008 Prize from the Government of the Russian Federation. Among the recipients of the award were staff members of the Department of Spectroscopy, I A Zhitnik and S V Kuzin — the leaders in the development of the X-ray instruments. The FIAN data bank, which now contains about one hundred thousand UV and X-ray spectroheliograms, is a major contribution to the world's data base for researchers in the field of solar physics.

3. Precision atomic spectroscopy

Let us turn to a different area of research, which is actively pursued at the Department of Spectroscopy of the FIAN Division of Optics — precision atomic spectroscopy. This research sprang up at FIAN in 1977 owing to N G Basov's support and the effort of I I Sobel'man, who organized the pursuance of experiments on parity nonconservation in atomic bismuth. In the late 1980s, when I I Sobel'man become leader of the Division of Optics at FIAN, spectroscopic research was aimed at the quest for ultranarrow resonances in atomic transitions induced by laser radiation. This research plays an important role in the solution to a diversity of problems, ranging from the development of optical frequency standards to the quest for the drift of world constants [8].

The pursuance of investigations in the area of precision atomic spectroscopy calls for the mastering and application of several experimental techniques. These include: the precision tuning of semiconductor laser frequencies and their matching to other reference frequencies, cooling of atoms in beams and traps, observation of narrow resonances specific to the bichromatic laser excitation of dipole-forbidden atomic transitions, and matching of optical frequencies to each other and to radio frequencies via femtosecond laser modes. We now turn our attention to examples of the investigations performed at the Department of Spectroscopy today.

One of the lines of inquiry in precision spectroscopy is the observation of narrow resonances of coherent population trapping in atoms. This resonance emerges in the excitation of a dipole-forbidden atomic transition by the radiation of two lasers via a third level which is dipole-coupled with the former two [for instance, in a Λ-scheme (see the inset to Fig. 5)].

Several observations of coherent population trapping resonances were performed in a cell with atomic samarium

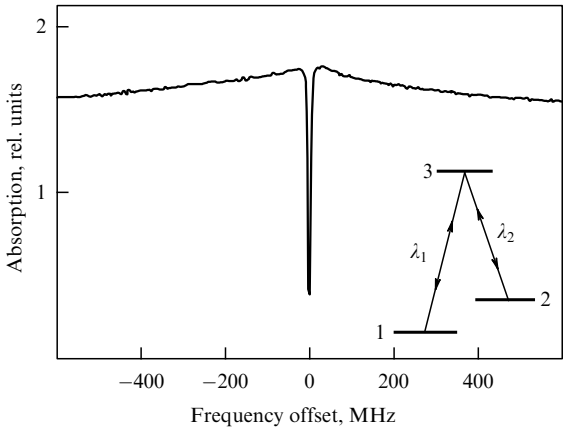

Figure 5. Resonance of coherent population trapping in a cell with ^{154}Sm vapor under the action of a bichromatic field, when the second laser radiation frequency is scanned about $\lambda_2 = 686$ nm [9]. The inset shows the energy level diagram of the atom: 1 — level $4f^6 6s^2$ ($J = 0$), 2 — $4f^6 6s^2$ ($J = 1$), and 3 — $4f^6 6s6p$ ($J = 1$).

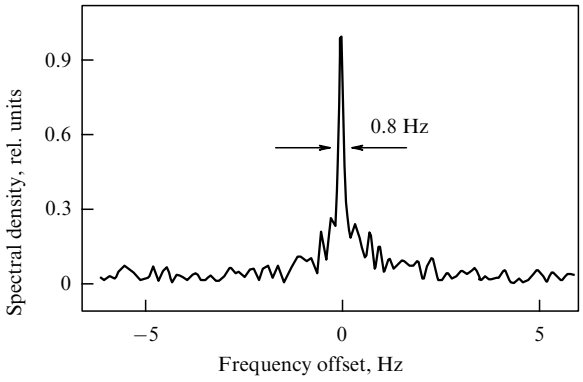

Figure 6. Beat signal of the frequencies of two semiconductor lasers stabilized relative to femtosecond radiation modes [12]. Although the initial difference beat frequency is far beyond the radio-frequency range of the conventional electronic equipment operated, in the stabilization scheme it is reduced by an integer number of mode spacings to become comparable to the frequencies of stable radio-frequency generators.

(^{154}Sm) vapor [9, 10]. Two semiconductor lasers with wavelengths $\lambda_1 = 672$ nm and $\lambda_2 = 686$ nm were employed for the excitation. The first laser was tuned to the 1–3 transition frequency via interferometric stabilization, while the second laser frequency was scanned about the 2–3 transition frequency. If the population trapping effect is ignored, the radiation of the second laser scans the absorption profile of the 2–3 transition with a width of several hundred megahertz. However, when the difference between the laser frequencies is exactly coincident with the 1–2 transition frequency (because this transition is dipole-forbidden, the uncertainty of its frequency is minimum), a significant lowering in absorption is observed (see Fig. 5). The spectral width of the absorption dip is determined by technical circumstances, in this case by the radiation linewidth of the second laser (several megahertz).

The central problem with the realization of these experiments is the relative radiation frequency stabilization of the lasers to better than the width of the expected resonance. When the frequency difference exceeds several dozen gigahertz, the most efficient way of stabilizing the frequency difference is referencing them to the longitudinal modes of a femtosecond laser. Owing to the broad output spectrum and suppression of the dispersion irregularity of femtosecond laser modes, it is possible to precisely couple the frequencies of two semiconductor lasers to the modes in the case of a substantial frequency difference.

The idea of using a femtosecond laser frequency 'comb' to stabilize the difference between laser frequencies and couple them to radio-frequency oscillators was conceived in T W Hänsch's laboratory (Nobel Prize in Physics 2005, Max-Planck Institute for Quantum Optics, Garching, Germany) [11]; staff members of the FIAN Department of Spectroscopy have cooperated with this laboratory for many years. Due to implementation of the method of coupling the frequency of a semiconductor laser to one of the femtosecond radiation modes, it has been possible to achieve stability at a level of ≈ 1 Hz (for a measurement period of 1 s) [12]. When frequencies of two lasers (for the observation of coherent population trapping resonances) were coupled to different femtosecond radiation modes, it was possible to stabilize the frequency difference with an accuracy of about 1 Hz [12, 13] (Fig. 6). This allowed performing several experiments involving observations of coherent population trapping with rubidium atoms in a vapor cell [12, 14], where the resonance widths were determined not by the properties of laser radiation but by the atom–light beam interaction time and were equal to several hundred hertz [14].

An important prerequisite to the observation of narrow atomic resonances is suppression of the Doppler broadening of atomic transitions. To this end, at the Department of Spectroscopy the experiments are performed with atoms cooled in a magnetooptical trap. The trap is made up of six orthogonally intersecting laser beams with specially selected frequency detuning. In combination with a gradient magnetic field, the beam intersection region forms a potential well for atoms.

Figure 7 displays a photograph of the facility with the magnetooptical trap in a vacuum cell with rubidium vapor,

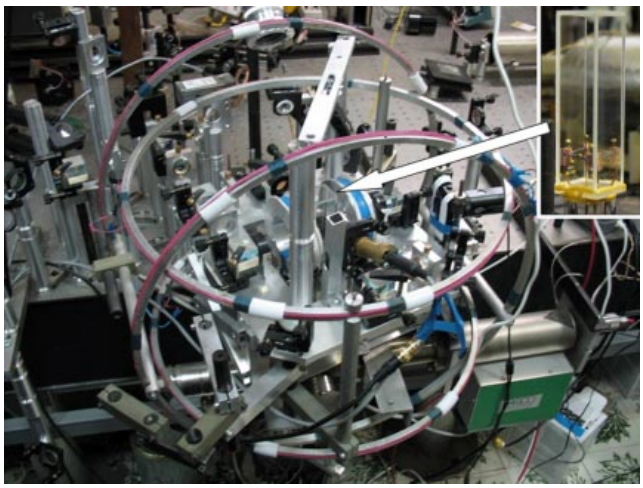

Figure 7. Photograph of the setup with a magnetooptical trap for rubidium atoms. The inset shows the cell with rubidium vapor; the cell is located at the center of the setup. Ring-shaped coils (approximately 50 cm in diameter), which induce the magnetic field of the requisite configuration, are clearly seen.

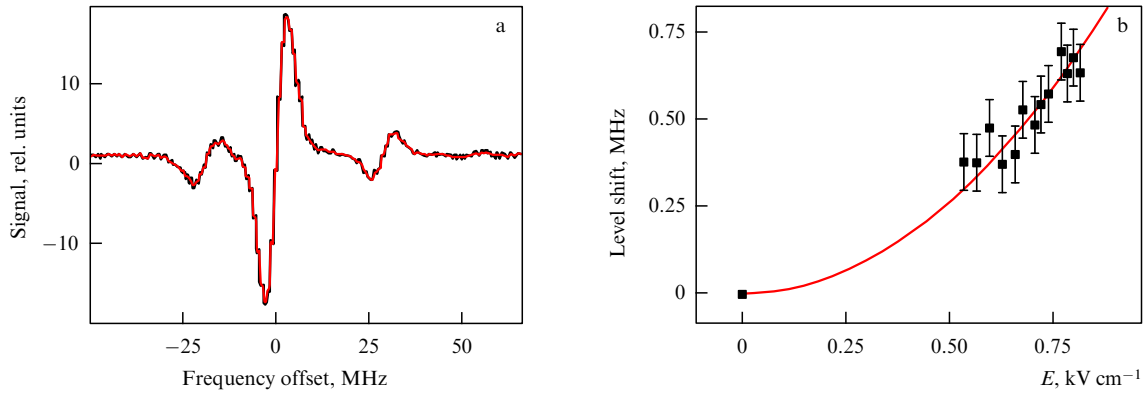

Figure 8. (a) Synchronous detection signal of the frequency sweep amplitude of the $5P_{3/2}-5D_{5/2}$ ($\lambda = 776$ nm) rubidium atomic transition on application of a slowly varying electric field plotted as a function of probe radiation frequency offset. (b) Frequency Stark shift as a function of electric field strength E calculated from the observational data (the solid curve is the best quadratic approximation).

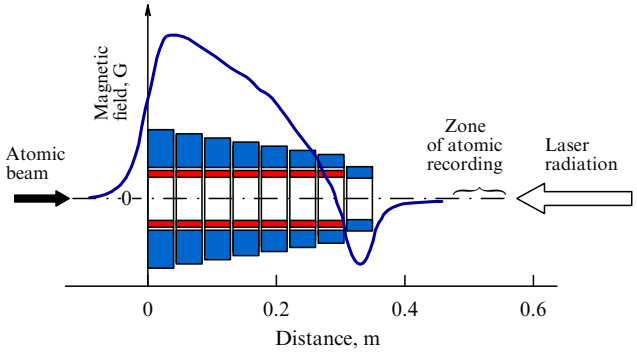

Figure 9. Schematic of the Zeeman neutral atomic beam cooler made up of a set of solenoids. The curve depicts the magnetic field induction as a function of the longitudinal coordinate. The atomic velocity distribution is monitored at the output of the cooler, where the action of a magnetic field is negligible.

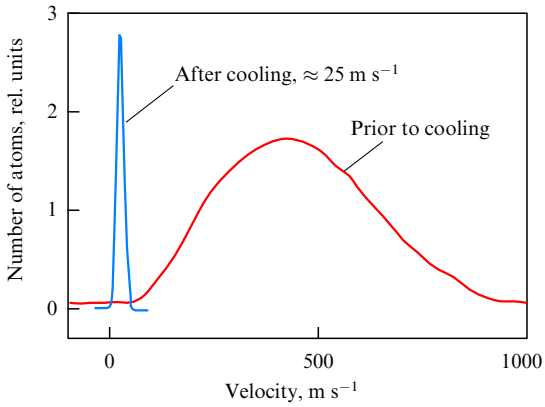

Figure 10. Atomic velocity distribution prior to and after cooling in the Zeeman cooler (nonnormalized). The data were obtained from the shape of absorption line of probing laser radiation.

with a cloud of cooled atoms at its center. One can clearly see ring-shaped coils (about 50 cm in diameter) intended for inducing a magnetic field with the requisite configuration. The inset shows the pumped glass cell with rubidium vapor measuring $30 \times 30 \times 120$ mm. An atomic cloud with a size of approximately 100 μm at the cell center contains about 10^6 atoms, and the temperature of captured atoms is close to 10^{-4} K.

A cooled atomic cloud lends itself conveniently to diverse measurements. In particular, measurements were made of the Stark shifts for excited atomic states (quadratic Stark effect). Measurements involving the $5D_{5/2}$ level of atomic rubidium are exemplified in Fig. 8. Figure 8a exhibits the synchronous detection signal for the intensity of fluorescence from the $5D_{5/2}$ level in the measurement of absorption on the $5P_{3/2}-5D_{5/2}$ transition upon application of a quasisteady (harmonically varying) electric field to the cell. When the wavelength of laser radiation is scanned, the recorded amplitude of the synchronous detection signal at the doubled frequency of the electric field is the differential profile of the transition under investigation, and is proportional to the dynamic atomic polarizability, i.e., to the Stark shift. The data on transition frequency shift versus electric field strength are summarized in Fig. 8b: the quadratic run of the curve is evident. The appropriate proportionality constant relating the frequency shift to the square of the electric field strength equals (2.0 ± 0.1) MHz kV^2 cm^{-2}. The methods of measuring the strength of a low-frequency electric field are of interest in connection with the problem of measuring the T-odd electric dipole moment of the neutron [15].

A new step forward in precision atomic spectroscopy involves moving to atoms with an open f-shell — erbium (Er), thulium (Tm), ytterbium (Yb), and other lanthanides. In these atoms, optical resonances arising from inner electron transitions are shielded from external action by the closed outer electron shell. This has the effect that some resonances not only turn out to be narrow but also have a low sensitivity to perturbations. It is precisely this circumstance that was the reason for staging experiments with thulium atoms at the Department of Spectroscopy.

Thulium occurs in nature in the form of a single isotope; its atom possesses a simple hyperfine level structure. To date, the cooling of atomic thulium has not been reported in the scientific literature. Because of the low density of thulium vapor, filling the magnetooptical trap requires a beam of preliminarily cooled atoms. The beam of thulium atoms is cooled employing the so-called Zeeman cooler (Fig. 9): the beam of atoms travels through a region of a nonuniform magnetic field in the opposite direction to the cooling laser beam. The magnitude of the shift of one of atomic sublevels in the magnetic field is matched to the Doppler shift of the atomic transition in such a way as to retain the optimal

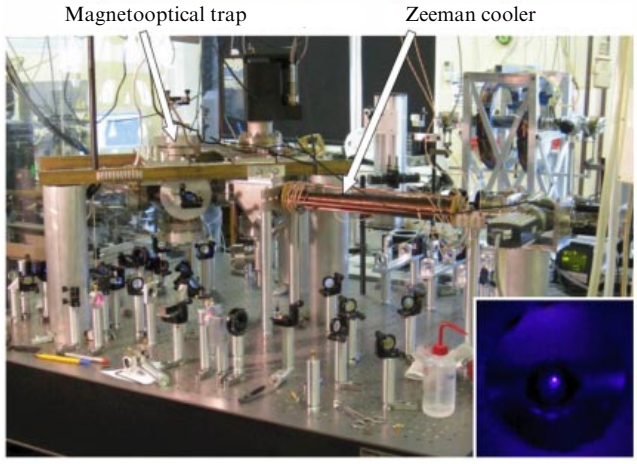

Figure 11. Facility with a magnetooptical trap for thulium atoms and a Zeeman atomic beam cooler (35 cm in length). The inset shows a photograph of the cloud of cold thulium atoms in the fluorescence light with a wavelength of 410 nm, which was taken through the trap window.

cooling conditions in the course of atomic deceleration. As a result, on exiting the region of the magnetic field the velocities of a substantial fraction of atoms are as low as several dozen meters per second (Fig. 10). It is precisely this atomic fraction that is subsequently captured by the magnetooptical trap with six orthogonally counterpropagating laser beams.

Figure 11 demonstrates a photograph of the facility with a magnetooptical trap for thulium atoms and a Zeeman beam cooler. Shown in the inset is a photograph of the atomic thulium cloud in the trap (a small bright spot at the center) in the light of atomic fluorescence at a wavelength of 410 nm. The number of atoms in the cloud is on the order of 10^6, the cloud measures less than 1 mm, and the temperature of trapped atoms is about 10^{-3} K.

Putting into service the facility with cooled thulium atoms opens up new possibilities in studies of ultranarrow optical resonances suitable for metrology applications and the development of a new generation of optical 'clocks'.

4. Conclusion

Only two lines of research pursued at the FIAN Division of Optics were mentioned above. Among other spectroscopic areas are studies of plasmas of different origins (laser-produced and electric-discharge plasmas) employing UV and X-ray radiation, as well as applied research into detection of small amounts of substances by different techniques. Special mention should be made of the investigations involving the development and operation of instrumentation intended for analyzing the altitude distribution of atmospheric ozone from the radiation of the millimeter wave range. The avenues of research listed above are traditional for the Division of Optics. A new trend in modern spectroscopy is the treatment of few-atom or few-molecule objects, for which the first-priority tasks involve investigations of their collective quantum behavior and sensitivity to local environment. Work in this area in the FIAN Division of Optics is still in its infancy.

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