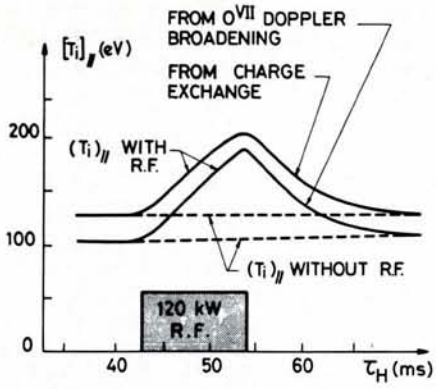

Fig. 4. Two determinations of $(T_i)_{//}$ by charge exchange and Doppler broadening on the Tokamak WEGA.

(at the Ioffe Institute) and WEGA (at the Grenoble Laboratory), but the most conclusive results are those obtained very recently (September 1977) on the Tokamak WEGA. In this machine, by injecting an RF power larger than the ohmic heating, it has been shown that the ion temperature was doubled. The maximum RF power which was launched in WEGA was 180 kW without any perturbation of the M.H.D. equilibria and deleterious effects. The measurement made by charge exchange, Fig. 4, and Doppler broadening of OVII, CV, and CIV lines along the direction of the toroidal magnetic field demonstrate without doubt that the ions of the plasma bulk, near to the discharge axis are heated. The location of these lines in the plasma are deduced from the electron temperature measurement by Thomson scattering, Fig. 5. Their evolution proves that the RF energy is first deposited in the bulk, which is later cooled by the impurities coming from the walls. The perpendicular ion energy distribution has again an energetic tail, which does not produce disruptive discharge as in the case of I.C.R.H.

Further experiments at higher power are needed to extend the scaling law of this heating process.

Future of RF heating

On the basis of the present experimental situation, L.H.R.H., T.T.M.P. and finally I.C.R.H. are three leading candidates for providing the additional heating needed for a large thermonuclear device. Yet, due partly to the simpler physical mechanisms involved, successful preliminary tests and historical reasons, world effort in additional heating is concentrating on neutral beam injection. This solution requires however, an important source development and two questions remain still open : the efficiency and the tolerance of the neutral beam source to an intense neutron flux coming from the reactor.

The situation is more favourable in the case of an RF heating scheme. Indeed the development required for

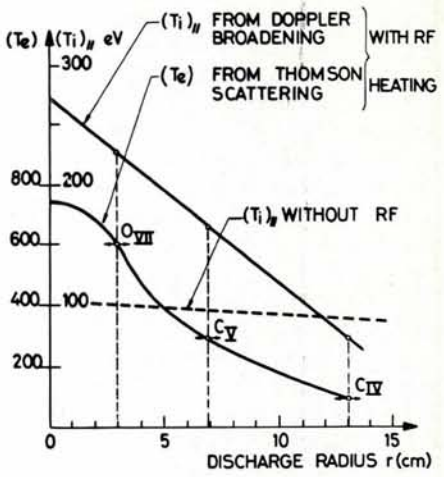

Fig. 5. Location of OVII, CV, CIV lines as a function of the electron temperature profile. $T_e(r)$ - $(T_i)_{//}$ is maximum at the centre of the discharge.

a 50-100 MW emitter at low ($f < 60$ MHz) and medium ($f < 3$ GHz) frequencies is very moderate compared to the work required for neutral beam injection. Efficiency is higher and in contrast to a neutral beam source, an RF emitter can be put very far from the neutron flux, and the wave transmitted and launched with an RF line, coupled to the plasma preferably by external coils or by wave guides.

It is hoped that as further progress is made on RF heating, it will receive a bigger share of attention in future programmes.

Non-Linear Optical Resonances and their Applications

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The production of narrow and frequency-stable resonances in absorption or emission spectra of substances over various ranges of electromagnetic radiation has always been an important problem in physics. Every discovery in this direction increases the accuracy of physical experiments and finds wide use in various fields of science and technology. Let us recall the two classical examples.

In the 1940s and 1950s, a technique was evolved of producing narrow resonances in the microwave frequency range using atomic and molecular beams. For example, Ramsey, using two separated electromagnetic fields interacting with a beam of Cs atoms at the transition between the hfs levels of the ground state, was able to obtain resonances with the width $\Delta\nu/\nu_0 = 5.10^{-9}$, in other words, with a "quality" (resolution) of resonance $R = \nu_0/\Delta\nu = 2.10^8$. Narrow microwave resonance has formed the basis for quantum frequency standards and the universally adopted atomic time scale (atomic clocks).

Extremely narrow resonances in a higher-frequency region of the spectrum were detected at nuclear transitions by Mössbauer. For instance, at a γ-transition with the energy of 93 keV in ^{67}Zn it is possible to obtain a resonance with the resolution of 2.10^{15}. Narrow resonance of nuclear transitions without recoil in a crystal lattice now ensure the highest resolution in physical experiments, of the order of 10^{15}.

In the intermediate (optical) spectral region, the relative resonance width until recently was no better than 10^{-6} because of Doppler broadening of spectral lines. The discovery of the subtle effects of resonant nonlinear interaction between the coherent light field and atomic or molecular gases described in this article, has allowed the relative widths of optical resonances to be narrowed by factors of 10^{-4} to 10^{-6}. This has given impetus to the development of

non-linear ultra-high resolution sub-doppler laser spectroscopy and precision optical spectroscopy [1]).

Doppler Broadening of Spectral Lines

A moving particle (an atom or a molecule) emits or absorbs radiation that is not exactly at the quantum-transition frequency ω_o, between two energy levels E_1 and E_2 ($2\pi\hbar\omega_o = E_2 - E_1$), but at a frequency somewhat shifted by the Doppler effect. The spectral line of a single particle is shifted by a value $\Delta\omega_{Dopp}$ that depends on the projection of the particle velocity $\vec{v}$ and on the direction of observation $\vec{n}$ ($\Delta\omega_{Dopp} \cong n\, v\, \omega_o/c$). At the thermal equilibrium, all directions are equiprobable and as a result, the spectral line of the assembly of particles has symmetrical Doppler-broadened profile with its centre at the quantum transition frequency ω_o.

A Doppler-broadened spectral line is, in essence, a set of a great number of much narrower spectral lines of absorption and emission of particles with different velocities. Therefore, the Doppler broadening is often described as inhomogeneous broadening. Homogeneous width is the ultimate width of a spectral line after total elimination of Doppler broadening, or the line width associated with a group of gas particles all moving with the same velocity.

To remove the limitations in optical spectroscopy caused by the Doppler effect, quite a number of methods have been developed to measure the structure of quantum transitions obscured by Doppler broadening of spectral lines. The atomic or molecular beam method developed in the 1930s and successfully applied subsequently, is among these. In the 1950s, some methods of spectroscopy without Doppler broadening (double microwave-optical resonance, level crossing, and quantum beats) were developed which were applied mainly to atomic transitions in the visible region. The advent of coherent tunable lasers has culminated in the discovery and wide application of non-linear laser spectroscopy which, like the atomic or molecular beam method, is very effective for atomic and molecular transitions over a very wide frequency range (UV, visible and IR).

Let us consider four fundamentally different approaches to sub-doppler non-linear laser spectroscopy which have been invented in the past ten years.

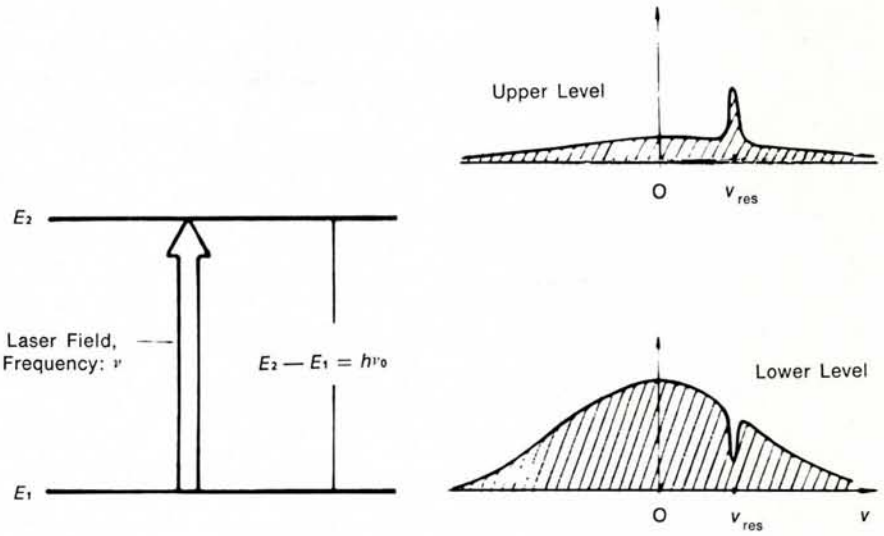


Fig. 1. Changes in the particle velocity distribution levels under action of a laser travelling wave ; (left) level diagram ; (right) distribution of z-component of velocity of the molecules on lower and upper levels of transition.

Saturation Spectroscopy

Consider the interaction of a plane, coherent laser light wave at the frequency ν, with a Doppler-broadened absorption line. Particles that have definite projections of their velocities on to the light beam direction $v_{res} = (\nu - \nu_o)\, c/\nu_o$ can resonate with the field. Therefore, the light wave can interact only with particles that have the corresponding Doppler frequency shift. Such a group of particles occupies a narrow spectral range in the Doppler profile ; its centre is at the field frequency ν and its width is equal to the homogeneous width. Let the intensity of the light field be sufficient to transfer a considerable part of the particles to the excited state of the transition. Preferential excitation of particles that have a definite velocity of motion, alters the equilibrium distribution of particle velocity at each of the transition levels (Fig. 1). The velocity distribution of particles in the lower level develops a shortage (hole) of particles with resonant velocities v_{res}. For the upper level, the velocity distribution, on other hand, has excess ("peak") particles with resonant velocities. The depth of the hole and the height of the peak are determined by the degree of absorption saturation.

In the laser cavity, there is a standing light wave that may be represented as a superposition of two counter-running waves that have the same frequency. In this case, as Lamb shows in his gas-laser theory, each wave burns its own "hole". Because these two waves run in opposite directions, there arise two holes symmetrically situated about the centre of the Doppler contour. Thus, in essence, the laser field absorbs the energy from two groups of amplifying particles that have opposite velocities. As the laser frequency is tuned to the centre of the Doppler profile, the two holes coincide and the standing light wave interacts with only one group of particles. This results in a resonant decrease of power at the centre of the Doppler amplification line now called the "Lamb dip".

The spectroscopic application of the Lamb-dip method in lasers is limited to amplifying transitions of low-pressure gas media only ; the dip width for real transitions of gas lasers is comparatively large (tens of MHz).

The situation has changed greatly since attention was turned to observation of the Lamb dip in resonant-absorption media. The first suggestions and experiments on using non-linear absorption resonances were performed independently at the Lebedev Physical Institute of the Academy of Sciences, USSR, at the Institute of Semiconductor Physics, Siberian Branch of the Acad. of Sci., USSR, and in the Perkin-Elmer Lab. in the USA. These investigations proposed inserting a resonant-absorption gas cell of low pressure into the laser cavity. Absorption saturation in a standing light wave gives rise to a narrow Lamb dip at the centre of a Doppler-broadened absorption line. As a result, efficient saturated amplification of the two-component medium in the laser acquires a narrow peak at the centre ot the absorption line, and the laser output power exhibits a narrow peak, often termed the "inverted Lamb dip". The virtues of this method are that the absorbing gas, at a low pressure and with proper selection of the particle and transition, may have a very narrow homogeneous width, of the order 10^3 to 10^4 Hz, particularly for infrared molecular transitions.

To obtain a narrow saturation resonance at the centre of an absorption line, it is not necessary to use a standing light wave but only to have a strong running wave and a weak counter-running wave (Fig. 2). If the frequency is coincident with the centre of the Doppler profile ν_0 the weak probe wave interacts with molecules, the absorption of which is already decreased by the counter-running strong wave. Consequently, the probe-wave absorption has a resonant minimum equal to the homogeneous width and centred exactly in the Doppler-broadened absorption line (Fig. 2 c). Narrow resonances were first observed experimentally by this method [2]).

Since that time the absorption saturation method of the Doppler broadened lines has become the basic and most developed method of superhigh resolution Doppler free spectroscopy. The development of tunable lasers made this method applicable to almost any atom, molecule and ion transitions. The problem of obtaining ultimate width of narrow resonances of absorption saturation, i.e. realisation of the maximum resolving power is now most important.

The width of narrow saturation resonance in molecular gases at vibrational-rotational molecule transitions, i.e. the homogeneous width, will be determined by collisions of particles. Collisional broadening has the magnitude of about 20-30 MHz/torr. Therefore it is necessary to operate at a gas pressure of 10^{-4}-10^{-5} torr to obtain resonances with the width of about a kHz. The free path length of the particles at such low pressures becomes more than 10 cm. If the diameter of a laser beam is smaller than this length, the finite time of the interaction of particles with the field gives a notable contribution to resonance broadening. In this case the resonance width will be determined by the flight time of a particle through the interaction region.

It is necessary to increase the laser beam diameter in order to reduce the flight width. To achieve this, telescopic beam expanders are required. Such a non-linear laser spectrometer with expansion of the light beam diameter to give a diffractional divergence up to 14 cm has been created at the Institute of Semiconductor Physics, Siberian Branch of the USSR Academy of Sciences, with a 5 m CH_4 absorbing cell placed inside the 10 m cavity of a He-Ne laser. The laser beam diameter in the CH_4 cell was 14 cm, while the operating pressure of CH_4 in the cell was 10^{-4}-10^{-5} torr.

The half width of narrow resonances of the spectrometer was 1 kHz that corresponds to a resolving power of 10^{11}. This made it possible to resolve distinctly three components of the hyperfine magnetic structure spaced at a distance of about 10 kHz. More than that we have managed to resolve the splitting of the spectral lines in the optical range due to the recoil effect :

$$\Delta\nu_{rec} / \nu_0 = 2\pi\hbar\omega_0 / Mc^2 \quad (3)$$

which for CH_4 was about 2.25 kHz. This splitting is observed inside the Doppler broadening which is 300 000 kHz !

The obtained resolution approximates to the practical limit, as its further increase within the absorption saturation method would require the application of light beams 50-100 cm in diameter with a diffractional limit of divergence. Moreover, during resonance narrowing of absorption saturation, the sensitivity reduces inevitably, as the fraction of the particles participating in the formation of a narrow resonance, falls proportionally with the ratio of the resonance width to the Doppler width. These restrictions are less essential in the other methods of non-linear Doppler free laser spectroscopy discovered later.

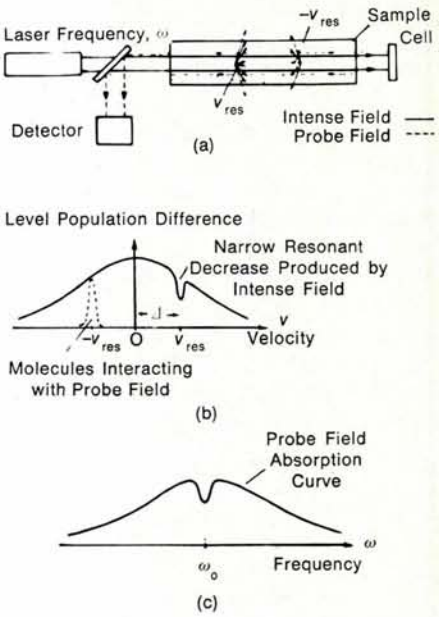


Fig. 2. Observation of the saturation narrow resonance by the single strong coherent travelling wave and counter-travelling weak probe wave; (a) A small part of the intense wave is reflected back through the cell; transmission of this weak wave is studied as a function of laser-field frequency ; (b) Molecular-velocity distribution ; (c) Probe wave absorption as a function of frequency.

Two-photon Laser Spectroscopy

This method of non-linear laser spectroscopy without Doppler broadening was proposed in the Institute of Semiconductor Physics, Siberian Branch of the USSR Academy of Sciences [3]). Consider a two-quantum atomic or molecular transition in the field of a standing wave of frequency ω. For a particle that is moving with velocity $\vec{V}$, the frequency of the relatively travelling waves is $\omega \pm \vec{K}\vec{V}$. The only particles that can absorb two photons from one travelling wave are those for which $\vec{K}\vec{V}$ complies with the condition of two-photon resonance. However, simultaneous absorption of two photons from equal and opposite travelling waves is possible. In this case, the condition of two-photon resonance is only that the doubled field frequency coincides with the frequency of the two-quantum transition, that is, with the centre of the Doppler-broadened line. In this type of resonance, all particles, regardless of velocity, participate in two-photon absoption, resulting in a sharp increase of the absorption signal.

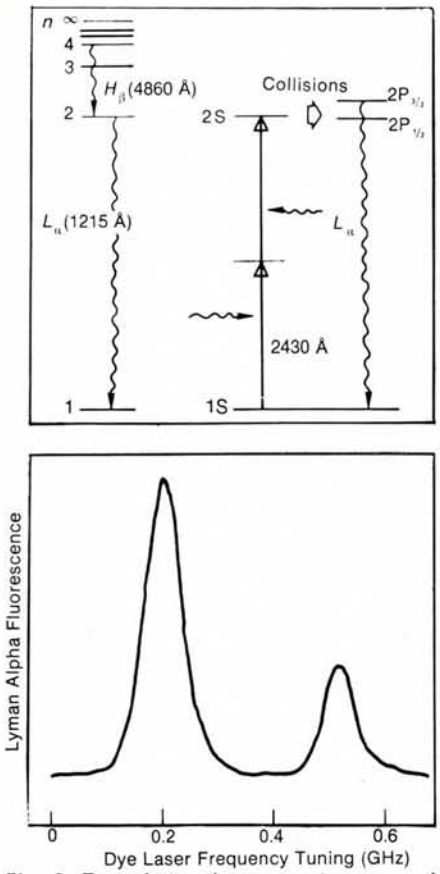


Fig. 3. Two-photon laser spectroscopy of 1S-2S transition of H atom; (a) Two-photon excitation of the metastable 2S state from the 1S ground state monitored by observing the collision-induced 2P-1S Lyman alpha fluorescence in the vacum-ultraviolet spectral region; (b) Doppler-free two-photon spectrum of the hydrogen 1S-2S transition.

Narrow two-photon resonance was first observed in studies of sodium-atom transitions in 1974 at Paris, Harvard and Stanford Universities using tunable dye lasers. One of the most interesting experiments performed in this field [4] is the two-photon excitation of 1S-2S transition of hydrogen by the irradiation of two counter running beams with 2430 Å wavelength as shown in Fig. 3.

Rapid progress of two-photon spectroscopy can be anticipated as it has several advantages over saturation spectroscopy. First, all of the particles on initial level 1 take part in the absorption, regardless of their velocities, whereas in saturation spectroscopy, only a small proportion of the particles participate in the production of narrow resonance lines. For extremely narrow resonance, the parameter $\Gamma/\Delta\omega_{Dopp} \simeq 10^{-3}$—$10^{-5}$ and the peak contrast in two-photon absorption is $\Delta\omega_{Dopp}/\Gamma \simeq 10^{3}$—$10^{5}$ times as much as the Lamb-dip contrast in saturation spectroscopy. Second, the two-photon absorption peak is accompanied by a corresponding peak in the density of excited particles. Since sensitive methods are available to detect particles in the excited state, experiments can be performed with a small number of particles, such as in atomic and molecular beams. Third, the width of the resonance peak does not depend on the curvature of the wave front, because the two photons are absorbed simultaneously at the same point of space. In absorption saturation, for narrow resonances to be attained, the wave vector should have strictly the same direction along the whole cross-section of the standing wave. Thus, it is possible to use light beams with large cross-section (tens of centimeters) for two-photon spectroscopy, and broadening of the resonance peaks due to the transit time can be made very small.

Non-linear Resonances in Separated Light Waves

If, when moving with velocity V_o, a particle interacts with a light beam of limited diameter *a*, any spectral resonance is broadened by an amount: $\Delta\omega_{tr} \simeq V_o/2$. The light beam may be regarded as a measuring tool with which the molecules interact in the finite time $\Delta t = \tau_{tr} = a/V_o$. According to the indeterminacy principle, the energy of the transition between levels cannot be evaluated to better than $\Delta E = 2\pi h/\Delta t$. This corresponds to an indeterminacy of the transition frequency, i.e., to a spectral line broadening caused by the finite time of particle flight through the light beam (transit-time broadening),

$$\Delta\omega_{tr} = 1/\tau_{tr} \qquad (4)$$

It is necessary to provide a long interaction length of a particle with the field in the methods of non-linear spectroscopy considered above, in order to obtain extremely narrow resonances. More than that it is necessary to provide a strict flatness of the wave front in the absorption saturation method along the whole interaction path. This fact makes the production of resonances with a width of less than 1 kHz practically unrealisable.

In the microwave range, the method of increasing the length of coherent interaction of a particle with the electromagnetic field was known long ago, as in Ramsey's method of spatially-separated fields. In the first microwave field (in the first cavity, Fig. 4 a) the atom obtains microwave polarization which is conserved during the flight to the second cavity. The field in the second cavity is coherent to the first one and interacts with the polarization induced in the first cavity. The resonance width of interaction of a freely flying atom with two fields is determined by the whole flight time through the fields including the empty spacing between them (Fig. 4 a). The formation of extremely narrow resonances in microwave spectroscopy is based on this method, which is actually used in a caesium microwave frequency standard.

It appeared that it was impossible to apply directly the Ramsey method in the optical range. The light wavelength appeared to be so small that the atoms having started from one point in the first light beam fly apart in a longitudinal direction to cover the distance ΔZ which is much larger than the light wavelength (Fig. 4 b). Therefore a coherent polarization induced in the atoms in the first light beam disappears completely before reaching the second beam. Quite recently two ways of overcoming this difficulty have been proposed at the Institute of Semiconductor Physics of the Siberian Branch of the USSR Academy of Sciences.

Firstly, it was proposed [5]) to observe a two-photon interaction of atoms with spatially-separated standing light waves (Fig. 4 c). As mentioned above, compensation of the Doppler effect takes place with a two-photon absorption of photons from the light waves travelling in opposite directions. Therefore at an exact two-photon resonance ($2\omega = \omega_o$) all the atoms regardless of their velocity interact with the fields. A polarization induced in the first standing light beam is coherent when it flies into the second light beam due to a two-photon compensation despite the transversal expansion of the atomic beam. A two-photon resonance width in two spatially-separated standing waves is determined by the total transit time between the beams as in the case of the Ramsey effect in a microwave range.

Second, it is possible to eliminate the spatial averaging effect of a coherent polarization even at a one-photon interaction. To achieve this, it is necessary to place an additional standing light wave interacting non-linearly with the atoms exactly in the middle of the spacing between two spatially-separated light beams [6]) (Fig. 4 d). The summing and interference of dipole moments induced in the first and intermediate light beams give a non-averaged component of a dipole momentum which interacts coherently with the third light beam. As a result, a narrow resonance appears. The width of this resonance is determined by the total time of coherent interaction of atoms during the flight from the first to the last light beam.

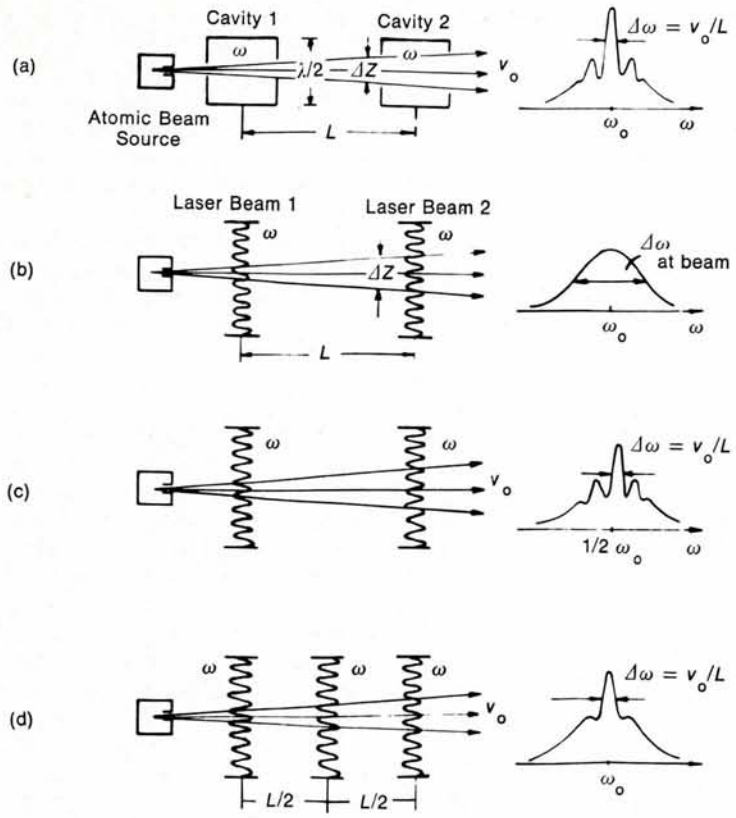


Fig. 4. Formation of the narrow spectral resonance in coherent interaction atoms or molecules with spatially-separated electromagnetic fields; (a) case of a microwave transition when the transversal spreading of particles is less than wavelength of field; (b) optical case, when the polarization at second light beam disappears due to transversal spreading of particles of value $\Delta Z > \lambda$; (c) formation of narrow resonance in the two separated beams at two-photon optical transition; (d) formation of narrow resonance in the three spatially-separated beams at single-photon optical transition.

The experiments that have been recently carried out confirmed both these methods. Thus we can obtain narrow frequency stable optical resonances with a width of about 1 kHz at forbidden transitions of atoms and molecules at long lifetime ($> 10^{-3}$ s) quantum states.

Note that it is impossible to narrow resonances further by any of the considered methods because of the influence of the square Doppler effect which shifts the central quantum transition frequency of a moving particle by a value which depends on its absolute velocity. The thermal distribution of absolute velocities of free particles inevitably results in a second-order Doppler resonance broadening of

$$\Delta = \omega_0 kT/Mc^2 = \omega_0(V_0/c)^2, \quad (5)$$

where T is the gas temperature, M is the mass of the particle, and c the speed of light. This effect limits the resolution obtained by both basic non-linear laser spectroscopy methods (saturation spectroscopy and two-photon spectroscopy) at the level of $(c/V_0)^2 \cong 10^{10}$-10^{11} that corresponds to room temperature.

So, a search for new basic methods of non-linear laser spectroscopy, free of this limitation, seems to be of great importance. From this standpoint we should focus our attention on the method of spectroscopy without Doppler broadening, based on the cooling of atoms and low-velocity particle trapping in a standing light wave.

Cooling and Trapping of Atoms by Laser Radiation

Unlike the three approaches in non-linear sub-doppler laser spectroscopy considered above, this fourth approach is still discussed theoretically. However the potential advantages of the method are great.

It is well known that an atom in a light field is acted upon by the light pressure force. This can be used to change the velocity and motion character of atoms and hence it can radically change the Doppler effect. In practice it is possible to eliminate Doppler shift of absorption or emission frequency if we transform the translational motion of a particle into the motion with a restricted amplitude a which is less than the light wave λ, for instance into the oscillatory motion with amplitude $a \leqslant \lambda$. This method is widely used in the radio frequency range, for example in Rb-atom quantum frequency standards and is known as the Dicke method or the method of buffer gas which transforms a translational motion of rubidium atoms into a random diffusion movement. This approach in an optical range requires the restriction of a particle motion in a very small volume λ^3. One of our colleagues suggested that a non-resonant strong standing wave should be employed for this purpose.

Such an approach is very attractive because, first, resonance broadening due to the finite time of flight through the light beam is completely eliminated as particles are constantly "hanging" in a beam. Second, the trapping of only very slow particles automatically provides elimination of the second-order Doppler effect. Unfortunately it is impossible to realise this approach because of the very small fraction of particles with velocity $V < 10^{-4}V_0$ in a thermal distribution at room temperature (about 10^{-12}). Recently a method of laser cooling of freely moving atoms was proposed by Hänsch and Schawlow [7]) which is very important for the practical realisation of trapped-particle laser spectroscopy and for the elimination of the second-order Doppler effect.

The simplest way to do it is the isotropic irradiation of a low frequency half of the Doppler broadened profile by a laser field (Fig. 5).

The calculations that have been carried out at the Institute of Spectroscopy [8]) show that it is possible to realise the regime of adiabatic radiative cooling up to ultralow temperatures of the order 10^{-3}K, by irradiating the atomic gas of low pressure in a three-dimensional standing wave scanned along the Doppler profile frequency. Such ultracold atoms have a thermal velocity of some cm/s. Their motion in a light field is no longer classical but quantum because the de Broglie wavelength is comparable with the light wavelength. The atoms that are cooled by a resonance light field can be trapped in a three-dimensional non-resonant standing light wave and confined for a long time in localized volumes having the size λ^3.

The method of atom cooling and trapping in a laser field is of considerable interest both for the optical spectroscopy of atoms free of the Doppler broadening and for dramatic enhancement of atom detection sensitivity and spectroscopic researches of individual trapped atoms.

Several laboratories are planning now experiments to pursue the realisation of this new approach in non-linear laser spectroscopy.

Applications in Quantum Electronics and Metrology

The most impressive application of narrow optical resonances is for frequency standardization of lasers which requires that :

1) The reference frequency must be stable and reproducible ;

2) The width of the resonance curve of the reference frequency should not exceed the required stability by a factor of more than 10^3 to 10^4. This condition is not strict, because it depends upon the state of the art of automatic setting on the centre of the resonance curve by use of servo-systems.

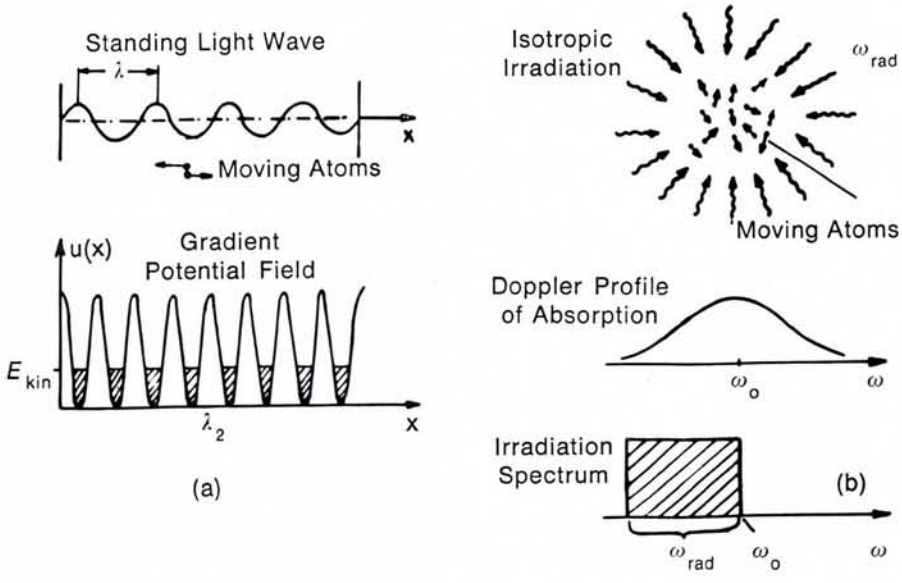
From this it follows that resonance with the same stability and reproducibility as the line centre and with a relative width of about 10^{-9} to 10^{-10} is required, to obtain frequency stability and reproducibility of the order of 10^{-13}. This corresponds to the stability and reproducibility already achieved in the microwave range.

To date, the fine frequency stabilization of many lasers has been carried out by means of narrow non-linear resonances induced by laser radiation at molecule absorption lines in the infrared and visible spectrum range. The best results have been achieved using the narrow saturation resonance on the absorption line of the methane molecule at the wave length 3.39 mcm. When looking for frequency stability and reproducibility to better than 10^{-13}, requirements are hard on laser and narrow resonance parameters, mechanical and electronic elements of the equipment. As the absorbing cell should have a pressure not more than 10^{-3} torr, its length should be about several meters. The whole laser construction with a length of 5-10 m should be very stable and isolated from the external mechanical and acoustic perturbations, so that the servo system of automatic frequency tuning should be able to tune the cavity length accurate within 10^{-6} of the light wavelength. It means that piezoceramics should constantly tune the laser cavity length accurate to within 10^{-3} Å.

The stability obtained for the unique set up at the Institute of Semiconductor Physics of the Siberian Branch of the USSR Academy of Sciences, with an averaging time of 100 s was 5.10^{-15}; i.e. the root - mean - square frequency deviation of 10^{14} Hz laser output did not exceed 0.5 Hz ! A short term frequency stability was 7.10^{-14} that corresponds to a line width of 7 Hz ! Thus this laser is the most monochromatic source of electromagnetic oscillations in any frequency range of coherent sources (from radiowaves to the optical range).

At the independent starting up and tuning of two He-Ne lasers with an intracavity CH_4 cell, a root - mean - square frequency deviation for 50 start-ups was about 3 Hz. This corresponds to a frequency reproducibility of 3.10^{-14}. As for accuracy of frequency tuning to the resonance top, this was 1 Hz, i.e. it was better than the experimental frequency deviation. The obtained reproducibility value was conditioned by the frequency instability of the narrow non-linear resonance itself.

Fig. 5. Trapping and cooling of atoms by laser fields ; (a) the potential field of non-resonant standing light wave and the possibility of trapping of particles with the kinetic energy much less than the height of potential barriers ; (b) irradiation of low-frequency half of Doppler profile of atomic absorption line resulting in the cooling due to multiple re-emission of photons.



The creation of quantum generators of coherent optical oscillations with a stable frequency is in principle important in many respects. First of all a quantum oscillator in the optical range, unlike microwave oscillators, may be simultaneously a standard of length and also of time.

A quantum standard of frequency in the optical range makes it possible to create a joint quantum standard of length and time and thus eliminate the difficulty connected with the application of two quite different spectral lines to determine international units of time and length (the transition of ^{133}Cs atoms at 3.27 cm as frequency (time) standard and transition of ^{86}Kr atom at 6056.9 Å as length standard).

Spectroscopic Applications

Experiments in which a resolving power of 10^8 is achieved are not uncommon at present. In the best experiments, using absorption saturation, a value of about 10^{11} has been attained [8, 9]), that is, 10^6 times better than with the best classical spectrometers and 10^5 times better than with linear laser ones. In comparing the non-linear laser methods we have stated that a resolving power of the order of 10^{13} to 10^{15} can be expected.

In atomic spectroscopy a multiplet or fine structure is usually well resolved by classical methods, but for highly excited states the fine splitting decreases in proportion to n^3 (n is the principal quantum number) and is masked by the Doppler effect. To study isotopic and hyperfine structures, which depend on the spin and quadrupole moment of the nucleus, as well as the hyperfine structure of isomeric nuclei, the resolving power has to be in the range 10^5 - 10^8. Many components of isotopic and hyperfine structure can be resolved by classical devices with high resolution (such as the Fabry-Perot interferometer) but it is necessary to work into the Doppler profile to investigate the structure fully.

In addition, non-linear spectroscopy methods also make it possible to measure spectral line broadening inside the Doppler profile caused by radiative decay and collisions.

In molecular spectroscopy, particularly in the infrared, classical methods do not provide very good resolution. Only with the advent of lasers was it possible to obtain infrared spectra of molecules with a resolution better than 10^5, in particular to observe the hyper-fine structure in rotational-vibrational spectra. The hfs rotational-vibrational transitions depend on quadrupole and magnetic interactions.

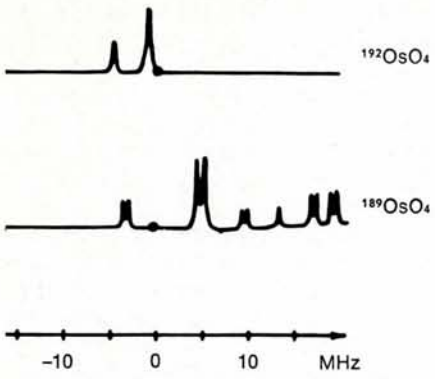


Fig. 6. Spectra of saturated absorption of $^{192}OsO_4$ and $^{189}OsO_4$ molecules measured through P(20) line of CO_2 laser at 10.6 mcm.

The quadrupole interaction gives rise to a splitting of rotational-vibrational lines by 10^6 - 10^7 Hz, depending on the quadrupole interaction constant and the molecular angular momentum. Fig. 6 shows an example of the lines of the ν_3 band in the non-linear absorption spectrum of $^{189}OsO_4$ and $^{192}OsO_4$ which were observed at the Institute of Spectroscopy of the USSR Academy of Sciences, using a number of lines of a CO_2 laser at 10 mcm. The doublet structure is due to the quadrupole moment of the ^{189}Os odd nucleus. Analogous spectra of $^{187, 190, 192}OsO_4$ show no such splitting because these Os nuclei have no quadrupole moment.

Magnetic interaction between the molecular angular momentum and the nuclear spin causes finer splitting ranging from 10^3 - 10^5 Hz. To detect this, the resolving power must be about 10^9 to 10^{11}. Hall and Borde first successfully detected the magnetic hfs in rotational-vibrational spectrum in experiments with $^{12}CH_4$; their resolving power was about 10^{10}.

There is another very fine effect in molecular spectra which lies beyond the scope of present experiments but in future may be detected by methods of ultra-high resolution non-linear laser spectroscopy. Two molecules that are mirror images of each other have different energy levels because of parity violation in weak interactions between electrons and nucleons in a molecule [10]). Physically, the effect occurs when the energy of the system contains a small admixture of odd potential of interaction between electrons and nucleons. Thus, for example, the vibrational energies of left- and right-handed molecules become different by an extremely small amount, of the order of 10^{-13} - 10^{-15} eV. First tentative experiments in this direction are going on in several laboratories [11]). If this effect were detected it might be possible to gain some insight into the fact that all natural proteins are composed of L-amino acids (the left-handed isometric form). This effect in biology was discovered by Pasteur more than a century ago, but has not yet been fully explained.

Conclusions

Discovered in the last ten years, new non-linear methods of formation of sub-doppler optical resonances and the consequent development of the non-linear ultra-high resolution laser spectroscopy provide a very effective tool for studying the structure of matter at the atomic and molecular level. This short outline of the latest ideas and achievements in the field testifies to its rapid progress. Many advanced methods are being introduced into laboratory practice. Developments in tunable infrared and visible lasers indicate that commercial non-linear laser spectrometers will be available in the near future.

New methods of non-linear laser spectroscopy without Doppler broadening are being studied, with the ultimate goal of achieving a resolving power of 10^{14} to 10^{15}, where the limit will be set by the natural width of the laser line. When this is reached, non-linear laser spectroscopy, like any really new research method, will find many far-reaching applications in science.

References

1. LETOKHOV, V.S. and CHEBOTAYEV, V.P. *Non-linear Laser Spectroscopy* (Springer-Verlag, Heidelberg) 1977
2. BASOV, N.G., KOMPANETZ, I.N., KOMPANETZ, O.N., LETOKHOV, V.S. and NIKITIN, V.V. *Pis'ma Zh. Eksp. i Teor. Fiz.* **9** (1969) 568
3. VASILENKO, L.S., CHEBOTAYEV, V.P. and SHISHAEV, A.V. *Pis'ma Zh. Eksp. i Teor. Fiz.* **12** (1970) 161
4. HANSCH, T.W. *Physics Today* **30** (1977) 34
5. BAKLANOV, E.V., DUBETZKII, B. Yu. and CHEBOTAYEV, V.P. *Appl. Phys.* **9** (1976) 171
6. BAKLANOV, E.V., CHEBOTAYEV, V.P. and DUBETZKII, B. Yu. *Appl. Phys.* **11** (1976) 201
7. HANSCH, T.W. and SCHAWLOW, A.L. *Optics Comm.* **13** (1975) 68
8. CHEBOTAYEV, V.P. *Proc. of the 2nd Frequency Standards and Metrology Symposium (5-7 July, 1976)* (Nat. Bureau of Standards, USA)
9. HALL, J.L., BORDE, C.J. and UEHARA, K. *Phys. Rev. Lett.* **37** (1976) 1339
10. LETOKHOV, V.S. *Phys. Lett.* **53A** (1975) 275 ; *Lettere al Nuovo Cimento* **20** (1977) 107
11. KOMPANETZ, O.N., KUKUDJANOV, A.R., LETOKHOV, V.S. and GERVITZ, L.L. *Optics Comm.* **19** (1976) 414 ; ARIMONDO, E., GLORIEUX, P. and OKA, T., "Laser Spectroscopy III" *Proc. of 3rd Intern. Conf. (4-8 July, 1977)* (Springer-Verlag, Heidelberg) 1977, p. 444.

Society News

Atomic Physics Division

Replacing G. zu Putlitz as secretary of the Division is :

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Replacing F.J. de Heer as secretary:
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Computational Physics Group

A conference on Computational Atomic and Molecular Physics will be held in Nottingham from September 12-15, 1978. The emphasis will be on computational and numerical methods appropriate for studies of stationary states and scattering of atoms and molecules. This conference is combined with the annual Quantum Theory Conference held at Nottingham and elsewhere. Further details can be obtained from : Dr. R.L. Hudson, Mathematics Dept., Univ. of Nottingham, Nottingham NG7 2RD, UK

Member Societies

New president of the **Belgian Physical Society** is Prof. J. Lemonne.

Re-elected president of the **Polish Physical Society** is Prof. Z. Wilhelmi.

Re-elected president of the **Turkish Physical Society** is Prof. E. Inönü.

EPS Lecturer

The first EPS lecturer, Prof. C. Cohen-Tannoudji is to open his European tour with a lecture on the "Interaction of Radiation with Atoms" at University College, London, on Feb. 20.

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Editor, EUROPHYSICS NEWS,
European Physical Society,
P.O. Box 39,
CH-1213 Petit-Lancy 2
Switzerland.
Tel. Geneva 93 11 30 Tx. 23 455 alarm ch

Published by the European Physical Society

Printed by: Ed. Cherix et Filanosa SA
CH-1260 Nyon, Switzerland