Development of hyper-atomic physics in Russia

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Researches into the problem of hyper-atom physics, a branch of atomic physics formed in recent decades as a result of study of highly excited hydrogen-like atoms with values of the principal quantum number of 10–1000, determining the size of the outer electron orbit, are reviewed. Efforts of a large research group were devoted to solution of this problem and to study of properties of hyper-atom medium both *in space* and in the *Earth atmosphere*. We describe a new found regularity of existence of strongly excited atoms at different medium parameters and present a new model of interaction between low-temperature plasma and neutral gas flows, which allowed one to explain some observed anomalous effects and relate them with specific critical phenomena in the field of interaction of these media. Wide prospects of hyper-atom technologies are demonstrated. The created wide-spectrum and wide-band generators are described; analogous quantum-electronic amplifiers are under development, and the possibility of creation of devices with high-temperature superconductivity is explored.

Introduction

Hyper-atomic physics is a branch of atomic physics formed in recent decades as a result of studies of highly excited hydrogen-like atoms with principal quantum numbers $n \sim 10 \dots 1000$, determining the outer electron orbit size (within limits of spectral emission from submillimeter to decameter wavelengths).

The Bohr model (1913) of hydrogen-like atom was constructed based on Balmer, Paschen, and Lyman (1885–1906) studies of optical emission spectra at low excitation levels ($n \sim 2$, 3, 4) of hydrogen; and it was verified by Brackett and Pfund series (for $n \sim 5$, 6) in 1922–1924, and Humphrey series (for $n \sim 7$) in 1953.

Experimental studies of highly excited atoms of alkali metals were initiated by Amaldi and Segre in 1934, and their results have been analyzed at the same time by Fermi who laid foundations for the theory of interaction of highly excited atoms with medium. Imperfect laboratory instruments of those years abandoned further research into this new field of physics until 1970s, when the invention of frequency-tunable lasers gave rise to intensive studies of properties of highly excited atoms and molecules under *laboratory conditions*.

Fermi was first who raised the question of maximum possible degree of excitation of atoms *in the environment*. This problem was found to be non-easy, and its solution and the study of properties of hyper-atomic medium, both *in space* and in *the Earth atmosphere*, have been the subject of many-year scientific work of a large research team. This group presents national scientific schools in the field of theoretical and experimental physics and chemistry in Russia. Among them, a marked role was played by such scientific organizations of our country as Sternberg Astronomic Institute (SAI) at Moscow University, Lebedev Physical Institute of RAS (FIAN), State Astronomical Observatory (SAO), Central Scientific Research Radiotechnical Institute (CNIRTI), Moscow Radiotechnical Institute of RAS (MRTI), Design Bureau Vympel (OKB Vympel), Experimental Design Bureau Almaz (OKB Almaz), State Unitary Enterprise SPA Astrofizika, Russian Research Center Kurchatov Institute (RRC Kurchatov Institute), Zhukov Central Aerohydrodynamic Institute (Zhukov TSAGI), Sukhoi Design Bureau (Sukhoi OKB), Gromov Flight-Research Institute (Gromov FRI), etc.

1. Hyper-atoms in interstellar plasma

1.1. Discovery of hyper-atoms

As is well known, nearly a half of interstellar matter, consisting mostly of hydrogen, is at ionized (plasma) state due to action of cosmic ultraviolet radiation. Emission of highly excited atoms with principal quantum number $n \geq 30$ corresponds to interlevel transitions in the radio frequency range

$$\nu \approx 2R_{\mathrm{M}}cn^{-3}\Delta n[1 + (m/M)]^{-1},$$

where R_{M} is the Rydberg constant; m and M are masses of electron and atomic nucleus; c is the velocity of light; and Δn is the change of quantum number.

A possibility of observation of recombination radio lines in spectra of emission nebulae (HII regions of ionized hydrogen) was first hypothesized by Kardashev[1] in 1959. Also in 1959, a unique radio telescope RT-22 FIAN with 22-m mirror was created at Pushchino Radioastronomy Observatory for measurements in centimeter and millimeter wavelength ranges.

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In April 1964, the radio line of excited hydrogen atoms, corresponding to transitions between levels with principal quantum numbers 91 and 90 at a frequency of 8872 MHz (a wavelength of 3.38 cm) was detected by Sorochenko and Borodzich[2] in emission of Omega nebula.

Simultaneously, in Pulkovo Observatory of Russian Academy of Sciences, A.F. Dravskikh, Z.V. Dravskikh, and V.A.Kolbasov have detected hydrogen radio line in Omega nebula at a frequency of 5763 MHz, a wavelength of 5.21 cm, corresponding to transitions between 105 and 104 quantum levels.[2] The discovery of radio lines of the excited hydrogen reported by our scientists at the Hamburg General Assembly of International Astronomical Association in August, 1964, turned to be a complete surprise because radio lines were thought by foreign experts very weak and blurred due to Stark broadening (because of interaction of highly excited atoms with charged particles and electric fields), and, consequently, invisible.

A year later, the hydrogen recombination radio lines were detected by the telescope at the US National Radio Astronomy Observatory (NRAO) (n = 109) and radio telescope at Harvard University (n = 156 and 158).

The success and priority of the national scientists were registered by the USSR State Committee on Inventions and Discoveries with the discovery formulation: Phenomenon of emission of radio lines, caused by transitions between highly-excited states of the atoms (authors: R.L. Sorochenko and E.V. Borodzich of FIAN; A.F. Dravskikh and Z.V. Dravskikh of SAO; and N.S. Kardashev of SAI). In 1967, the RT-22 radio telescope detected in Orion nebula the radio line of excited helium at a frequency of 5765.2 MHz (n = 104).

As is already noted above, searching for radio lines resulting from transitions between more and more highly excited levels in the rarefied interstellar medium is complicated by a strong influence of Stark broadening, which must be accompanied by steadily increasing line broadening and overlapping radio lines of the neighboring levels. For instance, the collision of excited atoms with electrons (so-called kinetic Stark broadening) must be proportional to the seventh power of the principal quantum number for homogeneous plasma.[3]

A refinement of this regularity has allowed reaching a possibility, earlier seemed unattainable, of observing more than hundredfold excited "radio atoms." New theoretical consideration has shown that in collisions of highly excited atoms with charged particles there occurs some kind of compensation for the Stark effect: very close neighboring levels are excited almost identically, so the energy difference between excited levels has a few orders of magnitude less variations than of the levels themselves. This made it possible to explain subsequent results, when radio lines up to $n = 166$ were detected.[2] This value is the limiting one for the revised theory, because the Stark broadening also increases with the frequency of emission radio lines.

In this regard, experimental observation of radio lines at $n = 220$ without quite strong Stark broadening has led to a new problem: to determine actual regularities governing the Stark broadening of lines of "hyper-excited radio atoms."

1.2. Solution of the problem of Stark broadening

Solution of this problem has required a significant improvement of observation facilities and organization of studies of inhomogeneous region of Orion nebula with two radio telescopes simultaneously in different wavelength ranges.

To do this, in 1968 the RT-22 FIAN radio telescope was equipped with a millimeter radio spectrometer and an input quantum paramagnetic amplifier tuned to a wavelength of 8 mm. All this, together with the improved antenna system, increased ten-fold the sensitivity of spectral measurements (with this modernized telescope, the hydrogen radio lines of $n = 56$ and 66 were first detected at wavelengths of 8.23 and 13.5 mm, respectively).

The RT-100 radio telescope (λ = 3.3 cm) at Max Plank Institute was also used in studies of Stark effect regularities.

The performed experiments[2,3] have shown that the observed Stark broadening of radio lines of excited atoms is proportional to electronic density of the medium and to 4.4 power of the principal quantum number:

$$\Delta\nu_{st} \sim N_e n^{4.4}\nu,$$

which was in a good agreement with the revised theory of spectral line broadening in inhomogeneous plasma.

1.3. Search for extremely large hyper-atoms

With solution of the problem of Stark broadening, it became possible to search for radio lines in meter and decameter ranges. This was done using the cross-like radio telescope DKR-1000 with 1000×1000-m antenna array, operated at FIAN radio astronomic station in the meter wavelength range, as well as the radio telescope UTR-2 with 1800 × 900 m antenna, operated at the Radio Astronomic Institute of Ukrainian Academy of Sciences in the decameter range.

Many-year observations of Konovalenko and Sodin with the UTR-2 radio telescope resulted in 1979 in recording for the first time of the absorption spectral line of a highly excited carbon atom at a frequency of 26.13 MHz (n = 631, λ = 11.5 m) in the radio source Lady in the Chair A. Further, in the same source, carbon radio lines (n = 603, 611, 630, 640, 686, and 732; λ = 10–18 m) were detected.

The scientists of FIAN and SAI in joint observations with the DKR-1000 radio telescope have detected four more carbon radio lines with n = 427, 486, 538, and 610–612 at $\lambda = 3.56–6.12$ m. Therewith, the line intensity in the meter wavelength range turned to be, contrary to the theory, less than the intensity of decameter lines, therefore, to detect them, the instrumental sensitivity was increased up to the level ensuring reception of a spectral signal as strong as $4 \cdot 10^{-4}$ of the signal in the continuous spectrum. The lower intensity of radio lines in the meter wavelength range was due to complex non-equilibrium population of the corresponding levels.

1.4. About upper excitation limit of atoms in space

The performed studies[4,5] have shown the atom, as a quantum system under conditions of Galaxy, to be possible to exist up to excitation levels $n \sim 1000$. The existence of highly excited atoms beyond this level becomes impossible because of the destroying effect of non-thermal magnetic bremsstrahlung radio emission filling entire Galaxy.

1.5. Sizes of hyper-atoms

As is well known, the "Bohr radius" of an atom at the basic (non-excited) state is one of the world's universal constants:

$$a_0 = 0.53 \cdot 10^{-8}\ \text{cm}.$$

Depending on the principal quantum number, the sizes of excited atoms are determined from the formula

$$a_n = a_0 n^2.$$

Therefore, the sizes of giant highly excited atoms with $n = 1000$ (radio atoms) emitting in decameter wavelength range, are equal to a macroscopic value $d \sim 0.1$ mm. Under conditions of cosmic medium with a density of about $10^4\ \text{cm}^{-3}$, the mean interatom distance is 20 cm; thus, the giant atom sizes are two orders of magnitude less than this distance.

1.6. Cosmic radio spectroscopy

The possibility of studying cosmos with the use of information obtained by radio astronomic methods from the analysis of recombination spectra of radio emission of interstellar medium has formed a new direction in cosmology, namely, the radio spectroscopy.

The recent measurements performed by national and foreign radio astronomers gave fundamentally new evidences[1,2] concerning the properties of interstellar medium as compared to the results obtained by traditional optical observational methods.

Various processes occur in the interstellar medium under impact of ultraviolet and Roentgen radiation from the Galaxy corona, extragalactic objects, and remnants of supernovae. It is affected by high-energy cosmic particles and shock waves, caused by stellar wind, interstellar cloud collisions, expanding ionized hydrogen regions, and supersonic gas flows connected with star formation and explosions of supernovae. These processes heat the interstellar gas and lead to excitation of energy levels of the gaseous constituents with subsequent emission in a wide spectral range including the radio range, as well as in a broad region of continuous braking radiation under conditions far from thermodynamic equilibrium.

The cosmic radio spectroscopy made it possible to answer many questions associated with the theory of star formation, construction and evolution of galaxies, as well as extragalactic phenomena. The obtained evidences were used in development of modern cosmology.

Mention main problems resolved by methods of cosmic radio spectroscopy.

The position of radio lines on the frequency scale is determined by the *mass of the chemical element*. In such a way, hydrogen, helium, carbon, magnesium, and some other elements were identified.

The radio line intensity (brightness temperature) signifies the *abundance of an element*. From the comparison of radio line intensities of different elements, the data were obtained indicating that helium is the next abundant element after hydrogen. Data on abundance of helium, which is 10% of the hydrogen abundance, were used in the *model of origin of Universe and in determination of its age.* The *content* of carbon relative to hydrogen in CII regions is $3 \cdot 10^{-4}$.

The Doppler shift of radio lines is used to determine the *motion velocities of emission sources and distances to them.* The radial velocities measured for different radio sources were found to range from 20 to 200–400 km/s.

The key parameter of the cosmic medium, *the electron temperature*, is obtained from relationship between hydrogen radio line intensities and adjacent intervals of the continuous spectrum in the ionized hydrogen regions. The temperature of galactic regions HII makes from 4000 to 13000 K, whereas in the regions CII it does not exceed 200 K. At the same time, some important regularity was established: the temperature of these regions decreases to 5000 K as they approach the galactic center, confirming the hypothesis that an intensive process of star formation proceeds at the Galaxy center. The temperature in these regions decreases due to thermonuclear reactions of heavy elements serving as coolants under these conditions.

Another important parameter of interstellar medium, *the electron density*, can be determined from the Stark broadening of radio lines. For instance, in Orion nebula the electron density is $1.5 \cdot 10^4\ \text{cm}^{-3}$ at the center of nebula and decreases towards its periphery. In the regions CII the electron density is $\sim 10\ \text{cm}^{-3}$ (corresponding to the density of neutral atoms of $10^5\ \text{cm}^{-3}$), at the Galaxy center it is also $\sim 10\ \text{cm}^{-3}$, while in the planetary nebula NGC 7027 it is $\sim 5 \cdot 10^4\ \text{cm}^{-3}$.

Outside of our Galaxy, several recombination radio lines of hydrogen were observed in irregular galaxy M82, located behind Magellanic Clouds at a distance of 3.3 Mpc. The gas temperature there was found to be equal approximately to 5000 K, and the electron density – to 10^2 cm^{-3}.

1.7. Star birth

At present, the study of recombination radio lines is the only way of gaining insight into the initial processes of star formation because radio waves pass through a dense dust, non-transparent for optical radiation, without significant losses.

During star formation, a circumstellar envelope of the ionized hydrogen is formed, which is followed by its expansion under impact of emerging stellar wind. The expansion speed is determined from the Doppler shift of the envelope's recombination radio emission. Given the size of the gas envelope, we can determine the time of its expansion and, hence, the *star age*. In addition, main physical parameters of the envelope, namely, its temperature and density, needed to describe star evolution processes, can also be obtained.

Note in conclusion of this section that the national science is assented to make a respectable contribution into creation of instrumentation for radio astronomy, development of cosmic radio spectroscopy, as well as discovery of hyper-atoms in space.[1,2]

2. Hyper-atoms in dense media

2.1. Modeling of strongly excited media

The Earth atmosphere (like the cosmic media) is under constant impact of the sun. The continuous, time-varying fluxes of radiative energy, solar wind, as well as cosmic rays and meteorites cause changes in atmospheric physical properties and determine the processes of its ionization and formation of ionospheric layers. The strong excitation of the atmospheric medium and attendant significant changes of its local parameters, are brought about by anthropogenic influences as well, such as shock waves arising at powerful explosions and hyper-sound motion of space-rocket vehicles.

In 1940s–1960s, in connection with development of atomic and rocket technologies, physics of shock waves and high-temperature gas-dynamic phenomena became one of the most important physical-technical directions.[3,4] In particular, of special concern was a calculation of thermodynamic functions by the method of statistical sums. It was thought therewith that in calculations of electron statistical sum it was sufficient to take into account only a few first (5–10 in exact calculations) terms in this sum, which was explained by the supposition that in a rarefied gas, it is more energetically "profitable" for electron in atom or ion to escape than to transit to a higher excitation level.

Another argument was that electron, moving along remote orbit, whose size is comparable with interatomic distance in the medium, does not differ, in essence, from free electron, and such highly excited atom does not differ from the ionized atom.

As an experimental confirmation of this idea, the facts served that the spectra of low-pressure arc discharges have no more than 5–10 hydrogen spectral lines of Balmer series, and that even the spectra of gaseous nebulae, where the density of particles does not exceed 10 cm^{-3}, have no more than 50–60 Balmer lines.[3]

2.2. Anomalous effects of extinction (amplification) of radio signals in shock waves (adjacent plasma flows)

In rocket-cosmic experiments, both foreign and national, cosmic location facilities detected radiophysical effects, previously unknown, which accompanied the process of ballistic body entrance into the atmosphere.[4]

At altitudes from 65–50 to 15–10 km, there were observed a failure of radio communication with cosmic vehicles, an interruption in reception of telemetric information, and a strong reflection of radio location signals, tracking the ballistic bodies, from adjacent flows, which exceeded the background level by tens and hundreds of thousand times (by 40–60 dB).

Simultaneously, at the same fraction of the atmospheric descent trajectory, with the use of radars equipped with Doppler spectral analyzing instrumentation, Nektarov in 1968 has found that the amplitude of radar signals, reflected from the surface of observed objects, gradually decreased by 100–10000 times toward the height of maximal deceleration of 20 km, and then regained toward the height 10 km, when the velocity decreased approximately to subsonic values.[5]

These effects turned to be connected with processes of interaction of radio signals with wall plasma and adjacent plasma flow. However, the available theoretical models, based on classical views on the processes of electromagnetic wave absorption in the impedance wall plasma and their scattering on fluctuations of electron density in ionized adjacent flow, failed to explain these effects. Attempts to estimate them numerically on the base of existing models led to a considerable (factor of 10–1000) underestimation, to say nothing of the arbitrary choice of the model key constants.[4]

2.3. Quantum model of radio wave scattering in dense media

In 1970s, Nektarov in collaboration with national scientists has developed and proposed an alternative model of the revealed effects, i.e., a *quantum electron model* of radio wave scattering in a substance with hyper-excited atoms.[5]

In this model, to explain the strong absorption of radar signals in the field of hyper-sonic flow behind the shock wave, the electromagnetic radiation interaction with properly populated excited medium of the high-temperature flow, compressed by the shock wave, was considered. The flow temperature at a height of about 40 km can reach 7000 K, while electron concentration gradually increases in relaxation layers behind the shock wave up to 10^{15} cm^{-3} near the body surface.

As will be shown below, in the transition zone between the plasma and incident air flow behind the shock wave front, there arises a layer of strongly excited atoms locking resonance radiation at heights of about 60 km, in which practically all atoms turn to be at highly excited states due to recombination of charged particels.[6] And in the case of proper population, this triggers the quantum mechanism of absorption of external resonance electromagnetic radiation.

To explain the reflection of radar signals from the ionized adjacent flow, a *maser model* of amplification of electromagnetic radiation in the inversely populated medium of the flow, expanding behind the ballistic body was proposed.[5] In this flow the temperature (electron density) decreases downstream from 5000 K (10^{14} cm^{-3}). The theory of this effect predicts that the most probable region of maser reemission therewith is located in zones of deviation from local thermodynamic equilibrium at the electron concentrations lower than 10^6 cm^{-3}.

As radar measurements showed, such zones are confined to finite adjacent-flow region decelerated to subsonic values. Therewith, because of scattering on density fluctuations of the excited flow, the radar signals reemitted by highly excited atoms could have returned to the receiving antenna.

However, most acute still remained the question whether or not *highly excited atoms with principal quantum number of 100–200 can exist in such strongly excited dense media,* motivating the development of radar observations in centimeter-decimeter wavelength range at satellite-based radar stations TsSO-C MRTI, RPTs-200 and C-300 of OKB Almaz, RTN and Argun of OKB Vympel.

2.4. Regularity of existence of highly excited atoms in complex media and the earth atmosphere

Radio astronomical observations under conditions of strongly rarefied interstellar medium have stated a possibility of observation of hydrogen-like atom emission from levels with $n \sim 1000$, which was experimentally determined and theoretically justified as maximum possible value for existence of such radio atoms.

Relation between maximum possible excitation of highly excited atoms $n_{\max}$ and electron density N_e in interstellar medium was suggested by Windsold[7] and has the form

$$n_{\max} = [(6a_0)^{-1}(4\pi N_e/3)^{-1/3}]^{1/2},$$

where a_0 is the Bohr radius of the atom.

This formula defines perturbation of Coulomb potential by plasma but disregards the role of kinetic processes in complex media with strongly excited atoms.

In 1970s, a large body of research on kinetics of sub-atomic collisions was performed and numerical results for probability of interaction of such atoms under different conditions were obtained. This made it possible to determine the *regularity of existence of highly excited atoms in complex media* for different parameters of the medium state. Such a dependence was derived by Nektarov[8] in 1977

$$n_{\max} = [h(m_e a_0^2 / \tau_a)^{-1}]^{1/3}.$$

This formula follows from comparison of minimally possible time of existence of excited atom defined by the external electron period

$$\tau_e = h^{-1} m_e a_0^2 n^3,$$

and the corresponding time of dynamical existence of excited atom expressed in terms of the ionization collision rate reciprocal

$$\tau_a \equiv \nu_{\text{ion}}^{-1}.$$

In essence, the obtained relation shows that, in addition to the density and velocity of the medium particles, of key importance for excitation of atoms is also the probability of ionization of excited atoms in collisions with particles.

The probability of ionization of excited atoms is found to be maximum (of the order of 10^{-10} cm^2) in collisions with electrons; it is nearly 10^{-18} cm^2 in collisions with ions; from 10^{-11} to 10^{-16} cm^2 in collisions with molecules, and from 10^{-16} to 10^{-25} cm^2 in collisions with atomic particles.

Numerical estimates based on these data have shown that there may exist highly excited atoms with principal quantum numbers $n \sim 100$ *near the earth surface*; while at an altitude of 60 km in the earth atmosphere, above which the ionosphere overlies, there may exist $n \sim 1000$ stipulating a strong absorption (up to 40 dB) of radio waves during increase of solar activity.[9]

The same maximum degree of excitation $n \sim 1000$ may also be characteristic of atoms in low-temperature plasma at $T_e \sim 1$ eV with electron density of $\sim 10^{10}$ cm^{-3} in peripheral regions of thermonuclear devices with a 10^{11}–10^{15} cm^{-3} density of the medium.

2.5. Hyper-atoms in thermonuclear systems

In 1980s, experiments on interaction of plasma flows with neutral gas were conducted at the Institute of Nuclear Fusion of Russian Research Center Kurchatov Institute with the purpose of lowering the thermal load on receiving diverters of the thermonuclear reactor of the Tokamak type.

These processes were modeled on linear set-ups of beam-plasma discharge developed under leadership of Shapkin. When local supplying diverter plates with a cold neutral gas, a new phenomenon was found: anomalously strong *2000-fold reduction of thermal load* on receiving plates, now known as the *marfe* effect, which was accompanied by detachment of plasma from the wall and transition of recombination from the wall to the chamber interior, anomalous diffusion of electrons across the magnetic field (far exceeding the boom diffusion), as well as *appearance of intense resonance emission of cold neutral gas in ultraviolet spectral region.* All this could not be explained in terms of accepted models of radiative-convective instabilities in plasma.

At one of set-ups of this type, Lenta, in the case of volume discharge to a high-energy electron beam of 1–3 cm in diameter with a power up to 1.5 kW, a 1.5-m flow of helium plasma of 16 cm diameter was created. The plasma density was 10^{12}–10^{13} cm^{-3}, and the electron temperature could reach 10–20 eV. When the cold neutral helium with a density higher than 10^{14} cm^{-3} was directed to the receiving plate, there appeared a 1 m region of interaction of neutral gas with plasma flow. At the same time, at distances of up to 40 cm from the receiving plate, the electron temperature dropped to 0.3 eV (at pressures exceeding 15 mTorr), indicating a strong dissipation of plasma flow energy in the interaction region.

Plasma parameters were measured by stationary Langmuir probes; optical and microwave spectra were measured by instruments based on the monochromator MDR-6 of 2500–7300 Å range and a broadband low-noise amplifier of 2.4–3.8 GHz decimeter range.

2.6. Optical and microwave spectra of highly excited atoms of helium plasma at interaction with a neutral gas

Nektarov and Shapkin were first who paid their attention to specific role of strongly excited atoms not only in atmospheric shock waves and adjacent flows, but also in thermophysical and emission processes proceeding in reacting low-temperature plasma of thermonuclear devices.

Khripunov and Petrov conducted thorough many-year investigations and spectrometric measurements in the region of interaction of plasma flow with neutral gas on beam-plasma discharge set-ups.

Study of stationary plasma flow emission at pressures of 1–5 mTorr (~10^{13} cm^{-3}) has shown that its emission spectrum is in the *optical* wavelength range 3889–7281 Å (corresponding to transitions between levels $n \leq 5$) and consists of the lines of neutral helium, usually observed at electron temperatures of 2–8 eV, while microwave radiation fills all recorded band of the amplifier from 2.4 to 3.8 GHz.

When the neutral helium enters the interaction zone, the character of the reacting medium spectrum (measured at a distance of 50 cm from the receiving plate and 3–4 cm away from the central chamber axis) drastically changes, starting from a *threshold* density of 15 mTorr (~10^{14} cm^{-3}): there appear intense lines corresponding to transitions from levels n = 10–14 (with orbital quantum number l = 0; 1) in the plasma cooled to the electron temperature 0.5–0.1 eV and placed to a denser medium of neutral gas at a pressure of 17 mTorr; and at a pressure of 70 mTorr – the same take place from levels n = 20–22 (at l = 2), which are located in the near ultraviolet region between 3200–3700 Å!

Analysis of spectrograms shows that the pressure increase results in the appearance and intensification of luminescence of neutral helium lines starting from levels located in immediate proximity to the boundary of the continual spectrum, whose excitation potential differs from the ionization potential by less than 0.03 eV; for instance, the excitation energy of the upper level of transition 20d → 3D is 24.55 eV, whereas the ionization potential of helium atoms is 24.58 eV. At the same time, there appear even lines of the HeII ions in the spectrum, whose intensity increases as the pressure grows.

As it will be shown below, the threshold character of appearance of anomalous emission in transitions between $n > 10$ levels is due to reaching the medium *critical state* in the region of interaction of flows, occurring just at a density exceeding 10^{14} cm^{-3}.

At the same time, as the measurements showed, the intrinsic intense microwave plasma emission, caused by cyclotron instability of plasma oscillations in the inhomogeneous magnetic field, turned out to be attenuated throughout the recorded band 2.4–3.8 GHz at least to the level of intrinsic amplifier noise.

Obviously, this effect should be associated with formation of properly populated medium absorbing microwave radiation; this medium has atoms excited up to n ~ 200, as in the case of atmospheric shock waves. As a parallel absorption channel of microwave radiation in the range 1.5–10 GHz may be transitions between sublevels n1 ~ 15 ... 201 degenerated over orbital quantum numbers.[10] However, comparison of absorption intensities in the both channels has not been conducted.

The standard character of population of excited levels is confirmed by the recombination emission spectrum of deuterium plasma in ASDEX-U in the regime of plasma detachment from the diverter; this emission has decreasing line intensities between neighboring transitions from $n = 6 \to 2$ to $n \geq 15 \to 2$.[11]

The spectral pattern is more spotty for helium plasma reacting with proper neutral gas, in particular, at a pressure of 39 mTorr:

- 3447.57 Å: 6p → 1P0;
- 3498.65 Å: 13d → 3D;
- 3512.51 Å: 12d → 3D;
- 3530.49 Å: 11d → 3D;
- 3554.40 Å: 10d → 3D;
- 3587.30 Å: 9d → 3D;
- 3613.64 Å: 5p → 1P0;
- 3634.20 Å: 8d → 3D.

A common regularity of the emission spectra in the near UV is a decrease of intensities in the series 8 ... 13d → 3D and 5 ... 6p → 1P0, indicating a standard population of the atomic excitation levels in the reacting plasma.

As was noted above, the intensity of spectral lines of reacting plasma increases with increase of the neutral gas pressure in all spectral regions (from ultraviolet to radio one).

Analysis of spectrograms shows that increase of sensitivity and widening of the recorded spectral band of spectrometric instruments makes it possible to determine the actual spectral composition of the reacting plasma medium.

Of undoubted interest is also a study of interaction of reacting plasma with external electromagnetic radiation, especially important for problems solved with the use of the radio and optical radar instruments.

Theoretical analysis of experiments concerning interaction of the helium plasma flow with a neutral gas, performed at the Institute of Hydrogen Enegetics and Institute of Nuclear Fusion under leadership of Sholin with participation of Nektarov, have shown that these effects can be explained with the help of the new physical model taking into account the process of accumulation (at plasma–gas interface) of strongly excited atoms with $n > 10$ and their resonance emission. At the same time, as mathematical simulation shows, there appears an ion-sonic barrier at the interface of plasma and neutral flows, just where the plasma flow detachment takes place; in this region the plasma considerably reduces its energy content through conversion of particle thermal energy to emission of strongly excited atoms in the interface region.[12]

2.7. New model of plasma interaction with neutral gas

The new model of plasma interaction with neutral gas is based on achievements in the physical-chemical kinetics of plasma processes.[13]

Special attention in this field is paid to the properties of *non-equilibrium processes*, where the electron temperature and rotational temperature of molecules far exceed the temperature of the complex gas medium; therewith, a low translational temperature of the neutral gas in the interaction region decelerates reverse reactions and ensures a stability of products formed in the non-equilibrium plasma.

In particular, the electron concentration in the reaction zone of non-equilibrium systems appears to be many orders of magnitude higher than the value predicted by Sah formula for equilibrium systems. At the same time, a large variety of physical-chemical mechanisms in the processes of conversion of the substance, energy, and radiation in the non-equilibrium plasma calls for detailed study of all possible ways of their interaction when simulating these processes.

In the considered problem, the "main product" in the complex non-equilibrium medium at the interface of plasma–gas interaction appears to be the anomalously high concentration of highly excited atoms due to a high density of resonance ultraviolet radiation and a wide spectrum of low-temperature electrons in this region.

Full and physically adequate consideration of conversions occurring under non-equilibrium conditions at the interface of plasma–gas interaction has resulted in the system of kinetic equations whose solution has made it possible to answer rather non-ordinary questions posed in the new model.

Until recently it was believed that the interaction of plasma and neutral flows in a rarefied media with coronal distribution cannot influence significantly the state of such a medium because of the negligible concentration of excited atoms. It was meant that the radiation decay rate of the levels $A_n \sim 10^8$ s^{-1} in such a medium far exceeds the collision rate $\nu_n \approx N_e \langle\sigma_{nj}\nu\rangle \sim 10^2$–$10^4$ s^{-1}, therefore, the population of excited levels must be negligibly small.

However, under conditions of performed experiments the coronal model turns out to be inapplicable for two reasons. First, in the low-temperature medium at $T \sim 0.1$ eV and the neutral flow density $N_0 \geq 10^{14}$ cm^{-3} the absorption coefficient of resonance emission of excited atoms is estimated to be no less than ~0.3 cm^{-1}. So, it turns out to be *locked* in plasma/gas interface layer of less than 3 cm in depth. Second, the rate of diffusion-caused variation of atom concentration at a characteristic depth of the interface layer of a few centimeters is comparable with the rate of their collisional excitation or ionization. Thus, there appear conditions in this region favoring the accumulation of excited atoms (with the energy E_n), linked to ground state via resonance transitions, and the establishment of their distribution close to the equilibrium one with the electron-defined temperature T_e

$$N_n \sim N_0 n^2 \exp(-E_n / T_e).$$

This qualitative pattern was then considered in more detail. The processes of transfer of resonance radiation, excitation and kinetic energy of electrons were extensively studied, which gave new results.[14,15]

Thus, the excited atoms of a neutral flow from diverter or shock wave front come into collision with electrons of plasma, and the resonance emission of excited atoms in the plasma flow direction fills the interface region and is accumulated there without absorption because, in accordance with the Sah equation, under local equilibrium conditions, the concentration of neutral atoms is negligible in comparison with their amount in the surrounding gas.

On the contrary, the resonance radiation emerging in the opposite direction to the diverter or shock wave front suffers a strong absorption; therefore, there appears a locking layer at the gas–plasma interface, which at a sufficient gas density may be considered as 100% reflective. The depth of this layer is related to the depth of the resonance emission penetration into gas l_{eff}, which depends on the Doppler line broadening and, hence, is related to the temperature distribution of neutral atoms in the transition layer.

Equating the temperature change of neutral atoms to the friction force between electrons and ions, we obtain the regularity of the atom temperature increase from the external boundary (the surface of the receiving plate or the shock wave front) to the gas–plasma interface and further into plasma flow interior. In the zero-order approximation, the depth of the mutual penetration of charged and neutral particles is determined by the ion path length l_0. The depth of the reverse penetration l_{eff} of atoms into plasma decreases because of the processes of ionization by the electron shock.

At a constant total particle number across the penetration depth, the larger the mutual penetration of interface layers the less the local concentration of neutral atoms in the length ratio l_{eff}/l_0; therefore, *just at these sizes the processes of anomalous population of excited atom states and change of thermodynamic properties of neutral gas will take place.*

To describe the stationary structure of transitional gas–plasma interface layer taking into account the role of emission, the following system of equations was considered.

Continuity equations

One equation is for neutral atoms (with description of the change of the state of atom excitation under influence of radiation and collisions with electrons) and the second is for a charged component. From continuity equation in the first approximation one obtains the Sah equation, the role of the principal state in which is played by the first excited level. Its population is supported by the resonance radiation, while the distribution of populations of other states is controlled by the local electron temperature.

Heat transfer equations

The heat transfer equations characterize both the kinetic energy of the charged component and the internal energy of the neutral component. They take into account both the resonance emission and the recombination continuum under assumption that the processes of usual heat transfer do not play a marked role for heavy particles, since in the transition layer, almost all atoms are in the excited state and velocity of their motion is very small.

The heat transfer equations lead to an *extremely important conclusion:* in the region, where the local electron temperature $(T_e)_{\text{loc}}$ decreases from the initial value to ~ 0.1 eV, the degree of plasma ionization at the interaction medium density $N_0 \geq 10^{14}$ cm^{-3} appears to be of the order of 1 (!) with regard for the resonance emission, otherwise it would be only 10^{-7}.

Thus, the resonance emission shifts the condition of equilibrium towards full ionization at a low temperature and, correspondingly, the population of highly excited levels changes up to states with $n \sim 1000$, which is the maximum possible number.

Underline that the presence in the medium with highly excited atoms of a strong internal friction between particles, stipulated by increase of the effective cross section σ_{ae} of interaction of these atoms with particles proportionally to the fourth power of the principal quantum number

$$\sigma_{\text{ae}} \sim \sigma_{\text{ai}} \sim a_0^2 n^4,$$

requires, in terms of thermodynamics, in description of such medium properties, to pass from the ideal gas equation to the Van der Vaals equation and to take into account the proper volume of gigantic highly excited atoms. Excitation of high levels, at which the size of excited atoms becomes equal to the interparticle distance in the medium,

$$a_0 n^2 \sim N_0^{-1/3},$$

corresponds to existence of a *critical* gaseous region in the interface layer of interaction between plasma and gas flows which is impermeable to other subatomic particles.

At the neutral gas concentration $N_0 \geq 10^{14}$ cm^{-3}, a sufficient requirement for formation of interface layer at a critical state will be the correspondence of excitation into levels with $n \geq 10$, which ensures a possibility of observation of resonance emission both in optical and radio ranges.

2.8. New critical phenomena in the gas–plasma system

Phenomena, occurring near critical points of state parameters both in simple substances and complex media and accompanied by specific anomalous manifestations of their physical properties, are now widely known. They range from critical opalescence in the liquid–vapor system to increase of magnetic susceptibility and dielectric constant in the neighborhood of Curie points in ferromagnetic and ferroelectric materials, as well as many other effects.

These phenomena are connected with anomalous growth of fluctuations of parameters and their interrelation, while critical characteristics of these phenomena are described by dependence of thermodynamic variables on the temperature, pressure, density, etc. near critical points or points of phase transition of the second kind. Sometimes, the entire region of parameters such as density, concentration, magnetization, and polarization constitute a critical region of states of some complex medium.

The developed new model of interaction of plasma and neutral flows has made it possible to identify new critical phenomena in the gas–plasma system.

Such a system was considered before as non-interactive. However, the revealed anomalous radiophysical and thermal-physical effects in such (found to be similar) media as hypersonic jets near surface of flight vehicles in the atmosphere and flows of neutral and ionized helium near diverters in thermonuclear devices indicate the following. Under some specified thermodynamic conditions, there exists a whole region of density values for such media (from 15 mTorr and higher), where the interaction of these flows gave rise to previously unknown effects. They are, for example, the anomalously strong absorption of external electromagnetic radiation behind the shock wave incident on the surface of hypersonic body, or anomalously large reduction of thermal loads on diverters of thermonuclear devices.

These phenomena can be explained by increase of internal friction in the medium during interaction of the flows, accompanied by anomalously (10^7 times!) high accumulation of strongly excited atoms. This causes anomalously strong absorption of electromagnetic radiation in such media with simultaneous conversion of kinetic (thermal) energy of plasma particles to ultraviolet radiation, removing thermal load on the surfaces. A critical parameter in manifestation of these effects turns to be the mixed medium density, typically, of the order of 10^{14} cm^{-3} at temperatures lower 1 eV.

Thus, the region of interaction of gas and plasma flows at these parameters is in the specific critical state, determining the manifestation of the above-mentioned anomalous effects.

2.9. New equation of the critical gas–plasma state

As is well known, the state of the real N-particle gas is described by Van der Vaals equation:

$$(p + N^2aV^{-2})(V - Nb) = NkT,$$

where p is the pressure; V is the velocity; T is the temperature; the second term in the first parentheses expresses the internal pressure, and the second term in the second parentheses represents the quadruple volume of gas molecules.

Representing the proper volume of the excited atoms in the form

$$b \sim \frac{4}{3}\pi a_0^3 n^6,$$

we can propose a new version of the Van der Vaals equation for description of critical state of the complex medium, where the phase transition from gas to hyper-atom plasma occurs:

$$P_{\max} = RT\left[V - \frac{8}{3}\pi h^2 m_e^{-2} a_0^{-1} N\left(\Sigma p\langle\sigma v\rangle\right)^{-2}\right]^{-1} - aN^2V^{-2}.$$

Note in conclusion that the new model of interaction of plasma and neutral flows makes it possible to describe very accurately microprocesses in such complex media.

2.10. Condensed hyper-atom media

The above-mentioned radiophysical effects associated with emission and absorption of electromagnetic radiation in space and earth atmosphere were described from the viewpoint of existence in these media of *free* strongly excited atoms.

In 1980s, Manykin et al. suggested a new concept of gaseous media consisting of strongly excited atoms and molecules, which considered the electron-hole state of condensed excitons (elementary excitations in semiconductors) in terms of physics of solids.[16,17]

The existence of metal-like phase in semiconductors was predicted by Keldysh in 1968. Such a hydrogen-like electron-hole Fermi liquid was also observed experimentally. Theoretically, the properties of such medium were described by Rice in 1977, as well as by Hensel, Phillips, and Thomas.

Interaction between strongly excited atoms in sufficiently dense media causes a qualitative change of the medium structure and properties: energetically more preferred condensed state is formed from "shared" external electrons of excited atoms and molecules (often called "Rydberg" state). Such a state becomes possible on fulfillment of the Mott condition:

$$N_n^{4/3} a_n \geq 1,$$

which corresponds to existence of critical state of a strongly excited medium.

Calculations of parameters of such media, performed in accordance with theory of density functional and the use of the concept of pseudo potential of excited atoms, point out to a possibility of a substantial change of physical properties of these media: they predict a significant increase of their lifetime, increase of the dielectric constant, considerable increase of conductivity, which can be used to obtain a high-temperature superconductivity, as well as a change of some other parameters.

As calculations show, the lifetime of condensed states excited to a higher than the thirteenth level may be several hours, while for still higher excitation degrees the lifetime can be infinitely long because of spatial separation of initial and final states of external electrons and formation of wide potential barrier between them.

This is confirmed experimentally by the existence of long-living formations under field conditions, which are observed by radars in the form of many-hour-lasting reflections from the regions formed in the form of extended plumes of ion-plasma engines, ballistic bodies, as well as powerful explosions in the atmosphere. At the same time, the observations in the decimeter wavelength range indicate that such hyper-atom media may have excitation degree up to the principal quantum number about 200, as well as that there exist excitations degenerated over the orbital quantum number.

Laboratory experiments on observation of condensates of highly excited cesium atoms were conducted in 1990–1991 by Aman, Peterson, Holmlid, Svensson, Lungren, and Lindrose.

Using the time-of-flight mass spectrometry method, they observed clusters (clumps of highly excited cesium atoms) consisting of about 10 000 atoms. It was determined that such a medium has the electric resistance with a specific resistance of the condensate of the order of $10^{-3} \ldots 10^{-2}$ ohm·m.

2.11. Fireball

One of the interesting applications of the theory of strongly excited media is a possibility of description of some physical properties of such a phenomenon of the atmospheric electricity as a fireball.

The fireball, arising most often during strong lightnings, is a sphere of low-temperature plasma of about 30 cm in diameter, flying in air, readily movable, and emitting cold radiation. It exists for approximately 10 s, and then decays, usually with sudden loud sound, often accompanied by ignition of surrounding objects.

Fireball models, as well as different processes occurring in fireball are the subject of many publications. Recently, of concern are low-energy microwave discharges under atmospheric conditions, accompanied by occurrence of localized spheroid-shaped plasma formations of about 5 cm in size. Energy content of such systems corresponds to 0.5–1.5 kW of absorbed microwave energy, which allows one to simulate some processes taking place in the fireball.[18]

It was found that the plasma density in such formations is 10^{12}–10^{13} cm^{-3} at a temperature between 2500 and 4000 K, sustained by the flow of microwave power through the surface of the plasmoid from 5 to 50 W/cm^2 at a specific absorbed power between 5 and 50 W/cm^3. Therewith, the depth of the skin layer is 1–3 cm, which corresponds to the radius of the plasmoid, while its potential is insignificant and makes +5 V with respect to metal surface or +0.05 ... 0.07 V with respect to dielectric wall. The rate of circulation flows in the plasmoid is also low and makes 0.3 m/s. In free flight the plasmoid ascends at a rate of about 0.5 m/s.

When the power exceeding 1.5 kW is introduced into the chamber, the plasmoids exist in a steady state during several hours, and their radiative losses are insignificant in comparison with heat-transfer and convective losses at the discharge chamber wall. Intensity of microwave electric field is maximal on the surface of the plasmoid and decreases towards its center. When the transfer of microwave power is stopped, the emission of the plasmoid decreases exponentially with a characteristic time of 0.1 s (under conditions of limited time of motion between chamber walls).

The hyper-atom model of fireball can explain such its physical properties as the long lifetime, stability, and mobility.

The long existence can be explained based on the assumption that the fireball skeleton is made up of the atoms with higher than 13-fold degree of excitation, because, as it was already mentioned, the time of existence of such excitations may exceed several hours. At the same time, the fact of the fireball energetic interaction with microwave radiation indicates that the level of atom excitation in its medium can exceed 200 times.

Concentration of strongly excited atoms under atmospheric conditions at a temperature of about 3000 K, calculated by the method of statistical sums at $n \sim 10$, can be 10^{13}–10^{14} cm^{-3}, whereas in accordance with new model of interaction of plasma with neutral gas flow absorbed by the plasmoid through the lower central channel, the concentration of strongly excited atoms in the fireball is of the order of its medium density, i.e., $\sim 10^{18}$ cm^{-3} for $n \sim 1000$.

Short fireball lifetime under natural conditions is obviously connected with the fact that hyper-atom condensate is a quite "loose" substance; so the actual decay mechanism of highly excited states in fireball may be a consequence of chemical reactions proceeding in it at a possibility of easy penetration of particles of the surrounding medium into its volume.

The fireball stability is determined by laminar circulation flows inside the plasmoid, as well as surface tension of condensed hyper-atom medium stipulated by the atomic binding energy in the condensate. For a 14-fold excited medium, the surface tension is about 0.06 dyn/cm with a binding energy of about 0.1 eV, which ensures the fireball stability with a temperature up to 1000 K in the surrounding medium.

Easy mobility of fireball can be explained by far less density of hyper-atom condensate in comparison with surrounding medium: equilibrium density of the 14-fold excited condensate is two orders of magnitude lower than the density of the surrounding medium under standard conditions.

Naturally, there are many unanswered questions concerning the nature and properties of this phenomenon, as well as many other puzzling and attractive ones; and our purpose is to recruit inquiring young scientists to clarifying these mysterious natural phenomena.

3. Hyper atom technologies

3.1. Thermal-physics technologies

For modern and promising thermonuclear reactors such as Tokamak and International

Thermonuclear Experimental Reactor (ITER), the impact of high thermal loads on receiving plates of the diverter device is one of the most serious scientific and engineering problems. During thermonuclear reactions, a large amount of thermal energy released in plasma must be removed; therefore, there is a need in new materials and constructions, which would help to solve this problem. Analogous problem is to find ways of lowering large thermal loads on the surface of space vehicles during motion in planetary atmospheres.

Studies of interaction processes between plasma and neutral gas flows in RRC Kurchatov Institute, allowed the development of practical recommendations for creation of devices based on *thermal-physical effects* in working media with strongly excited atoms; these devices are capable to reduce by 2000 times the enormous thermal loads on constructions of thermonuclear devices and space vehicles. The developed physical model of these processes makes it possible to understand and calculate microprocesses occurring in the interaction region of these flows.

3.2. Radiophysical technologies

Application of engineering devices based on *radiophysical effects* in media with strongly excited atoms presents another possibility for amplification or attenuation of electromagnetic radiation.[19]

Manifestations of these effects in shock waves and adjacent plasma flows observed during radar tracking of space vehicles in the earth's atmosphere were described above.

Engineering implementation of quantum radiophysical effects in artificial media with strongly excited atoms was first realized by CNIRTI and TSAGI researching teams in 1980s, and then turned to development works by Sukhoi OKB and Gromov FRI in 1990s. Such media allow a 100-fold decrease of the radio visibility of flight vehicles, thus reducing their detection range by almost a factor of two.[20]

3.3. Quantum electronics devices

Using the above-mentioned technique of the electromagnetic radiation conversion, the work is underway on finding artificial media with strongly excited atoms aimed at creation of wide-spectral and broadband devices for generation and amplification of electromagnetic radiation. Pilot versions of such generating devices were created in CNIRTI under leadership of Pustynsky, while the development of broadband amplifiers in artificial plasma media is underway at the Institute of Nuclear Fusion (INF) RRC Kurchatov Institute under leadership of Shapkin, Nektarov, and Khrustachev.

3.4. Promising works

Besides the above mentioned, further promising directions of hyper-atom media application are in the field of plasma-chemical reactions and interaction of these media with body surfaces, as well as in many other areas. Worthy of mention are the works of Sholin and colleagues, aimed at simulating solar chromosphere and interaction of cosmic solar ray fluxes and solar wind with earth ionosphere. A possibility of construction of high-temperature super-conductive devices is under study.

Conclusion

The fundamental theoretical and applied works in the field of hyper-atom physics, dealing with detection of highly excited atoms in space and interaction of highly excited atoms with external electromagnetic radiation in the earth atmosphere have made it possible to construct adequate mathematical models for description of physical processes in complex media.

The critical obstacle on the way of searching for the maximum possible degree of excitation of atoms in space was the problem of Stark broadening of emission radio lines, whereas for the earth atmosphere, the key question became a justification of the possibility itself for existence of strongly excited atoms in complex dense media, as well as the question of their possible concentration in these media.

The many-year studies have led to the following results:

– The principal quantum number $n \sim 1000$ corresponds to maximum excitation of atoms in space, under atmospheric conditions, and in low-temperature plasma;

– The concentration of strongly excited atoms in the interaction region of plasma and neutral media under conditions of low-temperature plasma is of the same order as the density of the medium at $N > 10^{15}$ cm^{-3}.

These results were obtained with radioastronomical and satellite radars, as well as via physical and mathematical modeling of measured anomalous effects of interaction of low-temperature plasma media with external electromagnetic radiation and neutral gas flows.

A new regularity for the existence of strongly excited atoms at different parameters of the medium was found and new model of low-temperature plasma interaction with neutral gas flows was developed. It allowed one to explain the observed anomalous effects and to attribute them to specific critical phenomena in the region of interaction of these media.

Hyper-atom technologies have a considerable promise. Wide-spectrum and broadband generators have been created, analogous quantum-electronic amplifiers are under development, and possibilities of creation of high-temperature super-conductive devices are explored. A flight vehicle of a reduced radio visibility is constructed.

Chronology of milestone works in hyper atom physics

1959: Kardashev (of SAI) predicted the possibility of radioastronomic observation of hyper-atoms in space.

1964: Sorochenko and Borodzich (of FIAN), and A. Dravskikh, Z. Dravskikh, and Kolbasov (of SAO) detected hyper-atoms in the interstellar medium.

1969–1977: Nektarov (of CNIRTI) developed a theory of hyper-atom media and determined the regularity of existence of hyper-atoms in complex media.

1978: Nektarov, Sychev, Ustinov, Chinareva (of CNIRTI, SPA Astrofizika) developed a new method of conversion of electromagnetic radiation in hyper-atom media.

1979: Nektarov, Sychev, and Ustinov (of CNIRTI, SPA Astrofizika) developed quantum model of radio wave scattering in hyper atom media.

1979–1999: CNIRTI, Zhukov TSAGI, Sukhoi OKB, and Gromov FRI designed artificial hyper atom media absorbing radio waves, and devices for diminution of radio radar visibility of flight vehicles.

1980–2000: Nektarov, Sychev, Petrov, Khripunov, Shapkin, Sholin, et al. (of CNIRTI, RRC Kurchatov Institute, and SPA Astrofizika developed a new physical-mathematical model of interaction of low-temperature plasma and hyper-atom flows with neutral gas flows.

1981–2000: Manykin et al. (of RRC Kurchatov Institute) developed a theory of condensed hyper atom media.

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