2. As can be seen in the above sections, the topics of the reports presented at CWS-2002 are much broader than the list of the topics of research in LT physics included in the plans of the Rosaviakosmos Agency, NASA, and other national space agencies for the next five years. The most promising areas of research that can be recommended for implementation and could be included in the list of ground experiments sponsored by national space agencies are (a) the study of properties of cryolayers that form as a result of condensation of the substance being studied onto a cold substrate (this problem was discussed in the reports by Strzhemechny [13] and Drobyshev et al. [14]), and (b) the recently opened-up field of research involving the study of the properties of extrinsic nanocluster condensates (gels) that form as a result of condensation of a stream of gaseous He with an admixture of vapor of the investigated substance in superfluid He II (the reports by Khmelenko et al. [15], Popov et al. [16], and Mezhov-Deglin and Kokotin [17]). The mechanism of formation of impurity clusters in a cold helium jet, the interaction of these clusters with each other and with the surrounding medium at temperatures near 1 K, the structure and properties of porous nanocluster systems (gels whose dispersive system, or frame, is formed by impurity clusters surrounded by a layer of solidified He, while liquid He is the disperse medium), and the effect of the gravity environment on the properties of the forming condensates (ground-based measurements and experiments in a microgravity environment) — the solution of all these problems is important not only for modern materials science, whose constituent part is the physics of a condensed state, but also for astrophysics and cosmology (dust clouds in outer space at a temperature of about 3 K, ice in outer space, etc.). There are reasons to believe that impurity gels in superfluid He II can be used to accumulate and store free radicals (low-temperature fuel cells [15]) and ultracold neutrons. The report by Nesvizhevsky et al. [18] at the closing session was devoted to the advances in the physics of ultracold neutrons.

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References

1. *3rd Intern. Chernogolovka Workshop on Low-Temperature Physics in Microgravity Environment* (*CWS-2002*), *12–18 August 2002, Chernogolovka, Russia*, Book of Abstracts (Chernogolovka, 2002)
2. Collaudin B, Rando N *Cryogenics* **40** 797 (2000)
3. Israelsson U E, Lee M C "Use of the International Space Station for fundamental physics research", see Ref. [1], p. 12
4. Pensinger J F et al. "The low-temperature microgravity physics facility", see Ref. [1], p. 15
5. Strayer D M, Paik H J, Moody M V "Short-range inverse-square-law experiment in space", see Ref. [1], p. 16
6. Okuda Y et al. "Manipulation of solid–liquid interface of ^{4}He by acoustic radiation pressure", see Ref. [1], p. 23
7. Anfimov N A et al. "Major directions of research on low-temperature physics and engineering on board the Russian segment of the International Space Station", see Ref. [1], p. 11
8. Buskin S V et al. "Technological integration of low-temperature studies at the ISS RS and optimization of experimental equipment", see Ref. [1], p. 14
9. Bondarenko S I et al. "Physical research of microgravity influence on physical phenomena in cryogenic liquids and general-purpose on-board cryogenic facility for realization of this research aboard International Space Station", see Ref. [1], p. 13
10. Dergunov I M et al. "Superfluid helium boiling in the model of porous structure at microgravity", see Ref. [1], p. 20
11. Polezhaev V I, Soboleva E B "Thermal gravity-driven convection of near-critical fluids in enclosures with different heating", see Ref. [1], p. 19; Gorbunov A A, Polezhaev V I "Isoenthropic equilibrium stability of the near-critical fluid under zero gravity", see Ref. [1], p. 63
12. Levchenko A A et al. "Capillary turbulence at the charged surface of liquid hydrogen", see Ref. [1], p. 29
13. Strzhemechny M A "Properties of quenched hydrogen-based alloys with lighter elements from diffraction measurements", see Ref. [1], p. 48
14. Drobyshev A et al. "Enthalpy of the hydrogen bonds from measurements made on thin water films", see Ref. [1], p. 50
15. Khmelenko V V, Kiselev S I, Lee D M "ESR investigation of hydrogen and deuterium atoms in impurity-helium solids", see Ref. [1], p. 37
16. Popov E A et al. "Emission spectroscopy of atomic and molecular nitrogen in helium gas jet, bulk liquid He-II, and in impurity-helium solids", see Ref. [1], p. 38
17. Mezhov-Deglin L P, Kokotin A M "Water-helium condensate (gel) in liquid helium", see Ref. [1], p. 39
18. Nesvizhevsky V V et al. "Quantum states of neutrons in the Earth's gravitational field", see Ref. [1], p. 55

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Quantum states of neutrons in a gravitational field and the interaction of neutrons with nanoparticles

V V Nesvizhevskiĭ

1. Introduction

This report presents the results of ultracold neutron (UCN) studies we have conducted over the past few years at the flow-line research reactor of the European Centre for Neutron Research of the Laue–Langevin Institute in Grenoble, France. ECNR, the institution currently dominating international studies in fundamental neutron physics, has Russia among its member countries. Since the first UCN storage experiment [1] in Dubna in 1968, there have been much research and applied activity in this dynamic field.

The great interest in UCNs arises from the fact that slow enough neutrons are reflected totally from a surface — a unique property which makes it possible to confine UCNs in a closed container for a period of time comparable to their beta-decay lifetime, which is ~ 15 min. The probability for a UCN to be lost into the walls can be much lower that for their beta decay. This large confinement time allows high-precision or very sensitive measurements both of neutron properties and of their interactions with matter and fields.

Because UCNs are usually reflected strictly elastically, there is not enough time for them to attain equilibrium with the trap. One example of the use of this nonequilibrium phenomenon is an experiment on measuring the quantum states of neutrons in a potential well in which one wall is formed by the gravitational field of the Earth, and the other by a horizontally positioned reflecting surface (plane mirror) [2–4]: in the lowest quantum state, the energy of a neutron's vertical motion in the gravitational field is ~ 1.4 peV, and in the thermodynamic equilibrium this would correspond to ~ 20 nK, much less than the temperature of the experimental setup under normal conditions. This experiment and the prospects of its development are discussed in the first part of the report (Section 2).

Still, the probability of UCNs being heated in collisions with the surface of the trap is different from zero (usually $10^{-4}-10^{-5}$ per impact) as has been shown in Ref. [5] and subsequent experiments. The energy of neutrons heated in this way is usually of the order of the energy of thermal vibrations, i.e. $10^{-2}-10^{-1}$ eV, in a trap at room temperature. Recently, however, we have discovered one more — and quite surprising — mechanism by which UCNs can be lost; this mechanism is due to their being weakly heated [6–9], a process in which the neutron energy increase is on the average as small as $\sim 10^{-7}$ eV, i.e., many orders of magnitude less than the usual heating due to thermal motion. The nature of this process and projections for future research in this area are discussed in the second part of the report (Section 3).

2. Quantum states of neutrons in a gravitational field

If a material object is placed in a potential well sufficiently wide and deep for the object, one naturally assumes that it will exist there in bound quantum states regardless of the precise nature of the potential. Examples of the quantum states of matter in electromagnetic and nuclear fields are well known. In particular, the quantum states of electrons in an electromagnetic field are responsible for the structure of atoms, and the quantum states of nucleons in the nuclear field determine the structure of atomic nuclei. The quantization of energy levels should also be taken into account in, for example, describing the motion of electrons levitating above the surface of superfluid helium in the external pressing electric field. The quantum states of matter in a gravitational field are much more difficult to observe because the gravitational field is much weaker than the electromagnetic and nuclear fields. Therefore, such observations require experimental conditions in which no other interactions will interfere with the measurements taken. UCNs are just such a unique object, and allow direct experimental examination of the quantum states of matter in a gravitational field: they are electrically neutral; their proper lifetime is sufficiently long to obtain high energy resolution necessary for the observation; their low mass facilitates the observation of quantum effects because it leads to a large uncertainty in their position, and the interaction of neutrons with a mirror departs from thermodynamic equilibrium, thus allowing for experimentation with UCNs that are less energetic by many orders of magnitude than the thermal fluctuations of the mirror surface. Clearly, the relatively weak gravitational field of the Earth can be used to create only one wall of the potential well in the laboratory conditions. The other wall is a horizontal mirror which, given the scale of the problem under study, represents an infinitely sharp and infinitely high potential barrier, so that its parameters do not affect the energy of neutrons in their bound states, nor the shape of the corresponding wave functions.

Classically, what is going on in the phenomenon under study is that a free neutron placed above a horizontally positioned mirror surface is reflected from and falls back onto the surface many times under the action of the gravitational field. The essential point is that, unlike classical mechanics, the neutron's vertical motion is not continuous and adhere to quantum laws: its energy may assume only selected values, and its wave function is a standing wave, the square of the amplitude of which gives the probability of finding the neutron at a certain height above the mirror surface. The quantum motion of objects in a gravitational field is like a movie: it only seems to us that the object on the screen is moving continuously, because the human eye is not given enough time to resolve such rapid motion into individual frames; an instrument with sufficient resolution will be able, however, to establish the discrete nature of the motion.

In a real experiment, methodical limitations due to the statistical measurement errors and due to the neutron detection technique used make it impossible for us to lift a neutron above the mirror and then to lower it and measure the probability of its being found as a function of the distance to the mirror. What we can do, however, is to collimate the broad phase space distribution of neutrons into a nearly horizontal beam of very cold neutrons incident at a small angle on the mirror surface. The gravitation will then affect only the vertical component of the neutron motion. As a consequence, the motion of neutrons along the vertical axis will be quantized. The horizontal motion in this case is described by classical laws. Of course, this picture is valid only for perfectly specular reflections, without the mixing of the horizontal and vertical motion components — the condition which, fortunately for UCN studies, is secured by using standard, well polished optical mirrors with vertical roughness dimensions typically of 10 to 20 Å.

The length of the reflecting mirror below the moving neutrons is determined from the energy–time uncertainty relation $\Delta E \Delta\tau \approx \hbar$, which may seem surprising given the macroscopic scale of the experimental setup. The explanation is that the observation of quantum states is only possible if the energy separation between neighboring levels is greater (preferably, much greater) than the level width. The energy levels E_n are determined only by the fundamental constants (neutron mass m, and the Planck constant $\hbar = 6.6 \times 10^{-16}$ eV s) and also by the free fall acceleration g in a gravitational field and by the level number n:

$$E_n \approx \sqrt[3]{\frac{9m}{8}\left[\pi\hbar g\left(n-\frac{1}{4}\right)\right]^2}\,.$$

As the serial number n increases, the energy separation between the neighboring levels decreases until the levels ultimately merge into a classical continuum. Clearly, the lower quantum states are simpler and more convenient to measure in methodical terms. As to the width of a quantum state, it is determined by its lifetime or (in our case) by the observation time, i.e., by the neutron's flight time above the mirror. Thus, the length of the mirror is determined by the minimum time of observation of the neutron in a quantum state and should provide the fulfilment of the condition $\Delta\tau \gg 0.5$ ms. In our experiment, the average value of the horizontal neutron velocity was chosen to be ~ 10 m s^{-1}, implying that a mirror 10 cm in length was good enough for the experiment. The vertical scale of the problem, on the other hand, is determined by the momentum – coordinate uncertainty relation $m\Delta v_z \Delta z \approx \hbar$. The reason is that the smaller the vertical component of the neutron velocity, the larger the neutron wavelength corresponding to this motion component. However, the classical height to which a neutron can rise in a gravitational field cannot be less than the quantum-mechanical uncertainty in its position, i.e., less than the neutron wavelength. In fact, it is this condition which specifies the lowest bound state of a neutron in a terrestrial gravitational field. The uncertainty in height is then ~ 15 μm (about the thickness of kitchen aluminium foil, to give a vivid example), whereas the uncertainty in the vertical velocity component is ~ 1.5 cm s^{-1}. Clearly, the horizontal neutron velocity in our experiment is much greater than the vertical, so that in the classical approximation neutrons proceed along glancing trajectories at a small angle with respect to the mirror. From the quantum mechanical point of view, the motion of a neutron is more like moving from one page to the next in a book with pages 10 μm thick. The square of the wave function of a pure quantum state with number n — namely, the quantity which gives the probability of finding a neutron at a certain height — has n maxima and $(n-1)$ minima between them, has zero values at the minimum points, and asymptotically tends to zero at the end points, i.e., the probability varies with height and is uniform in the horizontal plane.

The experimental setup involves an absorber, which is placed above the reflecting mirror and whose position can be smoothly changed and measured with sufficient accuracy. The absorber's surface, while macroscopically smooth and flat, is microscopically rough, with roughness elements measuring in microns. In the classical approximation one can imagine that this absorber eliminates the neutrons whose vertical velocity component is sufficient for them to reach its surface. Roughness elements on the absorber's surface lead to diffusive (nonspecular) reflection of neutrons and, as a result, to the mixing of the vertical and horizontal velocity components. Because the horizontal component of the neutron velocity greatly exceeds in our experiment its vertical component, such mixing leads to multiple successive impacts of neutrons on the absorber and, as a result, to the rapid loss of the scattered neutrons.

At the outlet from the mirror – absorber gap, a low-background detector is mounted to measure the full flux of the neutrons passing through the gap. If neutron motion in a gravitational field obeyed classical laws, i.e., if it took place in the absence of quantum states, the dependence of the detector's counting rate on the gap width would be $N_{\mathrm{cl}}(\Delta z) \sim (\Delta z)^{3/2}$ (linear dependence on the height Δz with increasing gap width plus a square-root dependence due to the increased range of allowed values of the vertical velocity component). In the ideal quantum-mechanical case, the monotonic dependence $N_{\mathrm{cl}}(\Delta z)$ should, at small values of Δz, turn into a step function $N_{\mathrm{qm}}(\Delta z)$ for the following reasons. If the gap is narrow — less than the spatial extent of the lowest quantum state — then the neutrons should not penetrate through the gap. As the gap width Δz is increased, the transmission of neutrons should increase in a jump at the very moment when the gap becomes ~ 15 μm wide. Increasing the gap further will not change its transmission until Δz becomes equal to the spatial extent of the second quantum state. This jump-like increase in the transmission of the gap should continue until the classical continuum is reached at a sufficiently wide gap: as the level number increases, the energy level spacing decreases and becomes more difficult to measure. In real conditions, this idealized dependence is smeared due to the finite resolution of the instrument as well as the shape of neutron wave functions which have no sharp bounds.

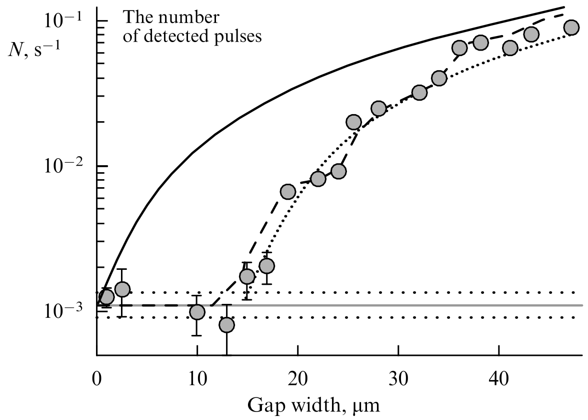

Figure 1. Neutron flux through a gap between a horizontal mirror and an absorber above it is given as a function of the distance between them. Experimental data are averaged over 2-μm intervals. The dashed line represents quantum-mechanical calculations in which both the level populations and the energy resolution of the experiment are treated as free parameters being determined by the best fit to the experimental data. The solid line corresponds to classical calculations. The dotted line is for a simplified model involving only the lowest quantum state.

The measurement results shown in the accompanying Fig. 1 differ considerably from the classical dependence $N_{\mathrm{cl}}(\Delta z)$ and agree well with the quantum-mechanical prediction $N_{\mathrm{qm}}(\Delta z)$. In particular, it is firmly established that the gap between the mirror and the absorber is opaque if the gap is narrower than the spatial extent of the lowest quantum state, which is approximately 15 μm. Check measurements suggest the conclusion that the experiment is free of systematic errors. In particular, subsequent measurements showed that the dependence $N(\Delta z)$ is the same for different values of the average horizontal component of the neutron velocity and that it is determined by its vertical component only. Precision in manufacturing the optical parts of the experimental facility is high enough to avoid systematic errors related to the shape of the parts. Precision in determining the position of the absorber turned out to be sufficient to identify the lowest bound state. The dashed line in the figure shows the results of a quantum-mechanical calculation of $N_{\mathrm{qm}}(\Delta z)$, in which the level populations and the height (energy) resolution were used as free parameters. The solid line shows the classical $N_{\mathrm{cl}}(\Delta z)$ dependence normalized so that at sufficiently large heights (above 50 – 100 μm) the experimental results are described well by the line. The dotted line given for illustrative purposes describes a simplified situation with the lowest quantum state alone, i.e., in drawing this line only the uncertainty relation was taken into account. As can be seen from Fig. 1, the statistics and energy resolution of the measurements are still not good enough to detect quantum levels at a wide gap, but the presence of the lowest quantum state is clearly revealed.

This measurement constituted the first experiment showing the existence of quantum states of matter in a potential well created by a gravitational field and a horizontal mirror, and thus far this is only a demonstration of this phenomenon. However, the quantization of neutron states in a gravitational field can also be used in further fundamental physics research because *a priori* this is a very pure system, one in which both the energy of the quantum states and the associated wave functions are determined only by the interaction of neutrons with a gravitational field. Clearly, precision measurements require a significant improvement in two parameters: the energy resolution and statistical accuracy. As can be inferred from the energy – time uncertainty relation $\Delta E \Delta \tau \approx \hbar$, larger energy resolutions require that neutrons be kept much longer in their quantum states. In principle, the energy resolution can be improved to $\sim 10^{-18}$ eV by increasing the observation time to a value comparable to the neutron beta-decay lifetime which is $\sim$ 15 min. The 'flight' technique is not up to this task, and we need instead to confine UCNs in a quantum trap, namely, a box with an ideally horizontal bottom and with vertical side walls. Preliminary analysis shows that this is not an entirely hopeless problem in purely technical terms. Neutron energies in the quantum states characteristic of such a trap can be determined by measuring the frequency of resonant transitions between the energy levels. The anticipated frequencies of the resonant transitions are very convenient for experimental purposes. For example, the frequency of the resonant transition between the first and second quantum levels is $\sim$ 260 Hz. By choosing another pair of states we can increase or decrease this value. A resonant transition between quantum states can be induced in a variety of ways: by low-amplitude mechanical vibrations of the quantum trap (in this case one wall of the neutron-confining well changes its position in a periodic manner, and transitions occur due to the presence of strong interaction in the system); by periodically varying the intensity of the electromagnetic field, and even — at the detection limits of the experiment — through periodical variation of the gravitational field by placing an oscillating mass close to the trap. Checking the electrical neutrality of neutrons or measuring gravitational forces at small distances of the order of 1 to 10 μm might be examples of experiments using such resonant transitions between neutron energy levels.

Performing such precision experiments within a reasonable period of time requires a significant increase in available UCN densities. One of the ways to achieve this, which we think is promising in connection with these experiments, is the thermalization of neutrons through their interaction with ultracold nanoparticles.

3. Interaction of neutrons with nanoparticles

Recently, when searching for the cause of systematically too large losses of UCNs on trap walls we discovered one more, quite remarkable, loss channel due to the weak heating of neutrons [6 – 9]; in this neutron heating process the average energy increase amounts to only 10^{-7} eV that is 5 to 6 orders of magnitude less than in ordinary heating due to thermal motion. In a great number of cases, the probability of this process was found to be $10^{-7}-10^{-5}$ per impact upon the surface. By creating special conditions, however, it was possible to either reduce the probability to at least 10^{-8} per impact or, alternatively, increase it to 10^{-3} per impact. The neutrons heated in this way we call EUCNs (evaporating ultracold neutrons), somewhat analogous to the process of evaporation of molecules from a liquid surface. Comprehensive studies of this process [10 – 14] indicate that it might be due to the Doppler shift in UCN energies, caused by their scattering from surface nanoparticles that are in a state of thermal motion [15].

As is well known, for a system in thermodynamic equilibrium the energy for any degree of freedom is $\sim kT/2$. This applies both to an individual atom and to a nanoparticle or a nanostructure at the surface. If a nanoparticle is strongly bound to the surface, it is virtually at rest and reflects neutrons elastically. If a surface nanoparticle is bound weakly, then the interaction of a neutron with it is a problem concerning reflection from a moving wall (classical or quantum mechanical, depending on the relation between the neutron – nanoparticle interaction time and the velocity — or frequency — of the particle motion). In the case of a classical interaction, a reflected neutron changes its velocity by twice the wall velocity. In the case of a quantum-mechanical interaction, the increase (decrease) in the energy $\hbar w$ is determined by the nanoparticle's vibration frequency w. This interaction is very selective in terms of the nanoparticle size: neutrons 'choose' nanoparticles with diameters close to the de Broglie wavelength of the neutron, which can be estimated from the relation $\lambdabar_n[\mathrm{nm}] \approx 63/V_n\,[\mathrm{m\ s^{-1}}]$. The reason is that the probability of a neutron to interact coherently with a nanoparticle is proportional to the sixth power of the nanoparticle diameter, provided the diameter is less than the neutron wavelength. Therefore, neutrons experience diffraction by too small nanoparticles almost without interacting with them. The velocity of excessively large particles, on the other hand, is so low that they have virtually no effect on the UCN energy. Thus, the bottom line is that we must only consider the interaction of UCNs with weakly bound surface nanoparticles whose diameter is roughly equal to the neutron wavelength. An experiment of this kind is extremely sensitive: changes in the UCN energies can be detected even if the probability of this process is of the order of 10^{-9} per impact. As a consequence, if not individual nanoparticles but indeed the whole of the reflecting surface vibrates, this situation corresponds to effective surface vibrations with amplitude less than one hundredth of an angstrom.

While these results are important for understanding the physics of the interaction of UCNs with a surface, they are also of applied interest: they necessitate the reinterpretation of many previous UCN storage experiments; they demonstrate new possibilities of studying the dynamics of nanoparticles and nanostructures on a surface, and finally they suggest a fundamentally novel method for obtaining superhigh UCN densities by thermalizing neutrons through their interaction with ultracold nanoparticles [15].

The point here is that in the UCN storage experiments described above, the temperature of the experimental facility — and hence the temperature of surface nanoparticles — was well above $\sim$ 1 mK, a temperature corresponding to the UCN energy. Therefore, neutrons were largely heated when interacting with nanoparticles. The problem can be inverted, however, if the temperature of the nanoparticles is below that of the neutrons. The principle of operation of such a UCN source is similar to that governing the cooling of neutrons in a reactor moderator, and requires a macroscopically large ensemble of weakly bound nanoparticles with a diameter on the order of the neutron wavelength; the temperature of the entire ensemble must be 1 mK, the value corresponding to the characteristic energy of the UCNs involved. Candidates for such a moderator are the gels of impurity nanoparticles in superfluid ^{4}He [16–18], which are prepared from inefficient neutron-absorbing materials such as, for example, heavy water or deuterium. Experiments to study the interaction of neutrons with such gels are now underway as a joint effort between our team and the authors of Refs [16–18].

4. Conclusion

In this report we have not attempted to review the subject but limited ourselves instead to presenting the results of our research. The report describes an experiment which has, for the first time, measured the quantum states of a particle in a potential well created by a gravitational field and a horizontal mirror. We also discussed prospects for further developing the experiment. Thus, the narrow resonant transitions between the quantum states of a neutron in the gravitational field of the Earth might be used in precision experiments in fundamental neutron physics — such as the verification of the electrical neutrality of neutrons or measurements of interactions at small distances. Part of the report is devoted to the interaction between neutrons and nanoparticles. In particular, we have discovered and investigated a new loss channel for UCNs in a trap, due to their being weakly heated when interacting with the surface. The heating presumably results from the Doppler shift in UCN energies, caused by their scattering from surface nanoparticles (nanostructures) being in thermal motion. Future research directions in this field include the dynamics of surface nanoparticles, increasing the UCN confinement time in traps, improving the reliability of UCN confinement experiments in fundamental neutron physics, and investigating the possibility of obtaining higher UCN densities by thermalizing neutrons in the gels of ultracold nanoparticles in superfluid ^{4}He.

References

1. Lushchikov V I et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **9** 40 (1969) [*JETP Lett.* **9** 23 (1969)]
2. Nesvizhevsky V V et al. *Nucl. Instrum. Meth. A* **440** 754 (2000)
3. Nesvizhevsky V V et al. *Nature* **415** 297 (2002)
4. Nesvizhevsky V V et al. "Measurement of quantum states of neutrons in the Earth's gravitational field" (2002) (to be published)
5. Strelkov A V, Hetzelt M *Zh. Eksp. Teor. Fiz.* **74** 23 (1978) [*Sov. Phys. JETP* **47** 11 (1978)]
6. Nesvizhevskiĭ V V et al. *Yad. Fiz.* **62** 832 (1999) [*Phys. Atom. Nucl.* **62** 776 (1999)]
7. Strelkov A V et al. *Nucl. Instrum. Meth. A* **440** 695 (2000)
8. Nesvizhevsky V V et al. *Eur. Phys. J.: Appl. Phys.* **6** 151 (1999)
9. Geltenbort P et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **70** 175 (1999) [*JETP Lett.* **70** 170 (1999)]
10. Lychagin E V et al. *Yad. Fiz.* **63** 609 (2000) [*Phys. Atom. Nucl.* **63** 548 (2000)]
11. Lychagin E V et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **71** 657 (2000) [*JETP Lett.* **71** 447 (2000)]
12. Nesvizhevsky V V et al. *Phys. Lett. B* **479** 353 (2000)
13. Lychagin E V et al. *Yad. Fiz.* **65** 2052 (2002) [*Phys. Atom. Nucl.* **65** 1995 (2002)]
14. Lychagin E V et al. *Poverkhnost': Rentgenovskie, Sinkhrotronnye Neĭtron. Issled.* (7) 81 (2002)
15. Nesvizhevskiĭ V V *Yad. Fiz.* **65** 426 (2002) [*Phys. Atom. Nucl.* **65** 400 (2002)]
16. Mezhov-Deglin L P, Kokotin A M *Pis'ma Zh. Eksp. Teor. Fiz.* **70** 744 (1999) [*JETP Lett.* **70** 756 (1999)]
17. Kokotin A M, Mezhov-Deglin L P *Fiz. Nizk. Temp.* **28** 235 (2002) [*Low Temp. Phys.* **28** 165 (2002)]
18. Kokotin A M, Mezhov-Deglin L P *Prib. Tekh. Eksp.* **44** (2) 159 (2001) [*Instrum. Exp. Tech.* **44** 279 (2001)]

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On the nature of radio emission from stars of late spectral classes

A V Stepanov

1. Introduction

We discuss mechanisms of intensive radio emission from stars of late spectral classes: red dwarfs, and close binaries of RS CVn and Algol types. These spectral classes (F, G, K, M) are positioned adjacent to the central and bottom parts of the main sequence in the Hertzsprung–Russell diagram, being chosen for following reasons. First, they show strong flaring activity. Second, they are located comparatively close to the Sun (a few units to several tens of parsecs). So the fluxes of their radio emission ($\sim 10^{-3}-1$ Jy) are sufficiently high for detection by modern telescopes. In addition, in order to explain the nature of activity of these stars, the solar–stellar analogies suggested by Gershberg and Pikel'ner [1] more than 30 years ago are largely used.

In contrast to daily observations of the Sun, the radio emission from stars, and especially stellar flares, is a genuine event for astrophysicists. Radio emission from UV Ceti stars was discovered in 1958 by Lowell on the Jodrell Bank telescope (on a frequency of 204 MHz). Up to the present, radio emission from several hundreds of stars of different spectral classes has been registered in the wavelength range from millimeters to decameters. Nevertheless, each observation of radio emission from stars, and especially stellar flares, lends important new information on the processes in stellar atmospheres.

The quiescent radio emission of stars is mainly thermal (bremsstrahlung and synchrotron) but frequently demonstrates a nonthermal character with a brightness temperature $T_b \sim 10^{10}$ K, which is usually related to gyrosynchrotron radiation from fast electrons. Radio emission from flares stellar is characterized by $T_b \sim 10^{10}-10^{16}$ K, a high degree of polarization and clearly has a nonthermal origin.

Table 1 lists energy characteristics of flares from different objects. In spite of radio emission energy from stars being by 4–10 orders of magnitude smaller than, for example, X-ray energy, the radio emission provides extremely rich information about the parameters of stellar atmospheres and processes therein since it is very sensitive to change in the states of plasma and high-energy particles. There is a number of excellent reviews [2–7] which describe the results of observations of stellar radio emission and its models. The existing reviews give preference to noncoherent radio emission mechanisms. The present report is dedicated to coherent mechanisms of the flaring radio activity of stars, in particular, to the nonlinear plasma mechanism which is especially effective in stellar coronae.

2. Experimental data

First observations of radio emission from stars were conducted at fixed frequencies. The indubitable progress in the end of the 1980s was due to spectrographic studies of stellar radio emission. Dynamic radio emission spectra of stars (intensity as a function of frequency and time) are similar to solar ones and demonstrate a distinctive fine structure,