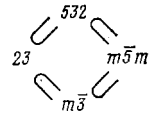
terns. However there is also disagreement with experiment, which gives peaks of finite width, corresponding to a distance of ~ 100 Å at which the translational order is lost. In addition, this is unrelated with the size of microcrystallites, which, judging, for example, by the correlation length of the orientational long-range order, is two orders of magnitude greater (see Refs. 6 and 7).

The disagreement is most likely attributable to the fact that a real quasicrystal differs from the mathematical model of an ideal quasicrystal, namely, the atoms in an ideal quasicrystal are located in nonequivalent and unsymmetrical environments and their positions at the sites of an ideal quasilattice are not positions of equilibrium. Therefore, in order to construct a real quasicrystal the atoms must be displaced into equilibrium positions by irregular forces exerted by neighbors. At the same time the quasiperiodic long-range order is destroyed, which broadens the δ function peaks of an ideal quasicrystal, and this is linked with phason variables, as can be easily followed in a continuum model of the quasicrystal.

Irregular forces acting on the phonon variables do not broaden the spots in precisely the same way that impurities in an ordinary crystal do not destroy the long-range translational order. But the same forces, acting on the phason modes, cause the correlation function of the phasons to diverge: the channel in six-dimensional space becomes bent and the amplitude of the deviation from the basal hyperplane diverges. This is what causes the finite width of the peaks. The orientational long-range order is not destroyed in this case; dislocations also remain well defined, so that a Berezinskiĭ phase with topological translational order is possible: in a circuit along a contour of length L Burgers' vector increases as $L^{1/2}$. This distinguishes a real quasicrystal from an amorphous body with orientational long-range order. The complete classification scheme for solids and liquids has yet to be constructed. It is possible that this scheme will be based on an extended symmetry group, including, for example, statistical symmetry and the group of diffeomorphisms.

[1]D. Shechtman, I. Blech, D. Gratias, and J. W. Cahn, Phys. Rev. Lett. **53**, 1951 (1984).
[2]L. Bendersky *et al.*, Scripta Metall. **19**, 909 (1985).
[3]D. Levine and P. J. Steinhardt, Phys. Rev. Lett. **53**, 2477 (1984).
[4]P. A. Kalugin, A. Yu. Kitaev, and L. S. Levitov, Pis'ma Zh. Eksp. Teor. Fiz. **41**, 119 (1985) [JETP Lett. **41**, 145 (1985)].
[5]A. L. Mackey, Kristallografiya **26**, 910 (1981) [Sov. Phys. Crystallogr. **26**, 517 (1981)].
[6]P. A. Bancel *et al.*, Phys. Rev. Lett. **54**, 2422 (1985).
[7]D. R. Nelson, Sci. Am. **255**, No. 2, 42 (August 1986).

V. Sh. Shekhtman. *Icosahedral symmetry and the diffraction experiment.* The discovery of new packing principles for atoms in solids requires a more detailed analysis of the group relations between the quasicrystal model and the crystal lattice. Thus systems with fifth-order symmetry adjoin families of crystallographic point groups, unified by the seven limiting Curie figures. Moreover, if there are no restrictions associated with the Bravais lattice, the two groups of the icosahedral system are the natural and only addition to the standard 32 groups. At the same time the minimum requirement—the finite rotation group constructed on nonorthogonal rotational axes—is satisfied. Thus only two systems are added to the hierarchy of higher-order limiting groups of the sphere (∞/∞ and $\infty/\infty mmm$): the cubic system (the groups 432, 23, $m3m$, $\bar{4}3m$, and $m\bar{3}$) and the icosahedral system (the groups 532 and $m\bar{5}m$).[1] We can immediately indicate important subgroup chains



It is useful to describe next the geometric relationships between the Bravais lattices and the quasicrystalline packing, taking into account the general properties of regular polyhedrons. It is well known that there exist only five so-called Plato bodies[2] with 4, 6, 8, 12, and 20 faces. In the language of crystallography they are all simple shapes (particular shapes) of the cubic or icosahedral system (Fig. 1). For the present discussion it is significant that there exist methods for mutual embedding of the indicated figures; for example, a cube can be inscribed into a dodecahedron with pentagonal faces. Let the cube belong to the group $m\bar{3}$, i.e., among its symmetry elements there are no fourth-order axes. Then the pentagon-dodecahedron is formed as a simple shape, if the starting face is given the indices $\{10\psi\}$ (where $\psi = (1+\sqrt{5})/2$). We call attention to the fact that in this procedure the application of the symmetry operations of a cube to a plane in a unique (irrational) orientation results in a figure which is a simple shape of the supergroup $m\bar{5}m$.

L. Pauling's[3] alternative interpretation of diffraction observations for annealed aluminum-manganese alloys can be regarded as a consequence of this construction. Indeed, right angles between the fifth-, third-, and second-order axes in electron diffraction pictures may be regarded as indications of a quasicrystalline cluster; but these angular relations could equally well characterize a system of 12 domains of the cubic phase, oriented during growth along planes close to $\{10\psi\}$ (for example {305},{508}, etc., from the Fibonacci sequence). In this case the experimental observations of fifth-order symmetry can also be regarded, as an indication of the existence of icosahedral packing, as a prephase, whose symmetry is inherited in the diffraction picture of a polydomain crystal according to the Zheludev-Shuvalov principle.[4]

In concluding this presentation we call attention to the metal systems, in which unusual results, which served as the beginning of the "icosahedral catastrophe" in solid-state physics, were obtained. It is by no means accidental that among aluminum-manganese and aluminum-iron-silicon alloys there exist intermetallides whose structure belongs to the space groups $Im3$ and $Pa3$, respectively. Here there is also the possibility of second-order phase transitions out of the icosahedral group $m\bar{5}m$ into its subgroup $m3$.

Proceeding now to diffraction problems, we point out

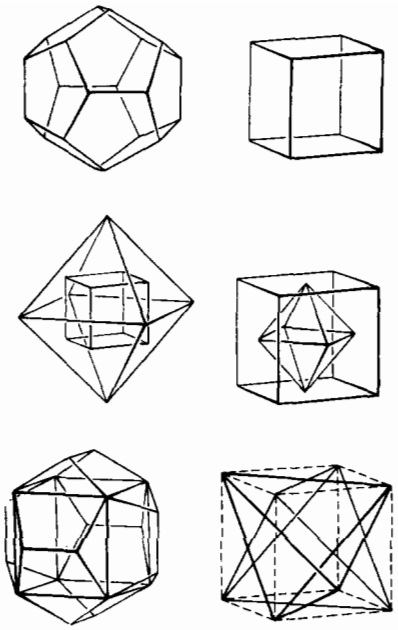


FIG. 1.

first of all the prospects for and the high level of the theoretical approach developed by P. A. Kalugin, A. Yu. Kitaev, and L. S. Levitov (report in this session). We call attention next to the priority-setting contribution of A. Mackey, who developed in 1981 the concept of a quasilattice.[5] Here the fundamental idea of a hierarchy of Penrose tilings, constructed on three-dimensional rhombi, triangles, and rhombohedrons with notable angles of the type 36°, 72°, 63.43°, etc., is very important. In particular, for later experiments it is important that the pattern can be constructed not only by expanding the tiling with decagons (triacontahedra), but also by separation with infinite "embedding" (reduction of scale) from the starting figure with five-fold symmetry.

The rate of publication of papers along this line is high (one to two papers per week during the last two years). Nevertheless, from the viewpoint of structural analysis, only the trial and error method survives at all levels of experimental work. The method for solving the inverse problem of diffraction, well-known from many years of x-ray structural analysis, has not yet been employed. It is obvious, of course, that the main difficulties are attributable to the fact that there is no distinct Bravais lattice. In particular, it is necessary to find approaches, for example, for introducing concepts which adequately describe the geometric structure factor F and the interference function Φ for the purpose of using the complete collection of intensities of the diffraction maxima in the reconstruction of the structure. The fact that the diffraction pattern depends on the structure of the icosahedral tiling and therefore the analysis must start from some analog of the expression

$$\rho(xyz) = \frac{1}{v}\sum_h\sum_k\sum_l F(hkl)\exp[-i2\tilde{n}(hx + ky + lz)]$$

was demonstrated in preliminary experiments. Optical modeling of diffraction effects was performed on two-dimensional Penrose tilings at the Institute of Solid State Physics of the USSR Academy of Sciences.[1)] Transparencies representing

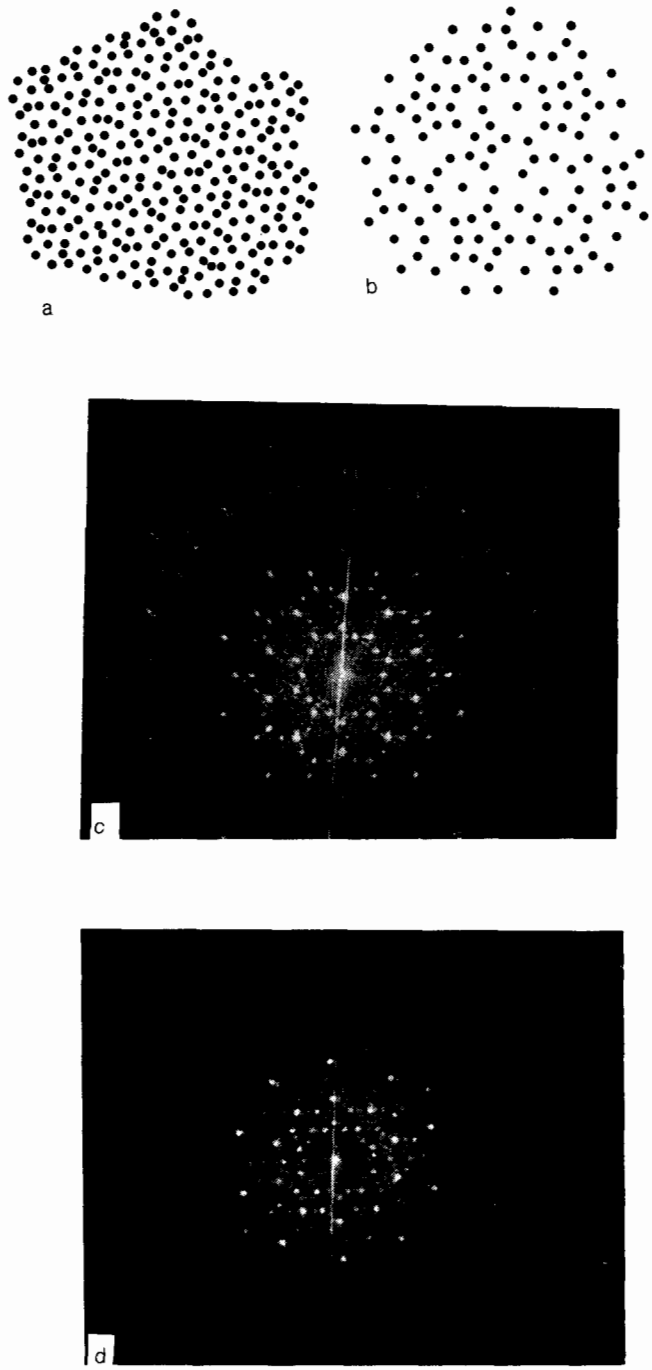


FIG. 2.

two algorithms for constructing the pattern were prepared (Figs. 2a and b). The Fourier transformation, realized in the optical diffractometer using a helium-neon laser, gave different diffraction patterns (Figs. 2c and d). This not only demonstrates the diffraction maxima obtained on nontrivial patterns, but it also indicates the change in the diffraction pattern depending on the restructuring of the icosahedral structure.

The foregoing leads to the conclusion that additional efforts must now be made to find theoretical and experimental solutions of the inverse problem of diffraction in order to determine directly the atomic structures examined in this session.

[1)]E. V. Shulakov, I. N. Ivoĭlov, and A. I. Erko participated in the experiments.

[1]B. K. Vaĭnshteĭn, Modern Crystallography. Vol. 1. Symmetry of Crystals: Methods of Structural Crystallography (in Russian), Nauka, Moscow (1979), p. 101.

[2]D. Hilbert and S. Cohn-Vossen, *Geometry and Imagination*, Chelsea Publishing (1952) [Russ. transl., Nauka, M., 1981, p. 99].
[3]L. Pauling, Nature **317**, 512 (1985).
[4]I. S. Zheludev and L. A. Shuvalov, Kristallografiya **1**, 681 (1956) [Sov. Phys. Crystallogr. **1**, 537 (1956)].
[5]A. L. Mackey, Kristallografiya **26**, 910 (1981) [Sov. Phys. Crystallogr. **26**, 517 (1981)].

V. S. Shpinel'. *Nuclear-spectroscopic studies of hyperfine interactions for impurities in metals.* Investigations of hyperfine interactions (HFI) by different nuclear methods, employing radioactive nuclei and accelerators, have made it possible to obtain a number of fundamental results, which are important for both nuclear and condensed-matter physics. Some results of investigations of magnetic HFI for magnetic impurities in dilute alloys Pd (Fe, Co) at ultralow temperatures and for nonmagnetic (NM) impurities Sn in rare-earth metals (REM), performed at the Scientific-Research Institute of Nuclear Physics at Moscow State University by methods of Mössbauer spectroscopy and oriented nuclei and by the method of the Mössbauer effect on oriented nuclei, are described in the report. The examples studied demonstrate the types of problems in the magnetism of metals that can be solved by such methods.

1. Studies of HFI in alloys of 3d elements with Pd are of special interest because of the unique properties of Pd. In this work the emission Mössbauer spectra with a ^{57}CO source, introduced into Pd(Fe) alloys with different Fe dopant concentrations, were studied. The samples were cooled with the help of an ^{3}He–^{4}He dilution refrigerator.

The hyperfine (HF) field on Fe measured at $T = 4.2$ K as a function of the applied field H_0 for the alloy with an Fe concentration of 0.01 at. % follows the Brillouin curve, describing the magnetization of the free spin with the "giant moment" $\mu_g = 10\mu_B$, known from other experiments. As the temperature was lowered to 0.55 K the magnetization curve corresponding to a reduction of μ_g down to $8\mu_B$ changed smoothly.[1] This behavior was predicted in Ref. 2.

When there is no applied field, at these temperatures the γ-resonance spectra contain a single line corresponding to fast paramagnetic relaxation. As the temperature is lowered still further, in this sample, just as in the more concentrated alloy with 0.06 at. % Fe, slow electronic relaxation, which is unusual for metals and as a result of which a nonzero HF field appears on the Fe nucleus, was observed. For the first and second alloys the spectra, for $T < 25$ mK and $T < 52$ mK, respectively, have the form of standard sextets, corresponding to almost maximum splitting (see Fig. 1; $T = 0.052$ K).

Computer analysis of the relaxation spectra showed that there exists a wide set of relaxation frequencies, which is a consequence of the distribution of exchange interactions in disordered alloys. The temperature dependence of the mean relaxation frequency is linear, and in addition the corresponding straight line for the most dilute alloy passes near 0 K, while for the alloy with 0.06 at. % Fe this dependence at temperatures near 0.1 K becomes markedly weaker.

Spectra obtained in longitudinal fields ($H_0 < 600$ Oe) at ultralow temperatures contain components corresponding to forbidden transitions with $\Delta m = 0$ (see Fig. 1; $H_0 = 200$ Oe). This indicates the existence of transverse spin components, i.e., the spins are not completely oriented along the applied field. The observed disorientation is explained by the sign-alternating RKKY interaction between the spins, which can lead to the spin-glass state. Our data showed that the alloy with an Fe concentratoin of 0.01 at. % must transform into the "spin-glass" state at a temperature below 20 mK.[3] Indeed, for this alloy a susceptibility peak characteristic for a spin glass was recently observed at $T = 8$ mK.[4] For the second more concentrated alloy this transition is manifested in the above-noted sharp change of the relaxation regime at ~ 0.1 K.[5]

The results of γ-resonance experiments and studies performed by the method of oriented nuclei show that the Co impurity in our alloys is in a Kondo state with $T_K = 0.14 \pm 0.04$ K, in agreement with the results of Ref. 6. The observed asymmetry of the spectra at temperatures below 52 mK with $H_0 = 0$ (see Fig. 1) is explained by the appearance of a molecular field, leading to a reduction of the spin compensation on Co and, therefore, the appearance of H_{hf} on the Co nucleus. This also supports the appearance of an ordered state of the spin-glass type, whose relaxation frequency spectrum contains frequencies of the order of or less than the nuclear spin-lattice relaxation frequency for Co $\bar{\lambda}_{sl} \sim 10^2$ rad/s. We measured this relaxation frequency in

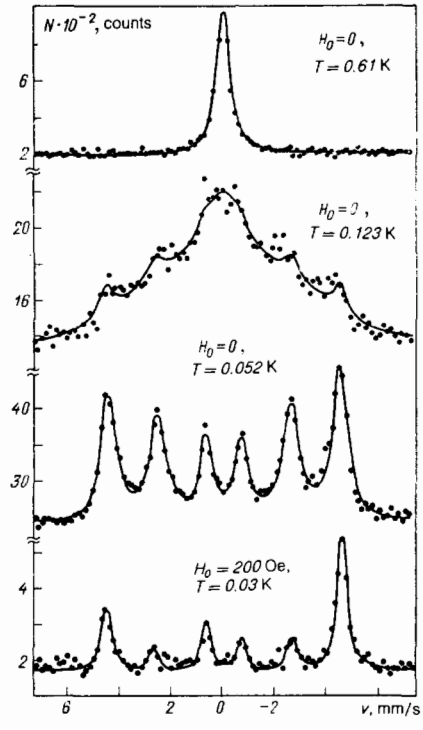


FIG. 1.