the considered case of a silicon MIS structure, the difference amounts to 12 decades (the electrostriction constant is of the order of 10^{-14} cgs esu).

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[1)]This is precisely the case realized in the experiments reported in Refs. 4 and 5.

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Effect of pressure on the hyperfine magnetic fields at the nuclei of iron impurity atoms in antiferromagnetic chromium

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The pressure dependences of the hyperfine magnetic fields H at ^{57}Fe nuclei in alloys of chromium with alloys were measured by the Mössbauer gamma-spectroscopy method. Values $\Delta H/H\Delta p = (-1.2\pm0.5)\times10^{-2}$ and $(-2\pm0.5)\times10^{-2}$ kbar^{-1} were obtained for alloys with concentrations 1.5 and 3.5 at.% Fe, respectively. The values of $\Delta H/H\Delta p$ are anomalously large and agree approximately with the relative changes of the magnetic moments of the Cr atoms under pressure $\Delta\mu_{Cr}/\mu_{Cr}\Delta p$. Doubts are expressed concerning the model of H described in the paper of Herbert *et al.* [J. Phys. Chem. Solids **33**, 979 (1972)]. An alternate mechanism for the onset of H is proposed, based on concepts concerning the nature of the field at nuclei of nonmagnetic atoms dissolved in a magnetic host.

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Hyperfine magnetic fields at nuclei of impurity magnetic atoms in magnets are determined by the values of the magnetic moments of the impurity atoms, the host atoms, and the impurity-host interaction. Accordingly, the resultant hyperfine field H should consist of several contributions. The values and the signs of the individual contributions to H cannot be predicted beforehand, since the mechanism of the transport of the spin density from the atoms of the magnetic host to the nuclei of the impurity atoms is not yet clear. Important information on the role of the individual contributions to H is made by experiments on the influence of the pressure on the hyperfine interaction in magnets with different types of magnetic ordering. So far, however, the pressure dependences of the hyperfine field $H(p)$ at the impurity magnetic atoms in monatomic antiferromagnets (consisting of atoms of the same species) have not been investigated. The present study fills this gap in part. We have investigated the $H(p)$ dependences at ^{57}Fe nuclei in three diluted alloys of chromium with iron.

Metallic chromium can have an unusual variety of magnetic structures, depending on the temperature, species, and concentration of the impurities.[1] Below the Néel temperature $T_N = 311$ K, the magnetic moments of Cr form spin-density waves that can be represented in the form

$$\mathbf{P}(x) = P_0\mathbf{n}\cos Qx, \tag{1}$$

where $\mathbf{P}(x)$ is the spin-polarization vector, $\mathbf{n}$ is a unit vector along the polarization vector, $\mathbf{Q}$ is the wave vector and is parallel to one of the ⟨100⟩ directions in a bcc lattice, and z is the coordinate. The SDW are polarized transversely ($\mathbf{n}\cdot\mathbf{Q}=0$), in the temperature interval $T_N > T > T_{SF}$, where $T_{SF} \approx 122$ K, and longitudinaly ($\mathbf{n}\cdot\mathbf{Q}=q$) in the region $T < T_{SF}$. At $T < 70$ K we have $Q = 0.95162\pi/d$ (d is the lattice parameter) and in the interval 70 K $< T < T_N$ the value of Q increases to $0.9626\cdot 2\pi/d$; the SDW length is then of the order of $20d$ and is not commensurate with d.

Introduction of the Fe impurity influences strongly the magnetic properties of the chromium: T_N decreases by approximately 20 K per at.% Fe, T_{SF} decreases to zero at 1.5 at.% Fe, and Q becomes equal to $2\pi/d$ at a concentration higher than 2.5 at.% Fe. The Fe im-

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purity ions are statistically distributed in the chromium lattice. Iron concentrations 0.5, 1.5, and 3.5 at.% were chosen in order to obtain at $T = 78$ K all three antiferromagnetic structures: transverse SDW (AF_2), longitudinal SDW (AF_1), and the simplest (AF_0) with two magnetic sublattices.[1]

According to the measurements of the magnetic susceptibility,[2] the Fe impurity atoms in the investigated alloys are paramagnetic and have localized magnetic moments equal to 1.7, 1.2, and 2.2 μ_B respectively. The form of the Mössbauer spectra at $T = 4.2$ K indicates that a set of hyperfine fields with mean value ~35 kOe exists at the ^{57}Fe nuclei. These data agree well with the earlier investigations.[3, 4]

A comparison of the results on the magnetic susceptibility and on the Mössbauer effect leads to a surprise. The point is that usually the fields at the ^{57}Fe nuclei in magnets at low temperatures are subject to the empirical relation $H \approx 100\mu_{Fe}/\mu_B$ [kOe]. Therefore if the magnetic moments of Fe are strictly oriented in the crystal lattice as a result of the exchange interaction, then the expected value of H should be of the order of 150 – 200 kOe. But if the Fe atoms are paramagnetic, then H should be zero. Thus, the experimental values of H do not correspond to these extreme cases. To explain the anomalous values of H and their temperature dependences, various mechanisms were proposed,[4-6] and the most detailed one[4] will be dwelled upon in the discussions.

The purposes of the present investigation were the following: 1) to study the singularities of the hyperfine fields under pressure for impurity Fe atoms in a monatomic ferromagnetic host, and 2) to attempt to explain the cause of the anomalous value of H for ^{57}Fe in chromium.

The alloys were prepared in a vacuum arc furnace and abruptly quenched from the melt. The components were Cr of 99.99% purity and iron enriched with ^{57}Fe. The Fe concentration was determined by x-ray microanalysis with relative accuracy ~1%. The Mössbauer absorption spectra were measured with a single-channel spectrometer with a ^{57}Co source in Cr. The hydrostatic pressure was produced using a steel chamber with beryllium windows for the passage of the x-ray beam. The experimental technique is described in detail elsewhere.[7] The measurements were made at 78 and 194 K, with the high-pressure chamber placed in a liquid-nitrogen bath or in a mixture of acetone with frozen CO_2. The pressure was maintained accurate to ±0.1 kbar. The mean values of the magnetic fields at the ^{57}Fe nuclei were calculated from the measured widths of the resonance spectra using the procedure described in Ref. 8, and the accuracy with which $\Delta H/H$ [$\Delta H = H(p) - H(0)$] was determined was 5%. The spectrometer was callibrated against sodium nitroprusside before and after the measurement of each resonant spectrum at fixed pressure.

Figure 1 shows the spectra of the ^{57}Fe sample with 1.5 at.% Fe, measured at liquid-nitrogen temperature at atmospheric pressure and at 9.9 kbar. The spectra

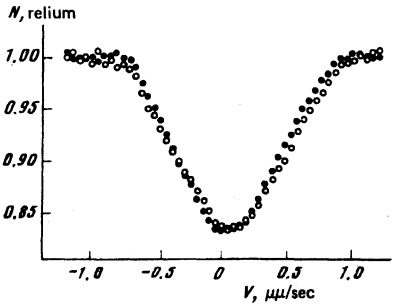

FIG. 1. Mössbauer spectra of ^{57}Fe sample of an alloy of chromium with 1.5 at.% Fe at $T = 78$ K: ○ – spectrum at atmospheric pressure, ● – at 9.9 kbar. The dimension of the point is equal to the statistical error. The Mössbauer source temperature is ~100 K.

have the form of broadened single lines because of the small values of H. Similar spectra were obtained for all other samples. At 78 K the fields at the ^{57}Fe nuclei are 15.7, 18.4, and 23.8 kOe in increasing order of the Fe concentration; this agrees well with the data of Ref. 4. The nonzero isomer shift is due to the difference between the source and the absorber. A comparison of the spectra of Fig. 1 shows clearly the effect of pressure on the width of the resonance line and hence on the absolute value of H.

Plots of the relative changes of the fields against pressure are shown for the three alloys in Fig. 2. The relatively large errors of $\Delta H/H$ are due to the rather low values of H. The dashed line shows the pressure dependence of the magnetic moments of the CR atoms in the SWD of a pure chromium host. We determined also the dependences of the isomer shifts ε at the ^{57}Fe nuclei on the pressure, and obtained for all alloys $\Delta\varepsilon = -0.02 \pm 0.01$ mm/sec per 10 kbar. The decrease of ε under pressure corresponds to an increase of the density of the s electrons at the nuclei. Attention is called to the anomalously large relative changes of the hyperfine fields under pressure: the observed values of $\Delta H/H\Delta p$ exceed by 50–100 times all the values known from preceding experiments.[10]

Herbert *et al.*[4] have shown that for alloys with small Fe concentrations the temperature dependences of the fields at the ^{57}Fe nuclei are anomalous—the $H(T)$ plots

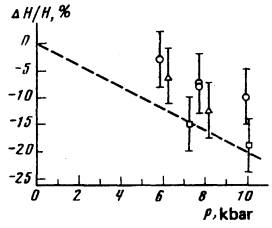

FIG. 2. Relative changes of the hyperfine magnetic fields at the ^{57}Fe nuclei with changing pressure at $T = 78$ K: Δ – alloy with 0.5 at.% Fe, ○ – alloy with 1.5 at.% Fe, □ – alloy with 3.5 at.% Fe. Dashed line—pressure dependence of the magnetic moments of the Cr atoms for pure chromium (from the data of Ref. 9).

deviate considerably from the Brillouin curve: in the region $T \lesssim 100$ K the field increases strongly with decreasing temperature, the value of H is practically independent of temperature in the interval $T_N \gtrsim T \gtrsim 100$ K (see Fig. 4 of Ref. 4). The temperature in our measurements (78 K) corresponds to the region where the derivative $\partial H/\partial T$ is relatively large. This raises the question of whether the anomalous $H(p)$ dependence is a trivial consequences of the shift, under the influence of the pressure, of the $H(T)$ curve towards lower temperatures. We have therefore measured H at $T = 194$ K and $p = 6.7$ kbar using a sample with 1.5 at.% Fe. This point (194 K) lies in the middle of the plateau of the $H(T)$ curve, so that $H(p)$ should not be affected by either the shift of the Néel point under pressure or by the possible shift of the $H(T)$ curve. The obtained $\Delta H/H\Delta p = (-1.2 \pm 0.5) \cdot 10^{-2}$ kbar^{-1} agrees with the value of $\Delta H/H\Delta p$ at 78 K. We can therefore conclude that no corrections need be introduced into the results of the measurements at 78 K.

The main results of our experiments are the following:

1) the absolute values of the hyperfine magnetic fields decrease under pressure;

2) the values of $\Delta H/H\Delta p$ are anomalously large and exceed by almost two orders of magnitude the compressibility of the chromium host $\Delta v/v\Delta p$;

3) the density of the s electrons at the nuclei increases under pressure.

To discuss the results we need data on the effect of pressure on the magnetic properties of chromium, some which we shall recall. Neutron diffraction yielded[9] the temperature dependence of the magnetic moments in SDW, which is close in practice to the Brillouin function, $\partial T_{SF}/\partial p \approx \partial T_N/\partial p = -6$ deg/kbar, and $\Delta\mu_{Cr}/\mu_{Cr}\Delta p = -2 \cdot 10^{-2}$ kbar^{-1}. Measurements of $\mu_{Cr}(p)$ were made at $T/T_N \approx 0.2$, so that $T_N(p)$ did not affect the result. We note that our measurements were made at the same ratio T/T_N, so that no correction for the effect of $T_N(p)$ was introduced. Thus, an anomalously large change of the magnetic properties is observed in pure chromium. It appears that this is due to singularities in the band structure of the chromium,[11] which lead, in particular, to the vanishing of the magnetic moments of the Cr atoms at $T > T_N$.[12]

We compare now the experimental result with the previously proposed[7] model of the hyperfine magnetic fields. According to this model the exchange interaction of the Fe and Cr atoms aligns the magnetic moments of the Fe atoms parallel to the SDW polarization vector. At low temperatures ($T \ll T_N$) the Fe and Cr interaction is saturated, i.e., the exchange interaction between the magnetic moments is strong. It is assumed also that near the Fe ions the conduction electrons produce magnetic moments directed opposite to the $3d$ moments of the Fe, introducing by the same token a spin-compensating state of the Kondo-anomaly type with a characteristic temperature $T_C \approx 60$ K. The field at the ^{57}Fe nuclei is given by

$$H = H_{sdw} + H_c, \tag{2}$$

where H_{SDW} is the field due to the intrinsic magnetic moment of Fe and H_c is the field of the conduction s electrons; H_c cancels in part the value 150–200 kOe expected from the intrinsic $3d$ moment of the Fe ion.

In our opinion, the model of Herbert *et al.* has two essential shortcomings: first, it ignores the paramagnetism of the Fe atoms; second it can not explain the anomalous $H(p)$ dependence. Let us clarify the last statement.

The decrease of the magnetic moments of the chromium atoms under pressure, its anomalously large value notwithstanding, cannot be reflected significantly in the H_{SDW} contribution, since the exchange of interaction of Fe and Cr at $T \ll T_N$ remains just as saturated also under pressure. As for the influence of the pressure on the spin-compensating state, at $T = 194$ K it does not exist at all, whereas $\Delta H/H\Delta p$ remains anomalously large as before.

We propose an alternate mechanism for the onset of the hyperfine magnetic fields at the ^{57}Fe nuclei in chromium. It can be concluded on the basis of the paramagnetic behavior of the Fe atoms up to 4.2 K (Ref. 2) that the exchange interaction of the Fe atoms in the SDW is close to zero, from which it follows also that the magnetic moments of the Fe atoms relax with a high frequency. It is known that if the relaxation frequency $\nu \gg 1/\tau$ (τ is the lifetime of the excited state of the nucleus), then the nucleus "does not see" the magnetic field of the intrinsic moment and in this sense the atom can be regarded as nonmagnetic. If the frequency ν for Fe in Cr satisfies this condition, then the contribution made to the field by the $3d$ moment of Fe is equal to zero. However, the absence of this contribution does not exclude the possibility of other mechanisms that produce H and act, for example, in the case of nonmagnetic atoms in antiferromagnetic hosts. Thus, the field at the nuclei of the Sn impurity atoms in Cr (~100 kOe, Ref. 13) is due to the magnetic moments of the Cr atoms in the first coordination sphere of Sn.

Let us apply the suggested description of the fields at nuclei of nonmagnetic atoms to the case of ^{57}Fe in Cr. According to the Delyagin-Kornienko empirical rule,[14] the expression for the field takes the form

$$H = -a\mu_1 + b\mu_2 + c\bar{\mu}, \tag{3}$$

where μ_1 and μ_2 are the magnetic moments of the atoms in the first and second coordination spheres of the magnetic atom, $\bar{\mu}$ is the average magnetic moment of the host, and a, b, and c are positive constant coefficients with $a \gg b$ and $c \gg b$.

We examine now qualitatively the $H(p)$ dependences from the point of view of this mechanism. In the simplest AF_0 structure $\bar{\mu} \equiv 0$. Then, neglecting the comparatively small term in (3), we obtain $H \approx a\mu_1$. Next, introducing the dependences of a and μ_1 on the pressure, we have

$$\Delta H/H\Delta p = \Delta a/a\Delta p + \Delta\mu_1/\mu_1\Delta p. \tag{4}$$

For Sn impurity atoms in magnets, the first term in (4) usually prevails, since $\Delta\mu_1/\mu_1\Delta p$ is smaller by one order of magnitude than $\Delta H/H\Delta p$. In our case the situation is reversed, and $\Delta\mu_1/\mu_1\Delta p$ is anomalously large,

so that $\Delta H/H\Delta p \approx \Delta\mu_1/\mu_1\Delta p$. As seen from Fig. 2, this relation agrees with experiments. The contributions made to the polarization of the conduction electrons, and consequently the contributions from the nearest spheres in the AF_1, AF_2, and AF_0 structures are apparently different. The quantity $c\bar{\mu}$ is in fact the sum of the contribution from the coordination spheres with numbers $n \geq 3$, the most substantial of which are the contributions from the third and fourth spheres, and the rest can be neglected. Therefore for most atoms $c\bar{\mu} \neq 0$ in the AF_1 and AF_2 structures, because of the large length of the SDW compared with the lattice period. When this circumstance is taken into account, the values of $\Delta H/H\Delta p$ for AF_1, AF_2, and AF_0 should be different. The accuracies of our measurements, strictly speaking, are insufficient for the observation of these differences, nonetheless the tendency towards such a difference does apparently exist (see Fig. 2).

Our experiments allow us therefore to draw the following conclusions: 1) the hyperfine magnetic fields at impurity iron atoms in chromium are determined by the nearest neighboring chromium atoms, 2) the anomalously large relative changes of the hyperfine fields at the ^{57}Fe nuclei in Cr under pressure are the consequence of changes of the magnetic moments of the chromium atoms.

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Density of states in a one-dimensional disordered crystal

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The Berezinskiĭ diagram technique is used to calculate the density of states in a one-dimensional crystal with a strong degree of disorder. The character of the Dyson singularity at the center of the band is studied. The structure of the state-density peaks produced at rational points of the band is investigated.

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1. INTRODUCTION

In connection with the intensive experimental investigations of quasi-one-dimensional crystals with strong structural disorder,[1] theoretical investigations of the electron spectrum in one-dimensional disordered structures have attracted great interest. The state density in such systems was investigated in many studies (see the review[2]). It was found that in one-dimensional problems the state density is very sensitive to the crystal structure. Great interest attaches therefore to allowance for the periodicity of the initial crystal potential. Among the most significant results in this field is the singularity observed by Dyson[3] in the state density near the middle of the band. It was subsequently observed in a large number of systems.[4-6] All the cited studies dealt with the case of weak disorder.

The present paper deals with the density of the electron states in a one-dimensional crystal with arbitrary disorder. It is shown that in this case the state-density peaks appear at all rational points of the band, and that the Dyson singularity at the center of the band is greatly enhanced. These effects are due to the strong Bragg scattering of the electrons in one-dimensional crystals and to the interference of the corresponding waves.

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