Figure 5. EPR pioneers: E K Zavoisky (center), S A Altshuler (left), and B M Kozyrev (1968).

Figure 6. Quantum electronics pioneers. Left to right: A M Prokhorov, C Townes, N G Basov (1965).

first reacted in much the same way, "Oh, no, that can't be right. You must be misunderstanding something," but came back in 15 minutes to say, "Hey, you are right."

These two episodes are followed in Townes's book by a passage from Arthur Clarke — the kind of commentary which, the reader may agree, needs no comment:

"People go through four stages before revolutionary development:

1) It's nonsense, don't waste my time.

2) It's interesting, but not important.

3) I always said it was a good idea.

4) I thought of it first."

Instead of a conclusion, I hope two historical photographs featuring the pioneers of paramagnetic resonance and quantum electronics will not be out of place (Figs 5, 6).

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Magnetic resonance modes in spin-gap magnets

A I Smirnov

In some dielectric crystals with the antiferromagnetic exchange interaction, the projections of spin moments fail to show magnetic ordering even at temperatures approaching absolute zero. Such crystals came to be known as collective paramagnets or spin liquids. Examples of magnetic structures whose spin-liquid ground state is stable to perturbations are quasi-one-dimensional antiferromagnets containing chains

of $S = 1$ spins (Haldane magnets) [1, 2] and chains of $S = 1/2$ spins with alternating exchange (the exchange integral alternates between $J \pm \delta$), including Peierls spin magnets [3], various dimer spin structures [4], and so-called spin ladders [5].

Spin-liquid states are singlets and can be either stable or unstable with respect to the transition into an ordered state under small perturbations. For example, crystals with regular $S = 1/2$ spin states become ordered under an arbitrarily small exchange at temperatures around $\sqrt{JJ'}/k_B$, where J and J' are the intrachain and interchain exchange integrals, respectively. In the examples of stable spin-liquid systems given above, the system has an energy gap (known as a spin gap) that separates the singlet ground state from excited magnetic states. The system remains stable as long as the perturbation energy per magnetic ion is less than a certain value of the order of the spin gap. In a Haldane magnet, the spin gap has an exchange origin and is equal to $0.41J$ [2], whereas in an alternating $S = 1/2$ spin chain, the spin gap is determined by alternation and is equal to 1.637δ [3].

Spin-liquid ground states are a purely quantum effect and have no classical analogs — unlike antiferromagnetic and ferromagnetic states, for which many properties can be obtained in the molecular field approximation. The susceptibility of a spin-liquid magnet cooled to below the gap temperature drops to zero because magnetic gap excitations 'freeze out.' As a result, the magnetic response of individual magnetic defects shows up well against the background of the nonmagnetic spin-gap matrix and magnetic excitations at low temperatures form a dilute gas.

The subject of this report is the magnetic resonance of collective, exchange-correlated states that occur in spin-gap magnets following the introduction of defects or the thermal activation of excitations.

Earlier, in [6, 7], we reported the formation of unusual clusters in the vicinity of nonmagnetic impurity ions introduced into the spin-gap matrix as a substitute for magnetic ions. In this collective state, spins restore their nonzero average projections near an impurity ion and form nanoscopic regions of local antiferromagnetic order — regions that have their own magnetic moment and a spin that, according to theory and experiment, is $S = 1/2$ (including the case of Haldane chains of ions with spin $S = 1$). We now report on a study of dynamic collective states and their interactions with nanoscopic clusters.

Because excitations in exchange-correlated spin chains correspond to spin changing its projection by unity, they must have the effective spin $S_{\text{eff}} = 1$. This means that transitions between the spin sublevels of these triplet excitations are influenced by the crystal field, resulting in the same splitting pattern as the one known for an isolated magnetic ion with spin $S = 1$. For this splitting to be observed, these excitations must be isolated from one another. This is indeed the case under the conditions of a concentrated magnet because of the presence of the gap. In Fig. 1, which presents results obtained in Ref. [8], panel (a) shows the increase in the magnetic-resonant absorption of a ceramic sample of the Haldane magnet $PbNi_2V_2O_8$ for magnetic fields far from the resonance value for the defects described above (for the g-factor 2.0); panel (b) shows zero-field absorption at a frequency about 100 GHz, which indicates that the paramagnetic resonance shifts in frequency due to the effective spin of the triplet excitation interacting with the crystal field. These results, revealing a nonzero frequency of a magnetic resonance of thermally activated excitations in a zero field, imply that triplet excitations in a Haldane magnet have the effective spin $S = 1$. The existence of a collective spin-gap state in this concentrated magnetic system leads to a situation where the gas of magnetic triplet excitations is dilute, and these excitations interact with the crystal field as isolated spins. This, in turn, results in a magnetic resonance spectrum similar to that of individual spins in a crystal field. We note that in magnetic objects with the effective spin $S = 1/2$, spin sublevels do not undergo splitting in the crystal field. The fact that absorption is caused by heating suggests that it is due to magnetic excitations with an energy gap; the value of this gap obtained from a neutron diffraction experiment is about 25 K [9]. Temperatures higher than that destroy the correlated Haldane state, turning the magnetic-resonance signal into an ordinary signal of a concentrated paramagnet, whose magnetic resonance spectrum consists of a single line with $g = 2.0$ (as a result of exchange narrowing). The theory in Ref. [10] predicts that the spin gap splitting by a crystal field in a Haldane magnet is $2D$, where D is the single-ion anisotropy constant. The value of this splitting also depends on the wave vector of the triplet excitations: it should decrease as the wave vector moves away from the Brillouin zone boundary, where the frequency of triplet excitations has a minimum [2]. Fitting the absorption spectra observed at 16 K results in the splitting value 86 GHz. At lower temperatures, the magnetic resonance signal of thermally activated excitations cannot be reliably detected, and therefore this value is not necessarily at the bottom of the excitation spectrum: what we see may be transitions between the spin sublevels within a whole group of excitations in a certain region of **k** space.

In samples of $Pb(Ni_{1-x}Mg_x)_2V_2O_8$, in which spin chains may be broken as a result of doping, we can trace how traveling triplet excitations interact with spin clusters that form near the ends of broken chains [7]. For this purpose, we examined magnetic resonance signals from clusters and triplets in samples with different impurity concentrations. Figure 2 shows the results in Ref. [11] on the temperature dependence of the resonance field for samples with different impurity concentrations. It is seen that slightly doped samples show well-resolved lines from the resonance defect and thermally activated excitations. Samples with impurity concentrations above 1% show a common collective spin resonance mode for defects and triplet excitations. The frequency of this 'hybrid' magnetic resonance mode is intermediate between those of the cluster resonance and triplet excitation resonance, and its center of gravity shifts to the triplet mode as the temperature is increased due to the exchange narrowing [12] that occurs as the population numbers of the triplet excitations increase.

To observe the effect of the interaction of triplet excitations in spin-gap systems with the crystal field and to examine how the parameters of this resonance depend on temperature, it is more convenient to use single-crystal samples. Figure 3 (from Ref. [13]) shows the magnetic resonance spectrum of crystals of the dimer compound $TlCuCl_3$. Line d of the spectrum corresponds to the transition from the singlet ground state to the lowest spin sublevel of the triplet excitation and is best resolved at low temperatures. Lines a, b, and c, which appear on slight heating, correspond to transitions between the (magnetic- and crystal-field-split) spin sublevels of the triplet excitations. We note that in this case, the magnetic ions of the matrix Cu^{2+} carry spin $S = 1/2$, and the effective spin $S = 1$ of the collective

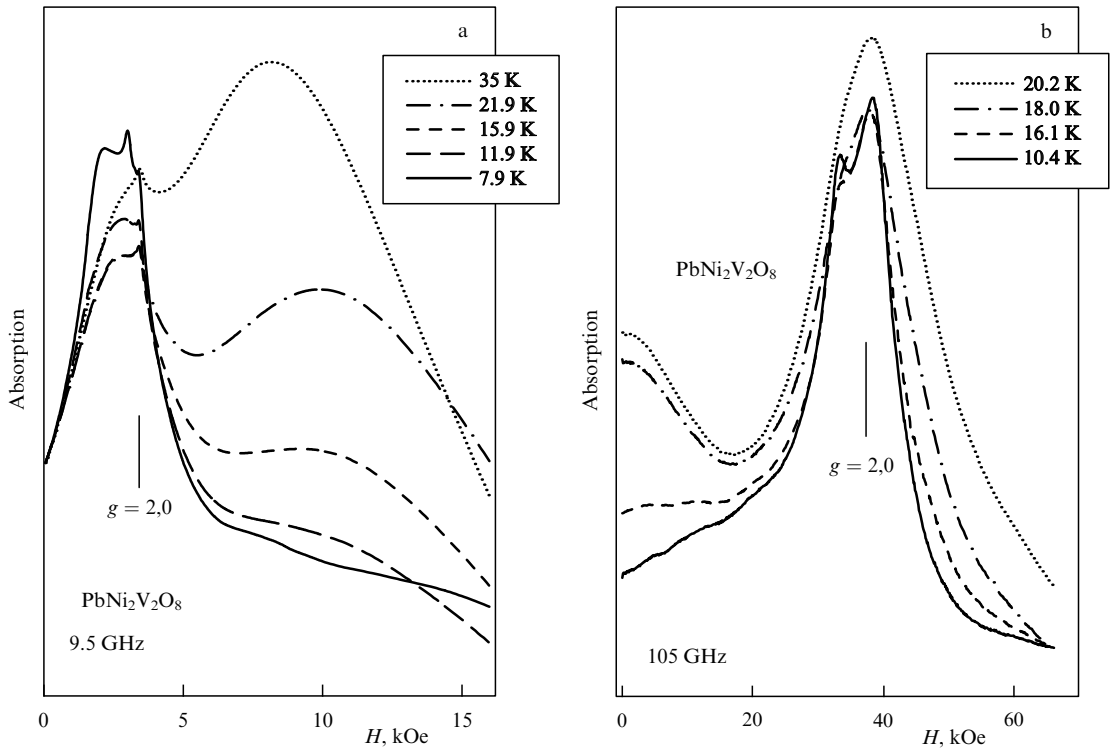

Figure 1. Absorption at the frequencies 9 GHz (a) and 105 GHz (b) as a function of the magnetic field for ceramic samples of $PbNi_2V_2O_8$ [8].

excited state demonstrates the corresponding splitting in the crystal field. The difference in structure between various resonance modes in Haldane and dimer magnets is that in the former the spin gap corresponds to a wave vector at the Brillouin zone boundary, and therefore direct singlet – triplet transitions are generally impossible to observe in a magnetic resonance experiment. In the dimer magnet $TlCuCl_3$, the spin gap corresponds to the zero wave vector, making it possible to observe direct singlet – triplet transitions using the spin resonance method.

The spin sublevels of triplets were found to split in a temperature-dependent manner. Figure 4 (from Ref. [13]) shows how the resonance magnetic fields of the triplet components vary with temperature. As the temperature increases from 1.2 to 4.0 K, splitting undergoes a significant change and assumes an intermediate constant value, but on further increase in temperature the lines come closer together to eventually merge into a single exchange-narrowed line of a concentrated paramagnet at a temperature above the spin gap energy (which is 7.7 K for this compound). That the splitting is temperature-dependent at low temperatures is presumably because the region in **k**-space where triplets are excited becomes larger and because the effective anisotropy parameter of a triplet excitation depends on the wave vector. The

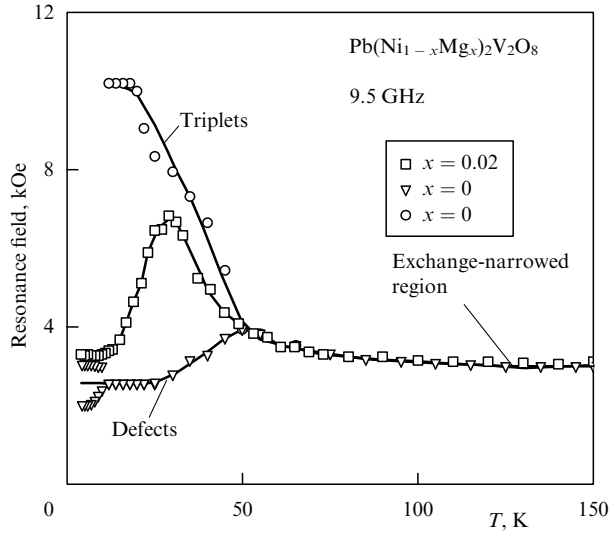

Figure 2. Temperature dependence of the magnetic resonance field for $Pb(Ni_{1-x}Mg_x)_2V_2O_8$ samples [11].

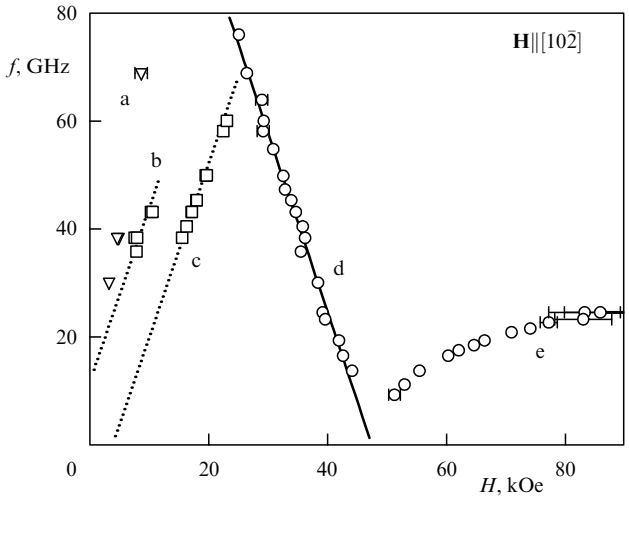

Figure 3. Magnetic resonance spectrum of the dimer magnet $TlCuCl_3$ at $T = 1.5$ K [13].

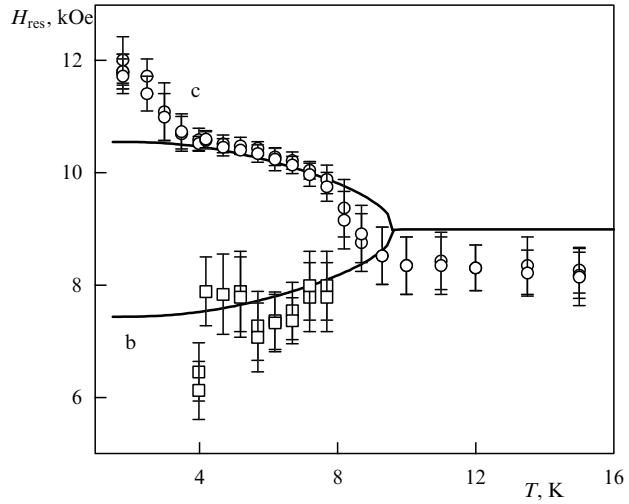

Figure 4. Resonance fields of components b and c at the frequency 25.94 GHz in the dimer magnet $TlCuCl_3$ for various temperatures and magnetic field $\mathbf{H}||b$ [13].

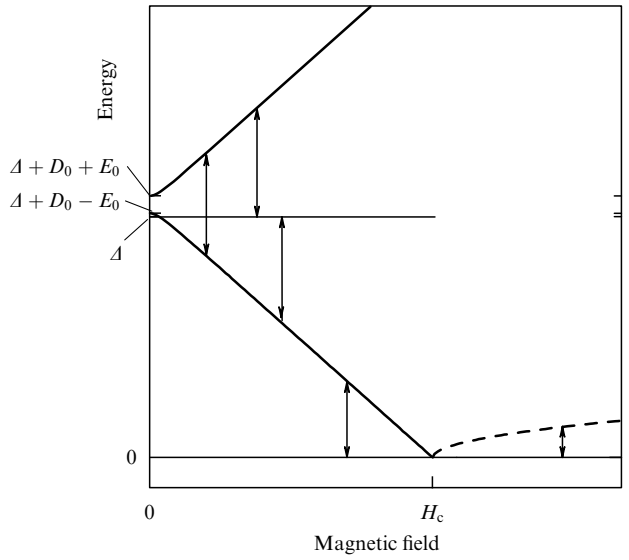

Figure 5. Energy level diagram of triplet $\mathbf{k} = 0$ excitations in the dimer magnet $TlCuCl_3$ [13].

energy level diagram of a triplet of zero-wave-vector excited states in the dimer magnetic $TlCuCl_3$ is shown in Fig. 5 (from Ref. 13]). Here, Δ is the spin gap in the exchange approximation and D_0 and E_0 are the anisotropy parameters of the effective spin Hamiltonian for a spin triplet in a crystal field. We note that in this case, $S = 1$ excitations arise as collective states in a crystal with spins $S = 1/2$ at its sites. In the magnetic field H_c that closes the spin gap for the lower triplet component, the spin-liquid state loses stability, giving way to a magnetic-field-induced antiferromagnetic ordering [14]. The nonlinear dependence of the frequency on the magnetic field signifies the onset of magnetic order and represents a branch of the antiferromagnetic resonance, as discussed in Ref. [13].

To conclude, magnetic resonance experiments have revealed a variety of collective states that are possible for magnetic ions in a singlet matrix of spin-gap crystals: states with the effective spin $S_{eff} = 1/2$ at the ends of $S = 1$ spin chains; excited spin states with the effective spin $S_{eff} = 1$ in spin-gap matrices of crystals carrying either spins $S = 1$ (Haldane systems) or spins $S = 1/2$ (dimer spin systems); and, finally, hybrid magnetic resonance modes in which nanoscopic clusters and the triplet excitations of a spin-liquid magnet have their spins involved in collective motions.

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The superconductor/ferromagnet proximity effect and its potential application in spintronics

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1. Introduction

The so-called proximity effect in superconductor/ferromagnet (S/F) systems — or, in other words, the interplay of superconductivity and ferromagnetism in thin-film heterostructures — has been the subject of intense research over the past ten years (see, e.g., Ref. [1]). In the past few years, interest in the effect has grown dramatically because of its potential uses in spintronics (see, e.g., Refs [2 – 5]). In multilayer thin-film systems, a certain combination of F and S layers can be created in which the superconducting transition temperature T_c may be controlled by the orientation of the magnetizations of the F layers relative to one another. The authors [2] first used the S/F proximity effect to theoretically design a spin valve for the superconducting current. In their scheme, denoted as S/F1/N/F2, the magnetizations of two ferromagnetic layers F1 and F2 are isolated from each other by a nonmagnetic metallic layer N, sufficiently thin for the superconducting pair wave function to penetrate from layer S to layer F2. In a theoretical design proposed by Tagirov [3], the superconducting layer is in contact with F layers on either side (F1/S/F2 spin valve). Calculations predict that in both structures, the parallel orientation of the F layer magnetizations provides lower T_c compared with the antiparallel orientation. In order to enable varying the relative orientation of F layer magnetizations, an antiferromagnetic film is usually deposited on the F2 layer, whose anisotropy fields have the effect of fixing the magnetization of the layer — after