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From Roentgen to Ioffe, from Giessen to Saint Petersburg — Relations Between Russian and German Physics

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Two former professors of physics at Giessen university contributed significantly to the development of the Ioffe Institute: Wilhelm Conrad Roentgen as a teacher of Abram Ioffe, and Wilhelm Hanle, whose effect found various applications, e. g., in the spectroscopy of hot electrons in low dimensional structures. A few examples will illustrate how topics of their scientific work found a continuation in the research activities at Giessen, but also in the collaboration between Giessen and Saint Petersburg. They range from sodium chloride, the old Roentgen / Ioffe material where we could prove the existence of an unusual isotope effect in nickel-doped crystals, over level-crossing experiments in gases, to GaAs/A1As superlattices, where level-anticrossing spectroscopy of excitons reveals detailed information about recombination processes and interface quality. A short summary of the efforts to keep the traditionally close and good relations between Russian and German physics vivid completes the report.

A talk given by a physicist from Giessen, Germany, at a conference with the title "Physics at the turn of the 21 century" naturally starts with the beginning of the 20 century and Wilhelm Conrad Roentgen, winner of the first Nobel prize in 1901. He became well known in the scientific community already before detecting the X-rays by an experiment which he did during his time in Giessen where he owned the physics chair from 1879 to 1888. Rowland proved in 1876 that a moved electrostatic charge, a so called convection current, had the same magnetic effect like a normal conduction current. Roentgen repeated first in 1885 these experiments in a much improved form and then extended them to the first experimental proof of Maxwell's dielectric displacement current [1]. For this purpose he used an apparatus in which a disk made from a dielectric material was rotating between two ring electrodes. The upper one was grounded, the lower one consisted of two halfs with opposite electric potentials. This caused two times per turn a change of sign of the polarization inside the dielectric, and Roentgen succeeded in an unambiguous proof of the magnetic field connected to this displacement current. In this field we find our first example for relations between Russian and German physics, since the Russian physicist A. Eichenwald later continued these experiments at the engineering school in Moscow and was the first to demonstrate the quantitative agreement of this magnetic field with that of a normal conduction current [2].

More important for the anniversary we celebrate this week was of course the long-lasting connection between Roentgen and Ioffe. At the end of a century in which the existence of quarks and Z bosons has been proved, it is very illustrative to read about the years from 1902 to 1905 when the founder of our Physical-Technical Institute spent as Roentgens student and assistant at Munich University. In his book "Vstretchi s fizikami" [3] he gives a very detailed description of Roentgen as an excellent experimentator, but very conservative physicist, who did not allow to use the word "electron" in his institute. Without this restriction, perhaps, Roentgen and Ioffe instead of Pohl, Gudden and Gyulai would have been the inventors of the F center since during their extensive experiments on the influence of X-rays and light upon the electrical conduction in crystals [4] they certainly dealt with such defects.

One year after Roentgen's death in 1923 another physicist who became important for Giessen University, namely Wilhelm Hanle, owner of the physics chair at Giessen from 1941 to 1969, reported [5] on an effect which later was named after him. This Hanle effect, depolarization of (resonance) fluorescence by an external magnetic field due to destruction of the coherence existing at zero-field level-crossing, is still one of the most accurate methods for measuring atomic lifetimes. Its main advantage are the low densities at which the experiments can be done in order to avoid disturbing effects like collision broadening etc.

For that reason it has been widely used in the Ioffe Institute [6] as well as in Giessen. Two examples shall be given here: The group of Boris Zakharchenya studied the photoluminescence of "hot" electrons created in a GaAs/AlGaAs multiple quantum well structure by excitation with a krypton laser [7]. In the emission, a pronounced peak shows up at the high energy edge of the spectrum stemming from the recombination of electrons from the point of photocreation, that means prior to any energy relaxation. The degree of polarization in this peak decreases with increasing magnetic field in the form of a typical Hanle curve $P(B)/P(0) = \left(1+4\omega_c^2\tau_0^2\right)^{-1}$ and allows to determine the "lifetime" τ_0 of the hot electrons which, in that case, corresponds to the emission time of a LO phonon. It is obvious that such results can be obtained only in experiments which avoid complicating factors like, for instance, phonon heating leading to a large spread in the times observed.

The second example is a result from my institute [7]. In this case, the level-crossing technique is used in a rather different context. Light emitted from the helium 4^1D level excited by atomic collisions with He^+ or Ne^+ projectiles with a polarization parallel to the ion beam has been registrated in dependence of external electric and magnetic fields. For zero electric field only the Hanle effect influences the intensity $I(B)$ of this (polarized) light which therefore has Lorentzian lineshape with a half-width depending on the lifetime of the excited state. At non-zero, but constant electric field the quadratic Stark effect causes several additional level crossings, but only those with $\Delta m = \pm 2$ can be observed with the experimental geometry used. So a splitting of the Hanle curve into three Lorentzians results whose intensities directly reflect the sublevel populations.

From these examples you may see the common interests which existed in our institutes a long time, and not only in this field. But all of you are aware of the problems hampering the relations between Russian and (West) German physics. Already Roentgen and Ioffe shared a fate which many of us experienced for a long time, too, namely to live in countries being for some time very unfriendly to each other. This becomes obvious from Roentgen's statement "Of course I could not publish during the war against Russia a scientific article together with a Russian physicist" (in [3]), explaining the long delay (from 1913 to 1921) between the two parts of their common paper [4] about "Electrical conductivity in some crystals and the influence of irradiation on it". I still remember my first visit in this beautiful town on occasion of the International Conference on Luminescence in 1972 and the strong barriers between East and West which existed at that time. Fortunately the situation became better and better in the beginning of the Eighties. Especially in my field, interaction of radiation with matter, the scientific community in Russia and Germany is very indebted to Albrecht Winnacker, who participates in this conference, and Kurt Schwarz, at that time in Riga, for organizing a series of Soviet- (now Russian-) German seminars on "Point defects in insulators and deep level centers in semiconductors", and to the Russian Academy of Sciences and Deutsche Forschungsgemeinschaft for funding.

From these seminars, starting with the first meeting at Heidelberg 1983, emanated a vivid scientific exchange between Giessen and Leningrad / Saint Petersburg. During one of these research stays we came back to "Steinsalz" (NaC1), the old material of Roentgen and Ioffe [4]. Here, however, in a special form, namely doped with divalent nickel. This incorporation needs a charge compensation by sodium vacancies. Andrey Badalyan detected in EPR two different centre configurations, one with the vacancy along an $\langle 100\rangle$, the other along an $\langle 110\rangle$ direction [9]. We concentrated one the first species. We have three of them, besides the one shown with a nickel-vacancy axis along [001], two others along [100] and [010] respectively. What do we expect from this $3d^8$ system? Its level scheme in a cubic environment with tetragonal distortion can be found in many textbooks. For our EPR experiment only the orbital singlet ground state with triplet spin configuration (the two d electrons couple to $S = l$) is relevant. The axial crystal field causes a fine structure splitting between the three m_S states competing with the Zeeman effect which makes the situation a little bit more complicated when the external magnetic field is not directed along the centre axis. But via exact diagonalization of the appropriate spin hamiltonian with help of the programme "V-epr" [10] it is possible to understand and fit completely the angular dependence observed for an [001] rotation. What was interesting and puzzling with these results is the structure observed on the resonance. A deconvolution of the integrated spectrum yields 5 Gaussians with an intensity ratio $1:6:13:6:1$.

The problem that this cannot be explained by a superhyperfine interaction with surrounding chlorine nuclei already arose in the case of silver chloride doped with Ni^{2+}, where a similar structure was observed [11]. The authors explained this by a different distribution of the two chlorine isotopes on the four neighbouring lattice sites in the plane perpendicular to the centre axis. Taking into account the natural abundance of ^{35}Cl being three times larger than that of ^{37}Cl one really calculates probabilities of $1:6:13:6:1$ for the different configurations. The idea behind is a distortion of the square due to different vibrational amplitudes as a result of the different isotope masses. This distortion leads to an orthorombic component of the crystal field and by that to a deviation of the resonance position proportional to $x^2 - y^2$. So the model can explain the existence of 5 lines with the intensity ratio observed, but until now no direct determination of the real distribution of the isotopes was done. Therefore we performed an electron-nuclear double resonance (ENDOR) experiment on this system. The result is a large number of ENDOR lines, which again with help of the "V-epr" programme can be completely analyzed. Analyzing the ENDOR intensities for the ^{35}Cl respectively ^{37}Cl nuclei at the 100 position over the five lines, one really finds a decrease for chlorine 37, an increase for chlorine 35, and surprisingly on the central line a ratio 1:5 instead of the natural isotope ratio (1 : 3). So our ENDOR experiments completely proved the model.

After the drastic changes in 1989 further programmes were started to support the cooperation between Russian and German physicists. Here I want to mention especially the Volkswagen Foundation which financed from 1990 to 1998 eighteen projects with scientific groups from Saint Petersburg, among them eleven with participation of the Ioffe institute. Altogether 17 million DM were given to Russia (10 percent of them to Saint Petersburg), a sum which amounts to nearly one half of the total funding for Central and Eastern Europe. An important role in this context played Gottfried Landwehr from Würzburg University as a head of the selection committee.

I am very glad that one of the eleven projects mentioned above was carried out by Boris Zakharchenya's and Pavel Baranov's groups from Ioffe institute and my group at Giessen. Its topic was photoluminescence of hot electrons and magnetic resonance in quantum well structures and superlattices. GaAs/AlAs superlattices are grown by molecular beam epitaxy and consist of a sequence of alternating GaAs and AlAs layers. This periodical arrangement shows up nicely in high resolution transmission electron microscopy. In addition, Roentgen's discovery also plays an important role for the characterization of such nanostructures, X-ray diffraction supplying complementary information about layer dimensions. Since these are of the order of a few monolayers, drastic quantum confinement effects appear. We studied a series of samples with nominally 5.5 monolayers (1.73 nm) GaAs and 8.5 monolayers (2.65 nm) A1As. For quantum wells with such dimensions the energy of the lowest electron state in A1As is lower than that in GaAs, so excitons are formed from X_z electrons in the A1As layer and from Γ-holes in the GaAs layer. This situation characterizes a type II superlattice and leads to a localization of the excitons at the interfaces. Due to the very low temperatures of our experiments (1.5 K) only the energetically lowest excitons (more exactly: the heavy hole excitons) play a role. The radius of such an exciton, which in the bulk material amounts to more than 10 nm, is strongly reduced in the growth direction. This fact together with the low local symmetry of the interface result in an exchange (or zero field) splitting of all four exciton sublevels. The heavy holes states $m_J = \pm 3/2$ couple with the $m_s = \pm 1/2$ states of the electron to resulting $m = 2$, 1, -1 and -2 exciton states. In magnetic field, circularly polarized optical transitions are allowed only from the $m = \pm 1$ states. If we connect them by microwave transitions to one of the nonradiative, higher populated $m = \pm 2$ states, we increase either the intensity of the σ^+ or the σ^- radiation. This shows up in the circular polarization of emission and can be used to detect magnetic resonance and to examine the energy level system of the excitons. Very important in this context is the fact that coupling of levels not only occurs due to microwave transitions, but also when the external magnetic field brings energy levels close to each other. Zero-field level crossing is the origin of the Hanle effect, which we discussed before. Here a level anticrossing occurs, which also effects level populations showing up in the intensity, circular or linear polarization of emission. Level anticrossing is a very helpful method of spectroscopy [12] since it does not have the limitations of optically detected magnetic resonance (ODMR), which usually fails for radiative lifetimes shorter than a 0.1 μs. A systematic investigation of a large number of superlattices [12,13] reveals an approximately exponential dependence of the exchange splitting on the superlattice period. The isotropic exchange splitting of excitons can be used to determine the period of a SL. Together with the dependence of the hole g factor on the thickness of the GaAs layer a complete geometrical characterization becomes so possible with very high resolution.

The main topic of our collaboration in the last time was the investigation of ODMR together with the linear polarization of level anticrossing signals. The reason for that is the following: The sequence of layers in growth direction differs in the orientation of the gallium respectively aluminum bonds to the arsenic atoms in the interface. Whereas in the so-called normal (AlAs on GaAs) interface, the AlAs bonds lie in a (110) plane, oriented along a $[1\bar{1}0]$ direction, and the GaAs bonds in a $(1\bar{1}0)$ plane, oriented along [110], for the inverted interface (GaAs on AlAs) the situation is just opposite. This results in an inversion of the radiative levels. The first level anticrossing (with increasing magnetic field) for the normal interface leads to a population increase of the level, from which light linearly polarized along [110] is emitted. The second anticrossing accordingly increases the intensity of the $[1\bar{1}0]$ light. For the inverted interface the sequence is reversed. In that way one can even distinguish at which interface the recombining exciton is localized [14]. Since the whole luminescence is a dynamic process and all levels are coupled by rate equations a population increase of one radiative level may cause a decrease in the other. Another consequence is the different dependence of ODMR of different excitons on the microwave chopping frequency we use to modulate the effect [15]. This provides an additional possibility to study exciton dynamics and to unravel different contributions.

Very detailed information which can be obtained experimentally was used to study in collaboration with Franz Ahlers and Klaus Pierz from the Physikalisch-Technische Bundesanstalt in Braunschweig the influence of growth parameters on the interface quality of superlattices. In a sample grown at 600°C with growth interruptions of 50 seconds after deposition of each GaAs layer, two luminescence lines were observed. In the ODMR experiment it could be clearly seen that the low energy line stems from the recombination of an exciton with a smaller exchange splitting than that of the excitons contributing to the high energy line. From the sign and shape of the level anticrossings in linear polarization we showed that in the low energy line only excitons localized at the inverted interface were observed, in the high energy line two excitons localized at both the inverted and normal interface were clearly separated [16]. In this way one can now determine in dependence of the growth parameters the ratio of excitons localized at different interfaces, check the physical background for that, control the quality of superlattices etc. It should be mentioned that the energy levels deduced from ODMR and from the level anticrossing resonance fields are absolutely consistent. The two different exchange splittings observed for the two luminescence lines prove the existence of regions larger than the radius of the exciton which differ in the local period and the GaAs layer thickness by one monolayer. Obviously, the better possibility for relaxation of the GaAs surface by the pause during growth enables the appearance of monolayer-high interface islands.

These few examples hopefully illustrated that relations between Russian and German physics are in a good shape and that Giessen and Saint Petersburg keep the old traditions vivid.

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