Neutron diffraction in widely divergent beams: neutron analog of the Kossel effect

V. P. Glazkov, A. V. Irodova, V. A. Somenkov, and S. Sh. Shil'shteĭn

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Diffraction effects have been observed in experiments on neutron scattering by single crystals when the source of the widely divergent radiation is inside the crystal. This is a neutron analog of the Kossel effect.

A special case in the interaction of radiation with a crystal lattice is that in which the radiation source is inside the crystal. The waves emitted by such a source are reflected from the lattice planes at angles corresponding to the Bragg conditions, so that the reflected rays form cones whose axes run normal to the reflecting planes. This effect is well known in x-ray diffraction (Kossel lines) and electron diffraction (Kikuchi lines). It is widely used to study structural imperfections and in the most precise determinations of lattice constants.[1] Analogous effects should evidently occur for other types of radiation, in particular, neutrons. In this letter we report an experimental observation of this effect in neutron scattering.

There are two ways to observed Kossel lines: with the radiation excited in the crystal material itself (true Kossel lines) or through the use of a widely divergent radiation beam from an external source (pseudo-Kossel lines). The idea underlying our experiments to observe pseudo-Kossel lines in neutrons is to use a highly incoherent scatterer to produce a widely divergent monochromatic neutron beam. Specifically, this incoherent scatterer is vanadium hydride, which scatters neutrons elastically and almost completely incoherently.

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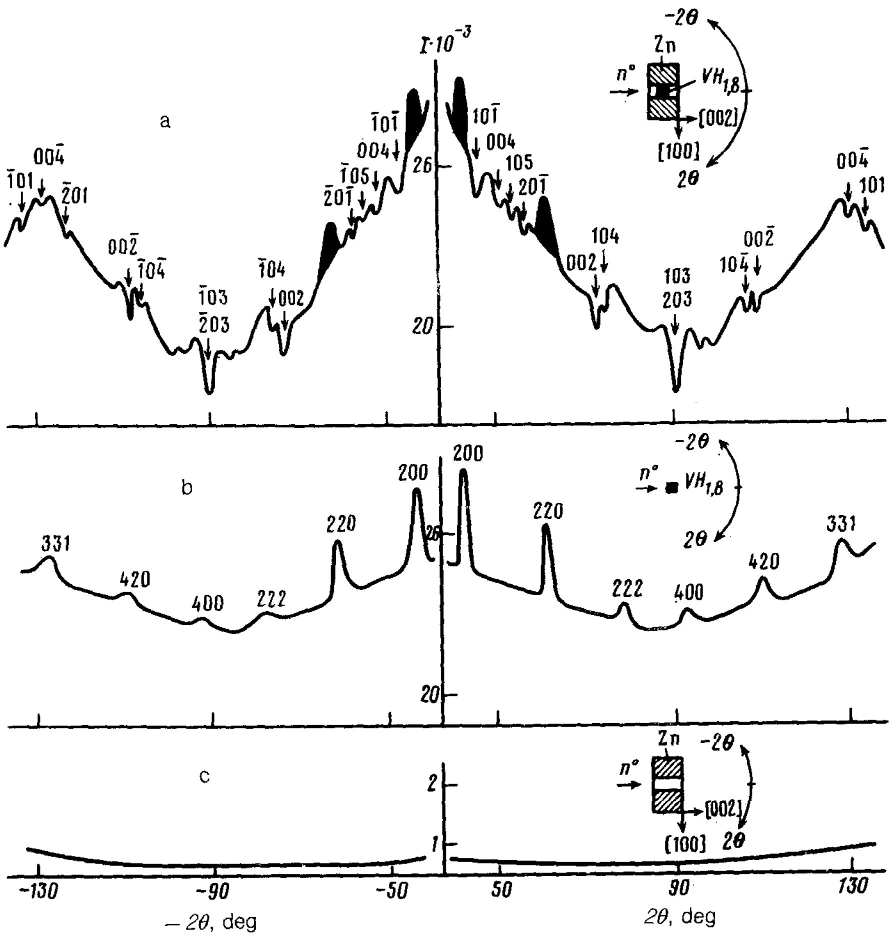

FIG. 1. a—Neutron diffraction pattern of a Zn single crystal, obtained in a widely divergent beam of monochromatic neutrons ($\lambda = 1.548$ Å) (the lines from the $VH_{1.8}$ source are blackened; the experimental arrangment is shown at the upper right); b—neutron diffraction pattern of the $VH_{1.8}$ source without the Zn crystal; c—neutron diffraction pattern of the Zn crystal without the $VH_{1.8}$ source.

The experimental arrangement is shown in Fig. 1. A monochromatic neutron beam ($\lambda = 1.548$ Å), collimated by a slit, is incident on a pressed tablet of vanadium hydride, $VH_{0.8}$ or $VH_{1.8}$, inside the sample single crystal. The crystal is positioned at the axis of a goniometer. One of the band axes of the crystal runs parallel to the goniometer axis, while another runs parallel to the axis of the primary neutron beam. The recordings are made on the DISK multidetector superposition neutron diffractometer[2] at the Kurchatov Institute of Atomic Energy in Moscow. The intensity of the scattered neutrons is measured over the angular interval $2\theta = \pm 157$ °C. The samples are single crystals of various quality levels: $Zn(\eta \simeq 20')$, $Cu(\eta \simeq 20')$, Ge and Si $(\eta \lesssim 1')$. The Zn crystal is $15 \times 30 \times 30$ mm in size, the Cu crystal $15 \times 100 \times 100$ mm, the Ge crystal $1 \times 30 \times 60$ mm, and the Si crystal $20 \times 80 \times 80$ mm. The VH_x source is 5 mm in diameter and 4 mm high.

Figure 1a shows the angular distribution of the intensity of the scattered neutrons from a Zn crystal (the [010] band axis is oriented parallel to the goniometer axis, while the [002] crystallographic axis runs parallel to the axis of the primary beam). In addition to the lines from the source, we can clearly see dips and peaks, which could be interpreted in a natural way as brightening and amplification lines of the Kossel type.[3] Control experiments in which only the source—without the crystal—or only the crystal—without the source—was placed in the neutron beam revealed that the dips and peaks appear only if there is a source inside the crystal, on which the beam of monochromatic neutrons is incident (Fig. 1, b and c). The lines are indexed in the standard way,[3] by constructing a stereo projection of the Kossel cones onto the (002) crystallographic plane. The calculated line positions (shown by the arrows in Fig. 1a) agree well with the experimental positions. The indexing shows that the diffraction pattern consists primarily of lines from crystallographic planes which belong to the band with [010] axis parallel to the goniometer axis. This result can be explained in a natural way on the basis of the experimental geometry, in which small-aperture detectors are placed in the equatorial plane. The contrast of the lines on the diffraction pattern reaches 10% and is quite sufficient for a reliable identification of the lines. The contrast is typically greater for the dips than for the peaks. It depends on the position of the source with respect to the crystal, in agreement with Ref. 3. Similar results were found with the Cu crystal, but with the high-quality Ge and Si crystals we did not observe this effect. In the experiments with those crystals we used a slightly different recording arrangement, placing the source at the surface of the crystal, rather than inside it. A similar situation has been known for a long time for the x-ray pseudo-Kossel effect[3]: Clearly defined lines are obtained only if the crystals have a certain quality level. The lines are not observed if the crystal quality is very high or very low.

In addition to the pseudo-Kossel lines, we attempted to observe true Kossel lines, using some single crystals containing hydrogen: KDP, ADP, and LiH. In this case, the crystal itself is the source of the incoherent radiation. We observed very weak effects (no greater than 0.5%) of the peak-dip type in the KDP and ADP crystals. Observation of the effects in this case was complicated not only by the high crystal quality ($\eta \lesssim 1'$), but also by the pronounced attenuation of the coherent effects as a result of the incoherent scattering by hydrogen nuclei in the crystal itself. To improve the reliability of the observation of the Kossel lines, we accordingly turned to nickel single crystals, with a mosaic angle of 20–30′, for which the cross section for incoherent scattering is roughly half that for coherent scattering. We could apparently expect the highest contrast when these cross sections are equal. On the neutron diffraction patterns from the nickel crystals we observed clearly defined (5%) dips (Fig. 2; the experimental arrangement is also shown here), at positions which agree well with the calculated values. Similar effects were observed in a divergent beam (with a source inside the crystal).

Observation of the neutron analog of the Kossel effect is interesting in connection with the multifaceted nature of the interaction of neutrons with crystals: elastic magnetic and nuclear, inelastic, quasielectric, etc. In particular, Petrascheck[4] has recently derived a theory for the appearance of Kossel lines in double elastic incoherent scattering of neutrons in an ideal crystal. The neutron Kossel effect might be used to solve a

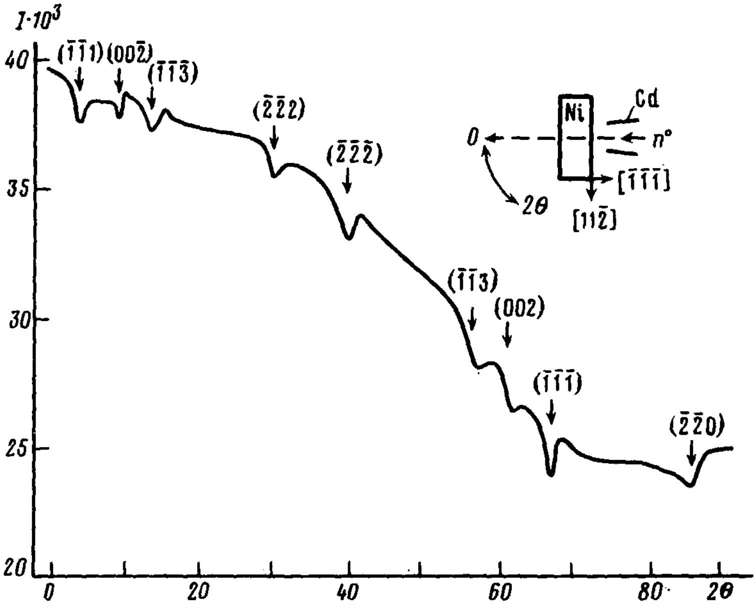

FIG. 2. Neutron diffraction pattern of a Ni single crystal. $\lambda = 1.548$ Å.

variety of physical problems, including some in conventional fields of application: precise determinations of lattice constants and determinations of crystal quality. In the latter case, the difference in the scattering powers of atoms could make the x-ray and neutron methods mutually complementary.

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