Effect of atomic vibrations on scattering of relativistic electrons in a crystal

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An experimental study has been made of how the intensity of the multiple scattering due to atomic vibrations varies with the direction in which the relativistic electrons are moving with respect to a crystallographic axis.

Scattering is one of the most important processes in the physics of orientational phenomena, since it is scattering that determines how and at what rate the particles are redistributed between states of motion as they penetrate into a crystal. The importance of this process is the reason for the unflagging interent in research on scattering, primarily of electrons, by various groups of theoreticians and experimentalists (Refs. 1–6, for example).

Although a crystal has a periodic structure on the average, there are certain interactions which cause the motion of the electrons to become stochastic: scattering by chains (see Ref. 6 and the bibliography there) and by disruptions of the periodicity due to atomic vibrations. Our purpose in the present experiments was to determine whether the intensity of the multiple scattering which results from atomic vibrations varies with the angle at which the relativistic electron beams enter the crystal with respect to one of the principal directions in the crystal (in our particular case, with respect to the direction of a crystallographic axis). The reason why this is not a trivial problem and thus why there has been no substantial progress in experimental research on this question is that under these conditions several scattering mechanisms are operating simultaneously, with the result that it is difficult to interpret the data obtained by a direct method: from measurements of the angular distributions of the beam of particles before and after the crystal. Specifically, in the case of motion near a crystallographic axis or plane, a deflection of an electron from its original direction may be caused by the joint effects of a large group of atoms (a continuous Lindhard potential), by multiple scattering by individual atoms (due to both the vibrations of these atoms and simply the discrete nature of the positions of these atoms, i.e., the "modulation" of the continuous potential), and, finally, by multiple scattering by groups of atoms, i.e., chains (in the axial case). It is thus not possible to extract data on the particular type of scattering which involves the vibrations of atoms, and which is the primary mechanism for the redistribution of particles among states of motion within a channel, from measurements of angular distributions.

Nevertheless, as follows from the results of Refs. 4 and 7, there is a fairly simple experimental procedure which can be utilized to determine the mean square angle of the multiple scattering of electrons. This procedure is to measure the yield of hard bremsstrahlung. The expressions derived in Ref. 7 make it possible to write the spectral density of the intensity of the hard incoherent bremsstrahlung from a unit length in the form $d^2W/d\omega dz = C\langle\theta^2\rangle_a$, where $\langle\theta^2\rangle_a$ is the mean square angle of the scattering caused by atomic vibrations, and the constant C does not depend on the spatial distribution of the scatterers. By measuring the intensity of the uncollimated bremsstrahlung from a crystalline target in various orientations, with the electron beam directed far from any principal direction (the scattering occurs as it would in an amorphous target) and with the beam directed nearly along a direction, one can find the relative change in $\langle\theta^2\rangle_a$. We used such a procedure in the present study.

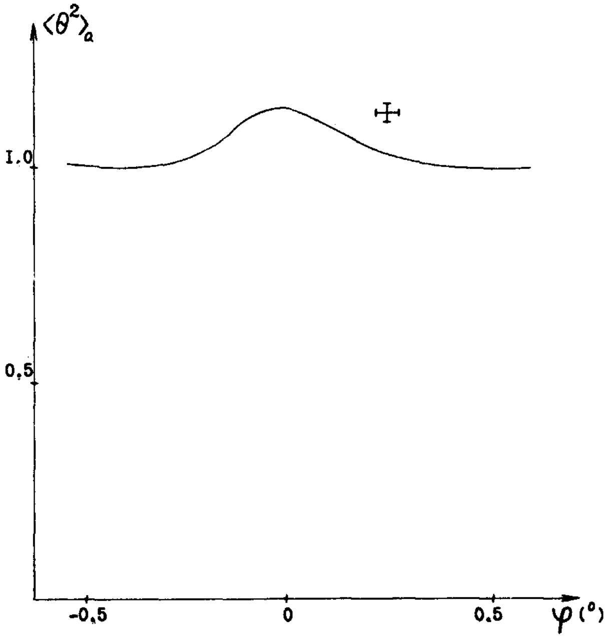

FIG. 1. Mean square multiple-scattering angle $\langle\theta\rangle_a$ versus φ, the angle at which the electrons enter the crystal with respect to a crystallographic axis. The measurement error is shown at the upper right; the crystal was 10 μm thick.

In the experiments we used a beam from the Fakel linear electron accelerator (Kurchatov Institute of Atomic Energy, Moscow) with an energy ~ 47 MeV and a divergence $\sim 4\times 10^{-4}$. The radiator was a perfect silicon crystal $\sim 10\ \mu$m thick, cut perpendicular to the $\langle 100\rangle$ axis within 0.5°. The emission was detected by a scintillation detector with a CsI(Tl) crystal 60 mm in diameter and 40 mm thick. The absorption in this crystal was essentially total. A layer of graphite ~ 40 mm thick was placed in front of the detector to absorb the soft part of the emission (up to about 300 keV). The collimation angle for the photons which were detected, ψ_c, was on the order of $\gamma^{-1}\approx 10^{-2}$ (γ is the Lorentz factor). In other words, this angle clearly satisfied the condition $\psi_c \gtrsim \psi_m \sim (3\text{–}5)\times 10^{-3}$, derived in Ref. 8. It can thus be assumed that there was no collimation of the emission.

The crystal was mounted on a goniometer with two angular degrees of freedom and was oriented with the $\langle 100\rangle$ axis along the electron beam with the help of a detector of soft radiation (no harder than 100 keV). The orientation curve found with the help of this detector with a silicon crystal 10 μm thick has a contrast ~ 4 at the axial maximum. The error in the orientation of the crystal in a given position is no worse than $0.2\psi_L$ (the Lindhard angle is $\psi_L \approx 2\times 10^{-3}$). The crystal was then "disoriented" along one of these angles, and the orientation dependence of the intensity of the hard bremsstrahlung was recorded, by means of a total-absorption detector.

The results of the measurements of the mean square angle of the multiple scattering found by this method are shown in Fig. 1. We see that $\langle\theta^2\rangle_a$ increases with the angle with respect to the crystallographic axis at which the electrons enter, $\varphi \lesssim \psi_L$. This study has therefore (first) demonstrated that it is indeed possible to study the multiple scattering by individual atoms as electrons pass through a single crystal and (second) provided experimental proof that the mean square angle of the multiple scattering due to atomic vibrations is larger in a channel than in an amorphous substance.

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