Spectra of the energy losses experienced by 31 GeV electrons due to emission of radiation in a silicon single crystal

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An investigation was made of the spectra of radiative energy losses experienced by a 31 GeV electron beam with a considerable angular divergence after passing through a single crystal of silicon positioned at various angular orientations. In the range of relatively large angles between the direction of the electron beam axis and a crystallographic axis the experimental results agreed with the well-known relationship describing the cross section of coherent bremsstrahlung in a single crystal. The results disagreed for small angles between such axes and this was clearly due to the process of spontaneous emission of radiation as a result of channeling of a greater proportion of electrons in the single crystal.

1. INTRODUCTION

Recent theoretical and experimental investigations have demonstrated the limited validity of the traditional ideas on the interaction between relativistic charged particles and the ordered structure of a crystal (for an extensive bibliography see Refs. 1 and 2). The subject has become topical once again, especially as modern proton accelerators make it possible to reach particle energies of hundreds of gigaelectron volts and this applies to electrons and positrons.

We shall report and discuss the experimental data, obtained using the Serpukhov proton accelerator, on the spectra of energy losses experienced by relativistic electrons due to emission of radiation in a silicon single crystal.

2. APPARATUS

Our experiments were carried out using an electron beam[3] in the configuration[4] used earlier to obtain a beam of high-energy labeled polarized photons. Use was made of the arrangement shown in Fig. 1. An electron beam was formed by a magnetooptic system MO and it passed through a silicon single crystal Cr placed on a goniometer G. Before reaching the crystal, the electrons were recorded with scintillation counters C_1 and C_2 connected in coincidence. A deflecting magnet M was used to remove electrons from a beam of bremsstrahlung photons behind the single crystal. Background processes associated with the electron beam and the associated cascade "halo" which accompanied it were eliminated by anticoincidence scintillation counters C_A and scintillation counter-collimators with lead converters C_K. The electron bremsstrahlung energy was measured by a shower lead scintillation detector L whose thickness along the beam was 20 radiation lengths.[5] The signal from the shower detector reached the input of a 256-channel amplitude analyzer, which was triggered by the $C_1 C_2 \bar{C}_A \bar{C}_K$ system.

The energy of the electron beam was $E_e = 31 \pm 0.2$

GeV and its intensity was ~10^4 particles/sec. The angular distributions of electrons reaching the crystal were near-normal with the horizontal and vertical variances $\sigma_H \approx 0.3$ and $\sigma_V \approx 0.8$ mrad, respectively. The shower detector was check-calibrated using the system above to study the electron beam as well as a beam of labeled photons of energies 8–31 GeV. The energy resolution of the detector in this range was ~25–12% (this was the width of the amplitude distribution at half-maximum). The energy threshold of the signals recorded by the shower detector was ~2 GeV. The normal operation of the apparatus as a whole was checked and the correction coefficient (representing miscounts of the amplitude analyzer and false operations of the trigger) was determined by measuring the Bethe–Heitler spectrum when the single crystal was replaced with a lead plate of equivalent thickness (expressed in radiation lengths).

The goniometer had vertical and horizontal axes of rotation and could be used to set the corresponding angles of orientation of the single crystal to within 0.025 mrad. The crystal was a disk 70 mm in diameter and it was cut from a silicon sample along the (100) planes; its thickness was $0.14X_0$, where X_0 is the radiation unit (for silicon, $X_0 = 21.8$ g/cm²). The [010] and [001] crystal axes were made to coincide with the vertical q_V and horizontal q_H rotation axes of the goniometer, respectively (Fig. 2). The crystal was aligned relative to the electron beam by the method described in Ref. 4.
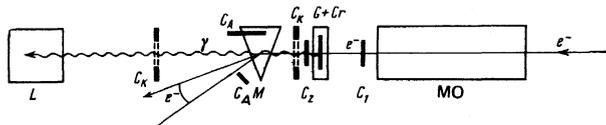

FIG. 1. Schematic diagram of the apparatus: MO is a magneto-optic system for shaping an electron beam; C_1 and C_2 are monitoring scintillation counters; C_A and C_K are guard scintillation counters; G + Cr is a goniometer with a single crystal; M is a clearing magnet; and L is a shower detector.
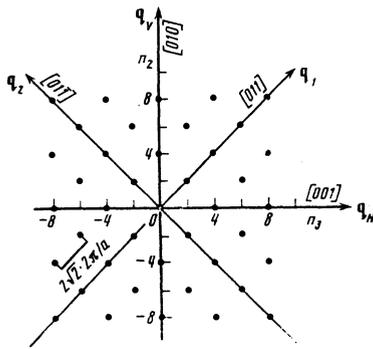
FIG. 2. Reciprocal-lattice (100) plane of a silicon single crystal shown in systems of goniometric (q_H, q_V) and auxiliary (q_1, q_2) rotation axes (a is the lattice constant in units of the Compton electron wavelength and n are the indices of the reciprocal lattice sites).

Under the experimental conditions the space in front and behind a single crystal, right up to the clearing magnet, was filled with an amorphous substance of thickness $0.08X_0$ and $0.03X_0$ (scintillation counters, air). However, the contributions of the amorphous substance and of the single crystal to the process under investigation were not additive because of the probable multiple emission of radiation by electrons. This made it impossible to determine experimentally, by the difference method, the effect solely due to the single crystal.

3. RANGES OF SINGLE-CRYSTAL ORIENTATIONS

The radiative energy losses of electrons were investigated in three ranges of the angular orientation of the single crystal:

a) the crystal was strongly disoriented and the energy losses were governed by the noncoherent part of the bremsstrahlung cross section[1];

b) the crystal was oriented in the range of angles corresponding to the strongest coherent electron bremsstrahlung at a chain of reciprocal lattice sites characterized by the index ratio $n_3/n_2 = 1$ (Refs. 1 and 4) (Fig. 2);

c) the crystal was oriented in the range of directions close to the [100] crystallographic axis and to the electron beam axis, when one would expect the emission of radiation from channeled electrons.[6-8]

When the [100] crystallographic axis was made to coincide with the electron beam, the orientation angles of the single crystals Φ_H and Φ_V relative to the goniometric axes q_H and q_V were taken to be zero. In the ranges a) and b) the orientation of the single crystal was described with the aid of a system of auxiliary axes q_1 and q_2 (Fig. 2) and the angles of rotation of Φ_1 and Φ_2 about them. When the angle Φ_1 in this system differed considerably from zero, coherent bremsstrahlung from a chain of reciprocal lattice sites with $n_3/n_2 = 1$ was practically governed by the angle $|\Phi_2|$ and by the angular divergence of the electron beam in a plane perpendicular to the corresponding auxiliary axis.[4]

The investigated orientations of the single crystal are

TABLE I. Orientation angles of silicon single crystal.

Angle, mrad	Orientation					
	1	2	3	4*	5	6
Φ_H	+73.75	+17.25	+16.25	–	0	0
Φ_V	+31.25	−16.25	−16.25	–	+1.25	0
Φ_1**	+28.63	+23.67	+22.98	+22.56	–	–
Φ_2**	+74.81	+1.16	+0.44	0	–	–

*In this experiment the orientation was not determined (for some data see Ref. 4).
**Calculated from the values given above allowing for the experimentally determined inaccuracy of the initial coincidence of the crystallographic axes, amounting to 19.10 mrad in the anticlockwise direction with the goniometric axes in the (100) plane (Fig. 2).

given in Table I. The total error in the determination of the orientation angles was ±0.06 mrad.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental spectra of the energy losses experienced by electrons due to emission of radiation in a layer of matter of the composition $0.08S_0$ (amorph.) $+ 0.14X_0$ (cryst.) $+ 0.03X_0$ (amorph.) are plotted in Fig. 3 for the orientation angles of the crystal listed in Table I. The spectra were not corrected for the energy resolution of the shower detector. The reproducibility of the spectra was 10–15% when the orientations were reset. Figure 3 includes also the corresponding spectra (continuous curves) calculated for the experimental conditions, i.e., allowing for the angular
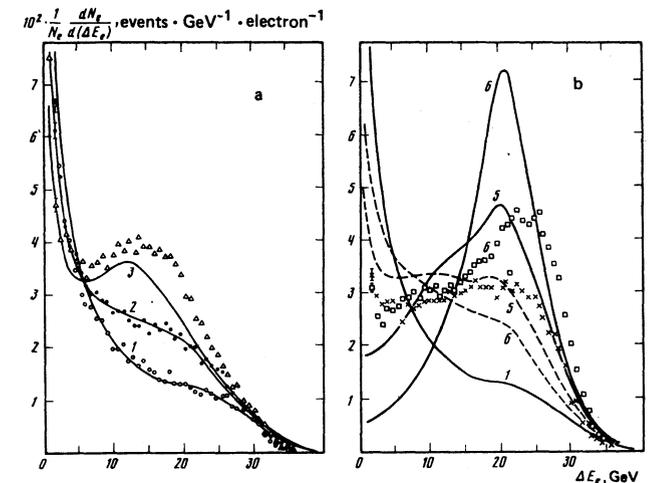

FIG. 3. Energy loss spectra experienced by a 31 GeV electron beam due to emission of radiation in a combined system of the composition $0.08X_0$ (amorph.) $+ 0.14X_0$ (silicon crystal) $+ 0.03X_0$ (amorph.). Here, N_e is the total electron flux and X_0 is the radiation unit. The points are the experimental values summed for five successive analyzer channels without corrections for the energy resolution of the shower detector. The random error varies along the spectrum proportionally to the square root of the number of events. The continuous curves are calculated for the experimental conditions allowing for multiple processes. The dashed curves are calculated on the basis of the assumptions reported in text and on the assumption that radiation is emitted by the channeled electrons in accordance with the Bethe–Heitler mechanism. The curves in Figs. 3a and 3b are numbered in accordance with the orientations of the silicon single crystal listed in Table I.

and energy scatter of electrons in a beam, for multiple noncoherent and coherent bremsstrahlung emission, for multiple Coulomb scattering, and for fluctuations of the amplitudes of the output signals of the shower detector. These spectra were calculated by the Monte Carlo method. The electron bremsstrahlung cross section of the single crystal was found using the relationships of Ref. 9 and the atomic form factor of silicon for the Molière potential.[10]

When the orientation of the single crystal was far from the coincidence of the [100] crystallographic axis with the electron beam axis (Fig. 3a), the agreement between the calculated and experimental spectra was good. Some discrepancy for the spectra labeled 3 was possibly due to different type of radiation emitted in the course of channeling by the (011) crystallographic planes, which affected a small proportion of the electron flux but which was ignored in the calculations. The agreement between the theoretical and experimental results in these cases made it possible to calculate the expected spectra 1–4 of the electron energy losses in the single crystal itself and the corresponding energy spectra of the bremsstrahlung photons. These spectra are given in Fig. 4. The results of Fig. 4b illustrate the considerable increase in the intensity of the electron bremsstrahlung in the region of the coherent effect. In this region there is also an increase in the average relative radiation energy losses of electrons per unit radiation length[11] in the material of the single crystal calculated using the relationships of Ref. 9 (Fig. 5). The results obtained support the validity of the well-known relationships for the coherent bremsstrahlung[1,9] emitted by the unchanneled electrons of ~31 GeV energy and the increase in the effective radiation length compared with the amorphous modification of the investigated material.

Figure 3b shows the spectra of the radiative energy losses experienced by electrons moving in the range of

FIG. 5. Average relative losses of the electron energy due to the emission of coherent bremsstrahlung in a silicon single crystal calculated per radiation length of its amorphous modification and plotted as a function of the electron energy and the orientation angle of a single crystal $|\Phi_2|$ (mrad). Here, the chain line represents the Bethe–Heitler mechanism; R is the thickness of silicon radiation units; A is the range of angles of capture by a planar (011) channel.

small angular deviations from the [100] crystallographic axis. In this range the experimental spectra did not agree with those calculated (continuous curves) on the same assumptions as before. The calculated probabilities of the electron energy losses in the range $\Delta E < 7$–10 GeV were too low and in the range $\Delta E_e \sim 20$–25 GeV the calculations exceeded considerably the experimental results. The nature of the calculated spectra could be explained by an increase in the effective radiation length in the single crystal, which should result in strong multiple emission of radiation by electrons, as found in the amorphous substance (Fig. 6). An increase in the rms angle of multiple scattering of electrons in the single crystal,[12] allowed for in the calculations of
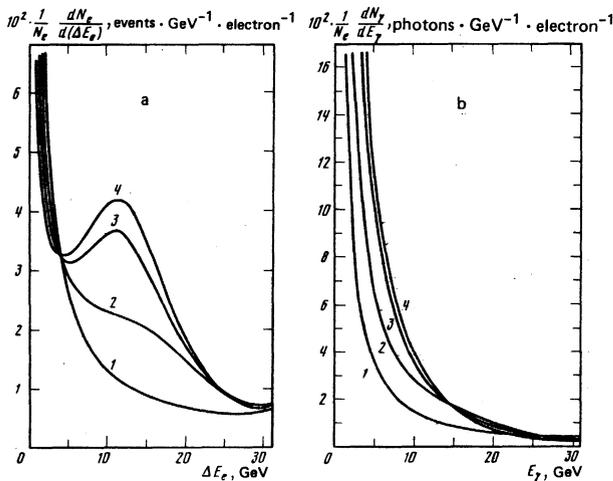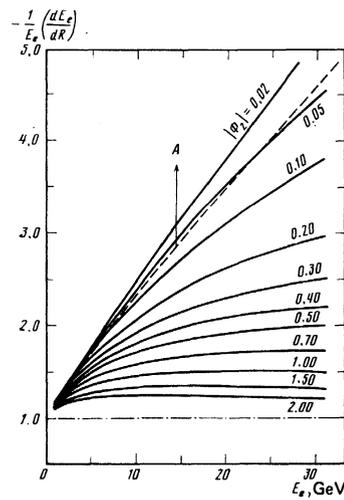

FIG. 4. Spectra of the energy losses experienced by a 31 GeV electron beam due to emission of coherent bremsstrahlung (a) and energy spectra of photons (b) emitted by a silicon single crystal $0.14X_0$ thick (N_e is the total electron flux, N_γ is the bremsstrahlung photon flux, X_0 is a radiation unit; the curves are labeled in the same way as the orientations of a single crystal in Table I).
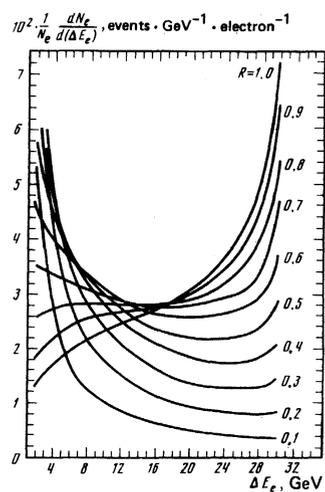

FIG. 6. Calculated spectra of the energy losses experienced by 31 GeV electrons due to the emission of bremsstrahlung in amorphous layers of thickness R radiation lengths (Monte Carlo calculations).
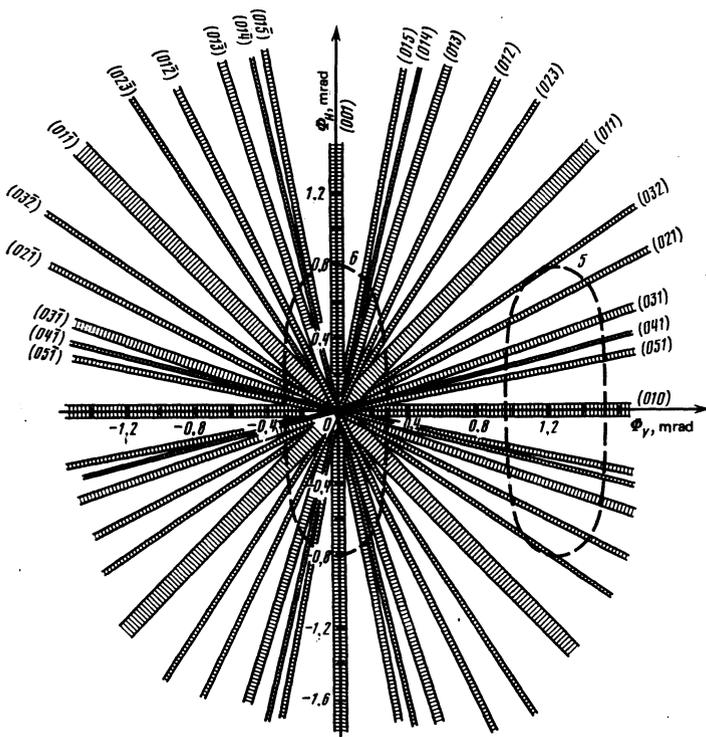
FIG. 7. Angular acceptances of the main planar channels in a silicon single crystal bombarded with 31 GeV electrons along the [100] crystallographic axis in the Bravais lattice (the ellipses represent variants 5 and 6 of the orientation of a single crystal in Table I and the angular dispersions of the electron beam in the experiments).

the spectra, had little effect on their shape.

The discrepancy between the experimental and calculated spectra 5 and 6 was probably due to the fact that the mechanism of coherent bremsstrahlung did not apply to a considerable proportion of the beam electrons which were now channeled by the planes in the single crystal of silicon,[6] as shown in Fig. 7. The angular acceptances of the planar channels were calculated for the relativistic case from the relationship $2\alpha_c = 2(2V_0/E_e)^{1/2}$, where α_c is the critical channeling angle, and the interaction potential V_0 of an electron with the crystallographic plane was approximated by the continuous Molière potential allowing for two planes forming a channel.[13]

A qualitative estimate of the energy losses due to emission of radiation by electrons in the channeling range was obtained by calculating the spectra 5 and 6 on the assumption that these electrons emitted in accordance with the Bethe–Heitler mechanism exactly as in an amorphous medium. The radiation of the unchanneled electrons was calculated in the same way as before. The results are given in Fig. 3b by the dashed curves. An analysis of the results in the figure shows that the intensities of the radiative losses of the electron energy in crystallographic channels are greater than those for an amorphous medium but smaller than those predicted by the relationship applicable to coherent bremsstrahlung. Of the two orientations of the single crystal 5 and 6, a considerably smaller proportion of the electron flux is channeled in the former case (Fig. 7) and, therefore, the coherent electron bremsstrahlung predominates. This is why the agreement between the calculations and experiment is better for spec-

trum 5 than for spectrum 6. On the whole, an analysis of the spectra in Fig. 3b suggests that, in this experiment as well as in the earlier investigations,[4,14-16] the observed effects are due to the predicted[6-8] basically new phenomenon of emission of spontaneous radiation when charged particles are channeled in single crystals.

A comparison of the radiative energy loss spectra of electrons obtained by us with similar spectra of the Bethe–Heitler bremsstrahlung (Figs. 3, 4, and 6) demonstrates that single crystals can be used more effectively than amorphous substances in selective reduction in the energy of electron beams with small angular divergences.

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P-odd nuclear forces—a source of parity violation in atoms

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We consider the electromagnetic P-odd interaction produced between an electron and a nucleus by parity-violating nuclear forces. New information on these forces can be obtained even now by experimentally investigating the optical activity of heavy atoms and diatomic molecules. In the case of the deuteron, the P-odd vector potential is expressed in terms of parameters that characterize parity violation in np scattering.

1. The discovery of the weak electron–nucleon interaction due to neutral currents, which was made in Novosibirsk[1] by observing the optical activity of atomic-bismuth vapor, is undoubtedly only the first positive result in the study of the structure of weak interactions by atomic-spectroscopy methods. The subsequent increase of the accuracy of this experiment[2] makes it quite realistic to obtain qualitatively new results in this field. We have in mind, in particular, the measurement, in atoms[3] and in molecules,[4] of the constant that characterizes the weak interaction of the electron with the nuclear spin. The natural scale of this effect is $-1/Z$ of the already measured one, since it receives contributions not from all the nucleons of the nucleus, but only from the one valence nucleon. It is realistic to expect to measure an effect of this order of magnitude even at present. However, within the framework of the Weinberg-Salam model, at the mixing-parameter value $\sin^2\theta = 0.23$ which follows from the available experimental data, the constant of the interaction in question is numerically very small.

We wish to note in the present article that parity-violation effects that depend on the spin of the nucleus can be produced in atoms not by neutral currents only. They are induced also by P-odd nuclear forces. These forces produce in the electromagnetic vector-potential of the nucleus an increment of incorrect P-parity, and this increment acts on the electron. The contribution of this mechanism can be noticeably larger than that of the neutral currents. Thus, experiments aimed at observing the effects in question are already realistic at present. They can yield valuable information on parity violation in a nucleus.

Effects peculiar to μ-mesic atoms and due to P-odd nuclear forces were considered earlier by Grechukhin and Soldatov.[5] Parity violation in the interaction of an electron with a nucleus, induced by P-odd nuclear forces, was discussed from a general point of view in a recent paper by Henley et al.[6]

2. The cause of the considered phenomenon is easier to understand by starting from the fact that violation of spatial parity in the nucleus produces in it a spiral spin structure[7,8] and toroidal currents.[7] It is the resultant contribution to the vector-potential of the nucleus which leads to the P-odd electron–nucleus interaction of interest to us. We shall show that this electromagnetic interaction must of necessity be of the contact type. This result is contained in essence in a number of papers. According to a private communication from P. Sandars, it was known already to N. Ramsey. None-