Spectroscopy of the radiation emitted by channeled particles—a new method of study of crystals

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Studies of the properties of the radiation occurring in channeling of relativistic electrons and positrons, carried out over the last eight years, have shown that it is possible to study a number of properties of single crystals on the basis of the features of the radiation spectrum and the location and width of the spectral lines. The greatest success in this area has been achieved in determination of the Debye temperature of crystals, more accurate determination of the crystal potential, and determination of the density of electrons near crystal strings and planes. As a consequence of the localization of relativistic electrons or positrons near certain atomic planes or strings, the radiation spectrum of the channeled particles, in contrast to diffraction methods, carries direct information on the crystal potential. The method permits study of the correlation of thermal vibrations of the atoms in the lattice, and also of some features of superstructures and complex crystals.

CONTENTS

1. INTRODUCTION

The prediction made by M. A. Kumakhov in 1976[2] that hard electromagnetic radiation will arise in channeling of relativistic electrons and positrons in crystals[1] and subsequently the experimental detection of this effect[3,4] have provided new stimulation of study of the radiation emitted by relativistic particles in oriented crystals. The large number of publications on this subject has been reflected in a number of reviews[5–8] and books.[9–11]

At first studies of the radiation emitted in channeling were concentrated mainly on the properties of the electromagnetic radiation itself, its spectrum, polarization, intensity, and relation with other types of particle radiation in crystals. The experimental investigations covered a range of relativistic particle energies from 1 MeV to 150 GeV. As many as ten simple and complicated materials have been used as crystalline targets.[10,11] In the course of the experimental and theoretical studies which have been carried out, the dependence of the channeled-particle radiation on the particle energy, crystalline-target structure, atomic thermal vibrations, and scattering by target electrons has been determined. In reporting on the International Conference on Channeling and Radiation of Relativistic Particles (Villa del Mare, Italy, 1986) the authors of the article[12] remark that "... many applications of channeling and of the radiation produced in channeling have already been found to be useful, and a number of other possible applications are of interest."

Among the possible applications of the radiation emitted by channeled particles, at the present time those most frequently discussed are the diagnostics of the properties of crystals, of defects in crystals,[13] and of the structures of superlattices which contain a large number of layers.

The possibilities of such diagnostics are due to the fact that the radiation spectrum emitted by channeled particles in particular those with energy 1–50 MeV, turns out to be extremely sensitive to the form of the averaged crystal potential; another important factor is the preferred localization of electrons near atomic axes and planes—and of positrons between atomic planes and axes. The accuracy in determination of the parameters of crystalline structures is directly related to the errors in measurement of the shape of the radiation spectrum of the channeled particles, which are determined by the characteristics of both the sources of relativistic particles and of the detecting apparatus.

Estimates[14] show that in measurements of the radiation

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spectrum of channeled electrons it is possible to use a current no greater than 10^{-13} A. The exposure time for obtaining a single spectrum is 20–30 min. Since with such doses of irradiation of crystals by electrons there is one dislocated atom out of 10^{12} atoms, the method of investigation by means of channeled-particle radiation can be considered nondestructive.[14] The location of the lines of the quasicharacteristic radiation can be determined within 1%, while their width can be measured within 10%.

2. MAIN FACTORS INFLUENCING THE RADIATION SPECTRUM EMITTED BY CHANNELED PARTICLES IN CRYSTALS

The main factor influencing the radiation spectrum emitted by channeled particles in a crystal is the shape of the crystal potential averaged along the particle motion (the Oz axis). In a perfect single crystal the average planar potential is determined by the expression[1]

$$U_{\text{pl}}(x) = \frac{1}{s}\int_0^\infty 2\pi r\, V_a\left((x^2+r^2)^{1/2}\right) dr, \quad (1)$$

and the potential of an atomic string by

$$U_{\text{st}}(r) = \frac{1}{d}\int_{-\infty}^{\infty} V_a\left((z^2+r^2)^{1/2}\right) dz, \quad (2)$$

where s is the area per atom in the atomic plane, d is the distance between atoms in a string, x is the coordinate perpendicular to the plane, $r = (x^2+y^2)^{1/2}$, and $V_a(r)$ is the potential of an individual atom.

The approximations most commonly used for $V_a(r)$ are the Moliere potential[15]

$$V_a^{M}(r) = \frac{Ze^2}{r}\sum_{i=1}^{3} \alpha_i \exp(\beta_i r), \quad (3)$$

where Ze is the charge of the nucleus, $\alpha_i = \{0.35; 0.55; 0.1\}$, and $\beta_i = \{-0.3; -1.2; -6\}$, and the Doyle-Turner potential[16]

$$V_a^{DT}(r) = \frac{\hbar^2 2\sqrt{\pi}}{\pi m_e}\sum_{i=1}^{4}\frac{a_i}{(B_i)^{3/2}}\exp\left(-\frac{r^2}{B_i}\right), \quad (4)$$

where m_e is the electron mass. Values of the coefficients a_i and B_i for each element are given in Ref. 16.

The Doyle-Turner potential (4) is especially suitable when the thermal vibrations of the atoms are taken into account, since in this case it is sufficient to make the substitution $B_i \to B_i + 2\rho^2$, where ρ is the mean square amplitude of thermal vibrations of the atoms. When the thermal vibrations of the atoms are taken into account, the thermalized potential of a string takes the form[17]

$$U_{\text{st}}^{DT}(r) = -\frac{e^2}{a_0}\frac{2a_0}{d}\sum_{i=1}^{4}\frac{a_i}{B_i+\rho^2}\exp\left(-\frac{r^2}{B_i+\rho^2}\right), \quad (5)$$

where $a_0 = \hbar^2/m_e e^2$ is the Bohr radius.

The planar potential is written in the form[18]

$$U_{\text{pl}}^{DT}(x) = -2\sqrt{\pi}\, e^2 N d_p a_0 \sum_{i=1}^{4}\frac{a_i}{(B_i+2\rho^2)^{1/2}} \times \exp\left(-\frac{x^2}{B_i+2\rho^2}\right), \quad (6)$$

where d_p is the interplanar distance. N is the density of atoms in the material. It should be mentioned that the averaged potentials determined in this way are a linear superposition of the potentials of the individual atoms and therefore do not take into account the redistribution of charge in the crystal. The crystal potential can be determined more accurately by taking into account x-ray diffraction data[20] or on the basis of measurements of channeled-particle radiation (see Section 2.2).

For a given form of averaged potential $U(\mathbf{r}_\perp)$ the amplitude of the wave function of a relativistic channeled particle $\varphi(\mathbf{r}_\perp)$ can be found from the Schrodinger equation[6]

$$\frac{\hbar^2}{2\gamma m_e}\nabla_\perp^2\varphi(\mathbf{r}_\perp) = (U(\mathbf{r}_\perp) - E_\perp)\varphi(\mathbf{r}_\perp), \quad (7)$$

where $\gamma = E/mc^2$, $\nabla_\perp^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2$, and $\mathbf{r}_\perp$ is the projection of $\mathbf{r}$ on the (x,y) plane.

Investigations of the solution of Eq. (7) for relativistic electrons with energy $E \lesssim 50$ MeV have shown that the spectrum of the "transverse energy" $E_\perp$ is discrete in the case of planar channeling, and in the case of axial channeling for $E \lesssim 10$ MeV.[6,9-11] The corresponding lines of spontaneous transitions with inclusion of the Doppler shift of the frequency in the case of radiation forward have energies

$$E_\gamma = 2\gamma^2 \Delta E_\perp. \quad (8)$$

The lack of equal spacing of the levels of the transverse motion leads to the presence in the radiation spectrum of separate lines, which greatly facilitates its interpretation and permits spatial localization of the initial state of the electron in the spontaneous transition process. We shall illustrate the diagnostic possibilities of the method with a number of specific examples.

2.1. Determination of the Debye temperature

The averaged potential of a string (5) or of a plane (6) depends strongly on the amplitude of thermal vibrations ρ primarily in the region close to the string or plane. In Fig. 2 we have shown the results of a calculation of the string potential of the ⟨111⟩ axis at temperatures $T = 110$, 300, and 500 K in a silicon crystal and the corresponding energy lev-

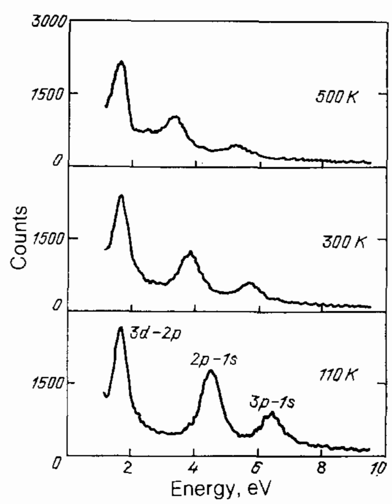

FIG. 1. Spectra of radiation emitted by 3.5-MeV electrons in channeling along a ⟨111⟩ string in silicon at temperatures $T = 110$, 300, and 500 K.[19]

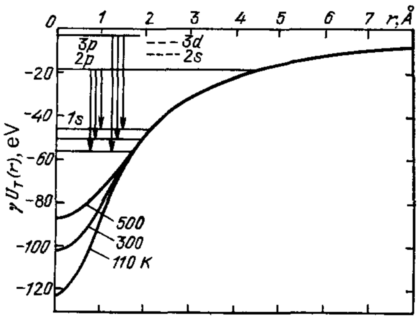

FIG. 2. Averaged potential of the ⟨111⟩ string in a silicon crystal at temperatures $T = 110$, 300, and 500 K and the corresponding energy levels of channeled electrons with energy 3.5 MeV.[19]

els for channeled electrons with energy 3.5 MeV.[19] The measured radiation spectra for temperatures 110, 300, and 500 K are given in Fig. 1.

It can be seen from Figs. 1 and 2 that with increase of the crystal temperature there is a shift of the maxima of the spectral density of radiation to lower energies, since the depth of the channel potential well decreases. It is characteristic that the shift of the $3p$-$1s$ line is most clearly expressed; this is due to localization of the electrons in the low-lying 1s level of the atomic string. Similar results for planar channeling of electrons with energy 54.5 MeV in the (100) plane of silicon[20] are shown in Fig. 3. The dependence of the energy of the radiation of channeled electrons on the crystal temperature can be used to find the Debye temperature T_D. Studies carried out by Berman *et al.*[20] show that the value $T_D = 495 \pm 10$ K obtained in this way for a silicon crystal

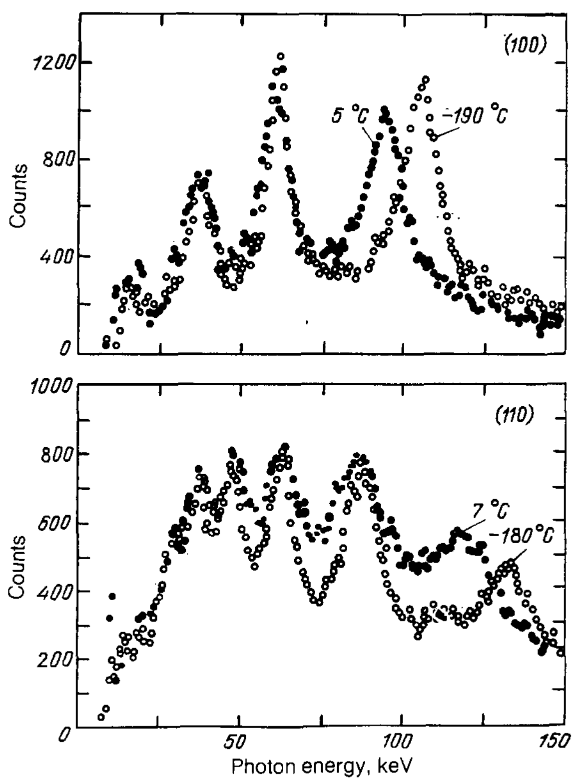

FIG. 3. Spectra of radiation emitted by electrons with energy 54.5 MeV in motion along the (100) plane of silicon at crystal temperatures 190 and 5 °C.[20]

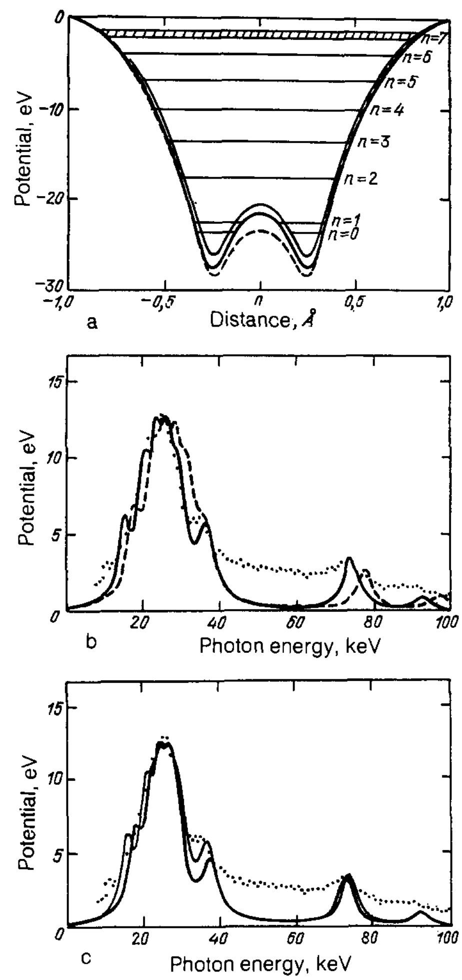

FIG. 4. (a)—Potentials of the (111) plane of diamond[20]: the "standard" potential calculated in the Hartree-Fock approximation (dashed line 1), corrected on the basis of x-ray diffraction data (thin solid line 2), and reproduced from measurements of the emitted radiation (3) for electrons with energy 30.5 MeV. (b) and (c)—photon spectra: experiment (points) and calculated spectra corresponding to the potentials in part (a).

differs considerably from the value 543 ± 8 K found in studies by means of x-ray diffraction.[21] It should be noted that the results of various theoretical models give values for the Debye temperature in the range from 500 to 530 K.[22]

2.2. Refinement of the crystal potential

The averaged potentials (5) and (6) correspond to superposition of the potentials of isolated atoms and not to a real crystal potential, which depends on the redistribution of charge in the crystal lattice. Therefore the location of the lines $(E_\gamma)_{ij}$ in the experimentally measured spectra can be used to obtain the crystal potential more precisely.

The authors of Ref. 20 used two methods for correction of the potentials of the (111) plane of diamond: 1) improvement of the atomic scattering factor $f(s)$ at small s on the basis of x-ray diffraction data and 2) construction of an empirical planar potential on the basis of the radiation spectra emitted by channeled electrons with energy 30.5 MeV. The forms of the potentials obtained are given in Fig. 4a. The radiation spectra corresponding to them, calculated for these potentials, are given in Figs. 4b and c.

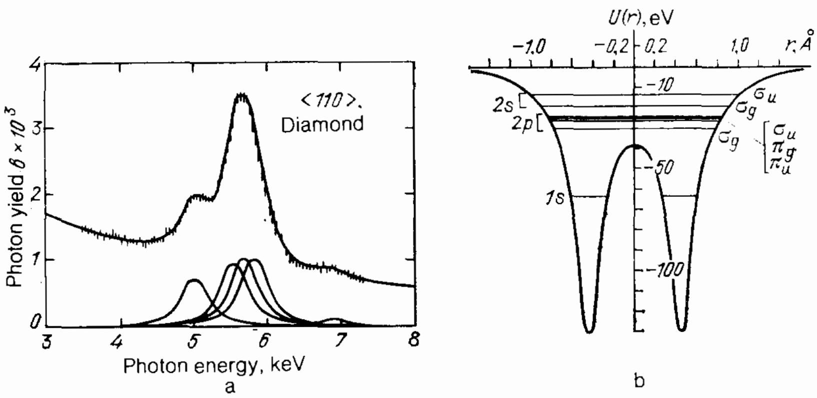

FIG. 5. Channeling of 4-MeV electrons in diamond along the ⟨110⟩ direction.[25] (a)—Measured radiation spectrum (above). (b)—Calculated shape of the potential of a plane passing through two ⟨110⟩ strings, and the corresponding energy levels of channeled electrons.

2.3. Determination of the density of electrons in a crystal

The shape of the potential curves can be used to find the distribution of electron density averaged along the Oz axis:

$$\rho_e(\mathbf{r}_\perp) = \frac{1}{4\pi}\Delta_\perp V(\mathbf{r}_\perp).$$

The electron density in a crystal is usually found on the basis of x-ray diffraction data (see for example Refs. 23 and 24). However, it should be noted that the use of diffraction methods requires taking into account a large number of reflected lines, since for a description with a minimum scale $r_{\min}$ Fourier harmonics with wave vectors $k_{\max} \gtrsim 4/r_{\min}$ are required, while on the other hand for description with a spatial scale $r_{\max}$ it is necessary to have $k_{\min} \lesssim 2/r_{\max}$. Therefore the total number of Fourier harmonics necessary for adequate reproduction of the electron density distribution is more than $2r_{\max}/r_{\min}$ in each coordinate.

The preferential localization of electrons near atomic strings was used in Ref. 25 for determination of the density of electrons between pairs of atomic strings in a diamond crystal in the ⟨110⟩ direction on the basis of channeled-electron radiation. The shape of the radiation spectrum emitted by 4-MeV electrons channeled along the ⟨110⟩ axis and the averaged potential are shown in Fig. 5. It can be seen that a change of the electron density which leads to a change of the potential at the point $x = 0$ leads to a shift of the energy levels of the 2s and 2p groups, which is reflected in the location of the 2p→1s radiation lines. The electron density determined in this way in the center of the covalent bond is 1.7 electrons/Å^3, which agrees with the results of x-ray diffraction.[24]

2.4. Investigation of nitrogen clusters in natural diamond

The shape of the averaged potential can depend also on the presence of foreign inclusions in the crystal, which distort its lattice. The investigation of nitrogen clusters in natural diamond on the basis of the radiation emitted by channeled electrons and positrons has been described by Datz *et al.*[26] Natural diamonds are classified in four categories: Ia, Ib and IIa, IIb, according to the difference in optical absorption, electron paramagnetic resonance, and electrical properties. The rarer crystals of type II are characterized by the presence of the 3 μm and 6 μm absorption bands of carbon in the infrared region and at 2250 Å in the ultraviolet. Diamonds of type I have additional infrared absorption bands from 7.5 to 10 μm and at 3065 Å in the ultraviolet region as the result of presence of nitrogen inclusions. Crystals of type II which have an admixture of boron are p-type semiconductors and are called IIb in contrast to diamonds of type IIa, which do not have impurities. Crystals of type Ia which have an absorption peak at 7.3 μm contain plate nitrogen clusters in the direction of the (100) planes (Fig. 6). The existence of the clusters leads to a change in the shape of the averaged potential of the (100) plane in comparison with a diamond of type IIa, which does not contain clusters (Fig. 7a).[20] The corresponding radiation spectra emitted by channeled electrons with energy 54.5 MeV are shown in Fig. 7b. The sensitivity of the spectrum to the presence of impurities and structure defects can be used for purposes of diagnostics.

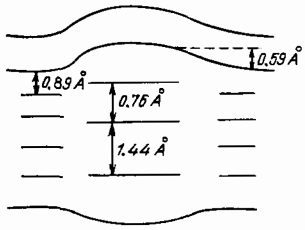

FIG. 6. Structure of a nitrogen cluster in diamond of type Ia.[26]

The influence of defects which lead to bending of atomic strings on the radiation emitted by relativistic positrons was investigated in Ref. 27. The influence of dislocations and packing defects was discussed by the same authors in Ref. 28, where it is concluded that channeled-particle radiation has diagnostic possibilities.

2.5. Study of superstructures

Recently there has been increasing interest in study of the radiation produced in channeling of electrons and positrons in crystals with a superstructure,[14,29-30] such as GaPa/GaAs$_x$P$_{1-x}$ or Ga$_{0.7}$Al$_{0.3}$As/GaAs. Reference 31 considered the radiation of channeled particles in scattering by periodically located point defects. Periodic deformation of the lattice in a superstructure leads to a change of the shape of the averaged potential and to a decrease of the energy of the photons radiated by relativistic electrons in GaP/GaAs$_x$P$_{1-x}$.[29] Comparison of the radiation spectra in a crystal with a superstructure and in GaP, which serves as a standard, in this case permits deduction of the presence of stresses which arise as the result of mismatch of the lattices at the boundary between different layers. Another effect in channeling of electrons in thin crystals is the resonance splitting of the bands of quasicharacteristic radiation.[30]

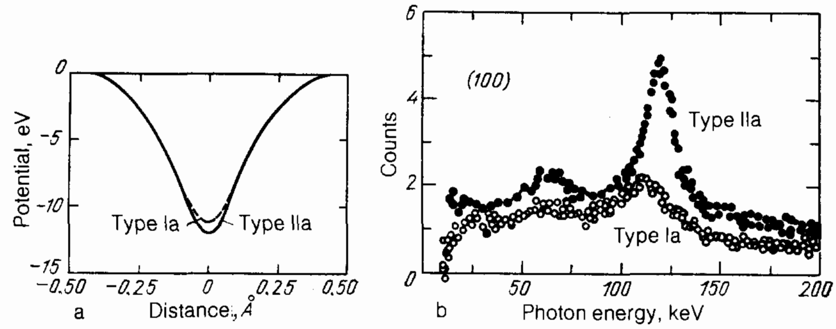

FIG. 7. Shape of the averaged potential of the (100) plane of diamond of type Ia and IIa (a) and the corresponding radiation spectra emitted by channeled electrons with energy 54.5 MeV (b).

2.6. Study of complicated crystals

At the present time studies have been carried out of the radiation produced in channeling in complicated crystals such as GaAs, GaP, AlAs,[14,32] LiF,[33] LiH and LiD,[20,34] and the alloys $Ga_{0.7}Al_{0.3}As$.[14] The radiation spectra emitted by channeled particles permit investigation of the anisotropy of the vibrations of the atoms in a crystal of a complex compound[33] and the redistribution of the electron charge in the lattice of a solid material. The influence of the lack of axial symmetry of the channel on the radiation spectrum emitted by hyperchanneled positrons has been investigated by us in Ref. 35.

2.7. Study of correlation of thermal vibrations

A substantial influence on the radiation spectrum emitted by channeled relativistic electrons is exerted also by incoherent scattering on the thermal vibrations of the nuclei in the lattice[18] and on atomic electrons.[36] As was already mentioned in Section 2, the accuracy in measurement of the widths of the quasicharacteristic radiation lines emitted by channeled electrons is 10%. Therefore the dependence of the line widths on the crystal temperature[19] can provide information on the Debye temperature of the crystal and on correlation of the thermal vibrations.[17,18,37] The dependence on the temperature of a silicon crystal of the energies and widths of the radiation lines for electrons with energy 3.5 MeV channeled along the ⟨111⟩ axis is shown in Fig. 8.[19] The nature of the theoretical temperature dependence of the line width in scattering by thermal vibrations of atoms (Γ_T) with allowance for their correlation, which leads to an increase of Γ_T by 1.2–1.3 times (the dashed line in Fig. 8b), is in good agreement with the experimental data, which are shown in the figure by the circles. The correlation with the six nearest atoms in a string is characterized by a number $C = \Sigma_{i=-3}^{i=3} (\mathbf{r}_a^{(i)}\mathbf{r}_a^{(0)})_T/\rho^2$, which turned out to be $C = 6$.[17] The contribution of electron scattering, as expected, depends only weakly on the temperature and amounts to about 10% of the total line width $\Gamma_T + \Gamma_e$.

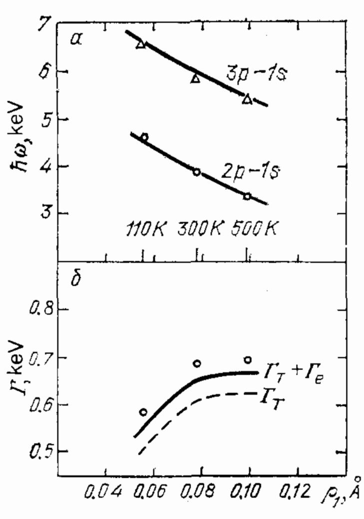

FIG. 8. Location of lines in the radiation emitted by 3.5-MeV electrons channeled along the ⟨111⟩ axis of silicon (a), and their widths (b) as functions of the crystal temperature.[19] The solid lines correspond to calculation of the scattering by thermal vibrations of the atoms with inclusion of their correlation Γ_T and scattering by atomic electrons (Γ_e).

The spectra of the radiation emitted by channeled relativistic electrons along atomic strings is apparently more convenient for evaluation of the correlation of thermal vibrations, since in this case the contribution of Doppler broadening of the lines is minimal.

The influence of a correlation of the thermal vibrations of atoms in the lattice on the shift of the radiation lines emitted by channeled electrons in the planes of LiF has been investigated in Ref. 38, and the scattering by vibrations of valence electrons in planar channeling of positrons and its influence on the shift and width of the radiation lines has been considered in Ref. 39.

2.8. Study of radiation defects

The influence of radiation defects on the spectrum of radiation emitted by 54.5-MeV electrons in a LiF crystal is shown in Fig. 9.[14] The crystal irradiation dose was respectively 0, 10^{17} 10^{18}, and 10^{19} el/cm^2. It can be seen from the results given that for radiation doses less than 10^{17} el/cm^2 the radiation spectrum remains unchanged. At the same time for large doses the spectrum shape changes greatly.[40]

The degradation of the radiation spectrum permits evaluation both of the degree of damage to the crystal and of the limit of application of the method as a nondestructive method of investigation of the properties of crystals.

3. EXPERIMENTAL TECHNIQUE. COMPARISON WITH OTHER METHODS OF STUDY OF CRYSTALS

For study of crystals by spectroscopy of channeled-particle radiation it is possible to use low-current electron accelerators which give particle beams with energies from a few MeV to tens of MeV. Such accelerators include Van de Graaff machines, linear accelerators, and microtrons. A typical experimental arrangement for spectroscopy of channeled-particle radiation is shown in Fig. 10. An electron

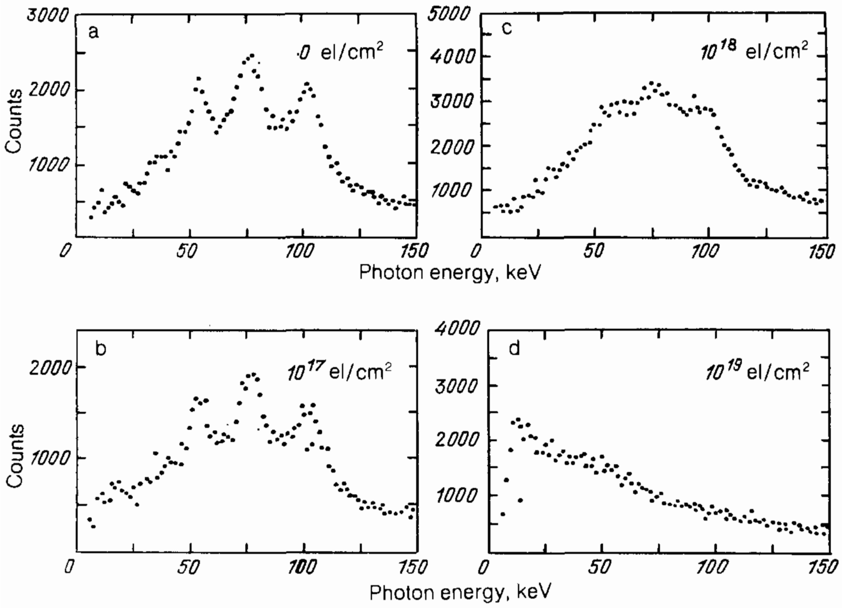

FIG. 9. Radiation spectra emitted by 54-MeV electrons in a single crystal of LiF after irradiation by electrons with a dose O (a), 10^{17} el/cm^2 (b), 10^{18} el/cm^2 (c), and 10^{19} el/cm^2 (d).[14]

beam from the accelerator 1 passes through a beam shaping system 2 consisting of quadrupole lenses and absorbing collimators and then hits the crystal being studied, which is placed in a triaxial goniometer 3. After passing the crystal the beam of particles is deflected by a bending magnet 4 into a beam dump 5. The channeled-particle radiation, cleared of the charged component, hits an x-ray detector 6. Study of a crystal by means of a positron beam is carried out similarly, with the only difference that the positrons are obtained by conversion of an electron beam. According to the data of Ref. 14, at currents of 10^{-13} A the heating of a crystal of thickness 20 μm does not exceed $2\cdot 10^{-4}$ K if one takes into account only cooling as the result of radiation, which greatly facilitates the performance of experiments.

Let us compare this method for study of crystals with other, already established traditional methods.

A comparison of the characteristic features of such methods of study of solids as electron microscopy, x-ray diffraction, and Rutherford backscattering of ions with channeled-particle radiation is given in Table I.[14] It can be seen from the table that the methods of crystal study listed supplement each other. Therefore study of crystals by means of channeled-particle radiation permits the class of objects of study to be extended and permits more complete information to be obtained on their properties.

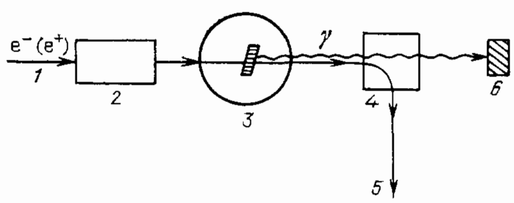

FIG. 10. Experimental arrangement for study of the spectroscopy of radiation emitted by channeled particles. 1—electron (or positron) accelerator, 2—beam shaping system, 3—triaxial goniometer with crystal, 4—bending magnet, 5—beam dump for charged particles, 6—x-ray detector.

4. PHOTONUCLEAR ANALYSIS OF MATTER WITH USE OF RADIATION EMITTED BY CHANNELED PARTICLES

The use of channeled-particle radiation considerably extends the possibilities of such methods of study of materials as photonuclear analysis. Photonuclear analysis is based on the nuclear reactions (γ,n), $(\gamma,2n)$, and (γ,p) in which energetic photons excite reactions with emission of neutrons and protons. Among a large number of methods of element analysis, photonuclear analysis is distinguished by high selectivity and sensitivity (10^{-5}–10^{-6}%).[41] At the present time bremsstrahlung of electrons with energies 10–30 MeV is used as a photon source for photonuclear analysis.[41] An important characteristic of the photon source in this case is the spectral brightness of the radiation. A comparative analysis of the spectral brightness of bremsstrahlung from electrons with energy $E = 9$ MeV in an amorphous target and the radiation used by channeled electrons with energy 900 MeV (Ref. 44) shows that the brightness of bremsstrahlung in graphite is

$$\frac{\Delta E}{\Delta\Omega} = 6\ \text{MeV/sr}\ ,$$

while for radiation produced by channeled particles in the $\langle 100\rangle$ axial channel of diamond[44]

$$\frac{\Delta E}{\Delta\Omega} = 2.0\cdot 10^{6}\ \text{MeV/sr}\ .$$

Thus, for the same average power of the accelerator, by increasing the electron energy by 100 times it is possible to obtain a gain in radiation brightness of almost 4000 times if the radiation produced by channeled particles is employed. The number of photons per electron in the latter case for $E = 900$ MeV is $\Delta N_{\text{ph}} = 1.2\cdot 10^{-3}$ photons/electron in a 0.5-MeV interval. These photons are emitted into an angle of $6\cdot 10^{-4}$ radian. The number of photons emitted in bremsstrahlung by an electron with $E = 30$ MeV in the same angle and energy interval is $\Delta N_{\text{ph}} = 4.2\cdot 10^{-8}$ photons/electron. Another advantage of channeled-particle radiation in application to photonuclear analysis is the possibility of control of

TABLE I. Comparison of a number of methods of study of crystals[14].

	Electron microscopy	Ion channeling	x-ray diffraction	Radiation emitted in channeling
1. Object character-obtained	Photography with high resolution	Identification and locations of impurity atoms	Study istics of bulk properties, interatomic distances, amplitude of atom vibrations	Study of bulk properties: crystal potential, amplitude of atom vibrations
2. Sample thickness	Not greater than $\sim 1.0\,\mu m$	Not greater than $\sim 1.0\,\mu m$	Thick samples can be used	From 1 μm to $\sim$ 1 mm
3. Means of obtaining information	Electrons up to the MeV range are used	Positively charged ions with energy from $\sim$ 1 keV up to $\sim$ 1 MeV	Information is obtained based on the intensity of the diffracted wave	Information is obtained based on the characteristics of radiation emitted by electrons and positrons with energies from 1.0 MeV up to 10 GeV
4. Features of the method	The object can be damaged			Electrons and positrons are different means of investigation

the maximum energy density in the radiation spectrum, which can be shifted into the giant-resonance region of photonuclear reactions, thus increasing the yield of photoneutrons or photoprotons, which increases the sensitivity of the method.

5. CONCLUSIONS

The spectroscopy of radiation emitted by channeled particles is a new method of study of the properties of crystals. An important feature of the method, like study of the location of atoms in a lattice on the basis of the orientation dependence of the yield of characteristic x rays excited by channeled electrons,[42,43] is the localization of the relativistic electrons or positrons near certain atomic planes or strings. Therefore, in contrast to diffraction methods, the spectrum of the radiation emitted by channeled particles carries direct information on the crystal potential In spite of the fact that study of the radiation of channeled particles began only eight years ago, the results which have been accumulated up to the present time show that investigators have begun to use the radiation spectra of channeled electrons and positrons to find the Debye temperature of crystals, to obtain crystal potentials more accurately, to determine the density of electrons near crystal strings and planes, to study various impurities in crystals, and also to investigate superstructures and complex crystals. In addition, the method permits study of the correlation of thermal vibrations of atoms in the lattice and also of radiation defects which arise in a crystal as the result of bombardment by charged particles.

For successful use of the method it is necessary to have sources of relativistic electrons with energies 4–50 MeV. At the present time most experimental studies have been carried out outside of the Soviet Union. The development of similar studies in the USSR is being held back by a shortage of relativistic electron sources in this energy region. Therefore further progress in the development of crystal studies by means of channeled-particle-radiation spectroscopy will be directly related to the coming into use of electron accelerators with energies of 4–50 MeV and small divergence.

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