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Radiation Effects, 1983, Vol. 71, pp. 185–189
0033-7579/83/7104-0185$18.50/0

IONIZATION ENERGY LOSSES OF RELATIVISTIC POSITRONS PASSING THROUGH A SILICON SINGLE CRYSTAL AND ELECTRON EMISSION

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Ionization-loss spectra have been measured for 1.2 GeV positrons transmitted through a silicon single crystal at different angles to the crystal axis ($\theta=0.4\times10^{-4}$ rad, 10^{-3} rad, 2.5×10^{-2} rad; θ being the angle between the [111] crystal axis and the positron beam direction). For the particles aligned with the axis ($\theta=0$), the most probable energy loss decreases by 20%. The dependence of the positron-induced electron emission on the silicon crystal orientation is found.

1 INTRODUCTION

The effect of crystal orientation on ionization-loss spectra has been studied in previous experiments[1] for heavy relativistic particles only. From these experiments it followed that under axial channeling conditions, the most probable energy losses of protons and positive pions decreased compared to random orientation by as much as 36%.

The main difference between ionization losses of protons, pions and positrons is caused by different maximum energies transferred to the target electron and dependent on the mass of the initial particle. A large amount of energy transferred to target electrons during one collision leads to the production of high-energy electrons that carry away the greater part of the energy. Therefore, we investigate here not only the ionization-loss spectra of positrons for different crystal orientations, but the orientational dependence of the electron emission from the crystal as well.

2 IONIZATION LOSSES

This work was performed using the LU 2 GeV linear accelerator at the Kharkov Institute of Physics and Technology of the Ukrainian Academy of Sciences. The 1.2 GeV positron beam was guided to hit the silicon single crystal, 1.8 mm thick, which simultaneously served as a semiconductor detector. The positron beam divergence was 2×10^{-4} rad, the beam spot on the crystal was about 4 mm in diameter, and the energy spread was estimated to be $\sim0.5\%$. The crystal orientation (the alignment of the [111] crystal axis with the particle beam direction) was performed with a goniometer arrangement using the positron radiation intensity in the crystal. The accuracy of reading the angles of crystal rotation was 5×10^{-5} rad. The energy-loss spectra were recorded by a pulse-height analyzer. The detector was energy calibrated against a 5.3 MeV α-particle source. The energy resolution of the detector was 64 keV, getting much worse (~ 160 keV) under the linac background conditions.

The positron ionization-loss spectra for the random ($\theta=2.5\times10^{-2}$ rad) and aligned ($\theta=0$) crystal are shown in Figure 1a. Here, θ is the angle between the [111] crystal axis and the particle beam direction. On the ordinate, we have plotted the number of particles in the energy range ΔE determined by the channel width of the analyzer and set to be $\Delta E=5.43$ keV. The energy E left by the positron in the detector is plotted on the abscissa. The solid curve in the figure shows the calculated distribution of energy losses with the energy-resolution correction for the detector.

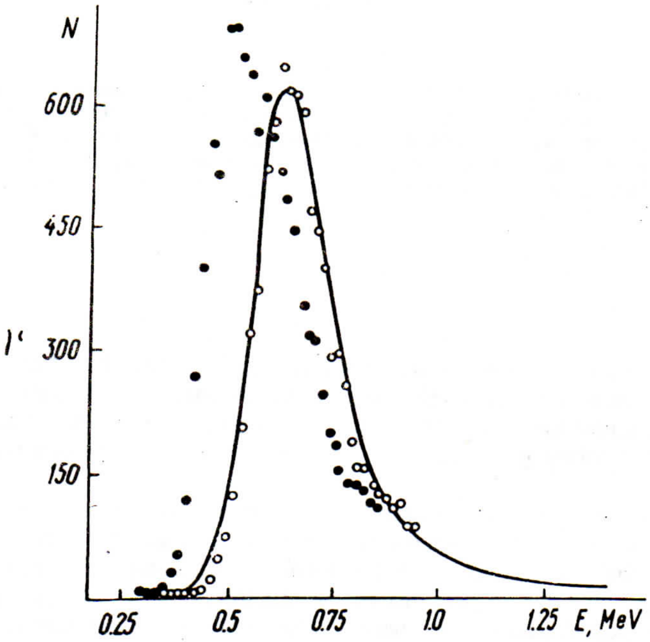

FIGURE 1a Ionization-loss spectra for 1.2 GeV positrons in the silicon single crystal. ●, $\theta=0$; ○, $\theta=2.5\times10^{-2}$ rad; —— calculation.

The energy-loss distribution function has been derived by Landau[2] and is written as

$$f(\lambda)=\frac{1}{\pi Ax}\int_0^\infty \exp\left(-\frac{\pi}{2}y\right)\cos(y\ln y-\lambda y)dy,$$

where

$$\lambda=\frac{E-Ax(\ln 2Ax\,mc^2/P^2-0.577-\delta)}{Ax},$$

$A = 183.3\times10^{-3}$ MeV/cm, x is the target thickness, cm, $P = 165\times10^{-6}$ MeV is the mean ionization potential, $\delta = -4.38$ is the correction for the environment polarization,[3] E is the energy loss, and $mc^2 = 0.511$ MeV.

The most probable energy loss is defined as the energy at which the function $f(\lambda)$ is maximum. Since $f(\lambda)$ has a maximum at $\lambda = -0.222$, the most probable energy loss may then be obtained from the expression

$$E_{\text{prob.}} = Ax\left(\ln\frac{2Ax\,mc^2}{P^2} + 3.58\right).$$

In our calculations we found it to be 0.59 MeV, which is in good agreement with the measured value of the most probable energy loss in the random crystal,

$$E_{\text{prob.}} = 0.58 \pm 0.02 \text{ MeV}.$$

The shape of the measured energy-loss distribution also shows good agreement with the calculated one.

For the positrons channeled along the [111] axis, the most probable energy loss decreases by 20% and is measured to be $E_{\text{prob.}} = 0.46 \pm 0.02$ MeV. The distribution becomes broader and has a steeper low-energy-loss side.

Figure 1b shows the energy-loss spectra of positrons for the silicon crystal alignments $\theta = 4\times10^{-4}$ rad and $\theta = 10^{-3}$ rad. When the angle between the [111] axis and

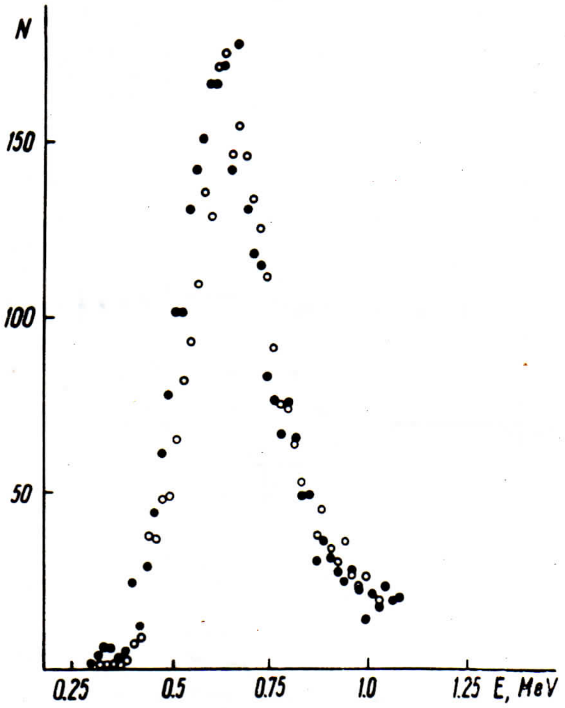

FIGURE 1b Ionization-loss spectra for 1.2 GeV positrons in the silicon single crystal. ●, $\theta = 4\times10^{-4}$ rad; ○, $\theta = 10^{-3}$ rad.

the beam direction is equal to the critical angle of channeling ($\theta=4\pm10^{-4}$ rad), the most probable energy loss increases and approaches the value for the random crystal. The distribution becomes more symmetrical and its width gets smaller than that for the aligned crystal. As the angle θ increases up to 10^{-3} rad, the most probable energy-loss value and the shape of the curve remain nearly the same as compared with the energy-loss distribution for $\theta=4\times10^{-4}$ rad, but the number of the particles, the energy losses of which are less than the most probable ones, decreases.

3 ELECTRON EMISSION

Some of the electrons produced from the atomic ionization and elastic positron scattering leave the crystal carrying away a fraction of the energy. Owing to the electron emission from the crystal, the latter becomes positively charged. The value of this charge characterizes the number of emitted electrons. The orientational dependences of the electron emission from 1.2 GeV positrons for a silicon single crystal, 0.18 mm thick, are shown in Figure 2. The electron emission spectrum consists of high-energy ($E>0.1$ keV) and low-energy ($E<0.1$ keV) electrons.[4] To determine the contribution from low-energy electrons, we used ring-shaped collectors,[5] located on both sides of the crystal, to which the voltage was applied. In the figure, I_0 is the electron emission from a random crystal for the cut-off potential

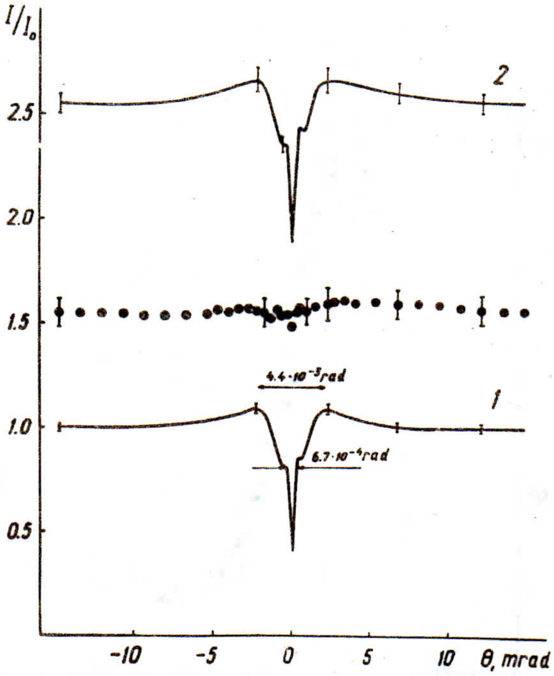

FIGURE 2 Orientational dependence of electron emission from the silicon single crystal. 1, high-energy electron yield; 2, the total high- and low-energy electron yield; ●, low-energy electron yield.

$U = -300$ V. Curve 1 was measured at $U = -300$ V, and curve 2 was obtained at $U = +300$ V. The dots show the difference between curves 2 and 1, which is responsible for the yield of low-energy electrons (not above 300 eV). Contrary to the yield of low-energy electrons, the yield of high-energy electrons (curve 1) essentially depends on the crystal orientation. (A similar property has been found for the transmission of relativistic electrons.[6]) The maximum yield is obtained at an angle of crystal orientation $\theta = 2.2 \times 10^{-3}$ rad. It decreases as the angle of orientation decreases and has a sharp fall-off at $\theta = 3.35 \times 10^{-4}$ rad. For the aligned crystal ($\theta = 0$), the high-energy electron emission decreases by a factor of 2.4 as compared to the random crystal ($\theta = 2.5 \times 10^{-2}$ rad).

Thus, not only the energy deposited by positrons in the crystal, but also the electron emission are highly influenced by crystal orientation.

ACKNOWLEDGEMENTS

The authors are grateful to V. V. Avdejchikov for his kind help in mastering the semiconductor technique, and to V. I. Artyomov and F. A. Peev for efficient provision of the positron beam from the electron linac.

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