Positron Production in Tungsten Crystals by 1.2-GeV Channeling Electrons

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The efficiency of positron production by a 1.2-GeV electron beam incident on a tungsten single crystal oriented in an axially channeling condition has been experimentally studied. Positron yields from a 1.2-mm-thick crystal have been measured to be $\sim 2.5-3.0$ times larger than those from amorphous targets with the same thickness. A simple model simulation of the positron production process shows that coherent bremsstrahlung, as well as channeling radiation, contributes to the enhancement of the positron yields. [S0031-9007(98)05357-5]

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The study on the interaction of relativistic electrons with a single crystal has revealed interesting physical phenomena such as channeling radiation, parametric x-ray radiation, as well as coherent bremsstrahlung. While these physical processes should be studied further, it is expected that they will be applied in the generation of various radiation beams.

Recently, there has been increasing interest in developing high-intensity positron sources for e^+e^- collider rings and future e^+e^- linear colliders in high-energy physics experiments. An intense positron source is also important in advanced storage rings for synchrotron radiation and accelerators for material science.

Positrons for accelerators have so far been obtained from high-energy electrons hitting an amorphous heavy-metal target with a thickness of $\sim 2-6$ radiation lengths, depending on the electron energy. Positrons are produced through the electromagnetic cascade shower process in the target. In this method, however, the electron-beam intensity is limited due to the heat load on the target. Also, the thick target causes an undesirable increase in the multiple-scattering angle of the produced positrons.

The use of a single crystal as the target has been proposed in order to improve the positron production efficiency [1–4]. This idea is based upon the fact that incident electrons channeled along the crystal axis emit the channeling radiation which is far more intense than the radiation emitted by the Bethe-Heitler process [5–8], and the target thickness corresponding to one radiation length is greatly reduced. Since the photon energies of the channeling radiation are low, the energies of produced positrons are also low, facilitating capture in the subsequent acceleration stage. Two different ways of fabricating the target can be considered [3]: One way is to use the thin crystal only for emitting photons, followed by the amorphous material to create e^+e^- pairs. In another way, the crystal works both as a photon emitter and as a e^+e^- producer. In the latter scheme, some of the produced positrons are expected to enter the channeling condition in the target resulting in a narrow angular spread. Motivated by these obvious advantages, several authors have estimated by simulation how promising the crystal target is. The results show positron yield from the crystal may be several times larger than that from the amorphous target with the same thickness for the multi-GeV electron beam [3].

If the crystal target were used in an actual accelerator, some difficulties such as radiation damage or the thermal deformation of the crystal might arise. Before the study of these foreseen problems, it is indispensable at this stage to make a proof-of-principle experiment. Thus, we have made an experiment to measure the fundamental features of the positron production in the crystal using the 1.2-GeV electron beam from the electron synchrotron at the Institute for Nuclear Study, University of Tokyo. The duty factor of the electron beam is 16% [9], which is high enough to allow the use of scintillation counters for measuring the momentum and the angular distribution of the produced positrons.

In the present measurement, the tungsten single crystal, which acted as a photon emitter and as a positron generator, was mounted on a goniometer. Photons from the target were Compton scattered by an aluminum plate situated 10 m behind the target, and were detected by a sodium-iodide (NaI) photon detector. The energy window of the NaI detector was chosen between 0.8 and 6.7 MeV, where the contribution of the channeling radiation was much larger than that from the Bethe-Heitler process. Thus, we could adjust the crystal axis relative to the electron beam by observing the yield from the NaI detector.

The positrons produced in the target were momentum analyzed by a magnetic spectrometer, which consisted of a 50° bending sector magnet, a double collimator, a pair of plastic scintillators and a total-absorption-type NaI detector situated at the focal point of the magnet. The momentum range was below 40 MeV/c, the momentum acceptance being 5%. The angular acceptances were 12 and 6 mrad in the horizontal and vertical directions, respectively. The whole path of the positron was enveloped in a helium bag to diminish multiple scattering, and counters were shielded against background radiation. A twofold coincidence of the plastic scintillators defined the positron emission from the target. The signals from the NaI detector were used to confirm the positron energies determined by the magnetic field. The spectrometer was mounted on a rotating table, which enabled us to measure the angular distribution of generated positrons.

The electron-beam intensity was monitored by a special device as outlined below. A stack of thin silicon crystal foils, 1.7×10^{-3} radiation length in total, was placed in the beam supported by a goniometer. The parametric x rays emitted from the crystal at 13° with respect to the beam were detected by the NaI detector [10]. The ratio of the x-ray counting rate to the electron-beam intensity was calibrated with a low-intensity electron beam. This intensity measurement system was highly reliable since it was free from the spurious signals due to the soft components accompanying the electron beam. The experiment was carried out with an intensity of about 10^6 electrons per second.

The beam emittance of the 1.2-GeV electron beam extracted from the synchrotron is known to be 1×10^{-7} mrad in both horizontal and vertical planes [11]. The FWHM beam size at the target was 3.0 mm, giving an estimate for the FWHM beam divergence at the target of about 0.12 mrad.

We prepared three tungsten crystals as listed in Table I. Mosaicities shown in the table have been obtained from Laue pictures, giving the states of the crystal surfaces. The thinnest crystal and the other two are from different factories, the former being of much better quality than the latter two. However, the large mosaicity of thicker crystals represents the local deformation of the crystal, and does not mean that the mosaic structure ranges over the entire crystal.

Results of the measurements are described below basically on the thinnest tungsten crystal with less imperfection. The positron-yield variation when the goniometer is rotated around the vertical axis near the axial channeling condition is shown in Fig. 1. The emission angle and the momentum of the positron are 0° and 20 MeV/c, respectively. One can see that the positron yield is drastically enhanced when the crystal axis ⟨100⟩ is parallel to the electron beam. The goniometer angle giving the positron-yield peak coincides exactly with the one giving the photon yield peak, and the angular widths of the peak are almost the same as each other. A conspicuous broadness of the peaks, together with a curve in the figure, is discussed below.

TABLE I. Tungsten crystals prepared for the experiment and measured positron-yield enhancements. All of the crystals were aligned along a ⟨100⟩ axis. FWHM is for the goniometer angle dependence of the enhancements.

Thickness (mm)/ Radiation Length	Mosaicity (mrad)	Enhancement	FWHM (degrees)
1.2/0.34	≤1.5	2.6 ± 0.3	1.2 ± 0.1
2.4/0.69	≈50	1.6 ± 0.3	2.4 ± 0.1
4.8/1.37	≈50	1.3 ± 0.3	2.2 ± 0.1

When the goniometer is rotated off the electron-beam direction by 5°, the positron yield can be regarded as the same as that from an amorphous target. The momentum distributions of the positrons at this goniometer position, together with those in the channeling condition, have been measured for various production angles. As an example, the momentum distributions at 0° are shown in Fig. 2. The enhancement of the positron yield at the channeling condition is seen over the measured momentum range up to 40 MeV/c. The emission-angle dependences of the positrons with a momentum of 20 MeV/c

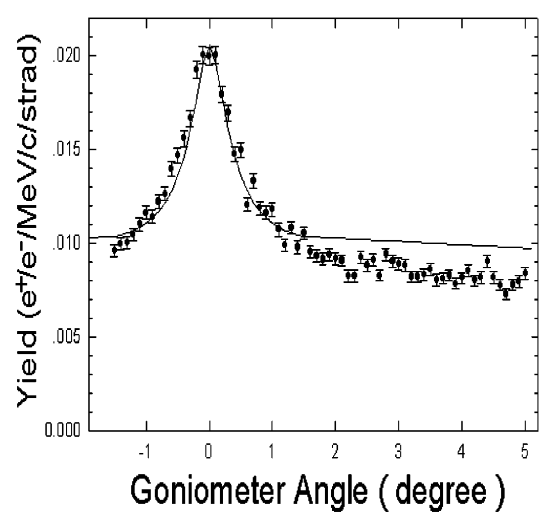

FIG. 1. Goniometer angle dependence of the positron production from the 1.2-mm-thick tungsten crystal. The positron momentum is 20 MeV/c, emission angle being 0°. The curve shows the results of calculation according to the coherent bremsstrahlung theory.

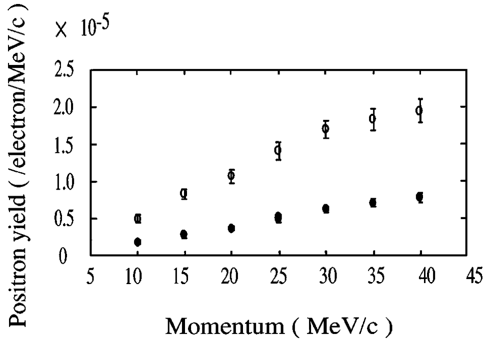

FIG. 2. Momentum distributions of the positrons from the 1.2-mm-thick tungsten crystal at the channeling condition (open circles) and off the channeling condition (solid circles) for the positron emission angle 0°.

are shown in Fig. 3. The positron-yield enhancement is observed up to 30°. Both distributions show an exponential decrease of the positron yield for large production angles, and are similar to each other showing that most of the produced positrons do not satisfy the channeling condition.

The enhancement factors defined by the ratio of the positron yield at the channeling condition to the one off the channeling condition by 5° are summarized in Fig. 4. The enhancement factors are seen to be almost the same for different production angles within the error. As for the momentum dependence, the enhancement factor ranges around 3 in a low momentum region and is about 2.5 for higher momenta, the weighted mean being 2.6 ± 0.3.

We made similar measurements for the other two pieces of crystal. The fundamental results are summarized in Table I. It is seen that, as the crystal thickness increases, the positron-yield enhancement for the aligned crystal decreases and the angular width of the enhancement becomes large. This behavior was expected because the incident electron may be subject to so-called dechanneling [7] and to multiple scattering during a short passage in the crystal, and also because the mosaicity is larger for the thicker crystals in the present experiment.

When one examines the results of the present experiment, it is notable that the peak of the positron-yield enhancement has a large angular width even for the thinnest crystal, as shown in Fig. 1. It is about 10 times wider than the critical angle for the channeling, $\sqrt{2U_0/E_0}$, where U_0 is the depth of a string potential in the crystal [12] and E_0 is the electron energy, being about 1 mrad in the present condition. This fact suggests that an appreciable part of the peak comes from other radiation processes than the channeling, such as the coherent bremsstrahlung at the very small angle along the crystal axis [14,15]. Thus, we have made rough estimates on the significance of each radiation process by simple calculations. First of all, the effect of the channeling radiation in creating positrons was calculated by combining the well-established computer code EGS-4 for the electromagnetic cascade shower [16] with the formula for channeling radiation [6,17]. In the calculation, the tungsten crystal was divided into layers with a thickness of 100 μm which corresponds to the dechanneling length [7], and the calculation was made at each layer with the initial conditions determined by the previous layer. The probability of electron capture into the channeling regime decreased sharply inside the crystal. The resultant positron-yield enhancement factor for the thinnest target remains 1.6 at most, which is about 60% of the experimental value. Thus, neither the positron-yield enhancement nor its angular width can be explained by the channeling radiation alone.

Another critical angle of radiation is the "strong field angle" or the so-called Baier angle, V_0/m, where V_0 is the scalar of a string potential and m is the electron mass

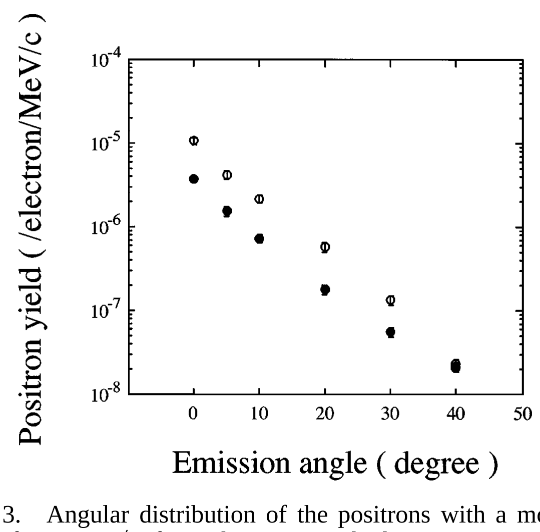

FIG. 3. Angular distribution of the positrons with a momentum of 20 MeV/c from the 1.2-mm-thick tungsten crystal at the channeling condition (open circles) and off the channeling condition (solid circles).

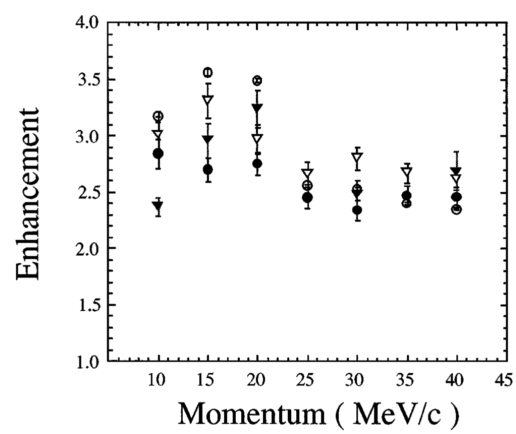

FIG. 4. The momentum and angular dependence of the enhancement factors of the positron emission from the 1.2-mm-thick tungsten crystal. The open circles, the solid circles, the open triangles, and the solid triangles are for the emission angles 0°, 5°, 10°, and 20°, respectively.

[18]. Since it is almost the same as the one for channeling, the most plausible process affecting the positron-yield enhancement is the coherent bremsstrahlung. The simulation calculation for this process was made according to the method of reference [15], taking the crystal mosaicity into account. Also, the energy loss and the multiple scattering of the incident electron as well as of the produced positron were taken into account. The multiple scattering and pair creation kinematics were assumed to be the same as for amorphous material. The result of the calculation for the thinnest target is shown as a curve in Fig. 1. The curve shows the angular width of the peak, and does not have exact meaning at the disoriented region. It is seen that the curve reproduces the experimental peak fairly well, strongly suggesting a contribution from the coherent bremsstrahlung to the positron-yield enhancement. Simulation calculation based upon more systematic theoretical treatment is now going on.

From the viewpoint of application, the results of the present proof-of-principle experiment support the novel idea of using crystals as targets for positron sources. A large characteristic angle of the positron-yield enhancement, which is clarified in the present experiment, seems to be favorable for the application of this process in actual accelerators. It can be expected that thicker crystals will also give large positron-yield enhancement for higher incident-electron energies due to the increase of the dechanneling length and also due to decreasing multiple-scattering angle with increasing energy.

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