Observation of parametric x-ray emission by protons

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(Submitted 20 September 1991)

Pis'ma Zh. Eksp. Teor. Fiz. **54**, No. 9, 493–495 (10 November 1991)

A parametric x-ray emission caused by 70-GeV protons in a silicon crystal has been observed. Values of the quantum yield of this emission were found experimentally for two observation angles. The angular distribution of the emission was found. The results are compared with corresponding theoretical predictions.

The construction of the Serpukhov accelerator and storage-ring complex (UNK) for a proton energy of 3 TeV by the Institute of High-Energy Physics makes it worthwhile to develop new methods for measuring the properties of beams of high-energy charged particles. One effect which could be used for this purpose is the parametric x-

 0021-3640/91/210494-04$01.00

ray emission which occurs during the uniform motion of a relativistic charged particle through a crystal.[1] The angular distribution and quantum yield of this emission depend on the Lorentz factor of the charged particle, so the particles can be identified, and their energy measured. This type of emission has the further advantage that for crystals of reasonable thickness the optimum quantum yield of the emission is reached at substantial values (on the order of a few degrees) of the observation angle, measured from the direction in which the particle is moving.

Parametric x-ray emission has been studied in detail both theoretically[2-4] and experimentally.[5-11] Its angular, frequency, energy, and polarization characteristics have been studied for diamond, silicon, gallium arsenide, and quartz crystals under a variety of experimental conditions. All the experiments which have been reported have used electron beams. It is thus worthwhile to study the parametric x-ray emission caused by other charged particles.

In this letter we are reporting the first experimental results on the observation of parametric x-ray emission by a 70-GeV proton beam. The experiments were carried out in the 14th channel of the Serpukhov U-70 proton synchrotron. The target was a silicon crystal with dimensions of $40\times40\times18$ mm. The crystal was oriented with respect to the proton beam in such a manner that the photons which were emitted were diffracted by (220) planes. The Bragg angle was 2–6°. The 70-GeV proton beam was deflected into the channel from the ring chamber of the accelerator with the help of a curved crystal. The beam intensity was $(1–5)\times10^6$ particles per burst. The angular divergence was ~3 mrad. The reason for the choice of these Bragg angles is that the theory predicts a maximum quantum yield of the parametric x-ray emission for targets ~1 cm thick, and the energy of the radiation is in the region 30–100 keV. A computer-controlled triaxial goniometer was used to adjust the crystal with respect to the proton beam. The radiation detector was moved by means of an x,y stage with stepping drives. The mechanical devices were controlled by a DVK-3M computer, which also accumulated the results, displayed them, and performed a preliminary analysis.

The x radiation was detected by a scintillation detector based on a $Ce:YAlO_3$ crystal 25 mm in diameter and 3 mm thick. This crystal had a short flash time ($\tau = 30$ ns) and a high light yield,[12] so a fast trigger could be reliably generated for controlling the spectrometric ADC. The energy resolution of the detector at the 59.5–keV γ-ray line of a collimated ^{241}Am source was 28%. The detection apparatus was organized to record only those x rays whose signals coincided in time with those pulses from the scintillation telescope of the channel which were associated with the passage of a proton. It was thus possible to raise the signal-to-background ratio substantially. The number of protons which interacted with the target was determined from the signals from a plastic scintillation detector with dimensions of 40×40 mm which was placed very close to the target and which was also operated in coincidence with the beam telescope of the channel.

Figure 1 shows spectra of the parametric x radiation caused by 70-GeV protons in the case of generation at (220) planes in Si for two Bragg angles, $\theta_{B1} = 5.7°$ and $\theta_{B2} = 4.7°$. Here $\omega_1 \approx 32.4$ keV and $\omega_z \approx 39$ keV. The distance from the target to the detector was 75 cm. The values found for the x-ray energies agree well with the

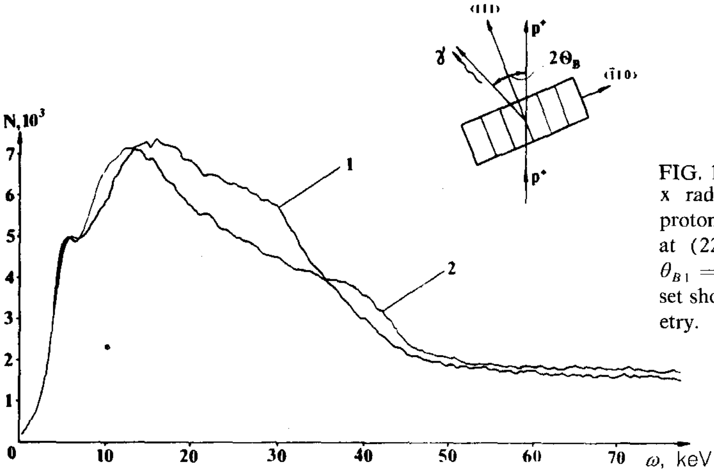

FIG. 1. Spectra of the parametric x radiation caused by 70-GeV protons in the case of generation at (220) planes in silicon. *1*—$\theta_{B1} = 5.7°$; *2*—$\theta_{B2} = 4.7°$. The inset shows the experimental geometry.

calculated energies. We also measured the quantum yield of the parametric x radiation for these two emission angles, finding $N_1 = (7.87 \pm 1.57) \times 10^{-6}$ photon/p^+ and $N_2 = (1.77 \pm 0.35) \times 10^{-5}$ photon/p^+. Theoretical quantum yields were then calculated from the formulas in Refs. 13 and 14. The results are $N_1^T = 8.42 \times 10^{-6}$ photon/p^+ and $N_2^T = 1.10 \times 10^{-5}$ photon/p^+. We see that the agreement of the theoretical and experimental values is good.

Figure 2 shows an angular distribution of the parametric x radiation caused by 70-GeV protons in the case of generation at (220) planes in Si. The distance from the detector to the target here was 60 cm. The detector was scanned in the horizontal

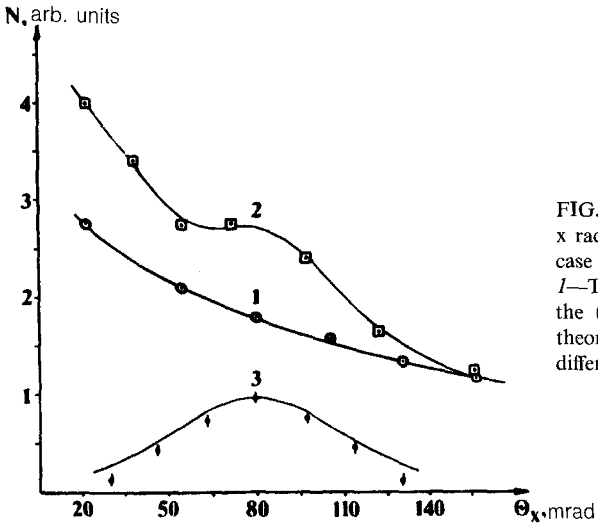

FIG. 2. Angular distribution of the parametric x radiation caused by 70-GeV protons in the case of generation at (220) planes in silicon. *1*—The angle between the proton velocity and the (220) plane is 0°; *2*—2.3°. Curve *3* is a theoretical distribution; the points on it are the differences between curves *2* and *1*.

plane at an average step of 25 mrad. The points on these curves were found by integrating the x-radiation spectrum over the energy interval 30–100 keV. Curve *1* was measured for the case in which the protons were incident on the target in a direction parallel to the (220) planes. The target was then rotated to a position such that the (220) planes made an angle of 2.3° with the proton velocity (the x-radiation yields are shown by curve *2*). Curve *3* shows the results of a numerical calculation based on the equations of Refs. 13 and 14. The points here are the differences between the experimental values of curves *2* and *1*. The peak in the angular distribution was observed at an angle $2\theta_B = 4.6°$ from the direction of the proton velocity. The experimental width of the angular distribution at half-maximum is $\Delta\theta_{\text{exptl}} = 50 \pm 7$ mrad; the theoretical value is $\Delta\theta_{\text{theo}} = 73$ mrad.

These results show that a parametric emission of x radiation due to protons was indeed observed in these experiments. The energy of the radiation, the quantum yield, and the width of the angular distribution all agree well with the theoretical predictions. The contribution of diffracted bremsstrahlung in this case is suppressed by four orders of magnitude, since multiple scattering of protons is extremely slight in this case.

This work was carried out within the framework of the POLÉKS project. We are deeply grateful to S. B. Nurushev, director of the project, for active support of this research. We also thank V. V. Rykalin of the Institute of High-Energy Physics for assistance in the experiments. Our thanks also go out to several of our colleagues at the Scientific-Research Institute of Nuclear Problems: M. V. Korzhik for furnishing the Ce:$YAlO_3$ crystal, A. A. Fedorov for assistance in preparing the detector, and I. Ya. Dubovskaya and G. K. Savchuk for useful discussions and a theoretical analysis of the yield of parametric x radiation for particles with various masses.

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Translated by D. Parsons