

## Ion tracks in apatite at high pressures: the effect of crystallographic track orientation on the elastic properties of fluorapatite under hydrostatic compression

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Static elasticity measurements at high pressures were carried out on oriented fluorapatite single crystals, some of which contained oriented amorphous ion tracks (ITs) implanted with relativistic Au ions (2.2 GeV) from the UNILAC linear accelerator at GSI, Darmstadt. High-pressure experiments on irradiated and non-irradiated crystal sections were carried out in diamond-anvil high-pressure cells under hydrostatic conditions. In situ single-crystal diffraction was performed to determine the high-precision lattice parameters, simultaneously monitoring the widths of X-ray diffraction Bragg peaks. High-pressure Raman spectra were analyzed with respect to the frequency shift and widths of bands, which correspond to the Raman-active vibrational modes of the phosphate tetrahedra. Swift heavy ion irradiation was found to induce anisotropic lattice expansion and tensile strain within the host lattice dependent on the ion-track orientation. The relatively low Grüneisen parameter for the  $\nu_{1b}(A_g)$  mode, which has been assigned to originate from the volume fraction of the amorphous tracks, and the  $\gamma(\nu_{1a})/\gamma(\nu_{1b})$  ratio reveals compressive strain on the amorphous ITs. The comparative compressibilities for the host lattice reveal approximately equivalent bulk moduli, but significantly different pressure derivatives ( $K_T = 88.4 \pm 0.7$  GPa,  $\partial K/\partial P = 6.3 \pm 0.3$  for non-irradiated,  $K_T = 90.0 \pm 1.7$  GPa,  $\partial K/\partial P = 3.8 \pm 0.5$  for irradiated samples). The axial compressibility moduli  $\beta^{-1}$  reveal significant differences, which correlate

with the ion-track orientation [  $\beta_a^{-1} = 240 \pm 5$  GPa,  $\beta_c^{-1} = 361 \pm 14$  GPa,  $\partial(\beta_c^{-1})/\partial P =$

$11.3 \pm 1.2$ ,  $\partial(\beta_c^{-1})/\partial P = 11.6 \pm 3.4$  for irradiation  $\perp(100)$ ;  $246 \pm 9$  GPa,  $364 \pm 57$  GPa,  $9.5 \pm 2.9$ ,  $14.7 \pm 14.1$  for irradiation  $\perp(001)$ ,  $230.7 \pm 3.6$  GPa,  $373.5 \pm 5.1$  GPa,  $19.2 \pm 1.4$ ,  $20.1 \pm 1.8$  for no irradiation]. Line widths of XRD Bragg peaks in irradiated apatites confirm the strain of the host lattice, which appears to decrease with increasing pressure. By contrast, the bandwidths of Raman modes increase with pressure, and this is attributed to increasing strain gradients on the length scale of the short-range order. The investigations reveal considerable deviatoric stress on the [100]-oriented tracks due to the anisotropic elasticity, while the compression is uniform for the directions perpendicular to the tracks, which are aligned parallel to the  $c$ -axis. This difference might be considered to control the diffusion properties related to the annealing kinetics and its observed anisotropy, and hence to cause potential pressure effects on track-fading rates.