We present a novel method for k-space mapping of electronic bands with utmost efficiency. The instrument combines the k-imaging properties of a cathode-lens microscope with the superior resolution of ToF spectroscopy and the parallel acquisition capability of ToF-PEEM [1]. For the first experiments a frequency-doubled Ti-sapphire laser was used for excitation by two-photon photoemission (2hv = 5.8 – 6.6 eV). A delay-line detector serves for rapid single-event counting with 150 ps time resolution and 10 Mcps maximum count rate. The dispersion behavior of the bands is observed in a 3D (k_x, k_y, E) matrix as schematically depicted in Fig.1, which is confined by the photoemission horizon (condition k_z =0) in the shape of a E-k_z paraboloid. The k_z- and energy-range are presently limited by the low excitation energy. Mapping a complete data set with good statistics requires only few minutes of acquisition time. An integral Ir-based imaging spinfilter [2] yields spin resolved 3D-maps.

The low excitation energy is well suited to study surface states close to the centre of the SBZ. As first system we chose the highly anisotropic Dirac-type surface state recently discovered on W(110) [3] and the analogous state on Mo(110). These states arise in a pocket-shaped partial bandgap region, nevertheless the existence of Dirac states on metals was very surprising [3,4]. Fig. 2 shows k_x-k_y sections at E_F (a,b) and E-k_z sections displaying the crossover points for clean W(110) at about E_B=1.25eV (c) and at 0.6eV for oxygen-covered Mo(110) (d). Hole doping by oxygen shifts the Dirac state to lower binding energy; in addition we found a pronounced pattern of very similar surface states on W(110)-O(1x1) and Mo(110)-O. No bulk bands are visible in this region of k-space. In all cases the Dirac state is highly anisotropic (2mm symmetry), revealing massless behavior (i.e. linear band dispersion) along one mirror plane and a high effective mass (flat band region) along the second mirror plane (g,h), similar as measured and calculated for clean W(110) [3,4]. For the oxidic surfaces we observe a complex 3D k-space behavior that is hard to elucidate in conventional ARPES. Using s-, p- and circular polarization we probe orbital symmetries and hybridization effects of the band states. The dichroism pattern in Fig. 2(e) is antisymmetric with respect to all mirror planes and can be understood in terms of a simple d_2-orbital model.


Acknowledgement: Project funded by BMBF (05K12UM2 and 05K12EF1).
Fig. 1: Scheme of the experiment; the 3D \((k_x,k_y,E)\) time-resolving single-electron counting detector registers each electron within the \(E-k\) paraboloid with a maximum count rate of \(10^7\) counts per second.

Fig. 2: Sections through the \((k_x,k_y,E)\) matrix (at \(2h\nu=6.6\) eV). a,b: Fermi surfaces of W(110) and Mo(110)-O, respectively; c,d corresponding E-\(k\) sections. e: circular dichroism in the region above the Dirac point of clean W(110), g: anisotropic shape of the Dirac point; f,h: calculated patterns for \(E_B=0.9\) and \(1.2\) eV [4].