Introduction and Motivation
The extraordinarily strong electric field provided by the nucleus of a very heavy one-electron ion exposed to its inner electrons is the testing ground for bound-state quantum electrodynamics (QED) in a largely unexplored domain. Experimentally the QED contribution to the 1s binding energy is accessible via a direct measurement of the K-shell transitions with sufficient accuracy. The corresponding Lyman transitions in high-Z ions lie in the hard x-ray region. Previously the x-ray energy has been measured with the aid of germanium x-ray detectors of limited resolution [1]. The present experiment marks the leap to wavelength-dispersive spectroscopy of substantially higher spectral resolving power simultaneously coping with the low x-ray intensity.

Experiment
Figure 1 schematically shows the twin crystal-spectrometer assembly. Bi-FOCAL, operated in the FOCAL geometry which has been arranged at the ESR gas jet. The spectrometer system [3, 4] equipped with two 2D position-sensitive Ge strip detectors [5, 6], F1 and F2, was used in an experiment with one-electron Au$^{78+}$ ions at a velocity corresponding to $\beta = 0.4711$. The twin spectrometers were deliberately arranged symmetrically around the ion-beam at observation angles of $\pm 90^\circ$ in an angular-sensitive geometry where the usual Doppler broadening and angular uncertainty are near their maximum. The imaging properties of the FOCAL crystal optics are turned to advantage retaining nearly full spectral resolution also for the fast moving source.

Complementary to the crystal spectrometer an array of low-temperature micro calorimeters were mounted in a velocity-sensitive geometry at an observation angle of 145°, where angular uncertainties are reduced. That experiment, run in parallel, is described in another report [7].

Besides the high background-suppression capabilities of FOCAL figure 2 demonstrates its slanted Lyman-$\alpha$ and -$\beta$ lines of Au$^{78+}$ in accordance with the underlying x-ray-optical design. Without crystal optics Doppler broadening would blur the whole spectral range displayed. The spectrum shown in figure 3 was obtained by projecting the intensity along the slanted lines. In the experiment the Lyman-$\alpha_1$ line was Doppler tuned to the position of the 63.1-keV gamma-ray line emitted from a radioactive sample of $^{169}$Yb used as a calibration source rendering dispersion uncertainties unimportant.

Systematic Effects
At an observation angle of exactly 90° the required transition wavelength $\lambda_{1\text{on}}$ in the emit-
The spectrum of hydrogen-like $\text{Au}^{78+}$ revealed as a position spectrum taken by F2. The Lyman-α and -β doublets appear as slanted lines caused by the Doppler effect in counterplay with the crystal optics employed.

The measured wavelength that do not simply cancel and which need to be carefully identified and analyzed. We are currently in the process of assessing systematic corrections and their corresponding uncertainties referring to the procedures and mathematical algorithms by which the spectral lines are located including long-term drifts plus all the geometrical effects due to the positions and angular orientations of the x-ray source, of the curved silicon crystals and of the x-ray detectors. A particularly important example is the position of the gas-jet target in the horizontal plane spanned by the ion-beam and the spectrometer axis. This was investigated in a separate experiment by scanning a thin wire across the gas jet [8].

Here we mention two other examples of the crystal optics which need to be understood: (i) the radius of curvature of the two crystals named Karl and Ludwig was measured by three different methods which gave consistent results as summarized in figure 4. (ii) the observed slope of the spectral lines along with the calculated prediction is summarized in Table 1. Although the slanting effect is generally confirmed the measured slopes tend to be slightly lower than predicted.

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References