FOCAL – PRECISION X-RAY SPECTROSCOPY FOR EXTREME FIELDS IN HIGH-Z IONS *

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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 **FO**cusing **C**ompensated **A**symmetric **L**aue [2] 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 $\pm 90°$ in an angular-sensitive geometry where the usual Doppler broadening and angular Doppler uncertainties 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].

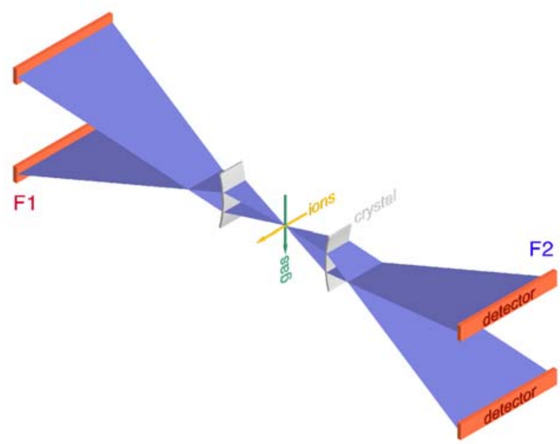

Figure 1: Two crystal-spectrometers, Bi-FOCAL, symmetrically arranged around the ion beam at the ESR gas jet. Wavelength dispersion occurs in the vertical direction and the spectra are recorded by two position-sensitive x-ray detectors F1 and F2 mounted at two of the possible four locations as indicated.

Besides the high background-suppression capabilities of FOCAL figure 2 demonstrates its slanted Lyman-α and -β 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-α_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 λ_{ion} in the emit-

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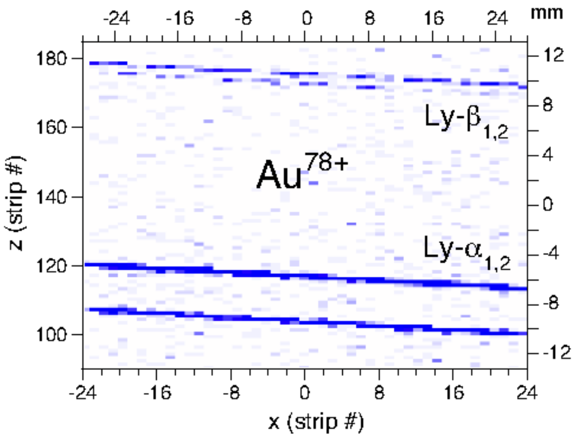

Figure 2: The spectrum of hydrogen-like Au^{78+} revealed as a position spectrum taken by F2. The Lyman-α and -β doublets appear as slanted lines caused by the Doppler effect in counterplay with the crystal optics employed.

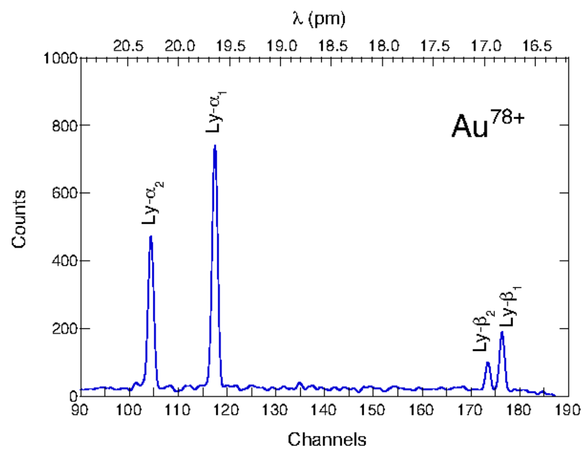

Figure 3: The Lyman-α and -β doublets of Au^{78+} obtained by a projection of the two-dimensional intensity distribution of figure 2.

ter frame is simply related to the laboratory wavelength by $\lambda_{lab} = \gamma\,\lambda_{ion}$ where γ denotes the relativistic Lorentz parameter. The two arms of the spectrometer assembly are mounted accurately inline resulting in observation angles $\lambda_{lab}(\vartheta)$ and $\lambda_{lab}(\pi - \vartheta)$, respectively. However missalignment of the ion beam relative to the spectrometer axis might still persist. This class of uncertainties are well canceled by averaging the two laboratory wavelengths as $\lambda_{ion} = (\lambda_{lab}(\vartheta) + \lambda_{lab}(\pi - \vartheta))/(2\gamma)$.

In addition there are a number of systematic influences on 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].

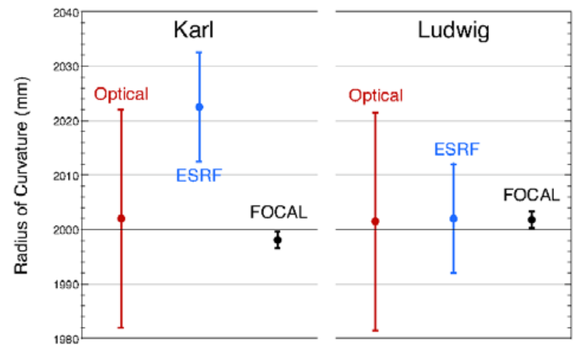

Figure 4: The radius of curvature of the two silicon crystals *K*arl and *L*udwig determined by three different methods: optical reflections on the polished crystal surfaces, mapping with synchrotron radiation at the ESRF and by operating FOCAL as a scanner.

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.

Table 1: Doppler slanting: predicted and observed slopes of the Lyman-$\alpha_{1,2}$ and Lyman-β spectral lines of Au^{78+} at a velocity of $\beta \equiv v/c = 0.4711$.

	Lyman-α_2	Lyman-α_1	Lyman-β
predicted	0.01922	0.01862	0.01597
observed			
FOCAL-1	0.0184(2)	0.0183(2)	
FOCAL-2	0.0188(3)	0.0179(2)	0.0165(4)

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References

[1] A. Gumberidze *et al.*, Phys. Rev. Lett. **94** (2005) 223001.

[2] H. F. Beyer, Nucl. Instrum. Methods. A**400** (1997) 137.

[3] H.F. Beyer *et al.*, Spectrochimica Acta **B 59** (2004) 1535.

[4] H.F. Beyer *et al.*, Spectrochimica Acta **B 64** (2009) 736.

[5] D. Protić *et al.* IEEE Trans. Nucl. Sc. **52** (2005) 3194.

[6] U. Spillmann *et al.*, Rev. Sc. Instr. **79** (2008) 083101.

[7] S. Kraft-Bermuth *et al.*, GSI scientific report 2013.

[8] T. Gaßner *et al.*, GSI scientific report 2013.