PAPER

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Phys. Scr. **T156** (2013) 014022 (3pp) doi:10.1088/0031-8949/2013/T156/014022

High-precision x-ray spectroscopy of highly charged ions with microcalorimeters

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Received 3 September 2012
Accepted for publication 29 October 2012
Published 23 September 2013
Online at stacks.iop.org/PhysScr/T156/014022

Abstract
The precise determination of the energy of the Lyman $\alpha 1$ and $\alpha 2$ lines in hydrogen-like heavy ions provides a sensitive test of quantum electrodynamics in very strong Coulomb fields. To improve the experimental precision, the new detector concept of microcalorimeters is now exploited for such measurements. Such detectors consist of compensated-doped silicon thermistors and Pb or Sn absorbers to obtain high quantum efficiency in the energy range of 40–70 keV, where the Doppler-shifted Lyman lines are located. For the first time, a microcalorimeter was applied in an experiment to precisely determine the transition energy of the Lyman lines of lead ions at the experimental storage ring at GSI. The energy of the Ly $\alpha 1$ line $E(\text{Ly-}\alpha 1,{}^{207}\text{Pb}^{81+}) = (77937 \pm 12_{\text{stat}} \pm 25_{\text{syst}})$ eV agrees within error bars with theoretical predictions. To improve the experimental precision, a new detector array with more pixels and better energy resolution was equipped and successfully applied in an experiment to determine the Lyman-α lines of gold ions $^{197}\text{Au}^{78+}$.

PACS numbers: 32.30.Rj, 31.30.J, 85.25.Oj, 7.20.Mc, 07.85.Nc

1. Introduction

The precise determination of the energies of the Lyman-$\alpha 1$ and Lyman-$\alpha 2$ lines in hydrogen-like heavy ions for the determination of 1s Lamb shift provides a sensitive test of quantum electrodynamics (QED) in very strong Coulomb fields, not accessible otherwise. Whereas QED effects in hydrogen have been studied and compared to theory with an accuracy of 10^{-6}, the experimental accuracy for high-Z elements is limited to about 1%, one order of magnitude less than the theoretical predictions [1]. As microcalorimeters for hard x-rays provide a versatile instrument which combines excellent energy resolution with an acceptable detection efficiency, this detector concept is now exploited for Lamb shift measurements [2, 3].

Microcalorimeters detect the temperature change of an absorber after an incoming particle has deposited its kinetic energy as heat. To keep the heat capacity of the absorber small to obtain a large temperature signal, such detectors are operated at low temperatures (50–100 mK). As the excitation energy for a phonon is almost independent of the absorber material, the absorber can be optimized for a specific experiment. For high-energy x-rays, superconducting high-Z materials like Pb or Sn are used to combine low heat capacity with high detection efficiency. As the heat capacity also limits the active area of one single microcalorimeter to typically 0.5–1 mm^2, arrays of many detectors are mandatory to cover large solid angles. The most commonly used thermometers are temperature-dependent resistances. A high temperature dependence $\mathrm{d}R/\mathrm{d}T$ for high sensitivity is achieved either

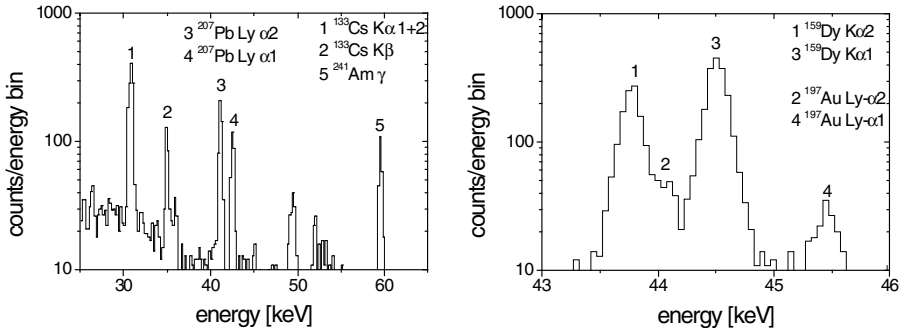

Figure 1. Example spectra of the measurement of the Lyman-α transition energies for ^{207}Pb (left side) and ^{197}Au (right side), including the calibration lines. The spectra are not yet corrected for the Doppler shift. The data for ^{197}Au are still preliminary.

with compensated-doped semiconductors or superconductors stabilized at the transition temperature (Transition Edge Sensors, TES).

2. Experimental setup

To meet the experimental requirements of the Lamb shift experiment, the microcalorimeters should have a relative energy resolution of the order of $\Delta E/E \leqslant 1 \times 10^{-3}$ for $E\gamma = 50$–100 keV and a total detection efficiency (including detector solid angle) of $\geqslant 10^{-6}$, which may be reached with a photo peak efficiency of $\geqslant 30\%$ and an active detector area of $\geqslant 50$ mm^2. The detector modules for the present experiments are designed on the basis of silicon microcalorimeters which were developed by the Goddard/Wisconsin groups [4]. Each module contains 36 detector pixels, which consist of silicon thermistors, micro-machined from a wafer of silicon and featuring an implanted area as the thermometer, and of Sn or Pb absorbers glued onto the thermistors with an epoxy varnish.

For the Lamb shift measurement the experimental setup was optimized with respect to energy resolution and detection efficiency for hard x-rays at the experimental area of the experimental storage ring (ESR). To obtain a reasonable detection solid angle, the detectors have to be located as close as possible to the interaction zone at the internal gas-jet target of the ESR. Accordingly, a special ^{3}He/^{4}He-dilution refrigerator with a side arm which fits to the internal target geometry was designed [5]. The detector array is mounted on the cold finger at the end of the side arm and can be irradiated through a system of aluminum-coated Mylar windows. The cryostat reaches a base temperature of 11.5 mK, and a cooling power of 400 μW at 100 mK. The operating temperature of the detectors may be chosen between 50 and 100 mK. To obtain the pulse height spectrum, the detector signals are amplified and digitized by a Flash ADC. Digital filtering algorithms as well as corrections for potential drifts of the operating temperature are applied offline to obtain the optimal energy resolution.

The experiments were carried out at the ESR storage ring at GSI: a beam of bare $^{207}Pb^{82+}$ or $^{197}Au^{79+}$ nuclei was injected into the ESR, stored, cooled and decelerated to a velocity of $\beta = v/c \approx 0.5$ with a momentum spread $\Delta\beta \leqslant 2 \times 10^{-5}$. When the ions interact with the gas-jet target, the nuclei may capture one electron and promptly emit Lyman-α x-rays. The Lyman-α x-rays were detected by the microcalorimeter mounted under $\Theta \approx 145^\circ$ relative to the ion beam at a distance of about 340 mm. Due to the high kinetic energy of the ions, the Lyman-α lines are Doppler-shifted to an energy of about 40 keV. In addition, x-rays and γ-rays from suitable calibration sources were detected.

3. Results

In the measurement for ^{207}Pb, a prototype detector array of eight pixels with Sn and Pb absorbers was used. The absorbers had an area of about 0.4 mm^2 and a thickness of about 100 μm for Sn and about 50 μm for Pb, respectively. The detector performance was tested under laboratory conditions with 59.6 keV photons from a ^{241}Am source. An excellent energy resolution of $\Delta E_{\mathrm{FWHM}} = 65$ eV was obtained, which exceeds the energy resolution of a Germanium detector by about one order of magnitude.

The pulse height spectrum for a single pixel with a Pb absorber is displayed in figure 1 (left side). The Lyman lines and the calibration lines are unambiguously identified. Unfortunately, under running conditions the energy resolution was of about $\Delta E_{\mathrm{FWHM}} = 200$ eV due to a worsened signal-to-noise ratio. An additional contribution comes from so-called 'Doppler broadening': the finite diameter of the gas jet as well as the ion beam leads to an emitting sphere with a radius of approximately 2.5 mm. This results in an uncertainty in the angle Θ which causes a broadening of the Lyman-α lines of ΔE_{FWHM} (target) ≈ 160 eV, independent of the intrinsic energy resolution of the detectors.

For the Lyman-$\alpha 1$ line, we obtain a value of $E(\text{Ly-}\alpha 1, {}^{207}\text{Pb}^{81+}) = (77937 \pm 12_{\mathrm{stat}} \pm 25_{\mathrm{syst}})$ eV [6]. This value is in excellent agreement with the theoretical calculation of $E(\text{Ly-}\alpha 1, {}^{207}\text{Pb}^{81+}) = 77934.4(5)$ eV [7]. Due to the nonlinearity of the $R(T)$ as well as the $C(T)$ characteristics, nonlinearity in the energy calibration has to be taken into account. The uncertainties in the nonlinear energy calibration, as well as the uncertainty in the exact position of the gas-jet target and the detector array are the main contributions to the systematic error.

To improve the statistical accuracy, a new array of the same type has been equipped, which consists of 32 pixels with Sn absorbers. The Sn absorbers were chosen because they have been found to show a higher signal amplitude and better noise performance. To reduce the overall high-frequency noise, the shielding of the room-temperature electronics was improved. Tests in the laboratory with the improved

setup showed an improved energy resolution of 30–40 eV at 59.6 keV for all 32 pixels.

This new array was recently applied in another Lamb shift measurement, namely for $^{197}Au^{78+}$. A preliminary spectrum for one of the pixels is displayed in figure 1 (right side). To eliminate the systematic error in the Lyman-α energy due to the uncertainty of the nonlinear energy calibration, a ^{159}Dy calibration source with lines close to the Lyman-α lines was used. In the small energy range covered by the calibration lines as well as the Lyman-α lines, nonlinearity can be neglected, which reduces the systematic error of the Lyman-α lines in the laboratory frame to about 8 eV per pixel. From our preliminary results we estimate a precision in the Lyman-α transition energy in the emitter frame of about 5 eV when averaging all pixels. This would already be close to the 4.6 eV which are the current best value obtained for uranium with conventional Germanium detectors [1]. However, data analysis is still in progress.

4. Conclusion and perspectives

The first successful measurement of the energy of the Lyman lines in hydrogen-like heavy ions with microcalorimeters was performed. The obtained energy of $E(\text{Ly-}\alpha 1, ^{207}\text{Pb}^{+81}) = (77937 \pm 12_{\text{stat}} \pm 25_{\text{syst}})$ eV agrees well with the theoretical predictions. To improve statistical and systematic errors, a new detector array with more pixels as well as improved read-out electronics was prepared and applied to measure the Lyman-α energy of gold ions. In combination with a new calibration source, the expected precision is about 5 eV, but data analysis is still in progress.

The main systematic limitation remains the uncertainty due to the absolute position of the gas-jet target and the lateral width of the ion beam. The ESR group at GSI is currently constructing a new target with an improved geometry which will reduce the diameter of the gas-jet from about 5 mm as of now to about 1 mm. Furthermore, one can reduce the velocity of the ion beam, or even stop the ions in an ion trap, where at zero velocity literally Doppler-free spectroscopy will be possible. At GSI, the ion-facility HITRAP will be able to stop bare ions up to uranium, cool them to a 'kinetic' temperature of 4.2 K and store them for many hours [8]. At such a setup, the excellent energy resolution of the microcalorimeters can be exploited in its full potential.

Acknowledgments

We thank K Eberhard and J Runke from the Institute of Nuclear Chemistry of the Johannes Gutenberg University for producing the ^{159}Dy source. We also thank our co-experimentators from the FOCAL group for good cooperation during the measurements. This work was supported by the Emmy Noether Young Researchers Program of the Deutsche Forschungsgemeinschaft (DFG).

References

[1] Stöhlker Th *et al* 2008 *Quantum Electrodynamics in Extreme fields* (*Lecture Notes in Physics* vol 745) (Berlin: Springer) p 157
[2] Egelhof P *et al* 1996 *Nucl. Instrum. Methods* A **370** 263
[3] Egelhof P and Kraft-Bermuth S 2005 *Cryogenic Particle Detection* (*Topics in Applied Physics* vol 99) ed C Enss (Berlin: Springer) p 471
[4] Stahle C *et al* 1996 *Nucl. Instrum. Methods* A **310** 173
[5] Bleile A *et al* 2002 *AIP Conf. Proc.* **605** 409
[6] Andrianov V *et al* 2009 *AIP Conf. Proc.* **1185** 99
[7] Johnson W R and Soff G 1985 *At. Data Nucl. Data Tables* **33** 405
[8] Kluge H-J *et al* 2007 *J. Phys.: Conf. Ser.* **58** 9