RAPID COMMUNICATIONS

PHYSICAL REVIEW A VOLUME 32, NUMBER 3 SEPTEMBER 1985

Rapid Communications

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Application of decelerated bare nuclei to precision spectroscopy of one-electron ions

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(Received 11 April 1985)

Bare Cl nuclei were decelerated and then allowed to capture a single electron in a He-gas target. By this method pure hydrogenlike Cl ions were prepared in an excited state from which the $2p$-$1s$ transition wavelength could be accurately ($\approx 10^{-5}$) measured without distortion by spectator electrons. After Doppler correction utilizing measurements at four different ion velocities ($v/c \approx 0.038$–0.067), fine-structure splitting and $1s$ Lamb-shift values were determined within 15% error bars, which, while far from the potential possible limits of our method, are in agreement with theoretical results.

High-precision x-ray spectroscopy of transitions in few-electron heavy ions was started mainly for the test of quantum electrodynamic (QED) radiative corrections to Dirac energy levels.[1,2] These corrections (which for such ions are dominated by the self-energy term) were examined rather accurately for the classical $2p_{1/2}$-$2s_{1/2}$ energy shift in atomic hydrogen itself, whereas for higher nuclear charges ($Z > 1$), sufficiently high accuracies which could really challenge QED predictions were never reached. The main reasons for extending such studies to heavy ions are first of all the strong increase with Z of the energy shifts from the QED corrections, and second, the possibility of combining QED corrections with electron correlations in ions with more than one electron.

The accuracy in the Lamb-shift spectroscopy is basically determined by the size of the energy shift relative to the width of the levels from which the transition is observed. Because the self-energy term scales with n^{-3}, and since the dominant width of the $2p$ states enters in the $2p_{3/2,1/2}$-$2s_{1/2}$ separation energy measurement as well as in the measurement of $2p_{3/2,1/2}$-$1s_{1/2}$ transition energy, the accuracy for a $1s$ energy shift can in principle exceed that for a $2s$ energy shift. The Lamb shift is consequently (in both cases) defined as the difference of the measured transition energy and the corresponding energy differences from the Dirac equation.

The $1s_{1/2}$ Lamb-shift measurements require very accurate determination of the Lyman-α energy interval because of its large size compared to the Lamb shift. In experiments of this type reported up to now[3–5] two main limiting problems were encountered in the production of high-Z Lyman-α spectra: The Lyman-α lines were found to be distorted by the presence of spectator electrons, and the correction for the Doppler effect, in the case of a fast-moving ion, proved to be a serious limitation on the accuracy of those measurements.

We want to present here a method which in principle overcomes both previous limits to the accuracy: the spectator electron and the Doppler problem. By utilizing modern accelerator technology, beams of bare Cl nuclei were prepared at 23.5, 38.7, 56.4, and 67.1 MeV by poststripping Cl^{+9} and Cl^{+11} at 130 MeV and decelerating with the linear accelerator of the Max-Planck-Institut für Kernphysik, Heidelberg.[6] A schematic diagram of the experimental apparatus is shown in Fig. 1. In a differentially pumped He-gas target a well-collimated part of the beam was allowed to capture a single electron. An atomic-hydrogen target would be in principle ideally suited for single-electron capture but, with He as the target, double-electron capture with one electron in a high n-state is negligible. The n distribution by electron capture from He was estimated by a straightforward Oppenheimer-Brinkman-Kramers (OBK) calculation[7] to range from $n = 2$ to about 14 with a maximum at $n = 6$ to 8, dependent on the velocity. The $2p_{1/2}$ and $2p_{3/2}$ levels are then filled by cascading transitions within a flight path of

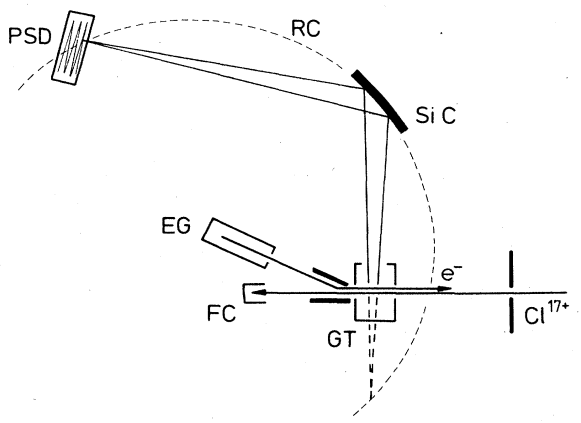

FIG. 1. Schematic view of the experimental setup for the comparison of the Cl Lyman-α wavelength with the Ar $K\alpha$ wavelength. GT is the He- or Ar-gas target, Si C the silicon (111) crystal, FC the Faraday cup, RC the Rowland circle, EG the electron gun, and PSD the position-sensitive x-ray detector.

less than 1 mm, so that the following Lyα transition can be seen with a crystal spectrometer.

The Lyα lines were examined by a Johann-type curved-crystal spectrometer equipped with a linear position-sensitive detector of the backgammon design.[8] The crystal was a highly perfect Si(111) specimen whose radius of curvature was 1896 mm. The distance from the crystal to the detector on the Rowland circle was 1273 mm, and that to the beam inside the Rowland circle was 760 mm. The mean Bragg angle for Cl Lyα is 41.9°, the dispersion about 0.387 mm/eV, and in our experiment the beam axis was in the plane of dispersion. The reason for choosing this geometry was that the source is more extended (about 10 mm) in the plane of dispersion than perpendicular to it (the maximum energy shift in the spectra corresponds to a spatial separation of less than 2.3 mm at the beam position), so that the spectra were not distorted in our geometry by a limited source length. This geometry, however, caused a more complex Doppler correction, as we shall show below.

A sample of two spectra collected over a running time of about four hours each is shown in Fig. 2. Separate (~ 3) runs for each beam energy were performed with calibrations in between. For calibration the gas target was supplied with Ar and ionized by an intense (100-μA) 9-KeV electron beam (see Fig. 1). The Ar $K\alpha_{1,2}$ lines (see Fig. 3) were used as a wavelength standard[4] with the connection to an I_2 stabilized laser wavelength.[9]

As seen clearly in Fig. 2, and this is the important message of this Rapid Communication, the Lyα lines are symmetric and stand on a flat background. The Voigt profiles[10] (66% Gaussian and 34% Lorentzian) plus a constant background give an excellent fit of the total spectrum. The Voigt profiles (60% Lorentzian, 40% Gaussian) do not fit so well the Ar $K\alpha_{1,2}$ calibration lines on the high-energy side (Fig. 3) where satellites due to multiple ionization by the electrons are visible. As seen in Fig. 2, there is a Doppler shift even at these low velocities and with an observation angle α near 90°.

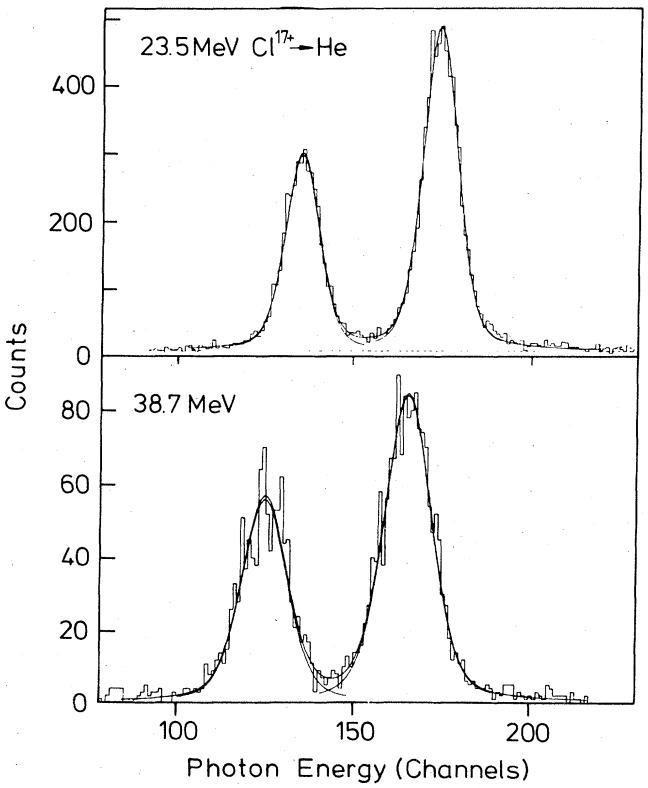

FIG. 2. Lyman-α_1 and -α_2 lines observed after single-electron capture of Cl^{17+} in He. The solid curves represent Voigt profiles fitted to the spectra.

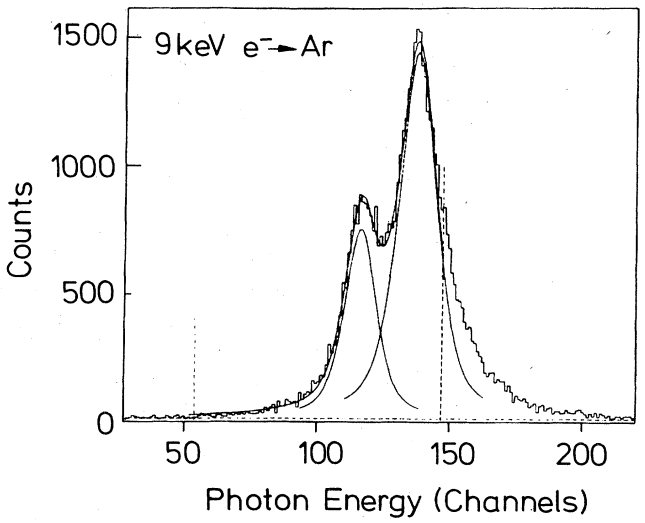

FIG. 3. Calibration spectrum of Ar $K\alpha_1$ and $K\alpha_2$ lines excited by 9-keV electron bombardment of Ar. The curves are Voigt profiles fitted to the spectrum.

The transformation of the measured laboratory energies E_L to the center-of-mass Lyα energies $E_{\text{c.m.}}$ was performed according to

$$E_{\text{c.m.}} = E_L(1-\beta^2)^{-1/2}(1-\beta\cos\alpha)\ , \tag{1}$$

by using the E_L values at the four different $\beta = v/c$ (v is the beam velocity).

A further complication is that here the angle α depends on β, since the beam axis was in the plane of dispersion. This dependence eventually brought a larger systematic error than the first expected. There are different ways to disentangle this correlation between α and E_L for a Johann-type spectrometer, which are based on different assumptions and also give somewhat different results. One is to assume that the reflection on the crystal does not move with β. Partly this was assured by bringing a knife edge to a distance of about 5 mm from the crystal and by the source length of 10 mm as explained above. The results based on this assumption give close to 10^{-5} accuracy in the energies of Lyα (E_{expt}) and therefore about 15% accuracy in the Lamb shift (ΔE_L) and the fine-structure splitting (ΔE_F). The numbers are listed in Table I, together with the observation angle α_0 (for $\beta \rightarrow 0$), and the comparison of the angle shift $\Delta\alpha$ expected from the fine-structure splitting with the one obtained from the analysis. All the values agree well within the error bars with theoretical values[11] (ΔE_{Lamb}), and with the results obtained with the assumption that the source point is fixed and the reflection on the crystal moves with β.

TABLE I. See text for an explanation of the symbols.

	E_{Dirac} (eV) (Ref. 11)	E_{expt} (eV)	ΔE_L (eV)	ΔE_{Lamb} (eV)	α_0 (deg)
$\text{Ly}\alpha_1$	2963.3095	2962.485 ±0.12	0.825 ±0.12	0.9335	89.8365
$\text{Ly}\alpha_2$	2959.4907	2958.684 ±0.15	0.807 ±0.15	0.9419	89.9094
ΔE_F (eV)	3.827	3.801 ±0.2			
$\Delta\alpha$ (deg)	0.067				0.0729

In conclusion, the results of the present experiment turn out to be more a demonstration of a powerful method than a statement of new very precise values for the Lamb shift. It has specifically been shown that single-electron capture by bare nuclei at medium and low velocities has considerable potential for high-precision spectroscopy of few-electron ions with complete elimination of spectator electrons and reduction of Doppler corrections to a manageable level. The present limitation on accuracy will be determined by beam emittance and energy spread. Here, new development in accelerator technology (such as heavy-ion cooler rings[12]) could avoid these problems so that further development of spectroscopic methods would be needed. Since this step appears practical, quite significant new results may be anticipated.

We wish to thank E. Jaeschke for the excellent operation of the linear accelerator in deceleration mode. R. D. D. acknowledges support of the Alexander von Humboldt Stiftung.

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