Lamb-Shift Measurement in Hydrogenic Phosphorus

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The Lamb shift in hydrogenic phosphorus ($Z = 15$) has been measured by the $2s_{1/2}$-$2p_{3/2}$ laser resonance-quenching method. An efficient synchronization between the light pulse from a tunable dye laser, pumped by a nitrogen laser, and the beam bursts of a cyclotron is used to enhance up to 0.8 the signal-to-background ratio. From the measured $2s_{1/2}$-$2p_{3/2}$ energy splitting, $\lambda = 5556.5(2.5)$ Å, and the calculated fine-structure splitting the Lamb shift $S = 20.18(25)$ THz was deduced. This result is confronted with the presently available calculations of QED.

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The conventional quantum electrodynamic (QED) calculations of the Lamb shift based on a perturbation series expansion in the fine-structure constant α and in αZ are not appropriate in high-Z hydrogenic ions. Two theoretical methods have been proposed[1,2] to describe the Z dependence of the Lamb shift in closed form yielding nonconcordant results.

While low-Z experiments are being continued[3] some Lamb-shift experiments in high-Z ions have been performed with either the laser resonance method[4] (F^{8+}, Cl^{16+}) or the Stark quenching method[5] (Ar^{15+}). The experiment we performed in hydrogenic phosphorus P^{14+} ($Z = 15$) is based on the resonance quenching of the $2s_{1/2}$-$2p_{3/2}$ splitting induced by a dye laser. The resonance is monitored by detection of the induced 2.3-keV Lyman α x rays as a function of the wavelength of the dye laser. The width of the resonance, as expected from the lifetime of the $2p_{3/2}$ state, is 50 Å; QED calculations[1,2] predict its centroid around 5557–5560 Å. The value of the Lamb shift is extracted by taking the difference between the fine-structure splitting, known with high accuracy,[2] and the measured value of the $2s_{1/2}$-$2p_{3/2}$ energy splitting.

A 500-nA current of P^{5+} ions of 87 MeV was extracted from the isochronous cyclotron CYCLONE of Louvain-la-Neuve. Bare P^{15+} ions, produced in a carbon foil 100 $\mu g/cm^2$ thick, are selected with the steering magnet of the cyclotron and made incident upon a second carbon adder foil (10 $\mu g/cm^2$), producing hydrogenic phosphorus ions P^{14+}, part of which are in the metastable $2s_{1/2}$ state ($\tau = 10.6\times 10^{-9}$ sec). A complete charge-state analysis and a detailed spectroscopic work have already been reported.[6-8] The ion beam was shaped by slits and antiscattering collimators to a spot of 1×20 mm^2 in the interaction region with the laser. Beam direction and shape were monitored by two dual grid-type beam scanners[9] placed before and after the interaction region. The phosphorus beam is delivered by the cyclotron in a pulsed mode with a burst duration of 5 ns full width at half maximum (FWHM) and a repetition rate of 12 MHz [cyclotron radiofrequency (rf)].

Our laser system[10] is composed of a high-peak-power (1-MW) pulsed nitrogen laser and a grating-tuned dye laser with a maximum repetition rate of 50 Hz and a pulse duration of 7 ns FWHM. The coumarin C495 dye used in this experiment allows us to tune the laser frequency through the complete $2s_{1/2}$-$2p_{3/2}$ resonance. The light pulse, focused to a spot of 1 mm diam, interacted with the beam at 90° with respect to its direction. We have[11,12] shown that the time delay of the laser output with respect to an external trigger is not constant but subject to a slow drift greatly exceeding the width of the ion burst (5 ns FWHM). In order to overcome this difficulty we have developed a new type of phaser[11] stabilizing the delay of the laser light output within 2 ns with respect to a time reference signal derived from the cyclotron rf.[12] The absolute synchronization with the ion beam is achieved by introducing a tungsten wire at the crossing point of the two beams and by recording with the same detector (plastic scintillator coupled to a photomultiplier) a time-to-amplitude converter spectrum with respect to the time reference signal, alternately with elastically scattered phosphorus ions and with scattered light of the dye laser. After this adjustment the wire is removed. In order to detect the x rays we have developed[13] a fast multiwire gas (Ar-CF_4-C_2H_2) counter with a large solid angle capable of resolving the time structure of the ion beam. Its time resolution was 30 ns FWHM which is to be compared to the cyclotron rf period of 83 ns. The electromagnetic induced noise has been completely suppressed by shielding both the laser and the x-ray detector with Faraday cages. The x-ray background, mainly due to the presence of metastable levels of heliumlike and lithiumlike phosphorus ions in the beam, was reduced by fixing the laser–ion-beam interaction region at a distance of 40 cm from the second adder foil.

Figure 1 shows the integrated x-ray counts as a function of time of several successive ion bursts separated by 83 ns. The burst hit by the laser pulse with the predicted resonance wavelength has an excess number of counts of 80% demonstrating thus the powerful possibilities of (i) pulsed accelerators in this kind of experiment, (ii) the synchronization method we achieved, and (iii) the background and noise reduction. Figure 2 shows the integrated induced x-ray counts as a function of the laser light frequency normalized to the laser power and the beam intensity.

A χ^2 best fit with a Lorentzian shape with three free parameters yields a centroid $\lambda = 5556.5(2.5)$ Å in the rest frame of the ions. The deduced value of the Lamb shift $S = 20.18(25)$ THz is in agreement with Mohr's calculations[1] $S = 20.254$ THz, Erickson's prediction, quoted by Kugel and Murnick,[14] being 20.550 THz. The experimental uncertainty includes a statistical one standard deviation 0.24 THz and an error of 0.07 THz due to the uncertainty on the angle between the ion and light beams. Uncertainties due to the beam velocity and its inhomogeneity and divergence are negligible. The value obtained for the width of the resonance, 1.8(4) THz, corresponding to the best χ^2 fit is about one standard deviation lower than the expected natural linewidth. If it is fixed to this latter value the centroid does not change significantly.

The hyperfine splitting of ^{31}P is negligible compared to the width of the resonance and has not been taken into account in the theoretical line shape.

Our experiment and those performed in hydrogenic chlorine[4] and argon[5] (Fig. 3) are in agreement with Mohr's calculations in the $Z = 15-18$ region. However, our result is also in agreement with the prediction using the perturbation-series expansion[15] giving accidentally in the $Z = 15$ region a result similar to Mohr's prediction. The predictions of the series expansion up to $Z = 15$ are between the values given by Erickson and Mohr, very close to those of Erickson for low Z and to those of Mohr for $Z = 15$. For higher-Z hydrogenic ions the series expansion[14] always gives the lowest value and drastically diverges from Erickson's and Mohr's calculations as shown in Fig. 3. The recently calculated

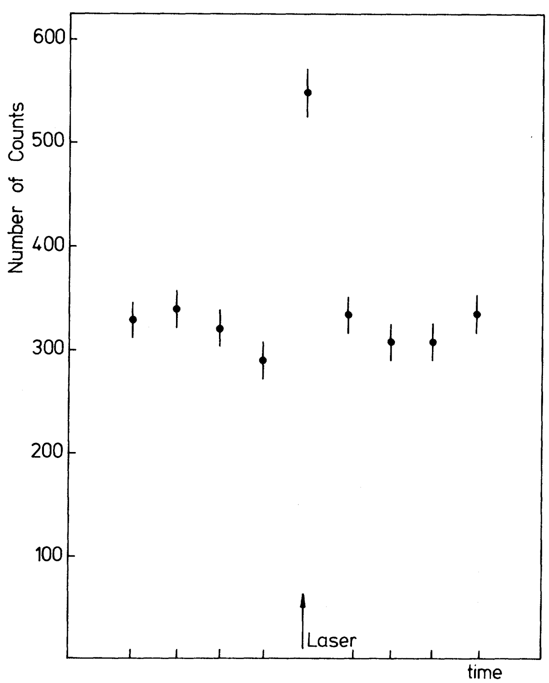

FIG. 1. Integrated x-ray counting of nine successive ion bursts as a function of time after triggering the electronics. Each point is separated from the next by 83 ns (the cyclotron rf period). The burst hit by the laser pulse has an excess counting of 80%.

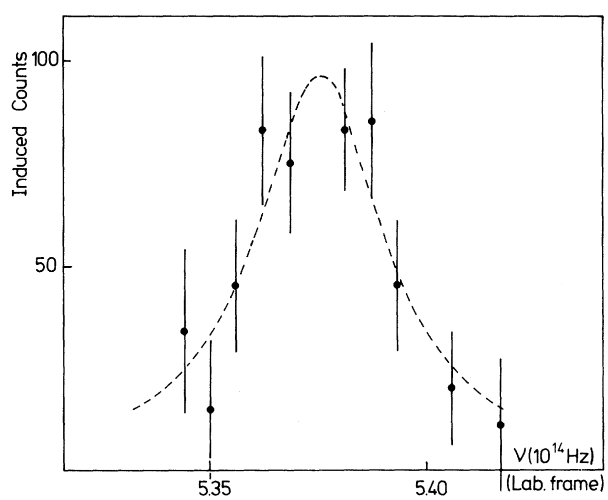

FIG. 2. Induced x-ray counts as a function of the laser light frequency normalized to the laser power and the beam intensity.

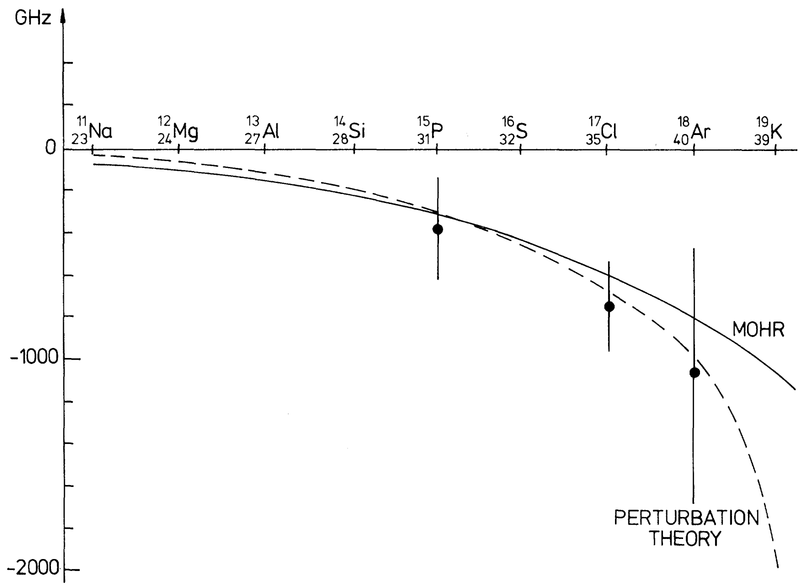

FIG. 3. Comparison between theoretical and experimental values of the Lamb shift. The full curve (Mohr) and the experimental data represent the difference with respect to Erickson's calculations. The dashed curve is the difference between the predictions of the series expansion and Erickson's calculations.

$A_{60}(1s)$ term in hydrogen by Sapirstein[16] (not directly the Lamb shift) agrees with the extrapolation of Mohr from higher Z rather than with Erickson's estimate.

A detailed description of this experiment will be given in a subsequent publication.

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